Sustainable Cities and Society: Advances 2 (2026) 100117

Contents lists available at ScienceDirect

Sustainable Cities and Society: Advances

journal homepage: www.sciencedirect.com/journal/sustainable-cities-and-society-advances

Evaluating flood-adaptive design principles: a systematic review of global practises

Funmilayo Ebun Rotimi *, Roohollah Kalatehjari, Taofeeq Durojaye Moshood

Built Environment Engineering Department, School of Future Environments Auckland University of Technology, Auckland, New Zealand

ARTICLE INFO

Keywords:
Flood-adaptive design
Flood resilience
Nature-based solutions
Sponge city
Green infrastructure
Flood risk management
Water-sensitive urban design
Systematic literature review

ABSTRACT

Flooding ranks among the most devastating natural hazards globally, affecting >1.65 billion people between 2000 and 2019 and causing direct economic losses exceeding USD 650 billion. Climate change trajectories consistently project escalating flood frequency, intensity, and geographic extent, while rapid urbanisation compounds exposure by expanding impervious surfaces, fragmenting floodplains, and concentrating vulnerable populations in coastal and riparian zones. Amid these converging pressures, the global flood management discourse has undergone a fundamental paradigm shift from resistance-based engineering towards multi-dimensional flood-adaptive design principles that embrace resilience, coexistence with water, and long-term sustainability. Despite the proliferation of case studies and sector-specific reviews, a comprehensive global synthesis evaluating the full typological spectrum of flood-adaptive design practises, their comparative effectiveness, and contextualised implementation guidance remains limited. This systematic literature review (SLR), guided by the PRISMA 2020 framework and drawing on 250 peer-reviewed articles retrieved from Scopus (2007–2026), addresses that gap by identifying, categorising, and evaluating global flood-adaptive design principles across five overarching thematic categories: Nature-Based Solutions and Green Infrastructure; Urban Water-Sensitive and Sponge City Design; Structural and Hybrid Engineering Approaches; Building-Level and Architectural Adaptations; and Governance, Community, and Spatial Planning Frameworks. Findings indicate that integrated multi-scalar strategies tend to outperform single-intervention approaches across the reviewed evidence, and that governance quality frequently emerges as a critical constraint on adaptation effectiveness across design categories. Significant disparities exist between high- and low-income contexts regarding the applicability of strategies, institutional capacity, and access to financing. Based on synthesised evidence, a Global Flood-Adaptive Design Framework (GFADF) is proposed as a conceptual framework that outlines differentiated implementation pathways for urban and rural settings across diverse geographic, climatic, and socio-economic conditions; the framework requires empirical validation before it is used as a decision-support tool. This review provides a theoretically grounded and empirically synthesised knowledge base for researchers, engineers, planners, architects, and policymakers navigating flood adaptation in an era of accelerating climate risk.

1. Introduction

Flooding is among the most severe and pervasive natural hazards worldwide, contributing disproportionately to fatalities, population displacement, and economic losses relative to other hydro-meteorological hazards. The United Nations Office for Disaster Risk Reduction estimates that between 2000 and 2019, floods affected >1.65 billion people, killed over 100,000, and caused direct economic losses exceeding USD 651 billion (UNDRR, 2020). Critically, these figures represent only reported events; the actual human cost, particularly in low- and middle-income countries (LMICs), where data collection is incomplete, is substantially higher. Projections under representative concentration pathways (RCPs) and shared socio-economic pathways (SSPs) consistently indicate that climate change will amplify flood hazard through intensified precipitation extremes, accelerated sea-level rise, and increasing frequency of compound events combining coastal and fluvial flooding (Aerts et al., 2024; Chen & Zhang, 2026; Tiggeloven et al., 2020). Simultaneously, rapid urbanisation is reconfiguring risk exposure by expanding impervious surfaces, encroaching on natural floodplains, and concentrating populations and economic assets in

* Corresponding author.
E-mail addresses: funmi.rotimi@aut.ac.nz (F.E. Rotimi), funmi.rotimi@aut.ac.nz (R. Kalatehjari), taofeeq.durojaye.moshood.moshood@aut.ac.nz (T.D. Moshood).

https://doi.org/10.1016/j.scsadv.2026.100117
Received 21 July 2026; Received in revised form 28 October 2026; Accepted 29 October 2026
Available online 30 October 2026
3051-052X/© 2026 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

flood-prone coastal and riverine zones (Dai et al., 2024; Liu et al., 2025a).

In response to these escalating pressures, the global flood management paradigm has undergone profound reconceptualisation over the past two decades (Rotimi et al., 2025b). The historically dominant approach, characterised by large-scale hydraulic engineering designed to exclude water from human settlements, has been progressively challenged by resilience-oriented frameworks that argue for adaptive coexistence with water rather than its categorical exclusion (Liao, Le & Van Nguyen, 2016; Niemann-Morris et al., 2025; Peck et al., 2022). This transition reflects growing recognition that hard infrastructure alone cannot provide adequate long-term protection, as climate uncertainty renders historical flood-return-period assumptions obsolete and the costs and ecological consequences of purely defensive engineering become increasingly untenable (Nasrollahi, Orton & Montalto, 2025). Under this broader paradigm shift, flood-adaptive design has emerged as an umbrella construct encompassing a diverse array of principles and practises operating across spatial scales from the individual building to the regional landscape, and across disciplinary domains spanning civil engineering, architecture, urban planning, ecology, social science, and governance (An & Ochiai, 2026).

Recent years have witnessed a significant expansion of the flood-adaptive design literature, leading to a broad but fragmented evidence base that spans a range of disciplines and academic journals (Qi et al., 2023). Flood-adaptive strategies have been studied under various labels: low-impact development (LID), water-sensitive urban design (WSUD), sponge city concepts, nature-based solutions (NbS), blue-green infrastructure (BGI), amphibious urbanism, floodplain restoration, and adaptive spatial planning, among others (Lu et al., 2026; Qi et al., 2023; Roggero, Brill & Tügel, 2025). While existing studies and reviews have advanced knowledge of flood-adaptive design, there remains a lack of a comprehensive synthesis that: (a) maps the complete typological spectrum of flood-adaptive design principles across global contexts; (b) systematically evaluates their comparative effectiveness across economic, environmental, and social dimensions; and (c) derives context-sensitive implementation guidance to support practise across the full spectrum of global flood-risk settings from rapidly urbanising West African cities (Ampofo, Owusu-Sekyere & Adongo, 2025; Naah et al., 2025) to coastal megacities in East and Southeast Asia (Chitwatkulsiri et al., 2025; Vichiensan et al., 2025) and rural floodplains in Europe (Palazzo, 2025; Roth & Winnubst, 2014).

This systematic literature review (SLR) addresses that gap. Employing the PRISMA 2020 framework, the overarching aim of this study is to evaluate and synthesise global practises in flood-adaptive design principles, with a view to identifying effective strategies to enhance resilience to flooding in urban and rural environments and to contribute to the development of innovative, sustainable solutions for flood risk management. Four specific objectives structure the enquiry:

To analyse the temporal, geographic, and methodological distribution of the included literature, establishing the empirical scope of flood-adaptive design scholarship.

To examine the theoretical and conceptual foundations of flood-adaptive design, tracing its paradigmatic evolution and situating key design categories within frameworks of resilience, sustainability, and equity.

To identify, categorise, and evaluate the principal categories of flood-adaptive design principles across global contexts, assessing their strategies, performance, and applicability across environmental, economic, and social dimensions.

To comparatively assess the effectiveness, sustainability, and context dependency of flood-adaptive design strategies and to synthesise the findings into a proposed conceptual framework, the Global Flood-Adaptive Design Framework (GFADF), outlining differentiated implementation pathways across diverse global contexts.

2. Methodology

This study follows a systematic literature review (SLR) methodology aligned with the PRISMA 2020 guidelines. The PRISMA framework was selected for its rigour, transparency, and reproducibility, which are particularly important for synthesising evidence across a multi-disciplinary domain such as flood-adaptive design (Bhanye, 2025). The review protocol encompassed four phases: identification, screening, eligibility assessment, and inclusion.

2.1. Search strategy and database

The primary database used for article retrieval was Scopus, a comprehensive peer-reviewed literature repository offering broad coverage across engineering, environmental science, social science, and built environment disciplines (Berlato et al., 2025). The search was conducted in May 2026 using the following Boolean search string, applied to titles, abstracts, and keywords:

TITLE-ABS-KEY (("flood-adaptive design" OR "flood resilient design" OR "flood resistant design" OR "climate-adaptive design" OR "flood adaptation" OR "amphibious architecture" OR "floating architecture" OR "flood-proof design" OR "floodproofing") AND ("flood resilience" OR "flood risk management" OR "flood mitigation" OR "urban flood" OR "sustainable drainage" OR "green infrastructure" OR "nature-based solutions" OR "blue-green infrastructure" OR "sponge city" OR "climate change adaptation" OR "sea-level rise" OR "coastal adaptation") AND ("design principles" OR "design strategies" OR "best practises" OR "global practises" OR "sustainable solutions" OR "built environment" OR "urban planning" OR "land use" OR "infrastructure")).

The search was restricted to peer-reviewed journal articles published in English between 2007 and 2026. The database query yielded an initial set of 352 records. After deduplication, title and abstract screening, and full-text assessment, 250 articles met the full eligibility criteria and were retained for data extraction and thematic synthesis.

2.2. Inclusion and exclusion criteria

Inclusion criteria were applied systematically to ensure that retained studies were directly relevant to flood-adaptive design principles and practises. Articles were included if they: (1) reported on empirically or theoretically grounded flood adaptation strategies applicable at the building, neighbourhood, city, or regional scale; (2) addressed design, planning, engineering, governance, or social dimensions of flood adaptation; (3) were published in peer-reviewed journals; and (4) were available in full text. Studies were excluded if they: (1) focused solely on flood damage estimation without adaptive strategies; (2) were conference proceedings, book chapters, or grey literature; (3) reported flood modelling without a design application; or (4) were published before 2007 or in a language other than English. Table 1 presents the inclusion and exclusion criteria used for the systematic literature review.

Table 1
Inclusion and exclusion criteria for the systematic literature review.

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles	Conference papers, book chapters, grey literature
Published 2007–2026, in English	Published before 2007
Flood adaptation strategies at any scale (from building to regional)	Flood modelling without design application
Design, engineering, planning, governance, or social adaptation dimensions	Studies focused solely on flood damage estimation
Full-text availability	Non-English language publications

2.3. Data extraction

Data were extracted from each retained article using a structured extraction template capturing: (1) publication year and journal; (2) geographic context and study region; (3) flood type addressed (riverine, pluvial, coastal, or compound); (4) primary design-principle category; (5) research methodology employed; (6) key findings and stated effectiveness of adaptation strategies; and (7) limitations and contextual conditions of applicability.

2.4. Thematic synthesis

Following data extraction, thematic synthesis was employed to identify, organise, and interpret recurrent themes across the 250 included studies. An inductive-deductive hybrid approach was adopted: initial codes were generated from the data, which were then clustered into descriptive themes aligned with the four research objectives. Five primary categories of flood-adaptive design principles emerged from this process: Nature-Based Solutions (NbS) and Green Infrastructure; Urban Water-Sensitive and Sponge City Design; Structural and Hybrid Engineering Approaches; Building-Level and Architectural Adaptations; and Governance, Community, and Spatial Planning Frameworks. These categories constituted the analytical framework underpinning the Results section.

2.5. Study selection and consideration of study quality

Screening and data extraction were conducted by two reviewers working independently, with title and abstract screening and full-text screening both cross-checked for consistency. Disagreements regarding study eligibility were resolved through discussion between reviewers, and no records required escalation. A formal risk-of-bias or study-quality appraisal was not conducted, given the heterogeneous, cross-disciplinary nature of the included literature spanning engineering, planning, and social-science methodologies, for which no single validated appraisal instrument is applicable across all study designs.

Differences in study quality were instead taken into account when interpreting the evidence, through four complementary procedures. First, the research methodology recorded for each study during data extraction (Section 2.3) was used to distinguish four broad types of evidence: (i) empirical evaluations of implemented measures, such as post-event observations, monitoring data, and cost-benefit analyses based on observed outcomes; (ii) scenario-based modelling and simulation studies; (iii) qualitative and case-study research; and (iv) conceptual papers and reviews. When judging effectiveness, greater interpretive weight was given to empirical evaluations and quantitative performance assessments, whereas modelling studies were read as indicating potential rather than demonstrated performance. Second, a finding was treated as robust only when it converged across several studies, methods, and geographic contexts; findings resting on a single study, a single context, or modelling evidence alone are reported with qualified wording (for example, "suggests" or "tends to"). Third, when studies reported conflicting findings, the transparency of their methods and the clarity with which they reported the conditions of applicability were considered. Fourth, where the evidence base for a context was thin, as for low-income and rural settings, the corresponding recommendations are explicitly flagged as provisional.

The systematic search on Scopus yielded 352 initial records. Following deduplication (removing 32 duplicate entries), 320 records proceeded to title and abstract screening. Of these, 48 records were excluded at the screening stage due to irrelevance (exclusive focus on flood modelling without adaptive design content, non-English language, or pre-2007 publication). The remaining 272 records progressed to full-text screening. Of these, 22 articles were excluded, including 10 that lacked primary empirical or design-focused content, 10 that focused solely on flood damage assessment without addressing adaptation strategies, and 2 for which the full text could not be accessed. The final sample comprised 250 studies that met the inclusion criteria and were retained for synthesis. The complete study selection and screening process is illustrated in the PRISMA flow diagram presented in Fig. 1.

3. Bibliometric and descriptive analysis

3.1. Temporal distribution and growth trajectory

The temporal distribution of the 250 included publications reveals a pronounced and accelerating growth trajectory that mirrors broader trends in climate adaptation research. The period 2007–2013 yielded only 15 studies (6.0%), reflecting the formative stage of flood-adaptive design as a recognised research domain, distinct from conventional flood control engineering. The middle period, 2014–2019, saw output rise to 51 papers (20.4%), coinciding with the adoption of three pivotal international frameworks: the Sendai Framework for Disaster Risk Reduction (2015), the Paris Agreement (2015), and the UN Sustainable Development Goals (2015–2030). These frameworks have driven significant research investment in adaptation, resilience, and sustainable infrastructure worldwide. The most remarkable growth occurred from 2020 onwards, with 184 papers (73.6%) published between 2020 and May 2026 alone. The 45 papers published in 2025 represent the single highest annual output in the dataset, reflecting the compounding urgency of the topic as major flood events in Europe (2021, 2024), Pakistan (2022), Libya (2023), and Brazil (2024) drove both political attention and research funding towards adaptation. The rapid growth in publications in 2025–2026 also reflects expanding coverage of LMIC contexts, with a notable increase in case studies from Africa, South Asia, and Southeast Asia.

3.2. Geographic distribution

The geographic distribution of studies reveals broad but uneven global coverage (Table 2). Asia dominates the literature, accounting for 95 studies (38.0%), followed by Europe with 74 studies (29.6%) and North America with 41 studies (16.4%). The United States (n = 37), China (n = 34), the United Kingdom (n = 15), the Netherlands (n = 13), and Germany (n = 12) emerge as the most frequently represented national contexts. In contrast, the Middle East and West Asia contribute 17 studies (6.8%), while Africa remains underrepresented with only 15 studies (6.0%) despite its high and increasing flood vulnerability. Oceania (2.0%) and Latin America (1.2%) are the least represented regions. This distribution highlights a pronounced geographical imbalance in the evidence base, with notable knowledge gaps in sub-Saharan Africa, Pacific Island nations, and Central Asian contexts, where flood risks are severe and escalating (Mabuku et al., 2019; Turner et al., 2025; Wang et al., 2024).

3.3. Research methodologies

Analysis of the 250 included studies (see Appendix 1) reveals considerable methodological diversity within the flood-adaptive design literature (Fig. 2). Quantitative methods were the most frequently employed (87 studies, 34.8%), particularly hydrological and hydraulic modelling, GIS, remote sensing, and cost-benefit analysis. Mixed-methods approaches accounted for 71 studies (28.4%), while qualitative designs comprised 57 studies (22.8%). Review-based studies represented the smallest category (35 studies, 14.0%). This distribution indicates the continued dominance of engineering-oriented analytical approaches, while the substantial use of qualitative and mixed-methods research reflects growing recognition of the social, institutional, and governance dimensions of flood adaptation (Cao et al., 2021; Ventura et al., 2026; Wamsler et al., 2023).

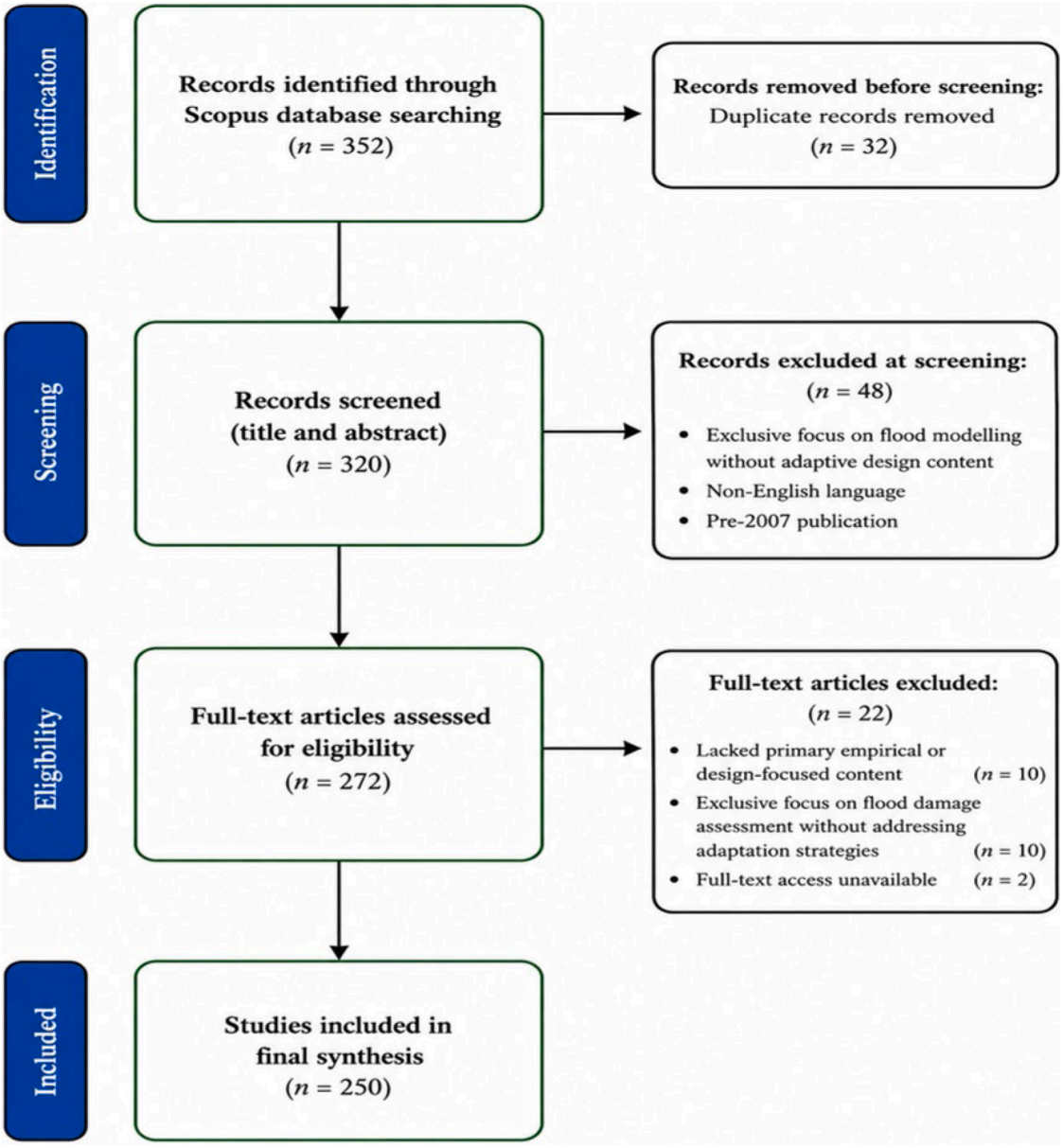


Fig. 1. PRISMA flow diagram for the systematic literature review.

4. Conceptual foundations of flood-adaptive design

This section synthesises the theoretical and conceptual foundations underpinning flood-adaptive design, drawing systematically on the included literature to trace the field's intellectual trajectory, delineate competing paradigms, and situate the principal categories of design practise within a coherent theoretical architecture. In doing so, it directly addresses Objective 2 of this study by establishing the conceptual scaffolding necessary for interpreting the empirical patterns identified in subsequent sections. It addresses four interconnected conceptual domains: the evolution of flood risk management paradigms; resilience theory and its application to flood adaptation; the sustainability dimensions of adaptive design; and the emerging literature on equity and justice in flood adaptation.

4.1. Evolution of flood management paradigms towards adaptive co-existence

The intellectual history of flood management can be characterised as a progression through three broad paradigms: resistance, accommodation, and adaptive transformation (Kraan, Haasnoot & Mach, 2025). The resistance paradigm, dominant throughout much of the 20th century, conceptualised floods as engineering problems requiring hydraulic solutions, such as levees, dams, channelisation, and storm drainage systems designed to exclude floodwater from inhabited areas. Kirshen, Knee and Ruth (2008), examining Boston's coastal flood risk under sea-level rise, demonstrated the limitations of this approach: even well-engineered coastal defences face escalating costs and diminishing returns as climate-driven hazard intensification renders historical design standards insufficient (Rotimi et al., 2025a). The 'levee effect', by which protective infrastructure paradoxically amplifies long-term risk by encouraging development in protected floodplains, has been documented across multiple national contexts (Junger & Seher, 2024; Kraan et al., 2025).

The accommodation paradigm, which gained traction from the 1990s onward, shifted the emphasis from excluding water to accepting its presence under controlled conditions. Liao et al. (2016) traced this evolution in the context of amphibious urbanism, arguing that cities had

Table 2
Geographic distribution of included studies (n = 250).

Region / Context	Countries Represented	No. of Studies	Percentage (%)
Asia *(East, South & Southeast Asia)*	China (34), Bangladesh (7), India (7), Indonesia (7), Vietnam (9), Malaysia (5), Nepal (5), Taiwan (5), Thailand (6), Japan (4), South Korea (3), Philippines (1), Myanmar (1), Singapore (1)	**95**	38.0%
Europe *(Western, Northern & Southern Europe)*	UK (15), Netherlands (13), Germany (12), Italy (9), France (5), Switzerland (5), Portugal (5), Poland (3), Austria (2), Belgium (2), Denmark (1), Finland (1), Hungary (1)	**74**	29.6%
North America	USA (37), Canada (4)	**41**	16.4%
Middle East & West Asia	Pakistan (6), Iran (5), Turkey (3), Lebanon (2), Iraq (1)	**17**	6.8%
Africa *(Sub-Saharan Africa & North Africa)*	Nigeria (5), Ethiopia (4), Ghana (3), South Africa (1), Tanzania (1), Zambia (1)	**15**	6.0%
Oceania	Australia (5)	**5**	2.0%
Latin America	Brazil (3)	**3**	1.2%
Total	**42 countries represented**	**250**	**100%**

generally moved away from overreliance on structural measures, but that urban flood hazard mitigation still faced substantial challenges from conventional planning frameworks and institutional path dependencies. The Netherlands' 'Room for the River' programme, analysed in depth by Roth and Winnubst (2014), epitomises this shift at a national scale: the deliberate removal of hard embankments and creation of floodplain space for rivers to expand represents an accommodation logic that prioritises long-term landscape resilience over short-term asset protection. An and Ochiai (2026) extended this analysis by examining how historical flood adaptation strategies in heritage cities could be re-integrated into contemporary resilience planning through 'Planning Heritage', the recovery and application of vernacular adaptive wisdom embedded in the built fabric of flood-experienced communities. Fig. 3 shows the evolution of flood management paradigms towards adaptive co-existence.

The adaptive transformation paradigm, which has come to dominate contemporary discourse, extends accommodation into a proactive, systems-oriented framework that integrates physical design intervention with governance reform, social learning, and ecological restoration (Haasnoot et al., 2021; Palazzo, 2025). Within this paradigm, flood-adaptive design is understood not as a collection of technical measures but as a socio-technical transition requiring simultaneous change across infrastructure systems, institutional arrangements, financial mechanisms, and cultural attitudes towards flood risk (Davids, Boelens & Tempels, 2020). Nasrollahi et al. (2025) provided a recent synthesis of adaptation strategies under climate change, finding that comprehensively evaluated strategies that were assessed for effectiveness across multiple dimensions were predominantly associated with adaptive transformation approaches rather than resistance or accommodation logic alone.

While the adaptive transformation paradigm currently represents the frontier of mainstream flood management practise, the cumulative weight of evidence reviewed here points towards an emerging fourth paradigm that existing frameworks have yet to fully institutionalise. This paradigm, termed transformative resilience, does not repudiate the achievements of adaptive transformation but rather exposes its ceiling: even the most sophisticated contemporary frameworks, including dynamic adaptive policy pathways (Haasnoot et al., 2021), the Room for the River programme analysed by Roth and Winnubst (2014), and integrated NbS-governance approaches (Peck et al., 2022), remain constrained by the institutional, financial, and cultural architectures within which they operate. They adapt systems without fundamentally questioning whether those systems, in their current spatial configuration, economic logic, and governance structure, remain viable under accelerating climate trajectories. Transformative resilience, by contrast, confronts this question directly. It calls for the deliberate reorganisation of human settlement patterns around dynamic flood envelopes rather than static defence perimeters, the proactive decommissioning of infrastructure in zones of untenable long-term risk, and the wholesale reorientation of land tenure, insurance, and financing systems to reflect the true and escalating cost of flood exposure (Kraan et al., 2025; Lockwood et al., 2024). Crucially, it positions social equity not as a co-benefit of adaptation but as its foundational precondition, recognising that transformative change which fails to address the structural

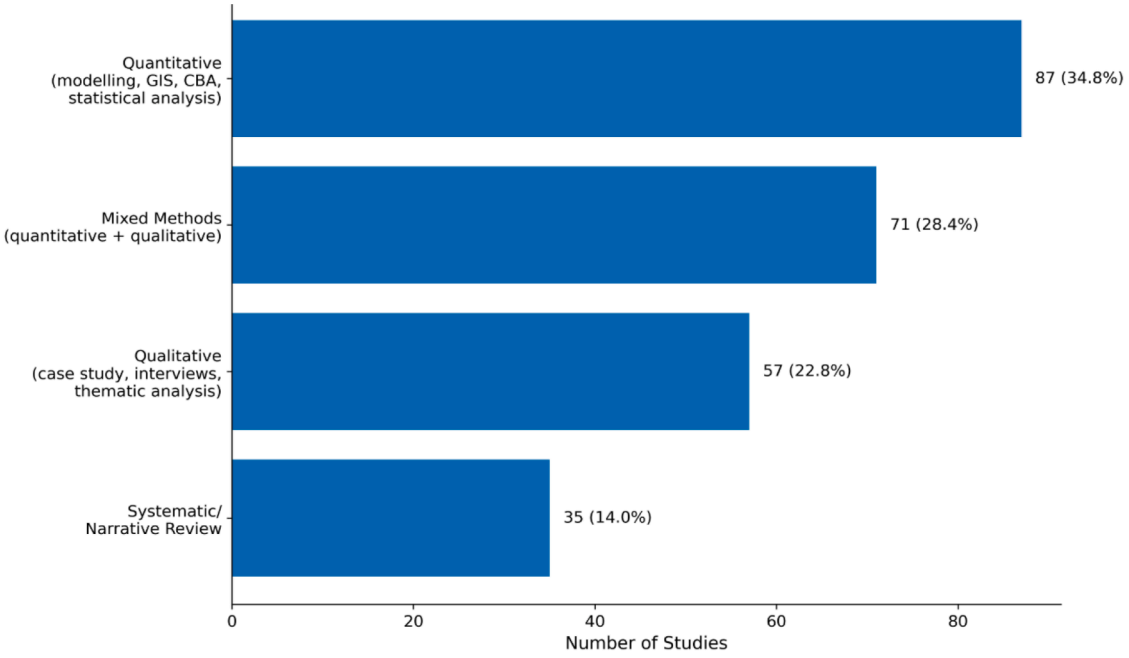


Fig. 2. Research methodology distribution of included studies.

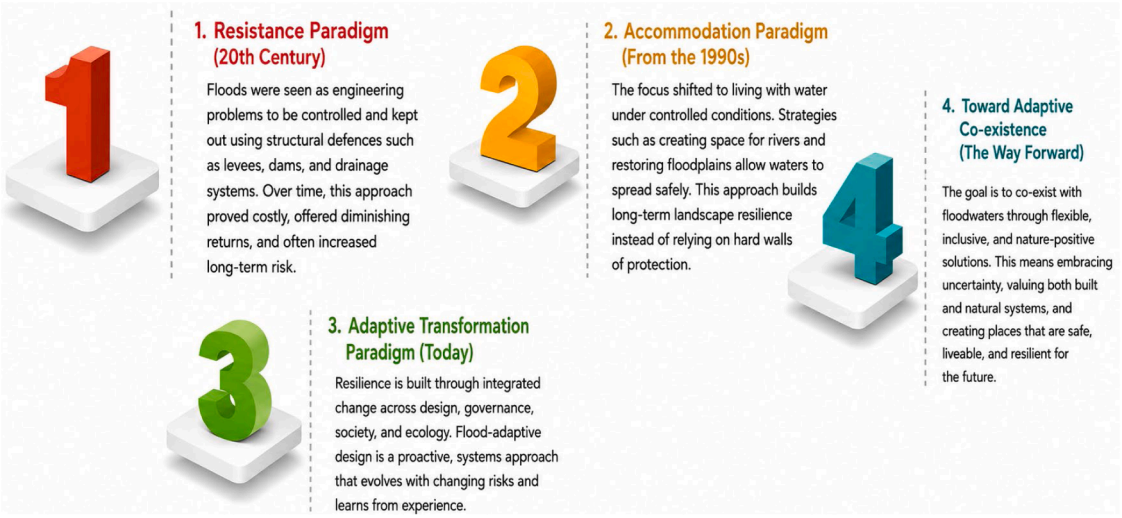


Fig. 3. Evolution of flood management paradigms.

inequalities producing differential flood vulnerability will inevitably reproduce the injustices it seeks to resolve (Bhanye, 2025; Gao et al., 2025; Naah et al., 2025). At the individual and community scale, it has been argued (Wamsler et al., 2023) that transformative resilience further demands inner transformation, a reorientation of values, worldviews, and agency, that enables communities and institutions to transcend path-dependent adaptation responses and embrace genuinely novel configurations of living with water. The way forward, therefore, lies not in perfecting existing frameworks but in building institutional courage, financial mechanisms, governance architectures, and social consensus necessary to operationalise transformative resilience as the next frontier of global flood adaptation practise. This four-paradigm progression, from resistance through accommodation and adaptive transformation to transformative resilience, provides the conceptual scaffolding within which the flood-adaptive design principles synthesised in subsequent sections are situated and evaluated.

4.2. *Resilience theory and flood adaptation*

Resilience has become the dominant conceptual frame for flood-adaptive design over the past decade, but the term's wide application across disciplines has generated definitional ambiguity that the literature has only partially resolved (Loli et al., 2022; Rotimi et al., 2025b). In the engineering tradition, resilience connotes the capacity of physical infrastructure to withstand, absorb, and recover from flood shocks, a functionality-oriented definition emphasising robustness and rapid restoration of service performance (Madhuri et al., 2021). In the socio-ecological tradition, resilience is defined as the capacity of a coupled human-natural system to maintain its essential functions and structures in the face of disturbance while retaining the ability to adapt and transform (Clercq-Roques, Chapagain & Hochrainer-Stigler, 2026; Wamsler et al., 2023). Khatooni et al. (2026) operationalised this distinction by developing an Improved Urban Flood Resilience Index (IUFRI) that integrates both physical and social resilience dimensions, including the novel 'Living with Flood' (LWF) component that captures individual flood attitudes, public awareness, and cultural adaptive capacity elements systematically missing from engineering-dominated resilience indices.

The literature increasingly recognises that resilience in flood contexts is not binary but scalar and dynamic, varying with event magnitude, system state, and the quality of anticipatory governance. Haasnoot et al. (2021) introduced dynamic adaptive policy pathways as a planning approach for managing deep uncertainty in sea-level rise and flood risk, arguing that static adaptation plans become maladaptive as climate conditions diverge from planning assumptions. This dynamic framing aligns with the adaptive pathways approach advocated by Lendering et al. (2019) and the 'safe-to-fail' design philosophy championed by Loos and Rogers (2016), both of which reject the optimisation of adaptation for a single future scenario in favour of flexible, reversible strategies that remain effective across a range of possible climate futures.

The distinction between engineered resilience (return to pre-disturbance state), ecological resilience (capacity to absorb disturbance without changing state), and transformative resilience (capacity to reorganise to a new, more adaptive configuration) (Gisevius et al., 2026) maps directly onto the typology of flood-adaptive design strategies reviewed in this paper. Hard engineering provides engineered resilience; NbS and ecological approaches provide ecological resilience; and governance and spatial transformation provide transformative resilience. The evidence reviewed here consistently supports multi-type portfolios as superior to single-type approaches for achieving durable flood adaptation outcomes (Khatooni et al., 2026; Madhuri et al., 2021). Fig. 4 shows the conceptual foundations and multi-type portfolios in flood-adaptive resilience.

4.3. *Sustainability dimensions of flood-adaptive design*

Flood-adaptive design has been evaluated through sustainability frameworks that extend beyond conventional engineering performance metrics to encompass economic viability, environmental co-benefits and costs, and social equity and acceptability (Wobus et al., 2021). This triple-bottom-line framing has become increasingly prevalent in the literature, driven in part by policy frameworks that require adaptation investments to demonstrate multi-dimensional value (Padhan & Madheswaran, 2022).

Economic sustainability in the flood-adaptive design literature is typically operationalised through cost-benefit analysis (CBA) or cost-effectiveness analysis (CEA), comparing adaptation costs with avoided flood damage over the planning horizon (de Ruig et al., 2020, 2023). Several studies document the strong economic case for proactive adaptation: de Ruig et al. (2020) found that building-level adaptation measures in Los Angeles offered benefit-cost ratios substantially greater than 1 under baseline and moderate sea-level rise scenarios. However, ratios declined under high-end scenarios, highlighting the importance of uncertainty quantification in adaptation appraisal. Lockwood et al. (2024) provided a United States coastal context analysis demonstrating that the economic benefits of proactive managed retreat significantly exceed those of reactive in-situ adaptation under high sea-level rise pathways,

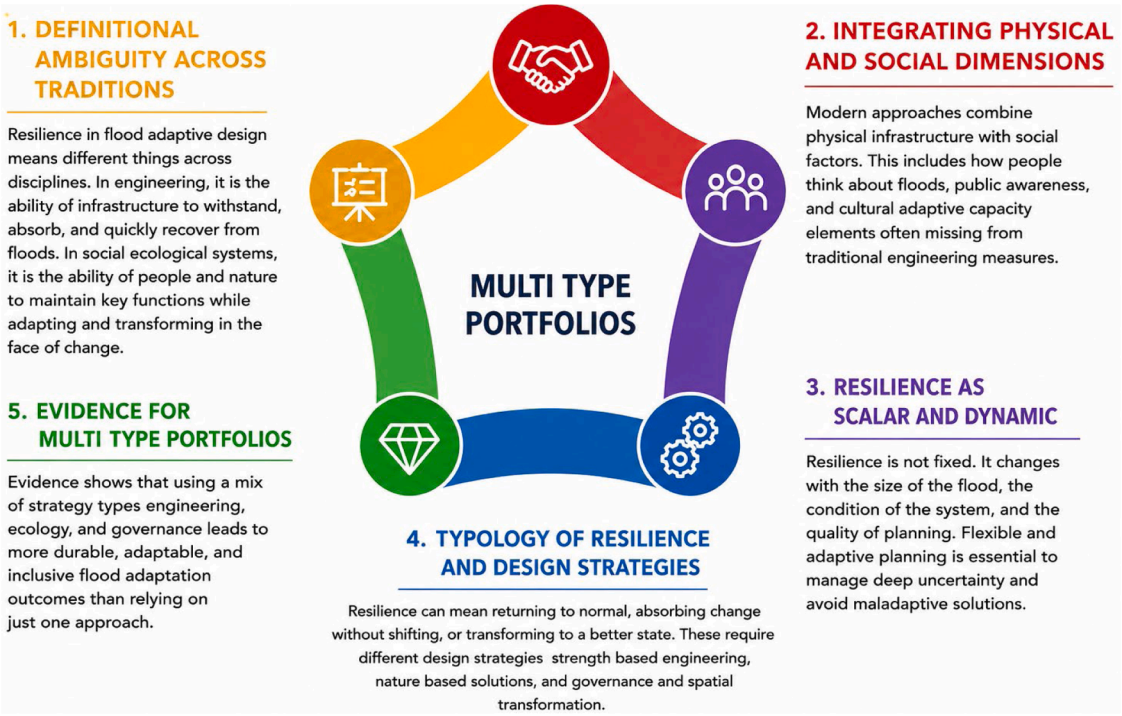


Fig. 4. Conceptual foundations and multi-type portfolios in flood-adaptive resilience.

particularly in low-density coastal settings.

Environmental sustainability dimensions are most prominently addressed in the NbS and BGI literature, where flood risk reduction co-benefits, including carbon sequestration, biodiversity enhancement, groundwater recharge, and water quality improvement, are documented alongside flood attenuation performance (Osawa, Sakurai & Wakai, 2025; Peck et al., 2022). Conversely, the environmental costs of structural approaches, including ecological fragmentation, riparian habitat loss, and altered sediment regimes, are identified as underweighted in many national benefit-cost frameworks (Cajilig, 2024; Pontee, 2007). Rezapouraghdam and Hidalgo-García (2025) recognised the interactive effects of urban landscape change on both flood risk and urban heat island intensity in semi-arid Iranian cities, illustrating the multi-hazard sustainability dimension of land-use-based adaptation interventions.

Social sustainability, encompassing equity, community acceptance, cultural appropriateness, and livelihood co-benefits, has emerged as the most contested and theoretically underdeveloped dimension of flood-adaptive design literature. Gao et al. (2025) demonstrated that social vulnerability indices systematically predict differential access to and benefits from sponge city measures in the United States context, raising questions about whether adaptation investments reinforce existing socio-spatial inequalities. Naah et al. (2025) documented culturally embedded flood adaptation behaviours in Ghanaian urban communities that operate largely outside formal planning frameworks, arguing that



Fig. 5. Three dimensions of sustainability in flood-adaptive design.

indigenous and informal adaptive practises constitute an underutilised resource for community resilience that formal programmes consistently fail to engage. Bhanye (2025), reviewing community-based flood adaptation in informal settlements across the Global South, found that adaptation is fundamentally a daily act of survival for low-income residents, a bottom-up, incremental, and deeply social process that technical adaptation programmes rarely accommodate. Fig. 5 shows the three dimensions of sustainability in flood-adaptive design.

4.4. *Justice and equity in flood adaptation*

A growing body of literature interrogates the distributional dimensions of flood-adaptive design, who bears flood risk, who benefits from adaptation investment, and whose knowledge and values shape adaptation decisions (Adekola et al., 2020). This literature challenges the techno-centric framing dominant in engineering-oriented flood research and introduces concepts from environmental justice, political ecology, and critical urban theory into the discourse on flood adaptation (Adegun, 2023; Naz & Doneys, 2022). El-Zein, Ahmed and Tonmoy (2021) examined geophysical and social vulnerability to floods at the municipal scale in Sydney, showing that flood vulnerability is unevenly distributed within cities; across the reviewed literature, this unevenness tends to disadvantage the poorest communities, those with the least physical infrastructure, least institutional representation, and least capacity for self-finance adaptation. This spatially differentiated vulnerability has been documented across contexts as diverse as Calabar (Adekola et al., 2020), informal settlements across the Global South (Bhanye, 2025), Ho Chi Minh City (Cao et al., 2021), and Dhaka (Akther, Morshed Ahmad & Lai Nguyen, 2024), suggesting a structural pattern rather than context-specific variation.

Indigenous and traditional knowledge systems represent a particularly underutilised resource for flood-adaptive design, providing culturally embedded, place-specific adaptive wisdom refined over generations of flood experience. Prana et al. (2024) examined urban planning approaches that support community-based flood adaptation in North Jakarta's kampungs, finding that local building practises and spatial organisation embody sophisticated flood adaptation logics that development interventions have often disrupted rather than built upon. Palazzo and Wang (2022), reviewing two decades of constructed ecologies in China, showed how landscape design that works with local ecological processes and land-use knowledge can strengthen flood adaptation, an approach that conventional engineering programmes have often overlooked. These studies collectively argue for genuine co-production of adaptive knowledge that integrates technical expertise with community and indigenous knowledge rather than supplanting it. Fig. 6 shows the justice and equity dimensions in flood adaptation.

5. Results: thematic synthesis of flood-adaptive design principal categories

The thematic synthesis identified five overarching categories of flood-adaptive design principles, each encompassing multiple typologically distinct strategies. These categories are not mutually exclusive; many studies address multiple design dimensions simultaneously, and the most effective adaptation portfolios documented in the literature integrate strategies across categories. Table 3 summarises the five categories, their strategy subtypes, and the number of included studies that primarily address each.



Fig. 6. Justice and equity dimensions in flood adaptation.
Note: (Bhanye, 2025; Davids et al., 2020; Gao et al., 2025; Haasnoot et al., 2021; Kraan et al., 2025; Laeni et al., 2020; Leitold et al., 2020; Lendering et al., 2019; Lu et al., 2026; Msongole et al., 2026; Naah et al., 2025; Nasrollahi et al., 2025; Osawa et al., 2025; Peck et al., 2022; Prana et al., 2024; Shan et al., 2025; Sufri & Lassa, 2026; Van Loon et al., 2025; Wu et al., 2025).

Table 3
Summary of flood-adaptive design principal categories and strategy sub-types.

Category	Primary Strategy Sub-types	No. of Studies	Key Representative Studies
1. Nature-Based Solutions & Green Infrastructure	Wetland restoration; riparian buffers; coastal mangroves; urban forests; constructed wetlands; green roofs	49	((Borah, Bardhan & Bhatia, 2023; (Kim & Kang, 2023); (Osawa et al., 2025); Peck et al., 2022); (Shan et al., 2025))
2. Urban WSUD & Sponge City Design	Sponge city; LID; SUDS; bioretention; permeable surfaces; BGI; rain gardens; green roofs	16	((Chitwatkulsiri et al., 2025; (Kim et al., 2022); (Lu et al., 2026); Qi et al., 2023); (Roggero et al., 2025))
3. Structural & Hybrid Engineering	Levees; dikes; floodwalls; retention dams; seawalls; grey-green hybrid systems	22	((Adhikari et al., 2025; (Junger & Seher, 2024); (Kraan et al., 2025); Roth & Winnubst, 2014); (Shan et al., 2025))
4. Building-Level & Architectural Adaptation	Amphibious design; floating architecture; floodproofing; elevated construction; vernacular adaptation	11	(Ameh, Badarnah & Lamond, 2024); (Liao, Chan & Huang, 2019; (Nekooie, Goodall & Mohamad, 2015); (Nguyen et al., 2025); (Ż yczkowska, 2025))
5. Governance, Community & Spatial Planning	Adaptive governance; land-use zoning; managed retreat; community EWS; participatory design; policy reform	152	((Bhanye, 2025); (Cao et al., 2021; (Leitold, Revilla Diez & Tran, 2020); (Naah et al., 2025); Ventura et al., 2026))

Note: WSUD = water-sensitive urban design; LID = low-impact development; SUDS = sustainable urban drainage systems; BGI = blue-green infrastructure; EWS = early warning system.

5.1. *Nature-based solutions and green infrastructure*

Nature-Based Solutions (NbS) and green infrastructure (GI) emerged as the most extensively studied physical-design category, featuring in 49 included studies (the governance category discussed in Section 5.5 is larger overall). NbS are broadly defined as actions that protect, sustainably manage, or restore natural or modified ecosystems to address societal challenges, including flood risk, while simultaneously providing human well-being and biodiversity benefits (Peck et al., 2022). Within flood adaptation, NbS encompass a spectrum from highly naturalised interventions (wetland restoration, riparian buffer zones, coastal mangrove rehabilitation) to engineered ecological systems (constructed wetlands, urban green corridors, soil bioengineering).

The performance of NbS in flood attenuation has been evaluated across a range of methodological approaches in the reviewed literature. Osawa et al. (2025) examined ecosystem-based disaster risk reduction (Eco-DRR) as a complement to structural flood measures under climate change scenarios in Japan, finding that green structural measures significantly reduced expected annual flood damage when integrated with hard defences across a range of return periods. Shan et al. (2025), in a modelling study of compound flood risk mitigation in Shanghai, demonstrated that NbS components substantially enhanced the performance of grey infrastructure when deployed at the catchment scale, reducing peak inundation depths and extending return periods to meet equivalent design standards. Kim and Kang (2023) developed a Hazard Capacity Factor Design (HCFD) model quantifying the flood risk reduction performance of green-grey infrastructure interactions across severe rainfall events in Seoul, finding that combined approaches reduced flood inundation extents by 28–43% compared to grey-only scenarios.

Green infrastructure in urban heritage contexts presents distinctive challenges. Borah et al. (2023) examined GI flood resilience in rapidly urbanising heritage cities of the Global South, identifying a dual constraint: limited spatial availability restricts the scale at which GI can be deployed, while complex urban hydrodynamics influenced by irregular street morphology, informal drainage, and mixed land tenure undermine modelled effectiveness assumptions derived from planned urban contexts. This finding underscores the importance of context-specific evaluation rather than generic performance claims. Chitwatkulsiri et al. (2025) found that Bangkok's conventional drainage systems were increasingly unable to manage peak runoff and that integrated BGI deployment required systemic urban redesign rather than incremental upgrades.

Lu et al. (2026) examined urban riparian green corridors as climate-adaptive infrastructure, showing that they mitigate urban heat island effects while also contributing to flood resilience, evidence for the multi-hazard co-benefit logic that strengthens the investment case for NbS relative to single-purpose grey alternatives. Rezapouraghdam and Hidalgo-García (2025), analysing spatiotemporal land use change in semi-arid Iranian cities, documented how vegetation loss amplifies both heat stress and flood risk, while landscape restoration offers a dual-purpose mitigation pathway. The co-benefit framing is central to the argument of Peck et al. (2022) that mainstream flood risk paradigms have systematically failed to capitalise on the services provided by intact and restored ecosystems, resulting in foregone risk reduction alongside foregone ecological and social value.

5.2. *Urban water-sensitive and sponge city design*

Water-sensitive urban design (WSUD) and the Sponge City concept represent the most comprehensive planning paradigms for integrating water management into urban design, combining NbS, low-impact development (LID), sustainable urban drainage systems (SUDS), and blue-green infrastructure into a systemic spatial design philosophy. This category featured in 16 studies in the corpus, with strong representation from China, Germany, Australia, and Thailand.

China's Sponge City Programme (SCP), described by Qi et al. (2023) in their sponge catchment management framework for Guiyang, was initiated in 2013 and draws on LID principles adapted to Chinese urban contexts. The SCP mandates participating cities to absorb, store, purify, and utilise at least 70% of annual rainfall through integrated NbS and engineered measures, with 30 pilot cities designated in the first phase. Kim et al. (2022) evaluated LID performance under carbon-neutral planning scenarios in Seoul, providing an optimisation framework for LID deployment that balanced runoff reduction effectiveness against spatial and cost constraints, a methodological contribution with broader applicability to sponge city and WSUD implementation planning globally. Roggero et al. (2025) provided a critical institutional analysis of decentralised rainwater management in Berlin, identifying social dilemmas at multiple governance levels, including free-riding on collective drainage investment, insufficient policy incentives for individual BGI adoption, and fragmented institutional responsibility as primary barriers to sponge city goals in a high-capacity European context. This finding has broad implications: if institutional barriers impede WSUD adoption in Berlin, analogous challenges are likely far more severe in cities with weaker planning systems and more fragmented governance.

Ramos et al. (2013), examining energy recovery in SUDS, offered an early articulation of multi-functional urban water system design, demonstrating that SUDS can be designed not only for runoff management but also for energy recovery through micro-hydropower, illustrating the creative potential of integrated design. Gao et al. (2025), examining social vulnerability and sponge city outcomes in the United States, found that Socially Vulnerable Populations (SVPs), as defined by the Social Vulnerability Index, are systematically underserved by sponge city infrastructure investments, locating adaptation inequity at the intersection of urban planning, political economy, and climate justice.

5.3. Structural and hybrid engineering approaches

Despite the broader paradigm shift towards resilience-oriented approaches, structural engineering measures remain central to flood risk management in many contexts, particularly where population density, asset values, and flood magnitude exceed what NbS or WSUD can address. This category featured in 22 studies, with additional structural content appearing as a contextual baseline or comparator in many more.

Roth and Winnubst (2014) provided the landmark case study of the Netherlands' Room for the River (RftR) programme. This paradigm-defining spatial planning intervention deliberately reversed the resistance logic by de-poldering floodplains, relocating levees landward, and creating floodable wetland parks in urban contexts. The RftR programme is significant not only for its technical innovation but for the governance framework that enabled it: a transparent multi-stakeholder planning process, provision of alternative livelihoods for displaced farmers, and a long-term political commitment spanning multiple parliamentary terms. Junger and Seher (2024) examined levee effect policies across multiple countries, finding persistent implementation gaps in communicating residual risk to floodplain developers and residents, and that most countries lack mechanisms to prevent post-levee intensification of land use in protected zones.

Kraan et al. (2025), synthesising the flood defence literature, argued that adapting to intensifying climate change may require alternatives or supplements to conventional defence structures, and that managed realignment and accommodation strategies deserve greater consideration as structural options become increasingly costly relative to their residual risk. Adhikari et al. (2025) provided an important LMIC perspective, demonstrating that in data-scarce developing-country contexts such as Nepal's Tinau River Basin, simple structural adaptations at the household level, combined with public preferences for improved drainage and embankment, offered the most feasible near-term risk reduction, given institutional and financing constraints. This finding echoes Lasage et al. (2014) in coastal Vietnam, where house elevation and local drainage improvements outperformed large seawall investment in benefit-cost terms for many low-income communities.

The hybrid engineering literature combining structural and ecological measures in integrated coastal and riverine defence systems has advanced significantly since 2020. Shan et al. (2025) demonstrated through comprehensive modelling that green-grey hybrid strategies consistently outperformed purely grey approaches in both cost-effectiveness and performance under climate change scenarios for coastal Chinese cities. Paprotny et al. (2024), analysing flood protection levels across European countries through an inferred vulnerability approach, found that structural flood defences substantially reduce hazards at given return periods but that vulnerability factors, such as material quality, building typology, and exposure density, remain important determinants of actual damage even behind defences. This finding underscores the case for layered adaptation, combining structural defences with building-level hardening and spatial planning restrictions on post-defence land-use intensification.

5.4. Building-level and architectural adaptations

Building-level adaptation strategies encompassing amphibious design, floating architecture, dry and wet floodproofing, elevated construction, and architecturally mediated vernacular adaptation represent a distinctive and increasingly important category of flood-adaptive design. Though comprising only 11 studies in the primary categorisation, building-level content appears as a complementary dimension in many additional papers, particularly those addressing community-scale resilience and LMIC contexts.

Amphibious buildings and structures, designed to float in place on their foundations when floodwaters rise and to return to ground level as waters recede, have attracted particular scholarly attention as a technically innovative response to recurring inundation that avoids the cost and disruption of managed retreat. Ameh et al. (2024) provided a detailed technical review of amphibious foundation systems, explaining the buoyancy engineering principles involved and noting that some systems incorporate mechanical guidance elements to control ascent and descent. The principal engineering challenges include: designing guidance systems (vertical post or rail) that allow free vertical movement while preventing lateral drift; accommodating utility connexions (electricity, water, drainage) through flexible service interfaces; and ensuring structural integrity under dynamic loading during flotation. Nekooie et al. (2015) examined the use of lightweight concrete containing expanded polystyrene (EPS) beads as a construction material for floating buildings, evaluating its sustainability credentials and structural performance. This material innovation directly addresses the weight-buoyancy engineering constraint in the design of floating structures.

Floating architecture, permanently water-based structures distinct from amphibious buildings that rest on land, was examined by Życzkowska (2025) through a systematic review of 18 exemplary projects. A striking finding was that 72% of analysed projects were planned or constructed for open-sea conditions rather than protected inland waterways, reflecting the growing ambition of maritime urbanism as a climate adaptation strategy for sea-level rise contexts. Penning-Rowsell (2020) examined the governance and planning dimensions of floating developments as climate adaptation, finding that while spatial planning frameworks in several European countries are beginning to accommodate floating residential and commercial development, navigational regulations, wave loads, and infrastructure connexion requirements present significant barriers to widespread adoption outside established marina and houseboat traditions.

For the majority of the world's flood-exposed residential buildings, simpler incremental adaptations offer greater near-term impact. Shrestha, Kawasaki and Zin (2021)) demonstrated, through detailed flood-damage modelling of residential buildings in Myanmar's Bago River basin, that elevating plinth levels by 0.3–0.5 m reduces expected annual flood damage by 20–50%, depending on house type and local flood-depth distributions. Madhuri et al. (2021) proposed an integrated framework for risk analysis and adaptation effectiveness assessment under urban flood and climate change scenarios in India, finding that adaptation at the building scale significantly reduced community-level risk and that combining building- and infrastructure-level measures yielded synergistic risk reduction. Nguyen et al. (2025) brought a cultural heritage dimension to building-level adaptation by developing and numerically validating a piston-house system for Japanese wooden architecture, showing how traditional building types can be adapted to flood conditions rather than replaced and raising questions about the role of cultural continuity in long-term adaptive capacity.

Santos and Kobayashi (2026) provided an important counterpoint to high-technology framings of building adaptation, documenting informal architectural strategies developed by residents of flood-prone communities in northeastern Brazil in the absence of government intervention. These vernacular responses elevated living floors, sacrificial ground-floor uses, and waterproof materials demonstrate that adaptive design intelligence exists within communities facing repeated flood exposure, and that formal programmes that ignore or displace this embedded knowledge may inadvertently reduce rather than enhance adaptive capacity.

5.5. Governance, community, and spatial planning frameworks

Governance, community engagement, and spatial planning form the largest category in the corpus (152 studies; Table 3), with explicit governance content in 73 studies and spatial planning content in 28. This dominance reflects a fundamental insight consolidating across the literature: the effectiveness of any physical flood-adaptive design intervention is contingent on the institutional quality of the systems responsible for planning, financing, implementing, maintaining, and

evaluating it over time.

Adaptive governance frameworks characterised by polycentric institutional arrangements, cross-sectoral coordination, evidence-based flexibility, and iterative learning have been repeatedly identified as superior to hierarchical, sector-specific governance for managing the complexity and uncertainty inherent in climate-adaptive flood management (Leitold et al., 2020). Leitold et al. (2020) highlighted the underappreciated role of the private sector in enabling climate change adaptation, finding that local firms' participation in adaptive governance was critical but systematically underresourced and under-incentivised in most national policy frameworks. Revilla Diez et al. (2024) extended this analysis to micro-businesses and household enterprises in Vietnamese flood-prone urban contexts, demonstrating that very small economic actors who face the greatest relative exposure to flood damage are also the least supported by formal adaptation programmes and have the lowest awareness of available risk reduction resources.

Spatial planning and land-use regulation represent upstream flood risk management tools with the potential to have the greatest long-term impact on reducing exposure. Ampofo et al. (2025), using geospatial flood risk mapping in Tamale, Ghana, demonstrated the feasibility and value of incorporating flood risk assessment into urban zoning regulations to prevent development in high-risk areas, a straightforward intervention that was found to be largely absent from Ghanaian planning practise despite its low cost and high effectiveness. Lotfata et al. (2024) investigated climate-adaptive spatial design interventions for high-density informal urban areas in a hot and humid climate, proposing an integrated framework for spatial planning that addresses heat, flood, and air quality risks simultaneously, a multi-hazard spatial planning approach of broad applicability to rapidly urbanising tropical contexts.

Community-based flood adaptation approaches have demonstrated consistent effectiveness in LMIC contexts where formal institutional capacity is limited. Msongole, Kanyangale and Lee (2026) compared the importance and performance of flood adaptation strategies in resource-limited regions of Malawi, finding that community-based and nature-based flood management offer an effective complementary pathway when formal government interventions are absent or insufficient. Sufri and Lassa (2026) documented the Climate Village Programme (ProKlim) in Aceh, Indonesia, examining barriers and opportunities to integrating climate change adaptation and mitigation at the community level, providing a nuanced institutional analysis of what works, for whom, and under what local governance conditions community-based adaptation programmes succeed or fail. Van Loon et al. (2025) examined linkages between communities and formal governance in semi-arid transboundary basins, demonstrating that effective drought-flood management requires bridging the persistent disconnect between local adaptive knowledge and formal institutional planning.

Early warning systems (EWS) bridge the governance and technology categories, representing fundamentally institutional interventions that require sustained investment, inter-agency coordination, and community trust to deliver effective risk reduction. Maharjan et al. (2025) documented the flood adaptation strategies of farming communities in Nepal's Chure-Terai region, highlighting the importance of community capacity building, clear communication, and culturally appropriate dissemination of warnings. Emiroglu et al. (2025) developed a game-based digital learning environment to build flood-mitigation awareness among school students, illustrating how digital tools can support risk communication when they are embedded in educational institutions. Yildirim, Alabbad and Demir (2023) optimised non-structural flood mitigation measures at the community scale, demonstrating technical potential whose realisation depends on governance and capacity building.

6. Cross-cutting analysis: effectiveness, sustainability, and context dependency

This section conducts a cross-cutting analysis that synthesises evidence across the five flood-adaptive design categories examined in Section 5, evaluating their comparative effectiveness, sustainability, and context dependency. Rather than treating each design category in isolation, this section examines how different strategies perform relative to one another across four dimensions: flood risk reduction, economic sustainability, environmental sustainability, and social acceptability. It further maps strategy applicability across diverse contextual settings, ranging from high-income urban environments to low-income urban, rural, and coastal contexts, demonstrating that no single strategy is universally optimal and that context fundamentally determines what works, for whom, and under what conditions. The section additionally interrogates the integration and scale dependencies that shape adaptation outcomes, establishing that multi-scalar, multi-category portfolios tend to outperform single-strategy interventions across the studies reviewed. Collectively, Section 6 provides the evidence base from which the proposed conceptual Global Flood-Adaptive Design Framework (GFADF) presented in Section 7 is derived.

6.1. *Comparative effectiveness assessment*

The ratings presented in Table 4 were derived through a systematic weight-of-evidence approach applied across the 250 included studies, rather than from any single article or scoring instrument. The rating rubric, the rating procedure, and the rules used to resolve conflicting findings are set out after Table 4. For each strategy category, ratings across the four assessment dimensions were assigned by aggregating and comparing findings reported across the primary studies addressing that category, with particular weight accorded to studies employing quantitative performance evaluation, cost-benefit analysis, or multi-criteria assessment frameworks. Specifically, Nature-Based Solutions and Green Infrastructure were rated Moderate-High for flood risk reduction and Very High for environmental sustainability on the basis of evidence from Osawa et al. (2025), Peck et al. (2022), Shan et al. (2025), and Kim and Kang (2023), all of which documented significant but event-magnitude-dependent flood attenuation performance alongside substantial ecological co-benefits. The High economic sustainability rating reflects the co-benefit logic documented by Lu et al. (2026) and Rezapouraghdam and Hidalgo-García (2025), wherein NbS investments deliver simultaneous flood, heat, and biodiversity value that conventional cost-benefit frameworks systematically undercount.

WSUD and Sponge City strategies were rated Moderate for flood risk reduction, reflecting the finding of Qi et al. (2023) that sponge city measures perform most effectively under small-to-moderate rainfall events but exhibit diminishing returns under extreme precipitation, a limitation further corroborated by Wu et al. (2025) in the context of the 2021 Zhengzhou rainstorm. The High long-term economic sustainability rating draws on Kim et al. (2022) and Roggero et al. (2025), who documented strong lifecycle cost-effectiveness when WSUD measures are integrated into urban planning systems from the outset. Structural and Hybrid Engineering approaches received a High flood risk reduction rating within design standards, supported by Kraan et al. (2025), Roth and Winnubst (2014), and Shan et al. (2025), but a Low-to-Moderate economic sustainability rating reflecting the capital-intensive nature of large-scale hard infrastructure documented by de Ruig et al. (2020) and Lockwood et al. (2024). The Moderate environmental sustainability rating acknowledges the levee effect risk and ecological fragmentation consequences identified by Junger and Seher (2024) and Paprotny et al. (2024), while the Moderate social acceptability rating reflects documented community resistance to large infrastructure projects in multiple national contexts.

Building-Level and Architectural Adaptations were rated Moderate for flood risk reduction given their plot-scale limitation, as established

Table 4
Comparative effectiveness of flood-adaptive design strategy categories.

Strategy Category	Flood Risk Reduction	Economic Sustainability	Environmental Sustainability	Social Acceptability	Context Dependency
NbS & Green Infrastructure	Moderate-High (event-dependent)	High (co-benefits)	Very High	High	High (land, hydrology)
WSUD / Sponge City	Moderate (small-moderate events)	High (long-term)	Very High	Moderate-High	High (density, governance)
Structural / Hybrid	High (within design std.)	Low-Moderate (capital-intensive)	Moderate (levee effect risk)	Moderate (NIMBY risk)	Moderate
Building-Level / Architectural	Moderate (plot scale)	Moderate-High (incremental)	High	High (autonomy)	Moderate
Governance / Community / Spatial Planning	High (enabling condition)	Very High (prevention)	High	Variable (process quality)	Very High

by Shrestha et al. (2021) and Madhuri et al. (2021), but Moderate-High for economic sustainability on account of the incremental and household-financed nature of measures such as plinth elevation and floodproofing documented by Santos and Kobayashi (2026) and Adhikari et al. (2025). The High social acceptability rating reflects the autonomy and agency that household-level adaptation confers, as noted across multiple LMIC studies including Bhanye (2025) and Naah et al. (2025). Finally, Governance, Community, and Spatial Planning frameworks were rated High for flood risk reduction as an enabling condition rather than a direct physical intervention, Very High for economic sustainability given the prevention logic documented by Ampofo et al. (2025) and Leitold et al. (2020), and Variable for social acceptability, reflecting the findings of Ventura et al. (2026) and Cao et al. (2021) that governance outcomes are highly sensitive to the quality, inclusivity, and legitimacy of participatory processes. The Very High context dependency rating reflects the consensus across Naah et al. (2025), Sufri and Lassa (2026), and Van Loon et al. (2025) that governance approaches are among the most context-sensitive of all flood adaptation strategies, with outcomes varying dramatically across institutional settings, political cultures, and community capacities.

To ensure transparency and reproducibility, ratings were assigned according to the following weight-of-evidence rubric: Low indicates that the majority of reviewed studies reported limited or context-restricted benefit on that dimension; Moderate indicates mixed or condition-dependent evidence of benefit; Moderate-High indicates a majority of studies reporting positive outcomes with some qualification; High indicates consistent positive findings across the majority of studies addressing that dimension; Very High indicates strong, convergent evidence across most or all studies with few contradicting findings; and Variable indicates that the evidence itself reports divergent outcomes depending on implementation context (e.g., governance quality, participatory process design) rather than a consistent direction of effect.

Ratings were assigned separately for each dimension and strategy category through a three-step procedure. First, the two reviewers who conducted screening and data extraction independently rated each category dimension combination against this rubric, applying the evidence-type weighting described in Section 2.5. Second, the two sets of ratings were compared; where they differed, the reviewers re-examined the underlying studies together and agreed a final rating by consensus. Third, each agreed rating was cross-checked against the studies cited in the narrative synthesis above. Conflicting findings were handled with explicit decision rules: (a) where studies disagreed, evidence from empirical evaluations and quantitative performance assessments took precedence over modelling-only or conceptual evidence; (b) where conflict persisted among studies of comparable evidence type, the rating was moderated by one level (for example, from High to Moderate-High), and the qualifier shown in Table 4 records the condition under which performance changes (for example, "event-dependent"); and (c) where divergent findings reflected systematic differences in implementation context rather than inconsistent evidence, the dimension was rated Variable. The resulting ratings are ordinal, evidence-informed judgements intended to support comparison across categories; they are not quantitative effect sizes.

6.2. *Context-specific applicability*

A central finding of this review is that the effectiveness of flood-adaptive design principles is profoundly context-dependent, varying with flood type (riverine, pluvial, coastal, compound), urban-rural character, income level, climatic zone, and social dynamics. Table 5 maps the applicability of eight flood-adaptive design strategies across five contextual settings (high-income urban, middle-income urban, low-income urban, rural/peri-urban, and coastal), revealing that no single strategy is universally optimal and that context fundamentally shapes what works.

Nature-based solutions and green infrastructure perform strongly across most settings but are constrained in low-income urban areas by limited land availability and maintenance capacity. Water-sensitive urban design and sponge city approaches are primary tools in wealthier cities where planning systems can sustain them but become selective in resource-constrained contexts. Structural and hybrid engineering measures shift from complementary in high-income cities to critical priorities in low-income urban and coastal settings where flood magnitudes are large and alternative options are limited. Building-level hardening measures, such as elevated floors and floodproofing materials, offer the most immediately accessible household-scale protection where area-wide infrastructure is absent. Amphibious and floating design remains innovative and context-specific. At the same time, managed retreat, though increasingly necessary in coastal zones threatened by sea-level rise, carries significant social and political risks, particularly in low-income communities.

Early warning systems are reported to be highly cost-effective across settings, making them among the most widely deployable life-saving interventions. Most critically, adaptive governance and spatial planning are rated essential in every context, confirming that institutional capacity, political commitment, and community engagement, not technical sophistication alone, are key determinants of flood adaptation success.

The table shows three clear patterns. First, richer contexts can afford integration: high-income cities use NbS and WSUD as primary tools because they have the capacity to maintain them. Second, poorer contexts need prioritisation. In low-income urban and rural settings, structural protection and building-level hardening are the priority because they deliver the most immediate risk reduction per unit of investment. Third, governance is non-negotiable everywhere: it is the only strategy rated Essential across all five columns, meaning that investing in governance reform, community engagement, and spatial planning is likely to be among the highest-return adaptation investments in any context.

Table 5
Strategy applicability across contextual settings.

Strategy	High-Income Urban	Middle-Income Urban	Low-Income Urban	Rural / Peri-Urban	Coastal (all income)
NbS / Green Infrastructure	Primary	Primary	Complementary	Primary	Primary
WSUD / Sponge City	Primary	Primary	Selective	Selective	Selective
Structural / Hybrid	Complementary	Primary	Priority	Selective	Priority
Building-Level Hardening	Complementary	Primary	Priority	Priority	Primary
Amphibious / Floating	Niche / Innovative	Experimental	Limited	Limited	Growing
Managed Retreat	Selective	Selective	Emergency only	Selective	Increasing
Early Warning Systems	Complementary	Priority	Priority	Priority	Priority
Adaptive Governance / Spatial Planning	Essential (enabling)	Essential (enabling)	Essential (enabling)	Essential (enabling)	Essential (enabling)

Legend: **Primary** = recommended core strategy; **Complementary** = supports primary strategies; **Priority** = most critical given resource constraints; **Selective** = applicable in suitable sub-contexts; **Niche/Innovative** = specialised application with high potential; **Essential** = enabling preconditions for all strategies.

6.3. Integration and scale dependencies

A recurrent finding across the literature is that integrated multi-scalar approaches tend to outperform single-strategy interventions. Nasrollahi et al. (2025) synthesised evidence on the effectiveness of flood adaptation strategies under climate change, finding that comprehensively evaluated programmes combining structural, NbS, and governance components yielded the most durable risk reduction across a range of climate scenarios. Shan et al. (2025) quantified this synergy for Shanghai, demonstrating that hybrid green-grey strategies outperformed grey-only approaches not only in flood risk reduction but also in economic efficiency, with NbS components providing disproportionate value in terms of cost-effectiveness for moderate and frequent events. Wu et al. (2025), analysing the catastrophic 2021 Zhengzhou rainstorm, demonstrated that even highly engineered cities with advanced drainage infrastructure are vulnerable to extreme pluvial events that exceed system design standards, underscoring the need for redundant, multi-layer adaptation portfolios that extend from drainage engineering through building-level adaptation to emergency response.

Scale mismatches between flood processes and governance jurisdictions are identified as a persistent structural barrier. Flooding is inherently a catchment- or coastal-cell-scale process that rarely respects administrative boundaries. Yet most flood management governance systems are configured along municipal, county, or national lines, fragmenting catchment-scale decision-making (Brockhoff, Koop & Snel, 2019). Liu et al. (2025b) demonstrated, in a Chinese context, that future urban flood risk trajectories are shaped by the interactions among hazard, exposure, and vulnerability trends, which can only be managed coherently at the metropolitan and river basin scales, not at the individual parcel or municipal catchment level. Eilander et al. (2023), using global compound flood modelling, highlighted the growing significance of scale in compound riverine-coastal flood events that require coordinated responses across upstream catchment management, coastal defence, and urban planning jurisdictions.

7. The proposed global flood-adaptive design framework (GFADF)

Drawing on the thematic synthesis, comparative effectiveness analysis, and context-applicability assessment, this section presents the Global Flood-Adaptive Design Framework (GFADF), a proposed conceptual framework that constitutes the original theoretical contribution of this review. The GFADF is structured as a three-level hierarchical framework: (Level 1) Context Classification; (Level 2) Strategy Portfolio

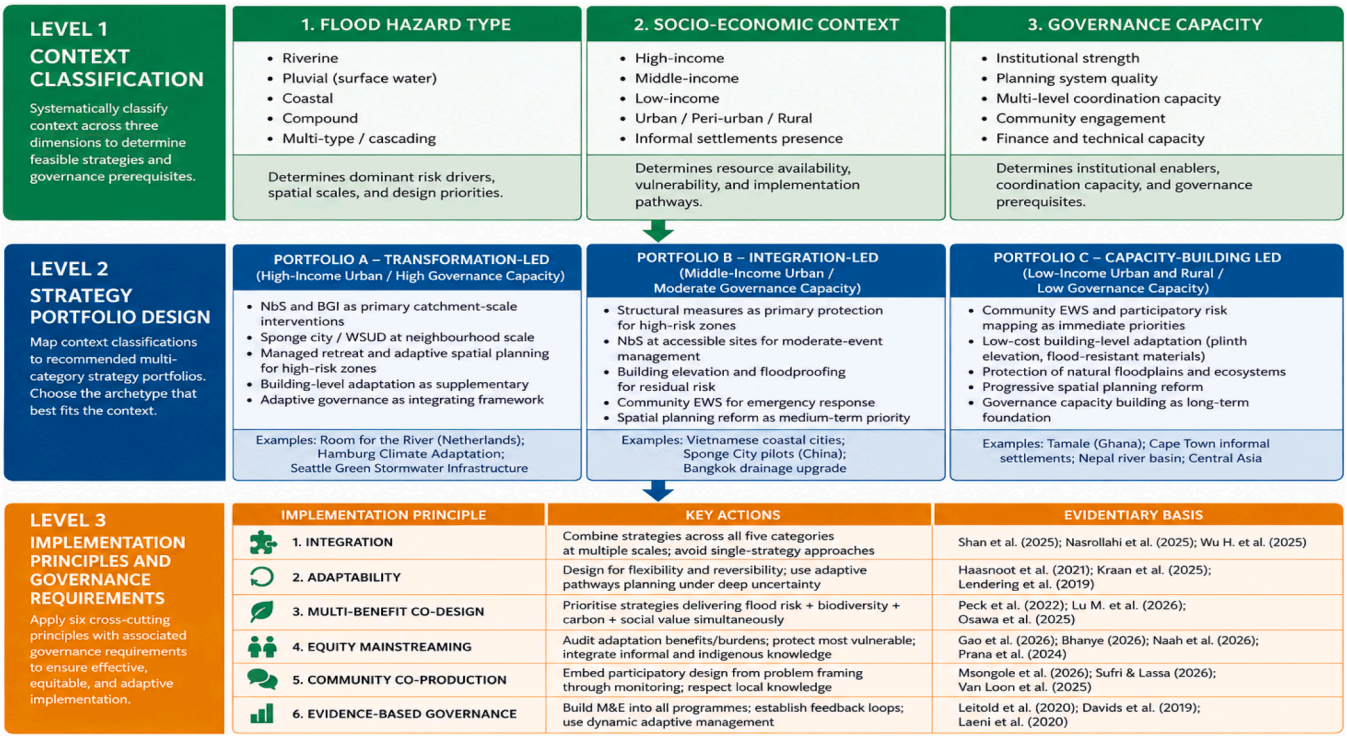


Fig. 7. Global flood-adaptive design framework (GFADF): context classification, strategy portfolio design, and implementation principles.

Design; and (Level 3) Implementation and Governance Requirements. The framework is intended to structure evidence-informed deliberation among practitioners, policymakers, and researchers working across diverse global settings; it has not been empirically validated and is not presented as a validated decision-making tool. Fig. 7 shows the Global Flood-Adaptive Design Framework (GFADF), including context classification, strategy portfolio design, and implementation principles.

It is important to distinguish what is directly supported by the reviewed evidence from what the GFADF contributes as an interpretive synthesis. The five design categories, their comparative ratings (Table 4), and the three context-classification dimensions (Section 7.1) are grounded directly in the included studies. The specific mapping of contexts to strategy portfolios (Section 7.2) and the framework's three-level architecture, however, represent the authors' conceptual synthesis of that evidence rather than a directly tested model. The GFADF is therefore best understood as an evidence-informed proposition requiring empirical validation, through pilot application, expert review, or case-study testing, before being treated as a validated decision-support tool. Three validation steps are envisaged: (1) structured expert review, for example a Delphi process involving practitioners and researchers from high-, middle-, and low-income contexts, to test the context classification and portfolio mapping; (2) retrospective application to documented flood events and adaptation programmes, to examine whether the indicative portfolios correspond to observed outcomes; and (3) prospective pilot application in contrasting urban and rural settings, with monitoring of implementation and performance. Until such validation is completed, the GFADF should be used as a structured starting point for context-specific deliberation rather than as a prescriptive tool.

7.1. Level 1: context classification

The GFADF begins with systematic context classification across three dimensions: (a) Flood Hazard Type, riverine, pluvial, coastal, compound, or multi-type; (b) Socio-Economic Context, high-income, middle-income, or low-income, with urban-rural sub-classification; and (c) Governance Capacity assessed through institutional strength, planning system quality, multi-level coordination capacity, and community engagement infrastructure. Context classification determines which strategy portfolio options are feasible and which governance prerequisites must be addressed before implementation. This classification recognises the central finding from Bhanye (2025), Cao et al. (2021), Naah et al. (2025), and Wang et al. (2024) that identical design interventions yield radically different outcomes across institutional and social contexts.

7.2. Level 2: strategy portfolio design

At Level 2, the GFADF proposes indicative strategy portfolios for each context classification, drawing on the evidence synthesised in Sections 5 and 6 (Tables 4 and 5). The framework advocates multi-category portfolios rather than single-strategy approaches, structured around three portfolio archetypes:

Portfolio A - Transformation-Led (High-Income Urban / High Governance Capacity): NbS and BGI as primary catchment-scale interventions; sponge city / WSUD at neighbourhood scale; managed retreat and adaptive spatial planning for high-risk zones; building-level adaptation as supplementary; adaptive governance as an integrating framework. This portfolio draws on evidence from the Room for the River programme in the Netherlands (Roth & Winnubst, 2014), the Utrecht flood-proofing strategy (Brockhoff et al., 2019).

Portfolio B - Integration-Led (Middle-Income Urban / Moderate Governance Capacity): Structural measures as primary protection for high-risk zones; NbS at accessible sites for moderate-event management; building elevation and floodproofing for residual risk; community EWS for emergency response; spatial planning reform as medium-term priority. This portfolio draws on evidence from coastal Vietnam (Lasage et al., 2014), Sponge City pilots in China (Qi et al., 2023), and drainage upgrading in Bangkok (Chitwatkulsiri et al., 2025).

Portfolio C - Capacity-Building Led (Low-Income Urban and Rural / Low Governance Capacity): Community EWS and participatory risk mapping as immediate priorities; low-cost building-level adaptation (plinth elevation, flood-resistant materials); protection of natural floodplains and ecosystems; progressive spatial planning reform; governance capacity building as long-term foundation. This portfolio draws on evidence from Tamale, Ghana (Ampofo et al., 2025); informal settlements across the Global South (Bhanye, 2025), Nepal river basin Adhikari et al. (2025); and Central Asia (Wang et al., 2024). This portfolio draws on a comparatively narrower evidence base than Portfolios A and B: only 15 of the 250 included studies (6.0%) focused primarily on African contexts, and low-income/rural settings more broadly remain underrepresented in the reviewed literature (see Section 8.1). Recommendations for this portfolio should therefore be treated as provisional pending further empirical validation in low-income and rural contexts.

7.3. Level 3: implementation principles and governance requirements

At Level 3, the GFADF specifies six cross-cutting implementation principles and associated governance requirements, synthesised from the literature included. Table 6 outlines six implementation principles for effective flood-adaptive design. Integration demands combining multiple strategies across scales rather than relying on single interventions. Adaptability requires flexible, reversible designs capable of responding to climate uncertainty through adaptive pathways planning. Multi-benefit co-design prioritises strategies simultaneously delivering flood protection, biodiversity, carbon sequestration, and social value. Equity mainstreaming ensures adaptation benefits reach the most vulnerable while incorporating indigenous and informal knowledge. Community co-production embeds genuine participatory processes from problem identification through monitoring. Finally, evidence-based governance mandates systematic monitoring, evaluation, and feedback mechanisms to enable dynamic adaptive management. Together, these six principles transform flood-adaptive design from purely technical practise into an integrated socio-technical governance framework.

8. Discussion

8.1. Temporal, geographic, and methodological landscape of flood-adaptive design scholarship (Objective 1)

The bibliometric and descriptive analysis conducted in Section 3 reveals a field undergoing rapid and accelerating expansion, with 73.6% of all included publications appearing from 2020 onwards, reflecting the compounding urgency of flood adaptation under intensifying climate trajectories. Methodologically, the dominance of quantitative modelling approaches mirrors the discipline's engineering origins, yet the substantial and growing body of qualitative and mixed-methods scholarship signals a maturing recognition that flood adaptation is as much a social and institutional challenge as a technical one. Geographically, however, the literature exhibits a structurally entrenched asymmetry: innovation and rigorous evaluation remain concentrated in high-income countries, while the communities most urgently requiring effective adaptation have the least access to the evidence base. Only 15 of 250 included studies (6.0%) focused primarily on African contexts, despite sub-Saharan Africa hosting many of the world's most flood-vulnerable urban populations. Oceania is represented by only five studies (2.0%), all from Australia, and no included study focused primarily on Pacific Island nations, despite the existential threat that sea-level rise poses to them. This bibliometric imbalance both reflects and reinforces a

Table 6
Implementation of principles and governance requirements.

Implementation Principle	Key Actions	Evidentiary Basis
1. Integration	Combine strategies across all five categories at multiple scales; avoid single-strategy approaches	(Nasrollahi et al., 2025; Shan et al., 2025; Wu et al., 2025)
2. Adaptability	Design for flexibility and reversibility; use adaptive pathways planning under deep uncertainty	(Haasnoot et al., 2021; Kraan et al., 2025; Lendering et al., 2019)
3. Multi-benefit Co-design	Prioritise strategies delivering flood risk + biodiversity + carbon + social value simultaneously	(Lu et al., 2026; Osawa et al., 2025; Peck et al., 2022)
4. Equity Mainstreaming	Audit adaptation benefits/burdens; protect the most vulnerable; integrate informal and indigenous knowledge	(Bhanye, 2025; Gao et al., 2025; Naah et al., 2025; Prana et al., 2024)
5. Community Co-production	Embed participatory design from problem framing through monitoring; respect local knowledge.	(Msongole et al., 2026; Sufri & Lassa, 2026; Van Loon et al., 2025)
6. Evidence-Based Governance	Build monitoring and evaluation into all programmes; establish feedback loops; use dynamic adaptive management.	(Davids et al., 2020; Laeni et al., 2020; Leitold et al., 2020)

structural inequity in global adaptation research investment that the field must urgently address.

8.2. Theoretical and conceptual foundations of flood-adaptive design (Objective 2)

At a theoretical level, the conceptual synthesis presented in Section 4 supports the adaptive transformation paradigm as the most robust framework currently available for guiding flood-adaptive design practise. The emerging socio-technical transition framing, in which flood adaptation is understood as a deliberate departure from dominant regimes characterised by hard engineering, defensive planning, and expert-led decision-making towards niches of innovation in NbS, participatory governance, and integrated design, is well-supported by the evidence reviewed here (An & Ochiai, 2026; Laeni et al., 2020; Palazzo, 2025). Resilience theory, sustainability frameworks, and equity and justice scholarship each contribute indispensable conceptual dimensions: resilience provides the performance logic, sustainability provides the evaluative criteria, and equity provides the ethical foundation without which adaptation programmes risk reinforcing the very vulnerabilities they seek to address (Bhanye, 2025; Gao et al., 2025; Naah et al., 2025). However, the literature also makes clear that transition pathways are path-dependent and contingent: the same strategies that facilitate transformative adaptation in the Netherlands require radically different enabling conditions in urban West Africa or rural Nepal, underscoring the necessity of context-sensitive theoretical application rather than universal prescription.

8.3. Principal categories of flood-adaptive design principles (Objective 3)

The thematic synthesis conducted in Section 5 establishes that the effectiveness of flood-adaptive design is fundamentally portfolio-dependent. Integrated multi-category approaches combining NbS, structural measures, building-level adaptation, and governance frameworks tend to outperform single-strategy interventions across the range of flood magnitudes and geographic contexts represented in the reviewed literature (Nasrollahi et al., 2025; Shan et al., 2025). This finding resonates with resilience theory's emphasis on redundancy and functional diversity as foundations of system robustness (Clercq-Roques et al., 2026; Gisevius et al., 2026). The studies addressing LMIC contexts in particular provide critical insights: community-based approaches (Msongole et al., 2026; Naah et al., 2025), low-cost building-level adaptation (Santos & Kobayashi, 2026; Shrestha et al., 2021), and progressive spatial planning reform (Ampofo et al., 2025) offer the greatest near-term impact where institutional and financial constraints preclude large-scale infrastructure investment. There is also growing evidence that indigenous and informal adaptive practises embody sophisticated flood-management wisdom (Bhanye, 2025; Prana et al., 2024) that formal programmes consistently fail to engage, resulting in sub-optimal adaptation outcomes and, at worst, the displacement of effective indigenous strategies by expensive and contextually inappropriate foreign interventions.

8.4. Comparative effectiveness, sustainability, context dependency, and framework development (Objective 4)

The cross-cutting analysis presented in Sections 6 and 7 establishes that governance quality emerges as a critical, and in many contexts decisive, constraint on adaptation effectiveness. The outcomes of technical design interventions are strongly conditioned by the institutional capacity of the systems responsible for implementing and sustaining them, a finding with profound implications for adaptation investment priorities in LMICs, where governance strengthening may yield substantially greater returns per unit of investment than physical infrastructure expenditure alone. The comparative assessment further confirms that no single strategy is universally optimal: context, defined by flood type, income level, urban-rural character, and governance capacity, fundamentally determines which portfolio of strategies is both feasible and effective.

These comparative findings directly informed the development of the Global Flood-Adaptive Design Framework (GFADF) presented in Section 7, which represents the principal conceptual contribution of this review. The GFADF organises the synthesised evidence into a proposed three-level conceptual framework that classifies contexts, outlines indicative strategy portfolios, and specifies cross-cutting implementation principles applicable across diverse geographic, socio-economic, and governance settings. In doing so, it moves beyond descriptive synthesis to offer evidence-informed propositions for practitioners, policymakers, and researchers navigating flood adaptation under conditions of deep uncertainty and resource constraint. Its three portfolio archetypes, transformation-led for high-income urban contexts, integration-led for middle-income settings, and capacity-building-led for low-income and rural environments, reflect the central finding that adaptation pathways must be calibrated to context rather than transferred wholesale across divergent institutional and socio-economic conditions. These propositions require empirical validation, through the expert review, retrospective application, and pilot testing outlined in Section 7, before the GFADF can be used as a decision-support tool.

Several emerging frontiers additionally warrant attention as the field advances and as future iterations of frameworks such as the GFADF are developed. Compound and cascading flood events are receiving growing scholarly attention as climate change increases their frequency and severity (Chen & Zhang, 2026; Eilander et al., 2023), presenting new design challenges that existing single-hazard frameworks are ill-equipped to address. Digital tools, ranging from game-based learning environments for flood awareness to optimisation models for community-scale mitigation, are generating new resources for adaptive system design and operation (Emiroglu et al., 2025; Yildirim et al., 2023), though the governance and equity dimensions of digital adaptation remain substantially underexplored and must be integrated into future framework iterations. Finally, the intersection of climate adaptation and mitigation, exemplified by the combined flood, heat, and

vegetation benefits of urban green infrastructure (Rezapouraghdam & Hidalgo-García, 2025), represents a growing area of integrated research with strong policy relevance for cities pursuing multiple climate goals concurrently, and one that the GFADF's multi-benefit co-design principle is specifically positioned to advance.

8.5. Limitations

Several limitations of this review warrant acknowledgement. First, reliance on a single database (Scopus) may have introduced selection bias, potentially underrepresenting literature in regional journals outside Scopus's indexing coverage. Future reviews should supplement Scopus with Web of Science, Google Scholar, and targeted manual searches of key specialist journals. Second, grey literature, government reports, technical guidance, and NGO evaluations were excluded, potentially leaving out important practitioner knowledge. Third, the bibliometric underrepresentation of LMIC contexts means the GFADF's Portfolio C guidance is less evidence-grounded than Portfolios A and B. Fourth, rapid publication growth (37% of the corpus published in 2025–2026) means some recent contributions have not yet been subject to citation scrutiny or independent replication. Finally, the thematic synthesis approach, while appropriate for the methodological heterogeneity of the corpus, cannot quantify uncertainty in effect estimates or attribute flood risk reduction to specific design interventions with the precision of experimental or quasi-experimental designs. In addition, no formal risk-of-bias or study-quality appraisal instrument was applied. Although differences in study quality were addressed through evidence-type weighting and convergence criteria (Section 2.5), the comparative ratings and portfolio recommendations may still reflect variation in the rigour of the underlying studies; future reviews that focus on narrower and more homogeneous sets of study designs could apply formal instruments such as the Mixed Methods Appraisal Tool. Similarly, the ratings in Table 4 rest on structured, consensus-based judgement and should be read as ordinal indications of relative performance rather than as quantitative effect estimates.

9. Conclusions

This systematic literature review has synthesised global evidence on flood-adaptive design principles across 250 peer-reviewed studies published between 2007 and 2026. By evaluating all five categories of flood-adaptive design within a single analytical framework, it complements earlier sector-specific and regional reviews. The review identified five overarching categories of flood-adaptive design: Nature-Based Solutions and Green Infrastructure; Urban Water-Sensitive and Sponge City Design; Structural and Hybrid Engineering; Building-Level and Architectural Adaptations; and Governance, Community, and Spatial Planning Frameworks; it then evaluated their comparative effectiveness across economic, environmental, and social dimensions.

The synthesis yields five principal conclusions with implications for research, practise, and policy. First, flood-adaptive design must be understood as a portfolio challenge, not a single-strategy problem. The evidence strongly supports integrated multi-scalar approaches combining physical design interventions across categories with enabling governance frameworks. Second, governance quality is frequently a decisive constraint: even the most innovative physical design solutions can fail to achieve their potential without institutional capacity, political will, and sustained financial commitment. Third, context specificity is paramount: the GFADF proposed in this review offers a conceptual basis for differentiated portfolio guidance, acknowledging that effective adaptation looks radically different across high-income and low-income, urban and rural, coastal and inland settings; as a proposed framework, it requires empirical validation before it can be applied as a decision-support tool. Fourth, equity must be central: adaptation programmes that ignore distributional dynamics risk reinforcing rather than reducing vulnerability. Fifth, indigenous and community knowledge must be treated as a genuine resource rather than an obstacle: the flood-adaptive wisdom embedded in vernacular architecture, agricultural practise, and community risk governance represents an underutilised asset for adaptation globally.

Priority research directions emerging from this review include: empirical validation of the proposed GFADF through expert review and pilot application; longitudinal evaluations of implemented NbS and BGI programmes at scale; expanded research investment in LMIC adaptation contexts, particularly sub-Saharan Africa and Pacific Island nations; comparative institutional analysis of governance conditions enabling transformative adaptation; equity-focused evaluation of adaptation benefit and burden distribution; and interdisciplinary investigation of compound flood events and cascading risk. As climate change drives flood risk to unprecedented levels across every inhabited region of the world, translating the best available evidence on flood-adaptive design into accessible, implementable, and equitable practise represents one of the most consequential contributions the research community can make to sustainable human development in the 21st century.

Statements and declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Funding The research work is supported by a contestable research fund granted by the School of Future Environments [R13077.08], Auckland University of Technology, New Zealand. Acknowledgement The research work is supported by a contestable research fund granted by the School of Future Environments, Auckland University of Technology, New Zealand, and is gratefully acknowledged.

CRediT authorship contribution statement

Funmilayo Ebun Rotimi: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Roohollah Kalatehjari:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Taofeeq Durojaye Moshood:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scsadv.2026.100117.

Data availability

No data was used for the research described in the article.

References

Adegun, O. B. (2023). Climatic disasters within a flood-prone coastal slum in Lagos: Coping capacities and adaptation prospects. *International Journal of Disaster Resilience in the Built Environment, 14*(2), 212–228.

Adekola, O., Lamond, J., Adelekan, I., & Eze, E. B (2020). Evaluating flood adaptation governance in the City of Calabar, Nigeria. *Climate and Development, 12*(9), 840–853.

Adhikari, P., Bhattarai, U., Devkota, R., & Pandey, V. P (2025). Techno-social flood assessment in a data-scarce region: A case of Tinau River, Nepal. *International Journal of Hydrology Science and Technology, 20*(3), 312–338.

Aerts, J. C. J. H., Bates, P. D., Wouter Botzen, W. J., Bruijn, J., Hall, J. W., Hurk, B., Kreibich, H., Merz, B., Muis, S., & Mysiak, J. (2024). Exploring the limits and gaps of flood adaptation. *Nature Water, 2*(8), 719–728.

Akther, H., Ahmad, M. M, & Nguyen, T. PL. (2024). Livelihood vulnerability to Urban flood: The case of urban poor households in Dhaka, Bangladesh. *Climate and Development, 16*(7), 551–562.

Ameh, H., Badarnah, L., & Lamond, J. (2024). Amphibious architecture: A biomimetic design approach to flood resilience. *Sustainability, 16*(3), 1069.

Ampofo, J. A, Owusu-Sekyere, E., & Adongo, R. (2025). Analysis of urban flood hazards and adaptation strategies in the Tamale metropolis of Ghana. *Discover Environment, 3*(1), 30.

An, Q., & Ochiai, C. (2026). Planning heritage in flood-prone zones: Planning responses and urban morphological evolution in the ancient City of Linhai, China. *Climate Risk Management, 51*, Article 100798.

Berlato, M., Binni, L., Durmus, D., Gatto, C., Giusti, L., Massari, A., Toldo, B. M, Cascone, S., & Mirarchi, C. (2025). Digital platforms for the built environment: A systematic review across sectors and scales. *Buildings, 15*(14), 2432.

Bhanye, J. (2025). A review study on community-based flood adaptation in informal settlements in the Global South. *Discover Sustainability, 6*(1), 595.

Borah, A., Bardhan, R., & Bhatia, U. (2023). Protecting heritage: Insights into effective flood management using green infrastructure in a highly urbanized environment. *International Journal of Disaster Risk Reduction, 98*, Article 104075.

Brockhoff, R. C., Koop, S. H. A., & Snel, K. A. W. (2019). Pluvial flooding in Utrecht: On its way to a flood-proof City. *Water, 11*(7), 1501.

Cajilig, P. G (2024). The seawall helps but—: Using 'material registers' to understand coastal infrastructure for disaster risk management in an island community. *Southeast Asia: A Multidisciplinary Journal, 24*(3), 221–239.

Cao, A., Esteban, M., Onuki, M., Nguyen, K., Thao Nguyen, D., & Van Trung, L.e. (2021). Decoupled formal and informal flooding adaptation and conflicts in coastal cities: A case study of Ho Chi Minh City. *Ocean & Coastal Management, 209*, Article 105654.

Chen, Z., & Zhang, H. (2026). Scaling inequity: Downscaling future compound flood risks and unequitable social vulnerability in Hong Kong. *Sustainable Cities and Society, 139*, Article 107233.

Chitwatkulsiri, D., Charoenpanuchart, R., Theepharaksapan, S., & Irvine, K. N (2025). Assessing the feasibility of pervious concrete blocks for urban flood mitigation in Bangkok using hydrological modeling. *Results in Engineering*, Article 108612.

Clercq-Roques, R., Chapagain, D., & Hochrainer-Stigler, S. (2026). Enhancing community flood adaptation by leveraging interdependencies between resilience capitals: A global empirical analysis. *Mitigation and Adaptation Strategies for Global Change, 31*(4), 36.

Dai, K., Cheng, C., Shen, S., Geng, J., & Zhang, T. (2024). Evaluating future flood risk mitigation capacities in major cities across China. *Urban Climate, 55*, Article 101890.

Davids, P., Boelens, L., & Tempels, B. (2020). The effects of tailor-made flood risk advice for homeowners in Flanders, Belgium. *Flood resilience of private properties* (pp. 51–65). Routledge.

de Ruig, L. T, Haer, T., Moel, H., Orton, P., Wouter Botzen, W. J., & Aerts, J. C. J. H. (2023). An agent-based model for evaluating reforms of the National flood insurance program: A benchmarked model applied to Jamaica Bay, NYC. *Risk Analysis, 43*(2), 405–422.

de Ruig, L. T., Haer, T., Moel, H., Wouter Botzen, W. J., & Aerts, J. C. J. H. (2020). A micro-scale cost-benefit analysis of building-level flood risk adaptation measures in Los Angeles. *Water Resources and Economics, 32*, Article 100147.

Eilander, D., Couasnon, A., Leijnse, T., Ikeuchi, H., Yamazaki, D., Muis, S., Dullaart, J., Haag, A., Winsemius, H. C., & Ward, P. J. (2023). A globally applicable framework for compound flood hazard modeling. *Natural Hazards and Earth System Sciences, 23*(2), 823–846.

El-Zein, A., Ahmed, T., & Tonmoy, F. (2021). Geophysical and social vulnerability to floods at municipal scale under Climate change: The case of an Inner-City suburb of Sydney. *Ecological Indicators, 121*, Article 106988.

Emiroglu, E., Grant, C. A, Sermet, Y., & Demir, I. (2025). Floodcraft: Game-based interactive learning environment using Minecraft for flood mitigation for K-12 education. *International Journal of Disaster Risk Reduction, 130*, Article 105799.

Gao, H., Xu, B., Pourmostaghimi, T., Zhang, G., & Van Zandt, S. (2025). Sponge City for whom? Leveraging social vulnerability index for extreme flood adaptation. *Sustainable Cities and Society*, Article 107068.

Gisevius, K., Niesters, L.-M., Larasati, A., & Braun, B. (2026). Local and translocal social capital in flood adaptation: Evidence from Indonesian coastal communities. *Environmental Hazards, 25*(1), 39–59.

Haasnoot, M., Winter, G., Brown, S., Dawson, R. J., Ward, P. J., & Eilander, D. (2021). Long-term sea-level rise necessitates a commitment to adaptation: A first order assessment. *Climate Risk Management, 34*, Article 100355.

Junger, L., & Seher, W. (2024). Mitigating the levee effect–Spatial planning approaches to address residual risk. *Progress in Disaster Science, 23*, Article 100355.

Khatooni, K., Hooshyaripor, F., MalekMohammadi, B., & Noori, R. (2026). IUFRI: An urban flood resilience index improved by flood adaptation strategy. *Applied Water Science, 16*(1), 3.

Kim, J., & Kang, J. (2023). Development of hazard capacity factor design model for Net-zero: Evaluation of the flood adaptation effects considering green-gray infrastructure interaction. *Sustainable Cities and Society, 96*, Article 104625.

Kim, J., Lee, J., Hwang, S., & Kang, J. (2022). Urban Flood adaptation and Optimization for Net-zero: Case study of Dongjak-Gu, Seoul. *Journal of Hydrology: Regional Studies, 41*, Article 101110.

Kirshen, P., Knee, K., & Ruth, M. (2008). Climate change and coastal flooding in Metro Boston: Impacts and adaptation strategies. *Climatic Change, 90*(4), 453–473.

Kraan, C. M., Haasnoot, M., & Mach, K. J. (2025). Expert perspectives on living with water (Meebewegen) as climate adaptation in the Netherlands. *Environmental Research: Climate, 4*(1), Article 15009.

Laeni, N., van den Brink, M., Busscher, T., Ovink, H., & Arts, J. (2020). Building local institutional capacities for Urban Flood adaptation: Lessons from the water as leverage program in Semarang, Indonesia. *Sustainability, 12*(23), Article 10104.

Lasage, R., Veldkamp, T. I. E., Moel, H. De, Van, T. C., Phi, H. L., Vellinga, P., & Aerts, J. (2014). Assessment of the effectiveness of Flood adaptation strategies for HCMC. *Natural Hazards and Earth System Sciences, 14*(6), 1441–1457.

Leitold, R., Diez, J. R, & Tran, V. (2020). Are we expecting too much from the private sector in flood adaptation? Scenario-based field experiments with small-and medium-sized firms in Ho Chi Minh City, Vietnam. *Climatic Change, 163*(1), 359–378.

Lendering, K. T., Sebastian, A., Jonkman, S. N., & Kok, M. (2019). Framework for assessing the performance of flood adaptation innovations using a risk-based approach. *Journal of Flood Risk Management, 12*(S2), Article E12485.

Liao, K.-H., Chan, J. KH., & Huang, Y.-L. (2019). Environmental justice and flood prevention: The moral cost of floodwater redistribution. *Landscape and Urban Planning, 189*, 36–45.

Liao, K.-H., Le, T. A, & Nguyen, K. V (2016). Urban design principles for flood resilience: Learning from the ecological wisdom of living with floods in the Vietnamese Mekong Delta. *Landscape and Urban Planning, 155*, 69–78.

Liu, W., Feng, Q.i, Zhang, X., & Engel, B. A. (2025a). Evaluating supply and demand relationship of urban flood regulation service and identifying priority areas for green infrastructure implementation in urban functional zones. *International Journal of Disaster Risk Reduction, 126*, Article 105640.

Liu, W., Zhang, X., Feng, Q.i, & Engel, B. A. (2025b). City-scale integrated flood risk prediction under Future climate change and urbanization based on the shared socioeconomic pathways (SSP) scenarios. *Journal of Hydrology, 655*, Article 132971.

Lockwood, J. W., Oppenheimer, M., Lin, N., & Gourevitch, J. (2024). Socioeconomic distributional impacts of evaluating flood mitigation activities using equity-weighted benefit-cost analysis. *Environmental Research Letters, 19*(7), Article 074024.

Loli, M., Kefalas, G., Dafis, S., Mitoulis, S. A., & Schmidt, F. (2022). Bridge-specific flood risk assessment of transport networks using GIS and remotely sensed data. *Science of the Total Environment, 850*, Article 157976.

Loos, J. R., & Rogers, S. H. (2016). Understanding stakeholder preferences for flood adaptation alternatives with natural capital implications. *Ecology and Society, 21*(3).

Lotfata, A., Cortesao, J., Zinsmeister, H., Steeneveld, G.-J., van Zeben, J., Taylor, Z., Tan, W., & Elkhateeb, S. (2024). Climate adaptation in informal areas in hot arid climates. *Sustainable Development, 32*(1), 777–794.

Lu, M., Fan, H., Yuan, L.u, Li, S., Wang, H., Cao, Y., & Liuyang, X. (2026). Urban riparian green corridors as climate-adaptive infrastructure: Quantifying ecological thresholds for cooling performance and sustainable management. *Buildings, 16*(3), 660.

Mabuku, M. P., Senzanje, A., Mudhara, M., Jewitt, G. P. W., & Mulwafu, W. O. (2019). Strategies for coping and adapting to flooding and their determinants: A comparative study of cases from Namibia and Zambia. *Physics and Chemistry of the Earth, Parts A/B/C, 111*, 20–34.

Madhuri, R., Sarath Raja, Y. S. L., Raju, K. S., Sai Punith, B., & Manoj, K. (2021). Urban flood risk analysis of buildings using HEC-RAS 2D in climate change framework. *H2Open Journal, 4*(1), 262–275.

Maharjan, M., Ayer, S., Newa, M., Timilsina, S., Thakuri, S., Manandhar, B., Singh, B., Rijal, M. L., & Sedhain, A. (2025). Farmers' flood adaptation strategies in the Mohana–Khutiya and East Rapti River basins in the Chure–Terai region of Nepal. *International Journal of Disaster Risk Reduction, 117*, Article 105182.

Msongole, A. G, Kanyangale, B. I, & Lee, C.-H. (2026). Lessons learned: Comparing the importance and performance of flood adaptation strategies in resource-limited regions: An analysis of Malawi. *Natural Hazards, 122*(2), 60.

Naah, B., Kaba Kanlisi, S., Pervarah, M., & Derbile, E. K (2025). Perennial flooding and indigenous adaptation strategies in Wa Metropolitan Area, Ghana. *Discover Sustainability, 7*.

Nasrollahi, F., Orton, P., & Montalto, F. (2025). Modeling the effectiveness of alternative flood adaptation strategies subject to future compound climate risks. *Land, 14*(9), 1832.

Naz, F., & Doneys, P. (2022). Gender-based differences in access to and use of loans from rural credit programs for flood adaptation in the farming-dependent char communities of Bangladesh. In *Women's studies international forum, 95*. Elsevier, Article 102651.

Nekooie, M. A, Goodall, H., & Mohamad, M. I (2015). Selection of sustainable materials for lightweight concrete. In *, 168. Proceedings of the Institution of Civil Engineers-Engineering Sustainability* (pp. 159–172). Thomas Telford Ltd.

Nguyen, M. H, Mai, T. TT., Van Rin Tran, S. O, & Ito, T. (2025). An innovative housing design strategy for flood adaptation: Conceptual development and numerical validation of a novel piston house system for Japanese wooden architecture. *Architectural Engineering and Design Management*, 1–22.

Niemann-Morris, J., Siders, A. R., Hino, M., Kraan, C. M., Agopian, A., Samoray, C., & Mach, K. J. (2025). Divergent priorities in flood adaptation. *Environmental Research: Climate, 4*(3), Article 35012.

Osawa, T., Sakurai, G., & Wakai, A. (2025). Developing national-scale basic guideline on flood-adaptation strategies under climate change using probabilistic and deterministic factors. *Water Research, 282*, Article 123723.

Padhan, N., & Madheswaran, S. (2022). Determinants of farm-level adaptation strategies to flood: Insights from a farm household-level survey in coastal districts of Odisha. *Water Policy, 24*(2), 450–469.

Palazzo, E. (2025). Sponge landscapes: Flood adaptation landscape type framework for resilient agriculture. *Land, 14*(10), 2023.

Palazzo, E., & Wang, S. (2022). Landscape design for flood adaptation from 20 years of constructed ecologies in China. *Sustainability, 14*(8), 4511.
Paprotny, D., Rhein, B., Vousdoukas, M. I., Terefenko, P.ł, Dottori, F., Treu, S., Śledziowski, J., Feyen, L., & Kreibich, H. (2024). Merging modelled and reported flood impacts in Europe in a combined flood event catalogue for 1950–2020. *Hydrology and Earth System Sciences, 28*(17), 3983–4010.
Peck, A. J., Adams, S. L., Armstrong, A., Bartlett, A. K., Bortman, M. L., Branco, A. B., Brown, M. L., Donohue, J. L., Kodis, M.'o, & McCann, M. J. (2022). A new framework for Flood adaptation: Introducing the flood adaptation hierarchy. *Ecology and Society, 27*(4).
Penning-Rowsell, E. (2020). Floating architecture in the landscape: Climate change adaptation ideas, opportunities and challenges. *Landscape Research, 45*(4), 395–411.
Pontee, N. I. (2007). Realignment in low-lying coastal areas: UK experiences. *Maritime Engineering, 160*(4), 155–166.
Prana, A. M, Curl, A., Dionisio, M. R, Gomez, C., Hart, D., Apriyanto, H., & Prasetya, H. (2024). Urban planning approaches to support community-based flood adaptation in North Jakarta Kampungs. *Disaster Prevention and Management: An International Journal, 33*(4), 383–405.
Qi, Y., Chan, F. KaS., Feng, M., Griffiths, J., Hutchins, M., O'Donnell, E., Thorne, C., Liu, L., Zhang, C., & Li, X. (2023). Developing a 'sponge catchment Management plan (SCMP)' Framework at the catchment scale: The Case of Guiyang, SW China. *River, 2*(1), 109–125.
Ramos, H. M., Teyssier, C., Samora, I., & Schleiss, A. J. (2013). Energy recovery in SUDS towards smart water grids: A case study. *Energy Policy, 62*, 463–472.
Revilla Diez, J., Leitold, R., Tran, V., & Garschagen, M. (2024). Micro-business participation in collective flood adaptation: Lessons from scenario-based analysis in Ho Chi Minh City, Vietnam. *Natural Hazards and Earth System Sciences, 24*(7), 2425–2440.
Rezapouraghdam, H., & Hidalgo-García, D. (2025). Impacts of urbanization on land surface temperature and vegetation cover in a semi-arid City: The case of Maragheh. *Earth Systems and Environment*, 1–26.
Roggero, M., Brill, F., & Tügel, F. (2025). Providers of decentralized blue-green flood adaptation measures protect others, not themselves, even in flat urban terrain. *International Journal of Disaster Risk Reduction, 128*, Article 105721.
Roth, D., & Winnubst, M. (2014). Moving out or living on a mound? Jointly planning a Dutch Flood adaptation project. *Land Use Policy, 41*, 233–245.
Rotimi, F. E, Kalatehjari, R., Dokyi, G. O, Moshood, T. D, & Ira, S. (2025a). Navigating urban hydrology: A comprehensive exploration of impervious area reduction techniques in New Zealand's residential landscapes. *Smart and Sustainable Built Environment*, 1–26.
Rotimi, F. E, Kalatehjari, R., Moshood, T. D, & Ali, Z. A (2025b). Assessing surface water flood mitigation strategies: A global comparative review. *Journal of Flood Risk Management, 18*(1), Article E70049.
Santos, J. TB., & Kobayashi, H. (2026). A comparative study between formal guidelines and resident-led practices for mitigating flood impacts on residential buildings: A case study in Santo Amaro Do Maranhão, Brazil. *International Journal of Disaster Risk Reduction, 138*, Article 106118.
Shan, X., Han, Y.u, Wen, J., Hu, H., Wang, J., Zhang, G., Scussolini, P., Ke, Q., Li, M., & Wang, J. (2025). Integrating nature-based solutions for compound flood risk mitigation in China: A case study of Shanghai. *Journal of Environmental Management, 380*, Article 125155.
Shrestha, B. B, Kawasaki, A., & Zin, W. W (2021). Development of flood damage assessment method for residential areas considering various house types for Bago Region of Myanmar. *International Journal of Disaster Risk Reduction, 66*, Article 102602.
Sufri, S., & Lassa, J. A (2026). Opportunities for sustainability and transformation in Climate change adaptation policy and practice: Insights from ProKlim in Aceh, Indonesia. *Environmental Hazards*, 1–29.
Tiggeloven, T., Moel, H. De, Winsemius, H. C., Eilander, D., Erkens, G., Gebremedhin, E., Loaiza, A. D, Kuzma, S., Luo, T., & Iceland, C. (2020). Global-scale benefit–Cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. *Natural Hazards and Earth System Sciences, 20*(4), 1025–1044.
Turner, H., Rogers, B., Kneebone, S., Ramirez, D., French, M., Sawailau, M. J, Volavola, F., Baran, S., Matavesi, K., & Newton, O. (2025). Nothing about us without us: Harnessing local voices in shaping community-based adaptation in the Pacific. *Sustainability Science, 20*(3), 877–902.
UNDRR. (2020). *The human cost of disasters: An overview of the last 20 years (2000-2019)*. Geneva: United Nations Office for Disaster Risk Reduction.
Van Loon, A. F., Matanó, A., Tirivarombo, S., Artur, L., Day, R., Rohse, M., Mustafa, S. M. T., Geris, J., Taylor, S., & Bharucha, Z. P. (2025). Towards more connection in drought and flood management in the Transboundary Limpopo Basin. *Jàmbá-Journal of Disaster Risk Studies, 17*(1), 1798.
Ventura, J., Oulahen, G., Nguyen, C., Mitchell, C. L., Henstra, D., & Thistlethwaite, J. (2026). Flood adaptation policy alignment with resident perceptions of resilience in Vancouver, British Columbia. *Journal of Environmental Planning and Management, 69*(4), 1010–1028.
Vichiensan, V., Wasuntarasook, V., Komkong, T., Takano, T., Wongsa, S., & Nakamura, S. (2025). Assessing the impact of pluvial flooding adaptation measures on urban transport in Bangkok. *Asian Transport Studies, 11*, Article 100167.
Wamsler, C., Mulligan, J., Bukachi, V., & Mumbi, C. (2023). Activating transformation: Integrating interior dimensions of climate change in adaptation planning. *Climate and Development, 15*(5), 366–378.
Wang, N., Sun, F., Yang, S., Liu, W., & Wang, H. (2024). The heterogeneity of Human flood adaptation characteristics in Central Asia based on Human-flood distance. *Environmental Research Letters, 19*(6), Article 064061.
Wobus, C., Porter, J., Lorie, M., Martinich, J., & Bash, R. (2021). Climate change, riverine flood risk and adaptation for the conterminous United States. *Environmental Research Letters, 16*(9), Article 094034.
Wu, H., Zhang, M., He, Y.i, Chen, P., Pasquier, U., Hu, H., & Wen, J. (2025). Scenario-based flood adaption of a fast-developing delta City: Modeling the extreme compound flood adaptations for Shanghai. *International Journal of Disaster Risk Reduction, 117*, Article 105207.
Yildirim, E., Alabbad, Y., & Demir, I. (2023). Non-structural flood mitigation optimization at community scale: Middle Cedar case study. *Journal of Environmental Management, 346*, Article 119025.
Życzkowska, K. (2025). Toward autonomous floating architecture. *Budownictwo i Architektura, 24*(4), Article 25012.