communications earth & environment

Review article

A Nature Portfolio journal

https://doi.org/10.1038/s43247-025-02779-z

Comprehensive portfolio of adaptation measures to safeguard against evolving flood risks in a changing climate

Mohammed Azhar[1], Bergen Kane[1], Farshid Vahedifard[1,2] & Amir AghaKouchak[2,3,4]

Flooding exacerbated by climate change presents growing risks to communities worldwide. Despite extensive research on flood risk, there is a lack of critical analysis of flood adaptation measures spanning traditional and emerging methods. Here, we compile a comprehensive portfolio of 39 adaptation measures classified into four groups: infrastructural/technological, institutional, behavioral/cultural, and nature-based measures. Each measure is evaluated for its advantages, disadvantages, co-benefits, and tradeoffs. Our analysis identifies four broad eras in the evolution of flood adaptation measures. While early efforts primarily focused on structural modifications, more recent projects shifted toward soft adaptation measures, with a growing interest in employing community-centered and nature-based solutions. We lay out key decision-making attributes to identify successful adaptation strategies that are socially just, practically feasible, and technically sound. Finally, we highlight gaps and provide recommendations for future research, with an emphasis on a transdisciplinary approach toward developing and implementing climate-resilient and equitable flood adaptation strategies.

The Earth's climate is changing, with global surface temperatures rising by ~1.1 °C over the past decade compared to pre-industrial levels[1]. This warming trend is intensifying key flood drivers, including rising sea levels, increasing precipitation, and more severe storm events[2,3]. Climate models project that global warming is likely to reach or exceed 1.5 °C in the near term (2021-2040) and, under current policies alone, is projected to reach ~3.1 °C by 2100, exacerbating flood risks worldwide[4–9]. Sea levels are currently rising at a rate of 3–4 mm per year and are projected to increase between 0.3 and 2.0 meters by 2100, threatening coastal and low-lying areas[10–12]. Alongside coastal inundation, other flood hazards such as fluvial flooding, land subsidence, and extreme precipitation are compounding risks and increasing the vulnerability of communities and infrastructure[13–18].

Flooding remains one of the most destructive climate-related hazards, contributing to profound social and economic disruption. Between 2000 and 2019, global flood-related losses totaled $651 billion (USD), affecting ~1.6 billion people[19]. Without proactive adaptation, these losses could increase twentyfold by the end of the century[20]. In the U.S. alone, floods have caused 738 fatalities and nearly $200 billion in inflation-adjusted damages over the past four decades. Flood-related losses are projected to increase by 26% by 2050 due to climate change alone[21,22]. These statistics highlight the urgent need for robust and comprehensive adaptation strategies to safeguard both lives and infrastructure[23].

Climate change amplifies the frequency, intensity, and complexity of flood hazards. Sea level rise, driven by thermal expansion and glacial melt, increases coastal inundation and reduces natural drainage capacity. At the same time, higher atmospheric temperatures elevate moisture-holding capacity, resulting in more intense and prolonged precipitation that overwhelms drainage infrastructure and triggers flash flooding. Storm systems, fueled by warmer ocean waters, are becoming stronger and more destructive, exacerbating both coastal and inland flood risks. These flood drivers often interact with local conditions such as land subsidence, deforestation, and aging infrastructure, creating highly localized and nonlinear flood dynamics. Consequently, effective flood adaptation requires a shift from reactive approaches to integrated, forward-looking strategies capable of addressing compound and cascading risks.

Adaptation to flood risk spans a range of strategies, including structural, nature-based, institutional, and behavioral measures. Traditional structural defenses such as levees, dams, floodwalls, and stormwater drainage systems remain critical components of many flood management plans. However, these systems face growing pressure from climatic stressors, such as sea level rise, extreme rainfall, drought, and non-climatic

---

[1]Department of Civil and Environmental Engineering, Tufts University, Medford, MA, 02155, USA. [2]Institute for Water, Environment, and Health (UNU-INWEH), United Nations University, Richmond Hill, ON, L4B 3P4, Canada. [3]Department of Civil & Environmental Engineering, University of California, Irvine, CA, USA. [4]Department of Earth System Science, University of California, Irvine, CA, USA. e-mail: farshid.vahedifard@tufts.edu

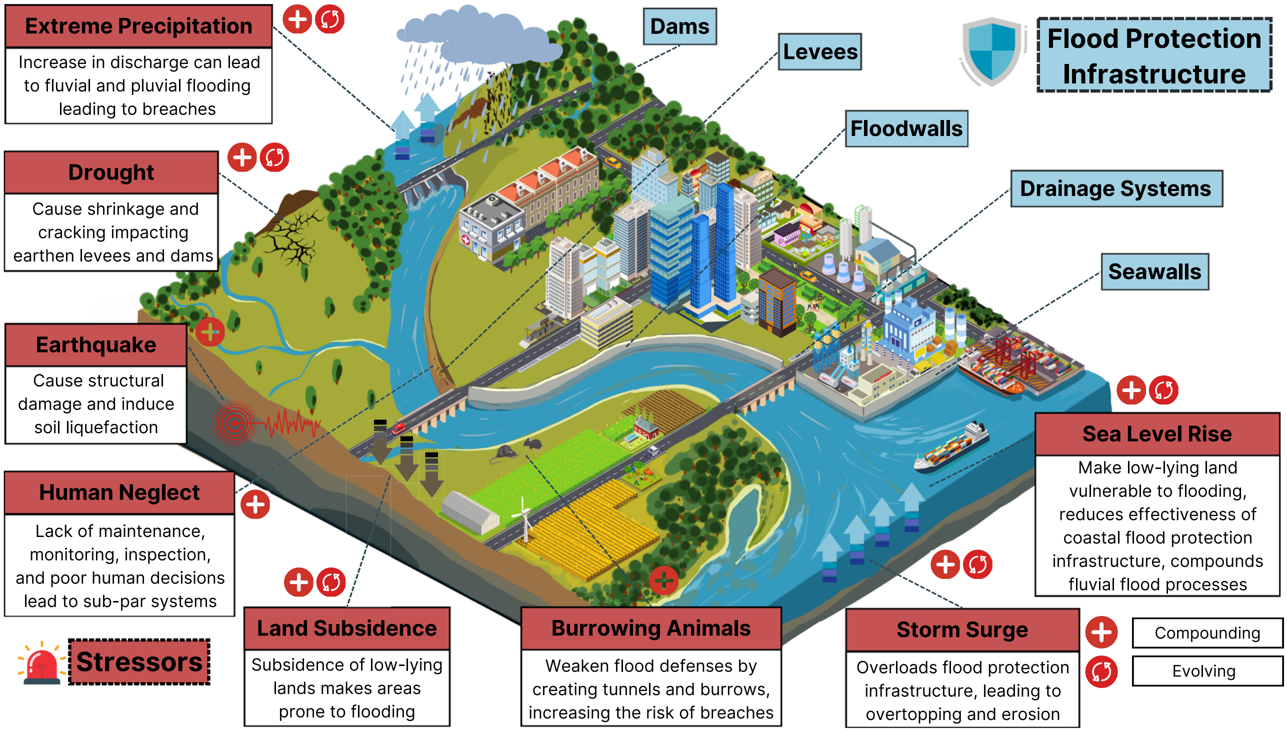

Fig. 1 | Stressors impacting flood protection infrastructure. Flood protection infrastructure systems, including dams, levees, floodwalls, drainage networks, and seawalls, are increasingly stressed by a range of environmental factors that threaten their performance and longevity. These systems are exposed to both climatic stressors (e.g., extreme precipitation, prolonged drought, sea level rise, and intensified storm surges) and non-climatic stressors (e.g., seismic activity, deferred maintenance, land subsidence, and biological interference such as burrowing animals), acting alone or in combination. As these pressures intensify, the risk of infrastructure failure grows, underscoring the urgent need for both structural and non-structural adaptation strategies to build resilience and ensure long-term flood protection.

stressors, like land subsidence, seismic events, and inadequate maintenance (Fig. 1). Urbanization, aging infrastructure, and fragmented governance further exacerbate vulnerability. For example, the 2023 dam failures near Derna, Libya, were caused by extreme rainfall in combination with outdated infrastructure and institutional breakdown, leading to devastating losses[24,25].

Given the rising complexity of flood risk, effective adaptation must go beyond traditional engineering solutions. Nature-based strategies such as wetland restoration, riparian buffers, and living shorelines enhance both flood resilience and ecosystem services while offering long-term cost savings. Institutional measures, including strengthened governance frameworks, emergency management systems, and integrated land use planning, are essential for managing risk in a dynamic climate. Behavioral and cultural approaches such as public education, and participatory planning further enhance community preparedness and adaptive capacity[26].

Despite decades of research, much of the existing flood adaptation literature has focused on individual strategies, with limited efforts to synthesize these measures into an integrated resource. To address this gap, this study compiles and critically analyzes a comprehensive portfolio of 39 flood adaptation measures, spanning 18 Infrastructural/Technological, 9 Institutional, 2 Behavioral/Cultural, and 10 Nature-Based strategies. This portfolio provides a unique and practical reference for policymakers, practitioners, and researchers to evaluate existing and emerging adaptation options. Each measure is described in terms of its advantages, disadvantages, trade-offs, and co-benefits, enabling more informed, context-sensitive decision-making. To guide effective implementation, we also identify key criteria for evaluating adaptation strategies, assuring that decisions are socially just, technically sound, and economically feasible. The paper concludes by outlining research gaps and recommendations for advancing equitable, climate-resilient flood adaptation through a transdisciplinary and systems-based approach.

Climate change adaptation

The term “climate adaptation” has seen a substantial rise in interest since it emerged as a focal point in the UN Framework Convention on Climate Change (UNFCCC) in 2001. The Paris Agreement further underscored its significance[27]. Several definitions of climate adaptation exist throughout the literature. In this study, we adopt the definition provided by the Intergovernmental Panel on Climate Change (IPCC), which describes climate adaptation as the process of making strategic adjustments and decisions to protect communities and assets from the adverse impacts of current or future climate conditions[1]. Nations around the globe have been employing adaptation measures to resist flooding for centuries, with a rapidly increasing trend over the past few decades primarily due to the escalating risk of flooding[28]. These measures range from structural modifications, such as the heightening of flood protection infrastructure (e.g., levees), to non-structural approaches, including community outreach initiatives. Although climate adaptation measures are multifaceted and interdisciplinary in nature, these measures share the common goal of enhancing resilience to climate change. Past studies define resilience as the capacity of communities and built environments to withstand and recover from flood events[29,30]. Flood resilience is particularly crucial in coastal and urban settings, where the built environment plays a central role in determining the ability of urban systems to respond to flood shocks through prevention, adaptation, or response measures[31].

As climate change continues to amplify the frequency and intensity of extreme weather events, the demand for climate adaptation is growing, often outpacing the effectiveness of traditional mitigation measures in many situations. A business-as-usual approach may lead to a future where adaptation becomes increasingly difficult. Compounding this difficulty, adaptation efforts often require substantial investment and long implementation times, influencing decisions spanning decades and introducing uncertainties primarily as a result of climate change and future

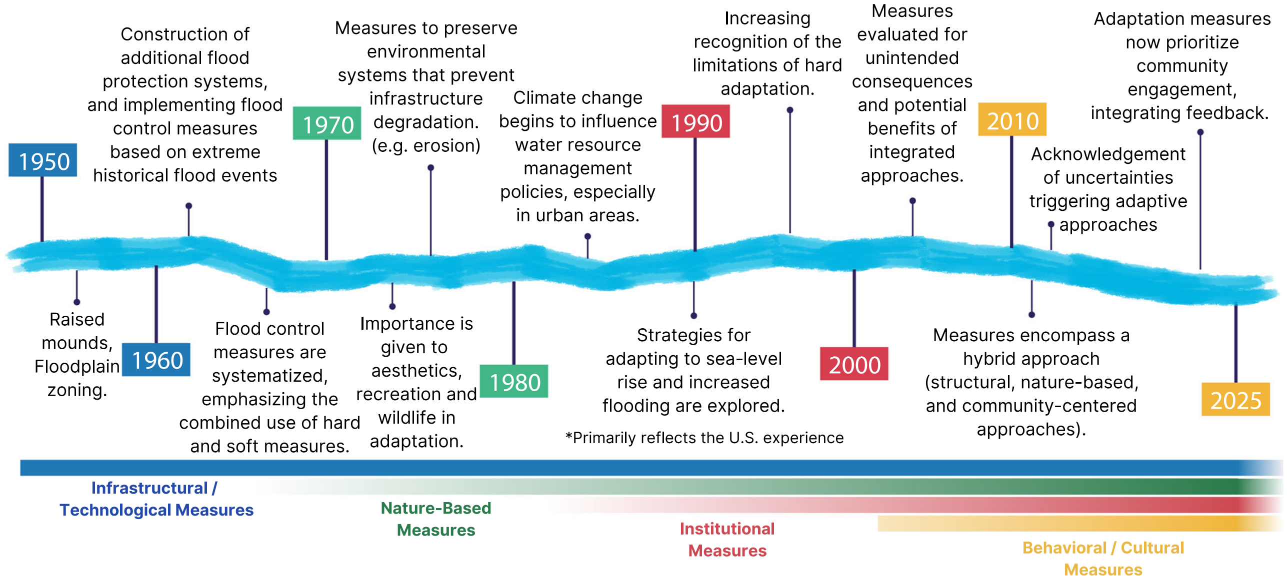

Fig. 2 | Evolution of flood adaptation strategies in the U.S. from the pre-1950s to the present. The figure illustrates the historical progression and growing complexity of adaptation approaches, from early reactive and infrastructure-based responses to more integrated, multi-dimensional strategies. The timeline highlights the overlapping and non-linear nature of these adaptation phases, shaped by evolving climate risks, societal priorities, and governance structures.

socioeconomic pathways. To navigate these complexities, adaptation measures must be grounded in robust assessments that account for climate uncertainty, enabling policymakers and stakeholders to make informed decisions and prioritize resilience-building efforts.

Evolution of flood adaptation measures

The concept of flood adaptation has evolved substantially over time, shaped by changing understandings of environmental processes, societal priorities, policy frameworks, and technological capabilities. In this section, we identify four broad eras in the evolution of flood adaptation (Fig. 2). While presented sequentially, these phases are not universally applicable and often overlap across regions depending on local conditions and governance contexts.

Historically, flood adaptation strategies were highly localized and reactive. Before the mid-20th century, societies employed a diverse array of practices such as constructing raised mounds, strategic retreats, and abandoning floodplains primarily in response to recent flood events rather than informed by formalized risk assessments. Early infrastructure, including levees and barriers, was typically built using trial-and-error approaches to mitigate known damage rather than anticipate future risk[32].

A shift toward infrastructure-centric resilience emerged in the early to mid-20th century. This period emphasized engineered solutions such as levees, dams, and dikes, often designed based on cost-benefit analyses and deterministic risk frameworks aimed at maximizing economic efficiency[33–35]. While influential, these approaches assumed environmental stationarity and failed to fully account for long-term uncertainty in hydrological or climate systems.

In the latter half of the 20th century, increasing environmental awareness catalyzed a broader view of flood management that incorporated ecological and social dimensions. There was growing recognition of the importance of maintaining natural vegetation for levee integrity and of integrating recreational and aesthetic benefits into flood infrastructure[36–39]. As adaptation discourse expanded, rigid top-down regulatory frameworks gradually gave way to more adaptive governance models emphasizing local engagement, intersectoral collaboration, and context-specific solutions capable of responding to evolving climate risks[40].

By the late 20th century, as concerns about climate change grew, long-term planning and ecosystem-based management were increasingly emphasized in adaptation strategies[41–44]. The dichotomy between "hard" (infrastructure-based) and "soft" (nature-based or social) measures became more prominent, and scholars and practitioners began advocating for integrated strategies that balance structural protection with environmental and social resilience[26,45–47].

More recently, hybrid adaptation strategies, which blend structural, nature-based, institutional, and community-centered approaches, have gained attention. These emphasize flexibility, cost-effectiveness, co-benefits, and long-term sustainability[48–52]. This evolution reflects a growing acknowledgment of uncertainty in both climate projections and hydrological modeling. The limitations of traditional stationarity-based assumptions have prompted the development of adaptive planning frameworks that incorporate flexibility, robustness, and iterative learning[53]. Notably, adaptive pathways planning and related methodologies such as decision-making under deep uncertainty provide tools to explore alternative futures, stress-test decisions, and revise strategies in light of new information, offering a more resilient foundation for flood risk management under uncertain conditions[32,54].

Although we present these four eras as a conceptual framework, they should not be interpreted as a strict linear or global progression. Regional experiences vary considerably. In some areas, large-scale structural solutions remain dominant, while others have adopted more community-based or nature-based approaches influenced by governance structures, resource availability, and local hazard characteristics. In practice, many regions operate with a blend of strategies across these phases. Finally, we recognize inherent limitations in the literature and the synthesis presented here. Engineering-focused publications often emphasize structural solutions, potentially overshadowing institutional, behavioral, or community-led strategies. Moreover, flood adaptation literature from North America and Europe tends to be more visible and accessible, while studies from the Global South, especially those in non-English languages or less-publicized outlets, are frequently underrepresented. These disparities highlight the need for more inclusive and globally representative research on flood adaptation.

Methodology

This study employed a scoping review to identify and synthesize recent literature on flood adaptation measures. Our objective was to capture the breadth and diversity of current strategies while ensuring that the selected sources provided meaningful insights into adaptation practices across global contexts. To ensure rigor, studies were included based on three primary criteria. First, eligible sources consisted of peer-reviewed journal articles, systematic reviews, case studies, or policy reports that addressed flood adaptation and, where relevant, broader climate adaptation themes. Second, the included studies needed to describe one or more flood adaptation measures in sufficient detail to enable classification. Third, the review focused on literature published between 2018 and 2024 to reflect recent advancements; however, select foundational works published before this period were also considered when deemed particularly relevant.

The review process followed a structured three-step approach. First, we analyzed key sections of the IPCC 6th Assessment Report, which informed the initial typology and categorization framework[1]. Second, we conducted systematic searches using Google Scholar with a predefined set of search terms combining flood-related keywords (e.g., “flood,” “risk,” “hazard”) with adaptation-related terms (e.g., “adaptation,” “nature-based solutions,” “relocation,” “evacuation”). Here, Google Scholar was selected due to its broad interdisciplinary coverage, including peer-reviewed publications, gray literature, and policy documents that are highly relevant to the cross-sectoral nature of flood adaptation research. Third, the identified adaptation measures were classified into four main categories: (1) Infrastructural/Technological, (2) Institutional, (3) Behavioral/Cultural, and (4) Nature-Based. Measures with overlapping characteristics were consolidated into a comprehensive portfolio.

The final review yielded 173 studies. See Supplementary Data for the full list of articles reviewed and the adaptation measures extracted from each. Infrastructural measures were the most frequently represented ($n = 99$), followed by Nature-Based ($n = 68$), Institutional ($n = 48$), and Behavioral/Cultural measures ($n = 10$). The count does not sum to the total number of studies as several studies addressed two or more adaptation types simultaneously, resulting in overlaps across categories. Studies were further categorized by methodological approach: case studies, data-driven modeling, systematic reviews, historical analyses, and experimental research. Case studies and modeling-based studies dominated the dataset. Geographically, most of the reviewed studies focused on North America, Northern and Western Europe, Eastern Asia, and South Asia, with relatively fewer studies from Africa, Latin America, and the Middle East.

Figure 3 illustrates the regional distribution and classification of adaptation strategies. Notably, infrastructural approaches were dominant in North America, Europe, and Eastern Asia. These findings, however, are subject to several limitations. Structural adaptation measures are more prominently featured in engineering and technical journals, which may contribute to their overrepresentation in the literature. Similarly, studies from well-funded and widely cited regions are more likely to be included, while valuable research from underrepresented regions, especially those published in non-English languages or local outlets, may be overlooked. These limitations underscore the need for greater inclusivity and geographic diversity in future flood adaptation research, particularly to better represent institutional, behavioral, and culturally embedded practices from the Global South.

Flood adaptation portfolio

Various classifications for organizing adaptation measures exist in the literature, among which a widely used framework distinguishes between structural and non-structural measures. Structural measures include engineering solutions such as the construction of levees, seawalls, and berms. In contrast, non-structural measures encompass a broader array of measures, including ecosystem-based, legal, institutional, and community-based approaches. Under this umbrella, alternate terms such as hard and soft adaptation are also used[26]. Some studies classify measures into in-situ and ex-situ adaptation, referring to locations where adaptation measures are implemented[55]. Another recent approach is the Protect, Accommodate, Retreat, and Avoid (PARA) model and its variants, discussed extensively in the literature[56–58]. However, the distinctions between these classifications are often subjective and unclear. In the current study, we organize adaptation measures based on the four categories provided in the IPCC: Infrastructural/Technological, Institutional, Behavior/Cultural, and Nature-Based adaptation measures[1]. We present a portfolio of 18 Infrastructural/Technological, 9 Institutional, 2 Behavior/Cultural, and 10 Nature-Based measures, as shown in Fig. 4. Although the measures were assigned to one of four broad categories based on their primary focus, several measures from our analysis overlap multiple domains. This section presents definitions of the adaptation classifications, detailed descriptions of each measure, and their associated advantages, disadvantages, tradeoffs, and co-benefits.

Infrastructural/technological measures

Infrastructural/Technological measures refer to measures that involve changes to infrastructure, such as the construction or enhancement of flood protection systems, including levees, flood walls, detention basins, and weirs[1,59]. These measures have been extensively studied in Europe compared to other continents[1]. While they offer a reliable form of protection, they often result in large-scale disturbances in local communities and ecosystems. These measures are generally expensive, time-consuming, and may lack the flexibility to accommodate the sudden changes in climate change projections. Additionally, infrastructural adaptation measures are characterized by their long-term nature, often lasting for several decades and potentially locking in new development and growth with the expectation of continued protection[60]. This section presents a comprehensive catalog of infrastructural and technological adaptation measures detailing their advantages, disadvantages, co-benefits, and tradeoffs. A summary of these measures is provided in Table 1.

Heightening of levees. Overtopping is the most common cause of levee failures[61]. To mitigate overtopping, increasing the height of levees along waterways is recognized as one of the oldest yet most commonly used hard adaptation methods designed to increase levees’ capacity. This method involves adding additional layers of soil, rock, or other materials to the existing levee structure to raise its elevation and provide greater protection against high water levels[62]. The heightening of levees is placed in the infrastructural/technological category because it involves substantial modifications to physical structures, employing engineering techniques and materials to enhance capacity and effectiveness. Increasing the levee height can decrease the probability of overtopping by enhancing channel capacity, but it also increases construction costs[63]. Moreover, consideration of the levee crown width alongside height is essential to avoid compromising the integrity of the levee system[64]. Heightening existing levees can also disrupt communities by changing the existing landscape and use of space[65]. According to Guida et al.[66], the Tisza River in Central and Eastern Europe has experienced increased flood levels despite an extensive levee system designed to prevent catastrophic flooding. Heightening these levees was found to be more cost-effective and politically expedient than setback alternatives, offering immediate protection. However, this approach does not address the long-term issues of wetland degradation, increased flood levels, and decreased floodway carrying capacity. Consequently, while levee heightening provides short-term benefits, more sustainable solutions for long-term flood management exist. While levee heightening reduces the frequency of inundation in flood-prone areas, it also diminishes flood attenuation, leading to heightened flood discharge downstream[67]. Thus, the effect of levee heightening on flood dynamics warrants careful consideration in flood risk management planning.

Notching. Notching involves deliberately lowering or removing sections of a levee to facilitate controlled flooding into adjacent floodplains. This technique aims to restore natural floodplain connectivity and enhance ecological conditions by allowing water to spill over during high flows while minimizing risks to critical infrastructure and inhabited areas[68]. Notching involves the strategic modification of levee structures to manage floodwaters, justifying its placement in the infrastructural/technological category. The success of notching projects is contingent upon understanding floodplain topography, which plays a pivotal role in floodplain restoration efforts. The interaction between erosion and deposition processes continuously alters the physical landscape at

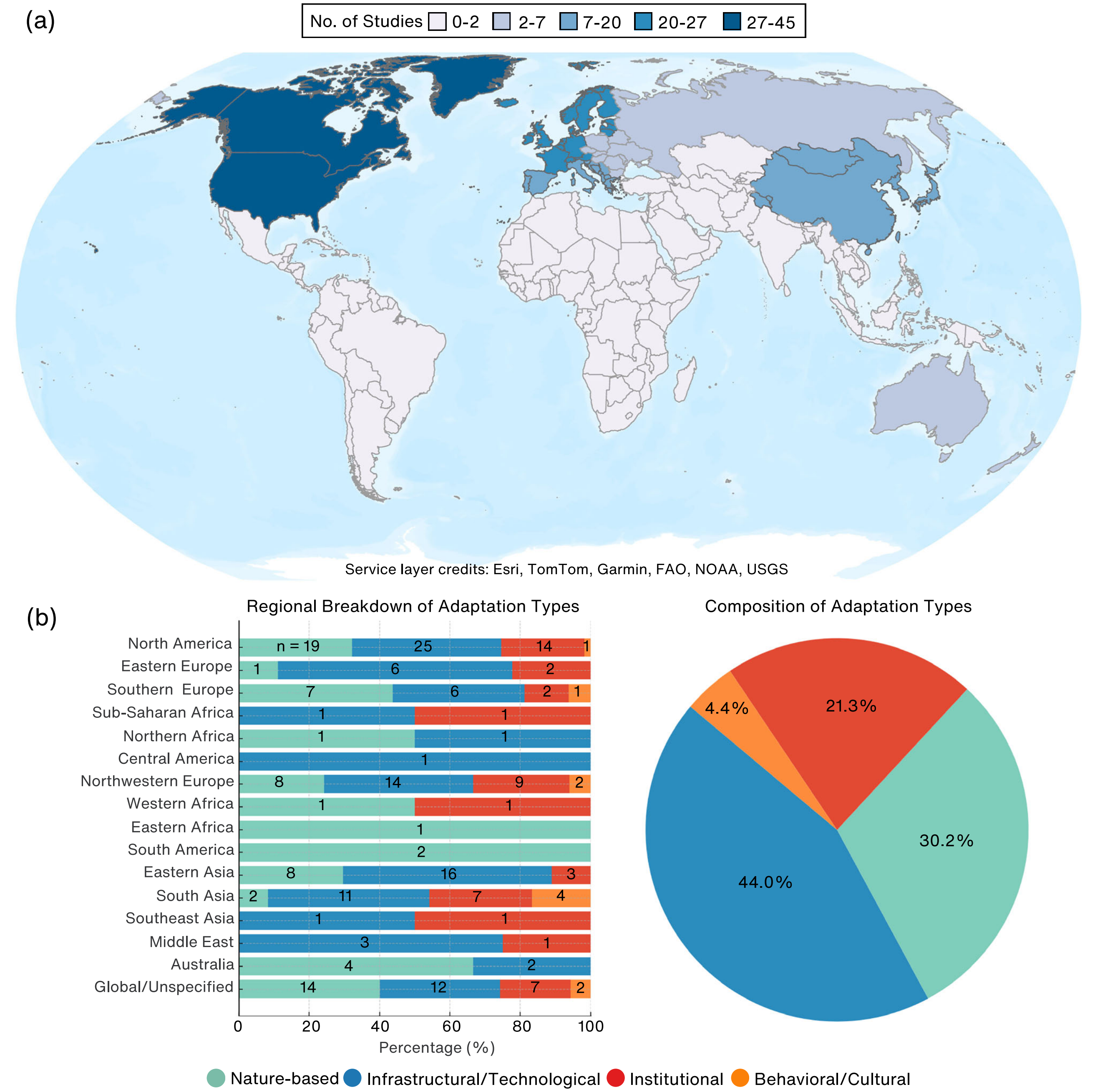

Fig. 3 | Regional distribution and composition of flood adaptation measures across reviewed studies. a Number of studies reviewed from each global region. **b** Stacked bar chart showing the regional distribution of adaptation measure types, Infrastructural/Technological, Institutional, Behavioral/Cultural, and Nature-Based, across the selected studies. The accompanying pie chart presents the overall composition of adaptation measures included in the portfolio, highlighting the relative prevalence of each category across the entire dataset. Shapefiles were sourced from the IPUMS International GIS Boundary Files (LSIB-based).

notched levees. Assessing both upstream and downstream impacts is imperative, as erosion and breach widening can affect flow patterns and sediment transport dynamics[69]. In the Matina River case study, Watson et al.[70] found that increasing the levee height was considered unfeasible due to substantial land loss and economic impacts on agricultural areas. Conversely, while notching can effectively manage peak flows and reduce pressure on levees, its benefits are largely localized and do not address the broader issues of floodplain management. Over time, the relief of the floodplain may evolve due to sediment redistribution and terrain reshaping during higher-magnitude floods. Notching projects hold potential ecological benefits through floodplain restoration while providing relief to levee systems, reducing the risk of catastrophic failure.

Underseepage control. Underseepage, which is exacerbated by internal erosion, is the second most common cause of levee failure after overtopping[71]. Underseepage control is a critical aspect of dam safety, especially for structures like the Willow Creek Dam in Oregon. Constructed between 1981 and 1983 by the US Army Corps of Engineers, this dam was the first major roller-compacted concrete dam in the U.S., primarily built for flood control[72]. During the initial reservoir filling, substantial leakage was observed through horizontal joints, reaching an alarming rate of 33 cubic meters per second. This necessitated a $2 million remediation effort involving grout injection to reduce the leakage to <11 cubic meters per second. Despite these efforts, concerns over the dam's safety and structural integrity persist, with ongoing seepage issues contributing to dense vegetation on the dam's face and

Fig. 4 | A comprehensive portfolio of 39 flood adaptation measures. Synthesized from the literature and classified into four categories: Infrastructural/Technological, Institutional, Behavioral/Cultural, and Nature-Based. To aid interpretation, the dominant flood drivers (pluvial, riverine, and coastal) associated with each measure are indicated using color-coded circles. These visual cues help illustrate the typical application contexts and hazard relevance for each adaptation measure.

Adaptation Classification	Flood Adaptation Measures
Infrastructural/ Technological Involve the development or modification of physical structures or technologies	Heightening of Levees 🔵🟠🟢 Notching 🟠🟢 Underseepage Control 🟠🟢 River Dredging 🟢 Intentional Breaches 🟠🟢 Relocation Multifunctional Design of Seawalls 🔵 Dam Rehabilitation 🟠🟢 Construction of Weirs 🟢 Construction of Flood Walls 🟠🟢 Construction of Flood Protection for Individual Buildings Construction of Channels and Floodways 🟠🟢 Construction of Drainage and Pump Systems 🟠 Construction of Detention Basins 🟠 Construction of Landside Stability Berms 🟢 Construction of Closure Structures 🟠🟢 Construction of Revetments 🔵🟢 Construction of Gabion Walls 🟠🟢
Institutional Involve changes or developments in governance, policies, and organizational structures	Flood Monitoring and Warning Systems Inspections and Maintenance Effective Groundwater Management Policy and Institutional Strengthening Funding for Flood Mitigation and Recovery Proactive Planning for Emergency Action Establishment of Multi-Layer Safety Real-time Control of Reservoirs and Detention Basins Managing Residual Flood Risk Behind Levees
Behavioral/Cultural Involve changes in individual or community behaviors, practices, and cultural norms	Community Education and Awareness Programs Diversification of Crops and Livestock
Nature-Based Involve the use of natural systems and processes	Set-Back 🔵🟢 Permeable Pavements 🟠 Green Roofs and Walls 🟠 Wetland Restoration and Creation 🔵🟢 Establish Riparian Buffers 🟢 Implement Beach and Shoreface Nourishment 🔵 Implement Living Shorelines 🔵 Vegetation on Levee Slopes 🟢 Forest Fire Prevention 🟠 Bio-Inspired Improvements of Soils

Main Flood Drivers: 🔵 Coastal 🟠 Pluvial 🟢 Riverine

continued debates about its long-term viability[72]. Several aspects contribute to levee underseepage, including the presence of a confining layer, geological deposition, the hydraulic conductivity of the foundation, anthropogenic activity, the influence of the root system, animal activity, natural erosion, and internal erosion[73]. Underseepage control measures, such as cutoff walls, seepage berms, filters, relief wells, and grouting, are widely used to mitigate the risk of erosion and underseepage in levees and dams by preventing water from seeping underneath these structures[74,75]. Underseepage control is classified under the infrastructural/technological category because it involves the application of specialized engineering techniques and construction methods to reinforce levee and dam structures. The successful implementation of underseepage control systems requires careful planning and execution. Prerequisites for their installation include thorough geological and hydrological studies to assess local conditions, adequate funding and resources, meaningful stakeholder engagement, regulatory approvals, and strict adherence to environmental and safety standards. Moreover, ongoing monitoring and maintenance are essential to uphold the effectiveness of these measures over time. When properly installed, underseepage control can enhance levee resilience to and better protect lives, property, and critical infrastructure from the impacts of inundation events.

River dredging. River dredging involves the removal of sediment and debris from river channels to increase their capacity and improve and regulate water flow by deepening and widening river channels. Dredging helps reduce the risk of overflow and alleviates flooding in downstream areas[76]. Dredging can increase the flow capacity of a river, decreasing the risk of overtopping and preventing sediment buildup that exerts lateral pressure on flood protection infrastructure. It also has the potential to disturb riverbed stability, leading to increased erosion and causing structural damage during dredging operations[77]. Despite these potential drawbacks, dredging plays a crucial role in reducing the risk of flooding in downstream communities, maintaining water quality, preserving aquatic habitats, and enhancing navigation and transportation. River dredging belongs in the infrastructural/technological category because it involves large-scale engineering operations that modify the physical

Table 1 | Infrastructural/Technological measures and their advantages, disadvantages, co-benefits, and tradeoffs

Measure	Advantages	Disadvantages	Co-benefits	Tradeoffs
Heightening of Levees	Provides increased protection against higher flood levels (Kiss et al., 2021; Wang, 2021).	- Expensive to implement (Del-Rosal-Salido et al., 2021). - Can create a false sense of security known as the levee effect (Di Baldassarre et al., 2009; Collenteur et al., 2015).	- Provides greater protection for critical infrastructure and reduces economic losses from flooding.	- May alter the landscape and affect ecosystems (Egberts & Riesto, 2021). - May not be sustainable in the long term as flood frequency and intensity increase.
Notching	- Alleviates pressure on levee systems by reducing water levels during high-flow events (Ma et al., 2022). - Reduces long-term maintenance costs for levees.	- Implementation may be costly and complex with regulatory and permitting challenges. - May impact upstream and downstream flow patterns, causing increased erosion and sediment transport dynamics. (Zimmerman & Miller, 2021)	- May enhance biodiversity and habitat restoration in floodplains. - Restored floodplains can provide recreational opportunities and improve the visual appeal of landscapes.	- May expose nearby infrastructure and communities to increased flood risk. - Requires ongoing monitoring and management to maintain desired outcomes.
Underseepage Control	- Prevents erosion and failure of levees due to seepage of water underneath (Zhang et al., 2022; Radzicki et al., 2021).	- Requires ongoing monitoring and maintenance. - Can be technically challenging to implement (Lanzafame & Sitar, 2018).	- Helps maintain the integrity of and longevity of levee systems (Salmasi et al., 2020).	- Potential environmental and social impacts during installation. - Sustained effort and investment are needed for long-term effectiveness.
Flood Walls	- Increases robustness of existing levees (Poppema et al., 2023).	- May require sustained maintenance. - Expensive to construct. - Requires proper geological conditions (Ravichandran et al., 2022).	- Can be designed to complement urban landscapes. - Enhances community resilience to flooding.	- May increase the risk of catastrophic damage if the wall fails (Zhang et al., 2022). - Can disrupt natural water flow and sediment deposition.
River Dredging	- Increases channel capacity and improves water flow. - Alleviates flooding in downstream areas Saad & Habib, 2021.	- High initial and ongoing costs to maintain proper function. - Requires extensive planning, environmental impact assessments, and regulatory compliance (Chou & Chiu, 2021).	- Can help sustain healthy aquatic environments. - Sediment removed can be repurposed for various beneficial uses. - Can improve the aesthetic and recreational value of waterways.	- Potential negative impact on aquatic ecosystems and habitats (Carse & Lewis, 2020). - Can temporarily disrupt local communities and wildlife during operations.
Intentional Breaches	- Redirect floodwaters away from critical infrastructure and populated areas, minimizing damage (Hu et al., 2024). - Reduces pressure on levee systems, decreasing the risk of failure.	- Requires careful planning and coordination of downstream impacts (Al-Hafidh et al., 2022). - May cause damage to infrastructure and property.	- Enhances ecological benefits by restoring natural floodplain processes and habitats. - Improves sediment deposition, creating fertile areas for vegetation.	- Redirected floodwaters may impact land uses (Johnson et al., 2022). - May disrupt local economies due to changes in land use and temporary flooding.
Relocation	- Reduces exposure to flood risk (Jacobs, 2018; Torabi & Dedekorkut-Howes, 2021). - Safeguards lives and property.	- Disruptive for communities (Sayers et al., 2022; Alexander et al., 2012; O'Donnell, 2022). - May face resistance from the affected community.	- Restores natural landscapes and enhances ecosystem services. - Reduces future maintenance costs of flood defenses.	- substantial upfront costs and logistical challenges. - Potential loss of cultural and historical sites. (Pinter & Rees, 2021).
Closure Structures	- Allows for controlled closure of flood barriers during high-water events (Tian et al., 2023). - Maintains access through the embankment during normal water levels.	- Requires regular maintenance to ensure functionality (Wurbs, 1996). - Can be costly to install and operate.	- Enable controlled water management and facilitate maintenance activities (Shi et al., 2022). - Enhance community resilience to flooding (Mooyaart et al., 2023).	- May disrupt traffic patterns and access when closed. - The effectiveness of closure structures relies on timely and effective operation during emergencies.
Multi-functional Seawalls	- Protects from erosion, flooding, and wave impacts (Hosseinzadeh et al., 2021).	- Vertical seawalls can exacerbate wave reflection and toe scouring (Hosseinzadeh et al., 2021). - Maintenance and repair challenges in eco-engineered structures (Salauddin et al., 2021).	- Creation of microhabitats (Clifton et al., 2022). - Support for a variety of ecological functions, bolstering coastal defense resilience (Vozzo et al., 2021).	- Potentially higher initial costs compared to traditional seawalls. - Complexity of integrating traditional and novel methods to achieve desired outcomes (Salauddin et al., 2021).
Dam rehabilitation	- Enhances flood control and mitigation by managing peak flows (Manfreda et al., 2021). - Prolongs reservoir life and improves dam safety (Adamo et al., 2020).	- Structural retrofits may be complex and technically challenging (Adamo et al., 2020). - Renovation efforts can be costly and resource-intensive (Kondolf & Yi, 2022).	- Reservoir reoperation can optimize water resources management (Kondolf & Yi, 2022). - Sustainable sediment management improves water quality and ecosystem health.	- Potential displacement of communities and ecological impacts during renovation activities. - Balancing flood control with ecological and societal needs (Manfreda et al., 2021).

Table 1 (continued) | Infrastructural/Technological measures and their advantages, disadvantages, co-benefits, and tradeoffs

Measure	Advantages	Disadvantages	Co-benefits	Tradeoffs
Weirs	- Effective flood control by regulating water flow volume and rate (Mahdi & Hillo, 2021). - Facilitates water measurement and water diversion for irrigation or industrial purposes.	- Interrupts natural river hydrodynamics, potentially affecting aquatic ecosystems (Kaushik et al., 2023). - May accumulate sediments that require periodic removal to maintain functionality.	- Provides stable water levels that can enhance navigation and recreational activities (Wicher-Dysarz et al., 2020). - Potential to improve local biodiversity through habitat creation (Kaushik et al., 2023).	- Potential negative impacts on fish migration and river connectivity (Kaushik et al., 2023).
Gabion Walls	- Effective for erosion control and retaining structures (Mummadisingh & Sengupta, 2023). - Utilizes local materials, making them adaptable to various sites. - Simple construction, minimal foundation depth, and low maintenance (Pereira & Fernandes, 2023).	- Requires comprehensive site investigations to prevent and mitigate failures (Chikute & Sonar, 2022). - Potential aesthetic concerns in certain environments (Mummadisingh & Sengupta, 2023).	- Enhances local biodiversity by providing habitats for small plants (Pereira & Fernandes, 2023). - Improves the lifespan and resilience of the structure through natural vegetation. - Can be constructed using locally available materials, supporting local economies.	- Long-term effectiveness and sustainability require extensive planning. - Feasibility is dependent on available local resources.
Protection for Individual Buildings	- Provides property-level flood protection measures. - Reduces damage and losses due to flooding (Botzen et al., 2017).	- It may not be feasible for all buildings or structures (Gersonius et al., 2008). - May face resistance from developers and property owners.	- Can lead to more sustainable development patterns. - Can lead to the adoption of additional risk reduction measures.	- Does not address community-wide flood risk. - Can be costly for property owners (Nofal et al., 2021)
Channels and Floodways	- Redirect floodwaters away from populated areas (Chen & Hobbs, 2020). - Reduce the pressure on existing levees and floodwalls.	- Requires extensive construction and land use (Bogárdi & Balogh, 2014). - Can be costly to maintain - Potential to displace communities and agricultural land.	- Can aid in floodplain restoration (Serra-Llobet et al., 2021). - Can enhance habitats for certain aquatic species.	- Can alter local hydrology and affect downstream areas.
Increased Capacity of Drainage and Pump Systems	- Expedites the removal of excess water during intense storm events (Chang et al., 2013). - Can be integrated into urban infrastructure planning.	- Requires substantial investment in infrastructure and maintenance (Jafari et al., 2018). - Efficacy may decrease during more extreme flood events.	- Reduce urban flooding and improve water quality. - Supports sustainable urban development.	- Require ongoing maintenance and updates to remain effective. - Can be expensive to retrofit into existing urban areas.
Detention Basins	- Helps reduce the risk of flooding by temporarily storing excess water (Dottori et al., 2023; Vorogushyn et al., 2012). - Can provide water supply benefits during dry periods.	- Requires large land area (Vorogushyn et al., 2012). - High construction and land acquisition costs.	- Can improve ecosystem quality by providing habitat for wildlife and promoting biodiversity. - Can help filter pollutants from stormwater runoff, improving water quality (Dottori et al., 2023).	- May disrupt existing habitats and ecosystems. - Requires regular maintenance to ensure proper functioning (Dottori et al., 2023).
Berms	- Provides increased slope stability (Calamak et al., 2020). - Helps erosion by intercepting and diverting rainwater, reducing the risk of bank retreat (Ozeren et al., 2018).	- Expensive to implement, especially for large-scale projects. (Calamak et al., 2020) - Requires frequent and ongoing maintenance to ensure effectiveness.	- Provides areas for construction and maintenance, inspections, repair, and reinforcement activities.	- May not eliminate erosion or prevent slope failures under extreme hydraulic conditions (Ozeren et al., 2018). - Can affect local ecosystems and land use.
Revetments	- Stabilizes riverbanks and prevents erosion. - Increases robustness of existing levee structures (Kiss et al., 2019).	- Expensive to install and maintain. - Long-term effectiveness may be compromised by changing water flow dynamics (Ohtsuka et al., 2021).	- Can provide a habitat for aquatic life. - Reduce economic losses and enhance community resilience to flooding (Shi et al., 2022).	- May alter natural river dynamics and habitats (Ohtsuka et al., 2021). - Can be visually unappealing.

characteristics of river channels. Prerequisites for dredging include environmental impact assessment, permitting and regulatory compliance, hydrology survey, design operations to minimize impacts on aquatic habitats, navigation, and water quality, as well as the development of a sediment management plan and implementation of monitoring programs[78]. In the Vermilion River, south-central Louisiana, a decline in dredging activities over the past two decades has led to riverbed shoaling and diminished conveyance capacity, contributing to severe flooding[76]. While dredging can effectively reduce water surface elevations during floods, it also has the potential to amplify tidal waves. The study also indicates that although spatially limited dredging can alleviate local water surface profiles, it may inadvertently increase downstream water levels during frequent events[76]. Additionally, large runoff volumes from tributaries can overwhelm the increased in-channel capacity, thereby reducing the anticipated flood relief benefits from dredging efforts. Therefore, while dredging may be a helpful method for managing sedimentation and maintaining waterway access, careful planning and mitigation measures are essential to minimize its negative impacts on aquatic ecosystems and surrounding environments.

Intentional breaches. Intentional breaches are planned openings in flood protection infrastructure designed to redirect floodwaters away from critical infrastructure or populated areas. By strategically breaching levees, authorities can manage floodwater more effectively and minimize damage to surrounding communities[79]. This strategy is categorized under infrastructural/technological measures because it involves the deliberate engineering and modification of flood protection infrastructure to control floodwaters. Intentional breaches of levees, such as the 2011 breach of the Birds Point Levee south of Cairo, Missouri, exemplify the concept of “graceful failure” where systems are designed to fail in a controlled manner to mitigate flood risks[80]. This strategy involves diverting floodwaters to designated floodways, protecting communities and infrastructure. Recent analysis identified 17 potential sites on the Birds Point Levee for floodwater detention through graceful failure, evaluated based on their capacity to store floodwaters at various elevations[80]. In the context of restoring lowland rivers, the topography of floodplains holds critical importance[81]. The development of floodplain topography at intentional levee breaches hinges on various factors related to breach hydraulics and sediment deposition. These factors include the transport capacity of sediment from the main river through the breach onto the floodplain, the sediment supply available to form a splay complex, and the characteristics of the flood pulse that inundates the floodplain[82]. The interplay of erosion and deposition processes at intentional levee breaches continually reshapes the physical structure of the landscape. It is crucial to assess both upstream and downstream impacts of a levee breach, as erosion and widening of the breach may alter flow dynamics and sediment transport. Over time, the relief of the floodplain may evolve as higher-magnitude floods redistribute sediment and reshape the terrain. Intentional breaches have the potential to have ecological benefits through floodplain restoration[83–85], as well as provide more control over where the flooding will occur first[86].

Relocation. Relocation or managed retreat involves the strategic relocation of flood-prone homes and buildings to higher ground without altering the levee infrastructure itself. This approach falls under infrastructural/technological adaptation because it aims to mitigate flood risks by modifying the physical landscape and infrastructure, physically moving vulnerable structures away from areas prone to inundation, reducing exposure to flood hazards, and safeguarding lives and property[87,88]. In the U.S., a number of towns have completed or are planning partial or complete relocations as part of managed flood retreat efforts[89]. Recent relocation projects in the U.S. typically include federally funded property acquisitions and have been substantially funded by the Federal Emergency Management Agency (FEMA), mostly through its Hazard Mitigation Grant Program[89]. A managed retreat can offer a more environmentally friendly, long-term, and sometimes more cost-effective approach to hazard mitigation than structural flood protection. While relocation can effectively remove the risk of flooding a community, it is limited by the social implications of displacing communities, along with the unequal distribution of federal property acquisition funds[90]. A study also evaluates the effectiveness of managed flood retreats and community relocations in 11 small rural towns in the Midwest USA, which relocated to mitigate flood risks from major riverine floods[89]. Their analysis highlights varied outcomes: while towns like Niobrara, NE, and Soldiers Grove, WI, saw successful flood risk mitigation and community stability post-relocation, others like Leavenworth, IN, experienced reintroduced flood risks due to new developments on former floodplains. Additionally, relocations often led to short-term population declines but frequently resulted in population rebounds or growth over time. The study underscores that while relocations are generally effective in reducing flood risks, they are complex and costly, and future projects should learn from these cases to improve long-term outcomes[89]. As flood frequency and intensity continue to rise, community relocation is increasingly considered an alternative to current strategies focused on engineering protection and rebuilding after disasters.

Multifunctional design of seawalls. The multifunctional design of seawalls integrates ecological considerations with structural requirements to protect shorelines from erosion, flooding, and wave impacts while enhancing biodiversity and ecosystem services. This strategy involves advanced engineering and modification of coastal defenses to enhance their protective capabilities while integrating ecological features, justifying its placement in the infrastructural/technological category. Traditional seawall designs (e.g., vertical, curved, and riprap) each offer distinct benefits and challenges. Vertical seawalls provide stability but can exacerbate wave reflection and toe scouring, whereas curved seawalls, which reduce wave overtopping and energy, offer better stability but are more complex to construct. Riprap retaining walls are cost-effective, absorb wave energy, and are easily repairable, often used in combination with other types[91]. A study evaluates the effectiveness of seawalls in mitigating storm surge damage along the Eastern U.S. coastline, highlighting the substantial costs associated with coastal flooding and the necessity for effective defenses[92]. Their model indicates that low seawalls (0.9–1.2 m high) can critically reduce damage from frequent surges. In contrast, higher seawalls are deemed maladaptive due to the lock-in effect limiting flexibility in adaptation and necessitating continuous height increases to keep pace with rising sea levels. Incorporating eco-engineering approaches, such as increasing topographic complexity, can mitigate wave impacts and enhance biodiversity, addressing the deficits of traditional structures[93]. Seawalls with added microhabitats can mimic the complex topography of natural rocky shores, providing refuge from predation and environmental stressors, which increases niche space and surface area[94]. By adding habitat structures, multifunctional seawalls can improve species diversity and filtration rates, which are crucial for water quality and ecosystem health[95]. These interventions not only strengthen the resilience of coastal defenses but also support a variety of ecological functions, making them a valuable strategy for sustainable coastal management.

Dam rehabilitation. Dams play a crucial role in flood control, mitigating the impact of flooding events on downstream communities and ecosystems. Dam rehabilitation is placed in the infrastructural/technological category because it involves technical interventions and upgrades to existing dam structures to address flood risks and changing environmental conditions. Continuous monitoring, maintenance, and rehabilitation of dams, particularly in the U.S., where the average age of dams is 63 years[96]. A study also assesses flood risks in the Bago River Basin, Myanmar, with a focus on dam operations for flood control[97]. They find that dam operations substantially reduce downstream flood hazards and damage. Accurate flood damage estimation is crucial for evaluating flood prevention measures and crafting effective policies. The study highlights that while future extreme floods could cause severe damage, effective dam management, along with additional measures such as land-use planning and crop adaptation, can help mitigate these impacts[97]. Traditional dams serve several purposes such as reducing flood frequency and the extent of flooded areas, while detention dams, specifically designed for flood control and mitigation, detain excess water during high-flow periods and release it gradually downstream. Detention dams help manage peak flows by restricting water flow during high-flow periods, thus reducing the risk of downstream flooding[98,99]. However, ensuring dam safety is paramount, with aging dams facing increased risk due to changing climatic conditions and potential failures[72,100]. Renovation efforts, including structural retrofits, fishway installations, reservoir reoperation, and sustainable sediment management, are essential to prolong reservoir life and mitigate dam impacts, especially in the face of evolving societal expectations and climate change[101].

Construction of weirs. Weirs serve as hydraulic structures deployed across rivers and streams to regulate water flow, playing multifaceted roles in various water management aspects. The construction of weirs involves engineering and building hydraulic infrastructure. Therefore, it is categorized as an infrastructural/technological adaptation measure. Flood control is a primary purpose of weirs, aiming to control the volume and rate of water flow to prevent downstream flooding[102]. Additionally, weirs facilitate water measurement, water diversion for irrigation or industrial purposes, and navigation by maintaining specific water levels[102,103]. Weirs, including varieties like labyrinth, piano key, and submerged weirs, interrupt river hydrodynamics while preserving water and accumulating sediment, thereby impacting water quality[104]. Adapting existing weirs is crucial for managing floods and regulating seasonal inundation, as demonstrated along rivers like the Rhine and Dambovita, where weirs are utilized for flood protection while considering environmental concerns[103]. Gate operation management is essential for weir efficacy in improving water quality, especially concerning high algal biomass concentrations, emphasizing the significance of monitoring and operational planning[105]. A study investigates the ecological impact of large weir constructions on river habitats in South Korea, focusing on the Nakdong and Geum Rivers, which underwent modifications during the Four Large Rivers Project, and comparing them to the unaltered Seomjin River[106]. The findings revealed that the Nakdong and Geum Rivers experienced a substantial increase in permanent water area by 36% and 11%, respectively, while seasonal and non-flooded habitats decreased substantially, highlighting the long-term habitat alterations caused by weir construction. In contrast, the Seomjin River, without weirs, exhibited minimal habitat changes, underscoring the direct impact of weir installations on the other rivers[106]. In summary, weirs serve as pivotal components in water resource management, offering versatile solutions for flood control, water diversion, and water quality enhancement while necessitating careful consideration of environmental impacts and operational strategies.

Construction of flood walls. Flood walls are robust barriers, often constructed from concrete and sometimes steel sheet piles driven deep into the ground to fortify flood defense systems and safeguard communities against flooding. By reinforcing or adding to the flood defense system, flood walls instill confidence in protection measures, enabling communities to remain in place even during severe flood events[107]. Flood walls are considered an Infrastructural/Technological measure because they represent a direct, structural approach to flood management. There are several types of flood walls, but the majority of these are I-walls and T-walls. For instance, after Hurricane Katrina, the United States Army Corps of Engineers (USACE) extensively used concrete T-walls with batter piles in the Hurricane Storm Damage and Risk Reduction System[108]. In several sections, these I-walls or T-walls were installed within the existing levee embankments. The design and selection of flood walls, such as I-walls and T-walls, depend on factors like availability of real estate, availability of earthen material since levees can be cheaper, exposed wall height, and required flood protection height[109,110]. In a detailed case study of the 17th Street Canal flood wall failure in New Orleans during Hurricane Katrina, the stability of the flood wall was shown to be highly dependent on both the design and the materials used[111]. The study highlights the substantial influence of underlying soil conditions on the functionality of flood walls, with non-homogeneous soil profiles necessitating careful consideration during the design phase. Moreover, robust design considerations were emphasized to account for varying soil strengths and the impact of water surcharges on the ground surface[111]. Additionally, various considerations, including the risk of overtopping, vegetation, encroachments, and foundation pipes, must be accounted for in flood wall construction to ensure their effectiveness and stability over time.

Construction of flood protection for individual buildings. Flood protection for individual buildings involves implementing building-level flood protection measures such as flood barriers, raised foundations, waterproofing, amphibious buildings, and retrofitting to minimize flood damage to homes, businesses, and infrastructure. It is an infrastructural/technological measure because it involves the use of engineering and construction techniques to modify or enhance building structures. These measures help to reduce property loss and ensure the safety of occupants during flood events[112]. These building-level measures contribute to reducing property loss and ensuring occupant safety during flood events. Flood resilience of buildings necessitates considering building occupation and material use under different flood conditions. This approach entails diversifying flood-proofing measures and defense levels based on vulnerability, considering the cost-effectiveness of different solutions[113]. Flood-proofing strategies can be achieved by elevated configuration, dry proofing by sealing or shielding, wet proofing, floating or amphibious solutions, temporary barriers, and pump systems at the building level[114]. The same study examined flood protection measures along the Mela River in northeastern Sicily; the effectiveness of flood doors and windows for individual structures was highlighted[114]. While traditional levees can reduce flood damage, their high costs often make them impractical for small-scale areas like the Mela catchment. In contrast, flood-proofing offers a more cost-efficient solution for protecting single houses, although they do not mitigate broader flood impacts. These measures can be implemented based on flood patterns, building elevation requirements, legal regulations, compliance of homeowners and businesses, and available funding and support[115]. Recent studies further distinguish traditional property-level protection (PLP), which focuses on keeping water out from the broader concept of Property Flood Resilience (PFR), which assumes that some water ingress is inevitable and therefore couples resistance devices with recoverability features such as waterproof plasters, raised utilities, and sacrificial finishes[116].

Construction of channels and floodways. Channels and floodways are engineered pathways designed to direct excess water away from developed areas during flooding events. The construction of channels and floodways is an infrastructural/technological measure because it involves the deliberate modification of the landscape to create controlled pathways that manage and redirect floodwaters. Directing floodwaters along predetermined routes, channels, and floodways helps prevent the inundation of homes, businesses, and vital infrastructure[117]. Sampang City, East Java, frequently faces flooding from the Kali Kemuning River. A study highlights the importance of incorporating floodways as a solution to manage these floods[118]. They emphasize that the design of floodways is influenced by runoff discharge and runoff coefficients, which are affected by changes in land use/land cover. They demonstrate that integrating floodways with normalized river dimensions can effectively prevent flooding, provided that the floodway dimensions are appropriately adjusted according to varying runoff coefficients[118]. Floodways established along rivers can be intentionally inundated during severe floods to attenuate water levels and reduce downstream flood damage and losses[118]. For instance, the Dutch flood management strategy involves setting aside land along rivers to widen floodplains and create retention basins for occasional inundation while still allowing for multifunctional uses such as agriculture or recreation[119]. The decision regarding when and how much water to divert into floodways is influenced by various factors, including upstream hydrological conditions, the size and location of the floodways, the effectiveness of the levee protection, potential flood losses in the event of levee failures, and the impact of such failures on downstream flood levels[119]. Additionally, flood diversions can redirect floodwaters into off-channel storage areas, relieving pressure on the main channel and levee system and allowing the river to accommodate higher flow volumes[120]. By strategically managing floodwaters by implementing channels and floodways, communities can enhance their resilience to flooding while safeguarding vital assets and infrastructure.

Construction of drainage and pump systems. Increasing the capacity of drainage and pump systems involves upgrading or expanding existing infrastructure to enhance its ability to manage flood risks in vulnerable areas. These systems can expedite the removal of excess water during intense storm events, reducing the likelihood of flooding[121]. Drainage and pump systems are considered an Infrastructural/Technological measure because they involve the engineering and upgrading of infrastructure systems. A study investigated the effectiveness of enhanced pump operations and capacity expansions in improving urban drainage system resilience in Seoul, a highly urbanized city with waterways such as the Han River and Dorim stream[122]. The research focused on a drainage system covering 2.5 km², incorporating 10 pump stations and two detention reservoirs. By evaluating various operational scenarios, including adjustments to pump stop levels and capacities, the study found that the operational strategies, such as implementing expanded pump capacities and additional monitoring, improved system resilience[122]. An emerging strategy involves adding smart drainage systems that utilize artificial intelligence and machine learning algorithms to steer water to the least sensitive parts of storage basins, minimizing damage by continuously learning and adapting to environmental conditions[123]. In urbanized areas, anthropogenic factors such as land use and storm drainage systems influence surface overland flow processes. The presence of impervious surfaces like rooftops, roads, and squares increases the surface runoff rate and volume, altering the natural flow direction[124]. Storm drainage systems, including storm sewers and pumping stations, play a vital role in mitigating surface inundations by draining excess runoff into underground sewers. If the surface runoff exceeds the capacity of the drainage system, water overflows onto land surfaces, leading to inundation. Flood damage can be reduced by redesigning and enlarging the capacities of storm sewer systems or pumping stations in the inundation-prone areas. Improving and expanding these drainage systems requires an approved point of discharge, proper permitting, retention/detention, an understanding of water dynamics, and identifying the best location[125].

Construction of detention basins. Detention basins, also known as detention areas, serve as crucial components of river flood risk management by temporarily retaining floodwater volumes[23,126]. Detention basins fit into the Infrastructural/Technological category because they are engineered structures designed to mitigate peak flows and reduce water levels during extreme events. They are widely implemented in flood-prone regions across several major river basins[127,128]. These basins offer several advantages, such as reducing downstream flood hazards and risks, improving ecosystem quality, and providing additional services like pollution reduction and recreational opportunities[128]. However, their implementation poses challenges, including the need for land occupation, potential impacts on land use practices, and the requirement for careful planning and optimization to address issues such as population growth and land development pressures, especially in densely populated areas[129,130]. Nonetheless, recent research emphasizes evaluating the efficacy of detention basins not only in terms of reducing peak flows but also in mitigating flood damage, highlighting their importance as adaptive measures in flood risk management strategies[23]. A study of the Poisar River catchment in Mumbai, India, examined the hydrological impacts of land use changes and the implementation of detention basins on urban flood hazards[131]. The researchers found that rapid urbanization led to substantial increases in peak discharge during flood events. However, the introduction of detention basins markedly reduced peak discharge, flood extent, and flood hazard areas, demonstrating the effectiveness of these basins as a flood control measure, particularly during severe flood events[131]. Detention basins, with their multifaceted benefits and challenges, stand as essential adaptation measures in the face of rising river flood risk, necessitating a balanced approach that considers both their effectiveness and potential limitations in flood risk management strategies.

Construction of landside stability berms. Berms are defined as shelves interrupting the continuity of a levee or earthen dam slope. Berms fall into the infrastructural/technological category because they are specifically engineered structures designed to enhance the stability and functionality of levees and earthen dams. They serve various purposes, including increasing slope stability, controlling erosion, extending seepage paths, and providing areas for construction and maintenance work. Berms can also act as effective seepage control measures when equipped with filters and drains. Different types of berms, such as upstream and downstream berms, toe berms, and waste berms, offer diverse functionalities, including augmenting seepage capacity, reducing liquefaction potential, and contributing to slope stability[132]. Seepage berms are particularly effective in preventing underseepage-related failures of levees and are often used alongside relief wells to manage seepage exits at the levee toe[132]. In a case study on climate change adaptation, the authors evaluate the costs and benefits of constructing an 8.2 mile berm along the Hackensack River in Bergen County, New Jersey, following the devastation of Hurricane Sandy[133]. The study examines a 50 year period and demonstrates that investment in the berm is cost-effective, with substantial long-term financial benefits, including the prevention of residential and commercial damages. Additionally, the berm would greatly enhance the region's resilience to future flooding events and provide substantial environmental and social benefits, such as the restoration of wetlands and the development of recreational areas to improve community well-being[133]. While berms may not drastically decrease total eroded volume, they typically delay bank retreat, providing valuable time for mitigation efforts[134]. Overall, berms represent a versatile and valuable adaptation option for reinforcing levees against flood hazards.

Construction of closure structures. Closure structures are engineered barriers or gates designed to close off openings in flood defense systems during flood events to prevent the ingress of floodwaters into protected areas[135]. This infrastructure requires specific technology to enhance flood defense systems on an as-needed basis, justifying their classification as an infrastructural/technological measure. Closure structures are essential if relocating or raising roads and pathways through levees is not possible. They can help maintain the integrity of levee systems and prevent inundation of flood-prone areas by improving emergency response, flood control, risk reduction, maintenance, and controlled releases. They mitigate flood risks for communities on an as-needed basis by safeguarding communities, preventing inundation, minimizing property damage, protecting infrastructure, and ensuring the safety of residents during high-water events[136]. Closure structures can also control the release of water from storage reservoirs and manage its flow through, around, or over dams[137]. The city of Padova, situated amidst the Brenta and Bacchiglione rivers and their interconnected channels, has experienced severe flooding historically and in recent years. Proper operation of floodgates at the Voltabarozzo Control Structure is crucial for balancing the discharge load across the Brenta-Bacchiglione river network. These floodgates are operated based on predefined, static operation rules that depend on real-time flow variables at different locations within the river network. This approach minimizes flood risk by optimally operating existing floodgate structures without substantial additional costs, demonstrating a cost-effective flood management solution[138]. Effective implementation of levee closure structures requires hydrological and hydraulic analysis, geotechnical investigation, hydraulic modeling, regulatory compliance, environmental impact assessment, and community engagement.

Construction of revetments. Revetments encompass various techniques such as placed-rock, gabion, and concrete block structures strategically placed along riverbanks to manage water flow dynamics. They fit into the infrastructural/technological category as they consist of constructed features that are specifically designed to stabilize riverbanks and levee systems. By mitigating the risk of inundation and minimizing the destructive potential of floodwaters, revetments contribute to enhancing the resilience of communities situated in flood-prone areas[139]. However, while revetments can be helpful in managing erosion due to water flow and increasing the stability of levees, if they fail, it could have devastating results on river dynamics and levee strength, potentially resulting in the failure of the levee[140]. Therefore, special attention should be paid to the stability of levee revetments and foundations, considering factors such as riverbed scouring and the dissipation of river water energy[140,141]. Additionally, revetments are introduced to a levee system to protect the crest and river-side slope of the levees against surge overflow and wave overtopping, which are crucial for ensuring a viable and safe levee system. Various strengthening systems, including cellular confinement systems, reinforced grass, concrete block systems, and soil cement/roller-compacted concrete, have been introduced to protect levees from erosion by surge overflow, wave overtopping, transverse and parallel flow[142]. In Ovar, a municipality in Portugal, substantial coastal erosion and sediment deficits have been exacerbated by dam constructions and sand dredging. A case study evaluating different intervention scenarios for longitudinal revetments revealed that raising the crest level is the most viable option due to its cost-effectiveness and efficiency in reducing overtopping. In contrast, artificial nourishment was deemed the least favorable due to high costs and the instability it introduces. Building an intermediate berm presented a viable middle-ground solution with moderate costs and benefits[143]. The implementation of revetment strategies has the potential to safeguard communities against flood-related hazards. However, the long-term resilience and stability of revetments must be considered in the face of changing water flow dynamics and potential inundation risks.

Construction of gabion walls. Gabion walls serve multiple purposes, such as erosion control, soil reclamation, retaining structures, and stream canal linings[144,145]. These walls consist of rectangular baskets made of zinc-coated steel wires filled with stones or cobbles, providing a flexible and monolithic structure. Gabion walls belong to the infrastructural/technological category because they are engineered structures that support flood control. Their construction is facilitated by the utilization of local materials, making them adaptable to various sites, and their high drainage properties make them suitable for soils prone to settlement[144]. Over time, gabion walls naturally enhance their strength and effectiveness as voids fill with silt and vegetation. Despite their advantages, failures in gabion walls are often attributed to factors such as improper stones, poor workmanship, and inadequate construction procedures rather than design flaws. Therefore, it is crucial to address construction-related issues, explore alternative materials and techniques, and conduct comprehensive site investigations to effectively prevent and mitigate gabion wall failures[146]. In a study examining the long-term effectiveness of gabion structures along the Zealand River, New Hampshire, gabion walls and sills were initially successful in mitigating flood flows, limiting bank erosion, and trapping bedload sediment. However, over time, these structures frequently became undercut, toppled, or overtopped due to ongoing channel incision and undermining, leading to substantial geomorphological changes and ecological challenges. The findings underscore the importance of thorough evaluation and robust maintenance planning for the continued effectiveness of gabions in river stabilization efforts[147]. Gabion walls offer numerous benefits, such as flexibility, permeability, low maintenance, simple construction, minimal foundation depth, and environmental sustainability due to their ability to allow small plants to take root, reinforcing the soil and improving the structure's lifespan[145].

Institutional adaptation measures

Institutional adaptation measures involve modifications to governance structures, policies, and organizational frameworks to better manage climate risks[1]. These measures include the development of regulations, such as zoning laws and building codes, the implementation of insurance schemes, and the creation of coordination mechanisms to improve institutional responses to climate impacts. However, there may be a reporting bias, as many institutional responses are documented in grey literature. Institutional adaptation emphasizes enhancing multi-level governance and building institutional capabilities to integrate climate adaptation into existing policy frameworks effectively. This section offers an extensive catalog of institutional adaptation measures, outlining their benefits, drawbacks, associated co-benefits, and potential tradeoffs. A summary of these measures can be found in Table 2.

Flood monitoring and warning systems. The implementation of flood monitoring and warning systems involves the installation of sensors, gauges, and monitoring stations to track water levels, rainfall intensity, and weather forecasts. These systems provide real-time data and early warnings to communities, enabling timely evacuation and preparedness actions[148]. These systems play a crucial role in providing advance notice of impending floods, facilitating the implementation of emergency plans, and minimizing the adverse impacts of floods[149]. The development and implementation of flood monitoring and warning systems fall under the infrastructural/technological category because they involve creating and deploying advanced technological infrastructure for real-time flood detection and response. A case study highlights Bangladesh's heightened vulnerability to floods due to its socio-economic conditions and geographic location within the Ganges-Brahmaputra-Meghna basins[150]. Focusing on the Sirajganj district, which has experienced severe flood damage in multiple years, the study found that traditional embankments are ineffective in mitigating flood risks. The research demonstrated that impact-based forecasting and warnings could be more effective than traditional flood warnings, as they translate hydro-meteorological forecasts into actionable information for end users such as farmers and disaster management personnel[150]. Several countries have operational flood warning systems, such as the Flood Forecasting system of DELFT-FEWS and the Central America Flash Flood Guidance[151,152]. Flood warning systems typically consist of four key elements: detecting flood potential, forecasting flood hazards, issuing warnings to authorities and the public, and coordinating flood response[153]. These systems utilize various methods, including monitoring weather patterns, estimating rainfall from satellite imagery, and analyzing hydrologic and hydraulic models[154]. Monitoring and warning systems are vital; effective flood management also requires evacuation plans, community trust, and evacuation capability. While many large-scale flood warning systems exist, many communities still lack their own monitoring and alert systems, highlighting the need for enhanced preparedness[155].

Table 2 | Institutional adaptation measures and their advantages, disadvantages, co-benefits, and tradeoffs

Measure	Advantages	Disadvantages	Co-benefits	Tradeoffs
Flood Monitoring and Warning Systems	- Provides early warning to residents and authorities (Li et al., 2021; Demir & Krajewski, 2013). - Allows for timely evacuation and emergency response (Nguyen et al., 2021).	- Depends on accurate and reliable data, which can be challenging to obtain in some regions. - Often requires long-term investment in infrastructure which may be a challenge for communities with limited capacities (Idowu & Zhou, 2019).	- Enhances overall disaster preparedness and response capabilities. - Improves coordination between government agencies, communities, and emergency services (Rana et al., 2020).	- Effectiveness depends on community awareness and response. - False alarms or inaccurate warnings can lead to complacency or unnecessary panic.
Inspections and Maintenance	- Helps prevent long-term degradation and reduce risk (Klerk et al., 2024). - Identifies vulnerabilities and addresses potential hazards early, preventing system failures (Tadda et al., 2020).	- Requires investment in personnel and resources (Assaf & Assaad, 2023). - It may be challenging to enforce compliance.	- Enhances overall infrastructure resilience and longevity (Klerk et al., 2021). - Can support procedural and environmental justice by prioritizing vulnerable areas.	- Effectiveness depends on the frequency and thoroughness of inspections. - Maintenance work may have temporary negative impacts on local ecosystems and habitats.
Groundwater Management	- Acts as a natural buffer against floods and droughts (Ward et al., 2020). - Enhances groundwater recharge.	- Frequent flooding poses risks of groundwater contamination and saltwater intrusion (Befus et al., 2020). - Overexploitation of groundwater resources lead to environmental concerns (Oppenheimer et al., 2019).	- Enhances sustainability of water resources (Bosserelle et al., 2022). - Supports agricultural productivity and food security. - Contributes to the overall health of ecosystems.	- Requires substantial investments in infrastructure. - Necessitates comprehensive monitoring and management to ensure both water quality and quantity.
Policy and Institutional Strengthening	- Enhances flood risk governance. - Builds local institutional capacities and mainstreams resilience policies (Laeni et al., 2020). - Improves adaptive capacity and proactive leadership.	- Fragmented responsibilities among government organizations (Vitale & Meijerink, 2023). - Institutional hurdles may compound technical challenges.	- Establishes knowledge networks to support local governments. - Facilitates public participation in resilience strategies. - Identifies strengths, weaknesses, and potential synergies within institutional systems (Ro & Garfin, 2023).	- Potential resistance from institutions to change existing governance structures (Vitale & Meijerink, 2023). - May need ongoing adjustments to address emerging challenges.
Funding for Flood Mitigation and Recovery	- Ensures availability of resources for advanced and effective flood mitigation and recovery efforts (Karim & Noy, 2020). - Provides financial support to those affected by flooding.	- Dependent on government budget allocations (Emrich et al., 2019). - May compete with other funding priorities (Verlynde et al., 2019).	- Enhances community awareness and preparedness for future flood events (Slavíková et al., 2020). - Encourages public-private partnerships and collaboration in flood mitigation.	- Special efforts are required to make sure that disadvantaged groups receive fair support (Tyler et al., 2023). - Must ensure that quick fixes do not compromise future flood resilience (Verlynde et al., 2019).
Planning for Emergency Action	- Provides guidelines and procedures for responding to flood events (Khantong et al., 2020). - Increase public knowledge about flood risks and appropriate responses.	- Effectiveness depends on the level of community engagement and participation (Bera, 2023). - Requires constant reassessment as flood risks evolve (Hammood et al., 2021).	- Can foster community resilience and preparedness. - Can lead to the adoption of additional risk reduction measures (Shah et al., 2021).	- May require extensive time and resources to implement and sustain (Shah et al., 2021). - Effectiveness may depend on the demographics and socio-economic conditions of the community.
Multi-layer Safety	- Redundancy in flood protection measures is provided (Zevenbergen et al., 2020). - Increased reliability of flood protection infrastructure (Karrasch et al., 2021); (Rehan, 2018).	- Requires careful consideration of measures across spatial scales and time horizons. - Requires collaborative efforts among various stakeholders, including governments, communities, and private entities.	- Encourages community engagement and awareness in flood risk management. - Promotes sustainable development in flood-prone areas.	- Requires coordination between structural and procedural components (Bosoni et al., 2023).
Real-time Control of Reservoirs and Detention Basins	- Dynamically lower downstream flood peaks (Sharior et al., 2019; Feng et al., 2023).	- High upfront costs for sensors, telemetry, and automated gates (Bilodeau et al., 2018).	- Allows multi-objective operation for flood control, water supply, recreation, and ecological base-flows (Oh & Bartos, 2023).	- Prioritizing flood mitigation can reduce hydropower revenue or restrict ecological flow releases at certain times (Feng et al., 2023).
Managing Residual Flood Risk Behind Levees	- Incorporates zoning, insurance, and emergency protocols to limit losses when levees overtop or fail (Serra-Llobet et al., 2022).	- Fragmented governance may slow the adoption of consistent standards across jurisdictions (Serra-Llobet et al., 2022).	- Strengthens community preparedness, evacuation drills, and flood-risk awareness campaigns (White et al., 2001).	- Strict land-use controls may constrain urban growth and affordable housing supply near levees (Serra-Llobet et al., 2022).

Inspections and maintenance. Regular inspections and maintenance of flood protection infrastructure, drainage systems, and flood-prone areas are essential for identifying vulnerabilities, addressing potential hazards, and ensuring the effectiveness of flood mitigation measures. These activities involve the systematic evaluation and upkeep of physical infrastructure and ensuring that technological systems remain effective and resilient against potential flood risks, justifying its placement in this category. Proper maintenance helps to prevent system failures and reduce the risk of flooding[156]. Flood defenses require regular interventions to cope with long-term degradation processes, changes in performance requirements, and hydraulic loads[157]. The degradation of flood defenses can occur through continuous-progressive degradation, which is typically a slow process, or shock-based degradation caused by randomly occurring shocks of varying sizes[158]. The case study of the Eilandspolder in North Holland, underscores the importance of rigorous inspections and maintenance for levee safety[159]. It advocates integrating real-world observations and degradation effects into levee safety assessments, allowing for a more accurate and performance-based evaluation. This approach emphasizes the need for continuous monitoring and timely repairs to ensure that levees maintain their protective functions against flooding[159]. Optimal inspection frequency and intervention levels for shock-based degradation depend on the inter-arrival time and size of shocks. Additionally, more frequent monitoring and maintenance not only enhances safety and risk reduction but also contributes to community confidence, economic stability, and growth[160]. Planning the frequency of levee inspections and maintenance requires understanding structural components, historical data, hydraulic patterns, and weather and climate events.

Effective groundwater management. Adaptation through groundwater management is a tool for providing protection against flooding, ensuring freshwater supplies, and supporting climate-resilient spatial planning. Effective groundwater management is categorized as an institutional adaptation measure as it involves coordinated policies, regulations, and practices that govern the sustainable use and protection of groundwater resources, integrating them into broader flood risk reduction and climate resilience strategies. In the case of New Orleans, a city with over 50% of its area below sea level, complex hydrogeology substantially influences groundwater dynamics and the associated risks of flooding and levee underseepage. Particularly, areas with permeable sediments and shallow confined aquifers face elevated risks of groundwater flooding. A study underscores the importance of understanding these hydrogeologic factors, as they help identify geo-hazard areas and inform more resilient engineering designs for coastal cities facing similar challenges[161]. Groundwater, although a vital resource, is being overexploited globally at unsustainable rates, leading to critical environmental concerns[162]. Effective management practices, such as improved land management in upper basins, rainwater harvesting, and the use of previous pavements in urban areas, can enhance groundwater recharge and sustainability[163]. Groundwater acts as a natural buffer against both floods and droughts, recharging during floods and providing water during droughts, thus mitigating the impacts of both extremes[164]. Additionally, targeted recharging of excess wet season flows into aquifers can protect downstream areas and boost agricultural productivity. However, frequent flooding poses risks of groundwater contamination, as surface flows can carry pollutants into aquifers, necessitating careful management to maintain groundwater quality[164]. Despite its importance, groundwater management is often neglected, highlighting the need for integrated disaster risk reduction strategies that consider both floods and droughts.

Policy and institutional strengthening. Policy and institutional strengthening are critical for effective flood risk management. This method involves enhancing the capacity and coordination of institutions and policies to effectively manage and govern flood risk through improved frameworks, leadership, and stakeholder engagement, justifying their placement into the institutional adaptation measures category. Institutions shape human interactions and flood risk governance through various actor networks, resources, and multi-level coordination mechanisms[165]. However, fragmented responsibilities among government organizations and insufficient collaborative public engagement create substantial institutional hurdles, compounding technical challenges in flood risk management. Programs like ACCCRN, 100 Resilient Cities, and Water as Leverage in Southeast Asia have made strides in building local institutional capacities by funding pilot projects and establishing knowledge networks to support local governments in mainstreaming resilience policies[166]. Adaptive capacity, a key attribute of resilience, can be enhanced through robust institutional frameworks that incorporate proactive leadership and public participation. Effective utilization of adaptive capacity criteria is crucial for assessing and designing resilience strategies. This approach helps in identifying strengths, weaknesses, and potential synergies within institutional systems, thereby bolstering urban flood resilience[167].

Funding for flood mitigation and recovery. Funding and financial support for flood mitigation projects, infrastructure improvements, and disaster recovery efforts may include aid from federal, state, and local government grants, loans, and assistance programs[168]. This institutional adaptation measure involves financial mechanisms and government programs that are essential for supporting infrastructure improvements, disaster recovery, and equitable flood risk management. In October 2015, South Carolina experienced severe flooding from Hurricane Joaquin, causing widespread damage to infrastructure, homes, and businesses. Only 28% of over 101,000 applicants for Individual Assistance received support, with disparities evident: higher-income areas received more aid, while Black populations and renters were underserved in both Small Business Administration (SBA) loans and National Flood Insurance Program (NFIP) payouts. This case study highlights the inequities in disaster recovery funding, underscoring the need for more equitable distribution in future disaster responses[169]. To adequately address flood risk, public funding should focus on both flood mitigation and recovery[170–172]. In the U.S., the Federal Emergency Management Agency (FEMA) offers the Flood Mitigation Assistance (FMA) program, which provides nearly $175 million in competitive grants to state, local, tribal, and territorial governments to reduce flood risks. Grants are awarded based on eligibility, project ranking, and cost-effectiveness to reduce National Flood Insurance Program (NFIP) claims. However, socially vulnerable counties are shown to be less likely to receive FMA funding[173]. Additionally, FEMA's Public Assistance (PA) program supports the repair and rebuilding of public and some private non-profit infrastructure and reimburses state and local governments for emergency management[174]. The PA program's importance is expected to grow with the increasing frequency and intensity of natural hazards. However, there are potential equity issues, as more resource-rich areas tend to benefit more from PA funds, demonstrating the importance of targeting vulnerable groups while ensuring equity in access to recovery funds[173].

Proactive planning for emergency action. Emergency action plans enable communities to respond effectively to flood emergencies and coordinate emergency services, evacuation procedures, and relief efforts. These plans outline roles, responsibilities, and protocols for local authorities, first responders, and community members during flood events[175]. Proactive planning for emergency action fits into the institutional adaptation measures category because it involves developing and coordinating structured plans and protocols by local governments and authorities. They establish clear procedures for emergency response actions, such as evacuation routes, shelter locations, and communication protocols, ensuring a coordinated and efficient response. Additionally, emergency action plans facilitate the identification and coordination of resources needed for response and recovery efforts, including personnel, equipment, and supplies[176,177]. Benefits of emergency action plans include better preparedness, reduced casualties and damage, and improved coordination, while drawbacks involve the risk of outdated information, lack of stakeholder engagement, and difficulties adapting to unforeseen events. Local governments play a critical role in managing disasters at the community level, leveraging their familiarity with local communities to effectively implement emergency management strategies[178]. In Kebomlati Village, Indonesia, effective planning for emergency action has proven essential in mitigating the impacts of frequent natural disasters such as river flooding, drought, and forest fires. The establishment of a Flood Disaster Management Committee, encompassing multiple stakeholders, highlights the critical role of coordinated emergency action. Furthermore, the strategic use of social capital and technology for communication and volunteer training exemplifies how preparedness and community collaboration can critically enhance disaster response efforts[179]. Current emergency action plans typically lack a comprehensive integration of climate change projections, which are crucial for anticipating and preparing for more severe and frequent flood events in the future. To avoid conflicts and duplication of efforts, there is also a need for improved mechanisms for cross-jurisdictional coordination, particularly in regions where floodwaters may affect multiple communities simultaneously. Challenges and failures in emergency management processes serve as opportunities for leaders and organizations to enhance their capabilities and confidence through continuous improvement efforts.

Establishment of multi-layer safety. Multi-layer safety refers to the concept of implementing redundant or overlapping layers of flood protection measures to enhance the overall resilience of flood defense systems. This approach emphasizes comprehensive measures for protection, prevention, preparedness, and recovery to ensure a robust response to potential hazards[180]. The establishment of multi-layer safety fits into the institutional adaptation measures category because it requires coordinated efforts across various policy domains and stakeholders to implement successful overlapping and redundant flood protection strategies. Multi-layer safety incorporates tactics such as compartmentalization, the subdivision of the at-risk area into smaller sections. This approach involves enhancing and, in some cases, removing certain flood defenses and community-level safety plans to manage water flow and protect urban areas during flood events[181]. Incorporating both public protection measures and individual protection measures into a multi-layer safety approach offers a comprehensive strategy to mitigate flood risk at both community and property levels. By combining structural defenses with targeted interventions for individual buildings, this approach not only enhances flood resilience but also fosters a synergistic effect that provides greater resistance to flood hazards than either measure alone[182]. However, the successful implementation of multi-layer safety necessitates collaborative efforts among stakeholders, integration of objectives from various policy domains, and careful consideration of a range of measures across spatial scales and time horizons[183]. This approach can also have high associated costs. Shanghai faces severe risks from coastal flooding due to its low-lying geography and historical reliance on outdated hard defenses like sea dikes and floodwalls. Projections indicate that Shanghai could experience the highest increase in flood risk worldwide due to climate change and socioeconomic development[48]. Hard strategies, such as storm-surge barriers, substantially reduce expected annual damages but come with high costs, whereas soft strategies like wet-proofing and coastal wetlands offer better benefit/cost ratios but are less effective against future risks. The hybrid strategy, which combines both approaches, provides the optimal balance of cost, effectiveness, and risk reduction, outperforming single-strategy approaches in managing future flood risks[48].

Real-time control of reservoirs and detention basins. Real-time control (RTC) of reservoirs and detention basins represents an advanced and adaptive flood mitigation strategy that leverages real-time data streams, including rainfall forecasts, river stage levels, and sensor network outputs, to dynamically adjust gate operations and optimize stormwater storage and discharge[184,185]. Unlike traditional static infrastructure, which is typically designed based on historical hydrologic patterns, RTC enables predictive and responsive system management. This functionality is especially critical in the context of climate change, which is increasing the intensity and frequency of extreme precipitation events, and in rapidly urbanizing areas with high levels of impervious surfaces that amplify runoff volumes[186].

RTC offers numerous benefits, including the ability to reduce downstream flood peaks, extend detention and retention times, and support multi-objective system performance ranging from flood mitigation to water supply management and ecological preservation[187]. Importantly, while RTC relies on engineered infrastructure, it is also inherently institutional in nature. Effective deployment requires coordinated governance reforms, revised operational policies, inter-agency collaboration, and financial incentives for municipalities to invest in sensor networks, telemetry systems, and data-driven modeling platforms[186].

A case study from Southwest Granby, Quebec, highlights the practical benefits of RTC. The system demonstrated the capacity to delay peak flows by up to 36 h, prevent overflows during extreme rainfall events, and improve pollutant sedimentation by extending storage times[186]. Additional studies also show that RTC can enhance water quality by reducing pollutant loads, managing sedimentation, and limiting combined sewer overflows[188].

Despite its advantages, RTC presents certain challenges. These include high initial capital and installation costs, the need for ongoing data collection and system calibration, and potential vulnerabilities associated with sensor malfunctions or communication failures. Nonetheless, the overall benefits of enhanced flood resilience, deferred infrastructure expansion, and improved water quality make RTC a highly promising and scalable solution, particularly in urban areas facing increasing climate variability and uncertainty.

Managing residual flood risk behind levees. One critical yet often underemphasized dimension of flood risk management is addressing residual risk behind levees, i.e., the risk that persists due to levee overtopping or failure during events that exceed their design standards. Despite providing a sense of security, levees can create false perceptions of safety, increasing development in protected areas, a phenomenon known as the "levee effect"[189]. A study provides a comparative analysis of how the U.S., France, and Quebec address this issue through regulatory flood maps[190]. While France and Quebec incorporate residual risk zones into flood regulation and land-use planning, the U.S. only includes these areas in regulatory flood maps if levees are not FEMA-accredited. This variation has substantial implications for risk communication, emergency planning, and insurance uptake.

Effective management of residual risk requires integrating multiple non-structural measures such as land use regulations, flood insurance, and emergency preparedness protocols alongside engineered infrastructure. It also demands regulatory transparency, public engagement, and consistent communication strategies. This topic highlights a key area where institutional adaptation intersects with infrastructural reliability, reinforcing the need for layered, cross-sectoral adaptation planning[190].

Behavioral/cultural adaptation measures

Behavioral/Cultural Adaptation Measures involve changes in individual and community behaviors, practices, and cultural norms to reduce vulnerability to climate impacts[1]. These measures are the most commonly observed form of adaptation, with extensive evidence showing individuals and households adopting strategies such as flood protection for homes, drought-resistant agricultural practices, relocation from hazard zones, and shifting livelihoods. In agriculture, for example, households are increasingly switching to crops and livestock that are more resilient to drought, heat, moisture, pests, and salinity. While behavioral changes are often the first line of defense, they are followed by technological innovation, infrastructural development, nature-based solutions, and institutional adaptation in broader climate resilience strategies. This section provides an extensive overview of behavioral and cultural adaptation measures, outlining their benefits, drawbacks, additional advantages, and associated tradeoffs. Table 3 offers a concise summary of these measures.

Community education and awareness programs. Community education and awareness programs are essential components of adaptive flood risk management. These initiatives support the broader shift away from overreliance on large-scale structural interventions by emphasizing the importance of behavioral change, local engagement, and non-structural strategies. Classical studies have long cautioned against excessive dependence on engineering solutions, noting that such approaches can sometimes exacerbate flood risks[191]. For example, the practice of "straitjacketing" continuously elevating and reinforcing levees may simply displace floodwaters to downstream or adjacent areas, amplifying risks elsewhere. Another well-documented phenomenon is the "levee effect," in which the presence of flood defenses fosters a false sense of security, encouraging development in flood-prone areas and ultimately increasing vulnerability when defenses are overtopped or fail[191–194].

Recognizing these unintended consequences has prompted calls for more holistic, integrated flood adaptation strategies. These approaches increasingly emphasize the role of community agency, social networks, and local knowledge in fostering resilience[195]. Empowering communities to actively participate in flood risk planning and response builds ownership, promotes more context-specific solutions, and enhances long-term adaptation outcomes. Community-led initiatives are particularly valuable in identifying localized vulnerabilities, developing appropriate interventions, and ensuring that measures are socially acceptable and sustainable.

Education and awareness programs fall within the behavioral/cultural category of adaptation measures because they aim to enhance individual and collective understanding, attitudes, and practices related to flood preparedness and response. A study outlines that effective community education spans multiple domains: disaster risk education, prevention education, preparedness training, and emergency response planning[196]. Another study further stresses the need for a comprehensive and sustained approach to education that builds both technical knowledge and civic responsibility[197].

In practice, the effectiveness of education programs depends on how well they are tailored to local contexts. In Accra, Ghana, for example, recurring seasonal floods are compounded by rapid urbanization, poor drainage, and limited maintenance of infrastructure. Structural measures have often proven ineffective, and relocation or eviction programs have met with strong community resistance, demonstrating the need for meaningful engagement through education and awareness initiatives[198]. Flood education can be disseminated through various media, including public campaigns, community events, school curricula, and visual materials. These programs should go beyond basic instruction to promote hands-on learning, enhance self-awareness, and foster long-term behavioral change[199].

Previous flood experience also plays a substantial role in shaping risk perception and adaptive behavior. Households that have experienced flooding tend to show higher levels of preparedness, partly because these events elevate awareness and highlight the importance of mitigation[200]. However, large-scale flood awareness campaigns have shown limited effectiveness, suggesting a need for more focused, community-based education initiatives to better engage households and businesses in integrated flood risk management[201].

Diversification of crops and livestock. Climate change poses a threat to food security in several regions of the world. In response, farmers worldwide are adopting innovative strategies. Diversification of crops and livestock involves changes in community behaviors to enhance resilience and adaptability, justifying its placement in the behavioral/cultural adaptation category. An interesting and creative example can be observed among farmers in Bangladesh, who have started rearing ducks instead of chickens for their ability to fly and swim, resulting in higher survival rates during floods[202]. Additionally, a study highlights the importance of community education and awareness programs in the context of managing catastrophic risks, particularly in the flood-prone regions of Khyber Pakhtunkhwa, Pakistan[203]. Given the region's high susceptibility to climate change and frequent flooding, local households have adopted both on-farm and off-farm livelihood diversification strategies to cope with these challenges. By educating communities about the benefits of diversifying livelihoods, especially through livestock investments, farmers can reduce their reliance on vulnerable crop yields and better adapt to flood risks[203]. Furthermore, several studies focus on investigating crop response to climate stressors such as extreme precipitation, storms, snow, hailstorms, and floods in a combined effort to develop climate-resilient crops[204,205]. The task of "adapting" crops has become a major challenge for breeders, extending beyond economic interests to address national and global food security concerns.

Nature-based adaptation measures

Nature-based adaptation measures refer to strategies that leverage natural systems and processes to mitigate climate risks and bolster resilience[1]. These approaches include actions such as wetland restoration, which can serve as natural flood buffers, and the implementation of green infrastructure to manage flood risks. Nature-based solutions encompass a range of ecosystem management practices, including species regeneration projects, wind breaks, erosion control, reforestation, and riparian zone management. While these measures enhance and protect ecosystem services, they also play a critical role in reducing the vulnerability of communities to the impacts of climate change. This section provides an inventory of nature-based adaptation measures, outlining their strengths, limitations, co-benefits, and tradeoffs. A summarized overview of these measures is available in Table 4.

Set-back. A set-back involves strategically altering levees to create additional space for water storage during high-flow events. Setback fits within the nature-based adaptation measures category as it utilizes natural floodplain restoration to enhance water storage, improve river ecosystem health, and reduce flood risks. By allowing controlled overflow into a designated floodplain, this approach reduces pressure on the main flood protection infrastructure and helps prevent catastrophic breaches. Inspired by floodplain restoration efforts, this approach aims to improve hyporheic flow between rivers and their floodplain regions, thus potentially enhancing river ecosystem health[206]. For instance, levee L536 on the Missouri River, built in 1951 and repeatedly damaged by floods, underwent a setback after a devastating flood in 2019. This project reconnected 5.2 km^2 of floodplain and was successful due to collaboration among local districts, USACE, non-profits, and federal and state agencies. The setback also integrates conservation lands into a habitat complex, enhancing ecological benefits[207,208]. By moving levees further away from the river channel, setback projects can increase floodplain area and facilitate better biogeochemical processing, water quality improvement, and habitat restoration[206]. While setbacks offer promising flood protection benefits by reducing water surface elevation and lessening the intensity of flood hazards acting on levees, they also pose challenges such as erosion and sediment management risks[207,208]. A major limitation of set-back adaptation is that it requires real estate landward. Therefore, the costs to set-back levees could be high. However, with careful planning and consideration of site-specific factors such as geomorphic characteristics and sediment distribution, setbacks may present an innovative and environmentally sustainable solution for flood risk management improvement[209].

Permeable pavements. Permeable pavements offer a sustainable solution to the challenges posed by urban stormwater management and flood control. Their design incorporates a permeable upper surface, sand,

Table 3 | Behavioral/Cultural adaptation measures and their advantages, disadvantages, co-benefits, and tradeoffs

Measure	Advantages	Disadvantages	Co-benefits	Tradeoffs
Community Education and Awareness	-Enhances flood preparedness and resilience (Tsai et al., 2020). - Increases individuals' knowledge and response capabilities (Kitagawa, 2021).	- Large-scale awareness campaigns have limited effectiveness (Osberghaus & Hinrichs, 2020). - Effectiveness can be variable based on community engagement levels.	- Creates an enhanced sense of civic responsibility. - Promotes adaptive behavior. - Encourages community-based education initiatives (Mondino et al., 2020).	- Continuous updates and engagement are needed to maintain effectiveness (Osberghaus & Hinrichs, 2020). - Balancing immediate needs with long-term educational goals.
Diversification of Crops and Livestock	-Enhance resilience by reducing the risk of crop or livestock failure (Darby, 2019). - Enhanced food security (Rivero et al., 2022; Kopec, 2024).	- Higher initial costs from transitioning to new crop or livestock varieties. - Complex nature of managing diverse farms.	- Economic stability during floods. - Provide vulnerable communities with a way of conserving their wealth.	- Farmers will have to navigate new supply chains and consumer preferences.

a bedding gravel layer, a base course layer, and natural soil, which collectively decrease the volume and rate of stormwater, contributing to reduced drainage system needs and potentially lowering the carbon footprint of drainage construction[210]. Unlike traditional drainage systems, which can be expensive and impractical in densely populated areas, permeable pavements are categorized as nature-based adaptation measures as they mimic natural hydrological processes by facilitating the infiltration, storage, evaporation, and detainment of runoff. These pavements are categorized based on their structure into drainage pavements, semi-permeable pavements, and fully permeable pavements[211]. In a case study conducted on a two-way, six-lane road in Nanjing, the authors investigated the effectiveness of permeable pavement in mitigating urban runoff and reducing flood risks[212]. The findings revealed that permeable pavements, particularly those with increased gravel thickness, substantially reduced surface runoff and delayed flood peaks. These results underscore the importance of carefully considering soil type and pavement design in urban planning for flood risk management[212]. As urbanization increases impermeable surfaces, the risk of flooding rises, making permeable pavements an attractive solution due to their ability to allow infiltration of rainfall and surface runoff, thereby reducing stormwater volume and aiding groundwater recharge[210,213]. However, conventional permeable pavements are prone to clogging, which diminishes their performance and requires costly maintenance[214]. High-strength clogging-resistant permeable pavements, developed to address these issues, boast improved performance and can be utilized on heavily trafficked roads, enhancing urban flood resilience. Consequently, new design guidance is essential to fully leverage the unique properties of these advanced materials.

Green roofs and walls. Green roofs and walls offer multifaceted benefits in urban areas, particularly in the context of climate change and rapid urbanization. Green roofs and walls fit within the category of nature-based adaptation measures as they naturally manage stormwater through the absorption and retention of rainwater. In addition to their environmental benefits, green roofs and walls play a crucial role in flood control by reducing surface runoff and enhancing infiltration. By storing rainfall in their soil substrate and delaying runoff peak generation, green roofs mitigate the impacts of extreme rainfall events, thereby reducing the risk of urban flooding[215]. Similarly, green walls help absorb and retain rainwater, reducing the volume of runoff and alleviating pressure on drainage systems during heavy precipitation events. Additionally, they enhance biodiversity, reduce energy consumption, prevent pollution, and contribute to urban aesthetics[216–218]. Native vegetation is often preferred for its adaptability and ecosystem restoration capabilities. However, structural limitations in older buildings and the need for ongoing maintenance and irrigation can present challenges to widespread adoption[219]. In Chile, rapid population growth and urban development have led to frequent flooding in central cities during the winter due to outdated rainwater drainage systems. A study proposes green roofs as a potential solution to mitigate these floods. Their simulations suggest that covering at least 60% of available roof surfaces could reduce flooding during heavy rain events[220]. However, the high costs and limited incentives for green roof implementation in Chile present challenges, highlighting the need for tailored green technology promotion in developing countries[220]. Overall, the utilization of green roofs and walls represents a sustainable strategy for enhancing urban resilience and addressing diverse environmental concerns. These nature-based solutions contribute to sustainable stormwater management strategies in urban areas, making them valuable components of flood control infrastructure.

Wetland restoration and creation. Wetland restoration and creation are essential strategies for enhancing ecosystem services and mitigating the adverse effects of urbanization and climate change. Wetlands are categorized as nature-based adaptation measures as they provide crucial benefits such as carbon storage, sediment trapping, nutrient retention,

Table 4 | Nature-based adaptation measures and their advantages, disadvantages, co-benefits, and tradeoffs

Measure	Advantages	Disadvantages	Co-benefits	Tradeoffs
Set-Back	- Alleviates stress on levees by providing extra space for floodwaters (Chambers et al., 2023). - Enhances the capacity to manage large volumes of water. - Facilitates improved filtration and water quality (Singh et al., 2018).	- High initial costs for planning, land acquisition, and construction. - Can change sediment dynamics, requiring careful management (Lammers et al., 2024). High costs to obtain real estate landward of levee	- Can aid in floodplain restoration (Singh et al., 2018). - Improves groundwater recharge and floodplain functionality. - Enhances recreational opportunities and aesthetic value of landscapes.	- Requires land acquisition and potential relocation of infrastructure (Chambers et al., 2023). - May impact existing land use and property values.
Permeable Pavements	- Reduces stormwater volume and rate, alleviating pressure on drainage systems (Lee et al., 2023). - Lowers the carbon footprint associated with drainage construction (Iqbal et al., 2022).	- Prone to clogging, which diminishes performance and requires costly maintenance (Kia et al., 2021). - Conventional designs may not be suitable for heavily trafficked roads due to durability concerns.	- Facilitates natural hydrological processes like infiltration, storage, evaporation, and detainment of runoff (Zhu et al., 2021). - Reduces the need for extensive and expensive traditional drainage systems.	- Requires new design guidance and standards. - Initial installation costs may be higher compared to traditional pavements. - Ongoing maintenance is crucial to ensure performance, particularly in areas with high sediment loads.
Green Roofs and Walls	- Reduces surface runoff and enhances infiltration (Liu et al., 2020). - Stores rainfall in a soil substrate and delays runoff peak generation.	- Structural limitations in older buildings may impede installation (Cristiano et al., 2020). - The scope of implementation is limited by the available roof and wall space.	- Enhances biodiversity by providing habitats for various species (Basu et al., 2021). - Reduces energy consumption by insulating buildings (Teotónio et al., 2021). - Improves urban aesthetics and contributes to ecosystem restoration.	- The need for regular maintenance and irrigation may increase operational costs. - Higher initial costs compared to traditional roofing and wall systems.
Wetland Restoration and Creation	- Provides carbon storage, sediment trapping, and nutrient retention. - Reduces flood risks by controlling water flow rates (Kumar et al., 2021).	- Potential for exacerbating flooding under certain geographical conditions (Wu et al., 2020). - May face challenges due to urban expansion and land use changes (Rojas et al., 2022).	- Supports biodiversity and habitat restoration (Tomscha et al., 2021). - Provides additional ecosystem services such as water purification. - Contributes to carbon sequestration.	- Integration with existing urban infrastructure can be complex and costly. - Long-term maintenance and monitoring are required to ensure sustained benefits (Spieles, 2022).
Riparian Buffers	- Supports watershed function, enhances baseflow, reduces peak flows (Gay et al., 2022). - Facilitate energy and matter exchange (Kuriqi et al., 2021).	- Varying effectiveness across different subbasins. - Requires proactive management strategies and policy reforms (Graziano et al., 2022).	- Enhances aquatic habitat suitability and improves river dynamics and bank stability. - Provides social and cultural benefits through the creation of green spaces (Riis et al., 2020).	- Challenges of proactive management and policy implementation to protect and restore riparian zones. - Balancing urban development and conservation efforts (Olokeogun et al., 2020).
Beach and Shoreface Nourishment	- Protects people and property from coastal flooding (Sancho, 2023). - Facilitates rapid post-flood recovery. - Counteracts coastal erosion.	- Requires effective monitoring of coastal erosion and deposition (Tiede et al., 2023) - Necessitates comprehensive environmental impact evaluations to ensure sustainable development (de Schipper, 2021; Mendes et al., 2021).	- Enhances the aesthetic and recreational value of coastal zones, benefiting local communities and economies (Saengsupavanich et al.,2023). - Supports marine resource utilization and infrastructure protection.	- Maintenance costs can be higher than hard structures due to shorter maintenance intervals (Staudt et al., 2021).
Living Shorelines	- Mitigates erosion, wave damage, and flood risks (Meguro & Kim, 2021). - Stabilizes sand dunes and dissipates wave energy (Jones & Pippin, 2022).	- Depends on factors such as wave energy, land use, sediment volumes, and community willingness. - Regulatory challenges and jurisdictional complexities (Manuel et al., 2021).	- Habitat creation and improved ecosystem services. - Recreation opportunities. - Increased economic value (U.S. DOT, 2019).	- May face resistance compared to traditional hard armoring methods. - Municipalities need to play an active role in facilitation and planning.
Vegetation on Levee Slopes	- Stabilizes levee slopes (van Zelst, 2021). - Reduces erosion (Boechat Albernaz et al., 2020).	- Effectiveness can be influenced by the width of the levee and vegetation type (Rosenberger & Marsooli, 2022). - May increase the risk of vegetation fires.	- Can provide a habitat for wildlife. - Sequesters carbon and mitigates climate change.	- Effectiveness depends on local climate and soil conditions. - Requires ongoing maintenance and monitoring (Boechat Albernaz et al., 2020).
Forest Fire Prevention	- Reduces the risk of wildfires, which can exacerbate flooding by increasing erosion and runoff (Ebel, 2020; Carabella et al., 2019).	- Requires ongoing efforts and investment in fire prevention measures (Xu et al., 2023).	- Enhances overall ecosystem health and resilience. - Supports biodiversity by maintaining natural habitats.	- It may be challenging to implement in remote or inaccessible areas (Yilmaz et al., 2023).
Bio-Inspired Improvements of Soils in Flood Protection Infrastructure	- Increases shear strength, stiffness, and erosion resistance of levee and embankment soils, improving slope stability during high water levels (Liu et al., 2024)	- Urea-based MICP generates ammonium; compliance with water-quality limits requires post-treatment or alternative pathways (Su et al., 2022)	- Can immobilize dissolved heavy metals and other contaminants, offering ancillary soil- and water-quality benefits (Rajasekar et al., 2025)	- Continuous monitoring (pH, Ca^{2+}, NH_4^+, microbial viability) and increase operation-and-maintenance costs

and flood reduction, which are vital for maintaining ecological balance and supporting human communities[221]. The loss and degradation of wetlands, primarily due to urban expansion, diminish their capacity to regulate floods and other natural hazards[222]. A study explores the role of wetlands in flood resilience within the Nenjiang River Basin in Northeast China. Their research highlights that wetlands are highly effective at reducing stream flows, particularly during extreme flow conditions. Wetlands in the Nenjiang River Basin play a key role in flood risk reduction, with their efficiency in mitigation closely tied to their location and size within the watershed[223]. Constructed wetlands, engineered for purposes like wastewater treatment, and restored wetlands, aimed at rejuvenating ecological functions, both play vital roles in flood management by controlling water flow rates and trapping nutrients during flooding[224,225]. Integrated Constructed Wetlands (ICW), which combine elements of both constructed and restored wetlands, offer a holistic approach to wetland service replacement, though they require further research to optimize design and management practices[225]. Additionally, geographical variations influence the effectiveness of wetlands in flood mitigation, with upstream wetlands notably reducing downstream peak flow and volume, though they may also exacerbate flooding under certain conditions[223]. Therefore, strategic wetland restoration and creation are crucial for bolstering flood resilience, particularly in urban and developing regions where the impacts of extreme hydroclimatic events are most pronounced[222].

Establish riparian buffers. Riparian buffers, which serve as transitional areas between terrestrial and aquatic ecosystems, are vital for maintaining ecological balance and providing numerous ecosystem services. These zones facilitate the exchange of energy and matter through processes such as surface runoff, subsurface flow, and flooding, thus playing a critical role in river dynamics, bank stability, and aquatic habitat suitability[226]. Riparian buffers are classified as nature-based adaptation measures because they enhance flood resilience and support ecological health while also mitigating the impacts of human-induced changes. These buffers support watershed functions and ecosystem services, especially where maintaining forest land cover is challenging[227]. These buffers can increase forest cover, enhance baseflow, and reduce peak flows in developing watersheds, although their effectiveness varies across different subbasins. Riparian vegetation can also provide social and cultural benefits by creating usable green space[228]. However, riparian zones are highly susceptible to human-induced changes such as urbanization, deforestation, and floodplain exploitation, which can increase flood vulnerability and degrade their ecological functions[229]. In the Meramec River Basin, a vital area for freshwater biodiversity in the U.S., riparian buffers are explored as climate adaptation tools to manage riverine flow and thermal regimes. A study finds that expanding riparian buffers can reduce the number of days exceeding high water temperatures, thus alleviating thermal stress and benefiting aquatic ecosystems. However, while these buffers are effective in mitigating temperature increases, their impact on streamflow regimes is more limited[230]. Given their ecological importance, there is a need for proactive management strategies and policy reforms to protect and restore riparian zones, ensuring their continued provision of critical services such as water purification, biodiversity conservation, and recreational opportunities[231].

Implement beach and shoreface nourishment. Beach and shoreface nourishment are strategies employed globally to counteract coastal erosion and maintain socio-economic value, as well as to protect people and property[232]. These practices involve the addition of large quantities of sand to beaches or shoreface, often sourced from inland sand pits, lagoons, estuaries, navigation channels, nearshore zones, offshore seafloors, or nearby jetties[233]. Coastal zones are vital for activities such as marine resource utilization, tourism, and infrastructure. Beach and shoreface nourishment strategies help to sustain ecosystems while also supporting socio-economic activities and addressing the impacts of sea-level rise and storm events, justifying their placement in the nature-based adaptation category. In a study conducted along the Dutch coast, characterized by its sandy shores and micro-tidal environment, the behavior of beach and shoreface nourishment was observed and modeled. The research found that while beach nourishment offers immediate flood protection by raising the beach elevation and preventing wave overtopping, shoreface nourishment provides a more sustained defense. Although slower to impact the inner surf zone, shoreface nourishments proved to be more persistent, with 40-80% of the added volume remaining after 3 years, offering a long-term sub-tidal buffer against storm erosion[234]. Beach nourishment has the potential to prevent coastal flooding and mitigate erosion, influenced by long-term sea-level rise and sediment availability. Effective management of beach nourishment requires monitoring coastal erosion and deposition over appropriate temporal and spatial scales, which depend on local conditions, stresses, and financial resources[235]. Despite their benefits, including enhanced recreational opportunities and rapid recovery post-storms, beach nourishment projects are finite and can have maintenance costs that are higher than hard structures due to shorter maintenance intervals[233,236]. Additionally, beach and shoreface nourishments can have complex environmental implications, necessitating regular maintenance and comprehensive environmental impact evaluations to ensure sustainable coastal development[237,238].

Implement living shorelines. Living shorelines represent a multifaceted approach to coastal resilience, integrating habitat restoration, coastal engineering, and conservation strategies to mitigate erosion, wave damage, and flood risks. Living shorelines are categorized as nature-based adaptation measures because they employ natural and restored coastal features to enhance coastal resilience while also providing additional ecological and socio-economic benefits that support sustainable coastal management. These approaches encompass a diverse range of natural and constructed or restored features such as salt marshes, wetlands, mangroves, coral reefs, oysters, dunes, and maritime forests. In a study conducted along the southern coast of Rhode Island, numerical simulations were used to assess the effectiveness of living shoreline methods in mitigating coastal erosion. Rhode Island's sandy coastline is particularly vulnerable to storm-induced breaching and overtopping. Additionally, state regulations discourage the use of hard coastal protection structures. The study found that living shorelines could be more effective at reducing erosion than traditional methods like offshore breakwaters[239]. Through the strategic use of vegetation, wave energy is dissipated, sand dunes are stabilized, and wave height and erosion are reduced more effectively than in non-vegetated areas[240]. Furthermore, living shorelines offer co-benefits beyond hazard mitigation, including habitat creation, improved ecosystem services, recreation opportunities, and increased economic value. These nature-based solutions are particularly appealing in contrast to traditional hard armoring methods like sea walls, which often disrupt natural processes and increase vulnerability[241]. Living shorelines also exhibit greater resilience to sea-level rise as they accommodate marsh migration and adapt to changing coastal conditions[241]. However, successful implementation relies on key factors such as wave energy, land use, sediment volumes, and community willingness to adopt innovative methods[240]. Municipalities play a crucial role in facilitating the adoption of living shorelines through land use planning zoning regulations and by setting examples for shoreline management practices. Despite regulatory challenges and jurisdictional complexities, continued community involvement and communication are essential for the success and expansion of living shoreline projects[242].

Vegetation on levee slopes. Intentional vegetation on levee slopes involves strategically planting grasses, shrubs, or trees along levees to stabilize soil, reduce erosion, and enhance the resilience of flood defenses[243]. Vegetation helps absorb rainfall, slow runoff, and improve soil permeability, reducing the risk of levee failure and enhancing flood protection[244]. Vegetation on levee slopes is classified under nature-based adaptation measures because it leverages natural processes such as soil stabilization and erosion control provided by grasses, shrubs, and trees to enhance the structural integrity of levees and improve their flood protection capabilities. Encouraging vegetation growth is a simple and cost-effective approach to bolstering levee stability. However, the impact of vegetation on levee slopes can vary depending on factors such as slope stability, levee dimensions, soil type, accessibility for maintenance, and the specifics of maintenance plans[245]. In a study on the Green-Duwamish River in King County, Washington, authors investigate the complex relationship between woody vegetation and the structural integrity of levees. The study finds that while the presence of deep-rooted trees and plants on levees can enhance stability by reinforcing soil and reducing erosion, the effects of vegetation are context-dependent[246]. Improperly maintained vegetation can pose risks, such as weakening the levee structure or creating pathways for water seepage, highlighting the need for careful management of levee vegetation[246]. While vegetation can offer hydrological benefits by reducing sediment mobility and increasing sediment retention, it may also exacerbate instability during flooding events by forming piping channels and affecting hydraulic conductivity. Therefore, the implementation and effects of vegetation on levee slopes require careful consideration on a case-by-case basis.

Forest fire prevention. Forest fire prevention strategies aim to mitigate the risk of wildfires, which can exacerbate flooding by increasing soil erosion and runoff in fire-affected areas[247]. Forest fire prevention strategies are categorized as nature-based adaptation measures because they focus on maintaining natural vegetation and soil stability, which helps to mitigate the increased flood risk associated with wildfire-affected areas. Wildfires not only threaten lives and cause environmental pollution but may also degrade river morphology and increase flood risk downstream for several years. From a hydrological perspective, post-fire degraded vegetation cover, reduced hydraulic resistance, and decreased soil infiltration capacity tend to generate higher surface runoff in basins[248,249]. This heightened surface runoff has the potential to increase flood risk downstream of burned areas for several years[250]. Additionally, wildfires alter hydrological processes by reducing forest water use due to vegetation loss, leading to increased runoff during intense rainfall events[251]. Several studies report an increase in landslides after wildfires, mainly attributed to loss of root reinforcement[252–254]. A study examines post-fire management strategies in Haifa, a city on the northern hillslope of Mt. Carmel, which is characterized by hot, dry summers and short, rainy winters, heightening the risk of fires and subsequent flooding. The research highlights how forest fires can lead to substantial changes in soil properties, including increased erosion and reduced vegetation cover, which contribute to more frequent and severe flooding[255]. To address these challenges, the study evaluates various post-fire management practices such as natural revegetation, afforestation, erosion barriers, and geotextiles to mitigate the impacts of fires by improving soil stability and reducing runoff[255]. Due to the complex relationship between burned landscapes and variability in precipitation events, post-fire hydrologic responses can vary widely, from minimal impact to devastating floods and hazardous debris flows. Therefore, employing effective forest fire prevention strategies can be a crucial tool for reducing flood risk by maintaining soil infiltration capacity, preserving vegetative cover to slow runoff, and enhancing hydraulic resistance[251].

Bio-inspired improvements of soils in flood protection infrastructure. Recent developments in bio-inspired engineering have yielded promising techniques for strengthening and enhancing the resilience of soils employed in flood-protection infrastructure[256,257]. Foremost among these innovations are Microbially Induced Calcite Precipitation (MICP) and biopolymer soil treatments, which have garnered substantial research interest[257]. By emulating natural processes, both approaches improve key geotechnical properties such as strength, stiffness, and erosion resistance while providing environmentally sustainable alternatives to conventional chemical stabilization methods. MICP involves stimulating microbial activity in the soil to precipitate calcium carbonate, which binds soil particles together[258]. This process increases soil strength and stiffness, reduces permeability, and improves resistance to erosion. Similarly, the use of biopolymers naturally derived long-chain molecules has shown substantial benefits in enhancing soil cohesion and compressibility[259]. Biopolymers can create a protective matrix that binds particles and reduces susceptibility to disintegration under hydraulic or mechanical stress.

These enhancements are particularly valuable for earthen flood protection systems such as levees, where soil strength and erosion resistance are critical to maintaining structural stability[260]. Improved soil strength contributes directly to increased slope stability, reducing the likelihood of slope failure during high-water events. Moreover, erosion is a primary mechanism driving levee overtopping and breach initiation, particularly under repeated cycles of wetting and drying. Bio-inspired soil improvements have demonstrated the potential to mitigate these vulnerabilities by increasing the soil's resistance to erosive forces and enhancing durability across fluctuating environmental conditions. Several previous studies have validated the effectiveness of MICP and biopolymer treatments in laboratory and field settings[257]. These approaches not only improve performance under normal operating conditions but also offer increased resilience during extreme events, making them highly suitable for application in the context of climate-adaptive infrastructure systems.

Decision-making for successful adaptation

In the face of evolving flood risks due to climate change, it is imperative to adopt a comprehensive approach to identify the most successful or series of successful adaptation measures. Currently, approaches like the Dynamic Adaptive Policy Pathways (DAPP) and Dynamic Adaptive Policy Pathways for multi-risk (DAPP-MR) are employed to plan both short- and long-term adaptation measures[261,262]. A study emphasizes that flood-adaptation decisions must address deep uncertainty situations in which the probability distributions of key drivers (e.g., flood frequency, exposure growth, behavioral response) are themselves unknown or contested[54]. They advocate moving from single-scenario, deterministic analyses toward exploratory modeling with large ensembles of plausible futures, coupled with multi-objective robust decision-making techniques, to identify adaptation pathways that perform acceptably across a broad spectrum of uncertain conditions. These methods investigate sequences of adaptation measures or pathways, considering a range of future scenarios. However, at the foundational level, we argue that a successful flood adaptation strategy must be tailored for each project, ensuring it is socially just, practically feasible, and technically sound (Fig. 5). This requires a multi-attribute decision-making process that carefully considers each project's unique technical and socio-economic characteristics.

Past studies indicate that socially vulnerable groups are often over-represented in 100 year flood zones and levee-protected areas in the U.S.[263–265]. Thus, adaptation measures must be socially just to minimize these flood risk disparities. Social justice in adaptation addresses systemic inequities by promoting inclusivity, transparency, and equitable resource allocation through community engagement and participatory decision-making processes[266,267]. A successful measure should also account for the varying adaptive capacities and risk thresholds of communities. We emphasize that social justice should be incorporated into every stage of the adaptation process to ensure that community perspectives and stakeholder feedback are integral to decision-making, with the goal of minimizing risk disparities among communities[267].

Practical feasibility is the extent to which adaptation measures are considered possible, either in binary terms or under specific conditional criteria[1]. Assessing practical feasibility ensures that adaptation measures can be successfully implemented while ensuring compliance with environmental and regulatory constraints. Practically feasible measures should also consider the technical expertise and experience of available human

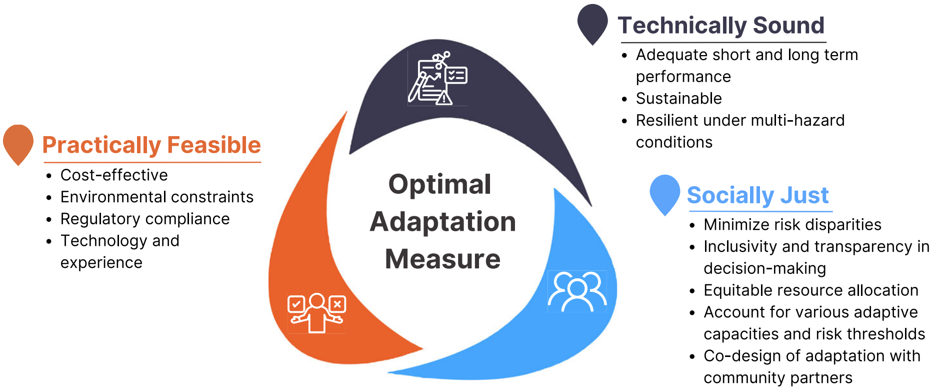

Fig. 5 | The three foundational attributes of a successful flood adaptation measure. Practical Feasibility, Technical Soundness, and Social Justice. These pillars collectively ensure that adaptation strategies are not only implementable and effective under evolving climate conditions but also equitable and aligned with community needs and institutional capacities.

resources. Moreover, assessments include evaluating trade-offs and prioritizing based on short- and long-term costs, including labor, land purchase, and materials, which vary with local geographic and socio-economic conditions[268]. Importantly, practical feasibility also incorporates institutional, cultural constraints, and societal acceptance, recognizing that successful implementation requires acceptance and alignment within these broader contexts.

For adaptation measures to be effective, they must be technically sound, grounded in proven methodologies, and supported by reliable engineering design. These measures should be resilient under multi-hazard conditions. Furthermore, these measures should be designed with flexibility in mind, allowing for incremental improvements over time. This adaptive capacity is essential for providing both immediate and long-term performance as climatic conditions evolve. By incorporating regular assessment and updating mechanisms, these strategies can remain effective even as environmental and socioeconomic conditions change, ensuring sustained protection and resilience for communities.

Research gaps and opportunities

Flood adaptation is a critical component of managing the growing risks posed by climate change, yet substantial gaps remain in both our understanding and implementation of effective measures. Advancing flood adaptation requires collaborative, cross-disciplinary progress[269,270]. Our review of flood adaptation research has identified key research gaps and opportunities, including: Integrating qualitative and quantitative approaches to improve decision-making, Bridging policy fragmentation to create cohesive and adaptive frameworks, Clarifying evolving risk thresholds for more effective risk management, Enhancing site-specific decision-making by balancing feasibility, technical soundness, and social justice, Leveraging emerging technologies and Big Data to strengthen flood resilience, and Incorporating vulnerability attributes to promote equitable adaptation strategies. Given the multidisciplinary nature of flood adaptation research, we acknowledge that these gaps may not fully encompass all existing research opportunities.

The first key gap is the limited integration of qualitative insights into quantitative risk assessment frameworks. While quantitative metrics such as expected annual damage or flood levels are commonly used, they fail to capture the nuanced perceptions of risk and the social realities on the ground[264,271]. A 2017 study demonstrates that reliance solely on qualitative flood risk mapping can lead to a coarse hazard classification that does not adequately represent actual flood scenarios[272]. Conversely, participatory integrated assessment tools combine scientific models with stakeholder insights, enabling decision-makers to evaluate adaptation choices within real-world constraints[273]. Moreover, incorporating indigenous knowledge and community-specific insights into quantitative models is essential. Studies argue that relying exclusively on quantitative methods overlooks social and cultural components of flood risk. Local knowledge, stakeholder experiences, and community-specific challenges remain underrepresented in current risk assessment frameworks[274,275]. Future research should, therefore, focus on developing methodologies that systematically incorporate qualitative data such as local expertise, participatory inputs, and self-assessment insights into quantitative risk modeling frameworks. This integrated approach would provide a more holistic view of flood risk, effectively addressing both the technical and social dimensions of adaptation.

The second critical research gap lies in the coordination of policy for flood adaptation. Even with substantial advances in modeling and decision-support tools, their potential is undermined by fragmented policy frameworks. Flood adaptation is inherently multifaceted and spans multiple levels of governance, local, national, and even international, resulting in different agencies and stakeholders often operating in silos. This fragmentation not only limits the effective implementation of adaptation measures but also creates challenges in aligning objectives across various policy sectors, where actions in one area may spill over and conflict with those in another. For instance, a policy decision to release water from a dam to fight wildfires may seem beneficial for emergency response; however, the rapid opening and closing of water levels can adversely impact levee integrity, thereby compromising flood protection measures downstream[276]. Future research should focus on developing comprehensive policy frameworks that foster inter-agency collaboration, ensure horizontal and vertical policy integration, and address potential spillover effects[277].

A third gap is the lack of clarity and consistency in defining risk thresholds and tipping points. There is an inherent ambiguity in determining what constitutes “acceptable,” “tolerable,” and “intolerable” flood risk. These thresholds vary not only across regions but also over time due to urbanization and changes in land use, land cover, and even adaptive actions. For example, the Dynamic Adaptive Policy Pathways (DAPP) framework, Adaptation-Tipping-Point (ATP) or Adaptive Delta Management employs tipping points defined by performance or risk thresholds, yet these thresholds differ by location and time[261,262,278,279]. Research opportunities exist to empirically investigate how these variable risk thresholds influence adaptive behaviors[280].

Fourth, there is a persistent challenge in supporting site-specific decision-making that balances technical feasibility, social justice, and practical implementation, particularly in the context of deep uncertainty. The proposed multi-attribute decision-making process, which balances practical feasibility, technical soundness, and social justice, highlights an interesting area for further investigation. Research should explore how these attributes interact and how trade-offs are managed in real-world settings. For instance, while technically sound measures may offer robust protection, they might not be socially just if they fail to address the needs of vulnerable communities. Future studies could focus on developing decision-support tools that explicitly incorporate these attributes, helping policymakers design strategies that are both effective and equitable.

Fifth, emerging technologies, including artificial intelligence (AI) and Earth observations, offer promising opportunities to improve flood risk management and adaptation planning[281,282]. However, a persistent challenge remains in capturing the full complexity of flood risk, which involves interactions among natural, built, and social systems over varying spatial and temporal scales. For example, performing a regional-scale assessment of levees requires real-time hydrological data and remote sensing imagery, which are critical for accurately characterizing real-time risk[283]. Further research is needed to investigate how emerging technologies can enhance forecasting, optimize adaptation pathways, and facilitate real-time decision-making in flood management.

Another important research gap lies in managing residual flood risk behind levees. While hydraulic infrastructure remains central to flood protection, events in the U.S., France, and Quebec demonstrate that areas behind levees can still face substantial risks during levee breaches or overtopping events. Despite recognition of this issue, current policies and regulatory frameworks vary widely, leading to inconsistencies in how these residual risks are managed, communicated, and mapped[190]. More research is needed to develop integrated approaches that explicitly address residual risk, including improvements in risk mapping, governance mechanisms, and community-level communication strategies.

Finally, integrating socio-economic factors into adaptation decision-making requires further exploration. Past studies have shown that socially vulnerable groups are disproportionately located in areas of heightened flood risks[263,265,284,285]. Future research should investigate the mechanisms by which socioeconomic or demographic vulnerabilities influence adaptive capacity, examining how investments in flood protection can be reallocated to mitigate these disparities. Studies demonstrate that integrating distributive justice measures into flood adaptation models not only enhances the assessment of impacts on different groups over time but also helps address existing inequalities in flood risk management[286]. By integrating equity considerations into adaptation decision-making, researchers can identify opportunities to improve resource allocation and reduce risk disparities.

Although this study employed the four broad categories of Infrastructural/Technological, Institutional, Behavioral/Cultural, and Nature-Based measures, several examples from our findings reveal overlapping domains that warrant further investigation. For instance, relocation of at-risk communities cannot succeed solely through infrastructural planning; it requires policy frameworks for land acquisition, funding mechanisms, and cultural acceptance to minimize social disruption. Similarly, living shorelines and wetland restoration require institutional coordination for zoning, technical planning, and community participation. Even conventional measures such as flood monitoring and warning systems represent a fusion of domains: they involve advanced sensor technologies (infrastructural/technological), data governance strategies (institutional), and timely public communication (behavioral/cultural). These examples highlight the importance of developing future frameworks that better capture these intersections to improve the effectiveness and equity of flood adaptation strategies.

Concluding remarks

The initial step towards enhancing the resilience of flood protection systems involves identifying and compiling traditional and emerging flood adaptation measures in a portfolio. Our scoping review of past literature identified 39 adaptation measures and their unique advantages, disadvantages, co-benefits, and tradeoffs. These measures were categorized into four classifications: (i) Institutional/technological (18 measures), which provide immediate and reliable protection, enhancing flood resilience and defense capabilities. However, they come with high costs and potential environmental disruptions, necessitating integration with other approaches for sustainable flood resilience. (ii) Institutional (9 measures) that are aimed at enhancing governance structures and policies for long-term flood resilience. They offer a systematic approach to managing climate risks but face challenges such as fragmented responsibilities and resource inequities. Success depends on robust frameworks, proactive leadership, and inclusive stakeholder participation. (iii) Behavioral/cultural (2 measures) that aim to empower communities to reduce climate vulnerability through low-cost, adaptable practices. These measures foster resilience but may face resistance to change and require sustained community engagement. Integration with broader strategies is essential to address severe climate risks. (iv) nature-based (10 measures) that leverage natural systems to enhance resilience, offering co-benefits like biodiversity enhancement and water management. However, they are site-specific and require careful planning, ongoing management, and community engagement to be effective within a broader climate adaptation strategy.

Effective flood adaptation necessitates an integrated approach to address the evolving risks associated with climate change. The challenge for decision-makers lies in identifying the most optimal adaptation measures. We propose that measures must be tailored to the unique requirements of each project. Here, we propose that adaptation strategies must be tailored to each specific project to ensure they are socially just, practically feasible, and technically sound. This involves addressing systemic inequities, incorporating community input, and evaluating the practicality of measures in relation to environmental, regulatory, and resource constraints while also ensuring technical robustness and the ability to adapt over time. The absence of one essential attribute may adversely affect the overall effectiveness and sustainability of adaptation efforts. For instance, neglecting social justice could lead to inequitable outcomes, while neglecting technical soundness may lead to failure under an evolving climate; fulfilling both social justice and technical soundness, however, neglecting practical feasibility results in issues in adaptation implementation. Therefore, a balanced approach is necessary for the long-term effectiveness of flood adaptation efforts.

Despite substantial advancements in flood adaptation research, there is a global need to advance these efforts through multidisciplinary collaboration. Here, we identify eight key research themes and highlight associated gaps that require attention. These gaps present opportunities for further exploration and development, highlighting the complexity and the need for a transdisciplinary approach in flood adaptation research. A notable gap includes the development of a risk-based adaptation framework for flood protection infrastructure that addresses social disparities, integrates community feedback, accounts for evolving hazard patterns and their impacts on defense systems, and quantitatively assesses the performance of adaptation. Such a framework has the potential to provide decision-makers with a robust tool to enhance the resilience and equity of flood adaptation measures.

Data availability

All data used in this study are publicly available through the provided repository: https://doi.org/10.6084/m9.figshare.29931908.

Received: 13 September 2024; Accepted: 10 September 2025;

References

1. IPCC. Intergovernmental Panel on Climate Change. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg2/ (2022).
2. Meinshausen, M. et al. Realization of Paris agreement pledges may limit warming just below 2 C. *Nature* **604**, 304–309 (2022).
3. Diffenbaugh, N. S. & Barnes, E. A. Data-driven predictions of the time remaining until critical global warming thresholds are reached. *Proc. Natl. Acad. Sci. USA* **120**, e2207183120 (2023).
4. IPCC. Intergovernmental Panel on Climate Change. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf (2023).
5. UNEP. United Nations Environment Programme. *Executive summary. In Emissions Gap Report 2024: No more hot air … please! Emissions Gap Report 2024*. https://cdn.unenvironment.org/egr-interactive/fs/2024-11/Executive%20Summary_EN_Final_24Oct24%20%281%29.pdf (2024).

6. Gehrels, R. Sea-level changes since the last glacial maximum: an appraisal of the IPCC fourth assessment report. *J. Quat. Sci.* **25**, 26–38 (2010).
7. Prein, A. F. et al. The future intensification of hourly precipitation extremes. *Nat. Clim. Change* **7**, 48–52 (2017).
8. AghaKouchak, A., Ragno, E., Love, C., & Moftakhari, H. *Projected Changes In California's Precipitation Intensity-Duration-Frequency Curves*. https://www.energy.ca.gov/sites/default/files/2019-11/CCCA4-CEC-2018-005_ADA.pdf (2018).
9. Bacmeister, J. T. et al. Projected changes in tropical cyclone activity under future warming scenarios using a high-resolution climate model. *Clim. Change* **146**, 547–560 (2018).
10. Watson, C. S. et al. Unabated global mean sea-level rise over the satellite altimeter era. *Nat. Clim. Change* **5**, 565–568 (2015).
11. Yi, S., Sun, W., Heki, K. & Qian, A. An increase in the rate of global mean sea level rise since 2010. *Geophys. Res. Lett.* **42**, 3998–4006 (2015).
12. Kopp, R. E. et al. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's. Future* **2**, 383–406 (2014).
13. Moftakhari, H. R., Salvadori, G., AghaKouchak, A., Sanders, B. F. & Matthew, R. A. Compounding effects of sea level rise and fluvial flooding. *Proc. Natl. Acad. Sci. USA* **114**, 9785–9790 (2017).
14. Moftakhari, H., Schubert, J. E., AghaKouchak, A., Matthew, R. A. & Sanders, B. F. Linking statistical and hydrodynamic modeling for compound flood hazard assessment in tidal channels and estuaries. *Adv. Water Resour.* **128**, 28–38 (2019).
15. Wahl, T., Jain, S., Bender, J., Meyers, S. D. & Luther, M. E. Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nat. Clim. Change* **5**, 1093–1097 (2015).
16. Bagheri-Gavkosh, M. et al. Land subsidence: a global challenge. *Sci. Total Environ.* **778**, 146193 (2021).
17. Huning, L. S. et al. Global land subsidence: impact of climate extremes and human activities. *Rev. Geophys.* **62**, e2023RG000817 (2024).
18. Ohenhen, L. O., Shirzaei, M. & Barnard, P. L. Slowly but surely: exposure of communities and infrastructure to subsidence on the US east coast. *PNAS Nexus* **3**, pgad426 (2024).
19. UNDRR. *United Nations Office for Disaster Risk Reduction. UNDRR Annual report 2021*. https://www.undrr.org/publication/undrr-annual-report-2021 (2021).
20. Winsemius, H. C. et al. Global drivers of future river flood risk. *Nat. Clim. Change* **6**, 381–385 (2016).
21. NOAA. *National Centers for Environmental Information. U.S. Billion-Dollar Weather and Climate Disasters*. https://www.ncei.noaa.gov/access/billions/ (2024).
22. Wing, O. E. J. et al. Inequitable patterns of U.S. flood risk in the Anthropocene. *Nat. Clim. Change* **12**, 156–162 (2022).
23. Mohammed, A., & Vahedifard, F. (2023). *Equitable Climate Adaptation Framework for Levees. In Life-Cycle of Structures and Infrastructure Systems* 1st edn (CRC Press, 2023).
24. Imran, J. A. S. I. M. et al. *Rising Waters, Falling Dams: Deciphering the Derna Flood Disaster.* https://www.researchgate.net/publication/377309092_Rising_Waters_Falling_Dams_Deciphering_the_Derna_Flood_Disaster (2024).
25. Shirzaei, M. et al. Aging dams, political instability, poor human decisions and climate change: recipe for human disaster. *npj Nat. Hazards* **2**, 5 (2025).
26. Sovacool, B. K. Hard and soft paths for climate change adaptation. *Clim. policy* **11**, 1177–1183 (2011).
27. United Nations Framework Convention on Climate Change. *Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement (2015)
28. Dottori, F., Mentaschi, L., Bianchi, A., Alfieri, L. & Feyen, L. Cost-effective adaptation strategies to rising river flood risk in Europe. *Nat. Clim. Change* **13**, 196–202 (2023).
29. Kuang, D. & Liao, K.-H. Learning from floods: linking flood experience and flood resilience. *J. Environ. Manag.* **271**, 111025 (2020).
30. Rezvani, S. M., de Almeida, N. M. & Falcão, M. J. Climate adaptation measures for enhancing urban resilience. *Buildings* **13**, 2163 (2023).
31. Mannucci, S., Rosso, F., D'Amico, A., Bernardini, G. & Morganti, M. Flood resilience and adaptation in the built environment: how far along are we?. *Sustainability* **14**, 4096 (2022).
32. Haasnoot, M., Middelkoop, H., Van Beek, E. & Van Deursen, W. P. A. A method to develop sustainable water management strategies for an uncertain future. *Sustain. Dev.* **19**, 369–381 (2011).
33. Schull, H. Design for Lake Okeeehobee levees. *Mil. Eng.* **47**, 207–210 (1955).
34. Van Dantzig, D. Economic decision problems for flood prevention. *J. Econ. Soc*. **24**, 276−287 (1956).
35. Schuleen, E. P. Flood plain zoning as supplement to flood control. *J. Hydraul. Div.* **82**, 954–1 (1956).
36. Yevjevich, V. Systematization of flood control measures. *J. Hydraul. Div.* **100**, 1537–1548 (1974).
37. Mifkovic, C. S. & Petersen, M. S. Environmental aspects—Sacramento bank protection. *J. Hydraul. Div.* **101**, 543–555 (1975).
38. Osmundson, T. Engineers relax controls to get a living levee. *Landsc. Architecture* **70**, 623–628 (1980).
39. Demerutis-Arenas, J. Á. & Escobosa-Burgara, J. Green infrastructure for metropolitan areas in Mexico. In *Proceedings of 54th ISOCARP Congress., International Society of City and Regional Planners (ISOCARP)*, 1−5 (2018).
40. Moser, S. C. Communicating climate change: history, challenges, process and future directions. *Wiley Interdiscip. Rev.: Clim. Change* **1**, 31–53 (2010).
41. Changnon, S. A. An assessment of climate change, water resources, and policy research. *Water Int.* **12**, 69–76 (1987).
42. Williams, P. Adapting water resources management to global climate change. *Climatic change* **15**, 83–93 (1989).
43. Gleick, P. H., & Maurer, E. P. *Assessing the Costs of Adapting to Sea-Level Rise: A Case Study of San Francisco Bay*. https://core.ac.uk/download/pdf/72851171.pdf (1990).
44. Zhu, T., Lund, J. R., Jenkins, M. W., Marques, G. F., & Ritzema, R. S. Climate change, urbanization, and optimal long-term floodplain protection. *Water Resour. Res*. https://doi.org/10.1029/2004WR003516 (2007).
45. Cuny, F. C. Living with floods: alternatives for riverine flood mitigation. *Land Use Policy* **8**, 331–342 (1991).
46. Gruntfest, E. Flood disaster relief, rehabilitation and reconstruction. In *Coping with Floods. NATO ASI Series* (eds. Rossi, G., Harmancioğlu, N., Yevjevich, V.) 257 (Dordrecht: Springer, 1994).
47. Fazey, I. et al. Adaptation strategies for reducing vulnerability to future environmental change. *Front. Ecol. Environ.* **8**, 414–422 (2009).
48. Du, S. et al. Hard or soft flood adaptation? advantages of a hybrid strategy for Shanghai. *Glob. Environ. Change* **61**, 102037 (2020).
49. Riera-Spiegelhalder, M. et al. Systematic review of socio-economic assessments of climate change adaptation in coastal areas. *Preprints* **2022**, 2022100394 (2022).
50. Simpson, N. P. et al. (2023). Adaptation to compound climate risks: a systematic global stocktake. *Iscience* **26**, 105926 (2023).
51. Tye, S., Pool, J. R. & Lomeli, L. G. The potential for nature-based solutions initiatives to incorporate and scale climate adaptation. *World Resour. Inst*. https://doi.org/10.46830/wriwp.21.00036 (2022).
52. Mabrouk, M. et al. Assessing the effectiveness of nature-based solutions-strengthened urban planning mechanisms in forming flood-resilient cities. *J. Environ. Manag.* **344**, 118260 (2023).
53. Milly, P. C. et al. Stationarity is dead: whither water management?. *Science* **319**, 573–574 (2008).

54. Reed, D. C. et al. Responses of coastal ecosystems to climate change: insights from long-term ecological research. *BioScience* **72**, 871–888 (2022).
55. Saroar, M. & Routray, J. K. Adaptation in situ or retreat? a multivariate approach to explore the factors that guide the peoples' preference against the impacts of sea level rise in coastal Bangladesh. *Local Environ.* **15**, 663–686 (2010).
56. Doberstein, B., Fitzgibbons, J. & Mitchell, C. Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience. *Nat. Hazards* **98**, 31–50 (2019).
57. Dedekorkut-Howes, A. et al. When the tide gets high: a review of adaptive responses to sea level rise and coastal flooding. *J. Environ. Plan. Manag.* **63**, 2102–2143 (2020).
58. Scott, M. et al. Climate disruption and planning: resistance or retreat?. *Plan. Theory Pract.* **21**, 125–154 (2020).
59. ISO. *International Organization for Standardization. Climate change Adaptation*. https://www.iso.org/files/live/sites/isoorg/files/store/en/PUB100449.pdf (2021).
60. Siders, A. R. Managed retreat in the United States. *One Earth* **1**, 216–225 (2019).
61. Hui, R., Jachens, E. & Lund, J. Risk-based planning analysis for a single levee. *Water Resour. Res.* **52**, 2513–2528 (2016).
62. Kiss, T. et al. Increased flood height driven by local factors on a regulated river with a confined floodplain, Lower Tisza, Hungary. *Geomorphology* **389**, 107858 (2021).
63. Wang, H. Flood your neighbors: spillover effects of levee building. In *94th Annual Conference* 29-30 (Warwick, UK, 2021).
64. Del-Rosal-Salido, J., Folgueras, P., Bermudez, M., Ortega-Sanchez, M. & Losada, M. A. Flood management challenges in transitional environments: assessing the effects of sea-level rise on compound flooding in the 21st century. *Coast. Eng.* **167**, 103872 (2021).
65. Egberts, L. & Riesto, S. Raise the dikes and re-use the past? Climate adaptation planning as heritage practice. *Marit. Stud.* **20**, 267–278 (2021).
66. Guida, R. J., Swanson, T. L., Remo, J. W. & Kiss, T. Strategic floodplain reconnection for the lower Tisza River, Hungary: opportunities for flood-height reduction and floodplain-wetland reconnection. *J. Hydrol.* **521**, 274–285 (2015).
67. Di Baldassarre, G., Castellarin, A. & Brath, A. Analysis of the effects of levee heightening on flood propagation: example of the River Po, Italy. *Hydrol. Sci. J.* **54**, 1007–1017 (2009).
68. Ma, D., Zhou, J. & Wang, Z. Simulation of scour and deposition in the flow field and adaptability of fishes around eco-friendly notched groins. *J. Hydrol.* **609**, 127754 (2022).
69. Zimmerman, T. & Miller, J. K. UAS-SfM approach to evaluate the performance of notched groins within a groin field and their impact on the morphological evolution of a beach nourishment. *Coast. Eng.* **170**, 103997 (2021).
70. Watson, F., Guzmán-Arias, I. & Villagra-Mendoza, K. Case Study: analysis of flood adaptation measures through the simulation of an event in the Matina Limón river, Costa Rica. *Rev. Tecnol.ía en. Marcha* **35**, 28–44 (2022).
71. Radzicki, K., Gołębiowski, T., Ćwiklik, M. & Stoliński, M. A new Levee control system based on geotechnical and geophysical surveys including active thermal sensing: a case study from Poland. *Eng. Geol.* **293**, 106316 (2021).
72. Adamo, N., Al-Ansari, N., Sissakian, V., Laue, J. & Knutsson, S. Dam safety problems related to seepage. *J. Earth Sci. Geotech. Eng.* **10**, 191–239 (2020).
73. Lanzafame, R. & Sitar, N. Reliability analysis of the influence of seepage on levee stability. *Environ. Geotech*. **6**, 284−293 (2018).
74. Salmasi, F., Nouri, M. & Abraham, J. Upstream cutoff and downstream filters to control of seepage in dams. *Water Resour. Manag.* **34**, 4271–4288 (2020).
75. Zhang, L., Wang, L. & Turcios-Lovato, K. Safety Assessment of Pile-Founded T-Walls in the Face of Flooding Hazards. *Geo-Congr.* **2022**, 272–280 (2022).
76. Saad, H. A. & Habib, E. H. Assessment of riverine dredging impact on flooding in low-gradient coastal rivers using a hybrid 1D/2D hydrodynamic model. *Front. Water* **3**, 628829 (2021).
77. Chou, J. S. & Chiu, Y. C. Identifying critical risk factors and responses of river dredging projects for knowledge management within organisation. *J. Flood Risk Manag.* **14**, e12690 (2021).
78. Carse, A. & Lewis, J. A. New horizons for dredging research: The ecology and politics of harbor deepening in the southeastern United States. *Wiley Interdiscip. Rev. Water* **7**, e1485 (2020).
79. Hu, Y. et al. Impact of levee-breach width on the channel–levee–floodplain: a case study in the Huaihe River Basin, China. *Water* **16**, 413 (2024).
80. Camp, J., Laning, N., Philip, C. & Williams, J. *Utilizing Graceful Failure As An Opportunity for Flood Mitigation Downstream to Protect Communities and Infrastructure*. https://rosap.ntl.bts.gov/view/dot/53900 (2020).
81. Al-Hafidh, I. A. I., Calamak, M., LaRocque, L. A., Chaudhry, M. H. & Imran, J. Experimental investigation of flood management by an instantaneous levee breach. *J. Hydraul. Eng.* **148**, 04021056 (2022).
82. Johnson, M. F., Edwards, P., Todd, R., Castro, J. M. & Thorne, C. R. Performance of an environmentally-aligned, low maintenance flood alleviation scheme on the Burn of Mosset, Forres, Scotland. *River Res. Appl.* **38**, 1544–1554 (2022).
83. Florsheim, J. L. & Mount, J. F. Restoration of floodplain topography by sand-splay complex formation in response to intentional levee breaches, lower Cosumnes River, California. *Geomorphology* **44**, 67–94 (2002).
84. Wiens, J. A., Hayward, G. D., Safford, H. D., & Giffen, C. (Eds.). *Historical Environmental Variation in Conservation and Natural Resource Management*. (John Wiley & Sons, 2012).
85. Nichols, A. L. & Viers, J. H. Not all breaks are equal: Variable hydrologic and geomorphic responses to intentional levee breaches along the lower Cosumnes River, California. *River Res. Appl.* **33**, 1143–1155 (2017).
86. FEMA. *National Levee Safety Guidelines*. https://www.leveesafety.org/pages/nlsg (2024).
87. Jacobs, J. W. *Cedar Rapids Flood Risk Management: A Case Study in Disaster Recovery*. https://asfpm-library.s3-us-west-2.amazonaws.com/Website/CON/B4-Jacobs.pdf (2018).
88. Torabi, E., Dedekorkut-Howes, A. When it's time to let go: re-imagining coastal urban living in the face of rising seas. In *Cities Research Series* (eds. Baumeister, J., Bertone, E., Burton, P. (eds) (Springer, 2021).
89. Pinter, N. & Rees, J. C. Assessing managed flood retreat and community relocation in the Midwest USA. *Nat. Hazards* **107**, 497–518 (2021).
90. Sayers, P., Moss, C., Carr, S. & Payo, A. Responding to climate change around England's coast the scale of the transformational challenge. *Ocean Coast. Manag.* **225**, 106187 (2022).
91. Hosseinzadeh, N. et al. Concrete seawalls: a review of load considerations, ecological performance, durability, and recent innovations. *Ecol. Eng*. **178**, 106573 (2021).
92. Yoo, J., Sinha, V. & Mendelsohn, R. Can seawalls help American cities adapt to coastal flooding?. *Int. J. Clim. Change Strateg. Manag.* **15**, 479–492 (2023).
93. Salauddin, M., O'Sullivan, J. J., Abolfathi, S., & Pearson, J. M. Eco-engineering of seawalls an opportunity for enhanced climate resilience from increased topographic complexity. *Front. Mar. Sci*. https://doi.org/10.3389/fmars.2021.674630 (2021).
94. Clifton, G. A., Dafforn, K. A. & Bishop, M. J. The ecological benefits of adding topographic complexity to seawalls vary across estuarine gradients. *Ecol. Eng.* **182**, 106735 (2022).

95. Vozzo, M. L. et al. Making seawalls multifunctional: The positive effects of seeded bivalves and habitat structure on species diversity and filtration rates. *Mar. Environ. Res.* **165**, 105243 (2021).
96. NID (2024). *National Inventory of Dams*. https://nid.sec.usace.army.mil/#/ (2024).
97. Shrestha, B. B. & Kawasaki, A. Quantitative assessment of flood risk with evaluation of the effectiveness of dam operation for flood control: a case of the Bago River Basin of Myanmar. *Int. J. Disaster Risk Reduct.* **50**, 101707 (2020).
98. Manfreda, S., Miglino, D. & Albertini, C. Impact of detention dams on the probability distribution of floods. *Hydrol. Earth Syst. Sci.* **25**, 4231–4242 (2021).
99. Thieme, M. L. et al. Navigating trade-offs between dams and river conservation. *Glob. Sustain.* **4**, e17 (2021).
100. Vahedifard, F., Madani, K., AghaKouchak, A. & Thota, S. K. Are we ready for more dam removals in the United States?. *Environ. Res. Infrastruct. Sustain.* **1**, 013001 (2021).
101. Kondolf, M. & Yi, J. Dam renovation to prolong reservoir life and mitigate dam impacts. *Water* **14**, 1464 (2022).
102. Mahdi, T. W. & Hillo, A. N. Flood control by weir design using HEC-ras model: the case of Al-Musandaq escape. *IOP Conf. Ser. Earth Environ. Sci.* **877**, 012025 (2021).
103. Wicher-Dysarz, J., Szałkiewicz, E., Jaskuła, J., Dysarz, T. & Rybacki, M. Possibilities of controlling the river outlets by weirs on the example of Noteć Bystra River. *Sustainability* **12**, 2369 (2020).
104. Kaushik, V., Awasthi, N., Gupta, S. K., Singh, D., Kumar, M. A review of sedimentation on different types of weirs. In *River Dynamics and Flood Hazards. Disaster Resilience and Green Growth* (eds. Pandey, M., Azamathulla, H., Pu, J. H.). (Springer, 2023).
105. Han, J.-K., Jung, W.-S., Kim, J.-M., Park, I.-H. & Kim, Y.-D. Analysis of water quality improvement effect of controlled river by multi-functional weir operation. *Appl. Sci.* **12**, 8883 (2022).
106. Im, R. Y., Kim, J. Y., Nishihiro, J. & Joo, G. J. Large weir construction causes the loss of seasonal habitat in riverine wetlands: a case study of the Four Large River projects in South Korea. *Ecol. Eng.* **152**, 105839 (2020).
107. Poppema, D. W. et al. (2023). *International Good Practices of Embankment Upgrading with Limited Footprint Increase. Policy Research Working Paper Series*. https://pure.tudelft.nl/ws/portalfiles/portal/170340243/Low_footprint_embankment_upgrading_report.pdf (2023).
108. Johnson, J. B. et al. Numerical simulation of T-walls supported by batter piles within a levee embankment. 11, 2–12 (2017).
109. Ravichandran, N., Wang, L. & Rahbari, P. Robust optimization for stability of I-walls and levee system resting on sandy foundation. *KSCE J. Civ. Eng.* **26**, 57–68 (2022).
110. Zhang, W. et al. Multifield coupling numerical simulation of the seepage and stability of embankment dams on deep overburden layers. *Arab. J. Sci. Eng.* **47**, 7293–7308 (2022).
111. Keawsawasvong, S. & Ukritchon, B. Finite element analysis of undrained stability of cantilever flood walls. *Int. J. Geotech. Eng.* **11**, 355–367 (2017).
112. Dal Cin, F., Hooimeijer, F., & Matos Silva, M. Planning the urban waterfront transformation, from infrastructures to public space design in a sea-level rise scenario: the European Union prize for contemporary architecture case. *Water* **13**, 218 (2021).
113. Attems, M. S., Thaler, T., Genovese, E. & Fuchs, S. Implementation of property-level flood risk adaptation (PLFRA) measures: Choices and decisions. *Wiley Interdiscip. Rev. Water* **7**, e1404 (2020).
114. Ventimiglia, U., Candela, A. & Aronica, G. T. A cost efficiency analysis of flood proofing measures for hydraulic risk mitigation in an urbanized riverine area. *Water* **12**, 2395 (2020).
115. Nofal, O. M., van de Lindt, J. W., Cutler, H., Shields, M. & Crofton, K. Modeling the impact of building-level flood mitigation measures made possible by early flood warnings on community-level flood loss reduction. *Buildings* **11**, 475 (2021).
116. Adedeji, T., Proverbs, D. G., Xiao, H. & Oladokun, V. O. Measuring property flood resilience (PFR) in UK homes. *Int. J. Build. Pathol. Adapt.* **42**, 1328–1349 (2024).
117. Chen, L., & Hobbs, B. F. (2020). Flood control through engineered avulsions and floodways in the lower yellow river. *J. Water Resour. Plan. Manag*. **146**, 2 (2020).
118. Suharyanto, A., Devia, Y. P., & Wijatmiko, I. Floodway design affected by land use changes in an urbanized area. *J. Water Land Develop*. https://doi.org/10.24425/jwld.2021.137120 (2021).
119. Bogárdi, I. & Balogh, E. Floodway system operation along levee-protected rivers. *J. Water Resour. Plan. Manag.* **140**, 04014014 (2014).
120. Serra-Llobet, A., Kondolf, G. M., Magdaleno, F. & Keenan-Jones, D. Flood diversions and bypasses: benefits and challenges. *Wiley Interdiscip. Rev. Water* **9**, e1562 (2022).
121. Teshome, M. *A Review of Recent Studies on Urban Stormwater Drainage System for Urban Flood Management*. https://www.preprints.org/manuscript/202010.0295/v2 (2020).
122. Lee, E. H., Lee, Y. S., Joo, J. G., Jung, D. & Kim, J. H. Investigating the impact of proactive pump operation and capacity expansion on urban drainage system resilience. *J. water Resour. Plan. Manag.* **143**, 04017024 (2017).
123. Zaki, T., Jahan, I. T., Hossain, M. S., & Narman, H. S. An IOT-based complete smart drainage system for a smart city. In *2021 IEEE 12th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)* 0553-0558 (IEEE, 2021).
124. Feng, B., Zhang, Y. & Bourke, R. Urbanization impacts on flood risks based on urban growth data and coupled flood models. *Nat. Hazards* **106**, 613–627 (2021).
125. Jafari, F., Jamshid Mousavi, S., Yazdi, J. & Kim, J. H. Real-time operation of pumping systems for urban flood mitigation: single-period vs. multi-period optimization. *Water Resour. Manag.* **32**, 4643–4660 (2018).
126. Suripin, S., Darsono, S., Kurniani, D., Hutagalung, W. F. & Dintia, D. V. Development of sustainable detention ponds for flood and sediment control in urban areas. *J. Phys. Conf. Ser.* **1625**, 012046 (2020).
127. Bellu, A., Fernandes, L. F. S., Cortes, R. M. & Pacheco, F. A. A framework model for the dimensioning and allocation of a detention basin system: the case of a flood-prone mountainous watershed. *J. Hydrol.* **533**, 567–580 (2016).
128. Terêncio, D. P., Fernandes, L. S., Cortes, R. M. V., Moura, J. P. & Pacheco, F. A. L. Flood risk attenuation in critical zones of continental Portugal using sustainable detention basins. *Sci. total Environ.* **721**, 137727 (2020).
129. Bhusal, A., Kalra, A. & Shin, S. Resilience effect of decentralized detention system to extreme flooding events. *J. Hydroinform.* **25**, 971–988 (2023).
130. Liao, S. et al. Balancing flood control and economic development in flood detention areas of the Yangtze River Basin. *ISPRS Int. J. Geo-Inf.* **13**, 122 (2024).
131. Zope, P. E., Eldho, T. I. & Jothiprakash, V. Hydrological impacts of land use–land cover change and detention basins on urban flood hazard: a case study of Poisar River basin, Mumbai, India. *Nat. Hazards* **87**, 1267–1283 (2017).
132. Calamak, M., Kilic, Y. & Yanmaz, A. M. On the stability of moderate height berm-type earthen dams: the Hancagiz dam example. *Geotech. Geol. Eng.* **38**, 4169–4179 (2020).
133. Cooper, W., Garcia, F., Pape, D., Ryder, D. & Witherell, B. Climate change adaptation case study: benefit-cost analysis of coastal flooding hazard mitigation. *J. ocean Coast. Econ.* **3**, 3 (2016).

134. Ozeren, Y., Wren, D. G. & Yasarer, H. Assessment of levee treatments for an irrigation reservoir in Arkansas. *Trans. ASABE* **61**, 1677–1689 (2018).
135. Tian, Z. et al. Dynamic adaptive engineering pathways for mitigating flood risks in Shanghai with regret theory. *Nat. Water* **1**, 198–208 (2023).
136. Mooyaart, L. F., Bakker, A. M., van den Bogaard, J. A., Rijcken, T. & Jonkman, S. N. Economic optimization of coastal flood defence systems including storm surge barrier closure reliability. *J. Flood Risk Manag.* **16**, e12904 (2023).
137. Shi, S., Yang, B. & Jiang, W. Numerical simulations of compound flooding caused by storm surge and heavy rain with the presence of urban drainage system, coastal dam and tide gates: a case study of Xiangshan, China. *Coast. Eng.* **172**, 104064 (2022).
138. Mel, R. A., Viero, D. P., Carniello, L. & D'Alpaos, L. Optimal floodgate operation for river flood management: the case study of Padova (Italy). *J. Hydrol.: Regional Stud.* **30**, 100702 (2020).
139. Timea, K., Amissah, G. J. & Fiala, K. Bank processes and revetment erosion of a large lowland river: a case study of the lower Tisza River, Hungary. *Water* **11**, 1313 (2019).
140. Ohtsuka, S. et al. Levee damage and revetment erosion by the 2019 Typhoon Hagibis in the Chikuma River, Japan. *Soils Found.* **61**, 1172–1188 (2021).
141. Klerk, W. J., Kanning, W., Vos, R. J., & Kok, M. Risk-based maintenance of asphalt revetments on flood defences. In *Life-Cycle Civil Engineering: Innovation, Theory and Practice* (eds. Chen, A., Ruan, X., Frangopol, D. M.) 384 (CRC Press, 2021).
142. Liu, L. L., & Wang, Y. C. Classification and applicability analysis of ecological revetment in different types of river. *Earth Environ. Sci.* **612**, 012008 (2020).
143. Coelho, C., Cruz, T. & Roebeling, P. Longitudinal revetments to mitigate overtopping and flooding: effectiveness, costs and benefits. *Ocean Coast. Manag.* **134**, 93–102 (2016).
144. Mummadisingh, J. V. & Sengupta, A. Study of the dynamic performance of a gabion wall. *Structures* **50**, 576–589 (2023).
145. Pereira, B., Fernandes, W. Gabion walls a remedial measure for slope stabilization. In *Earth Retaining Structures and Stability Analysis Lecture Notes in Civil Engineering* (eds. Muthukkumaran, K., Umashankar, B., Pitchumani, N. K.) 303 (Springer, 2021).
146. Chikute, G., Sonar, I. (2022). Investigation of gabion wall failures and recommendations. In *Recent Advancements in Civil Engineering. ACE 2020. Lecture Notes in Civil Engineering* (eds. Laishram, B., Tawalare, A.) 172 (Springer, 2022)
147. Thompson, D. M., Puklin, L. S. & Marshall, A. E. The long-term impact of channel stabilization using gabion structures on Zealand River, New Hampshire. *Ecol. Eng.* **95**, 779–792 (2016).
148. Li, D., Fang, Z. N., & Bedient, P. B. (2021). Flood early warning systems under changing climate and extreme events. In *Climate Change and Extreme Events* (ed. Fares, A.) 83−103 (Elsevier, 2021)
149. Rana, I. A., Bhatti, S. S. & Jamshed, A. Effectiveness of flood early warning system from the perspective of experts and three affected communities in urban areas of Pakistan. *Environ. Hazards* **20**, 209–228 (2020).
150. Sai, F., Cumiskey, L., Weerts, A., Bhattacharya, B. & Haque Khan, R. Towards impact-based flood forecasting and warning in Bangladesh: a case study at the local level in Sirajganj district. *Nat. Hazards Earth Syst. Sci. Discuss.* **2018**, 1–20 (2018).
151. Werner, M. et al. The Delft-FEWS flow forecasting system. *Environ. Model. Softw.* **40**, 65–77 (2013).
152. Díaz, J. D. N. et al. *Application of the Central America Flash Flood Guidance System for Weather-Ready Nations Capacity Development and Implementation in Costa Rica*. https://wrn.hrcwater.org/case-studies/et-incidunt-rem-expedita-sit/ (2022).
153. Nguyen, L. D., Nguyen, H. T., Dang, P. D., Duong, T. Q. & Nguyen, L. K. Design of an automatic hydro-meteorological observation network for a real-time flood warning system: a case study of Vu Gia-Thu Bon River Basin, Vietnam. *J. Hydroinform.* **23**, 324–339 (2021).
154. Zang, Y., Meng, Y., Guan, X., Lv, H. & Yan, D. Study on urban flood early warning system considering flood loss. *Int. J. Disaster Risk Reduct.* **77**, 103042 (2022).
155. Idowu, D. & Zhou, W. Performance evaluation of a potential component of an early flood warning system a case study of the 2012 flood, lower Niger River Basin, Nigeria. *Remote Sens.* **11**, 1970 (2019).
156. Tadda, M. A. et al. *Operation and Maintenance of Hydraulic Structures*. https://www.intechopen.com/chapters/72208 (2020).
157. Assaf, G. & Assaad, R. H. Optimal preventive maintenance, repair, and replacement program for catch basins to reduce urban flooding: integrating agent-based modeling and Monte Carlo simulation. *Sustainability* **15**, 8527 (2023).
158. Klerk, W. J., van Bergeijk, V., Kanning, W., Wolfert, R. & Kok, M. Risk-based maintenance and inspection of riverine flood defence systems. *Struct. Saf.* **106**, 102406 (2024).
159. Rikkert, S. J. H., Kok, M., Lendering, K. & Jongejan, R. A pragmatic, performance-based approach to levee safety assessments. *J. Flood Risk Manag.* **15**, e12836 (2022).
160. Klerk, W. J., Kanning, W., Kok, M., Bronsveld, J. & Wolfert, A. R. M. Accuracy of visual inspection of flood defences. *Struct. Infrastruct. Eng.* **19**, 1076–1090 (2021).
161. Yang, S. & Tsai, F. T. C. Understanding impacts of groundwater dynamics on flooding and levees in Greater New Orleans. *J. Hydrol. Reg. Stud.* **32**, 100740 (2020).
162. Oppenheimer, M. et al. *Sea Level Rise and Implications for Low Lying Islands, Coasts and Communitie*s. https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/ (2019)
163. Bosserelle, A. L., Morgan, L. K. & Hughes, M. W. Groundwater rise and associated flooding in coastal settlements due to sea-level rise: a review of processes and methods. *Earth. Future* **10**, e2021EF002580 (2022).
164. Ward, P. J. et al. The need to integrate flood and drought disaster risk reduction strategies. *Water Security* **11**, 100070 (2020).
165. Vitale, C. & Meijerink, S. Flood risk policies in Italy: a longitudinal institutional analysis of continuity and change. *Int. J. Water Resour. Dev.* **39**, 211–235 (2023).
166. Laeni, N., Brink, M. V. D., Busscher, T., Ovink, H. & Arts, J. Building local institutional capacities for urban flood adaptation: Lessons from the water as leverage program in Semarang, Indonesia. *Sustainability* **12**, 10104 (2020).
167. Ro, B. & Garfin, G. Building urban flood resilience through institutional adaptive capacity: a case study of Seoul, South Korea. *Int. J. Disaster Risk Reduct.* **85**, 103474 (2023).
168. Verlynde, N., Voltaire, L. & Chagnon, P. Exploring the link between flood risk perception and public support for funding on flood mitigation policies. *J. Environ. Plan. Manag.* **62**, 2330–2351 (2019).
169. Emrich, C. T., Tate, E., Larson, S. E. & Zhou, Y. Measuring social equity in flood recovery funding. *Environ. Hazards* **19**, 228–250 (2020).
170. Emrich, C. T., Tate, E., Larson, S. E. & Zhou, Y. Measuring social equity in flood recovery funding. *Environ. Hazards* **19**, 228–250 (2019).
171. Karim, A., & Noy, I. *The Determinants of Subnational Public Spending Allocation for Disaster Risk Reduction in Bangladesh*. https://www.ifo.de/en/cesifo/publications/2020/working-paper/determinants-subnational-public-spending-allocation-disaster-risk (2020).
172. Slavíková, L., Hartmann, T., & Thaler, T. Paradoxes of financial schemes for resilient flood recovery of households. *WIREs Water* **8**, e1497 (2020).
173. Tyler, J., Entress, R. M., Sun, P., Noonan, D., & Sadiq, A. Is flood mitigation funding distributed equitably? evidence from coastal

states in the Southeastern United States. *J. Flood Risk Manag.* **16**, e12886 (2023)
174. Ghaedi, H., Best, K., Reilly, A., & Niemeier, D. Statistical learning to identify salient factors influencing FEMA public assistance outlays. *Nat. Hazards* **120**, 10559–10582 (2024).
175. Khantong, S. & Ahmad, M. N. An ontology for sharing and managing information in disaster response: in flood response usage scenarios. *J. Data Semant.* **9**, 39–52 (2020).
176. Shah, A. A., Wu, W., Gong, Z., Pal, I. & Khan, J. Multidimensional six-stage model for flood emergency response in schools: a case study of Pakistan. *Nat. Hazards* **105**, 1977–2005 (2021).
177. Hammood, A. W. et al. A systematic review on flood early warning and response system (FEWRS): a deep review and analysis. *Sustainability* **13**, 440 (2021).
178. Bera, M. K. Flood emergency management in a municipality in the Czech republic: a study of local strategies and leadership. *Nat. Hazards Res.* **3**, 385–394 (2023).
179. Rustinsyah, R., Prasetyo, R. A. & Adib, M. Social capital for flood disaster management: case study of flooding in a village of Bengawan Solo Riverbank, Tuban, East Java Province. *Int. J. Disaster Risk Reduct.* **52**, 101963 (2021).
180. Karrasch, L., Restemeyer, B. & Klenke, T. The ‘Flood Resilience Rose’: a management tool to promote transformation towards flood resilience. *J. Flood Risk Manag.* **14**, e12726 (2021).
181. Zevenbergen, C., Gersonius, B. & Radhakrishan, M. Flood resilience. *Philos. Trans. R. Soc. A* **378**, 20190212 (2020).
182. Rehan, B. M. Accounting public and individual flood protection measures in damage assessment: a novel approach for quantitative assessment of vulnerability and flood risk associated with local engineering adaptation options. *J. Hydrol.* **563**, 863–873 (2018).
183. Bosoni, M., Tempels, B. & Hartmann, T. Understanding integration within the Dutch multi-layer safety approach to flood risk management. *Int. J. River Basin Manag.* **21**, 81–87 (2023).
184. Sharior, S., McDonald, W. & Parolari, A. J. Improved reliability of stormwater detention basin performance through water quality data-informed real-time control. *J. Hydrol.* **573**, 422–431 (2019).
185. Feng, W., Wang, C., Lei, X. & Wang, H. Optimize the real-time operation strategy of urban reservoirs in order to reduce flooding. *Energy, Ecol. Environ.* **8**, 344–355 (2023).
186. Bilodeau, K., Pelletier, G. & Duchesne, S. Real-time control of stormwater detention basins as an adaptation measure in mid-size cities. *Urban Water J.* **15**, 858–867 (2018).
187. Oh, J. & Bartos, M. Model predictive control of stormwater basins coupled with real-time data assimilation enhances flood and pollution control under uncertainty. *Water Res.* **235**, 119825 (2023).
188. Li, J., Johnson, R. & Burian, S. Modeling operations in system-level real-time control for urban flooding reduction and water quality improvement an open-source benchmarked case. *Water* **16**, 3078–3078 (2024).
189. Tobin, G. A. The levee love affair: a stormy relationship? 1. *JAWRA J. Am. Water Resour. Assoc.* **31**, 359–367 (1995).
190. Serra-Llobet, A., Tourment, R., Montané, A. & Buffin-Belanger, T. Managing residual flood risk behind levees: comparing USA, France, and Quebec (Canada). *J. Flood Risk Manag.* **15**, e12785 (2022).
191. White, G. F. Human adjustment to floods: a geographical approach to the flood problem in the United States. In *Chicago* (ed. T.U.O.) 29 (The University of Chicago, 1945).
192. Di Baldassarre, G. et al. Hess Opinions: An interdisciplinary research agenda to explore the unintended consequences of structural flood protection. *Hydrol. Earth Syst. Sci.* **22**, 5629–5637 (2018).
193. Hutton, N. S., Tobin, G. A. & Montz, B. E. The levee effect revisited: Processes and policies enabling development in Yuba County, California. *J. Flood Risk Manag.* **12**, e12469 (2019).
194. Hino, M., Field, C. B. & Mach, K. J. Managed retreat as a response to natural hazard risk. *Nat. Clim. change* **7**, 364–370 (2017).
195. McEwen, L., Holmes, A., Quinn, N. & Cobbing, P. ‘Learning for resilience’: Developing community capital through flood action groups in urban flood risk settings with lower social capital. *Int. J. disaster risk Reduct.* **27**, 329–342 (2018).
196. Van Valkengoed, A. M. & Steg, L. Meta-analyses of factors motivating climate change adaptation behaviour. *Nat. Clim. change* **9**, 158–163 (2019).
197. Kitagawa, K. Conceptualising ‘disaster education. *Educ. Sci.* **11**, 233 (2021).
198. Atanga, R. A. The role of local community leaders in flood disaster risk management strategy making in Accra. *Int. J. disaster risk Reduct.* **43**, 101358 (2020).
199. Tsai, M. H., Chang, Y. L., Shiau, J. S. & Wang, S. M. Exploring the effects of a serious game-based learning package for disaster prevention education: the case of battle of flooding protection. *Int. J. disaster risk Reduct.* **43**, 101393 (2020).
200. Mondino, E., Scolobig, A., Borga, M. & Di Baldassarre, G. The role of experience and different sources of knowledge in shaping flood risk awareness. *Water* **12**, 2130 (2020).
201. Osberghaus, D. & Hinrichs, H. The effectiveness of a large-scale flood risk awareness campaign: evidence from two panel data sets. *Risk Anal.* **41**, 944–957 (2020).
202. Darby, S. *The ducks of Bangladesh. The Atlantic*. https://www.theatlantic.com/international/archive/2019/07/bangladesh-climate-change-floods-ducks/593581/ (2021).
203. Shah, A. A. et al. Livelihood diversification in managing catastrophic risks: evidence from flood-disaster regions of Khyber Pakhtunkhwa province of Pakistan. *Environ. Sci. Pollut. Res.* **28**, 40844–40857 (2021).
204. Rivero, R. M., Mittler, R., Blumwald, E. & Zandalinas, S. I. Developing climate-resilient crops: improving plant tolerance to stress combination. *Plant J.* **109**, 373–389 (2022).
205. Kopeć, P. Climate change the rise of climate-resilient crops. *Plants* **13**, 490 (2024).
206. Singh, H. V., Faulkner, B. R., Keeley, A. A., Freudenthal, J. & Forshay, K. J. Floodplain restoration increases hyporheic flow in the Yakima River Watershed, Washington. *Ecol. Eng.* **116**, 110–120 (2018).
207. Chambers, M. L. et al. Nature-based solutions for leveed river corridors. *Anthropocene* **44**, 100417 (2023).
208. Chambers, M., Lammers, R., Gupta, A., Bilskie, M. V. & Bledsoe, B. Modeling the flood protection services of levee setbacks, a nature-based solution. *J. Hydrol.* **634**, 131106 (2024).
209. Lammers, R. W., Chambers, M. & Bledsoe, B. P. Modeling the effects of levee setbacks on flood hydraulics. *J. Flood Risk Manag.* **17**, e12963 (2024).
210. Iqbal, A., Rahman, M. M. & Beecham, S. Permeable pavements for flood control in Australia: spatial analysis of pavement design considering rainfall and soil data. *Sustainability* **14**, 4970 (2022).
211. Zhu, Y. et al. Permeable pavement design framework for urban stormwater management considering multiple criteria and uncertainty. *J. Clean. Prod.* **293**, 126114 (2021).
212. Zhu, H., Yu, M., Zhu, J., Lu, H. & Cao, R. Simulation study on effect of permeable pavement on reducing flood risk of urban runoff. *Int. J. Transp. Sci. Technol.* **8**, 373–382 (2019).
213. Lee, Y. T., Ho, M. C., Chiou, Y. S. & Huang, L. L. Assessing the performance of permeable pavement in mitigating flooding in urban areas. *Water* **15**, 3551 (2023).
214. Kia, A., Delens, J. M., Wong, H. S. & Cheeseman, C. R. Structural and hydrological design of permeable concrete pavements. *Case Stud. Constr. Mater.* **15**, e00564 (2021).
215. Liu, L., Sun, L., Niu, J. & Riley, W. J. Modeling green roof potential to mitigate urban flooding in a Chinese city. *Water* **12**, 2020 (2082).
216. Tamburrino, A. (2010). Water technology in ancient mesopotamia. In *Economics Of Green Roofs And Green Walls: A Literature Review*

(eds. Teotónio, I., Silva, C. M., & Cruz, C. O.) (Springer Netherlands, 2021).

217. Basu, A. S. et al. Theoretical framework to assess green roof performance in mitigating urban flooding as a potential nature-based solution. *Sustainability* **13**, 13231 (2021).
218. Teotónio, I., Silva, C. M. & Cruz, C. O. Economics of green roofs and green walls: a literature review. *Sustain. Cities Soc.* **69**, 102781 (2021).
219. Cristiano, E. et al. Analysis of potential benefits on flood mitigation of a CAM green roof in Mediterranean urban areas. *Build. Environ.* **183**, 107179 (2020).
220. Mora-Melià, D., López-Aburto, C. S., Ballesteros-Pérez, P. & Muñoz-Velasco, P. Viability of green roofs as a flood mitigation element in the central region of Chile. *Sustainability* **10**, 1130 (2018).
221. Tomscha, S. A. et al. Multiple methods confirm wetland restoration improves ecosystem services. *Ecosyst. People* **17**, 25–40 (2021).
222. Rojas, O., Soto, E., Rojas, C. & López, J. J. Assessment of the flood mitigation ecosystem service in a coastal wetland and potential impact of future urban development in Chile. *Habitat Int.* **123**, 102554 (2022).
223. Wu, Y., Zhang, G., Rousseau, A. N., Xu, Y. J. & Foulon, É On how wetlands can provide flood resilience in a large river basin: a case study in Nenjiang River basin, China. *J. Hydrol.* **587**, 125012 (2020).
224. Kumar, S. et al. Constructed wetland management in urban catchments for mitigating floods. *Stoch. Environ. Res. Risk Assess.* **35**, 2105–2124 (2021).
225. Spieles, D. J. Wetland Construction, Restoration, and integration: a comparative review. *Land* **11**, 554 (2022).
226. Kuriqi, A., Pinheiro, A. N., Sordo-Ward, A., Bejarano, M. D. & Garrote, L. Ecological impacts of run-of-river hydropower plants current status and future prospects on the brink of energy transition. *Renew. Sustain. Energy Rev.* **142**, 110833 (2021).
227. Gay. et al. Riparian buffers increase future baseflow and reduce peakflows in a developing watershed. *SSRN Electron. J*. **862**, 160834 (2022).
228. Riis, T. et al. Global overview of ecosystem services provided by riparian vegetation. *BioScience* **70**, 501–514 (2020).
229. Olokeogun, O. S., Ayanlade, A. & Popoola, O. O. Assessment of riparian zone dynamics and its flood-related implications in Eleyele area of Ibadan, Nigeria. *Environ. Syst. Res.* **9**, 6 (2020).
230. Knouft, J. H. et al. Forested riparian buffers as climate adaptation tools for management of riverine flow and thermal regimes: a case study in the Meramec River Basin. *Sustainability* **13**, 1877 (2021).
231. Graziano, M. P., Deguire, A. K. & Surasinghe, T. D. Riparian buffers as a critical landscape feature: insights for riverscape conservation and policy renovations. *Diversity* **14**, 172 (2022).
232. Sancho, F. Evaluation of coastal protection strategies at Costa da Caparica (Portugal): nourishments and structural interventions. *J. Mar. Sci. Eng*. **11**, 1159 (2023).
233. Saengsupavanich, C., Pranzini, E., Ariffin, E. H. & Yun, L. S. Jeopardizing the environment with beach nourishment. *Sci. Total Environ.* **868**, 161485 (2023).
234. Huisman, B. J., Walstra, D. J. R., Radermacher, M., de Schipper, M. A. & Ruessink, B. G. Observations and modelling of shoreface nourishment behaviour. *J. Mar. Sci. Eng.* **7**, 59 (2019).
235. Tiede, J., Jordan, C., Moghimi, A., & Schlurmann, T. Long-term shoreline changes at large spatial scales at the Baltic sea: remote-sensing based assessment and potential drivers. *Front. Mar. Sci*. https://doi.org/10.3389/fmars.2023.1207524 (2023).
236. Staudt, F. et al. The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. *J. Coast. Conserv.* **25**, 34 (2021).
237. De Schipper, M. A., Ludka, B. C., Raubenheimer, B., Luijendijk, A. P., & Schlacher, T. A. Beach nourishment has complex implications for the future of sandy shores. *Nat. Rev. Earth Environ*. **2**, 70–84 (2021).
238. Mendes, D. et al. Beach response to a shoreface nourishment (Aveiro, Portugal). *J. Mar. Sci. Eng*. **10**, 1112 (2021).
239. Hayward, S. et al. Numerical simulation of coastal erosion and its mitigation by living shoreline methods: a case study in southern Rhode Island. *Shore Beach* **86**, 13 (2018).
240. Meguro, W., & Kim, K. *Designing Resilient Coastal Communities with Living Shorelines. Climate Adaptation and Resilience Across Scales* 1st edn, Vol. 19 (Routledge, 2021).
241. Jones, S. C. & Pippin, J. S. Towards principles and policy levers for advancing living shorelines. *J. Environ. Manag.* **311**, 114695 (2022).
242. Manuel, P., Rapaport, E., Ewashen, N., Kowal, C. & Warren, K. *Town Of Shelburne Bank Stabilization And Living Shoreline Project: A Case Study Of Nature-based Coastal Adaptation In Nova Scotia*, https://static1.squarespace.com/ (2021).
243. USACE. U.S. *Army Corps of Engineers. Best Practices for Vegetation Management on Levees. In the National Levee Safety Program*. https://mmc.sec.usace.army.mil/NLSP_website/NLSG_PublicDraft/FINAL%20Vegetation%20Review%20Draft%20March%2029%202024.pdf (2021).
244. Boechat Albernaz, M., Roelofs, L., Pierik, H. J. & Kleinhans, M. G. Natural levee evolution in vegetated fluvial-tidal environments. *Earth Surf. Process. Landf.* **45**, 3824–3841 (2020).
245. Rosenberger, D. & Marsooli, R. Benefits of vegetation for mitigating wave impacts on vertical seawalls. *Ocean Eng.* **250**, 110974 (2022).
246. Adams, A. N. *Determining the effects of vegetation on levee structural integrity on the Green River in King County, Washington (Doctoral dissertation)*. https://your.kingcounty.gov/dnrp/library/water-and-land/flooding/2014-UW-Sponsored-Research-Agreement-report.pdf (2015).
247. Ebel, B. A. Temporal evolution of measured and simulated infiltration following wildfire in the Colorado front range, USA: Shifting thresholds of runoff generation and hydrologic hazards. *J. Hydrol.* **585**, 124765 (2020).
248. Lucas-Borja, M. E. et al. Changes in ecosystem properties after post-fire management strategies in wildfire-affected mediterranean forests. *J. Appl. Ecol.* **58**, 836–846 (2021).
249. Vahedifard, F. et al. Interdependencies between wildfire-induced alterations in soil properties, near-surface processes, and geohazards. *Earth Space Sci.* **11**, e2023EA003498 (2024).
250. Yilmaz, O. S. et al. Evaluation of pre- and post-fire flood risk by analytical hierarchy process method: a case study for the 2021 wildfires in Bodrum, Turkey. *Landsc. Ecol. Eng.* **19**, 271–288 (2023).
251. Xu, Z., Zhang, Y., Blöschl, G., & Piao, S. Mega forest fires intensify flood magnitudes in Southeast Australia. *Geophys. Res. Lett.* **50**, e2023GL103812 (2023).
252. Carabella, C., Miccadei, E., Paglia, G. & Sciarra, N. Post-wildfire landslide hazard assessment: the case of the 2017 montagna del morrone fire (Central Apennines, Italy). *Geosciences* **9**, 175 (2019).
253. Abdollahi, M., Vahedifard, F. & Leshchinsky, B. A. Hydromechanical modeling of evolving post-wildfire regional-scale landslide susceptibility. *Eng. Geol.* **335**, 107538 (2024).
254. Abdollahi, M., Vahedifard, F. & Tracy, F. T. Post-wildfire stability of unsaturated hillslopes against rainfall-triggered landslides. *Earth's. Future, AGU* **11**, e2022EF003213 (2023).
255. Wittenberg, L., van der Wal, H., Keesstra, S. & Tessler, N. Post-fire management treatment effects on soil properties and burned area restoration in a wildland-urban interface, Haifa Fire case study. *Sci. Total Environ.* **716**, 135190 (2020).
256. Dejong, J. T. et al. Biogeochemical processes and geotechnical applications: progress, opportunities and challenges. In *Bio-and*

Chemo-Mechanical Processes in Geotechnical Engineering: Géotechnique Symposium 143–157 (Ice Publishing, 2014).
257. Liu, Z. et al. Microbial induced calcite precipitation for improving low-cohesive soil: mechanisms, methods and macroscopic properties. *Low. Carbon Mater. Green. Constr.* **2**, 1–20 (2024).
258. Cheng, L., & Shahin, M. A. Microbially induced calcite precipitation (MICP) for soil stabilization. *Materialstoday Proc*. **93**, 357−361 (2019).
259. Kwon, Y. M., Chang, I. & Cho, G. C. Xanthan biopolymer-based soil treatment effect on kaolinite clay fabric and structure using XRD analysis. *Sci. Rep.* **13**, 11666 (2023).
260. Jiang, X., Rutherford, C., Cetin, B., & Ikuma, K. (2018). *Use of Biocementation for Slope Stabilization of Levees*. https://www.intrans.iastate.edu/wp-content/uploads/2018/12/biocementation_for_levee_slope_stabilization_w_cvr.pdf (2018).
261. Haasnoot, M., Kwakkel, J. H., Walker, W. E. & Ter Maat, J. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Glob. Environ. change* **23**, 485–498 (2013).
262. Schlumberger, J., Haasnoot, M., Aerts, J., & De Ruiter, M. Proposing DAPP-MR as a disaster risk management pathways framework for complex, dynamic multi-risk. *Iscience* **25**, 105219 (2022).
263. Qiang, Y. Disparities of population exposed to flood hazards in the United States. *J. Environ. Manag.* **232**, 295–304 (2019).
264. Sanders, B. F. et al. Collaborative modeling with fine-resolution data enhances flood awareness, minimizes differences in flood perception, and produces actionable flood maps. *Earth's Future* **8**, e2019EF001391 (2020).
265. Vahedifard, F., Azhar, M. & Brown, D. C. Overrepresentation of historically underserved and socially vulnerable communities behind levees in the United States. *Earth's. Future* **11**, e2023EF003619 (2023).
266. Wagner, S. et al. When does risk become residual? a systematic review of research on flood risk management in West Africa. *Reg. Environ. Change* **21**, 84 (2021).
267. Giovannettone, J. P. et al. Equitable infrastructure: Achieving resilient systems and restorative justice through policy and research innovation. *PNAS Nexus* **3**, pgae157 (2024).
268. Aerts, J. C. A review of cost estimates for flood adaptation. *Water* **10**, 1646 (2018).
269. Vorogushyn, S. et al. Evolutionary leap in large-scale flood risk assessment needed. *Wiley Interdiscip. Rev. Water* **5**, e1266 (2018).
270. Schumann, G. J., Bates, P. D., Apel, H. & Aronica, G. T. *Global flood hazard: Applications in Modeling, Mapping, and Forecasting*, Vol. 272 (John Wiley & Sons, 2018)
271. Luke, A. et al. Going beyond the flood insurance rate map: Insights from flood hazard map co-production. *Nat. Hazards Earth Syst. Sci.* **18**, 1097–1120 (2018).
272. Scorzini, A. R. & Leopardi, M. River basin planning: from qualitative to quantitative flood risk assessment: the case of Abruzzo region (central Italy). *Nat. Hazards* **88**, 71–93 (2017).
273. Harrison, M. B. et al. Guideline adaptation and implementation planning: a prospective observational study. *Implement. Sci.* **8**, 49 (2013).
274. Thongs, G. Integrating risk perceptions into flood risk management: trinidad case study. *Nat. Hazards* **98**, 593–619 (2019).
275. Arosio, M. et al. Unveiling the assessment process behind an integrated flood risk management plan. *Int. J. Disaster Risk Reduct.* **112**, 104755 (2024).
276. Pinyol, N. M., Alonso, E. E., & Olivella, S. Rapid drawdown in slopes and embankments. *Water Resour. Res*. https://doi.org/10.1029/2007WR006525 (2008).
277. Jensen, C. B. A flood of models: mekong ecologies of comparison. *Soc. Stud. Sci.* **50**, 76–93 (2020).
278. Kwadijk, J. C. et al. Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley Interdiscip. Rev. Clim. change* **1**, 729–740 (2010).
279. Bloemen, P. J., Hammer, F., van der Vlist, M. J., Grinwis, P., & van Alphen, J. DMDU into practice: adaptive delta management in the Netherlands. In *Decision Making Under Deep Uncertainty: From Theory to Practice* (eds. Marchau, V., Walker, W., Bloemen, P., Popper, S.) 321-351 (Springer, 2019).
280. Aerts, J. C. et al. Exploring the limits and gaps of flood adaptation. *Nat. Water* **2**, 719–728 (2024).
281. Rumson, A. G., Hallett, S. H. & Brewer, T. R. Coastal risk adaptation: the potential role of accessible geospatial big data. *Mar. Policy* **83**, 100–110 (2017).
282. Ford, J. D. et al. Big data has big potential for applications to climate change adaptation. *Proc. Natl. Acad. Sci. USA* **113**, 10729–10732 (2016).
283. Azhar, M., Vahedifard, F. & AghaKouchak, A. Regional data-driven modeling of levee failure due to overtopping. *Geotech. Front.* **2025**, 308–317 (2024).
284. Burton, C. & Cutter, S. L. Levee failures and social vulnerability in the Sacramento-San Joaquin Delta area, California. *Nat. hazards Rev.* **9**, 136–149 (2008).
285. Chakraborty, L. et al. Assessing social vulnerability and identifying spatial hotspots of flood risk to inform socially just flood management policy. *Risk Anal.* **43**, 1058–1078 (2023).
286. Cano Pecharroman, L. & Hahn, C. Exposing disparities in flood adaptation for equitable future interventions in the USA. *Nat. Commun.* **15**, 8333 (2024).

Acknowledgements

This material is based upon work supported by the National Science Foundation (NSF) under Grants No. CMMI-2401545 and CMMI-2332263. AA acknowledges support from Caltrans Agreement No. 74A1414.

Author contributions

F.V. conceived the idea, M.A. and F.V. formulated the idea and outline for the analysis. A.A. and B.K. contributed to the scope of analyses. M.A. and B.K. collected and analyzed the data. M.A. and B.K. wrote the first draft and created the figures. All authors (F.V., M.A., A.A. and B.K.) reviewed the results and the manuscript and contributed to the final draft.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-025-02779-z.

Correspondence and requests for materials should be addressed to Farshid Vahedifard.

Peer review information *Communications Earth & Environment* thanks Marjolijn Haasnoot and Steven Ashley Forrest for their contribution to the peer review of this work. Primary Handling Editors: Emmanuel Raju and Joe Aslin. A peer review file is available.