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CRITICAL PERSPECTIVES

Climate-resilient water infrastructure: A call to action

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Abstract

The effects of climate change have put tremendous stress on our existing water infrastructure and necessitate rethinking of how we govern and manage these systems. This commentary is a call to action for placing a holistic understanding of climate resilience at the center of water governance, understanding and approaching the issues as contextual and interdisciplinary in nature. Drawing from experiences from the Netherlands and the United States, this commentary outlines climate adaptation as policy dilemma and the role and characteristics of engineering, nature-based, and community-focused approaches. It concludes with some thoughts on pathways forward and an invitation for future research and dialog.

KEYWORDS

climate adaptation, climate change, climate resilience, infrastructure, water governance

1 | INTRODUCTION

Water plays an important role in everyone's daily lives in extremely profound ways—safe drinking water, flood risk management, access to sanitation, and the mitigation of pollution into rivers, lakes, and coastal waters. Yet, with climate change the provision of these services has become increasingly less self-evident.[1] Communities everywhere experience the impacts of climate change first-hand. Sea level rise due to climate change[2] is a threat in coastal areas around the world, while at the same time sustained drought in places as disparate as Cape Town, South Africa,[3] Mexico City,[4] and the Colorado Basin in the American Southwest,[5] and record lows in the Rhine River in Europe[6] illustrate the highly visible and significant effects of climate change. Meanwhile, increased occurrences of torrential flooding events, cyclonic storms, tornadoes, and other weather events around the world[7] also give voice to the coming crisis, especially in terms of water infrastructure.

Over the past several centuries, humans have designed and built a wide variety of infrastructure systems to control, harness, and exploit water resources. Some of these systems are primarily constructed to provide safety against flooding. Others are meant to capture, store, transport, and treat water for human consumption; to harness water for hydroelectric uses, agricultural irrigation, transportation of goods; or to treat water to remove pollutants. All of these infrastructures were designed and built for the weather and hydrologic patterns as they existed at the time. For much of this period, the climate has remained relatively stable, and thus predictable. However, climate change begets instability. In turn, the water infrastructure in place now faces unexpected threats to its capacity, operability, and usefulness. As the effects of climate change have put tremendous stress on our existing water infrastructure, how we govern and manage these systems needs attention.

Our investment in water infrastructure is nearly unimaginable in scope. In the Netherlands alone, the Dutch for centuries have spent a significant fraction of their national wealth in their efforts to reclaim land from the North Sea, and to keep that land safe from flooding. Dikes and other flood control infrastructure are continually updated and improved. At the same time, recent droughts in Europe have created other (unexpected) challenges for the Netherlands, including ensuring a supply of fresh water for human consumption, agricultural irrigation, and navigation of the Netherlands' many rivers and canals. Additionally, unstable weather patterns caused by global warming have led to an increasing number of torrential rain events. In a nation where much of the land is at or below sea level, these rains can cause significant nuisance and damage, especially in urbanized areas.[8]

These challenges are not limited to the Netherlands but faced throughout the European continent. According to the recent European climate risk assessment,[9] Europe is the fastest-warming continent in the world. As a consequence, heatwaves and prolonged droughts are occurring more often, causing acute crises including infrastructure failure and affecting water resources that humans, ecosystems, and infrastructure services depend on. With the increase of extreme precipitation events, flood risks have increased as well. While the European Union and its member states have made a great deal of progress in adapting to climate change, policy implementation is lagging behind the quickly increasing risk levels. Moreover, societal preparedness to respond to climate-induced shocks and stressors continues to be low.

Similar issues are found across the United States. In the American West, years of sustained drought have threatened both agriculture and human habitation, especially in southern California, Arizona, and Nevada. The Los Angeles Basin, a relatively arid region, has relied heavily on water transported hundreds of miles from the Sierra Nevada Mountains and the Colorado River. However, sustained drought has significantly reduced the water flow in the Colorado River and the snowpack in the mountains. In central California, a remarkably prolific agricultural area, much of the water used to support agriculture is transported from the mountains of northern California.[10] Years of drought have placed increasingly heavy demands on aquifers under the valley, which have now reached historic lows. Paradoxically, as we write this, California is experiencing a series of "atmospheric rivers" of moisture from the Pacific Ocean that have led to significant flooding events.[11] However, as the infrastructure does not exist to capture and store this water, much of the rainfall runs directly back into the Pacific Ocean.

These events are not limited in the United States to the West. Reduced water flow in the Mississippi River system has created a crisis in and around New Orleans as salt water has infiltrated from the Gulf of Mexico at the mouth of the river to threaten the drinking water supply for New Orleans and the surrounding communities. This situation has also been exacerbated by the loss of land south of New Orleans (see Tidwell[12]), a consequence of the decision more than 150 years ago to control the Mississippi River floods with the use of thousands of miles of levees (see Barry[13]). Rather than replenishing the river delta with new soil and silt, that silt is now transported well out into the Gulf of Mexico, leaving cities and towns in Louisiana exposed to erosion and saltwater intrusion. Meanwhile, coastal communities in Alabama and across the Southeastern regions of the United States are regularly impacted by extreme hydrological events, such as tropical storms and hurricanes, which are then coupled with fast urbanization in some areas.[14]

Many of the challenges we face today are the direct result of past decisions. Those decisions were made with the best information available at the time, yet assuming an engineering perspective on resilience. In this perspective, resilience is understood as the ability of a system to resist disturbances and return to its original state, and where efficiency and predictability are taken as starting points.[15] With climate change, a key assumption underlying this perspective and past decisions about water infrastructure, that is, that weather extremes and system behavior can be fully predicted and controlled, no longer holds. Not only has it become more difficult to predict extremes and to assess their impacts,[16] infrastructure systems have also become more interdependent and complex. As such, contemporary water infrastructures can be understood as "a conglomeration of interdependent social-ecological-technical systems" (see Mehvar et al.,[17] p. 1383). The resilience of such systems depends not only on whether a system is able to (1) anticipate and resist disturbances, such as floodings or droughts but also on its ability to (2) absorb disturbances and recover, and (3) transform and adapt, for example, by learning from prior unforeseen events.[17–19] The latter two abilities critically depend not only on the hard infrastructure in place but also on the functioning of ecosystems and characteristics of communities served by water infrastructure (e.g., in the form of protection from floods, wastewater treatment, or drinking water provision). As such, ecological social systems have to be equally considered in water infrastructure decision-making.

Making water infrastructure climate-resilient poses policymakers with the dilemma: what risks should be prevented and what risks should be accepted? After outlining this dilemma in the next section, we discuss three approaches to making infrastructures more climate-resilient: engineering, nature-based, and community-focused. None of these approaches provides a single panacea for infrastructure resilience. Depending on the biophysical, governance, and other contextual factors, different combinations of approaches may be more desirable and effective. Hence, this commentary calls for a more holistic understanding of water infrastructures and their resilience, perceiving them as complex technical-ecological-social systems. Given this complexity, multidisciplinary collaboration is essential for research and policy to have a positive impact on the climate resilience of water infrastructure.

2 | CLIMATE ADAPTATION AS A POLICY DILEMMA

Climate change and extreme weather events lead to significant adverse societal costs. The World Meteorological Organization reports that there has been a sevenfold increase in the reported disaster losses from extreme weather since the 1970s.[20] As a result, the attention for climate change adaptation and, more recently, for improving climate resilience[21] has been growing, not just among policymakers but also within the private sector. For example, in the Netherlands, financial institutions expressed concerns that climate change will make housing more expensive. Hence, they call for making plans and taking measures now to ensure climate-proof living in more extreme climate-related scenarios after 2100.[22] Also, in other countries, we see evidence of policymakers and communities learning how to adapt and become more resilient following extreme weather events. In the United Kingdom, the experience with the 2007 Tewkesbury floods has generated new understandings of the value of local knowledge, and how these might be successfully used in flood risk management practice.[23] In Denmark, the experience with a cloudburst in Copenhagen in 2011, which caused damage of approximately USD $1 billion, led to a strategic process for planning and designing blue-green interventions.[24] In 2012, the lessons from Hurricane Sandy made New York City known as a first-responder city due to the explicit inclusion of increasing climate change risks in the rebuilding effort.[25] In the Netherlands, learning from these and other international extreme weather events, the Dutch government developed a so-called Delta Program on Spatial Adaptation.[26] To reduce the impact of climate change, this program organizes a process for public decision-making on preventive spatial measures. Risk dialogs between responsible public authorities, other public and private actors, and communities play a key role in this process. Through these dialogs, stakeholders can create a mutual understanding of vulnerabilities, determine what risks are acceptable and which ones should be prevented, and finally, decide what meaningful preventive measures could be taken by whom and who should incur the costs.

At the heart of risk dialogs, such as the ones that take place in the Netherlands, is what we perceive as one of the central dilemmas in public policy-making on climate adaptation: what risks to prevent and what risks to accept? If governments opt for risk prevention, they can basically choose one or a combination of three types of adaptation measures: engineering ("gray" or technical solutions), nature-based ("green" or ecosystem-based solutions that make use of nature), or "soft" (managerial, legal and policy measures that aim at altering human behavior and governance approaches) measures.[27] Throughout history, the water sector has commonly relied on engineering approaches. The abundance of dikes, seawalls, dams, storm surge barriers, and hydraulic structures such as pumps and sluices, in areas close to the open sea, rivers, and lakes are a testimony of this prevalence in flood protection infrastructures. In the sections below we reflect on the role that these technical measures (engineering approaches) can play in becoming more resilient next to measures that aim at altering the ecological system (nature-based approaches) and the social system (community-focused approaches). As so-called soft measures are relevant to each approach, they are not discussed separately.

To further illustrate the policy dilemma, we draw here from a study by a Dutch office for urban design and landscape architecture[28] that links the presented approaches to three possible future scenarios. One possible scenario is that political willingness and resources are present, yet the willingness to transform existing patterns, infrastructure, and landscapes or spatial opportunities are missing. In such a scenario, it is more likely that the effects of climate change will be mitigated with technological solutions. In this "technology first" scenario climate challenge is addressed entirely with technology; it involves an extensive exploration of new techniques and ways to make landscapes function as a cleverly designed water machine. In other words, human behavior does not necessarily need to be changed or transformed.

Another possible scenario is that political willingness to adapt to climate change in a transformative way is present, and resources and spatial opportunities are available. In this scenario, policymakers are more likely to consider transforming landscapes into climate landscapes, including infrastructure in the form of more nature-based solutions. This "sponge" scenario entails a maximum exploration of possibilities for the city or a landscape to retain and reuse its area's own water while using as much green space as possible for this purpose. This would require some changes in the form of reserving green space and limiting development of the city in certain areas. If the political willingness and policy resources are missing, it will be more likely that preventive measures are not adopted, and risk acceptance will be the outcome.

This "flexible citizen" scenario includes an extreme appeal to the adaptive capacity of people; it means survival in extreme climate scenarios and embracing the new climate extremes as much as possible. In this scenario, adaptation takes place on an individual scale or in a self-organized collective. The "flexible citizen" scenario could be the result of political inertia in which politicians cannot decide upon preventive measures and leave risk acceptance to society. As such, this scenario could impose high adverse societal costs and an inequal and unfair distribution of climate impacts, since climate change affects different communities and members of society in different ways. Factors such as community wealth and socioeconomic status, social capital, political capacity and will, and historical policy decisions and public investments/disinvestments are all underlying factors that affect what risks *can* be prevented and what risks *have to be* accepted. Alternatively, this scenario could involve an explicit decision to leave climate risks to some extent to society based on a political belief that individuals should individually bear the costs of climate risks to some extent including the option of purchasing hazard insurance assuming that it will be available. Lastly, recognizing that risk can never be fully eliminated, it could be an approach to increasing community resilience. In the latter two cases, the community itself is the starting point for climate adaptation efforts. The characteristics of such an approach are elaborated in the section on community-focused approaches.

3 | ENGINEERING APPROACHES

Hard infrastructures such as drainage systems, dikes, or wastewater treatment plants have played and continue to play an important role in reducing the exposure of societies to natural hazards. Engineered water infrastructure delivers a wide range of invaluable services to society. Tideway tunnels and storage have improved the water quality of the Thames River in London to mitigate the adverse effects of combined sewer overflows.[29] In the Netherlands, large-scale dams and storm surges such as the Delta Works play a key role in protecting the population from flooding.[30] They generally require relatively small amounts of land, are relatively easily monitored and controlled, and can be very effective. For example, concrete walls have proven most effective in protecting coastal communities from tsunamis and other types of storm surges. Moreover, as they are made of concrete or other long-lasting materials, they tend to be very durable.[31]

Yet, with climate change weather extremes and system behavior have become less predictable. Hence, the long-term effectiveness and desirability of installing and maintaining hard infrastructures, which tend to be very costly and inflexible, are increasingly questioned.[31] In this regard, the cascading effects of failing infrastructures during and after Hurricane Katrina that hit New Orleans in 2005 has been a hard lesson learned for many. Levee failures caused widespread disruption of electric power, widespread pollution and affected more than 1000 drinking water supply systems and 173 sewage treatment plants. In addition to poor maintenance, a lack of expertise and collaboration, levee failures could have such devastating impacts since pumping stations were left unattended as human operators were relieved of duty.[32] The Netherlands is one of the countries that learned from this. Reflecting on the impacts of Hurricane Katrina, the Delta Programme is now striving for an appropriate balance between protection, prevention, and preparedness as opposed to reliance on a single approach that provides complete protection.[33] The lessons of the “single approach” solution is also evident in the case of Taro, Japan. Surrounded by a wall that was designed to stop a tsunami, the tsunami that formed following the earthquake in 2011 breached the wall, completely destroying the city.[34]

Engineering approaches amount to a fail-safe mentality with intolerance for risks and emphasis on safety. Yet, the unpredictability of climate change effects rather warrants a safe-to-fail mentality for infrastructure.[35] With sea level rise and extreme rainfall events, the primary function of fail-safe infrastructure could be rendered obsolete in the nearby future. This is certainly no plea for a marginal role of engineered solutions for climate-resilient water infrastructure, nor for the abandonment of a fail-safe mentality altogether. However, it does result in a particular type of path dependency potentially standing in the way of climate-resilient water infrastructure, which is best explained by the principle of asset specificity.

Asset specificity refers to investments that actors make for a specific transaction, which cannot be used efficiently for other transactions. Economists have stressed the multidimensional character of asset specificity,[36,37] of which three dimensions are especially relevant to water infrastructure. The physical attributes of infrastructure and the processes surrounding its design and management display a high degree of asset specificity.[38] Indeed, a dike or a dam is designed to protect a specific area (*physical specificity*) while taking certain parameters and standards in mind, such as expected sea-levels, water flows, rainfall (*temporal specificity*). Lastly, policy makers, engineers, project managers have a specific skill set that are linked to gray solutions (*human specificity*). The high degree of asset specificity of water infrastructure demands taking existing infrastructure, and the routines and practices that are associated with its design and management as starting point for designing approaches fit for climate-resilient water infrastructure. At the same time, existing infrastructures “lay down both material and imaginative pathways and constraints that themselves effectively delimit what may be seen as possible future developments” (Wynne, in Feenberg[39] p. x). Indeed, van Staveren and van Tatenhove[40] show that the Dutch landmark hydraulic storm surge barriers, the Delta Works, fundamentally shape the development pathway of river deltas.

Investments in vulnerable but protected areas play a role in this and so does risk perception. As risk acceptance in the Netherlands is low, citizens are generally unaware of flood risks and expect the government to take care of flood protection. Changing this requires a change in mindset of people.[41]

The transformative change, or transition, that is needed for engineering approaches to include a safe-to-fail mentality is also complex due to asset specificities amounting to an intractably interwoven configuration of physical infrastructure, actors, routines and practices, values, policies, and institutions that characterize the water infrastructure sector. As such, water infrastructure can be seen as a socio-technical system, in which technologies and institutions, rules, practices, and networks form a complex configuration.[42] Transitions imply changes in structural elements of socio-technical systems.[43] Markard[44] outlines seven infrastructure dimensions that have implications for transformative change.

We reflect here on the role of techno-economic characteristics (capital intensity and asset durability) and regulation. Water infrastructure is *capital intensive*, which creates the incentive to maintain infrastructural assets, even though this might be inconsistent with a climate-resilient future. Indeed, although *asset durability* is a balance to the high capital costs of infrastructure, the frame conditions (public values, societal needs) that applied when infrastructure was constructed can change over the lifespan of infrastructure assets, bringing along considerable uncertainties.[45] The long-lived nature of hard infrastructure (typically more than 100 years), and the fact that they involve large amounts of resources impose both challenges and opportunities. Challenging aspects include uncertainties about technological developments, changing societal values and user demands and how climate change impacts their effectiveness. Current values, which may be incompatible with climate-resilient futures, are likely to be prolonged over decades as they are embedded in physical infrastructure.

At the same time, infrastructure investments provide policymakers with the opportunity to incorporate long-term objectives such as sustainability and resilience.[46] Yet, for decisions about hard infrastructures to have a positive impact on climate resilience, it is essential that they are forward-looking. Pot et al.[47] developed three criteria to evaluate whether infrastructure investment decisions are forward-looking: (1) a problem definition that considers future challenges and needs and has a time horizon of 10 years minimum; (2) a solution that is proven to be robust in extreme scenarios and/or is monitored and can be adapted when in case of changing insights or conditions; and (3) a justification that connects to a future vision or goals and/or relies on multiple scenarios for one or more future developments. Application of this framework to a sea lock investment in the Netherlands shows that, in reality, policymakers may not have the intention to anticipate the future and do not necessarily make forward-looking decisions. The study identified three mechanisms that are likely to contribute to making forward-looking decisions: the use of forward-looking argumentation in strategic framing, reliance on visions, scenarios, and flexible solutions to avoid political risks and rules with forward-looking features.

In addition to capital intensity and durability, a dimension particularly relevant for water infrastructure is the prominent role of *regulations*. Indeed, government actors and well-established policy frameworks support engineered solutions for water protection.[48] In the Netherlands, where prevention is deeply entrenched in institutions, the process of introducing spatial and flood risk management approaches next to prevention approaches has proved to be particularly challenging.[41] Gray solutions are preferred as they align with safety standards, legal regulations, and policy ambitions.[49] This is only changing slowly since the government introduced a multipronged approach to flood risk management (so-called multilayered safety) in the 2009 National Water Plan. In this approach, protection approaches should be complemented with spatial planning and disaster management. While water safety is increasingly integrated into spatial planning as a result, disaster management—a domain that alludes to community-focused resilience—remains detached.[50] A path dependency mechanism that contributes to this are that resources are skewed toward prevention and standards are strongly embedded in legislation. Changing this is complex and takes time as it requires changing existing ways of knowing, routines, and practices.[41]

4 | NATURE-BASED APPROACHES

A disadvantage of engineering approaches is that they tend to largely ignore ecological systems and may even harm them. In urban areas, hard infrastructures are often associated with a loss of biodiversity whereas in coastal areas they tend to disrupt natural processes.[31] In climate adaptation decisions, nature-based or landscape-based approaches are therefore increasingly considered as add-on or alternative to engineering approaches.[51] In the case of adapting to sea level rise and flooding, such decisions could be about choosing between only relying on dikes and embankments to prevent flooding versus allowing more controlled flooding in flood landscapes. In the case of adapting to drought and reduced freshwater availability, it could be the choice between only relying on constructing canals for new supply routes or desalinization of seawater versus saving and storing more rainwater in sponge landscapes. In case of adapting to weather extremes it could be the choice between more drainage systems against excessive rainfall and more air-conditioning against heat versus more open space for water and trees.

Nature-based approaches refer here to the wide range of solutions that, according to the European Commission, "are inspired and supported by nature" and "benefit and support the delivery of a wide range of ecosystem services."[52] This definition includes blue and green infrastructures that are "principally constituted by well-functioning biophysical systems to which some management and restoration may apply,"[31] as well as hybrid infrastructures that combine solutions that fully rely on ecosystems with engineering infrastructure. In the literature, they are also referred to as natural water retention or sponge measures. In urban water management, such nature-based approaches are increasingly applied as urbanization and an increase of extreme precipitation events challenge the effectiveness of conventional drainage systems, which were generally designed to convey stormwater via underground infrastructure as quickly as possible outside of urban areas. Alternatives are increasingly considered and referred to as "water-sensitive urban design," "alternative actions," or "sustainable urban drainage systems." What makes them nature-based is that they intend to manage water runoff in a more natural way to increase the sponge functioning of a city, for example, by investing in daylighting or the restoration of urban streams, permeable surfaces, parks, green roofs, vegetated swales, and rainwater gardens.[53] In rural areas, including coastal areas and river systems, nature-based approaches are also known as natural water retention measures or sponge measures. Examples of such approaches include creating or restoring mangroves, forests, river vegetation, wetlands, salt marshes, coral reefs, floodplains, streams, or rivers.[54]

Nature-based approaches have a prominent position in the 2021 European strategy on adaptation to climate change, which reads that "implementing nature-based solutions on a larger scale would increase climate resilience and contribute to multiple Green Deal objectives. Blue-green (as opposed to gray) infrastructures are multipurpose, "no regret" solutions and simultaneously provide environmental, social and economic benefits and help build climate resilience."[21] Since 2022 their potential has been recognized by a wide range of international organizations and programs, such as the United Nations Environment Assembly, Convention on Biological Diversity Conference of the Parties, Ramsar Convention on Wetlands, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and Intergovernmental Panel on Climate Change.[52]

In the Netherlands, nature-based or "building with nature" approaches that make use of natural dynamics and materials (e.g., wind, currents, and sediments) play an important role in maintaining coastal safety while providing opportunities for nature development. An iconic example of such approach is the so-called "Sand Engine," a large-scale sand nourishment peninsula that was created in 2011 to test the feasibility of mega-sand nourishments as a more cost-effective and environmentally friendly alternative for hard infrastructure investments to counteract coastal erosion and to ensure flood safety.[55] While sand nourishment has become a common ecological engineering approach to coastal management in countries around the world, including the United States, the scale and manner in which the Dutch apply the approach is quite exceptional. Not only is the nourished volume remarkably large, the Dutch also employ a long-term strategy for coastal maintenance and an overall monitoring framework that is integrated into the legal framework.[56] In the aftermath of hurricane Katrina, various scholars (see Costanza et al.[57] and Farber et al.[58]) particularly called for solutions that include ecosystem services and are more resilience-oriented, such as coastal wetlands, as opposed to solely resorting to rebuilding gray solutions such as levees.

Nature-based approaches are often presented as win-win or no-regret measures and to some extent they are since they are more flexible across a range of climate change scenarios and have co-benefits beyond reducing risks.[59] These include benefits for society in terms of human health and well-being (e.g., improved air quality, noise attenuation, accessible public space, and temperature regulation), the environment (e.g., erosion protection, ecological connectivity, and carbon storage), and the economy (e.g., reduced cost of stormwater run-off, increase of property values, and energy savings).

Yet, they may also have negative impacts or may involve trade-offs. For example, improving environmental quality can contribute to gentrification which may have adverse effects on social justice and social cohesion.[60,61] A review of the literature on the water and energy impacts of urban green infrastructure shows that while a wide range of studies set out quantifying positive impacts (e.g., green roofs, rainwater harvesting, and ground-based vegetation), existing studies tend to be biased toward positive impacts and limited in scope, focusing only on very specific water or energy impacts. Moreover, as most empirical studies concern small-scale experimental sites, it remains unclear how well green infrastructure actually performs and how local characteristics affect this. As such, the evidence base of urban green infrastructure performance remains limited.[62]

Yet, such holistic understanding of potential synergies and trade-offs is essential when designing, implementing, and evaluating nature-based approaches.[61] This implies, for example, that if nature-based solutions are to be assessed on a more equal footing with gray solutions, it is crucial that the cost-effectiveness assessments account for ecosystem services.[63] In this context, Alves et al.[64] conclude that when co-benefits are set as an objective for assessing blue–green–gray infrastructure measures for urban flood mitigation, it encourages the selection of blue–green infrastructure. For decisions about water infrastructure, this implies that alternatives should be compared on criteria that go beyond sectoral costs and effectiveness to include criteria co-benefits and disbenefits that go beyond the water sector and might not have been monetized before.

Nature-based approaches are often perceived with skepticism, both by stakeholders and experts. Comparative research into public preferences and acceptance across three European nations provides several explanations. First, as the general public is skeptical about the effectiveness of nature-based approaches, both in terms of cost-effectiveness and risk reduction, they prefer engineering or hybrid approaches. For example, they consider the effectiveness of nature-based solutions to be uncertain, either taking a long time to become effective or becoming less effective over time. Engineered solutions, on the other hand, are expected to be more reliable, to last longer and to be effective immediately. Second, as nature-based approaches influence landscapes, they influence the public's sense of place. Place-based factors, such as regional identity and needs to be factored in for successful implementation of nature-based approaches. Community-focused approaches can play a role in improving public acceptance, for example, through engaging the public in monitoring through citizen science initiatives or actively involving community leaders in activities.[59,65]

Skepticism among experts is mostly linked to two major issues: (1) uncertainties associated with the feasibility and impacts of nature-based approaches; and (2) complexity of implementing nature-based solutions as they require more—often privately owned—land compared to gray solutions.[66] Both issues are real. Compared to engineering approaches, the effectiveness and other impacts of nature-based approaches are far more uncertain as natural dynamics—for example, wind and currents in the case of coastal nourishment or precipitation and temperature in the case of green infrastructure—are inherently unpredictable. This unpredictability can have multiple cascading effects with regard to understanding societal impacts. For example, in the design of the aforementioned Sand Engine, unpredictable weather conditions led to uncertainty about swimming conditions, and thus to uncertainty about recreational safety. This uncertainty was exacerbated by an uncertainty that was of technical nature, that is, the whereabouts of dumped ammunition. The resulting uncertainty about recreational safety made societal stakeholders question the acceptability of the entire Sand Engine project.[55]

The other issue, the additional land needed for implementing nature-based compared to engineering approaches, can be limiting as well. In urban areas, the existing fabric may not even allow for the implementation of green infrastructure or requires households taking measures themselves. Yet, oftentimes measures such as green roofs, rainwater harvest by decoupling rainwater pipes, or greening of gardens are only effective when applied by many households, creating a collective action problem. In river systems, making more space for water plays an important role in climate adaptation. Also here, making land available and/or persuading landowners to take measures to increase the sponge functioning of landscapes is difficult, again also because evidence of the effectiveness and efficiency of such solutions at larger scales is lacking.[66]

This being said, nature-based solutions can also provide solutions to wicked societal problems, such as, the improving flood protection near nature areas, a very widespread and persistent problem in the Netherlands where 50% of the dikes are located in protected nature areas. In these cases, we see that realizing such win-win solutions crucially depends on whether key stakeholders can create so-called integrative action situations, which implies redesign of formal and informal institutional rules, such as, how decisions are made, information is shared, and costs and benefits are distributed.[67] As nature-based approaches require not just technical expertise, disciplines such as civil engineering, land use planning, and the political sciences have to engage in interdisciplinary research to better support decision-making and implementation processes.

5 | COMMUNITY-FOCUSED APPROACHES

Responses to climate change are not just about physical infrastructure and policy choices. Climate change has a profound impact on communities of people. How communities react, or are able to react, to climate change imperatives is a critical component of climate resilience. In this light, the policy dilemma can be viewed as: what risks *can* be prevented and what risks *have to be* accepted by various communities of people? Understanding resilience from a community perspective and engaging them can help in implementing measures that reduce disaster impacts more equitably, effectively, and efficiently while also making communities less vulnerable and more resilient.[68] In this context, community-focused approaches center on the people who are affected by climate change and their roles in the decision-making processes, and how the outcomes for both can be improved in an equitable way.

While one might argue that climate resilience is everyone's problem, empirical evidence suggests that individual communities think differently and experience climate-related events differently. In the US state of Virginia, for example, the Hampton Roads region is at significant risk from sea level rise due to climate change.[69] Even within that region, different political jurisdictions (and even different neighborhoods within cities) take very different stances on climate resilience. In addition, some communities are at enhanced risk and are capable of action, while other communities are at equal risk and are unable to respond. Wealthy communities in Southern California exercise an unfair advantage over smaller communities closer to the water source, even in times when water supplies are high. In times of drought, the level of conflict increases significantly,[10] and water continues to flow toward the communities with the advantages of wealth and social capital. Along the water-scarce Front Range area of Colorado (which includes Denver, Colorado Springs, Boulder, and other cities), there is a saying that "water flows uphill, toward money" (Attributed to LeRoy Kaufman, a retired water engineer with the Denver Water Authority. Mr. Kaufman was the lead engineer on several proposed dam projects designed to increase the available water supply for the growing population of the Front Range). Therefore, when we consider community-focused resilience approaches, we must take into account factors such as community wealth and socioeconomic status, social capital, political capacity and will, and historical policy decisions and public investments/disinvestments, among other factors that affect a specific community's ability to prevent or accept (or not) climate change risks.

The disparate effects of water issues related to climate change, and how they cut across an array of different geopolitical scales, governmental entities, and laws and regulations, are quite visible in the US state of Alabama. For example, residents of a predominately African American neighborhood in Shiloh, Alabama, have claimed that a highway expansion construction project undertaken by the Alabama Department of Transportation has resulted in the ongoing flooding of their homes. A civil rights investigation by the Federal Highway Administration is currently underway.[70] While flooding—or an excess of water—is a concern for many communities, a lack of access to clean, safe drinking water is also a major concern. Prichard, Alabama, is a primarily African American and low-income community, situated northwest of Mobile along the Gulf Coast that has experienced a lack of safe drinking water compounded with extremely high costs for water. After years of neglect and mismanagement of the city's water system, the Prichard Water Works and Sewer Board had their authority removed and transferred to an external entity by court order.[71] Access to clean water also means having effective wastewater systems. According to the Consortium for Alabama Rural Water and Wastewater Management, due to a lack of wastewater management and infrastructure, "it is estimated that hundreds of thousands of gallons of raw sewage are being discharged daily to the ground surface in the Black Belt region of central Alabama,"[72] causing tremendous health and safety risks to the residents and negative environmental and economic impacts. With these issues of mismanagement, careless if not reckless planning, and a lack of resources already present, the ability of these communities to respond and adapt to climate change is a challenge.

Therefore, it is extremely important that the role of social vulnerability is also factored into understanding, building, and maintaining a community's capacity to withstand, adapt, and improve their quality of life, regardless of stresses or shocks to the community, including climate change-related events.[73,74] As the Environmental Protection Agency notes, "those who are already vulnerable due to a range of social, economic, historical and political factors have a lower capacity to prepare for, cope with, and recover from climate change impacts."[75]

An examination of the social vulnerability of a community encompasses a range of factors.[76,77] Common variables that are used to determine social vulnerability include income, poverty levels, age, gender, race and ethnicity, and housing status/tenure. In addition to a physical proximity to certain geographic features (e.g., coastal areas, rivers) that make certain communities vulnerable to climate change, socio-geographic characteristics, such as concentrated poverty and racial segregation, highlight the important and complicated interactions between members of a community and where they are living, which in many cases is a direct result of policy actions, some with long historical legacies (e.g., in the United States, zoning laws and ordinances, the Federal Aid Highway Act, and Housing Acts of the 1930s–1950s). Access to political systems and actors, information and data for informed decision-making, and social capital are also factors that affect a community's ability to plan for, respond to, and recover from climate change-related events—that is, what risks *can* be prevented and what risks *have to be* accepted by various communities of people. Therefore, the role that social vulnerability plays in decision-making processes, and oftentimes the disparate outcomes that result, must be critically examined.

A community-focused resilience approach centers on the people who are affected by climate change—the human and social infrastructures that create and support resilient communities. This also includes community involvement in the decision-making process. This is done through participation, inclusion, collaboration, and communication.[78] These efforts cannot be a means for placation, consultation, informing, or manipulation, in which information flows in one-direction and the input from the community is not seriously considered; rather, they need to be a means for partnerships, co-learning, and genuine power, influence, and control in the decision-making processes.[79] Access to accurate information and reliable data is essential so community members can participate meaningfully and make informed decisions.[80] The importance of linking communication and participation is illustrated by a comparative study on flood resilience and risk communication in Finland, Ireland, Italy, and Scotland. A key cross-country finding is that even if residents are aware of risks, they are alarmingly reluctant to adequately prepare for and respond to them. As such, the researchers conclude that more and better information is insufficient to mitigate flood risks; a more multidimensional approach is needed that includes things such as, the provision of concrete information on how to prepare for risks, creating lines of communication between authorities and the public, making responsibilities clear to the public, and the use of multiple channels of communication.[81]

Communicative participation models promote dialog and interaction, and the sharing of local knowledge and lived experiences, to define, through consensus, future actions—a "multidimensional model where communication, learning, and action are joined together and where the polity, interests, and citizenry co-evolve" (Innes and Booher,[82] p. 422). Participation must also involve inclusion. Quick and Feldman's[83] distinction between participation and inclusion is important to community-focused resilience approaches: "…participation is oriented to increasing input for decisions … inclusion is oriented to making connections among people, across issues, and over time" (274). Participatory processes involve creating opportunities for many people to participate, making sure the processes are accessible to all, and collecting input from a wide ranging, but representative sample, of the community to inform policy or take action on a particular issue. Inclusive processes involve creating "an expansive and ongoing framework for interaction" that builds a community's capacity to implement the called for changes or actions, as well address future issues (Quick & Feldman,[83] p. 274).

In addition to communication, participation of community members and inclusive processes can also contribute to improving resilience.[84] Participation, inclusion, and communication can be implemented as stand-alone activities. Yet, a more promising approach would be to integrate these activities into the development and implementation of strategies, projects, and measures as is done, for example, in the form of risk dialogs in the Netherlands. An inspiring example of how infrastructure interventions and community-focused approaches can be combined is provided by an urban stream restoration project in Enschede, the Netherlands. To reduce water nuisance and flooding, which was expected to become more severe with climate change, the municipality decided to invest in a combination of engineering measures (infiltration and drainage pipelines, and water storage facilities), nature-based measures (restoration of an urban stream), and to complement these with an intense participation and communication process to increase their effectiveness. From the beginning of the project, residents were regularly engaged and educated about the problems in the areas as well as the physical measures. In addition, they were invited to codesign some of the measures. When the measures were implemented, the municipality launched an intense communication campaign and a personal engagement approach. Through newsletters, an app, and websites, residents were made not only aware about the progress of construction works but also about the problem that was addressed and actions they could take themselves to make their area more climate resilient.[85]

Community-focused resilience approaches center on the human and social infrastructures that create and support resilient communities and recognize that an array of factors affect a specific community's ability to prevent and accept (or not) climate change risks. Through participation, inclusion, collaboration, and communication, we can gain a better understanding of how different people are affected differently by climate change and what the underlying factors are that are resulting in disparate impacts (i.e., social vulnerabilities), with the goal of improving outcomes in an equitable and systemically sustainable way. Community-focused resilience approaches can work well with nature-based and engineering approaches.

6 | CONCLUSION

The profound effects of climate change have become increasingly visible in countries and communities around the globe. We are now at a critical point—policy decisions to make our long-lived water infrastructure more climate resilient are urgently needed to avoid deterioration of the foundation of basic human needs.[9] While both engineering and nature-based approaches can play an important role in reducing risks, climate change is ultimately also about people.

In this commentary, we explored climate adaptation as a policy dilemma—what risks should (or can) be prevented and what risks should (or have to) be accepted—through three different approaches, nature-based, engineering, and community-focused, and the roles that each can play, separately, as well as in combination. Each of these approaches have their own strengths and weaknesses, and contextual applicability; and all three can be utilized simultaneously. Therefore, this commentary has called for a more holistic understanding of water infrastructures and their resilience to climate change, where multidisciplinary collaboration for research and policy is central. There are several implications for research.

6.1 | Interdisciplinarity

As decisions about and the implementation of climate-resilient water infrastructure cuts across academic disciplinary lines, it requires interdisciplinary research agendas and teams. An interdisciplinary approach would include, at a minimum, civil engineering and geosciences to design and evaluate the effects of engineering and nature-based approaches in a more integrated manner as well as policy sciences to develop and incorporate community-focused approaches and to better understand policy dilemmas and policy implementation.

6.2 | Engaged scholarship

For researchers to support policymakers in understanding the policy dilemma of how much risk to prevent or accept using what approach, they need to closely collaborate with actors in the policy domain—that is, the area where policies and political choices are made—as well as with other societal stakeholders. Such transdisciplinary knowledge coproduction processes are likely to require researchers to become more self-reflective and reflexive in knowledge development and to take on new roles, for example, to mediate and communicate between people with diverse backgrounds.[86] It requires researchers to engage with nonacademic stakeholders in all research phases, from understanding the problem and designing the research, to elaborating theory and communicating findings.[87] Such an engaged approach can play an important role in helping practitioners reflect on routines and practices as a first step in unlearning them and adopting new ones.

6.3 | Collaborative and participatory research

Considering the disparate impacts of climate change and the opportunities associated with combining engineering and/or nature-based approaches with community-focused approaches, researchers should be prepared to harness new types of data through collaborative and participatory research endeavors. This will require examining underlying inequities and vulnerabilities to understand why and how different communities or members of society experience climate change-related events differently, and how this impacts their ability to plan for, withstand, and recover from them. It will also require researchers and policymakers to engage with and involve the public and community members in their research, as well as planning and decision-making processes. This will create opportunities for data to come directly from the people most affected by these events, as well as opportunities to examine the participatory processes themselves.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

This article uses no empirical data.

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REFERENCES

1 Morris, John C., and Richard G. Little. 2019. "Symposium Issue: Climate Change and Infrastructure—The Coming Challenge." *Public Works Management & Policy* 24(1): 3–5.
2 Church, John A., and Neil J. White. 2006. "A 20th Century Acceleration in Global Sea Level Rise." *Geophysical Research Letters* 33(1): 1–4. https://doi.org/10.1029/2005GL024826
3 Orimoloye, Israel R., Olusola O. Ololade, Sonwabo P. Mazinyo, Ahmed M. Kalumba, Olapeju Y. Ekundayo, Emmanuel T. Busayo, Akintomide A. Akinsanola, and Werner Nel. 2019. "Spatial Assessment of Drought Severity in Cape Town Area, South Africa." *Heliyon*, 5 (2019), e02148. https://doi.org/10.1016/j.heliyon.2019.e02148
4 Pattison, Laura., Jack Guy, and Fidel Gutierrez. 2024. One of the World's Biggest Cities May be Just Months Away from Running Out of Water. *CNN.com*. https://www.cnn.com/2024/02/25/climate/mexico-city-water-crisis-climate-intl/index.html
5 Udall, Bradley, and Jonathan Overpeck. 2017. "The Twenty-First Century Colorado River Hot Drought and Implications for the Future." *Water Resources Research* 53: 2404–18. https://doi.org/10.1002/2016WR019638
6 Van Schoot, Foekje. 2021. *Estimating Current and Possible Future Irrigation Water Requirements: An Approach for the Rhine Basin During the Growing Season on Periods of Drought*. Enschede, Netherlands: University of Twente. http://essay.utwente.nl/85890/1/Schoot_MA_ET.pdf
7 Moore, Travis R., H. Damon Matthews, Christopher Simmons, and Martin Leduc. 2015. "Quantifying Changes in Extreme Weather Events in Response to Warmer Global Temperature." *Atmosphere-Ocean* 53(4): 412–25. https://doi.org/10.1080/07055900.2015.1077099
8 Kuks, Stefan M. M. 2023. "Commentary for the RAIN Symposium: Dutch Water Infrastructure Challenged by Climate Change." *Public Works Management & Policy* 28(1): 89–100.
9 European Environmental Agency. 2024. *European Climate Risk Assessment—Executive Summary*. Luxembourg: Publications Office of the European Union. https://data.europa.eu/doi/10.2800/204249
10 Farley, Jonathan D., Jonathan M. Fisk, and John C. Morris. 2024. *The Drought Dilemma: State Politics, Context, and Policy Choices*. New York and Oxon: Routledge.
11 Golembo, Max, Melissa Griffin, and Emily Shapiro 2024. California Faces Flooding, Mudslides as Rain Inundates State. *ABC News.com*. https://abcnews.go.com/US/california-storm-atmospheric-river-flooding-forecast/story?id=107359053
12 Tidwell, Mike. 2003. *Bayou Farewell: The Rich Life and Tragic Death of Louisiana's Cajun Coast*. New York: Vintage Books.

13 Barry, John M. 1997. *Rising Tide: The Great Mississippi Flood of 1927 and How it Changed America*. New York: Touchstone Books.

14 Heim-LaFrombois, Megan E., Charlene LeBleu, Sweta Byahut, and Stephanie Rogers. 2023. “Planning for Green Infrastructure Along the Gulf Coast: An Evaluation of Comprehensive Plans and Planning Practices in the Mississippi-Alabama Coastal Region.” *Journal of Environmental Planning and Management* 66(11): 2352–72. https://doi.org/10.1080/09640568.2022.2074822

15 Holling, Crawford. S. 1996. “Engineering Resilience Versus Ecological Resilience.” *Engineering within Ecological Constraints* 31(1996): 32.

16 Pahl-Wostl, Claudia. 2006. “Transitions Towards Adaptive Management of Water Facing Climate and Global Change.” *Water Resources Management* 21(1): 49–62. https://doi.org/10.1007/s11269-006-9040-4

17 Mehvar, Seyedabdolhossein, Kathelijne Wijnberg, Bas Borsje, Norman Kerle, Jan Maarten Schraagen, Joanne Vinke-de Kruijf, Karst Geurs, et al. 2021. “Review Article: Towards Resilient Vital Infrastructure Systems—Challenges, Opportunities, and Future Research Agenda.” *Natural Hazards and Earth System Sciences* 21(5): 1383–407. https://doi.org/10.5194/nhess-21-1383-2021

18 Hegger, Dries L. T., Peter P. J. Driessen, Mark Wiering, Helena F. M. W. van Rijswick, Zbigniew W. Kundzewicz, Piotr Matczak, Ann Crabbé, et al. 2016. “Toward More Flood Resilience: Is a Diversification of Flood Risk Management Strategies the Way Forward.” *Ecology and Society* 21(4): art52. https://doi.org/10.5751/Es-08854-210452

19 Helfgott, Ariella. 2018. “Operationalising Systemic Resilience.” *European Journal of Operational Research* 268(3): 852–64. https://doi.org/10.1016/j.ejor.2017.11.056

20 Newman, Rebecca, and Ilan Noy. 2023. “The Global Costs of Extreme Weather that are Attributable to Climate Change.” *Nat Commun* 14: 6103. https://doi.org/10.1038/s41467-023-41888-1

21 European Commission. 2021. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Forging a Climate-Resilient Europe—The New EU Strategy on Adaptation to Climate Change (COM(2021)82 Final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN

22 Bani, Mirjam, Ester Barendregt, Marieke Blom, Sander Burgers, Carola de Groot, Rianne Hordijk, Anne Nobel, Sandra Phlippen, and Bram Vendel 2024. *Climate Change and the Dutch Housing Market: Insights and Policy Guidance Based on a Comprehensive Literature Review*. Report prepared by ING, Rabobank and ABN AMRO. https://media.rabobank.com/m/22215b794f64e4e5/original/Climate_change_and_the_Dutch_housing_market_202402.pdf

23 McEwen, Lindsey, and Owain Jones. 2012. “Building Local/Lay Flood Knowledges into Community Flood Resilience Planning after the July 2007 Floods, Gloucestershire, UK.” *Hydrology Research* 43(5): 675–88. https://doi.org/10.2166/nh.2012.022

24 ASLA. 2016. *The Copenhagen Cloudburst Formula: A Strategic Process for Planning and Designing Blue-Green Interventions*. American Association of Landscape Architects. https://www.asla.org/2016awards/171784.html

25 Rosenzweig, Cynthia, and William Solecki. 2014. “Hurricane Sandy and Adaptation Pathways in New York: Lessons from a First-Responder City.” *Global Environmental Change* 28: 395–408. https://doi.org/10.1016/j.gloenvcha.2014.05.003

26 Staff of the Delta Programme Commissioner. 2018. *Delta Programme 2018: Continuing the Work on a Sustainable and Safe*. Delta. https://klimaatadaptatienederland.nl/en/policy-programmes/delta-plan-sa/

27 EEA. 2013. *Adaptation in Europe: Addressing Risks and Opportunities from Climate Change in the Context of Socio-Economic Developments*. Copenhagen, Denmark: European Environment Agency. https://doi.org/10.2800/50924

28 De Urbanisten. 2024. *Twente 2075, City and Water, Overijssel, the Netherlands*. De Urbanisten. https://www.urbanisten.nl/work/twente2075

29 Thomas, Gareth B., and David Crawford. 2011. “London Tideway Tunnels: Tackling London's Victorian Legacy of Combined Sewer Overflows.” *Water Science and Technology* 63(1): 80–7. https://doi.org/10.2166/wst.2011.012

30 VanKoningsveld, Mark., Jan P. M. Mulder, Marcel J. F. Stive, L. VanDerValk, and Arjan W. VanDerWeck. 2008. “Living with Sea-Level Rise and Climate Change: A Case Study of the Netherlands.” *Journal of Coastal Research* 242(2): 367–79. https://doi.org/10.2112/07A-0010.1

31 Depietri, Yaella, and Timon McPhearson. 2017. “Integrating the Grey, Green, and Blue in Cities: Nature-Based Solutions for Climate Change Adaptation and Risk Reduction.” In *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Theory and Practice of Urban Sustainability Transitions*, edited by Nadja Kabisch, Horst Korn, Jutta Stadler and Aletta Bonn, 91–109. Cham: Springer. https://doi.org/10.1007/978-3-319-56091-5_6

32 Leavitt, William M., and John J. Kiefer. 2006. “Infrastructure Interdependency and the Creation of a Normal Disaster: The Case of Hurricane Katrina and the City of New Orleans.” *Public Works Management & Policy* 10(4): 306–14. https://doi.org/10.1177/1087724X06289055

33 van Herk, Sebastiaan, Jeroen Rijke, Chris Zevenbergen, and Richard Ashley. 2015. “Understanding the Transition to Integrated Flood Risk Management in the Netherlands.” *Environmental Innovation and Societal Transitions* 15: 84–100. https://doi.org/10.1016/j.eist.2013.11.001

34 Fukue, Natsuko. 2021. *The Towering Sea Wall Legacy of Japan's 2011 Tsunami*. *The Jakarta Post*. https://www.thejakartapost.com/life/2021/03/05/the-towering-sea-wall-legacy-of-japans-2011-tsunami.html

35 Ahern, Jack. 2011. “From Fail-Safe to Safe-to-Fail: Sustainability and Resilience in the New Urban World.” *Landscape and Urban Planning* 100(4): 341–3. https://doi.org/10.1016/j.landurbplan.2011.02.021

36 Malone, Thomas W., Joanne Yates, and Robert I. Benjamin. 1987. “Electronic Markets and Electronic Hierarchies.” *Communications of the ACM* 30(6): 484–97. https://doi.org/10.1145/214762.214766

37 Williamson, Oliver E. 1981. “The Economics of Organization: The Transaction Cost Approach.” *American Journal of Sociology* 87(3): 548–77. https://doi.org/10.1086/227496

38 Finger, Matthias, John Groenewegen, and Rolf Künneke. 2005. “The Quest for Coherence between Institutions and Technologies in Infrastructures.” *Journal of Network Industries* 4: 227–59.

39 Feenberg, Andrew. 2010. “Between Reason and Experience *Essays in Technology and Modernity*. Massachusetts: MIT Press. https://mitpress.mit.edu/9780262514255/between-reason-and-experience/

40 van Staveren, Martijn F., and Jan P. M. van Tatenhove. 2016. “Hydraulic Engineering in the Social-Ecological Delta: Understanding the Interplay between Social, Ecological, and Technological Systems in the Dutch Delta by Means of “Delta Trajectories.” *Ecology and Society* 21(1): art8. https://doi.org/10.5751/ES-08168-210108

41 Van Buuren, Arwin, Gerald Jan Ellen, and Jeroen F. Warner. 2016. “Path-Dependency and Policy Learning in the Dutch Delta: Toward more Resilient Flood Risk Management in the Netherlands?” *Ecology and Society* 21(4): art43. https://doi.org/10.5751/ES-08765-210443

42 Smith, Adrian, Andy Stirling, and Frans Berkhout. 2005. "The Governance of Sustainable Socio-Technical Transitions." *Research Policy* 34(10): 1491–510. https://doi.org/10.1016/j.respol.2005.07.005
43 Smith, Adrian, Jan-Peter Voß, and John Grin. 2010. "Innovation Studies and Sustainability Transitions: The Allure of the Multi-Level Perspective and its Challenges." *Research Policy* 39(4): 435–48. https://doi.org/10.1016/j.respol.2010.01.023
44 Markard, Jochen. 2011. "Transformation of Infrastructures: Sector Characteristics and Implications for Fundamental Change." *Journal of Infrastructure Systems* 17(3): 107–17. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000056
45 Dominguez, Damian, Hagen Worch, Jochen Markard, Bernhard Truffer, and Willi Gujer. 2009. "Closing the Capability Gap: Strategic Planning for the Infrastructure Sector." *California Management Review* 51(2): 30–50. https://doi.org/10.2307/41166479
46 Pot, Wieke D. 2021. "The Governance Challenge of Implementing Long-Term Sustainability Objectives with Present-Day Investment Decisions." *Journal of Cleaner Production* 280: 124475. https://doi.org/10.1016/j.jclepro.2020.124475
47 Pot, Wieke D., Aart Dewulf, G. Robbert Biesbroek, Maarten J. van der Vlist, and Catrien J. A. M. Termeer. 2018. "What Makes Long-Term Investment Decisions Forward Looking: A Framework Applied to the Case of Amsterdam's New Sea Lock." *Technological Forecasting and Social Change* 132: 174–90. https://doi.org/10.1016/j.techfore.2018.01.031
48 Johns, Carolyn M. 2019. "Understanding Barriers to Green Infrastructure Policy and Stormwater Management in the City of Toronto: A Shift from Grey to Green or Policy Layering and Conversion?" *Journal of Environmental Planning and Management* 62(8): 1377–401. https://doi.org/10.1080/09640568.2018.1496072
49 Kaufmann, Maria, Willemijn V. Doorn-Hoekveld, Herman K. Gilissen, and H. F. Marleen W. Van Rijswick. 2016. *Analysing and Evaluating Flood Risk Governance in the Netherlands: Drowning in Safety*. Utrecht: STARFLOOD Consortium.
50 Bosoni, Mattia, Barbara Tempels, and Thomas Hartmann. 2021. "Understanding Integration within the Dutch Multi-layer Safety Approach to Flood Risk Management." *International Journal of River Basin Management* 21(1): 1–7. https://doi.org/10.1080/15715124.2021.1915321
51 Fisk, Jonathan M., Paul A. Harris, Stefan M. M. Kuks, John C. Morris, and Joanne Vinke-De Kruijf. 2023. "Framing Water Infrastructure for Climate Resilience: Governance Dimensions and Challenges." *Public Works, Management & Policy* 29(2): 13-3-145. https://doi.org/10.1177/1087724X231212556
52 European Commission. 2024. *Nature Based Solutions. Directorate-General for Research and Innovation*. https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions_en
53 Dobre, Catalina C., Joanne. Vinke-de Kruijf, Luisa Moretto, and Marco Ranzato. 2018. "Stormwater Management in Transition: The Influence of Technical and Governance Attributes in the Case of Brussels, Belgium." *Environmental Science & Policy* 85: 1–10. https://doi.org/10.1016/j.envsci.2018.03.015
54 NbS Initiative. 2024. *Case Study Platform: Examples of Good Nature-Based Solutions from Around the World*. Nature-based Solutions Initiative, Department of Biology, University of Oxford. https://casestudies.naturebasedsolutionsinitiative.org/case-search/
55 van den Hoek, Ronald E., Marcela Brugnach, Jan P. M. Mulder, and Arjen Y. Hoekstra. 2014. "Analysing the Cascades of Uncertainty in Flood Defence Projects: How "Not Knowing Enough" is Related to "Knowing Differently"." *Global Environmental Change* 24: 373–88. https://doi.org/10.1016/j.gloenvcha.2013.11.008
56 Brand, Evelien, Gemma Ramaekers, and Quirijn Lodder. 2022. "Dutch Experience with Sand Nourishments for Dynamic Coastline Conservation–An Operational Overview." *Ocean & Coastal Management* 217: 106008. https://doi.org/10.1016/j.ocecoaman.2021.106008
57 Costanza, Robert, William J. Mitsch, and John W. Day. 2006. "A New Vision for New Orleans and the Mississippi Delta: Applying Ecological Economics and Ecological Engineering." *Frontiers in Ecology and the Environment* 4(9): 465–72. https://doi.org/10.1890/1540-9295(2006)4[465:ANVFNO]2.0.CO;2
58 Farber, Stephen, Robert Costanza, Daniel L. Childers, Jon Erickson, Katherine Gross, Morgan Grove, Charles S. Hopkinson, et al. 2006. "Linking Ecology and Economics for Ecosystem Management." *Bioscience* 56(2): 121–33. https://doi.org/10.1641/0006-3568(2006)056[0121:LEAEFE]2.0.CO;2
59 Anderson, Carl C., Fabrice G. Renaud, Stuart Hanscomb, and Alejandro Gonzalez-Ollauri. 2022. "Green, Hybrid, or Grey Disaster Risk Reduction Measures: What Shapes Public Preferences for Nature-Based Solutions?" *Journal of Environmental Management* 310: 114727. https://doi.org/10.1016/j.jenvman.2022.114727
60 Ommer, Joy, Edoardo Bucchignani, Laura S. Leo, Milan Kalas, Saša Vranić, Sisay Debele, Prashant Kumar, Hannah L. Cloke, and Silvana Di Sabatino. 2022. "Quantifying Co-Benefits and Disbenefits of Nature-based Solutions Targeting Disaster Risk Reduction." *International Journal of Disaster Risk Reduction* 75: 102966. https://doi.org/10.1016/j.ijdrr.2022.102966
61 Raymond, Christopher M., Niki Frantzeskaki, Nadja Kabisch, Pam Berry, Margaretha Breil, Mihai R. Nita, Davide Geneletti, and Carlo Calfapietra. 2017. "A Framework for Assessing and Implementing the Co-Benefits of Nature-Based Solutions in Urban Areas." *Environmental Science & Policy* 77: 15–24. https://doi.org/10.1016/j.envsci.2017.07.008
62 Vink, Karina, and Joanne Vinke-de Kruijf. 2023. "The Impacts of Urban Green Infrastructure on Water and Energy Resources: Lessons from and the Need for Integrated Studies. In *Urban Green Spaces-New Perspectives for Urban Resilience*, edited by Monteiro, Cristina M., Cristina Santos, Cristina Matos, Ana Briga Sa. IntechOpen. https://doi.org/10.5772/intechopen.113868
63 Morris, Rebecca L., Teresa M. Konlechner, Marco Ghisalberti, and Stephen E. Swearer. 2018. "From Grey to Green: Efficacy of Eco-Engineering Solutions for Nature-Based Coastal Defence." *Global Change Biology* 24(5): 1827–42. https://doi.org/10.1111/gcb.14063
64 Alves, Alida, Zoran Vojinovic, Zoran Kapelan, Arlex Sanchez, and Berry Gersonius. 2020. "Exploring Trade-Offs Among the Multiple Benefits of Green-Blue-Grey Infrastructure for Urban Flood Mitigation." *Science of the Total Environment* 703: 134980. https://doi.org/10.1016/j.scitotenv.2019.134980
65 Anderson, Carl C., Fabrice G. Renaud, Stuart Hanscomb, Karen E. Munro, Alejandro Gonzalez-Ollauri, Craig S. Thomson, Eija Pouta, et al. 2021. "Public Acceptance of Nature-Based Solutions for Natural Hazard Risk Reduction: Survey Findings from Three Study Sites in Europe." *Frontiers in Environmental Science* 9: 678938. https://doi.org/10.3389/fenvs.2021.678938
66 Hartmann, Thomas, Lenka Slavíková, and Simon McCarthy. 2019. "Nature-Based Solutions in Flood Risk Management." In *Nature-Based Flood Risk Management on Private Land*, edited by T. Hartmann, L. Slavíková and S. McCarthy, 3-8. Cham: Springer. https://doi.org/10.1007/978-3-030-23842-1_1
67 Warbroek, Beau, Bunyod Holmatov, Joanne Vinke-de Kruijf, Maarten Arentsen, Moozhan Shakeri, Cheryl de Boer, Johannes Flacke, and André Dorée. 2023. "From Sectoral to Integrative Action Situations: An Institutional Perspective on the Energy Transition Implementation in the Netherlands." *Sustainability Science* 18: 97–114. https://doi.org/10.1007/s11625-022-01272-2
68 Tariq, Hisham, Chaminda Pathirage, and Terrence Fernando. 2021. "Measuring Community Disaster Resilience at Local Levels: An

Adaptable Resilience Framework." *International Journal of Disaster Risk Reduction* 62: 102358. https://doi.org/10.1016/j.ijdrr.2021.102358

69 Ezer, Tal. 2018. "The Increased Risk of Flooding in Hampton Roads: On the Roles of Sea Level Rise, Storm Surges, Hurricanes, and the Gulf Stream." *Marine Technology Society Journal* 52(2): 34–44. https://doi.org/10.4031/MTSJ.52.2.6

70 Kofsky, Jared, Maia Rosenfeld, and Steve Osunsami 2023. Alabama Accused of 'Highway Robbery' Following Flooding of Predominantly-Black Community." *ABC News*. https://abcnews.go.com/US/alabama-accused-highway-robbery-flooding-predominantly-black-community/story?id=104049059

71 Schrader, Esther. 2023. *Residents of Alabama City Face Water Crisis Like Some Other Black Communities*. Southern Poverty Law Center. https://www.splcenter.org/news/2023/11/03/residents-alabama-face-water-crisis-black-communities

72 Consortium for Alabama Rural Water and Wastewater Management. 2023. *Facing the Issues*. https://ruralwastewater.southalabama.edu/facing-the-issues/

73 American Planning Association. 2023. https://planning.org/

74 Resilient Cities Network. 2023. https://resilientcitiesnetwork.org/what-is-urban-resilience/

75 EPA. 2021. *Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts*. U.S. Environmental Protection Agency, EPA 430-R-21-003. https://www.epa.gov/cira/social-vulnerability-report

76 Masterson, Jaimie H., et al. 2014. *Planning for Community Resilience: A Handbook for Reducing Vulnerability to Disasters*. Island Press.

77 Wilson, Barbara B. 2018. *Resilience for All: Striving for Equity Through Community-Driven Design*. Washington: Island Press.

78 Morris, John C., and Katrina Miller-Stevens. 2015. "The State of Knowledge in Collaboration." In *Advancing Collaboration Theory*, edited by J. C. Morris and K. Miller-Stevens, 23–33. Routledge.

79 Arnstein, Sherry R. 1969. "A Ladder of Citizen Participation." *Journal of the American Institute of Planners* 35(4): 216–24. https://doi.org/10.1080/01944366908977225

80 Hanna, Kevin S. 2000. "The Paradox of Participation and the Hidden Role of Information: A Case Study." *Journal of the American Planning Association* 66(4): 398–410. https://doi.org/10.1080/01944360008976123

81 O'Sullivan, John J., Roisin A. Bradford, Marino Bonaiuto, Stefano De Dominicis, Pia Rotko, Juha Aaltonen, Kerry Waylen, and Simon J. Langan. 2012. "Enhancing Flood Resilience Through Improved Risk Communications." *Natural Hazards and Earth System Sciences* 12(7): 2271–82. https://doi.org/10.5194/nhess-12-2271-2012

82 Innes, Judith E., and David E. Booher. 2004. "Reframing Public Participation: Strategies for the 21st Century." *Planning Theory & Practice* 5(4): 419–36. https://doi.org/10.1080/1464935042000293170

83 Quick, Kathryn S., and Martha S. Feldman. 2011. "Distinguishing Participation and Inclusion." *Journal of Planning Education and Research* 31(3): 272–90. https://doi.org/10.1177/0739456X11410979

84 Morris, John C., Madeleine W. McNamara, and Amy Belcher. 2018. "Building Resilience Through Collaboration Between Grassroots Citizen Groups and Governments: Two Case Studies." *Public Works Management & Policy* 24(1): 50–62.

85 Warbroek, Beau W. D., Joanne Vinke-de Kruijf, and Mitchell van Dijk 2021. *The Influence of Citizen Participation on Climate Behaviour in the Stadsbeek Project: Inventory of Participation Measures*. University of Twente. https://klimaatadaptatienederland.nl/publish/pages/182394/report-part-1-stadsbeek-project.pdf

86 Vinke-de Kruijf, Joanne, Laura Verbrugge, Barbara Schröter, Robert-Jan den Haan, Juliette Cortes Arevalo, Jan Fliervoet, Jennifer Henze, and Christian Albert 2022. "Knowledge co-production and researcher roles in transdisciplinary environmental management projects." *Sustainable Development* 30(2): 393–405. https://doi.org/10.1002/sd.2281

87 Van de Ven, Andrew H. 2007. *Engaged scholarship: A guide for organizational and social research*. USA: Oxford University Press.