From Flood Control to Flood Adaptation

Katharine J. Mach, University of Miami, Miyuki Hino, University of North Carolina at Chapel Hill, A.R. Siders, University of Delaware, Steven F. Koller, University of Miami, Caroline M. Kraan, University of Miami, Jennifer Niemann, University of Miami, and Brett F. Sanders, University of California, Irvine

https://doi.org/10.1093/acrefore/9780199389414.013.819
Published online: 22 November 2022

Summary

Societies throughout the world are experiencing more severe and frequent flooding with consequences for people's livelihoods, health, safety, and heritage. Much flood risk management to date has aimed to maximize economic benefits, reduce the likelihood of flood disasters, and facilitate recovery where needed. It has assumed a stationary climate and focused on extremes and financial losses. But this paradigm of flood control is increasingly at odds with the full set of challenges and requirements for flood risk management.

Critical challenges motivate a shift from flood control to flood adaptation. First, under climate change, flood risks are intensifying and changing, and new normals are appearing, such as daily high-tide flooding or permanent inundation. Fully controlling flood hazards with one-time interventions is increasingly untenable. Second, floods affect numerous, multidimensional aspects of human and ecological well-being and social justice. Past flood control efforts, and the decision-making processes that produced them, have often failed to address these multidimensional concerns or even had negative side effects. Fundamental adjustments are emerging and will be needed: a guiding paradigm of flexibility rather than control, a system-wide approach with coordinated action across scales, and increased attention to the full range of priorities relevant to successful interventions.

For example, science and research for flood risk adaptation increasingly involve processes supporting usable, inclusive knowledge tailored to decision contexts. Integrative science partnerships such as collaborative flood modeling can incorporate the dynamic physical and social landscapes of flood drivers, impacts, and management. Flexible processes allow updating as flood risks change, and collaborative processes can build intuition, trust, and understanding of risks, including improved awareness of the values and relationships that are threatened and preferred response options. The goal of flood risk management is no longer limited to preventing floods; flood risk management must balance risk tolerances with ecological and social benefits and weigh the trade-offs of management strategies against other societal goals. This "science for society" is inherently political, requiring careful attention to and evaluation of who participates, whose goals are prioritized, and who benefits.

Furthermore, methods of evidence-based decision-making must be able to accommodate deep uncertainties, changing risks and values, and limits to responses. Shifts are already occurring, including dynamic adaptive management practices and improvements to tools such as cost–benefit comparisons. These changes illustrate a larger reframing within flood risk management, away from disaster management focused on extreme isolated events and toward adaptation in response to enduring changes across both extreme and average conditions.

The current challenges of flood risk management create opportunities for integrating lessons from diverse domains of actionable science and public policy and thereby innovating processes of climate adaptation relevant to a range of climate risks.

Keywords: flood risk management, disaster risk reduction, flood control, flood adaptation, equity, transformation, science–society interactions, usable knowledge, policy reforms

Subjects: Management and Planning

Flooding is among the most damaging climate-related hazards. Approximately 90% of the global population lives within 10 km of a surface freshwater body (Kummu et al., 2011), and more than 600 million people live in low-lying coastal areas fewer than 10 m above average sea level (United Nations, 2017), with particularly large population exposure in coastal settlements in Asia and Africa (Glavovic et al., 2022). Living near water provides economic and other benefits that can improve quality of life. Yet it also creates exposure to highly damaging flood hazards (Kousky et al., 2020; National Oceanic and Atmospheric Administration [NOAA], 2021). Despite the risks, the population exposed to flood hazards is increasing (Ceola et al., 2014; Jongman et al., 2014). From 2000 to 2015, populations grew faster in areas inundated by flooding (34.1%) compared to the total population (18.6%) (Tellman et al., 2021). Even after flood disasters occur, people generally rebuild their lives and economies in the same places (Kocornik-Mina et al., 2020; Kousky et al., 2020). These patterns of development, in combination with climate change, are intensifying flood risks (Wing et al., 2022).

As flood risks grow, the limitations of historical flood management practices are becoming more evident. Much of flood risk management to date has aimed to support economic priorities, reduce the likelihood of flood disasters, and facilitate recovery to pre-flood baselines. It has been designed under assumptions of a stationary climate and attuned to extremes and financial losses. But this paradigm of flood control is increasingly at odds with the full set of challenges and requirements for flood risk management. Two critical challenges particularly reveal the limitations. First, under climate change, flood risks are non-stationary, and new normals are emerging as hazards, such as daily high-tide flooding or permanent inundation. Second, flood managers and stakeholders have growing recognition that floods affect numerous, multidimensional aspects of human and ecological well-being and social justice. Past flood control efforts, and the decision-making processes that produced them, have often failed to address these multidimensional concerns or even had negative side effects.

Compared to past efforts at flood control, flood adaptation for the decades ahead therefore must involve approaches better suited to changing flood risks, holistic well-being, and the many decision-making contexts that are relevant. Flood adaptation under intensifying climate change requires attention to historical biases and the ways in which future flood-related research and decision-making will need to be different. This article first introduces fundamental shifts relevant to flood adaptation. It then describes emerging approaches and tools to support flexible, coordinated flood adaptation across the many decision-makers and contexts relevant to flooding. The review integrates and critiques literature on flood risk management, disaster risk reduction, and climate adaptation and draws from relevant examples globally.

Fundamental Shifts Inherent to Flood Adaptation

Much of flood risk management historically has focused on flood control aiming to support economic development and public safety. However, fully controlling flood hazards with one-time engineering interventions and infrastructure projects is increasingly untenable as the changing climate exacerbates existing flood hazards, creates new ones, and introduces greater uncertainty into flood predictions. Past practices have also had negative effects on broader societal priorities such as ecosystem services and social equity. Fundamental shifts in moving toward flood adaptation therefore include managing changing risks rather than controlling stationary hazards, increasing attention paid to the full range of priorities relevant to successful interventions, and recognizing the wide range of decision-makers and contexts relevant to the governance of flood risks (figure 1). There are immense barriers to these shifts, and all of the shifts will need to explicitly address social justice and empower communities to pursue their values, both through equitable distribution of flood risks and resources and through inclusive participatory processes that recognize and seek to redress injustices.

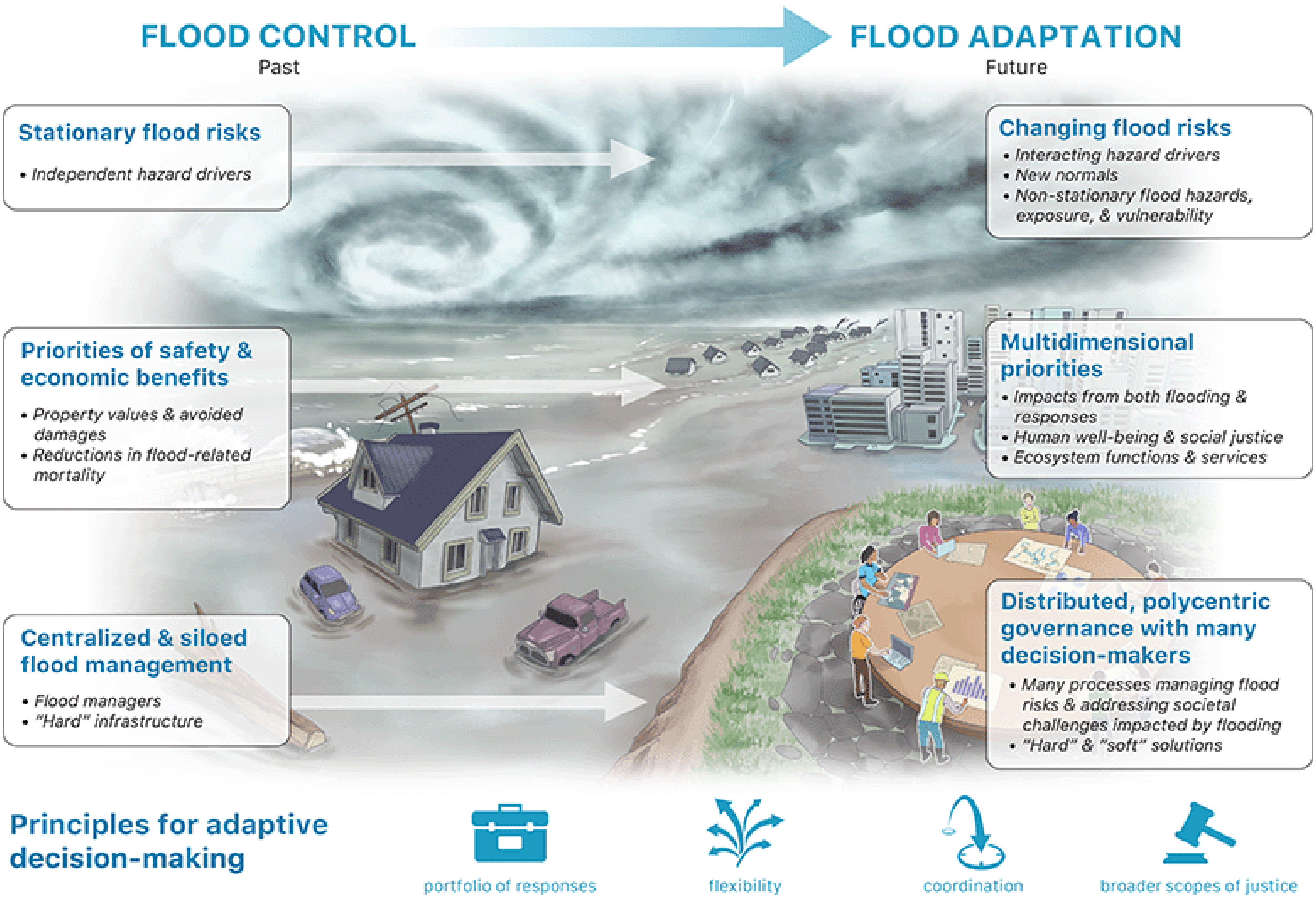

Figure 1. Flood control to flood adaptation. Fundamental shifts include managing changing risks, increasing attention paid to the full range of priorities shaping the success of interventions, and recognizing the wide range of decision-makers and contexts relevant to the governance of flood risks.

Changing Flood Risks

Flood management has often prioritized control of flood hazards to prevent flood disasters, redirecting flows and keeping water out via engineering projects and hard infrastructure (Mees et al., 2014; Molinaroli et al., 2019; Montz & Gruntfest, 1986). Although deliberate practices of thoughtful settlement limiting exposure to hazards and living in harmony with local landscapes date back millennia, modern built environments have greatly expanded in areas exposed to flood hazards (Tam et al., 1999), and flood control projects have sought to protect infrastructure against extreme flood events. Many countries still frame flood risk management as flood control, whether under the "flood control districts" central to flood management throughout the United States (Box 1), the sequence of dikes constructed over time in Thailand (Shi et al., 2021), or current flood control practices in the Nadi River Basin, Fiji (Oppenheimer et al., 2019). Early flood control efforts destroyed critical ecosystem functions through aggressive efforts to channelize rivers or install storm barriers that hindered tidal water exchanges (Molinaroli et al., 2019; Pinto et al., 2018). They also permitted—or even encouraged—dense development within areas at risk of flooding (Brody et al., 2007; Glavovic et al., 2022; Jongman et al., 2014; Montz & Gruntfest, 1986). Invariably, residual risks exist in the wake of flood control projects (Pinter et al., 2016; Wagner et al., 2021). Increasing exposure has led to growing damages and losses addressed with insurance and aid (Molinaroli et al., 2019).

Box 1. The Evolving History of Flood Control

The United States' evolving history of flood control reveals broadening priorities through time, barriers to effective and equitable flood management, and needs for flood adaptation. Flood control has been managed and financed by state, local, and private interests since the country's founding (Carter, 2012; U.S. Army Corps of Engineers [USACE], 2019b). Over time, the U.S. federal government has come to play a pivotal role in flood hazard mitigation through legislation, national programs and funding, and provision of construction and technical services (Figure 2).

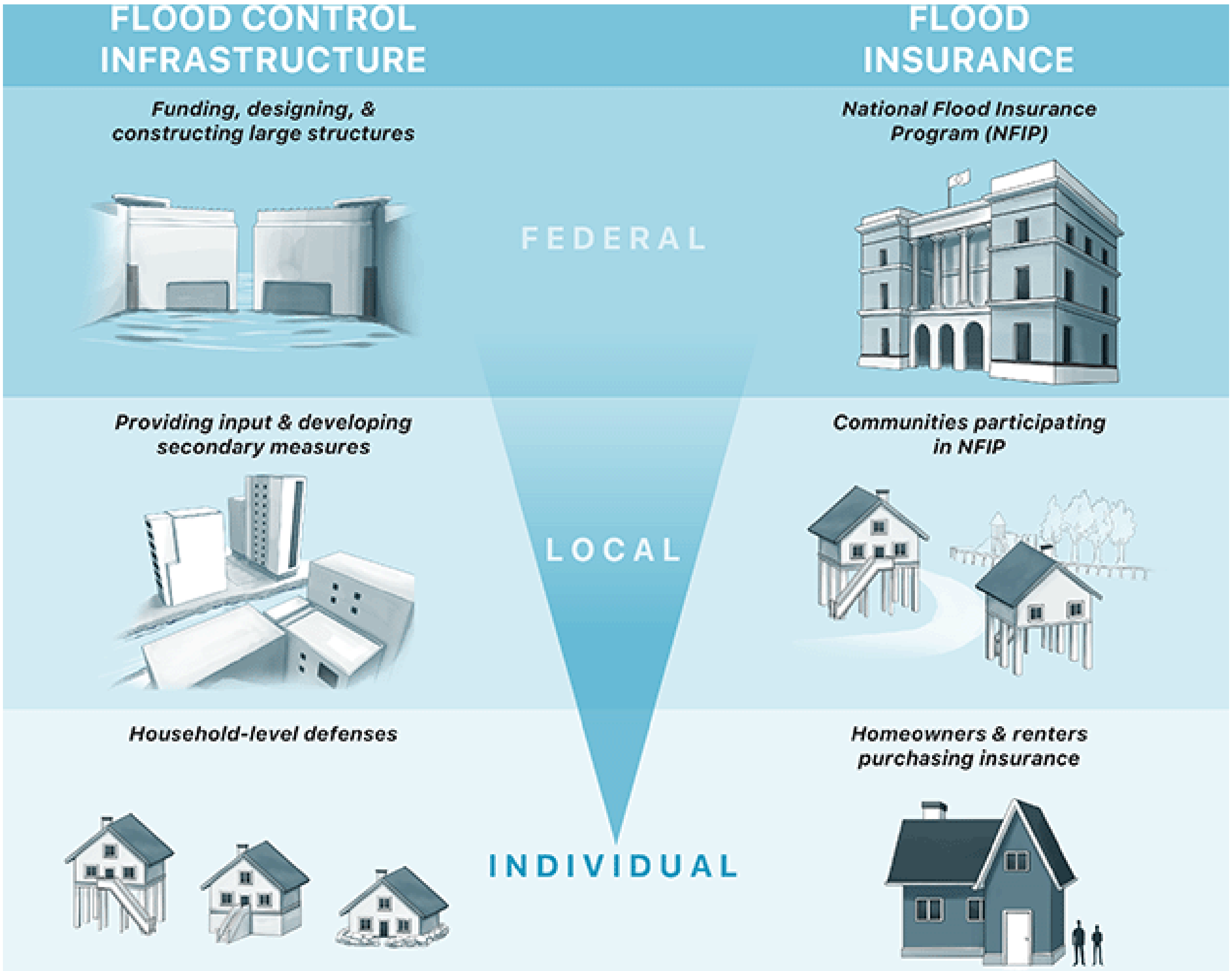

Figure 2. Distributed governance of flood risks. Responsibility for flood risk management is shared among federal, state, and local government agencies and programs, as well as individuals (ASCE, 2014; USACE, n.d.).

Many U.S. federal policies have encouraged development in floodplains, notably starting with the Swamp Land Acts of 1849 and 1850 (Barry, 1998). The priorities of these acts are indicative of the era's prevailing attitude that flood hazards could be dominated and overcome with engineering. The Acts actively incentivized the drainage of naturally inundated areas to make land usable for economic development. Federally controlled wetlands were ceded to states on the condition that the lands would be made fit for cultivation (U.S. Congress, 1850). Between passage of the Acts and 1906, swamplands equivalent to roughly 3.6% of total current U.S. land area were claimed by 15 states, with Florida and Louisiana reclaiming the most (U.S. Department of Agriculture, National Agricultural Statistics Service, 2014; Wright & U.S. Department of Agriculture, 1907). States sold lands to developers, and revenues from the sales funded locally constructed and managed levees, often uncoordinated across jurisdictions.

U.S. policies have historically favored flood-control infrastructure such as levees instead of managing flood risks by avoiding development in floodplains. In 1861, a USACE officer and future USACE Chief Engineer, Andrew A. Humphreys, released an authoritative report firmly favoring a “levees only” policy to manage flooding along the Mississippi River. Alternatives such as diversion channels, spillways, tributary reservoirs, or disincentives for development in the river's floodplains were avoided, and the “levees only” policy was accepted as a guiding principle by USACE for the next six decades (Reuss, 1985). Following a historic flood in 1874 (Wiltz, 1874/2005), the 1879 Mississippi River Commission Act formalized the federal government's role in flood control, naming the Mississippi River Commission objectives as deepening the channel and protecting the banks of the Mississippi River, improving safety and ease of navigation, preventing destructive floods, and facilitating commerce (Arnold, 1988; U.S. Congress, 1879).

Construction of flood control infrastructure may reduce impacts from relatively frequent events, but it also has the potential to increase vulnerability and exposure to rare, most-extreme ones (Kates et al., 2006; Tobin, 1995) and to create path dependencies influencing future flood risk management decisions (Glavovic et al., 2022; van Buuren et al., 2016). The narrow "levees only" policy for flood control came under heavy scrutiny after the Great Mississippi River Flood of 1927, then the "greatest disaster of peace times in [U.S.] history" (Withington, 2013). At least 17 major cracks and breaches in federal levees contributed to widespread destruction spanning seven U.S. states (Barry, 1998). The floods ultimately displaced more than 700,000 people from their homes (Arnold, 1988). A disproportionate share of those displaced were African American, and the disaster spurred a substantial, lasting decline in the total African American population in the Mississippi River Delta and surrounding regions (Hornbeck & Naidu, 2014).

The catastrophic flooding from the Great Mississippi River Flood of 1927 motivated the U.S. Congress to pass the Flood Control Act of 1928, appropriating an unprecedented $325 million for levee construction and strengthening. The bill reaffirmed the principle of federal–local cost-sharing and also placed the responsibility of repairs and maintenance of federally constructed flood control projects on states, levee districts, and local interests (U.S. Congress, 1928), a cost-sharing and management arrangement still in effect in the 21st century (see figure 2). The Act emphasized interstate commerce, mail delivery, and prosperity as national priority, meriting federal intervention, while also clarifying responsibility of local and private interests in the financing and maintenance of flood mitigation infrastructure. Subsequently, the 1936 Flood Control Act (U.S. Congress, 1936) empowered the federal government to engage in expansive preventative flood control activity nationwide on a continuing basis, including features such as dams, dikes, and levees. It also established the criterion requiring flood infrastructure projects' economic benefits to exceed their costs. As of 2022, there are 6,978 levee systems and 24,570 miles of levees in the United States in total, with an average levee age of 58 years (USACE, 2016). State and local governments or levee management districts control 72% of U.S. levees, many in poor repair and at risk (*ASCE*, 2021). There is currently no national standard for levee design, construction, operation, or maintenance (*ASCE*, 2021).

By contrast to the narrow "levees only" historic emphasis, many U.S. federal programs in the second half of the 20th century and into the 21st century grew to be more multipurpose, nonstructural, or broader in their hazard mitigation and resilience goals (Kousky, 2015). Insurance, avoidance, and other strategies have become more prominent. Since the passage of the 1968 National Flood Insurance Act, the 1%-annual-chance floodplain has been the dominant base floodplain designation in U.S. federal policy, shaping mandatory purchase of National Flood Insurance Program policies for property owners exposed to this level of flood hazard, incentives to communities to deploy portfolios of flood risk management activities, and also the central standard for which USACE considers alternatives in their flood risk management studies (FEMA, 2021a;

Kousky et al., 2020; USACE, 2019a). In the 21st century, at least five U.S. federal agencies have the capacity, authority, and budget to provide funding or technical assistance to non-federal sponsors for flood mitigation projects: USACE, FEMA, Department of Housing and Urban Development, Environmental Protection Agency, and Department of Agriculture (Junod et al., 2021).

Limits to flood control are being realized as the changing climate intensifies the extremes and alters the more commonly occurring, "normal" conditions of flooding. Flood risks are unambiguously changing through time rather than being fixed or stationary (Milly et al., 2008). Climate change is altering the characteristics of the planet's water cycle and flood hazards through thermal expansion in the oceans, declining ice mass balance in glaciers and the Antarctic and Greenland ice sheets, shifting patterns of precipitation and storms, and more extreme individual precipitation events (Chung et al., 2014; Collins et al., 2013; Elsner et al., 2008; Fleming et al., 2018; Moftakhari et al., 2017). And flood risks are increasingly resulting not only from climate extremes and flood-related disasters but also from "climate normals"—changes to the normal conditions that present novel threats such as high-tide flooding, rising groundwaters, or rainfall overwhelming urban stormwater infrastructure (Hauer et al., 2021; Hino et al., 2019; Parkinson, 2021; Sweet et al., 2021; Wakefield, 2019). However, much less is known about the social and economic impacts and thresholds associated with these new and more frequently occurring types of floods.

The shift from a flood control paradigm—one that focuses on controlling water to prevent or limit discrete disaster events—toward flood adaptation—an emphasis on living with new and changing risks (Milly et al., 2008)—represents a fundamentally different attitude toward flood risk management. A historic focus on large-scale river floods gives way, for example, to recognition that multiple climate-related drivers are causing floods at different scales and frequencies, including higher frequency floods during high-tide conditions or permanent inundation. Defining a 1%-annual-chance flood requires iterative updating through time across multiple possible types of flood hazards, challenged by the fact that small floods have been substantially understudied and underdocumented, although they can have substantial impacts especially in urban areas (Hauer et al., 2021; Li et al., 2021). Shifting climate normals also call into question the appropriateness of considering only the 1%-annual-chance flood, because flood events with shorter return periods may incur increasing damage. Furthermore, there are different implications of "normal" conditions becoming more dangerous compared to extreme conditions becoming more dangerous—for risk perceptions, detection of changes, communication of the risks, and needs and opportunities for adapting (Bakkensen & Barrage, 2017; Glavovic et al., 2022; Haer et al., 2017; Hemmati et al., 2021; Kousky et al., 2020). The resulting complex dynamics can involve shifting baselines, the normalization of increasing risk levels, cognitive biases serving to downplay risks, and varying beliefs in one's capacity to undertake adaptive adjustments. This complexity is a profound challenge for flood adaptation.

Flood disasters in some cases have been viewed as "acts of God." However, under increasing climate change and an "expanding bull's-eye effect" (Strader & Ashley, 2015), all determinants of risk are socially influenced, mediated, and constructed. The determinants of risk (e.g., hazards, vulnerability and sensitivity, and exposure) and interactions across risks and responses are also non-stationary, variable, and interacting and changing through space and time (Billings et al., 2021; Di Baldassarre et al., 2013; Domingue & Emrich, 2019; Masozera et al., 2007). Multiple stressors, socioeconomic structures, and climate-related hazards combine to determine risk factors and the potential for and limits to responses across households and communities (Oppenheimer et al., 2019; Swain et al., 2020; Tanoue et al., 2021; Wing et al., 2018). The social determinants of risk therefore pose limits to flood control as a prevailing or sole strategy (American Society of Civil Engineers [ASCE], 2014; Highfield et al., 2014; Zarekarizi et al., 2020). Effectively planning for changing risks increasingly requires more up-to-date information gathering, a wider range of responses, and greater coordination and collaboration to achieve implementation (Butler et al., 2021; Lyles et al., 2013). And as adaptive responses reshape the distribution of flood risks, there is potential for social reconstruction of risk as well (Maskrey et al., 2021; Shi, 2020; Simpson et al., 2021).

Multidimensional Consequences of Flooding

Flood control to date has strongly prioritized economic objectives—in particular, enabling economic development; reducing economic impacts from extreme flooding; and evaluating potential and implemented projects through monetized costs, benefits, and avoided damages (Box 1). At times, the economic rationales underpinning policy criteria have been detrimental to efforts to protect all people, including lower wealth communities. For example, evaluation of flood control projects in Cedar Rapids, Iowa, identified benefits exceeding costs for levees and flood walls protecting the downtown but not the highly exposed residential areas where people live (Aschbrenner, 2016; Tate et al., 2016).

Flooding, however, causes multiple types of harm, not just economic damages narrowly defined and easily quantified in monetary terms. The adverse outcomes most often tabulated in evaluations of flood impacts and interventions include financial losses from property and infrastructure damage, and also mortality. Yet there are broader sociocultural, economic, ecological, psychological, health, and well-being impacts of flooding (Association of State Floodplain Managers [ASFPM], 2020; England & Knox, 2015; Glavovic et al., 2022; Markhvida et al., 2020). For example, flooding can degrade livelihoods such as in tourism or fisheries or lead to the failure of small businesses. It often causes involuntary displacement and results in trauma. It can increase exposure to water-borne diseases or pollutants. Furthermore, flooding can heighten inequalities based on differential vulnerability. Flooding may reshape the comparative advantages of different regions, reduce funds available for governments for other uses, or erode connections to places including through existential risks to low-lying nations facing potential submergence in this century and beyond.

Multidimensional consequences of flooding often arise from interactions across sectors and both climate- and non-climate-related influences, which also challenge the quantification of past and future impacts. For example, impacts from flooding frequently involve cascades, such as flooding leading to power outages, disrupted transportation and communication, and subsequent adverse outcomes from these failures (England & Knox, 2015). And flood impacts are exacerbated by compounding factors, for instance, linked to the season in which flooding occurs or the social and cultural circumstances of residents (Glavovic et al., 2022; Shi et al., 2021). Where there is unequal access to key services and resources—such as differential access to electricity or transportation, varying burdens from the pandemic, or disproportionate reliance on agricultural livelihoods—flooding may further exacerbate underlying structural inequities.

A more holistic understanding of flood impacts makes it clear that flood risks are not borne uniformly across populations (Wing et al., 2022). There are substantial differences in vulnerability to flooding between the poor and the wealthy, across gender and racial lines, and among those with differential access to decision-making power, at both household and national levels (Cutter & Finch, 2008; Khajehei et al., 2020). Furthermore, flooding is related to and may drive the marginalization of, disinvestment in, and decline of communities (Glavovic et al., 2022; Shi et al., 2021). For instance, people living in informal settlements often have especially high vulnerability to flooding given the semi-permanence of building structures, the limited wealth of residents, reduced access to public services, and disenfranchisement in decision-making processes. In many cities, such as Mumbai, India, or Ho Chi Minh City, Vietnam, informal settlements are also disproportionately exposed to flooding (Glavovic et al., 2022). In some cases, the flood-prone nature of the land and informal nature of the tenancy are used as reasons not to invest in these areas, perpetuating flood exposure and potentially denying the provision of other services (e.g., transportation, health services, and access to credit). A new term, "bluelining," has been coined to describe the process of governments and institutions purposefully avoiding or changing the terms of investment in flood-prone communities (Keenan & Bradt, 2020). For example, a mortgage lender might offer higher interest rates in a neighborhood with high flood exposure.

Flood control itself may cause multiple types of harm, not just in its failures to prevent flood damages. Flood control has often gone hand in hand with industrialized capitalism, with its reliance on resource extraction, wealth accumulation, and domination (Shi et al., 2021). Flood-related policies have, in some cases, perversely served to increase the accumulation of assets in hazardous places, and individual, local actions are not adding up to socially optimal adaptation at scale (Brody et al., 2007; Di Baldassarre et al., 2013; Jongman et al., 2014; Montz & Gruntfest, 1986).

In many cases, flood management practices have actually created or exacerbated social, economic, and political inequities and injustices (Billings et al., 2021; Domingue & Emrich, 2019; Hornbeck & Naidu, 2014; Smiley, 2020). For example, risk management policies that rely on common economic evaluation criteria can perpetuate legacies of injustice (Bullard & Wright, 2012; Tate et al., 2016). In megacities in South and Southeast Asia, procurement of water supply and management of flood waters have served to repeatedly disadvantage most-marginalized groups in both rural and urban areas, dispossessing people of water and livelihoods in rural areas, excluding them from access to water and land once they migrate into cities, and minimizing their flood protection or even evicting them from urban areas during processes of flood management in order to protect higher wealth residents (Ajibade, 2019; Shi et al., 2021). In England, an analysis of expenditures for flood risk management found that communities most exposed and socially vulnerable to flooding received the least funding per person (England & Knox, 2015). In North Carolina, "shoreline armoring" measures tend to be located near communities with high relative home values and low relative racial diversity, whereas property acquisitions have tended to occur in communities with low home values (Siders & Keenan, 2020). Variations in the quality and accuracy of flood risk estimates across categories of race and ethnicity can further exacerbate inequities in risks and responses (Chakraborty et al., 2014, 2019; Smiley, 2020).

Existing disparities in social vulnerability to flooding and in influence on flood management generate serious equity concerns about how risks will be distributed in the future as climate change continues to disrupt economies and societies (Glavovic et al., 2022). For these reasons, there is a renewed and strengthened focus on equity in flood risk management, and social justice is emerging as an increasing imperative for flood risk management (England & Knox, 2015). Many dimensions of social and environmental justice are relevant, including the unequal distribution of flood risks and of benefits from flood management, the exclusionary procedures of flood risk management and governance, and failures to recognize the unfairness of historic and ongoing processes (Shi et al., 2021).

Distributed, Polycentric Governance with Many Decision-Makers

The multidimensional, non-stationary nature of flood risks leads to another reframing of flood risk management: The success of flood management depends on more than preventing flooding. As a result, flood adaptation cannot be achieved by siloing flood management and confining it to individual actors such as flood managers and engineers. Instead, there is a third fundamental shift toward understanding flood adaptation as involving the many decision-making processes working to address societal challenges that are impacted in different ways by flooding.

The distributed decision-making and fragmented governance of flood adaptation necessarily involve many perspectives on flood risks and the outcomes and processes of flood responses. These understandings of what is at risk, what levels of risk should be managed, and how they should be managed are, ultimately, socially negotiated. Flood-relevant policies are shaped not only by risks, economics, and analyses by dedicated flood managers but also by a wide range of social processes, including politics and cultural norms. Flood adaptation is not a simple objective calculation but, rather, a socially mediated process (Crabbé et al., 2015; Pinto et al., 2018; Wakefield, 2019). Perceptions of risks, the uptake of policies, and the effectiveness and fairness of responses are all socially determined in complex ways (ASFPM, 2020; Hino & Burke, 2021; Horn & Webel, 2021; Kousky et al., 2020). Flood management priorities must also be balanced against other critical integrated water resource management interests. In many countries (e.g., Bangladesh), flood management decisions impact the provision of safe drinking water supply and reliable electricity supply, among other activities (Gain et al., 2017).

Recognizing that the goals of flood management are not confined to simply preventing floods leaves open the question of what those goals are—an exciting, yet stark challenge for flood adaptation science moving forward. Across different countries, the nature of the social contract between residents and government has differed in flood management to date, as have the values prioritized (Jongman et al., 2014; Mees et al., 2014). Nonetheless, the evolution of goals through time is nearly universal, and in many countries, decision priorities have broadened over time (see Box 1; Crabbé et al., 2015; Golnaraghi et al., 2020). Under continuing climate change, the goals for flood management will also continue to emerge and evolve from changing, novel flood risks and their social mediation and construction.

Flood adaptation cannot be confined to an infrastructure problem because it is a much larger problem of interlinked human–environmental systems. Stormwater infrastructure deployed to protect one community can increase risks for another, dependent on hazard drivers and topography (Griggs et al., 1994; Hummel et al., 2021; Jafino et al., 2021; Pilkey & Wright, 1988). Cascading and systemic risks across regions and sectors result from the interaction of individual and institutional actions mediated by complex dynamics of individual and social psychology and policy forces (Covi et al., 2021; Kousky et al., 2020; Maskrey et al., 2021; Treuer et al., 2017). The distribution of flood risks, responses, and resources is the product of complex histories of housing, development, culture, and social justice. New approaches and tools are necessary for flood information and science to fit, inform, and support the many decision-making processes relevant to changing flood risks and the multidimensional goals of flood management.

Emerging Approaches and Tools for Flood Adaptation

To better address changing, multidimensional flood risks into the future, adaptive approaches are therefore required. Principles for adaptive decision-making include flexibility, coordination, and participation in iterative, inclusive decision-making processes (see section on "Principles for Adaptive Decision-Making"). Understanding of these principles is informed by a rich set of emerging experiences. Despite significant constraints and limits, innovative tools are being developed and applied in support of more proactive and distributed evidence-based decision-making (see section on "Tools and Processes for Adaptive Decision-Making"). Flood adaptation benefits from deliberate methods to support the multitudes of decision-making processes relevant to flood risks and the diverse societal challenges they affect.

Principles for Adaptive Decision-Making

To achieve flood adaptation to non-stationary, multidimensional flood risks, decision-making has to change. For example, post-disaster circumstances have been seen as a reasonable time to make forward-looking changes because perceived risk and issue salience are high, but post-disaster recovery and rebuilding efforts, under time pressure and with limited opportunities for input and deliberation, often entrench the status quo (e.g., wealth accumulation for elites) or involve short-term choices (e.g., buying flood insurance for only a few years) before risks are forgotten again (Brody et al., 2009; Kousky et al., 2020; Shi, 2020). Sometimes choices involve longer term foresight (e.g., major retreat programs after tsunamis in Asia), but such approaches seem the exception more than the rule (Li & Landry, 2017). With changing risks, new normals, and multidimensional impacts, the need for different decisions, compared to past approaches, is a cross-cutting priority (Wakefield, 2019; Zarekarizi et al., 2020). The shift applies for hazard mitigation, emergency preparedness, disaster risk reduction, and adaptation to both small and large flood events.

Proactive adaptation requires decision-makers and flood managers to ask a broader set of questions, across the full portfolio of responses, both structural and nonstructural, with adjustments and learning through time (table 1; ASCE, 2014; Brody et al., 2010; Butler et al., 2021; Golnaraghi et al., 2020; Highfield et al., 2014; Oppenheimer et al., 2019). What flood management decisions need to be made *better* going forward, and who will define what better means? Is it how societies invest in infrastructure (Wakefield, 2019); manage development through zoning, building codes, and other regulations (Brody et al., 2007, 2013); or administer insurance (Jongman et al., 2014; Kousky et al., 2020)? Is it how governments provide aid and who gets it? Is it about relocation schemes and equitable adaptation attentive to the spatial interactions of property markets, livelihoods, risk management, and migration (Mach & Siders, 2021)? How can policymakers and organizers equitably prepare for policy action windows after extreme events (Brody et al., 2009; Lyles et al., 2013)? Furthermore, who is and is not participating (Odemerho, 2015)? What is policy design considering (e.g., possible damages) and not considering (e.g., job losses, structural racism, and climate change)? What tools do communities have that they are not using, such as for limiting new development in floodplains, and what tools, knowledge, or resources do they need but do not have (Brody et al., 2007, 2010; Glavovic et al., 2022)?

Table 1. Examples of Flood Adaptation Options[a]

Adaptation Strategy	Examples of Flood Risk Management Options
Resist (reducing probability of hazards)	Flood control structures, seawalls, grade raising, levees, canals, green–gray infrastructure, living shorelines, beach replenishment
Accommodate (reduce sensitivity)	Management of flood control, stormwater drainage and pumping, building elevation, building codes, septic tank permitting, flood proofing, permeable surfaces, risk communication to residents, flood insurance policies, emergency management, disaster relief
Avoid (reduce exposure pre-development)	Land use zoning, down zoning, priority investment areas, property tax policies, development rights transfers, setbacks, preservation of waterfront access, siting of infrastructure outside floodplain
Retreat (reduce exposure post-development)	Property buyouts, rebuilding restrictions, eminent domain, rolling easements, wetland restoration, pre-disaster plans for post-disaster relocations, withdrawal of government services from highly hazardous areas

a Preparing for non-stationary flood risks and their multidimensional consequences requires portfolios of responses.

Sources: Brody et al. (2010), Doberstein et al. (2019), Dyckman et al. (2014), Grannis (2011), Spidalieri (2020), Urban Land Institute (2020), USACE (2020).

Although it is not possible to identify all of the ways in which decision-making will need to change and past experiences reveal deep challenges in achieving such adjustments, there are emergent principles and directions that can serve as a guide for flood adaptation. They include portfolios of responses, flexibility, coordination, and broader scopes of justice.

Portfolios of Responses

Preparing for non-stationary flood risks and their multidimensional consequences requires portfolios of responses, structural and nonstructural, not just flood control narrowly defined (table 1). Empirical studies find that flood resistance and accommodation projects such as levees and seawalls, beach nourishments, constructed dunes, restoration of green spaces, elevation of structures, and education and awareness programs can all provide significant flood protection benefits and improve property values in affected areas, in combination with measures to avoid the development of open spaces, limit development in floodplains, and retreat from most-hazardous areas (Brody & Highfield, 2013; Glavovic et al., 2022; Highfield et al., 2014; Oppenheimer et al., 2019; Sun & Carson, 2020).

Structural measures for flood resistance have often been the preferred and dominant response in flood control, however, even though there are trade-offs involved with infrastructural deployment beyond its high costs and long time frames of implementation (Highfield et al., 2014; Jafino et al., 2021). Surge barriers can alter ecosystems and increase mortality risks for marine life; seawalls may obstruct ocean views, erode adjacent beaches, and increase risks outside the areas protected; and raising revenue to pay for public infrastructural projects has the potential to hamper inclusive economic growth if taxes are poorly designed and distortionary. Investing in flood infrastructure may also amount to an implicit subsidy of existing land uses and can encourage new development in areas supposedly made "safe," yet with the potential for catastrophes during low-probability, high-impact events if design standards are exceeded and projects are not designed to fail (Brody et al., 2007; Di Baldassarre et al., 2013). Under current policy processes, elements such as cost–benefit analysis and long-standing coalitions between local government officials and land-owning businesses also have the potential to favor infrastructure investments for protection of wealthy communities instead of low-wealth communities, communities of color, or communities otherwise marginalized or underserved because monetized property values carry significant weight in these analyses and historical injustices and differences in political influence are generally not taken into account (Covi et al., 2021; Shi, 2020). Political incentives and institutional settings may incentivize deployment of large-scale flood protection projects because they can generate salient political benefits and private gains, including through corruption (Lebel et al., 2009).

Flexibility

Adaptation to non-stationary, intensifying risks requires ongoing processes of adjustment, embracing change and recognizing that many determinants of risk cannot be easily controlled (Brody et al., 2009; Glavovic et al., 2022). An emphasis on staying where and as people are—controlling the environment and emphasizing stability—therefore gives way to more flexible, proactive, adaptive, and potentially transformative adjustments (Crabbé et al., 2015). Resilience, from this perspective, is not just returning to the status quo but also learning and transforming in adjustments and recognizing that living with water and changing flood risks is the reality. Iterative updating of understanding through time, contemplation of wider ranges of responses, monitoring of implemented interventions, and working across jurisdictions and levels of government and with the private sector and civil society all become increasingly important in building necessary capacities, coordinating actions, and improving the quality of plans and actions (Butler et al., 2021; Lyles et al., 2013). However, currently, many adjustments being made are still incremental, reflecting awareness of changing risks but not yet the necessarily deep capacities to iteratively update responses through time (Butler et al., 2016; Molinaroli et al., 2019). Adaptation requires changing our development approaches and flood management actions such that the changing environment is acknowledged, rather than assuming the environment can be controlled to match human desires and political will. At the same time, how those adjustments to the environment improve (or harm) human well-being is context-dependent and often difficult to predict.

Building governance capabilities sufficient for the complexity of changing risks and multidimensional impacts is crucial but often remains out of reach. Continual change and widening uncertainties demand different planning and management strategies, not just static plans and policies (Butler et al., 2021; Glavovic et al., 2022). Strategies can involve adopting a long-term view in implementing current responses, such that options can remain open into the future (Kousky et al., 2020; Oppenheimer et al., 2019). Associated enablers include avoiding new development in hazardous locations or buffer zones such as wetlands; fostering shared understanding of increasing flood risks and responses appropriate in different contexts; building the organizational capacity necessary for policy learning; creating new financial instruments and flows; and creating fora for inclusive, iterative deliberation and collective problem-solving (Brody et al., 2007, 2009, 2010; Highfield et al., 2014; Sun & Carson, 2020). Yet experiences with adaptive management demonstrate institutional barriers to such flexibility and learning, such as the difficulty of revisiting regulatory adjustments or investments after policy windows pass, underscoring the magnitude of transformations needed.

Coordination

Expanding beyond a narrow focus on flood control and economic evaluation requires increased coordination, networks, and linkages across levels of government and between the public and private sectors (Brody et al., 2010; Butler et al., 2021; Crabbé et al., 2015; Glavovic et al., 2022; Li & Landry, 2017; Lyles et al., 2013; Oppenheimer et al., 2019). Given that flood damages and policies have exacerbated social inequities, dedicated approaches to advancing social justice are necessary. Approaches benefit from multiple knowledge systems, strengthened community capabilities, and meaningful participation.

There are substantial tensions of scale, ranging from individual action to government action, from the local to the national and global (Maskrey et al., 2021; Pinto et al., 2018). The heuristic for adaptation is often that it is local (Fu, 2020). And indeed, many determinants of flood risk and constraints and enablers on flood mitigation and land use planning are dependent on context and place.

However, there are limits to local flood adaptation. First, local action often focuses on maximizing local benefits at the expense of regional or national interests (e.g., develop locally for the property taxes and rely on national government for post-disaster aid) (Brody et al., 2007; Li & Landry, 2017). Second, local governments often perpetuate inequities in their distribution of resources (Shi, 2020; Wakefield, 2019). Scarce resources exacerbate these dynamics. Flood mitigation infrastructure often accrues disproportionate benefits to waterfront property owners with high real estate values (McNamara et al., 2015; Qiu & Gopalakrishnan, 2018), challenging fair siting and jurisdictional funding arrangements, and some individuals will feel more entitled to requesting government action locally or be more heard and responded to in such requests (Shi, 2020; Wakefield, 2019). Many developing countries also lack the financial and technical capacity to produce tailored flood risk information to support local adaptation, suggesting the potential for growing adaptation gaps across international contexts (Webber & Donner, 2017). Third, there will also be individual and hyperlocal "autonomous" adjustments dealing with the risks (e.g., walking around in wading boots, switching to a vehicle with higher ground clearance, and installing flood defenses for individual homes) that may add up to higher costs compared to adaptive action at greater social scales. Finally, local actions can affect neighboring jurisdictions. For example, flood infrastructure in one area can exacerbate flood risks in neighboring regions (Griggs et al., 1994; Hummel et al., 2021; Pilkey & Wright, 1988), and increased coordination of shoreline stabilization efforts among towns that share a coastline has been shown to improve aggregate welfare (Gopalakrishnan et al., 2017).

Government action at increasing social scales is often required for more transformative management and adaptation to flood risk attuned to equity, affordability, livelihoods, and other dimensions of well-being. Yet there are profound constraints, disincentives, pushback, and lack of coordination across scales that limit effective, adequate, and transformational adaptation (Brody et al., 2010; Kousky et al., 2020; Molinaroli et al., 2019; Onda et al., 2020). It is often not straightforward to determine which levels of government should take action and how actions across levels of government can act to collectively reduce risk (Butler et al., 2021; Lyles et al., 2013). The scale at which floods are managed also changes perceptions about equity (Cooper & McKenna, 2008). It is important to consider multiple scales but not allow aggregation and thinking at large scales to permit injustice at local scales. Emerging coordination of flood risk adaptation requires extensive cooperation and shifting responsibilities across national, subnational, and local governments, the private sector, and civil society, whether the adaptation of interest is wetland restoration and horizontal levees, urban regeneration, adaptive land use planning, or relocation of communities (Albert et al., 2018; Mees et al., 2014; Pinto et al., 2018). In certain contexts—for example, urban centers in Senegal and Tanzania—a lack of significant climate change adaptation and flood risk management policy capacity in public agencies is a critical constraint for effective coordination and implementation of public policy solutions (Vedeld et al., 2015). How resources and decision-making power are allocated from the individual through higher levels of government is extremely influential for equitable outcomes.

Broader Scopes of Justice

Analysis of adaptation to climate change in U.S. cities suggests that in efforts to date, the disproportionate focus on procedural justice and an expansion of democracy has limited, perhaps counterintuitively, the scope and durability of these efforts (Shi, 2020). In particular, in prioritizing participation, the role of adaptation in redistributing wealth and resources and the structural reforms necessary for enduring change have simultaneously received much less attention in adaptation plans and guidance. Although engagement of residents and communities is occurring, the drivers of urban spatial inequality, exclusion, and displacement motivating their participation are not being adequately addressed. A typology of urban adaptation emerges, ranging from "neoliberal cities" ignoring social inequities and climate risks except in post-disaster circumstances in which "disaster economies" favor those with economic and political power and reinforce marginalization of some groups to "transformative cities" holistically addressing climate change through emissions reductions and adaptation and advancing collective well-being and sustainable relationships among people and places (Shi, 2020). In addition to coordination of social movements across cities and levels of government, more transformative approaches may be supported through (a) alliances among the urban and rural communities adversely affected by the spatial concentration of wealth in cities, into which flood risk management and adaptation figure; (b) collaborations among lawyers, insurance experts, economists, and planners to innovate new architectures of land policy; and (c) development of concrete and also hopeful visions and policy designs to support equitable adaptation against the backdrop of the spatial interactions of flood adaptations and ongoing legacies of injustice (Shi, 2020).

Tools and Processes for Adaptive Decision-Making

Deliberate methods can support adaptive decision-making responsive to changing, multidimensional flood risks. Approaches and tools can include new forms of knowledge governance, distributed decision-making, and policy revisions, supporting capacities to respond to changing, novel flood risks and promote well-being more holistically.

Participatory Processes Supporting Usable, Inclusive Knowledge Tailored to Decision Contexts

Participatory processes incorporating information on flood risks and response options can support iterative decision-making over time, responsive to a wider range of societal priorities. For example, participatory scenario planning has been widely deployed (e.g., in Nigeria, Bangladesh, China, Mozambique, Brazil, the Netherlands, and Indonesia) to support shared visions of coastal adaptation, reconcile different values, and address power imbalances and imperatives of human security (Oppenheimer et al., 2019). Longer term adaptive pathways have been catalyzed in New Zealand through use of serious games and processes integrating methods of decision analysis with public participation and deliberation (Lawrence & Haasnoot, 2017). Integrative science partnerships such as more collaborative flood modeling can incorporate the dynamic physical and social landscapes of flood drivers, impacts, and management (Box 2). They can also build intuition, trust, and understanding of attributes and relationships that are threatened and preferred response options. Where such processes become self-sustaining, they can enable updating as flood risks change, responses and learning occur, or priorities evolve.

Box 2. Collaborative Flood Modeling

One way to increase participation in flood adaptation is collaborative flood modeling, an integrative science partnership supporting actionable knowledge tailored to decision contexts (figure 3).

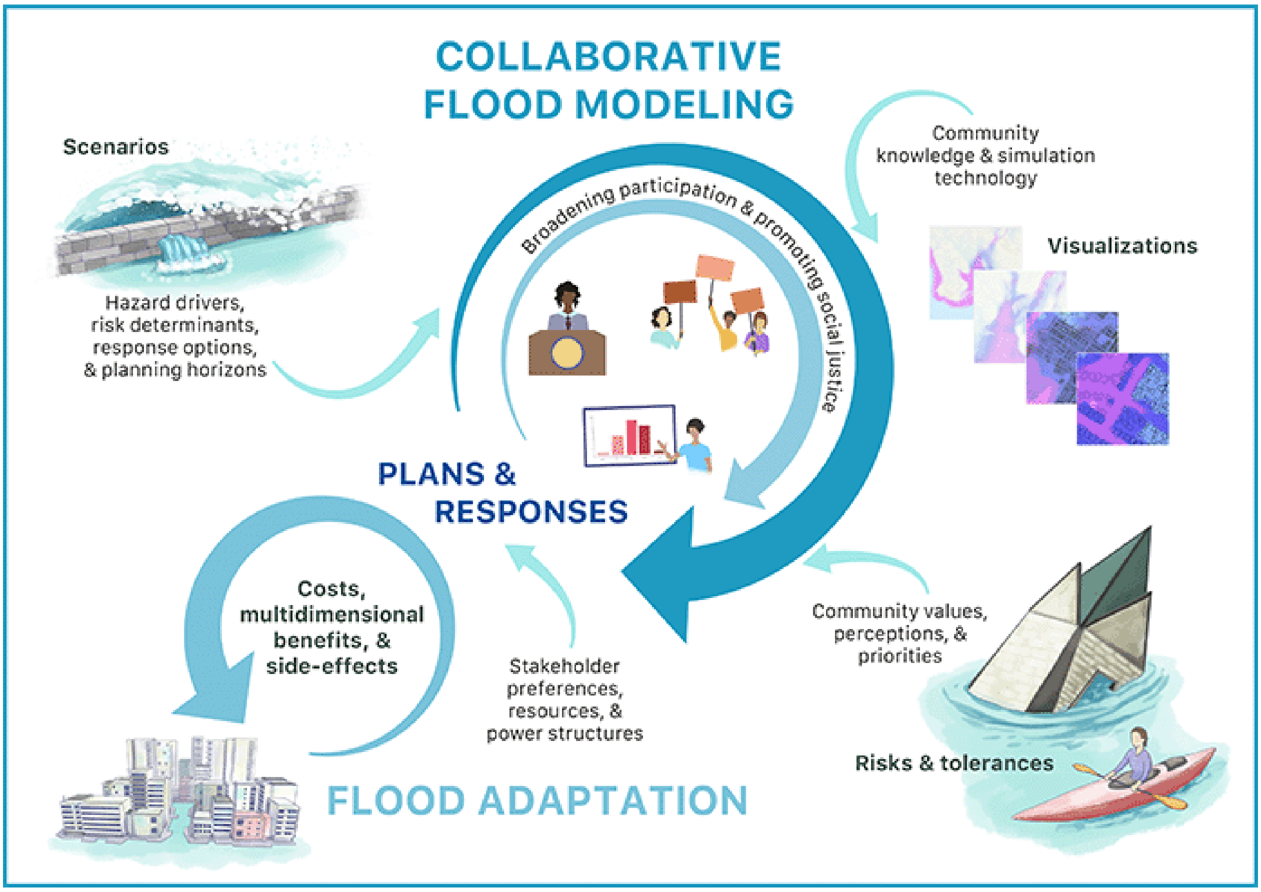

Figure 3. Collaborative flood modeling for integrative science partnerships supporting flood adaptation. In collaborative flood modeling, community and stakeholder participation is interwoven, iteratively through time, with flood inundation modeling, adaptation planning, and learning and adjustment through time.

Flood maps, education and awareness programs, and flood forecasting and warning inform many aspects of flood management and adaptation decision-making. For example, they shape choices about developing infrastructure or moving into floodplains, flood-proofing structures, or maintaining good drainage (Highfield et al., 2014), as well as understanding of residual risks where flood infrastructure exists, such as from controlled releases of floodwaters or infrastructural failures (ASFPM, 2020). They inform development incentives, regulations, and planning across sectors (Highfield et al., 2014). Community participation and awareness yield benefits for flood preparations, also reducing reliance on government assistance for flood relief and recovery (Auynirundronkool et al., 2012; Li & Landry, 2017).

Emerging adaptation efforts, however, face a range of barriers related to flood modeling that limit equitable, effective flood adaptation. Fundamental constraints include differential flood awareness, risk perception, and prioritization (Barrage & Furst, 2019; Hino & Burke, 2021; Keys & Mulder, 2020; Palm & Bolsen, 2020); and uneven access and control among stakeholders over data, modeling tools, and scenarios used to characterize present and future flood risks (Grove et al., 2020; Sanders et al., 2020). In many flood-prone locations, flood maps, data sets, and products do not exist, or they are substantially out of date, not reflecting changes in the topography of watersheds, development and more impervious surfaces, shifts in precipitation or water levels, or improvements in data sets and modeling (Li et al., 2021). Furthermore, such constraints illuminate a power structure whereby control over flood modeling and adaptation planning frames problems in ways that favor existing wealth and marginalize participation (Bullard & Wright, 2012; Siders & Keenan, 2020). Those in control of flood modeling decide on the data used, the scenarios and interventions considered, and the metrics applied to quantify performance (Bourget, 2011; Evers et al., 2012; Maskrey et al., 2016; Sanders et al., 2020). These power structures remain active especially in the evaluation of flood control projects justified by damages avoided with selectively chosen scenarios and damage functions (USACE, 2020). In turn, the "modeling power structure" builds mistrust, seeds conflict, and limits coordinated responses. Without a change in the power structure of flood modeling that broadens and deepens participation, responses to climate change are unlikely to address the growing challenges of social inequities and ecosystem degradation, against the backdrop of rising flood risks and disproportionate impacts for underserved and marginalized communities (U.S. Government Accountability Office, 2020; Kousky et al., 2019).

A growing number of interactive online tools are a first step toward more equitable flood risk modeling for adaptation. Examples include bathtub-style inundation modeling of sea level rise (e.g., Climate Central, 2020; NOAA, 2020) and initial region-wide and continental-scale modeling of multiple flood hazards (e.g., FEMA, 2020; First Street Foundation, 2022; U.S. Geological Society, 2021; Wing et al., 2017). However, a drawback of these tools is that users lack control over data and the representation of processes needed to build understanding of flood dynamics—for example, under rainfall, streamflow, and storm tide drivers; context-specific determinants of social and ecological vulnerability; and diverse response options.

Across many contexts, there is a need for interactivity, rigor, and distributed access and control in flood modeling. This can be achieved with collaborative flood modeling, in which stakeholder participation is interwoven, iteratively through time, with flood inundation modeling (Goodrich et al., 2020; Sanders et al., 2020). Collaborative flood modeling is enabled through a new class of flood models that address both power structures inherent in traditional modeling and the gap that exists between the high-resolution urban flood models necessary for engineering plans and the coarse-resolution urban flood models that are widely available for open-ended and iterative adaptation planning purposes. During the past decade, multiple collaborative flood modeling projects have demonstrated promising results in building shared awareness of threats and impacts (e.g., Houston et al., 2019), improving the usefulness and actionability of flood maps for diverse groups of stakeholders (e.g., Luke et al., 2018), and inclusively developing strategies to manage flood risks (e.g., Evers et al., 2012; Maskrey et al., 2016) and to adapt to increased flooding from sea level rise (e.g., Sanders et al., 2020). Especially important under conditions of political polarization and mistrust in science and government (Covi et al., 2021), collaborative modeling has been shown to increase trust in and the use of scientific information in decision-making (Cheung et al., 2016; Ulibarri, 2018), to build intuition about valued attributes and relationships that are threatened and preferred response options, and to promote more long-lasting engagement (Goldberg et al., 2020; Goodrich et al., 2020). It also provides equity in access to information and support for stakeholder-driven learning. Importantly, however, this science for society is inherently political, requiring careful attention to and evaluation of who participates, how they are treated in the process, what goals are prioritized, and who benefits. Collaborative flood modeling partnerships can incorporate the dynamic physical and social landscapes of flood drivers and management. They can provide information at the spatial scales and for the time frames that are meaningful, also with guidance on how to interpret the information (Glavovic et al., 2022). Such processes of actionable knowledge allow updating as flood risks change, and they can directly address drivers of inequitable flood protection to date.

Inclusive decision-making can support local ownership and increased equity in flood adaptation. More inclusive processes not only foster awareness of flood risks and the needs for adaptation but also can make calls for recognizing pre-existing socioeconomic vulnerability and drivers of inequity, increase the voice of communities and residents in prioritizing adaptation options, build capacity in marginalized and underserved communities, bridge formal and informal institutions, and create fora for meaningful public deliberation and conflict resolution (Glavovic et al., 2022; Shi, 2020). For instance, a rights-based approach to participatory adaptation planning in Maputo, Mozambique, has revealed drivers of structural inequities, connected coastal adaptation with human development, and increased public support for equitable adaptation (Oppenheimer et al., 2019). Contexts as diverse as Pacific Islands states, the coastal Arctic, the Philippines, and Cambodia have suggested that Indigenous knowledge and local knowledge can support perceptions of relationships with the environment as hazards shift, build the cohesion of communities, empower groups especially vulnerable to flooding, and facilitate adaptive behaviors and responses (Glavovic et al., 2022).

Decision Support for Decision-Making Under Deep Uncertainty

Methods of evidence-based decision-making must be able to accommodate the deep uncertainties inherent to non-stationary, evolving flood risks and the ways in which evolving values and limits to responses interact to shape preferred response pathways. Deep uncertainty cannot be eliminated by simply conducting more research, and it often arises in complex, nonlinear systems with many stakeholders (Marchau et al., 2019).

Increasingly, methods of decision support have responded to the challenges of deep uncertainties, and their innovative approaches have been applied in contexts as diverse as delta management in Bangladesh (Mutahara et al., 2018; Zevenbergen et al., 2018), sea level rise adaptation in Australia (Barnett et al., 2014), infrastructural adjustments in the United Kingdom (Ranger et al., 2013), or evolving approaches in the Netherlands (Box 3). In Ho Chi Minh City, Vietnam, robust decision-making methodologies for integrated flood risk management have aimed to satisfy objectives across many possible futures, rather than aiming for optimality under any given scenario (Lempert et al., 2013). In Hawkes Bay, New Zealand, tools for decision-making under deep uncertainty have shaped the development of a 100-year Coastal Hazard Strategy (Oppenheimer et al., 2019). A dynamic adaptive policy pathways approach and a modified real options analysis were combined with multi-criteria decision analysis to inform a decision framework considering response effectiveness and flexibility. Remaining challenges include funding, identifying triggers for changing response approaches, incorporating the strategy into statutory plans, and building the support of the wider public for the strategy. The process included technical advisory councils and community panels consisting of people affected, iwi Mãori, business and conservation interests, and infrastructure agencies, and it demonstrated the importance of collaboration, leadership, trust building, and a community-based approach.

Box 3. Dynamic Adaptive Flood Management

The Netherlands, located in the Rhine-Meuse-Scheldt delta in northwestern Europe, has a long history with managing flood risk. The 20th century was the age of engineering feats, such as the Enclosure Dam; the creation of the province of Flevoland through land reclamation; and the Delta Works, protecting the country to handle flood events with 0.25% annual chance and 0.01% in densely populated areas (Jorissen et al., 2016). Under continuing climate change, major additional investments are needed, including for physical infrastructure that cannot be moved, and deep uncertainties mean that such investments may be too little, too late—or too much, too early. In order to continue protecting the nation against flooding, a Delta Program has been implemented, using Adaptive Delta Management to sustain well-being and livelihoods for generations to come (Marchau et al., 2019). The Delta Program focuses not only on flood risk management but also on climate-resilient land use planning and freshwater availability.

Adaptive Delta Management is based on a decision-making under deep uncertainty approach called Dynamic Adaptive Policy Pathways (DAPP) (figure 4). The premise is that decisions are made over time as a result of a changing environment, and sound management needs to consider the sequencing and path dependencies of these decisions (Marchau et al., 2019). A plan of action under the DAPP approach consists of a series of decisions, from short- to long-term actions, grouped into logical strategies called pathways. A crucial part of the DAPP approach is the use of adaptation tipping points—that is, changes in circumstances that cause a policy decision to fail and require a decision for a new action. The first tipping point likely to be reached in the Netherlands, at ~1.5 m of sea level rise, concerns the frequency of closing storm surge barriers (Haasnoot et al., 2020). Nationwide pathways to adapt to extreme sea level rise have been presented in 2019 with the policy goal to "keep options open" until at least 2050 (Haasnoot et al., 2019). Keeping options open allows for policy decisions that match well with future societal preferences and needs, although the strategy is difficult to implement in practice because it constrains regional development (Gersonius et al., 2016).

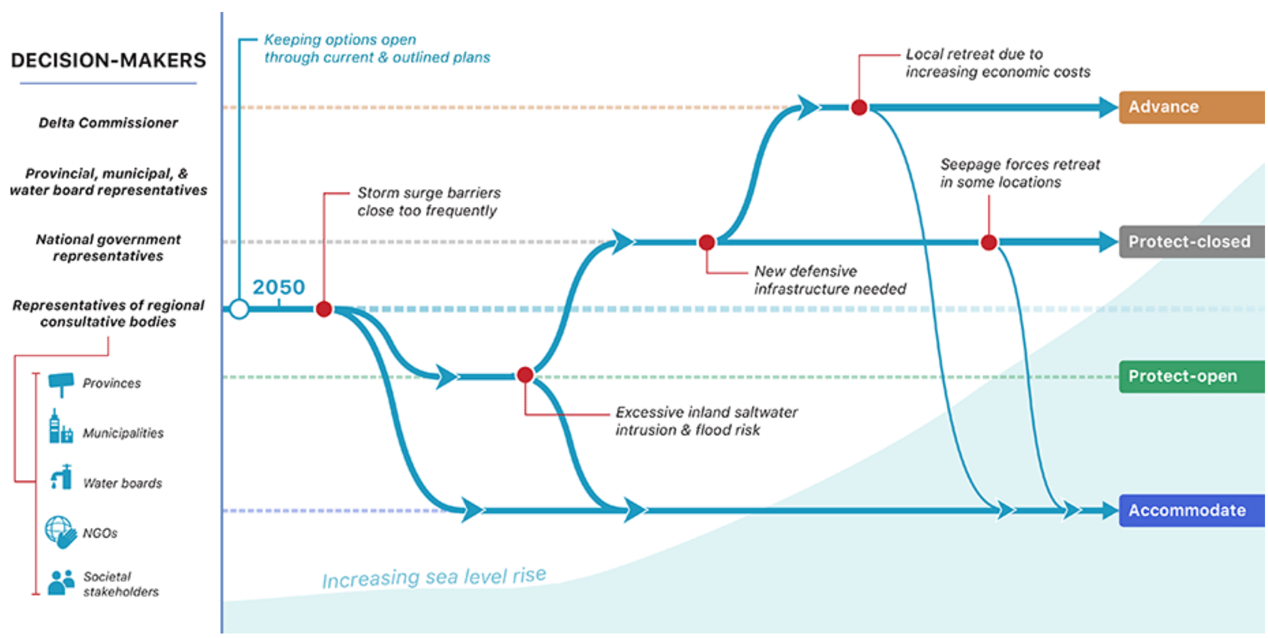

Figure 4. Adaptive Delta Management through Dynamic Adaptive Policy Pathways. The Dutch Delta Program Steering Committee is an organized decision-making collaboration among the national government, different local and regional government levels, and regional consultative bodies. The Delta Program creates substantiated plans on a 6-year cycle, aiming to keep options open for the longer term. Building from these plans, after 2050, the country will be required to adjust its strategy when the system encounters tipping points (red dots), depending on the level and rate of sea level rise. Four adaptation pathways have been sketched for the longer future (Haasnoot et al., 2019). Protecting the coast while allowing an open connection between the rivers and the North Sea (protect-open) will be the first to fail at significant sea level rise. Completely closing off the rivers and estuaries from the North Sea will be able to handle more sea level rise but with significant economic and ecological impacts. The two other alternatives are to create new land in the North Sea that will form a new coast or to accommodate rising sea levels by adjusting land use and creating more room for water.

The Adaptive Delta Management approach has been spearheaded nationwide. However, much of the implementation of the Delta Program takes place regionally. In each of seven regions, there is close collaboration among the national government, water boards, provinces, municipal governments, and other societal stakeholders such as for agriculture, shipping, environmental protection, recreation, and residents (Delta Commissioner, n.d.). These regional committees focus on local applications of the Adaptive Delta Management approach—for example, with respect to managing the water level in Lake IJsselmeer (Zandvoort et al., 2017) or protecting the cities of Rotterdam and Dordrecht from flooding (Gersonius et al., 2016; Zandvoort et al., 2017). Stakeholders have considered shared ownership, coherence (across regions, interlinked issues, and temporal scales), and adaptivity among the most important qualities of the Adaptive Delta Management approach (Bloemen et al., 2018).

Policy Revisions

In many policy processes, a project cannot move forward without passing a cost–benefit analysis, and some have argued the weight provided to monetized property values in these analyses systematically deprives low-wealth communities, as well as communities with marginalized racialized groups, of flood protection (Becker et al., 2021; Junod et al., 2021). As a result, some have argued for deeper use of criteria beyond simple cost–benefit analysis, as well as more flexible cost–benefit analysis, to determine project eligibility and prioritization, and to expand funding opportunities for local sponsors in need (Greer et al., 2022; Junod et al., 2021). In the Netherlands, for example, costs–benefits and social protection (e.g., based on minimum safety standards, societal disruption from flooding, and protection of critical infrastructure) have been analyzed separately, followed by standard-setting based on the higher requirement of the two (England & Knox, 2015). As another example, multiple studies have demonstrated the importance of including aggregated and disaggregated measures of equity performance (e.g., via Gini coefficients and spatial inequality patterns) to evaluate adaptive measures, in addition to more common measures of economic losses, benefits, and output (Jafino et al., 2021; Markhvida et al., 2020). Means-tested assistance for flood insurance or flood risk reduction measures could also increase affordability concerns across residents (Kousky et al., 2020).

In addition, some policy options have historically been underutilized despite their potential benefits. For example, land acquisition can result in avoided damages exceeding acquisition costs by ratios as great as 5 to 1 (Brody & Highfield, 2013; Johnson et al., 2020). Large-scale protection of lands that naturally store waters (e.g., riverbank wetlands) may have benefits outweighing costs only under certain conditions, such as for large areas of land under development pressure with flood-exposed settlements downstream and low land costs (Kousky, 2015). Other mechanisms of land conservation, such as easements, zoning, or other land use policies, may carry lower implementation costs, and estimated benefits may increase with consideration of outcomes beyond damages to properties and economic efficiency. Where floodplains are not mapped until development occurs, however, the value of open space preservation may be overlooked (ASFPM, 2020).

Intensifying, multidimensional flood risks also pose challenges for the long-term viability of risk financing systems. Across country contexts, risk financing systems relevant to potential flood losses differ. Different approaches in Europe, for example, include largely private insurance systems as in the United Kingdom, public–private partnerships as in France, and fully public compensation schemes as in the Netherlands (Jongman et al., 2014; Surminski, 2018). In light of continuing accumulation of people and assets in flood-prone areas, a number of policy reforms have been suggested for flood insurance (Kousky et al., 2020; Surminski, 2018). They include all-hazards insurance policies to provide more reliable and efficient financial protection to households, expanded mandatory purchase requirements, better and earlier communication of flood risks in housing searches, and increased public–private partnerships and community investments in flood resilience. Currently in the United States, the pricing of National Flood Insurance Policy premiums is being adjusted to reflect more types of flooding, more granular estimations of risk based on the location and types of structures, and flood-mitigation measures taken at household and community scales (Federal Emergency Management Agency [FEMA], 2021b; Kousky et al., 2016).

Moving toward actuarially sound flood insurance that is equitable involves reform of the risk-management policies themselves as well as deep, complementary public policy addressing equity. Historic and current structural, systematic injustices (e.g., linked to racism in housing markets or disaster aid) challenge revisions across both categories (i.e., risk management and equity), and within the political economies of decision-making, it is not clear that adaptive insurance will easily emerge. Market strategies in inequitable societies and systems have potential to make flood risks, damages, and losses—and their inequitable distribution across communities—worse, not better.

Emerging examples across country contexts demonstrate that flood adaptation can range from intensive, extended processes, such as for multi-stakeholder dynamic adaptive management, to simple precautionary approaches, such as elevation standards applying inside and outside floodplains, erring on the side of safety. Many of these changes illustrate a larger reframing away from disaster management and toward adaptation in response to changes across both extreme and average conditions.

Conclusion

Much of flood risk management to date has disproportionally focused on static assumptions and characterizations of risk, assets and financial impacts rather than the full well-being of people, and stressors at the extremes rather than stressors from everyday conditions. Flood management is broadening from its historical narrow focus on economic development and disaster risk reduction to a more holistic focus on human and ecological well-being and social justice, in light of flood risks that will continue to evolve. Although there are examples of flood control not adding up to adaptive flood risk management at present, there are also emerging examples of reforms, processes, and tools for more transformative flood risk adaptation in the future. As perhaps the greatest challenge of this evolution, the goals of flood adaptation moving forward, as well as the flood risks themselves, will continue to change and to be socially negotiated. This broadening creates opportunities for flood management to contribute to policies addressing social justice, if flood management decisions are made in equitable ways. The fundamental shifts from the historic silos of flood control to the distributed decision-making of flood adaptation raise new questions and opportunities for governance and science alike. These challenges of flood risk management can be addressed by integrating lessons from diverse domains of actionable science and public policy. Where innovations occur, they will likely support adaptation to flooding as well as many other stressors and threats.

Acknowledgments

We thank Elena S. Hartley for graphical illustration. The University of Miami Rosenstiel School of Marine, Atmospheric, and Earth Science and Leonard and Jayne Abess Center for Ecosystem Science and Policy provided funding for this work. K. J. M., M. H., and A. R. S. acknowledge the support of the National Science Foundation (award Nos. 2034308, 2033929, and 2034239). A. R. S. acknowledges support from the University of Delaware Research Foundation.

Further Reading

Bullard, R. D., & Wright, B. (2012). *The wrong complexion for protection: How the government response to disaster endangers African American communities*. New York University Press.

Glavovic, B., Dawson, R., Chow, W., Haasnoot, M., Singh, C., Garschagen, M., & Thomas, A. (2022). Cities and settlements by the sea. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *AR6 climate change 2022: Impacts, adaptation and vulnerability. The Working Group II contribution to the sixth assessment report of the intergovernmental panel on climate change* (pp. 2163–2194). Cambridge University Press.

Haasnoot, M., Kwadijk, J., van Alphen, J., Le Bars, D., van den Hurk, B., Diermanse, F., van der Spek, A., Essink, G. O., Delsman, J., & Mens, M. (2020). Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands *<https://doi.org/10.1088/1748-9326/ab666c>*. *Environmental Research Letters*, *15*(3), 034007.

Kousky, C., Kunreuther, H., LaCour-Little, M., & Wachter, S. (2020). Flood risk and the U.S. housing market *<https://doi.org/10.1080/10527001.2020.1836915>*. *Journal of Housing Research*, *29*(Suppl. 1), S3–S24.

Marchau, V. A. W. J., Walker, W. E., Bloemen, P. J. T. M., & Popper, S. W. (Eds.). (2019). *Decision making under deep uncertainty: From theory to practice* *<https://doi.org/10.1007/978-3-030-05252-2>*. Springer.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? <https://doi.org/10.1126/science.1151915> *Science*, *319*(5863), 573–574.

Sanders, B. F., Schubert, J. E., Goodrich, K. A., Houston, D., Feldman, D. L., Basolo, V., Luke, A., Bondreau, D., Karlin, B., Cheung, W., Contreras, S., Reyes, A., Equiarte, A., Serrano, K., Allaire, M., Moftakhari, H., AghaKouchak, A., & Matthew, R. A. (2020). Collaborative modeling with fine-resolution data enhances flood awareness, minimizes differences in flood perception, and produces actionable flood maps. *Earth's Future*, *8*(1), e2019EF001391.

Shi, L. (2020). From progressive cities to resilient cities: Lessons from history for new debates in equitable adaptation to climate change <https://doi.org/10.1177/1078087419910827>. *Urban Affairs Review*, *57*(5), 1442–1479.

Shi, L., Ahmad, S., Shukla, P., & Yupho, S. (2021). Shared injustice, splintered solidarity: Water governance across urban–rural divides <https://doi.org/10.1016/j.gloenvcha.2021.102354>. *Global Environmental Change*, *70*, 102354.

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., van Aalst, M., . . . Trisos, C. H. (2021). A framework for complex climate change risk assessment <https://doi.org/10.1016/j.oneear.2021.03.005>. *One Earth*, *4*(4), 489–501.

Tellman, B., Sullivan, J. A., Kuhn, C., Kettner, A. J., Doyle, C. S., Brakenridge, G. R., Erickson, T. A., & Slayback, D. A. (2021). Satellite imaging reveals increased proportion of population exposed to floods <https://doi.org/10.1038/s41586-021-03695-w>. *Nature*, *596*(7870), 80–86.

Wing, O. E. J., Lehman, W., Bates, P. D., Sampson, C. C., Quinn, N., Smith, A. M., Neal, J. C., Porter, J. R., & Kousky, C. (2022). Inequitable patterns of US flood risk in the Anthropocene <https://doi.org/10.1038/s41558-021-01265-6>. *Nature Climate Change*, *12*(2), 156–162.

References

Ajibade, I. (2019). Planned retreat in Global South megacities: Disentangling policy, practice, and environmental justice <https://doi.org/10.1007/s10584-019-02535-1>. *Climatic Change*, *157*(2), 299–317.

Albert, S., Bronen, R., Tooler, N., Leon, J., Yee, D., Ash, J., Boseto, D., & Grinham, A. (2018). Heading for the hills: Climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5°C future <https://doi.org/10.1007/s10113-017-1256-8>. *Regional Environmental Change*, *18*(8), 2261–2272.

American Society of Civil Engineers. (2021). *A comprehensive assessment of America's infrastructure: 2021 report card for America's infrastructure* <https://infrastructurereportcard.org/wp-content/uploads/2020/12/National_IRC_2021-report.pdf>.

American Society of Civil Engineers, Task Committee on Flood Safety Policies and Practices. (2014). *Flood risk management: Call for a national strategy* <https://doi.org/10.1061/9780784478585>.

Arnold, J. L. (1988). *The evolution of the 1936 Flood Control Act* <https://www.publications.usace.army.mil/Portals/76/Publications/EngineerPamphlets/EP_870-1-29.pdf> (Engineer Pamphlet No. 870–1–29). U.S. Army Corps of Engineers, Office of History.

Aschbrenner, J. (2016, October 10). Why Cedar Rapids' flooding plan will probably never get federal funding <https://www.desmoinesregister.com/story/news/2016/10/09/why-cedar-rapids-flooding-plan-probably-never-get-federal-funding/91269958/>. *Des Moines Register*.

Association of State Floodplain Managers. (2020). *Flood mapping for the nation: A cost analysis for completing and maintaining the nation's NFIP flood map inventory* <https://asfpm-library.s3-us-west-2.amazonaws.com/FSC/MapNation/ASFPM_MaptheNation_Report_2020.pdf>.

Auynirundronkool, K., Chen, N., Peng, C., Yang, C., Gong, J., & Silapathong, C. (2012). Flood detection and mapping of the Thailand central plain using RADARSAT and MODIS under a sensor web environment <https://doi.org/10.1016/j.jag.2011.09.017>. *International Journal of Applied Earth Observation and Geoinformation*, *14*(1), 245–255.

Bakkensen, L., & Barrage, L. (2017). Flood risk belief heterogeneity and coastal home price dynamics: Going under water? <https://doi.org/10.3386/w23854> [Working paper no. w23854]. National Bureau of Economic Research.

Barnett, J., Graham, S., Mortreux, C., Fincher, R., Waters, E., & Hurlimann, A. (2014). A local coastal adaptation pathway <https://doi.org/10.1038/nclimate2383>. *Nature Climate Change*, *4*(12), 1103–1108.

Barrage, L., & Furst, J. (2019). Housing investment, sea level rise, and climate change beliefs <https://doi.org/10.1016/j.econlet.2019.01.023>. *Economics Letters*, *177*, 105–108.

Barry, J. (1998). *Rising tide: The great Mississippi flood of 1927 and how it changed America* <https://www.simonandschuster.com/books/Rising-Tide/John-M-Barry/9780684840024>. Simon & Schuster.

Becker, E., Magos, C., Navabi, M., Neely, C., Ramirez, A., & Zumwalt, C. (2021). *Turning the tide: Advancing racial justice in federal flood infrastructure projects* <https://naacp.org/resources/turning-tide-advancing-racial-justice-federal-flood-infrastructure-projects>. Columbia University School of International and Public Affairs and NAACP Environmental and Climate Justice Program.

Billings, S. B., Gallagher, E. A., & Ricketts, L. (2021). Let the rich be flooded: The distribution of financial aid and distress after Hurricane Harvey <https://www.sciencedirect.com/science/article/abs/pii/S0304405X21005067>. *Journal of Financial Economics*, *48*, 1–23.

Bloemen, P., Reeder, T., Zevenbergen, C., Rijke, J., & Kingsborough, A. (2018). Lessons learned from applying adaptation pathways in flood risk management and challenges for the further development of this approach <https://doi.org/10.1007/s11027-017-9773-9>. *Mitigation and Adaptation Strategies for Global Change*, *23*(7), 1083–1108.

Bourget, L. (Ed.). (2011). *Converging waters: Integrating collaborative modeling with participatory processes to make water resources decisions*. IWR Press.

Brody, S., Kim, H., & Gunn, J. (2013). Examining the impacts of development patterns on flooding on the Gulf of Mexico coast <https://doi.org/10.1177/0042098012448551>. *Urban Studies*, *50*(4), 789–806.

Brody, S. D., & Highfield, W. E. (2013). Open space protection and flood mitigation: A national study <https://doi.org/10.1016/j.landusepol.2012.10.017>. *Land Use Policy*, *32*, 89–95.

Brody, S. D., Kang, J. E., & Bernhardt, S. (2010). Identifying factors influencing flood mitigation at the local level in Texas and Florida: The role of organizational capacity <https://doi.org/10.1007/s11069-009-9364-5>. *Natural Hazards*, *52*(1), 167–184.

Brody, S. D., Zahran, S., Highfield, W. E., Bernhardt, S. P., & Vedlitz, A. (2009). Policy learning for flood mitigation: A longitudinal assessment of the community rating system in Florida <https://doi.org/10.1111/j.1539-6924.2009.01210.x>. *Risk Analysis*, *29*(6), 912–929.

Brody, S. D., Zahran, S., Maghelal, P., Grover, H., & Highfield, W. E. (2007). The rising costs of floods: Examining the impact of planning and development decisions on property damage in Florida <https://doi.org/10.1080/01944360708977981>. *Journal of the American Planning Association*, *73*(3), 330–345.

Bullard, R. D., & Wright, B. (2012). *The wrong complexion for protection: How the government response to disaster endangers African American communities*. New York University Press.

Butler, W., Holmes, T., & Lange, Z. (2021). Mandated planning for climate change: Responding to the Peril of Flood Act for sea level rise adaptation in Florida <https://doi.org/10.1080/01944363.2020.1865188>. *Journal of the American Planning Association*, *87*(3), 370–382.

Butler, W. H., Deyle, R. E., & Mutnansky, C. (2016). Low-regrets incrementalism: Land use planning adaptation to accelerating sea level rise in Florida's coastal communities <https://doi.org/10.1177/0739456X16647161>. *Journal of Planning Education and Research*, *36*(3), 319–332.

Carter, N. T. (2012). *Federal involvement in flood response and flood infrastructure repair: Storm Sandy recovery* (p. 12). Congressional Research Service.

Ceola, S., Laio, F., & Montanari, A. (2014). Satellite nighttime lights reveal increasing human exposure to floods worldwide <https://doi.org/10.1002/2014GL061859>. *Geophysical Research Letters*, *41*(20), 7184–7190.

Chakraborty, J., Collins, T. W., & Grineski, S. E. (2019). Exploring the environmental justice implications of Hurricane Harvey flooding in Greater Houston, Texas <https://doi.org/10.2105/AJPH.2018.304846>. *American Journal of Public Health*, *109*(2), 244–250.

Chakraborty, J., Collins, T. W., Montgomery, M. C., & Grineski, S. E. (2014). Social and spatial inequities in exposure to flood risk in Miami, Florida <https://doi.org/10.1061/(ASCE)NH.1527-6996.0000140>. *Natural Hazards Review*, *15*(3), 04014006.

Cheung, W., Houston, D., Schubert, J. E., Basolo, V., Feldman, D., Matthew, R., Sanders, B. F., Karlin, B., Goodrich, K. A., Contreras, S. L., & Luke, A. (2016). Integrating resident digital sketch maps with expert knowledge to assess spatial knowledge of flood risk: A case study of participatory mapping in Newport Beach, California <https://doi.org/10.1016/j.apgeog.2016.07.006>. *Applied Geography*, *74*, 56–64.

Chung, E.-S., Soden, B., Sohn, B. J., & Shi, L. (2014). Upper-tropospheric moistening in response to anthropogenic warming <https://doi.org/10.1073/pnas.1409659111>. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(32), 11636–11641.

Climate Central. (2020). *Surging seas: Sea level rise analysis by Climate Central* <https://sealevel.climatecentral.org/>.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Jr., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J., & Wehner, M. (2013). Long-term climate change: Projections, commitments and irreversibility. In T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 1029–1136). Cambridge University Press.

Cooper, J. A. G., & McKenna, J. (2008). Social justice in coastal erosion management: The temporal and spatial dimensions <https://doi.org/10.1016/j.geoforum.2007.06.007>. *Geoforum*, *39*(1), 294–306.

Covi, M. P., Brewer, J. F., & Kain, D. J. (2021). Sea level rise hazardscapes of North Carolina: Perceptions of risk and prospects for policy <https://doi.org/10.1016/j.ocecoaman.2021.105809>. *Ocean & Coastal Management*, *212*, 105809.

Crabbé, A., Wiering, M., & Liefferink, D. (2015). Adapting flood management to climate change: Comparing policy frames and governance practices in the low countries <https://doi.org/10.2166/wcc.2014.018>. *Journal of Water and Climate Change*, *6*(1), 55–70.

Cutter, S. L., & Finch, C. (2008). Temporal and spatial changes in social vulnerability to natural hazards <https://doi.org/10.1073/pnas.0710375105>. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(7), 2301–2306.

Delta Commissioner. (n.d.). *Organisation of the delta programme* <https://english.deltaprogramma.nl/delta-programme/organisation-of-the-delta-programme>.

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Salinas, J. L., & Blöschl, G. (2013). Socio-hydrology: Conceptualising human–flood interactions <https://doi.org/10.5194/hess-17-3295-2013>. *Hydrology and Earth System Sciences*, *17*(8), 3295–3303.

Doberstein, B., Fitzgibbons, J., & Mitchell, C. (2019). Protect, accommodate, retreat or avoid (PARA): Canadian community options for flood disaster risk reduction and flood resilience <https://doi.org/10.1007/s11069-018-3529-z>. *Natural Hazards*, *98*(1), 31–50.

Domingue, S. J., & Emrich, C. T. (2019). Social vulnerability and procedural equity: Exploring the distribution of disaster aid across counties in the United States <https://doi.org/10.1177/0275074019856122>. *American Review of Public Administration*, *49*(8), 897–913.

Dyckman, C. S., St. John, C., & London, J. B. (2014). Realizing managed retreat and innovation in state-level coastal management planning <https://doi.org/10.1016/j.ocecoaman.2014.09.010>. *Ocean & Coastal Management*, *102*, 212–223.

Elsner, J. B., Kossin, J. P., & Jagger, T. H. (2008). The increasing intensity of the strongest tropical cyclones <https://doi.org/10.1038/nature07234>. *Nature*, *455*(7209), 92–95.

England, K., & Knox, K. (2015). *Targeting flood investment and policy to minimise flood disadvantage* <https://www.jrf.org.uk/report/targeting-flood-investment-and-policy-minimise-flood-disadvantage>. Joseph Rowntree Foundation.

Evers, M., Jonoski, A., Maksimovič, Č., Lange, L., Ochoa Rodriguez, S., Teklesadik, A., Cortes Arevalo, J., Almoradie, A., Eduardo Simoes, N., Wang, L., & Makropoulos, C. (2012). Collaborative modelling for active involvement of stakeholders in urban flood risk management <https://doi.org/10.5194/nhess-12-2821-2012>. *Natural Hazards and Earth System Sciences*, *12*(9), 2821–2842.

Federal Emergency Management Agency. (2020). *FEMA flood map service center* <https://msc.fema.gov/portal/home>.

Federal Emergency Management Agency. (2021a). *Flood insurance* <https://www.fema.gov/flood-insurance>.

Federal Emergency Management Agency. (2021b). *Risk rating 2.0: Equity in action* <https://www.fema.gov/flood-insurance/risk-rating>.

First Street Foundation. (2022). *Flood factor* <https://firststreet.org/flood-factor>.

Fleming, E., Payne, J., Sweet, W., Craghan, M., Haines, J., Hart, J. F., Stiller, H., & Sutton-Grier, A. (2018). Coastal effects: Impacts, risks, and adaptation in the United States. In *Fourth national climate assessment* (Vol. 2, pp. 322–352). U.S. Global Change Research Program.

Fu, X. (2020). Measuring local sea-level rise adaptation and adaptive capacity: A national survey in the United States <https://doi.org/10.1016/j.cities.2020.102717>. *Cities*, *102*, 102717.

Gain, A. K., Mondal, M. S., & Rahman, R. (2017). From flood control to water management: A journey of Bangladesh towards integrated water resources management <https://doi.org/10.3390/w9010055>. *Water*, *9*(1), 55.

Gersonius, B., Rijke, J., Ashley, R., Bloemen, P., Kelder, E., & Zevenbergen, C. (2016). Adaptive Delta Management for flood risk and resilience in Dordrecht, The Netherlands <https://doi.org/10.1007/s11069-015-2015-0>. *Natural Hazards*, *82*(S2), 201–216.

Glavovic, B., Dawson, R., Chow, W., Haasnoot, M., Singh, C., Garschagen, M., & Thomas, A. (2022). Cities and settlements by the sea. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *AR6 climate change 2022: Impacts, adaptation and vulnerability. The Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Goldberg, M. H., Gustafson, A., & van der Linden, S. (2020). Leveraging social science to generate lasting engagement with climate change solutions <https://doi.org/10.1016/j.oneear.2020.08.011>. *One Earth*, *3*(3), 314–324.

Golnaraghi, M., Surminksi, S., & Kousky, C. (2020). *Building flood resilience in a changing climate: Insights from the United States, England and Germany*. Geneva Association.

Goodrich, K. A., Basolo, V., Feldman, D. L., Matthew, R. A., Schubert, J. E., Luke, A., Eguiarte, A., Boudreau, D., Serrano, K., Reyes, A. S., Contreras, S., Houston, D., Cheung, W., AghaKouchak, A., & Sanders, B. F. (2020). Addressing pluvial flash flooding through community-based collaborative research in Tijuana, Mexico <https://doi.org/10.3390/w12051257>. *Water*, *12*(5), 1257.

Gopalakrishnan, S., McNamara, D., Smith, M. D., & Murray, A. B. (2017). Decentralized management hinders coastal climate adaptation: The spatial-dynamics of beach nourishment <https://doi.org/10.1007/s10640-016-0004-8>. *Environmental and Resource Economics*, *67*(4), 761–787.

Grannis, J. (2011). *Adaptation Tool Kit: Sea-level rise and coastal land use* <https://www.georgetownclimate.org/files/report/Adaptation_Tool_Kit_SLR.pdf>. Georgetown Climate Center.

Greer, A., Brokopp Binder, S., & Zavar, E. (2022). From hazard mitigation to climate adaptation: A review of home buyout program literature <https://doi.org/10.1080/10511482.2021.1931930>. *Housing Policy Debate*, *32*(1), 152–170.

Griggs, G. B., Tait, J. F., & Corona, W. (1994). The interaction of seawalls and beaches: Seven years of monitoring, Monterey Bay, California. *Shore and Beach*, *62*(3), 21–28.

Grove, K., Cox, S., & Barnett, A. (2020). Racializing resilience: Assemblage, critique, and contested futures in Greater Miami resilience planning <https://doi.org/10.1080/24694452.2020.1715778>. *Annals of the American Association of Geographers*, *110*(5), 1613–1630.

Haasnoot, M., Diermanse, F., Kwadijk, J., de Winter, R., & Winter, G. (2019). *Strategieën voor adaptatie aan hoge en versnelde zeespiegelstijging: Een verkenning* (Strategies for adaptation to high and accelerated sea-level rise: An exploration) <https://publications.deltares.nl/11203724_004.pdf>. Deltares.

Haasnoot, M., Kwadijk, J., van Alphen, J., Le Bars, D., van den Hurk, B., Diermanse, F., van der Spek, A., Essink, G. O., Delsman, J., & Mens, M. (2020). Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands <https://doi.org/10.1088/1748-9326/ab666c>. *Environmental Research Letters*, *15*(3), 034007.

Haer, T., Botzen, W. J. W., de Moel, H., & Aerts, J. C. J. H. (2017). Integrating household risk mitigation behavior in flood risk analysis: An agent-based model approach <https://doi.org/10.1111/risa.12740>. *Risk Analysis*, *37*(10), 1977–1992.

Hauer, M. E., Hardy, D., Kulp, S. A., Mueller, V., Wrathall, D. J., & Clark, P. U. (2021). Assessing population exposure to coastal flooding due to sea level rise <https://doi.org/10.1038/s41467-021-27260-1>. *Nature Communications*, *12*(1), 6900.

Hemmati, M., Mahmoud, H. N., Ellingwood, B. R., & Crooks, A. T. (2021). Unraveling the complexity of human behavior and urbanization on community vulnerability to floods <https://doi.org/10.1038/s41598-021-99587-0>. *Scientific Reports*, *11*(1), 20085.

Highfield, W. E., Brody, S. D., & Blessing, R. (2014). Measuring the impact of mitigation activities on flood loss reduction at the parcel level: The case of the Clear Creek Watershed on the upper Texas coast <https://doi.org/10.1007/s11069-014-1209-1>. *Natural Hazards*, *74*(2), 687–704.

Hino, M., Belanger, S. T., Field, C. B., Davies, A. R., & Mach, K. J. (2019). High-tide flooding disrupts local economic activity <https://doi.org/10.1126/sciadv.aau2736>. *Science Advances*, *5*(2), eaau2736.

Hino, M., & Burke, M. (2021). The effect of information about climate risk on property values <https://doi.org/10.1073/pnas.2003374118>. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(17), e2003374118.

Horn, D. P., & Webel, B. (2021). *Introduction to the National Flood Insurance Program (NFIP)* <https://sgp.fas.org/crs/homesec/R44593.pdf> [CRS Report for Congress R44593]. Congressional Research Service.

Hornbeck, R., & Naidu, S. (2014). When the levee breaks: Black migration and economic development in the American South <https://doi.org/10.1257/aer.104.3.963>. *American Economic Review*, *104*(3), 963–990.

Houston, D., Cheung, W., Basolo, V., Feldman, D., Matthew, R., Sanders, B. F., Karlin, B., Schubert, J. E., Goodrich, K. A., Contreras, S. & Luke, A. (2019). The influence of hazard maps and trust of flood controls on coastal flood spatial awareness and risk perception <https://doi.org/10.1177/0013916517748711>. *Environment and Behavior*, *51*(4), 347–375.

Hummel, M. A., Griffin, R., Arkema, K., & Guerry, A. D. (2021). Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks <https://doi.org/10.1073/pnas.2025961118>. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(29), e2025961118.

Jafino, B. A., Kwakkel, J. H., Klijn, F., Dung, N. V., van Delden, H., Haasnoot, M., & Sutanudjaja, E. H. (2021). Accounting for multisectoral dynamics in supporting equitable adaptation planning: A case study on the rice agriculture in the Vietnam Mekong Delta <https://doi.org/10.1029/2020EF001939>. *Earth's Future*, *9*(5), e2020EF001939.

Johnson, K. A., Wing, O. E. J., Bates, P. D., Fargione, J., Kroeger, T., Larson, W. D., Sampson, C. C., & Smith, A. M. (2020). A benefit–cost analysis of floodplain land acquisition for US flood damage reduction <https://doi.org/10.1038/s41893-019-0437-5>. *Nature Sustainability*, *3*(1), 56–62.

Jongman, B., Koks, E. E., Husby, T. G., & Ward, P. J. (2014). Increasing flood exposure in the Netherlands: Implications for risk financing <https://doi.org/10.5194/nhess-14-1245-2014>. *Natural Hazards and Earth System Sciences*, *14*(5), 1245–1255.

Jorissen, R., Kraaij, E., & Tromp, E. (2016). Dutch flood protection policy and measures based on risk assessment <https://doi.org/10.1051/e3sconf/20160720016>. *E3S Web of Conferences*, *7*, 20016.

Junod, A. N., Martín, C., Marx, R., & Rogin, A. (2021). *Equitable investments in resilience: A review of benefit–cost analysis in federal flood mitigation infrastructure* <https://www.urban.org/sites/default/files/publication/104302/equitable-investments-in-resilience.pdf>. Urban Institute.

Kates, R. W., Colten, C. E., Laska, S., & Leatherman, S. P. (2006). Reconstruction of New Orleans after Hurricane Katrina: A research perspective <https://doi.org/10.1073/pnas.0605726103>. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(40), 14653–14660.

Keenan, J. M., & Bradt, J. T. (2020). Underwaterwriting: From theory to empiricism in regional mortgage markets in the U.S. *Climatic Change*, *162*(4), 2043–2067.

Keys, B., & Mulder, P. (2020). Neglected no more: Housing markets, mortgage lending, and sea level rise <https://doi.org/10.3386/w27930> (Working paper no. w27930). National Bureau of Economic Research.

Khajehei, S., Ahmadalipour, A., Shao, W., & Moradkhani, H. (2020). A place-based assessment of flash flood hazard and vulnerability in the contiguous United States <https://doi.org/10.1038/s41598-019-57349-z>. *Scientific Reports*, *10*(1), 448.

Kocornik-Mina, A., McDermott, T. K. J., Michaels, G., & Rauch, F. (2020). Flooded cities <https://doi.org/10.1257/app.20170066>. *American Economic Journal: Applied Economics*, *12*(2), 35–66.

Kousky, C. (2015). A historical examination of the Corps of Engineers and natural valley storage protection: The economics and politics of “green” flood control <https://doi.org/10.1080/19390459.2014.963372>. *Journal of Natural Resources Policy Research*, *7*(1), 23–40.

Kousky, C., Kunreuther, H., LaCour-Little, M., & Wachter, S. (2020). Flood risk and the U.S. housing market <https://doi.org/10.1080/10527001.2020.1836915>. *Journal of Housing Research*, *29*(Suppl. 1), S3–S24.

Kousky, C., Lingle, B., & Shabman, L. (2016). *NFIP premiums for single-family residential properties: Today and tomorrow* <https://www.rff.org/publications/issue-briefs/nfip-premiums-for-single-family-residential-properties-today-and-tomorrow/>. Resources for the Future.

Kousky, C., Ritchie, L., Tierney, K., & Lingle, B. (2019). Return on investment analysis and its applicability to community disaster preparedness activities: Calculating costs and returns <https://doi.org/10.1016/j.ijdrr.2019.101296>. *International Journal of Disaster Risk Reduction*, *41*, 101296.

Kummu, M., de Moel, H., Ward, P. J., & Varis, O. (2011). How close do we live to water? A global analysis of population distance to freshwater bodies <https://doi.org/10.1371/journal.pone.0020578>. *PLOS ONE*, *6*(6), e20578.

Lawrence, J., & Haasnoot, M. (2017). What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty <https://doi.org/10.1016/j.envsci.2016.12.003>. *Environmental Science & Policy*, *68*, 47–57.

Lebel, L., Sinh, B. T., Garden, P., Seng, S., Tuan, L. A., & Van Truc, D. (2009). The promise of flood protection: Dikes and dams, drains and diversions. In F. Molle, T. Foran, & M. Kakonen (Eds.), *Contested waterscapes in the Mekong Region: Hydropower, livelihoods and governance* (pp. 283–305). Earthscan.

Lempert, R., Kalra, N., Peyraud, S., Mao, Z., Tan, S. B., Cira, D., & Lotsch, A. (2013). *Ensuring robust flood risk management in Ho Chi Minh City* <https://papers.ssrn.com/abstract=2271955> (World Bank Policy Research working paper no. 6465, pp. 283–306). The World Bank.

Li, J., & Landry, C. E. (2017). Flood risk, local hazard mitigation, and the community rating system of NFIP <https://doi.org/10.2139/ssrn.2516525> (SSRN scholarly paper no. ID 2516525). Social Science Research Network.

Li, Z., Chen, M., Gao, S., Gourley, J. J., Yang, T., Shen, X., Kolar, R., & Hong, Y. (2021). A multi-source 120-year U.S. flood database with a unified commonformat and public access <https://doi.org/10.5194/essd-2021-36>. *Earth System Science Data*, *13*(8), 3755–3766.

Luke, A., Sanders, B. F., Goodrich, K. A., Feldman, D. L., Boudreau, D., Eguiarte, A., Serrano, K., Reyes, A., Schubert, J. E., AghaKouchak, A., Basolo, V., & Matthew, R. A. (2018). Going beyond the flood insurance rate map: Insights from flood hazard map co-production <https://doi.org/10.5194/nhess-18-1097-2018>. *Natural Hazards and Earth System Sciences*, *18*(4), 1097–1120.

Lyles, L. W., Berke, P., & Smith, G. (2013). Do planners matter? Examining factors driving incorporation of land use approaches into hazard mitigation plans <https://doi.org/10.1080/09640568.2013.768973>. *Journal of Environmental Planning and Management*, *57*(5), 792–811.

Mach, K. J., & Siders, A. R. (2021). Reframing strategic, managed retreat for transformative climate adaptation <https://doi.org/10.1126/science.abh1894>. *Science*, *372*(6548), 1294–1299.

Marchau, V. A. W. J., Walker, W. E., Bloemen, P. J. T. M., & Popper, S. W. (Eds.). (2019). *Decision making under deep uncertainty: From theory to practice* <https://doi.org/10.1007/978-3-030-05252-2>. Springer.

Markhvida, M., Walsh, B., Hallegatte, S., & Baker, J. (2020). Quantification of disaster impacts through household well-being losses <https://doi.org/10.1038/s41893-020-0508-7>. *Nature Sustainability*, *3*(7), 538–547.

Maskrey, A., Jain, G., & Lavell, A. (2021). *Social construction of systemic risk: Towards an actionable framework for risk governance* <https://www.undp.org/publications/undp-social-construction-systemic-risk-towards-actionable-framework-risk-governance> [Discussion paper]. United Nations Development Programme.

Maskrey, S. A., Mount, N. J., Thorne, C. R., & Dryden, I. (2016). Participatory modelling for stakeholder involvement in the development of flood risk management intervention options <https://doi.org/10.1016/j.envsoft.2016.04.027>. *Environmental Modelling & Software*, *82*, 275–294.

Masozera, M., Bailey, M., & Kerchner, C. (2007). Distribution of impacts of natural disasters across income groups: A case study of New Orleans <https://doi.org/10.1016/j.ecolecon.2006.06.013>. *Ecological Economics*, *63*(2–3), 299–306.

McNamara, D. E., Gopalakrishnan, S., Smith, M. D., & Murray, A. B. (2015). Climate adaptation and policy-induced inflation of coastal property value <https://doi.org/10.1371/journal.pone.0121278>. *PLOS ONE*, *10*(3), e0121278.

Mees, H. L. P., Driessen, P. P. J., & Runhaar, H. A. C. (2014). Legitimate adaptive flood risk governance beyond the dikes: The cases of Hamburg, Helsinki and Rotterdam <https://doi.org/10.1007/s10113-013-0527-2>. *Regional Environmental Change*, *14*(2), 671–682.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? <https://doi.org/10.1126/science.1151915> *Science*, *319*(5863), 573–574.

Moftakhari, H. R., Salvadori, G., AghaKouchak, A., Sanders, B. F., & Matthew, R. A. (2017). Compounding effects of sea level rise and fluvial flooding <https://doi.org/10.1073/pnas.1620325114>. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(37), 9785–9790.

Molinaroli, E., Guerzoni, S., & Suman, D. (2019). Do the adaptations of Venice and Miami to sea level rise offer lessons for other vulnerable coastal cities? *<https://doi.org/10.1007/s00267-019-01198-z>* *Environmental Management*, *64*(4), 391–415.

Montz, B., & Gruntfest, E. C. (1986). Changes in American urban floodplain occupancy since 1958: The experiences of nine cities *<https://doi.org/10.1016/0143-6228(86)90034-2>*. *Applied Geography*, *6*(4), 325–338.

Mutahara, M., Warner, J. F., Wals, A. E. J., Khan, M. S. A., & Wester, P. (2018). Social learning for adaptive delta management: Tidal river management in the Bangladesh Delta *<https://doi.org/10.1080/07900627.2017.1326880>*. *International Journal of Water Resources Development*, *34*(6), 923–943.

National Oceanic and Atmospheric Administration. (2020). *Sea level rise viewer v 3.0.0* *<https://coast.noaa.gov/slr/>*.

National Oceanic and Atmospheric Administration, National Centers for Environmental Information. (2021). *U.S. billion-dollar weather and climate disasters* *<https://www.ncdc.noaa.gov/billions/>*.

Odemerho, F. O. (2015). Building climate change resilience through bottom-up adaptation to flood risk in Warri, Nigeria *<https://doi.org/10.1177/0956247814558194>*. *Environment and Urbanization*, *27*(1), 139–160.

Onda, K., Branham, J., BenDor, T. K., Kaza, N., & Salvesen, D. (2020). Does removal of federal subsidies discourage urban development? An evaluation of the US Coastal Barrier Resources Act *<https://doi.org/10.1371/journal.pone.0233888>*. *PLOS ONE*, *15*(6), e0233888.

Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R. M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., & Sebesvari, Z. (2019). Sea level rise and implications for low-lying islands, coasts and communities *<https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/08_SROCC_Ch04_FINAL.pdf>*. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (pp. 321–446). Intergovernmental Panel on Climate Change.

Palm, R., & Bolsen, T. (2020). Results from South Florida experiment *<https://doi.org/10.1007/978-3-030-32602-9_6>*. In R. Palm & T. Bolsen (Eds.), *Climate change and sea level rise in South Florida: The view of coastal residents* (pp. 81–92). Springer.

Parkinson, R. W. (2021). Speculation on the role of sea-level rise in the tragic collapse of the Surfside condominium (Miami Beach, Florida, U.S.A.) was a bellwether moment for coastal zone management practitioners *<https://doi.org/10.1016/j.ocecoaman.2021.105968>*. *Ocean & Coastal Management*, *215*, 105968.

Pilkey, O. H., & Wright, H. L., III. (1988). Seawalls versus beaches. *Journal of Coastal Research*, (Special issue 4), 41–64.

Pinter, N., Huthoff, F., Dierauer, J., Remo, J. W. F., & Damptz, A. (2016). Modeling residual flood risk behind levees, Upper Mississippi River, USA *<https://doi.org/10.1016/j.envsci.2016.01.003>*. *Environmental Science & Policy*, *58*, 131–140.

Pinto, P., Kondolf, G. M., & Wong, P. (2018). *Adapting to sea level rise: Emerging governance issues in the San Francisco Bay Region* *<https://doi.org/10.31230/osf.io/mjkcu>*.

Qiu, Y., & Gopalakrishnan, S. (2018). *Shoreline defense against climate change and capitalized impact of beach nourishment* *<https://doi.org/10.2139/ssrn.3117979>*. SSRN.

Ranger, N., Reeder, T., & Lowe, J. (2013). Addressing “deep” uncertainty over long-term climate in major infrastructure projects: Four innovations of the Thames Estuary 2100 Project <https://doi.org/10.1007/s40070-013-0014-5>. *EURO Journal on Decision Processes*, *1*(3), 233–262.

Reuss, M. (1985). Andrew A. Humphreys and the development of hydraulic engineering: Politics and technology in the Army Corps of Engineers, 1850–1950 <https://doi.org/10.2307/3104527>. *Technology and Culture*, *26*(1), 1–33.

Sanders, B. F., Schubert, J. E., Goodrich, K. A., Houston, D., Feldman, D. L., Basolo, V., Luke, A., Bondreau, D., Karlin, B., Cheung, W., Contreras, S., Reyes, A., Equiarte, A., Serrano, K., Allaire, M., Moftakhari, H., AghaKouchak, A., & Matthew, R. A. (2020). Collaborative modeling with fine-resolution data enhances flood awareness, minimizes differences in flood perception, and produces actionable flood maps <https://doi.org/10.1029/2019EF001391>. *Earth’s Future*, *8*(1), e2019EF001391.

Shi, L. (2020). From progressive cities to resilient cities: Lessons from history for new debates in equitable adaptation to climate change <https://doi.org/10.1177/1078087419910827>. *Urban Affairs Review*, *57*(5), 1442–1479.

Shi, L., Ahmad, S., Shukla, P., & Yupho, S. (2021). Shared injustice, splintered solidarity: Water governance across urban-rural divides <https://doi.org/10.1016/j.gloenvcha.2021.102354>. *Global Environmental Change*, *70*, 102354.

Siders, A., & Keenan, J. (2020). Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina <https://www.sciencedirect.com/science/article/pii/S0964569119305836>. *Ocean & Coastal Management*, *183*, 105023.

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O’Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., van Aalst, M., . . . Trisos, C. H. (2021). A framework for complex climate change risk assessment <https://doi.org/10.1016/j.oneear.2021.03.005>. *One Earth*, *4*(4), 489–501.

Smiley, K. T. (2020). Social inequalities in flooding inside and outside of floodplains during Hurricane Harvey <https://doi.org/10.1088/1748-9326/aba0fe>. *Environmental Research Letters*, *15*(9), 0940b3.

Spidalieri, K. (2020). Where the wetlands are—And where they are going: Legal and policy tools for facilitating coastal ecosystem migration in response to sea-level rise <https://doi.org/10.1007/s13157-020-01280-x>. *Wetlands*, *40*(6), 1765–1776.

Strader, S. M., & Ashley, W. S. (2015). The expanding bull’s-eye effect <https://doi.org/10.1080/00431672.2015.1067108>. *Weatherwise*, *68*(5), 23–29.

Sun, F., & Carson, R. T. (2020). Coastal wetlands reduce property damage during tropical cyclones <https://doi.org/10.1073/pnas.1915169117>. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(11), 5719–5725.

Surminski, S. (2018). Fit for purpose and fit for the future? An evaluation of the UK’s new flood reinsurance pool <https://doi.org/10.1111/rmir.12093>. *Risk Management and Insurance Review*, *21*(1), 33–72.

Swain, D. L., Wing, O. E. J., Bates, P. D., Done, J. M., Johnson, K. A., & Cameron, D. R. (2020). Increased flood exposure due to climate change and population growth in the United States <https://doi.org/10.1029/2020EF001778>. *Earth’s Future*, *8*(11), e2020EF001778.

Sweet, W., Simon, S., Dusek, G., Marcy, D., Brooks, W., Pendleton, M., & Marra, J. (2021). *2021 state of high tide flooding and annual* *outlook* *<https://tidesandcurrents.noaa.gov/publications/2021_State_of_High_Tide_Flooding_and_Annual_Outlook_Final.pdf>*. National Oceanic and Atmospheric Administration.

Tam, C. M., Tso, T. Y. N., & Lam, K. C. (1999). Feng shui and its impacts on land and property developments *<https://doi.org/10.1061/(ASCE)0733-9488(1999)125:4(152)>*. *Journal of Urban Planning and Development*, *125*(4), 152–163.

Tanoue, M., Taguchi, R., Alifu, H., & Hirabayashi, Y. (2021). Residual flood damage under intensive adaptation *<https://doi.org/10.1038/s41558-021-01158-8>*. *Nature Climate Change*, *11*(10), 823–826.

Tate, E., Strong, A., Kraus, T., & Xiong, H. (2016). Flood recovery and property acquisition in Cedar Rapids, Iowa *<https://doi.org/10.1007/s11069-015-2060-8>*. *Natural Hazards*, *80*(3), 2055–2079.

Tellman, B., Sullivan, J. A., Kuhn, C., Kettner, A. J., Doyle, C. S., Brakenridge, G. R., Erickson, T. A., & Slayback, D. A. (2021). Satellite imaging reveals increased proportion of population exposed to floods *<https://doi.org/10.1038/s41586-021-03695-w>*. *Nature*, *596*(7870), 80–86.

Tobin, G. A. (1995). The levee love affair: A stormy relationship? *<https://doi.org/10.1111/j.1752-1688.1995.tb04025.x>* *Journal of the American Water Resources Association*, *31*(3), 359–367.

Treuer, G., Koebele, E., Deslatte, A., Ernst, K., Garcia, M., & Manago, K. (2017). A narrative method for analyzing transitions in urban water management: The case of the Miami-Dade Water and Sewer Department *<https://doi.org/10.1002/2016WR019658>*. *Water Resources Research*, *53*(1), 891–908.

Ulibarri, N. (2018). Collaborative model development increases trust in and use of scientific information in environmental decision-making *<https://doi.org/10.1016/j.envsci.2018.01.022>*. *Environmental Science & Policy*, *82*, 136–142.

United Nations. (2017). *Factsheet: People and oceans* *<https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf>*.

Urban Land Institute. (2020). *The business case for resilience in southeast Florida: Regional economic benefits of climate adaptation*.

U.S. Army Corps of Engineers. (2016). *National levee database* *<https://levees.sec.usace.army.mil/#/>*.

U.S. Army Corps of Engineers. (2019a). *Risk assessment for flood risk management studies* *<https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/ER%201105-2-101_Clean.pdf>* (No. ER 1105-2-101).

U.S. Army Corps of Engineers. (2019b, January). *Mississippi River commission history* *<https://www.mvd.usace.army.mil/Portals/52/docs/MRC/MRC%20Web%20Docs/MRC_History_WEB.pdf>*.

U.S. Army Corps of Engineers. (2020). *Miami-Dade Back Bay coastal storm risk management draft integrated feasibility report and programmatic environmental impact statement: Draft feasibility study* *<https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/14453>*.

U.S. Army Corps of Engineers. (n.d.). *Partners in shared responsibility* *<https://www.iwr.usace.army.mil/Missions/Flood-Risk-Management/Flood-Risk-Management-Program/Partners-in-Shared-Responsibility/>*.

U.S. Congress. (1850). *Grants of swamp and overflowed lands* *<https://uscode.house.gov/view.xhtml?path=/prelim@title43/chapter23&edition=prelim>*.

U.S. Congress. (1879). *1879 Mississippi River Commission Act* <https://www.mvd.usace.army.mil/Portals/52/docs/MRC/Appendix_C_1879_Miss._River_Commission_Act.pdf>.

U.S. Congress. (1928). *Flood Control Act of 1928* <https://www.mvd.usace.army.mil/Portals/52/docs/MRC/Appendix_E._1928_Flood_Control_Act.pdf>.

U.S. Congress. (1936). *Flood Control Act of 1936* <https://govtrackus.s3.amazonaws.com/legislink/pdf/stat/49/STATUTE-49-Pg1570.pdf>.

U.S. Department of Agriculture, National Agricultural Statistics Service. (2014). *2012 Census: Farms and farmland* <https://www.nass.usda.gov/Publications/Highlights/2014/Highlights_Farms_and_Farmland.pdf> (ACH 12–13).

U.S. Geological Society. (2021, September 1). *Coastal Storm Modeling System (CoSMoS)* <https://www.usgs.gov/centers/pacific-coastal-and-marine-science-center/science/coastal-storm-modeling-system-cosmos>.

U.S. Government Accountability Office. (2020). *National flood insurance program: Fiscal exposure persists despite property acquisitions* <https://www.gao.gov/assets/gao-20-508.pdf> (No. GAO-20–508).

van Buuren, A., Ellen, G. J., & Warner, J. (2016). Path-dependency and policy learning in the Dutch delta: Toward more resilient flood risk management in the Netherlands? <https://doi.org/10.5751/ES-08765-210443> *Ecology and Society*, *21*(4), 43.

Vedeld, T., Kombe, W. J., Kweka-Msale, C., Ndour, N. M., Coly, A., & Hellevik, S. (2015). Multi-level governance, resilience to flood risks and coproduction in urban Africa <https://doi.org/10.1007/978-3-319-03982-4_9>. In S. Pauleit, A. Coly, S. Fohlmeister, P. Gasparini, G. Jørgensen, S. Kabisch, W. J. Kombe, S. Lindley, I. Simonis, & K. Yeshitela (Eds.), *Urban vulnerability and climate change in Africa: A multidisciplinary approach* (pp. 287–318). Springer.

Wagner, S., Souvignet, M., Walz, Y., Balogun, K., Komi, K., Kreft, S., & Rhyner, J. (2021). When does risk become residual? A systematic review of research on flood risk management in West Africa <https://doi.org/10.1007/s10113-021-01826-7>. *Regional Environmental Change*, *21*(3), 84.

Wakefield, S. (2019). Miami Beach forever? Urbanism in the back loop <https://doi.org/10.1016/j.geoforum.2019.10.016>. *Geoforum*, *107*, 34–44.

Webber, S., & Donner, S. D. (2017). Climate service warnings: Cautions about commercializing climate science for adaptation in the developing world <https://doi.org/10.1002/wcc.424>. *WIREs Climate Change*, *8*(1), e424.

Wiltz, L. A. (2005). The great Mississippi flood of 1874: Its extent, duration and effects./A circular from Mayor Wiltz, of New Orleans, to the mayors of American cities and towns, and to the philanthropic throughout the Republic, in behalf of seventy thousand sufferers in Louisiana alone <http://name.umdl.umich.edu/ACL0983.0001.001>. University of Michigan Library. (Original work published 1874)

Wing, O. E. J., Bates, P. D., Sampson, C. C., Smith, A. M., Johnson, K. A., & Erickson, T. A. (2017). Validation of a 30 m resolution flood hazard model of the conterminous United States <https://doi.org/10.1002/2017WR020917>. *Water Resources Research*, *53*(9), 7968–7986.

Wing, O. E. J., Bates, P. D., Smith, A. M., Sampson, C. C., Johnson, K. A., Fargione, J., & Morefield, P. (2018). Estimates of present and future flood risk in the conterminous United States <https://doi.org/10.1088/1748-9326/aaac65>. *Environmental Research Letters*, *13*(3), 034023.

Wing, O. E. J., Lehman, W., Bates, P. D., Sampson, C. C., Quinn, N., Smith, A. M., Neal, J. C., Porter, J. R., & Kousky, C. (2022). Inequitable patterns of US flood risk in the anthropocene <https://doi.org/10.1038/s41558-021-01265-6>. *Nature Climate Change*, *12*(2), 156–162.

Withington, J. (2013). *Flood: Nature and culture* <https://press.uchicago.edu/ucp/books/book/distributed/F/bo16826611.html>. Reaktion Books.

Wright, J. O., & U.S. Department of Agriculture. (1907). *Swamp and overflowed lands in the United States: Ownership and reclamation* <https://doi.org/10.5962/bhl.title.87650>. U.S. Government Printing Office.

Zandvoort, M., Campos, I. S., Vizinho, A., Penha-Lopes, G., Lorencová, E. K., van der Brugge, R., van der Vlist, M. J., van den Brink, A., & Jeuken, A. B. M. (2017). Adaptation pathways in planning for uncertain climate change: Applications in Portugal, the Czech Republic and the Netherlands <https://doi.org/10.1016/j.envsci.2017.08.017>. *Environmental Science & Policy*, *78*, 18–26.

Zarekarizi, M., Srikrishnan, V., & Keller, K. (2020). Neglecting uncertainties biases house-elevation decisions to manage riverine flood risks <https://doi.org/10.1038/s41467-020-19188-9>. *Nature Communications*, *11*(1), 5361.

Zevenbergen, C., Khan, S. A., van Alphen, J., Terwisscha van Scheltinga, C., & Veerbeek, W. (2018). Adaptive delta management: A comparison between the Netherlands and Bangladesh delta program <https://doi.org/10.1080/15715124.2018.1433185>. *International Journal of River Basin Management*, *16*(3), 299–305.