BACKGROUND PAPER

ADAPTATION'S THIRST: ACCELERATING THE CONVERGENCE OF WATER AND CLIMATE ACTION

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Vision

We can only see a short distance ahead, but we can see plenty there that needs to be done.

– Alan Turing

A vision of enduring, effective adaptation for communities, poverty alleviation in the face of major environmental change, and greening of economic development requires a commitment to climate action through resilient water management choices. Many institutions are well along the path to implementing climate-resilient water management, but many groups are still struggling with basic strategy: how do we ensure that our climate actions will be effective in the face of emerging and uncertain impacts? Here, we suggest that water has a role in coordinating climate action and provisioning climate coherence.

About this paper

This paper is part of a series of background papers commissioned by the Global Commission on Adaptation to inform its 2019 flagship report. This paper reflects the views of the authors, and not necessarily those of the Global Commission on Adaptation.

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Water has long been recognized as a central component of climate change impacts as well as a tool to ensure effective adaptation. In the words of Carter Roberts, CEO, WWF-US, at the 15th session of the Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen in 2009, "The language of water *is* the language of climate change." Nevertheless, miscommunication and misunderstanding remain an issue between the water and climate change communities.

Indeed, there has been a fear that water may come to dominate climate change adaptation. In 2015, in the run-up to the UNFCCC's COP 21 in Paris, the French Ambassador for Climate Change confronted the world's water community gathered at the World Water Forum in the Republic of Korea, and asked: "Water is already mentioned in 80 percent of the national climate change plans. What more do you want?"

The problem may have been more broadly articulated at COP 22 in Marrakesh in 2016, when Morocco sponsored the first-ever official Water Action Day. Some 50 groups—national, United Nations, multilateral and bilateral donor, nongovernmental and civil society organizations—participated in the event. In providing guidance to the event's moderators, a UNFCCC official suggested two questions: what can the water community do to help advance climate change targets, and what can the climate community do to help advance water resilience targets? Today, these questions remain the core issues for the intersection of policy and decision-making on water and climate change.

The challenge for both defining and implementing answers to these questions is that water is both the "water sector" as well as profoundly cross-sectoral. Simplistically acknowledging that water is important for climate change or that the "water sector" must be resilient to climate change impacts misses the critical need for system-wide coherence on water across many agendas and, indeed, the opportunities made possible by that coherence.

What people commonly call the "water sector" addresses water supply, storage, and sanitation, especially for cities, but water is also a resource critical to and embedded within many other sectors, development goals and communities, including: health; energy; agriculture; cities; equality and poverty alleviation; ecosystems and natural resource management; forestry; and disaster preparation, recovery, and management.

Clearly, we must continue to manage water beyond and across sectors. Can we also harness the ubiquity of water as a tool to advance climate change adaptation for many communities of practice? Is there a shared vision for water and climate change? Can the dual nature of water flip from being a challenge to becoming an opportunity to align policy and implementation for water and climate change adaptation agendas around water resilience?

The UNFCCC's guiding questions for the water and climate change communities are more relevant today than ever before. This background paper points to evidence of a growing and convergent synthesis that the space shared by the "water sector", other sectors that critically rely on water, and the policy and practice of climate change adaptation is climate-resilient water management. Climate-resilient water management should be the common ground and a unifying agenda for water and climate change adaptation. The emerging practice of water management for resilience is well founded and can be implemented today.

Climate-resilient water management has been developing as a strategy, target of investment, and body of practice in climate change adaptation since about 2007. It contains two key elements: defining robust actions that perform well across a wide range of possible future climates, and defining flexible actions to climate shocks and stressors and long-term uncertainties in future climate change impacts. Clear priorities for policy and action on climate change adaptation can be defined through the combination of robust and flexible approaches in building resilience through water management.

The goal here is to answer the fundamental two-audience question posed by the UNFCCC in 2016: what can the water community do to help advance targets for climate change adaptation, and what can the climate community do to help advance targets for water resilience?

1. Water and Adaptation: Menace with Hope

The language we use for climate change paints a grim picture, in which vulnerabilities overwhelm our infrastructure and institutions, and, even if we can slow the rate of climate change, we face a fast-rising tide of climate crises. In this drama, the water cycle amplifies our peril, menacing us with floods, droughts, tropical cyclones, extreme precipitation, lost snowpack, drained aquifers, polluted rivers, and parched wetlands. Damaging and destructive impacts are occurring and will continue to occur—populations will be displaced, livelihoods abandoned, agriculture and food security imperiled, the human right to water and sanitation undermined, and beloved cultural and natural expressions lost. Water will be the claws and teeth of climate change, now and in the future.

But, in its real telling, the story of water and climate change is both more complex and more hopeful.

The world's community of water professionals has come largely to share the insight that water is the key to climate change adaptation. If we can build resilience by managing water, we can move from a reactive, defensive approach to climate change to imagining how we can thrive. Yes, big changes must occur, and some of these will even be radical. But much of what we need to do is pretty clear. Our response to climatic uncertainty and looming impacts should be neither despair nor inaction but courage and hope; we should be choosing the future we want to move toward, and finding valid and realistic means of reaching that future. In this vision, the future we choose is resilient to climate change, and water is not solely a menace but also a source of solutions, enabling adaptation.

The global water cycle is embedded in the global climate system. Most often, we view water narrowly and locally: *our* river or lake, *our* irrigation system, *our* flood levee, *our* cooling reservoir or wastewater treatment plant. The water cycle is far more, however, than the water we can see. It is a complex system that interconnects uses of water in rural communities, towns and cities with struggles for dignified lives, health and equality; that couples the energy, agricultural and industrial sectors with nature and the future survival of ecosystems; and that embeds risks from flows of water on land, below ground and in the atmosphere within multibillion dollar decisions taken in corporate boardrooms and at cabinet tables in world capitals. Climate change is reconfiguring this water system. Accelerating evaporation, shifts in the seasonality of precipitation or rates of groundwater recharge, or changing risks of unexpected deluge are unravelling basic assumptions about how we manage water in agriculture and cities or for public health, rural livelihoods and nature conservation. But therein lies opportunity – through adaptation of water management, we can build resilience to climate change across these priorities.

Seen through a resilience lens, adaptation to climate change is not a quest for a single fix for a static problem; adaptation is putting in place levers and tools for adapting a complex system to a dynamically changing future. Resilience emerges by managing interconnected changes in institutions, knowledge, incentives, infrastructure, ecosystems, and social constructs. The goal is to equip people and societies with the means to make the adjustments across systems, sectors, and scales that are needed to withstand, recover from, and anticipate the impacts of climate change. Water management provides these vital levers and tools for resilience.

Seizing this opportunity will be made possible by matching institutions and infrastructure to new climates. The perils of failing to do so were recognized in the 19th century by John Wesley Powell, director of the U.S. Geological Survey between 1881 and 1894. He made the radical proposition that the western part of North America would be damaged and disserved by having "wet climate" institutions that had evolved in humid eastern North America—and by extension in Great Britain—imposed on an arid landscape. He knew that forcing farmers to work in small increments of land that assumed ample rain-fed water supply for row crops rather than larger parcels to support dry-range livestock or collective irrigation schemes would doom those farmers to fail. He saw that defining political boundaries that did not match hydrological basins would plant deep seeds of lasting conflict between farmers, corporations, cities, and indigenous populations. Powell saw that institutions and infrastructure must match their climate carefully to facilitate success, growth, and resilience.

As old assumptions about a stable climate are replaced by dynamic and changing climatic uncertainty, contemporary water managers around the world have much in common with Powell. They must align water management with emerging understanding of new realities. They must design new policies to guide institutions, strategies, planning, and investment as the climate continues to shift. They must do so while recognizing that water infrastructure built now will effectively lock in our choices for decades or centuries while the climate continues to change, and that regulatory frameworks, cross-sectoral water allocations, and water-sharing agreements, if not well structured, will cause water management to be rigid when it needs to be adaptive and agile.

Fortunately, there are many Powells today, reminding us of the need to align our institutions and infrastructure with a shifting climate and a dynamic, uncertain water cycle. The agendas for both water and climate security are converging as a result. We have effective, powerful lessons to build on and, despite high levels of uncertainty, enough knowledge to know that big changes have already occurred and larger changes will be coming. Every decision we make now about water management is also a chance to build resilience more broadly. We can take effective action, and we can prepare.

2. Water-Related Impacts of Climate Change

2.1 Impacts of Changes in the Water Cycle

A warming atmosphere holds more water vapor. Observed warming has been linked as a result to changing precipitation patterns, intensity and extremes, and to changes in runoff to rivers, lakes and wetlands, in addition to melting of ice and reduced snow cover. These changes cause many of the most serious and most high-profile projected risks from climate change:[1,2]

- Intensification of the global water cycle, bringing about **changes to fundamental hydrology,** such as precipitation, runoff, tropospheric water vapor, soil moisture, glacier mass balance, evaporation, evapotranspiration, and growing season length. Over varying timescales, these changes impact water resource availability, in both quantity and quality.[3]
- **Variability in seasonal patterns** of rainfall, onset and length of seasons, heat waves and extreme cold, associated with sea-surface temperature changes and changes in atmosphere-ocean dynamics linked to observed anomalies in the North Atlantic Oscillation (NAO), Atlantic Multi-decadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO).[4,5,6]
- Increased human exposure to **flooding,** because of more frequent heavy rainfall events, projected particularly in South, Southeast and Northeast Asia, parts of Africa and South America.[2] Flood risks will expand as warming increases, with three times more people exposed to the equivalent of a 20th century 100-year flood event by the end of the 21st century for high-emission than very low-emission scenarios.[2,7]
- More frequent and intense extreme events such as **tropical storms.**[7] Tropical cyclone rainfall has increased, which has resulted in increased flooding and saltwater intrusion in coastal regions.[8]
- Increased frequency of **drought,** with a higher proportion of land in extreme drought at any time.[1] The area of land subject to increasing **water stress** is projected to more than double by 2050, while for each degree of global warming, approximately 7 percent of the global population is projected to be exposed to a decrease in renewable water resources of at least 20 percent.[2]
- An estimated 0.5-3.1 billion additional people will be living with **water scarcity** by 2050 because of climate change.[9]
- Reduced water availability in warm and dry periods for the one-sixth of the world's population that live in regions dependent on meltwater from major mountain ranges, and possibly reduced summer flows downstream because of **less snow cover and loss of glacier ice.**[2]
- **Reduced river runoff** leading to reduced water availability by mid-century in arid and semi-arid areas such as the Mediterranean basin, Southern Africa, Western USA and North-eastern Brazil. River runoff is projected to increase at high latitudes and in some wet tropical areas.[1,2]
- Sea-level rise leading to increased **salinization of water supplies** in estuaries and from coastal aquifers.[2] Sea-level rise imposes higher risks of coastal erosion and inundation of coastal wetlands, while bringing

about rapid changes in coastal hydrodynamics and morphology.[10]

- **Lower water quality** because higher temperatures strongly influence increases in organic matter, nitrate and phosphorus levels in river water.[8] Record levels of harmful algal blooms have been observed in lakes and reservoirs in different regions, triggered by high temperatures.[11]
- Increased **water pollution,** because of the effects of more frequent extreme events and higher runoff of sediments, nutrients, dissolved organic carbon, pathogens, pesticides, and salt, and higher water temperatures.[1,2]
- Significant **changes in flow patterns in rivers** and hence the habitat of aquatic biota. Particularly in low-flow conditions, climate change is predicted to cause stream macroinvertebrate species abundance to decrease by up to 42 percent as a result of transformative ecological droughts.[12]
- Impacts on **groundwater availability** because of direct and indirect effects of climate change. Groundwater storage in the Murray-Darling basin in Australia declined substantially and continuously from 2000 to 2007 in response to a sharp reduction in recharge during the multi-annual Millennium Drought.[13] Long-term loss of glacial storage in mountain ranges is estimated to reduce summer baseflow in many regions and groundwater recharge.

Impacts from changes in hydrology caused by climate change are faced across society. Drinking water supply is at risk from damage to infrastructure by flooding, reduced water availability because of lower rainfall, and changes in water quality.[14] In agriculture, crop water stress is a major driver of yield loss. Increased frequency of drought, unpredictability of the onset of rainy seasons, and flooding caused by more intense rainfall can all lead to seasonal crop failures, long-term loss of production and food insecurity.[15,16] In the energy sector, thermoelectric power and hydropower, which contribute 98 percent of electricity generation worldwide, are both highly dependent on water. Modeled estimates show reductions in usable capacity for 61–74 percent of hydropower and 81–86 percent of thermoelectric plants worldwide for the period 2040–2069 because of reduced water availability and higher water temperatures.[17] Spatial and temporal changes in the distribution of water caused by climate change have multifaceted implications for ecosystem services (Figure 2.1).[18] Evidence is growing that climate change is also a major driver of water quality impacts.[19,20]

Water is a connector for climate change adaptation, linking impacts felt across sectors, by all social groups, in cities, in factories, and on farms. Therefore, approaching adaptation to water-related impacts of climate change as a problem limited to the water sector is a mistake. Water is not a sector. It is a resource managed across economies, from local to national and higher levels. The impacts of climate change on water are systemic, with interdependencies and linkages across sectors. They cascade across systems in complex ways, with consequences for economies, food systems and ecosystems, for the movement of people and the security of communities, and for the eventual success or failure of sustainable development.[21,22]

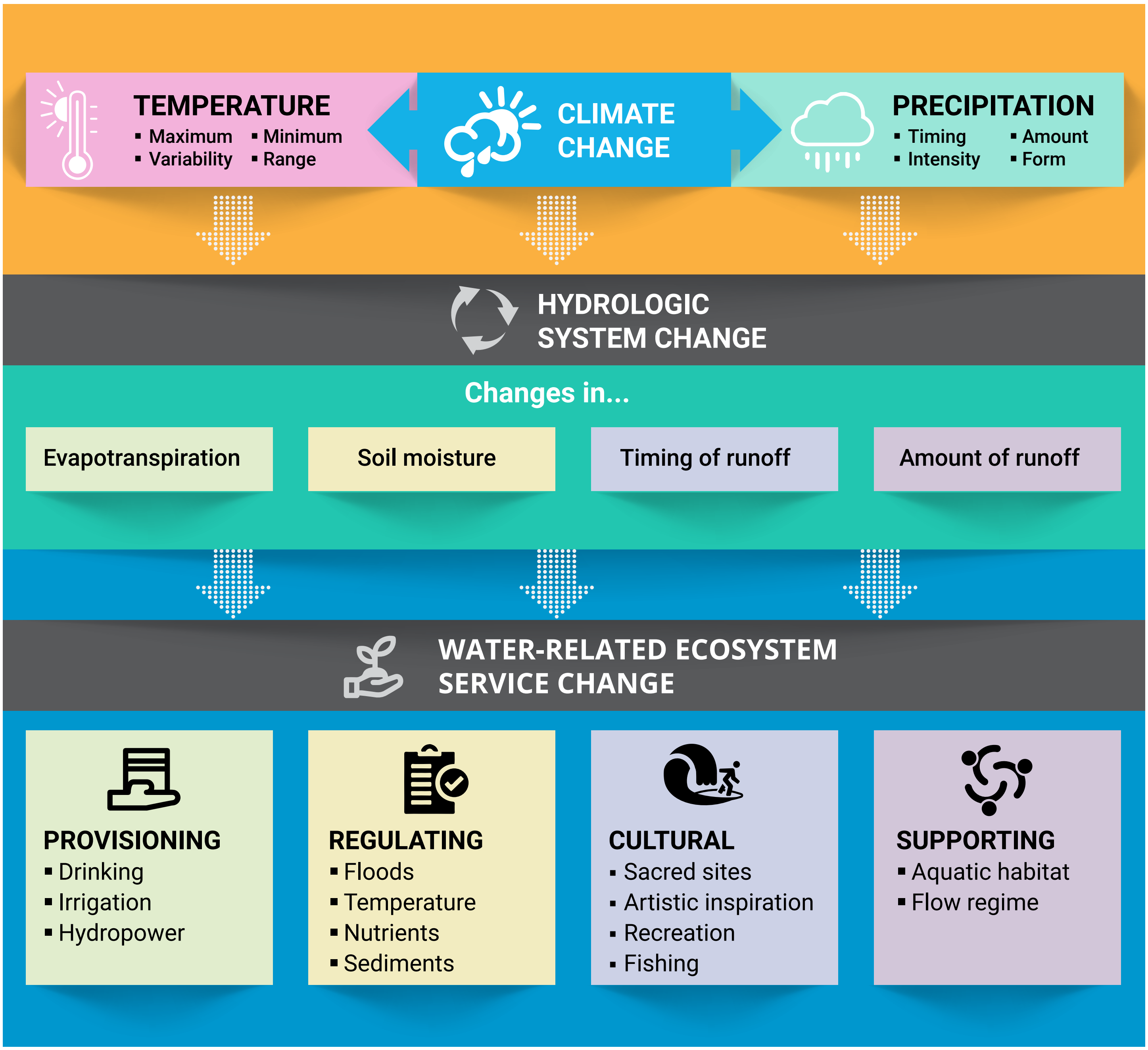
2.2 Economic Effects of Water-related Impacts of Climate Change

Where water is reliably available, economic opportunities are enhanced. Where it is variable and unpredictable, global analysis shows that it creates a drag on economic growth, especially where agriculture accounts for a large share of the economy.[23,24,25] Annual water availability has a measurable effect on economic growth each year across all sectors, with more predictable runoff related to higher growth in gross domestic product (GDP).[26,27] The costs of inaction on water-related climate change impacts are therefore expected to be high.

Cost estimates for water-related impacts of climate change, however, tend to vary widely because water resources are entangled and embedded in so many ways in our economies and societies. Global analysis suggests expected annual flood damage of US$120 billion per year from property damage alone,[26] and in the absence of adaptation, coastal flood risk could increase fourfold, while fluvial flood risk could double by 2030.[26] Such estimates do not factor in the economy-wide and indirect damages caused by flooding, such as through loss of investor confidence or disruptions in supply chains, and hence the true picture is likely worse. Economic impacts of drought are even more difficult to circumscribe, but are thought to account for about one-fifth of the damage caused by all natural hazards and amount to at least US$80 billion per year on average.[28,29]

The costs of water insecurity extend well beyond those quantified in economic assessments. For instance, although drought might lead to temporary negative economic growth, the consequences for human development and women's empowerment among other issues can be long-lasting and permanent.[30] In sub-Saharan Africa, women exposed to drought conditions during their early childhood are significantly less wealthy as adults, have reduced adult height, and fewer years of formal education.[30] Even more worryingly, evidence

FIGURE 2.1 Cascading Effects of Climate Change on Water-related Ecosystem Services



Source: Chang and Bonnette.[18]

suggests that these impacts may be transmitted across generations, with children of women affected by drought more likely to be born at low birth weight.[31]

Water-related challenges in the face of climate change may also have spillover effects on the stability of social and political systems. Where populations are particularly vulnerable to the direct impacts of water insecurity and where water insecurity can intensify perceptions that the government is unwilling to or unable to meet the needs of its citizens, water acts as a destabilizing force and risk multiplier.[32] Evidence does not suggest that there is a direct causal linkage between water crises and conflict, social tensions and unrest, migration, or other manifestations of fragility. What is clear, however, is that institutions and policy choices can reduce water-related impacts on people and economies, and that failure to address these impacts plays into the complex and more fundamental dynamics underpinning social, economic, and political stability.

2.3 Systemic Challenges for Water and Climate Change

The systemic nature of water creates challenges for climate change adaptation. Water is both a sectoral and a multi-sectoral problem in climate change that cannot be resolved without both sectoral and multi-sectoral interventions. Just as impacts of climate change are connected by water, so is action taken on adaptation. Adaptation in one sector can have impacts on other sectors because of water. If irrigation expands to reduce crop yield loss as temperatures rise and rainfall patterns shift, for example, then less water is available for hydropower, which would increase demand on thermoelectric power plants and hence water for cooling. In response to shifts in the timing and intensity of precipitation as well as patterns of water consumption, the mayor of Udon Thani, Thailand, has had to try to balance increased urban flooding, dry-season trade-offs between hydropower and rice irrigation, and urban water quality.[33] The new complexities of climate require more cross-sectoral solutions and synergies; effective adaptation requires that systemic chains of cause and effect are understood and managed. Otherwise, poorly planned or ill-conceived adaptation can inadvertently lead to higher exposure to climate change risks. Failure to account for water and the interconnections it creates across sectors and systems puts the efficacy of climate change adaptation at risk.

The converse is also true: the systemic nature of water creates vital opportunities to make adaptation strategies more effective. If floods, water scarcity, more intense storms or melting ice cause vulnerabilities for livelihoods, infrastructure, health, and peace and security, for example, then well-designed and well-planned action on water-related adaptation can synergize solutions. Water management is therefore an enabler and amplifier of adaptation.

Recognition of water as an enabler of adaptation is being increasingly mainstreamed in action on climate change. The Green Climate Fund (GCF), for instance, explicitly prioritizes water management as a mechanism for joining sectoral and multi-sectoral adaptation.[34] Indeed, the GCF hierarchy of adaptation funding priorities describes how adaptive water resources management serves as a vehicle between adaptation actions in agriculture, land use and forestry, and more transformative approaches in infrastructure and urban resilience. GCF also supports "transformative resilience" within its adaptation portfolio, linking disaster risk reduction (DRR) with both hard and soft solutions for resilient integrated infrastructure (transport, energy, water networks) and resilient cities. Such hard and soft resilience solutions need to incorporate Integrated Water Resources Management (IWRM) with ecosystem management and restoration in order to ensure sustainability. Water management is the bridge linking adaptation and "transformative resilience," and natural and built infrastructure.[34] The mayor of Udon Thani used similar insights in plotting a way forward for adaptation in the city, and chose a set of green solutions to reduce flood risk, increase water quality, and reduce competition for water supply, as well as improve long-term quality of life in the city.[33]

Water-centric adaptation demands management of water risks across systems where, as climate change unfolds, hydrology is no longer stationary and uncertainty is increasing. Strategies for adaptation must therefore combine robustness—through measures that work well because they help us to adjust to and prepare for many possible climate futures—as well as flexibility to ensure we retain the capacity to adjust course and overcome hazards, impacts, and vulnerabilities that may arise in the future. Both strategies contribute to and can be embedded in resilience.

3. Adaptation Principles: Applying Climate-Resilient Water Management

3.1 Water Management under Non-Stationary Future Climates

Water is naturally variable, and that variability has always challenged human interactions with water—will we have water when and where we need it, with suitable quality? Can we endure, resist, and recover from short-term shocks, such as flood events or droughts? Can we identify and compensate for long-term stressors?

Throughout human history, we have tried to manage water to reduce the impact of variability—lowering the risk of potential disasters, making sure water was available when and where we needed it, with the right level of quality, for the services we needed, for energy, agriculture, drinking water, drought and flood protection. In most cases, we have reduced variability by building infrastructure and institutions. Archeological evidence suggests that controlled rice irrigation began in eastern China about 7000 BCE. Evidence of sophisticated water infrastructure in Mesopotamia, South America, Pacific Islands, South Asia, and North Africa goes back many millennia, implying long-term governance, adaptive management, and the ability to alter course in the face of shifting conditions and needs, including climate changes over the past 5,000 years. *Waterschappen* or "water authorities" in the Netherlands, for instance—which continue to form the basic unit of water governance in the country in the modern era—were first formed about 800 CE by small settlements to organize reclamation of land from rivers and the sea for agriculture and communities, and to control flood risk through dyke management.

For at least two centuries, however, the basic premise for managing water variability has been the assumption of stationarity[35,36] —that we can understand future weather patterns and water risks by analyzing trends and patterns from past decades and centuries.[i] Using this concept of stationarity, the past is assumed to predict the future. Stationarity is a simplifying assumption: agreements, institutions, investments, regulations, and infrastructure used to help manage risks and reduce variability can be planned based on the statistical properties of past hydrology. Predictability is much easier to manage than uncertainty—decision-making in water management, planning, policy, and investment function more smoothly if the past can be used to confidently predict the future.

Indeed, by assuming a stable climate, we can confidently quantify variability in future hydrology and then develop highly efficient, optimized "single-solution" plans and designs for the future. We can optimize our operations, economic choices, regulations, and governance for one climate, one set of conditions. If we know what the future looks like, then we have little need to hedge our bets across multiple or competing futures. Flood management, for instance, has traditionally used past records of flood frequency and severity to develop design standards for 1-in-100-year flood protection (referred to as the "return period"). Such calculations are widely used as the basis for regulatory standards, insurance schemes, and policy frameworks, and would continue to do so if—and only if—the assumption that climate conditions will remain stable was valid.

In 2008, however, Milly and colleagues argued for initiating a new era of resilient water management by famously declaring the assumption of stationarity "dead."[36] Climate change undermines this core tenet of planning and design because of the profound uncertainties we face as the water cycle shifts. The past is no longer a reliable predictor of the future. In many cases we no longer have enough confidence in what the future might look like to develop highly optimized solutions. What does a 1-in-100-year flood event mean, if we can expect the frequency and severity of flood events to evolve for many additional decades as the climate changes? Likewise, for critical assets and institutions with long lifetimes whose failure or degradation would have severe consequences, determining a single optimized design or set of operational guidelines may no longer be possible. Figures 3.1 and 3.2, for example, illustrate some of the largest water investments of the 20th century and how, because of the growing mismatch between their design parameters and a non-stationary climate, they are becoming systemic threats for diverse

[i] Stationarity is used here to refer to patterns of water variability remaining within the bounds of historical records of availability, scarcity, seasonality, and frequency of climatic events or extremes. It does not imply that past water regimes were static.

FIGURE 3.1 The Hoover Dam and its reservoir, Lake Mead, on North America's Colorado River

One the largest dams in the world, it was built in the 1930s for flood control, drinking water supply, and hydropower generation. The white strip along the reservoir's shore is over 100 m high and represents that increasing gap between the design parameters for the dam and its current climate. The original intake tunnels are too high above the reservoir level to receive water. Extensive renovations have been carried out in recent years to attempt to retain the dam's storage and hydropower functions. The false assumption of a stationary climate now threatens the power needs and water supply and, by extension, the agricultural and urban development plans, for a large section of the southwestern USA.

Photo credit: Bart Wickel..

FIGURE 3.2 The Kariba Dam on East Africa's Zambezi River

Much younger than the Hoover Dam, it faces problems similar in scope, with electricity production reduced to a few hours a day for much of the year, and straining regional economies as a result. Repairs and adaptation options are limited, and mechanisms to replace the lost capacity will be challenging and expensive for Zambia and Zimbabwe.

Photo credit: Lynn Yeh / Adobe Stock

sectors and needs, such as cities, agriculture, and DRR. Can we continue to generate hydropower or purify drinking water or maintain reliable transport networks, if precipitation patterns deviate significantly from those assumed in their design?

As stationarity breaks down, using only past data to guide plans and decisions can lead to maladaptive results. For example, defenses designed to withstand a 1-in-100-year flood will foster a false sense of security, leaving vulnerabilities unrecognized and unaddressed. Precipitation levels during Hurricane Harvey in the Houston, Texas region in the USA in 2017 surpassed a return period for three-day extreme precipitation of 1-in-1,000 years for most locales, and in one city, 1-in-9,000 years. Similar patterns are emerging for droughts as well. Cape Town's "Day Zero" drought that ended in 2018 has been estimated as a 1-in-300-year event as documented by 400 years of historical records. When two large tropical cyclones—Idai and Kenneth—hit Southeastern Africa in 2019, it was, according to the World Meteorological Organization (WMO), the first time on record that two storms of such intensity struck Mozambique in the same season.[ii]

As the climate changes, an alternative is now needed to management of water based on static return periods. Focus is shifting therefore to assessing the level of negative impact at which critical failures occur. Management can then be guided by the question of what actions—relating to infrastructure, ecological integrity, policy and regulation—are required to maintain performance and avoid failure. How likely is it that impacts

[ii] Jordans, F. 2019. Ocean Changes Affected Deadly Duo of Mozambique Cyclones. Bloomberg, April 26. https://www.bloomberg.com/news/articles/2019-04-26/ocean-changes-affected-deadly-duo-of-mozambique-cyclones

will surpass performance tolerances in the future? This approach emphasizes engaging early and often with stakeholders on their objectives, as return periods provide a false confidence and a weak means of communicating risk in a time of non-stationarity.

Planning and investment for sustainable development are deeply challenged by the implications of the breakdown in stationarity for current best practices in planning, economic development, supply chains, agricultural water management and disaster risk reduction. If the frequency and duration of drought increases, for instance, reliance on past data for planning of water storage may leave cities or farms dangerously short of water in the future. The challenge of climate uncertainty is now understood across many sectors and industries as a major crisis in our processes for decision-making. Climate uncertainties relating to the water cycle may be the most important and least certain climate change impacts of all. The non-profit organization CDP reports, for instance, that of some 650 businesses surveyed, about 75 percent are responding to climate uncertainty by increasing water efficiency to reduce vulnerability to water-related climate risks.[38]

Many working in the fields of planning and design of long-lived assets now refer to "deep uncertainty" in decision-making. Deep uncertainty reflects the widespread situation of decision-makers unable to determine the credibility of widely divergent visions of the future: will conditions grow drier, wetter, or wetter *and* drier? Will the current timing of seasonal monsoons be maintained, become more variable, arrive earlier or later, or arrive both earlier and later? Will snowpack reliably continue to accumulate and act as dry-season storage, or will there be a shift to a rain-fed system with little natural storage? Highly optimized management of water resources, as conventionally sought, may result in inflexible, "brittle" solutions prone to sudden and potentially catastrophic failure, such as floods that overtop flood defenses and inundate communities that had assumed they were "safe." These situations are no longer theoretical; such conditions have become so endemic and disruptive in Jakarta, Indonesia, that authorities discuss less how to reduce flood risk and instead openly discuss relocating the nation's capital.[iii]

3.2 Resilience as a Strategic Response to Water Risks: Integrating Robustness and Flexibility

New approaches are needed urgently for anticipating and reducing threats resulting from the high levels of uncertainty associated with a climate-altered water cycle. To cope with increasing uncertainty and more extreme and unexpected weather events, we need to be resilient, which requires that we are able to adjust to and recover from climate change impacts and, when recovery cannot be achieved, to reorganize ourselves to meet needs for development and well-being in new ways. Resilience depends on the performance of engineered infrastructure and functions of ecosystems, as well as institutions and decisions made locally and at higher levels.

Building resilience to water risks in uncertain future climates balances robustness with flexibility. Deep uncertainty is critical in decisions about long-lived institutions and infrastructure, sustainability, and services whose loss or disruption would be debilitating, such as, for example, energy systems, food systems and irrigation, or ecosystems. As deep uncertainty emerges, our ability to identify the most likely and credible future water regime among a wide range of possibilities recedes. It is becoming harder to assign probabilities of future events with confidence limits and to then weigh alternative decisions. Instead, the best options for managing water are those that are robust because they show satisfactory performance across a wide range of possible futures.[39] If such robustness can then be complemented by flexibility, we also retain the ability to respond to unexpected future events, changes in climatic and hydrological patterns, and residual risk. The critical need addressed by strategies based on robustness and flexibility is to avoid traps that limit future choices as conditions (and needs) evolve over time and that are expensive, difficult, or impossible to undo, modify, or adjust over time.

Water decisions that build resilience address robustness and flexibility in concert (see Box 3.1). Robustness and flexibility can be applied to all aspects of decision-making for water resources management, including infrastructure design, institutional analyses, and policy formulation. The

[iii] Englander, J. 2019. As Seas Rise, Indonesia is Moving Its Capital City. Other Cities Should Take Note. Washington Post, May 3. https://www.washingtonpost.com/opinions/2019/05/03/seas-rise-indonesia-is-moving-its-capital-city-other-cities-should-take-note/

concept of "sponge cities" used in China attempts to do this by bringing together urban stormwater engineering with flexible approaches to using green spaces to buffer flows of water during extreme events.[40] In the Netherlands, increasing flooding is expected in the coastal city of Rotterdam across a wide range of future scenarios for climate change as a result of higher river flows and sea-level rise, and thus robust interventions for flood defense can be taken now to ensure that the city remains livable, and shipping and port functions can continue far into the future. Alongside these solutions, ways of retaining flexibility are needed to respond to multiple potential futures, and indeed Rotterdam is considering how flood patterns may shift in the future in ways that are hard to predict and unexpected.[41] Similarly, South Africa, for example, has developed a strategic policy framework for water-related decision-making that includes strong elements of both robustness and flexibility[42] for use in a diversity of sectors, including cities, agriculture, water, energy, and natural resources.

BOX 3.1 Defining Resilience: Robustness + Flexibility

In a climate-resilient future, economies, livelihoods, and ecosystems are able to withstand or recover from the impacts of climate change and, in time, transform so that they thrive under new climatic regimes. As decisions are made about policies, strategies, plans, and investments for managing water, they will need to coordinate and ensure complementarity between:

- robustness—for measures that perform well in a wide range of future climate change scenarios, and in which, as a result, there is high confidence from analytical studies;[43] and
- flexibility—for measures that ensure that, when climate change results in impacts that were not expected, or when choices between alternative credible futures cannot be made, societies have the ability to adjust, change course and reorganize as conditions evolve and information about the future becomes clearer.[44]

The need for both robustness and flexibility requires an assessment of future climatic risks and the levels of risk we can tolerate. Adaptation decisions that are robust are needed where we have low tolerance to failure for threats from climate change that emerge across future climate scenarios and therefore we have (relatively) high confidence will occur. For example, decisions need to be robust for the design of a long-term manufacturing supply chain that crosses a number of regions or countries, because failure or disruption due to climate change may not be easily tolerated without severe economic impacts. In contrast, a policy framework for sharing of water among communities, corporations, and different ministries can incorporate flexible designs for water allocation mechanisms (see Figure 3.3).[45]

Levels of confidence hence shape adaptation strategies. In the case of water, our challenge is that while the scientific basis for confidence in future water regimes is relatively weak, many of the decisions we make about water management, institutions, and infrastructure can predetermine our future decisions for decades or centuries to come. As stated by Hallegatte et al. with regard to future climate uncertainty:[46]

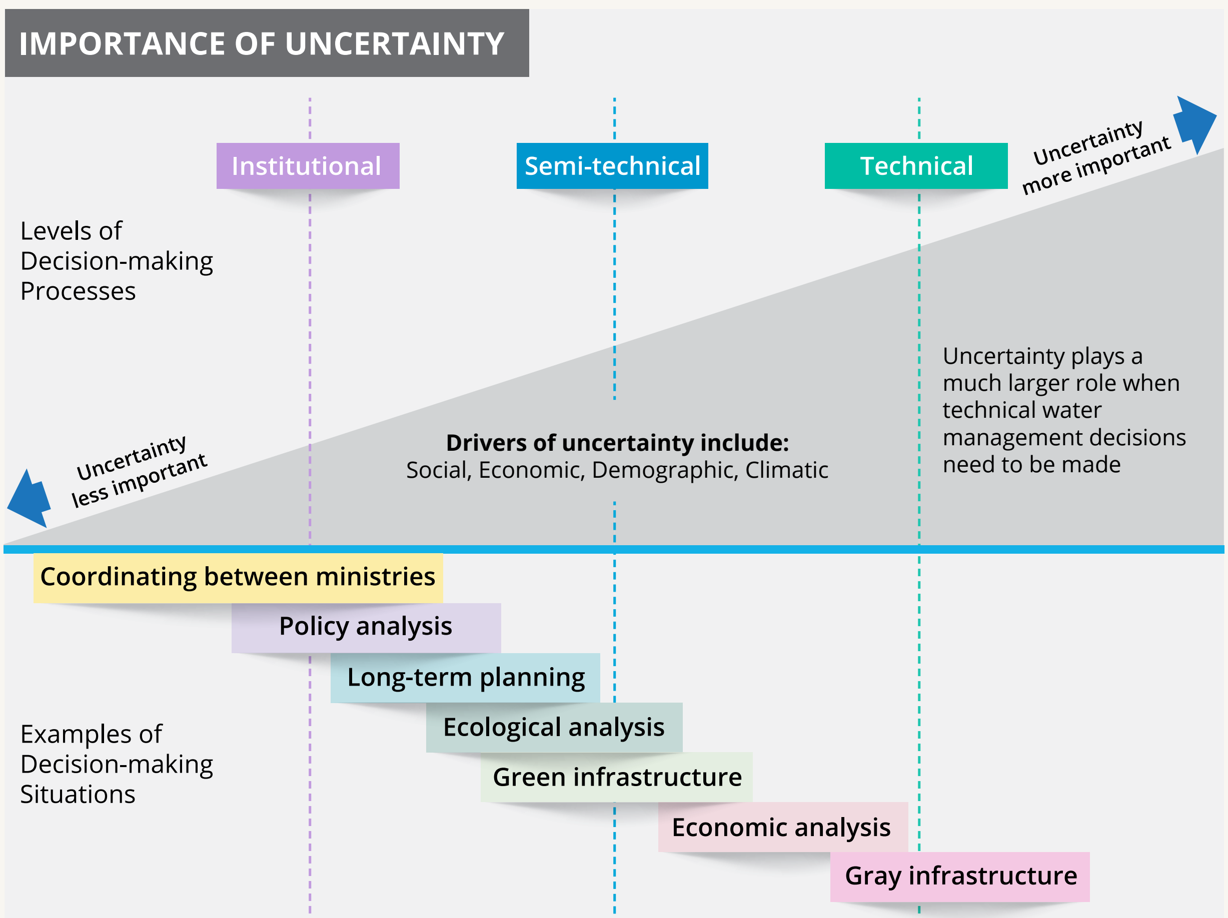
"Many investment decisions have long-term consequences. Infrastructure in particular can shape development for decades or centuries, a duration that often extends beyond infrastructure's lifetime because the economic system reorganizes itself around them."

A bad decision may not be forever, but it can have a very long-term impact on ecosystems, communities, critical systems, and even whole economies. As a result, the temporal period for assessing uncertainty and risk and our responses to them is key. Uncertainty increases as we look farther into the future, with more diverse and more unexpected events likely to occur as climate change continues to intensify the water cycle (Section 2). Generally speaking, adaptation decisions should aim for robustness to high-confidence, short-term risks while ensuring a strategic emphasis on retaining flexibility in the long term.

For example, are there modular or extensible solutions to managing drought? The European Union Water Framework Directive and more localized water management agreements such as in Tanzania's Pangani basin both convene periodic re-normalization of water conditions as a way to reduce climate risk by shortening the time horizon for management, allocation, and sharing.[47] An alternative approach is to look at longer periods of time, such as the Dutch approach to develop a 1-in-10,000-year failure standard for severe flooding, [48] the Washington, DC, USA, public utility's choice to share climate risk with investors over the operational lifetime of a major climate change adaptation investment,[49] or the development of guidelines for green bonds that specify the use of 100 years for evaluation of nature-based solutions when evaluating and planning green and hybrid investments.[50]

FIGURE 3.3 Examples of the Relative Sensitivity to Uncertainty of Broad Categories of Water-Related Decisions for Climate Change Adaptation

For governance and policy coordination, low confidence (high uncertainty) can be tolerated by provisioning flexibility and periodic revisitation of agreements to take account of changing climatic conditions. Some decision-making, however, requires more quantitative knowledge and relatively high confidence. In general, a lack of confidence should result in a greater emphasis on flexibility for long-lived institutions, agreements, and infrastructure, or when the potential impacts of failure or loss of function would be catastrophic or severely damaging, such as when critical ecosystem services may be lost.



Source: Matthews et al.[45]

3.3 Co-building Resilience: A Framework for Climate-Resilient Water Management

The opportunity now is for climate change adaptation practitioners to embed robustness and flexibility into their water-relevant decision-making and planning, and for the broader water community to modify standard water management practices—used across sectors—to include climate awareness within practical ways of implementing resilience. Climate-resilient water management (CRWM) is an integrated approach to building resilience for water-related decision-making to address short- and long-term impacts of climate change.[51,33] As shown in Figure 3.4, this can be summarized in four domains for action, based on principles for increasing resilience[52] in social-ecological systems.[iv] Robust decision-making and flexibility are embedded across these domains of action, within key governance, knowledge, social, engineering, conservation and management dimensions of resilience. This Action Framework for Climate-Resilient Water Management provides a means of structuring recommendations for policy and action on adaptation to increasingly uncertain, non-stationary climate futures through water management.

FIGURE 3.4 An Action Framework for Climate-Resilient Water Management

GOVERNANCE AND PARTICIPATION

Put in place multi-level water governance to promote participation in decision-making and self-organization. Higher level institutions empower robust and flexible decisions at lower levels.

- Reform policies, laws and institutions for multi-level governance
- Integrate rights-based approaches
- Ensure inclusion and participation
- Collaborative co-creation of solutions

INFORMATION AND LEARNING

Ensure data and information is accessible at all levels and that people have the skills to apply it to managing dynamically changing risks. Foster systems thinking and knowledge sharing.

- Climate and water information systems and monitoring
- Training and skills development
- Use scientific and local knowledge
- Disseminate data and stimulate learning at all levels

SYSTEM DIVERSITY AND CONNECTIVITY

Maintain or restore diversity in water-related systems to provide redundancy and fail-safes. Use diversity and connectivity for flexibility in responding to unexpected events and changes.

- Conserve ecological diversity and connectivity
- Promote economic diversity
- Utilize a range of water storage options
- Guard against maladaptive engineering

INFRASTRUCTURE, TECHNOLOGY AND MANAGEMENT

Reduce vulnerabilities using infrastructure, technologies and water management that will be robust for high-confidence threats but flexible in response to emerging futures.

- Assess response options
- Apply systems-oriented risk assessment in decisions
- Use both engineered and nature-based solutions
- Use adaptive management

[iv] Water is a renewable resource that is recycled relatively rapidly through the natural environment of which it is an integral part, above and below ground. It is essential for all social and economic activity, and often has deeply embedded cultural values. Furthermore, water resource systems comprise engineered and natural infrastructure, institutions (governance structures) and a large number of social actors. As such, water resource systems are the epitome of complex social-ecological systems.

4. Action on Adaptation for Water

The Action Framework on Climate-Resilient Water Management (Figure 3.4) provides a guide for action on water in adaptation. Policies, strategies, plans, investments, and project interventions should address or be coordinated with action in all four action domains. By doing so, they will align building blocks for resilience, from governance and institutions, information and learning to enhancing diversity and choices about infrastructure and technologies and their management and operation. Robustness and flexibility play out in different ways across each of the action domains, as well as across different sectors and scales. Application of the Action Framework ensures that approaches to water-related adaptation are equipped with a broad range of levers and tools for adapting complex water resource systems to uncertain and dynamically changing future climates.

4.1 Governance and Participation

Water governance is full of inherent complexities, even without the added challenges of non-stationarity and deep uncertainty. No universal blueprint for how to govern water resources exists (nor would one be useful), but there are principles, drawn from both conceptual frameworks and pragmatic experience, that outline a basic architecture for water governance needed for climate change resilience. Water governance that builds on these principles is the foundation for action on adaptation.

Viewed simplistically, water governance sets the rules of the game for how water is allocated and managed (and inherently, therefore, which water users stand to benefit most) as well as how conflicts over water can be avoided, negotiated, reduced, and resolved. Such simplicity is deceptive, however, and in a changing climate where uncertainty is expanding, a rigid framework of rules for water management will be brittle. Water governance, in reality, is shaped not only by law and policy and concepts such as IWRM, but also by social and institutional norms and the intersection of culture and both informal and formal institutions;[53] it addresses not just managerial concerns but also value systems, rights regimes, and the navigation and negotiation of contested knowledge. With a balance between rule making and ensuring effective and democratic spaces for decision-making, water governance can help to build climate change resilience. For adaptation, rule making is reserved for climate change impacts with high confidence, thus providing robustness. When combined with more democratic, inclusive and decentralized decision-making, crucially for adaptation, we add flexibility to water governance.

Ensuring optimal responses to climate change in both policy and practice, and therefore the right investment choices, is not straightforward because uncertainties mean knowledge is neither perfect nor neutral and uncontested, and decisions are inherently value-laden.[54] Local priorities for infrastructure investment and outcomes for development differ depending on who you are, whether your principal interests are, for example, in household food security or national energy security, and whether your understanding of hydrology is based more on local knowledge or scientific models. Adaptation responses are shaped by the political economy of decision-making and how power is used to achieve particular outcomes. As the influence of climate change on decisions in water management grows, choices for adaptation risk are dominated by powerful interests that further marginalize groups most vulnerable to climate change. Climate change hence poses a difficult challenge to water governance: how can institutional arrangements for water accommodate both the inevitable and constantly evolving demands of "adaptation politics" alongside the changing dynamics of the hydrological system?

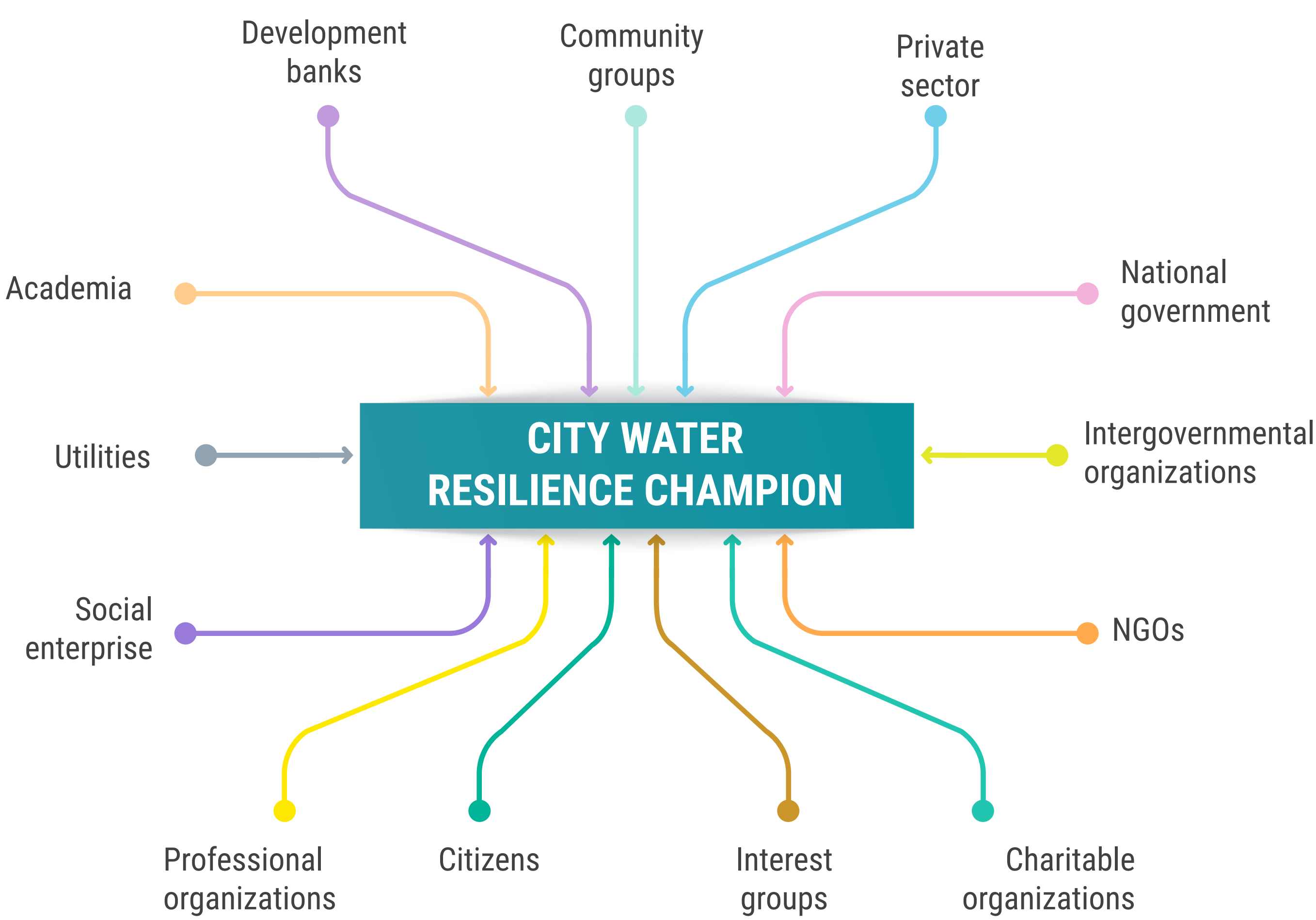
Fortunately, there is a way forward. Water governance that strengthens inclusion in decision-making also builds climate change resilience (see Box 4.3). Decentralization and more democratic approaches to water governance needed to balance flexibility and robustness in response to climate change also help to build inclusion in decision-making. The key is multi-level governance in which institutions working at local, basin, aquifer, national and transboundary levels have complementary responsibilities. In cities such as Amman, Jordan, and Mexico City, Mexico, new efforts at inclusion have coalitions of stakeholders and decision-makers working to develop a shared, coherent vision of their cities to become more just, equitable, and resilient despite ongoing climate change impacts. With real-time collaborative modeling guiding decision-makers, these cities are choosing to solve complex, multi-layer challenges with more holistic and multi-institutional solutions. Rather than simply looking at supply-side solutions such as new water storage infrastructure, by soliciting the active participation of hundreds, even thousands, of stakeholders, these and other cities can generate active and broad support for shifts in demand, allocation, and finance (Box 4.3). So-called bottom-up decision-making (sometimes referred to as scenario-led decision-making) can foster a major transformation in generating comprehensive solutions that also have widespread support to facilitate implementation and efficacy (see also Figure 4.1).[55,56]

In multi-level water governance, institutions at higher levels make only decisions that cannot be made at lower levels. They create the frameworks to establish and empower robust and flexible decision-making at lower levels. Multi-level water governance includes mechanisms to promote self-organization and active participation and representation in decision-making, including marginalized groups. As climate change impacts unfold, as a result, local institutions can then manage adaptively, with decisions made flexibly according to local needs and knowledge, through consensus and trust building and collective action.

FIGURE 4.1 Bottom-up Approach to Water Resilience

(A) The City Water Resilience Approach (whose development has been led by Arup) and (B) collaborative modeling (represented by an image created by Deltares and adapted here) both represent "bottom-up" approaches to resilience that engage diverse stakeholders, technical experts, and decision-makers to solve complex, multi-layer problems by developing a shared vision for resilience to negotiate comprehensive solutions with widespread support.

(A) CITY WATER RESILIENCE APPROACH



(B) COLLABORATIVE MODELING FOR DECISION SUPPORT

WHY	HOW
ACCEPTANCE AND OWNERSHIP Increased acceptance and ownership over developed plans and strategies	Stakeholder participation in **MODEL DEVELOPMENT**
SYSTEM UNDERSTANDING Improved system understanding and model performance through the incorporation of shared multi-sector and local knowledge	**DATA COLLECTION** ➔ Model definition ➔ Model construction ➔ Model validation ➔ Verification
TRANSPARENCY Increased transparency of both modeling and decision-making processes	Stakeholder involvement in **MODEL APPLICATION**
CONSENSUS Improved consensus relating to system function and preferred strategies	Model use ➔ Design, formulation and evaluation of **MEASURES AND STRATEGIES**
STAKEHOLDER RELATIONS Improved stakeholder relations, by opening channels of communication, generating mutual understanding and negotiating compromise solutions	Create the necessary cooperative environments to facilitate the joint formation of **NEGOTIATED SOLUTIONS**

Sources: (A) Arup[57] and (B) Naffaa[58]

4.2 Information and Learning

Action on adaptation requires that people and institutions have the skills, knowledge, and capacities for learning that they need to manage water while stationarity breaks down and uncertainty expands. This challenge goes far beyond the familiar need to develop knowledge and capacities for water management. It is inevitable that, if the historical record and past experience can no longer be used to guide water management, better information, regularly updated, and new types of information are needed (see Box 4.1).

Applying this information demands, in addition, new skill sets and capabilities in water management that are in part radically different from the past. Given how pervasively climate change impacts on water cut across sectors and social groups, action to upgrade the knowledge, information and skills used in water management is urgent.

Non-stationarity in hydrology has not gone unrecognized in climate change adaptation. Until recently, the response has typically been to attempt to substitute the outputs of climate models for statistical analyses of past weather and climate in assessments to support decision-making on future water management. By itself, this would be a viable approach if there was sufficient confidence in these models for quantitative applications to water resource planning and management. In situations where high-confidence quantitative data have traditionally been needed, risk-based approaches can instead be used that begin with understanding the operational limits of the system or problem in question and then use climate projections to help constrain the credibility of threats and drivers (described in more detail in Section 4.4). Groups as diverse as the World Bank, the Dutch Ministry for Infrastructure and Water Management, and the U.S. Army Corps of Engineers are mainstreaming these approaches to

BOX 4.1 Digital Innovation for Water Management and Climate Change Adaptation

Information has always been a vital resource for reducing uncertainties in water management; scarcity of data can be a major constraint in making the investments needed to lower water risks. As uncertainty expands under climate change, and past data (even where available) become a less reliable indicator of future conditions, the importance of water information and regular updating of water- and climate-related data only grows. A key component of climate change adaptation and building resilience is therefore investment in hydro-meteorological monitoring and information systems together with innovation in technologies for data acquisition, management, and analysis.

Planning and decision making for climate change adaptation needs information on water resources and how they might change under future scenarios for climate change. Innovations that help to get this information into the hands of decision–makers are increasingly emerging. One example is water accounting, a technique that assesses the balance among water flows, storage and consumption in a basin. Water accounting-plus (WA+), developed by the International Water Management Institute (IWMI) and IHE-Delft, integrates satellite-derived data, modeling and ground-based measurements to generate spatially-distributed information on how much water is available, when and how it used, and how this changes over time. WA+ can be applied where conventional hydro-meteorological data are scarce to provide hydrological baselines for adaptation planning and assessment of future changes, and that can then be updated regularly over time. For example, IWMI used WA+ to assess changes in water availability in future scenarios for climate change to guide investment in new irrigation infrastructure in the Nam Phoung, Nam Mat and Song Ma watersheds of Lao PDR. Results showed that as a result of increasing risks of low water availability in the dry season, management of dry season flows will be critical to the success of planned irrigation investments.

The World Resources Institute's (WRI) Aqueduct suite of tools makes global water-related risk data available online to companies, governments and international organizations, using the best available global datasets and indicators for physical water risk. Since its launch in 2011, Aqueduct has been used by hundreds of global companies, investor information providers, and international organizations, such as the IEA (International Energy Agency) and the Red Cross Red Crescent to provide a comprehensive overview of water-related risks. A new version of Aqueduct was released in 2019 including monthly data, better groundwater modeling and specific tools for flood and food-related water risks.

Adaptation is also benefiting from new, rapidly emerging digital technologies for drought monitoring. IWMI, working with the CGIAR Research Programs on Water, Land and Ecosystems and Climate Change, Agriculture and Food Security, developed the South Asia Drought Monitoring System (SADMS), which uses a multi-criteria integrated drought severity index, based on data from remote sensing, to generate district-level drought bulletins for drought-prone Indian states. Updated weekly, authorities use this information to better target drought-relief efforts. SADMS has been used, for example, by authorities in Andhra Pradesh and Maharashtra since 2017 for real-time drought contingency planning, supporting village-level coordination of drought-response actions such as distribution of drought-tolerant seed varieties, supplementary irrigation, rainwater harvesting and spraying of potassium nitrate to reduce drought stress.

assessing and reducing climate risks, often in conjunction with shared-vision, bottom-up stakeholder engagement approaches.[61,62,33]

What, then, is the way forward? The precautionary principle, because it asserts a societal preference for risk aversion under uncertainty, is a key starting point for rethinking management of water risk under climate change.[51] This tells us that adaptation for water should be based on higher rather than lower risk projections. For instance, planning should be designed around high-risk (low-frequency) floods and droughts, to provide a degree of redundancy in water management systems. With higher uncertainty and non-stationarity, therefore, actions taken to enhance climate change resilience—and critically so for high-value, long-lived infrastructure—should build in spare capacity, or safety margins, to buffer against residual risk.

4.3 Diversity and Connectivity: Increasing Options

Action on adaptation that increases options for water management helps to build resilience to climate change. As a principle, therefore, there are benefits for adaptation from actions that strengthen diversity in how water is managed. However, because water interconnects sectors and uses and different groups in society, connectivity in water systems can, in some contexts and unless managed appropriately, reduce the effectiveness of adaptation.

Diversity in water systems is a result of diversity in the economy, in ecosystems, and in the history and culture of the institutions, businesses and groups engaged in water management. The diversity these provide in water systems increases flexibility in management responses to unexpected events and changes. Maintaining diversity increases redundancy or "fail-safes" within a water system by allowing some components to compensate for the loss or failure of others. For example, with diversity in the economy, vulnerability to drought or flood of one sector can be offset by other, less-vulnerable sectors. With diversity in agricultural systems, the costs of extreme events to livelihoods may be lower than where farmers and communities rely on a single crop or value chain. In the case of managing water storage, utilizing a range of different options—including both surface water and groundwater, and natural as well as engineered infrastructure—ensures that in interconnected systems, failure occurs only when concurrent shortfalls arise in multiple storage types.[63]

Connectivity can, however, both enhance and reduce resilience to climate change. Yes, in the case of water storage, overcoming and recovering from disturbances can be more rapid for well-connected systems, by making it possible to switch from one source of stored water to another. In other contexts, however, connections across water resource systems may lead to the rapid spread of disturbances or unpredictable consequences from change. Increasing connectivity in water systems can therefore be maladaptive and the systemic effects of changes in connectivity across water systems should be assessed as part of planning for climate change adaptation. For example, while maintaining the ecological integrity and connectivity of river systems helps to protect the benefits of biodiversity and ecosystem services within a basin, engineering of connections between basins—for example, for inter-basin transfer of water—can be maladaptive if this leads to the introduction of non-native or invasive aquatic species, with unpredictable consequences for fisheries or other sectors.

4.4 Infrastructure, Technology, and Water Management

Conventional water management, premised on stationarity, has typically aimed to provide optimized solutions for water resource constraints and risks. Put simplistically, risks of scarcity have conventionally been tackled by expanding water storage, and risks of flooding by construction of dams, levees, and barriers, with the dimensions for each based on historical hydrological and climatic data. Now, in a changing climate, this age-old, received wisdom on how to plan, build, and operate water management infrastructure and technologies has to be redeveloped. Their purpose, to reduce water-related risks and secure water services, remains the same. However, to cope with deep uncertainty and unexpected, extreme events, alongside coordinating strategies to build resilience across the Action Framework (Figure 3.4), water managers need to incorporate robustness across a wide range of credible futures and flexibility into their plans and designs.

Options for water management address a range of vulnerabilities, and are integral to a variety of "action tracks" for adaptation. This is consistent with the role of water management as an enabler of adaptation. Table 4.1 lists practical examples of water-related adaptation measures for these action tracks. While not comprehensive, these examples include measures such as water storage, irrigation and insurance that are frequently highlighted as priorities for adaptation (see Box 4.2 for an example for smallholder farming). New methods are emerging to help decision-makers identify which of these options are most appropriate for the vulnerabilities and contexts they are trying to address. Critically, these methods incorporate assessment of how to enhance robustness and flexibility.

As outlined in Section 4.2, in the past decade, a new generation of uncertainty-tolerant approaches have emerged to confidently diagnose risk and to prepare for a range of possible futures in water-related planning and investment. These approaches can provide high-confidence quantitative assessments by understanding how the system in question functions rather than by assuming that downscaled climate projections can provide a high level of confidence in future water patterns.

These systems-oriented approaches focus the attention of stakeholders and decision-makers on the challenge of action on adaptation and climate-resilient water management. Examples include robust decision-making,[64] many-objective robust decision-making,[65,66] stochastic and robust optimization,[67] dynamic adaptive policy pathways,[68] information-gap decision theory,[69] and decision scaling.[70] They have been designed explicitly to help make robustness and flexibility in adaptation practical, by helping decision-makers identify decisions that have satisfactory performance across a range of possible futures—i.e., that will be robust—as well as to help them make plans that can be flexibly adapted over time in response to how the world actually unfolds.[44,71] Tools such as the Decision Tree Framework (DTF)[72,73] —developed by the World Bank and increasingly emulated—integrate systems-oriented risk assessment and reduction within existing decision-making systems at operational level (see Box 4.3) These methods fully respect the uncertainties and risks associated with shifts in the water cycle, the increasingly complex economic and social objectives for planning and management, and the risks and insights that have emerged from the climate change communities.

BOX 4.2 Climate-Resilient Infrastructure Development for Smallholder Farming in Zimbabwe

In the Lower Save Catchment of Zimbabwe, climate change has impacted water supply, health, and livelihoods of local agricultural communities. Due to decreasing rainfall, smallholder farmers' crop productivity has come under pressure, increasing risks to food security in their communities. In response, farmers have expanded cultivation of land closer to water sources, which in turn has had a detrimental impact on river health (e.g., increased erosion and river siltation). Communities also lack proper water, sanitation, and hygiene (WASH) facilities. Low rainfall and reliance on river water for bathing, cleaning, and drinking has resulted in water contamination and disease incidence.

Abstraction, pumping, irrigation, and WASH infrastructure offer a solution. The Climate Resilient Infrastructure Development Facility (CRIDF), a donor-led program, works toward enhancing resilience to climate change in Southern Africa through water infrastructure projects. It works with local partners to couple financing with development of the capacities and institutions needed for implementation. The challenge was to create mechanisms that would allow local communities to pay for water infrastructure and maintain it on their own. CRIDF worked with local communities and organizations to set up a community-managed fund to operate and maintain water abstraction and irrigation infrastructure. A local seed company partnered with CRIDF to provide smallholders with agricultural inputs and access to markets through a contract farming agreement. Pumped irrigation allowed communities to farm land closer to their villages and away from rivers, leading to improvements in river health. Climate resilience was further improved by increased access to safe drinking water at WASH facilities. The secondary benefits (especially for women and girls) included time saved in fetching water for consumption and irrigation.

Notes: More information at www.cridf.net/livelihoods-projects.

TABLE 4.1 **Sectoral Examples of Infrastructure and Technology Options for Use within the Action Framework for Climate-Resilient Water Management (see Figure 3.4).** Robustness and flexibility are addressed by combining measures from columns 2, 3 and 4

<table>
<tr><th>1. Action track</th><th>2. Possible water infrastructure, technology and risk management responses</th><th>3. Measures to enhance robustness[45]</th><th>4. Measures to enhance flexibility[45]</th></tr>
<tr><td>Water supply[76]</td><td>▪ Water storage dams and reservoirs, conjunctive management, managed aquifer recharge
▪ Deeper wells and boreholes
▪ Source water protection, watershed and wetland restoration
▪ Wastewater recycling and reuse</td><td rowspan="6">▪ Increased safety margins in design and operations
▪ Expandable/ modular/ removable designs
▪ Multiple water supply options
▪ Backup systems integrated in infrastructure design
▪ Scalable solutions that can track shifts in climate
▪ Increased monitoring and evaluation for operational decision-making, to support adaptive management
▪ Planning for failure, by ensuring acceptable fallback options in case of unpredicted events</td><td rowspan="6">▪ Periodic, planned re-normalization of hydrological baselines
▪ Planned redundancy to support reliability of systems as conditions evolve or unanticipated extreme weather events occur
▪ Water allocation agreements based on proportions of available water, in place of fixed, volumetric water sharing
▪ Staged water allocation where prioritization of users is triggered by events or thresholds
▪ Mixed systems of built and natural infrastructure
▪ Contingency planning for high-risk/low-probability events such as extreme precipitation or super-droughts
▪ Dynamic adaptation policy pathways, using assessed decision-making pathways for alternative credible futures
▪ Adaptive institutions that track emerging conditions and develop rapid responses</td></tr>
<tr><td>Public health</td><td>▪ Climate-resilient water safety planning[14]
▪ Composting toilets and reduced water dependency for sanitation[77]
▪ Sewerage, septic systems, fecal sludge management
▪ Wastewater treatment</td></tr>
<tr><td>Cities</td><td>▪ Diversification of water sources and supply augmentation, desalination, water recycling
▪ Demand management and reduced non-revenue water
▪ Flood protection using barriers, nature-based solutions and stormwater management
▪ Decentralized water systems and wastewater treatment</td></tr>
<tr><td>Food security</td><td>▪ Irrigated agriculture
▪ Higher water productivity through water-efficient technologies and changes in governance and water management
▪ Climate-smart agriculture
▪ Drought/flood-tolerant varieties
▪ Conserving and restoring ecosystem service</td></tr>
<tr><td>Rural livelihoods[79]</td><td>▪ Adoption of less water-intensive crops, production systems and practices
▪ Weather-based insurance
▪ Rainwater harvesting
▪ Raising well-heads of tube wells[14]</td></tr>
<tr><td>Nature-based solutions</td><td>▪ Natural water infrastructure
▪ "Room-for-the-river" floodplain management
▪ Sustainable groundwater management and managed aquifer recharge
▪ "Sponge cities"</td></tr>
</table>

BOX 4.3 Resilience by Design in Mexico City and the Valle de México

In 2017, the World Bank commenced a multi-year effort to analyze the robustness and resilience of investments in water infrastructure for Mexico City, the surrounding Valle de México, and two other basins that provide supplemental sources of water to the city.[74] The project applies the World Bank's DTF approach to mainstreaming adaptation in decision-making on investments in water-related projects, with much of the technical analysis performed by the Hydrosystems Research Group at the University of Massachusetts, Amherst.

Mexico City and the wider Valle de México are projected to see continued population growth combined with anthropogenic and climatic pressures exacerbating water scarcity. Natural groundwater reserves are being overexploited while illegal capture and water system leakages lead to additional losses. Meanwhile, Mexico City continues to slowly subside, making it especially vulnerable to urban flooding and—as seen in 2017—devastating earthquakes. The World Bank, Mexican water management agencies, and dozens of other governmental, civil society, nongovernmental organizations (NGOs), and community groups recognize the growing need for a more comprehensive approach to water-centric resilience. When systems such as these face limited financial resources and uncertain future conditions, investments must be proven to demonstrate robustness and resilience under many future scenarios.

Unlike traditional water resource planning, which uses cost minimization as the single or most important metric, the DTF seeks solutions that are more robust to climate stressors, inclusive of social equity issues, and considerate of environmental conditions and needs. Project cost is still included in the analysis, but projects are prioritized if they are found to produce the best results for cost and resilience of social, economic, and environmental goals across multiple future scenarios.

Defining resilience is an integral part of the analysis. Through intensive stakeholder engagement and collaborative modeling, performance metrics to gauge and measure resilience were defined for distinct social, economic, and environmental elements. The variables ranged from agricultural output to environmental flows to aquifer depletion. Equality and inclusion, and protection of poor people from climate change impacts emerged as critical components of the long-term shared vision of the region.

DTF analysis involves testing each performance metric through systems analysis as inputs such as governance, demographic or climate changes alter system conditions. Numerous management interventions and/or infrastructure options are being tested in order to help decision-makers better evaluate investment options with an understanding of how resilient or robust each is relative to multiple possible future scenarios. Results of the study are expected later in 2019, with the expectation that a staged multi-institutional approach to implementation over the coming decades can ensure the long-term resilience of Mexico City and its environs.

Climate Risk Informed Decision Analysis (CRIDA) emulates the DTF approach for situations where there is high uncertainty and low technical capacities.[33] CRIDA guides a technical analyst in working with stakeholders and decision-makers to define the decision context and performance indicators for resilience, and for success and failure that are applicable in standard engineering and economic analyses. These indicators are used to develop a set of robust solutions for high-confidence risks using decision scaling, and a set of flexible solutions for low-confidence risks using adaptation pathways.[33]

New methods for decision analysis go hand-in-hand with adaptive management, to enhance resilience by ensuring that flexible and adaptable systems are prioritized over static solutions. Adaptive management has been explicitly adopted as a central organizational framework by many water management institutions, focusing on learning and adapting through partnerships of water resource managers, scientists, water users and others.[75] They learn together to create and maintain sustainable systems in the face of shocks and stresses.

5. Choosing a Future We Want: Water, Adaptation, and Equality

While the Action Framework (Figure 3.4) can guide overall strategies for managing adaptation through water, the impacts of climate change do not fall on all groups equally; climate change creates new winners and losers. The burden of negative impacts such as water scarcity, flooding, salinization or eutrophication differ among countries as well as among different groups in the same locality. How people experience climate change depends on wealth, social status, and other issues affecting their ability and capacity to adapt, such as education, water infrastructure, health services and governance structures.[80,81] Differences in social vulnerability hence have critical implications for action on adaptation. If the needs of the wealthy or one ethnic group or class are prioritized over the needs of others—or men's priorities are given more weight than women's—then some adaptation options may exacerbate inequalities. Vulnerability and adaptation have social and political dimensions[82,83] and, as a result, who has a say in climate change adaptation and building resilience is important. Who decides what should be made resilient to which risks, to what degree of resilience, and for what purpose?

Debate among developed and developing countries on application of the principles, enshrined in the UNFCCC and the Paris Agreement, of equity and common but differentiated responsibilities for climate change have focused mainly on mitigation and carbon markets,[84] the global architecture for climate finance,[85] and the need for "loss and damage" policies within the UNFCCC.[86] However, vulnerabilities are largely experienced at subnational and local levels. An overarching objective of adaptation should therefore be reducing the gap in vulnerability between developed and developing countries as well as between different groups in local communities. A key test for building resilience is inclusion of those who are most vulnerable to climate change impacts. This implies that implementation of the Action Framework (Figure 3.4) should empower self-organization and provide space for vulnerable groups to work toward their "desired outcomes."[87]

The goal of ensuring that climate change adaptation integrates the needs of groups with the highest vulnerability should be addressed by incorporating action to strengthen equality and inclusion into the Action Framework (Figure 3.4), through:

1. *Balancing scientific and local knowledge.* Local communities on the frontlines of climate change are monitoring impacts as they emerge, and building knowledge and perspectives that help to reveal and identify thresholds of change in water availability and risks, agriculture, ecosystems and well-being.[88] Local communities are therefore a vital source of knowledge for planning and action on climate-resilient water management and climate change adaptation, which should be drawn into the national and international debate on adaptation.[89] Farmers' knowledge of local water resources is being used, for example, in adaptation strategies in the Mekong Delta in Vietnam.[90] In Indonesia, paddy farmers are adjusting to locally observed changes in climate using centuries-old systems for managing irrigation water (e.g., the Balinese subak system). Local knowledge hence brings to light different views in communities on climate change and adaptation as well as technological and management response options. The benefits of local knowledge for building resilience are then strengthened through multi-level water governance, which enhances local participation in decision-making, opens access to local knowledge from higher levels, and enables local and scientific knowledge to be used together.

2. *Linking local participation in decision-making to adaptation practices.* Integration of local knowledge into planning and decision-making at higher levels helps to ensure that climate change adaptation is rooted in local practices. At the same time, it gives communities access to adaptation measures from beyond their local context and, critically, helps them gain the means they need to prepare for or respond to climate change impacts that outstrip local adaptation capacities. Combining scientifically based measures and local knowledge through local participation in discussion of water management under future climate scenarios builds local buy-in needed for effective implementation while making identification of potential winners and losers easier. It hence strengthens efforts to make adaptation decisions more accountable and transparent, and promotes the emergence of new political spaces for deliberative decision-making on water management under climate change.

3. *Recognition of rights-based approaches to adaptation.* Application of rights-based approaches through the Action Framework is needed to ensure that adaptation reinforces the human right to water and sanitation, and does not override customary land and water rights. Otherwise, there is a significant risk that action on adaptation will be rejected by local and indigenous groups, as has been the case where rights were not recognized in implementing global measures on climate change mitigation (e.g., REDD+, the Clean Development Mechanism). Failure to give recognition to rights will hence undermine efforts to build resilience, and top-down, centralized approaches to the formulation of adaptation and action—as have been typical for National Adaptation Plans of Action (NAPAs) developed in response to global-level agreements—will reinforce asymmetries in power and weaken inclusion in action on adaptation. Rights-based approaches instead ensure that local voices and the voices of women and poor or marginalized people are included in deciding "for whom resilience is managed and for what purpose."

6. Valuing Water in a Shifting Climate: The Economics and Finance of Resilience

Valuing water in a shifting, uncertain climate presents new risks for allocation of water resources as well as for how we prioritize and choose between alternative adaptation options. Economics as a discipline is central to how we evaluate most policy and investment decisions, but economists are only now starting to come to terms with the valuation of assets in the light of new metrics, such as the value of resilience in the context of disruption, high levels of uncertainty, and new types change in non-stationary contexts.

Finance and funding mechanisms more generally are also going through a transition period. While the broad topic of climate finance has received much attention, how risk associated with water and climate change is communicated to investors, donors, and other types of funders remains uneven. However, new patterns are beginning to emerge that hold the promise of diverting financial flows toward resilience, and to more robust financial risk assessments that articulate expectations for those seeking finance as well as those looking for "good" investments.

6.1 The Economics of Resilience: The Discount Rate (and Beyond)

Economics, as the science of value, should help in navigating complex decisions and become an enabler of adaptation across sectors, groups, and scales. While the risks associated with failure to adapt our economies to a shifting climate have been well documented—notably in the Stern Review[91] and a follow-up study 10 years later[92] —the use of economic analysis as a tool for adaptation is much less well developed.

New approaches are needed that recognize the costs and benefits across a range of systems rather than for single investments in isolation. Climate change presents special problems for traditional economic analyses, which normally assume high confidence and certainty when evaluating costs and benefits, especially for long-lived investments that interact with or use uncertain water resources. When considering distant or potential impacts, the science of economics is far more optimistic than the discipline's dismal reputation: traditional economic evaluations heavily "discount" impacts and trends that are not major drivers or issues in the present but may (or will be) in the future. In effect, climate adaptation interventions are typically considered poor investments when using traditional economic assessment methods. Using standard cost-benefit approaches, the additional costs associated with building a higher flood levee or developing a secondary source of water supply are unlikely to be justified if the need is not both certain and imminent.

Most project-scale cost-benefit analyses, for instance, tend to be highly optimized for short-term needs, minimizing the benefits that follow from the "extra" costs designed to reduce potential impacts that may (or may not) occur over longer terms. Traditional economic methods for assessing costs and benefits work best with the assumption of a single known or knowable climate.

Moreover, in many cases, when the period for evaluating costs and benefits does not match the operational lifetime of the asset, the longevity of many water investments represents a very significant climate risk. Traditional economic methodologies tend to devalue or discount uncertainty about resources, distant risks, potential (rather than certain) benefits, and the costs of learning (i.e., maintaining additional options until more definitive information is available). Nature-based solutions—such as restoration of forested watersheds to reduce flooding and improve filtration and water quality benefits— present another challenge because the value of the investment appreciates over time, and over longer timelines, as compared with traditional engineered solutions.[93,94] Thus, options for including robustness and flexibility may be excluded from planning and design choices using traditional economic analyses.

Although hydrologists and engineers may have declared that stationarity is dead, many economic tools cling to the assumption. A hydropower dam or irrigation facility optimized only for current climate conditions will be much more difficult and expensive to modify as, or after, the climate shifts beyond the design parameters. Maladapted investments are probably widespread, especially those that have not considered the potential risks associated with a rapidly evolving water cycle.[95] The legacy of decisions made today about water-dependent infrastructure can easily extend over centuries.

Recognition of these challenges is growing rapidly, and has given rise to a range of approaches for water investment decision-making and economic analysis under uncertainty.[96,97] These share the principle that a narrowly defined cost-benefit analysis or return on investment, especially over short timescales, will not lead to adaptation.[98] Extending cost-benefit analyses over longer time periods and evaluating performance in terms of non-traditional costs and benefits, including robustness and flexibility metrics, can help attain climate-resilient water management. For instance, by including the transfer expenses associated with switching to alternative options as new conditions materialize and certainty and confidence about emerging impacts grow, we can arrive at a much more realistic assessment of the timing and potential benefits of flexibility.[99]

Decisions on potential investment are most often made, from an economic point of view, using estimates of potential profitability based on the net present value (NPV) or the economic internal rate of return (EIRR). The period of evaluation for profitability (e.g., 10–20 years) and the discount rate used in both NPV and EIRR are normally specified at a high administrative level rather than for the needs of a particular project, where uncertainty or risk associated with a specific investment might lead to reconsideration of the evaluation term and discount rate. More adaptive approaches therefore explicitly address robustness and flexibility in economic analysis of investments.

Real options analysis links flexibility with a decision tree assessment, a method which predates by decades any awareness of anthropogenic climate change. Real options analysis addresses the challenge of economic assessment of flexibility in investment decisions, where:

> *In a context of increasing knowledge—and thus decreasing uncertainty—the decision on an investment project is not between "investing" and "not investing," but between "investing now" and "investing later with more information."* [46]

Real options and similar methods emphasize when to reconsider costs and benefits as the level of security and confidence change, often in conjunction with other insights, such as the lead time necessary to secure approval, financing, and construct major infrastructure investments.

Robustness is often a more familiar strategy in a cost-benefit context. Comparisons of the incremental costs and benefits of alternative robustness strategies can be evaluated,[33] assuming that all comparisons are made on the basis of the same set of climatic data.

Recent innovation in economics for climate change adaptation has included efforts to use climate-related resilience or robustness metrics alongside NPV or EIRR in investment analyses.[100] Similarly, multi-objective "resilience assessments" allow economists to compare the impact of an array of objectives on resilience and the implications of uncertainty in this valuation, including the sensitivity of traditional economic variables.[101] Quite different investment priorities can emerge through such multi-objective analyses than might occur through traditional economic analyses.

6.2 Leveraging Water into Climate Finance and Climate into Water Finance

Climate finance can accelerate the mainstreaming of climate-resilient water management, and interest has been growing in aligning water and climate issues through finance.[102] Design and implementation of investments should be guided by the Action Framework (see Sections

3.3 and 4), actions to strengthen equality and inclusion (Section 5), and application of tools for decision analysis under uncertainty and dynamically changing risks (Sections 4.4 and 6.1).

Many of the basic parameters around water, climate change and finance are in dispute. What is the pool of finance at play? Should we consider only water-related investment in adaptation or also adaptation-related investment in water? And, given the systemic nature of water, is there really a meaningful distinction between climate finance and the much larger, more general pools and targets of water finance?

"Climate finance" refers to labeled, formal channels through which aid is directed for climate change mitigation, adaptation, loss and damage, and other specific targets of climate change action. Development banks, aid agencies, some foundations, and a few commercial and private sector sources have tended to make up the bulk of climate finance. In a few cases, wholly new multilateral institutions such as the GCF and the UNFCCC's Adaptation Fund have been created to directly fund climate change-related activities, specializing in climate-directed grants and loans. Bilateral climate financing initiatives are also an emerging source of funding in both developed and developing countries, though they too focus predominantly on mitigation. National governments, through their expenditures on Nationally Determined Contributions, have also been a growing source of climate finance since the ratification of the Paris Agreement.

Water-related projects make up a substantial proportion of the projects funded through formally labeled climate finance, but no consensus standards exist for assessing their effectiveness relative to climate-resilient water management, and most institutions do not ask for or evaluate the water-climate risks and opportunities in their water portfolio. Historically, the Global Environment Facility's adaptation funds have not required detailed documentation of strategies to assess or reduce climate risk, while groups such as the UNFCCC's Adaptation Committee and many development banks may not recognize that the success of an irrigation project or ecosystem restoration is, in fact, contingent on the application of knowledge on water and resilience, and they may be unlikely to make good use of water expertise. Climate finance is often a domain of highly sectoral and siloed approaches. Therefore, highlighting the wide overlap between water and climate-related sectors can serve to open up the broader climate finance pool to resources for water management.[101]

Moreover, formal climate finance mechanisms often require "additionality" as a means of targeting their support. To the donor community, additionality in the context of climate change adaptation means that adaptation should not bleed into or replace existing "traditional" development aid programs and should be "additional" and above and beyond such aid. The assumption behind additionality is that we can distinguish clearly between adaptation projects and non-adaptation projects or that specific aspects of a larger project are designed to address specific climate change impacts, such as increased flood risk or greater storage capacity to address increasing water scarcity.

Additionality is a problematic term for water-related investments. In theory, we could easily specify that an urban stormwater system needed to have an additional 20 percent capacity to cope with forthcoming climate change impacts. In practice, additionality often creates tension between different types of projects (for instance, disaster relief and reduction versus water supply and sanitation for the urban poor). Even within individual water-related projects, additionality is difficult to document. The uncertainties associated with the water cycle mean that effectively running two types of analyses—an investment in a world without climate change and the same investment in a climate-shifted world, with the differences constituting the additionality—seems strained and sometimes even impossible to calculate. Several institutions such as the GCF have recognized these concerns, and have highly modified or eliminated the requirement to document additionality very strictly. The major development banks have, in contrast, created an additionality reporting framework so that their reports follow similar reporting criteria and standards in how they track and document additionality.[104]

6.3 Plumbing the Pools of Finance for Water-Centered Adaptation

The pool of international climate finance available remains relatively small in comparison to other flows of development-relevant finance. The Asian Development Bank has recently set a target of several billion U.S. dollars for annual adaptation funding, while the GCF is expected to capitalize at US$100 billion by 2020, with half of their total funding going to adaptation. In contrast, the global bond market—which loosely represents privately sourced funding for many infrastructure projects—is of the order of several trillion U.S. dollars in size. The green and climate bonds market—which are bonds that target climate mitigation and/or adaptation—was more than twice the GCF's target for 2020 and approached US$200 billion in 2017.

The broader pool of money available globally for water resources is difficult to tally, but is probably of the order of several trillion U.S. dollars if we consider water-related investment across sectors. Single groups such as the European Investment Bank, the World Bank or national agencies such as the U.S. Army Corps of Engineers have collective portfolios spending tens of billions of U.S. dollars per year. Although much harder to estimate, the private sector too spends very large sums on water management. For example, the energy sector is the largest consumer of water in the USA, France, and Japan and, as a result, is a major investor in water management. In middle- and lower-income countries, agriculture (including livestock and aquaculture)—because it often typically accounts for 50–90 percent of national water consumption—similarly has a major impact on water investment.

All of these human and institutional resources should be aligned to building climate change resilience. Can we convert the budgets of an irrigation ministry, an electrical utility or a mayor into instruments for implementation of climate-resilient water management?

A few institutions have begun to move in this direction. The DTF developed by the World Bank's Global Water Practice[72] (see also Section 4.4) has been applied to local-scale facilities such as water utilities as well as basin-scale planning processes, with the intention of developing thoroughly robust investments; and applications to, for example, hydropower are in development. The Asian Development Bank is expected to launch a comparable methodology for their water portfolio in 2019, while groups such as the International Hydropower Association are looking to apply DTF-based approaches to help private sector developers reduce water-climate risks. The DTF does not emphasize additionality as in formal climate finance methods.

6.4 Climate and Green Bonds

Public utilities and private sector investors have not been silent or inactive either on these issues, as can now be seen in the growth of green and climate bonds. This market was launched in 2007 by the European Investment Bank and the World Bank to demonstrate to private investors that funds were being applied to "green" projects—or in the lexicon of bonds, to environmentally friendly "use of proceeds"—typically for low-impact infrastructure projects and/or climate mitigation and adaptation projects. Typical investors in green and climate bonds are large institutional investors such as pension funds, which are interested in steady returns, long term lengths, and (increasingly) credibly "green" credentials for the investments.

The climate and green bonds market remained quite small (a few billion U.S. dollars annually) until about 2013, when many other categories of bonds issuers began to move into this space, often mediated or led by commercial banks. For several years, the green and climate bonds market underwent exponential growth, reaching almost US$200 billion by 2017. Europe and North America were the most significant issuers in this market until 2016, when China launched its own domestic green and climate bond market. Since then, growth has spread to South Asia, Africa, and across Latin America.

However, these bonds have largely been self-labeled, with little or no verification about their use of proceeds or if the climate change adaptation benefits are indeed credible and accurate. Concerned about the systemic risks to the green and climate bonds market associated with a lack of transparency as well as the potential to leverage very large sums of money, the Climate Bonds Initiative (CBI) began creating a set of principles, verification standards, and sectoral criteria to ensure that investors could trust the climate promises made by issuers—and that the projects being financed had thoroughly accounted for climate risks. In 2016, a set of water-resilience criteria for evaluation of investments in built water infrastructure were developed by water and climate experts and potential issuers, verifiers, and buyers convened by CBI. These criteria went live in 2017, while additional resilience criteria for nature-based solutions were added in 2018 (see Box 6.1), with criteria for hydropower expected in late 2019.

BOX 6.1 Netherlands Finances Nature-Based Solutions through Green Bonds

In May 2019, the Government of the Netherlands issued a certified climate bond for €5.98 billion to finance projects addressing current and future climate change impacts and an advanced low carbon economy. Much of the bond focuses on using coastal and river ecosystems as a safeguard for negative climate change impacts such as high flood risk, further supporting the Netherlands' "room for river" approach.

The issuance came from the Dutch State Treasury Agency (DTSA) and was certified by CBI. The bond raised capital for projects including renewable energy facilities, low-carbon transportation systems, and water and flood defense infrastructure. Projects being financed by the bond included traditional "built" water infrastructure as well as nature-based solutions, all of which were certified under the Water Infrastructure Criteria of the Climate Bonds Standard. Although several prior climate bonds have included elements of nature-based solutions in their proposals, the Dutch issuance was the first to receive certification for resilient nature-based water infrastructure.

The Dutch bond offering demonstrated a robust market for certified climate bonds. Within 90 minutes of the bond's issuance, investors had placed over €21.2 billion worth of orders for the €5.98 billion of certificates, making the bond oversubscribed by over three times. Investor interest combined with the need to raise funds for climate resilience projects means that more certified climate bonds are on the horizon.

These criteria explicitly evaluate flexibility, based on governance and regulatory frameworks related to water allocation, as well as robustness, based on the thoroughness and sophistication of the climate risk assessment. To date, these criteria have been applied and certified for at least US$7 billion in assets for projects in the USA, Nigeria, South Africa, China, and Australia, inclusive of climate-related risks with drought, inland and coastal flooding, snowpack changes, and other potential and realized impacts. This type of reporting should be promoted across all industries facing climate and water challenges, to allow regulators and investors to better evaluate the future performance of investments.[100]

The green bond market is only expected to grow as more emerging economies begin to issue their own certified climate bonds. Conservation finance as a whole is seeing further expansion beyond just climate bonds. New tools such as "sustainability bonds," "blue bonds," "social bonds," and other standards are being developed to address the mounting set of global development challenges associated with water resources.[103]

6.5 Beyond Funding: The Role of Insurance

The role of finance in climate-resilient water management goes beyond providing resources and measuring and managing climatic risks in water-related investments. Insurance provision is a key role for finance, helping to make societies more resilient to the impacts of climate change, especially those related to extreme water risks. Some water risks will exceed society's risk reduction measures (the so-called "residual risks"), and insurance and risk transfers can hence support adaptation and recovery at multiple scales, from insurance for smallholder farmers to re-insurance.

Models for risk transfer are undergoing rapid innovation, including, for example, payment mechanisms based on drought, flood and precipitation intensity index monitoring, credit rescheduling, risk-contingent credit, and crop insurance linked to the purchase of core inputs such as seeds and fertilizer, and livestock insurance. Especially for smallholder farms, trust in shared risk systems and networks will be essential to ensure that many agricultural economies can persist and adjust to increasing variability and large-scale change (see Box 6.2).

Insurance also plays a role in assessing, communicating, and signaling risk through premiums and payments, thus promoting resilient behaviors and investments.[106] In addition, insurance is closely related to investments in assets that can reduce physical water-related risks, contribute to resilience, and also reduce insured losses, resulting in lower insurance premiums.[100] These benefits are

BOX 6.2 Index-Based Flood Insurance for Smallholder Farmers in Bihar, India

Farmers in the state of Bihar, India, face frequent flooding, leading to loss of crops and livelihoods. To help reduce financial losses caused by flooding, IWMI, through CCAFS and WLE, developed and piloted Index-Based Flood Insurance (IBFI) for farmers in cooperation with government agencies and the global reinsurer Swiss Re. Satellite images were used to identify historic floods and develop a flood-risk map, which when combined with a hydrological model based on 35 years of observed rainfall and discharge data, enables prediction of where runoff will travel and collect, and where flooding is likely. When used with contemporary rainfall data, the model indicates the location, depth, and duration of flooding in farmers' fields, providing a flooding index that can be used as the "trigger" for payments to insured farmers. The use of an index in this way helps to keep the cost of insurance low and administration efficient. The scheme went live in 2017 and 2018, covering 650 households, with a total insurance payout of Indian Rupee 814,030 (US$11,500).

Bundling of IBFI with dissemination of stress-tolerant crop varieties is now being trialed in a new public-private partnership initiative focused on post-flood recovery. Good access to seeds just after the flood season means farmers can take advantage of excess soil moisture for crop production, strengthening their resilience by further reducing vulnerability to flooding and enabling farm households to recover more quickly after flood events.[108]

critical for affordability and increasing insurance coverage, particularly in developing countries, and arguably to reduce some of the increasing stress on disaster-risk finance due to the joint occurrence of water-related disasters over large spatial scales, such as continental scale floods.[107]

It is important to emphasize that insurance alone, without consideration of efforts to finance risk reduction, is not a sustainable solution for adaptation. In fact, financing to build resilience is essential to maintenance of the insurability of the residual risks of climate change. Financing for risk reduction and insurance are therefore mutually reinforcing measures for resilience to water-related impacts of climate change.[109]

7. Global and National Policy: Synergies across Scales

Water may be the claws and teeth of climate change, a cause—as stories about floods, droughts, storms and drying reservoirs, rivers and wetlands make headlines—of deepening anxieties about a climate crisis, but it is also by managing water that we will adapt.

Policy frameworks that set priorities for action on climate change or management of river basins guide decisions that shape approaches to resilience. For instance, transboundary water-sharing agreements that do not include tools for anticipating and updating the means of sharing water resources as the timing, quantity, and quality of those waters shift may foster conflict and discord, weakening economies, ecosystems, and even reducing the ability of institutions and communities to respond to shocks and stresses. Policies and processes in global finance (Section 6) can signal to investors and private and public sector decision-makers the need to assess and reduce climate risks in water-intensive investments, such as through certified green bonds. Policy frameworks can make effective water-based resilience much easier—or much harder.

7.1 Water as the "Glue" between Global Policy Frameworks

As of 2019, national and global policies that directly target water and climate resilience remain rare, but recognition of water as a crosscutting mechanism for improving the effectiveness of global and national climate change policies is expanding (as briefly described in a history of advocacy for water coverage in climate policy through COP 22[110]). Globally, three policy frameworks in the 2030 Agenda are helping to align water management with the complex, systemic challenges of building climate change resilience across sectors and scales:

- **Sustainable Development Goals (SDGs)** form the world's agreed roadmap for transformation to sustainable development, including through integration of sustainable management of water and sanitation for all (SDG 6) across the other social, equality, economic, and environmental goals.[111]
- the **Sendai Framework for Disaster Risk Reduction 2015–2030** calls for proactive strategies for the prevention of disasters, and advocates strongly to "build back better." With the overwhelming majority of disasters related to water, the Sendai Framework can help steer priorities toward climate-resilient water management as a way to address long-term stressors such as drought, and prevent and buffer communities from water-related disasters.
- the **UNFCCC Paris Agreement,** while making no mention of water, is viewed by some as the largest agreement on water in human history because water is inseparable from implementation of the commitments made to both climate change mitigation and adaptation.

While these frameworks are not formally linked by design, water (and especially resilient water management) has been suggested as a vehicle for ensuring coherence among them—to align the SDGs and the Paris Agreement, for urban resilience and agriculture for example, or the Sendai Framework, the SDGs, and the UNFCCC.[112,113] Indeed, unless coherence is explicitly considered, there is significant potential for conflict among sectors in pursuing the multiple ambitions of the 2030 Agenda. Recognizing this, El Salvador, Morocco, and other countries have put forward a draft document, in advance of the 2019 UNFCCC Conference of the Parties, for reaching coherence among sectoral investments and projects in their Nationally Determined Contributions (NDCs) under the Paris Agreement through water (see Box 7.1)[114] Integration of climate and water policy at the national level is, hence, increasingly being identified as a tool for strengthening coherence related to the 2030 Agenda among sectors and projects.

Given that new investments for clean energy and resilient cities, ecosystems, agriculture, and disaster management will be with us for decades, if not centuries, failure to integrate resilient water knowledge into climate policy and finance could promote many years of ongoing conflict over water allocation and governance, and could limit our ability to reduce poverty and sustain green growth. While these global frameworks acknowledge the interlinkages between their agendas, they stop short of providing mechanisms for improving coherence; as such, these processes are largely happening in parallel. New efforts by the United Nations Office for Disaster Risk Reduction (UNDRR) and the UNFCCC's Subsidiary Bodies, in particular the Adaptation Committee, are working to address the gap.

BOX 7.1 Driving the Global Agenda toward Water-Wise Climate Policies

As countries turn their attention toward implementation of the Paris Agreement, water will play an implicit and explicit role in meeting their national commitments, or NDCs. Water is both a vital asset and a systemic risk to be considered in national climate change plans and activities. To ensure that NDCs, National Adaptation Plans (NAPs), and other commitments are effective and successful in meeting their goals, a cross-sectoral consortium of NGOs and parties to the UNFCCC has begun to develop recommendations on "watering the NDCs."

Below are five guiding principles for resilient water management under climate change adapted from AGWA.[114] They are designed to help parties strengthen their respective country's commitments for adaptation and mitigation.

1. Create national-level, cross-sectoral water governance mechanisms for monitoring water consumption.
2. Create national-level mechanism in charge of adaptive and flexible water allocation.
3. Create a national ministry or comparable department for managing water use within and across sectors.
4. Conduct a nationwide analysis of explicit and implicit water commitments (domestic and transboundary).
5. Understand and respect the value of intact freshwater ecosystems and source waters.

7.2 Articulating Water through National and Regional Policies

Climate change adaptation is already becoming integrated within the planning and policy frameworks of many countries, encouraged in many cases through SDG implementation plans and NDCs. The cycle of submitting full NDCs to the UNFCCC, beginning in 2020, should help accelerate this process, especially since the "Paris Rulebook" for NDCs explicitly endorsed the use of NDCs for climate change adaptation and mitigation planning. However, water-resilient adaptation is proceeding slowly, and the UNFCCC generally and the Paris Rulebook specifically have yet to make explicit any recommendations around the role of water.

Other types of policy frameworks can also serve to accelerate water-based resilience, such as transboundary water-sharing agreements. The Dniester basin, for instance, spans Ukraine and Moldova, and the two countries recently ratified a transboundary water agreement to align their water management policies. One of the first activities under this new agreement is to develop a resilient disaster risk reduction strategy to cope with a trend of increased flooding as well as to place water closer to the center of economic and natural resource planning. Basin-scale agreements may yet prove to be an important mechanism for linking water and adaptation policies.

Bottom-up efforts to address the intrinsic interconnections between water and climate policy (Section 4.4) are also being elevated to the national and international levels as existing water-sharing agreements must now grapple with the implications of climate change (see Box 7.2).

A key implication of global trends is that many types of national policies need to include processes to assess climate risks, consider the importance and relevance of uncertainties to decision-making, and integrate resilient water components. These should include sectoral strategies and plans such as energy and agriculture, to hard-wire water as an implementing force for climate change adaptation. Water helps to achieve coherence among what otherwise may seem a wide-ranging

BOX 7.2 The Colorado River Compact's Shift toward Adaptive Management

Within the U.S. part of the Colorado River basin (that is, excluding the part of the basin in Mexico), sharing the river's waters between states is managed under a collective agreement signed nearly a century ago. The Colorado River Compact was drafted during a time of tremendously different climatic, demographic, and political conditions. Due to a critical lack of understanding concerning the Colorado's average flow at the time of the agreement, the river is now massively over-allocated. On top of that, this region of North America is currently in the midst of a 16-year drought, reducing the Colorado's annual flow by nearly a third. While such periods of drought have been common over the river's paleoclimatic history, climate change, economic transformation, and massive population growth since the signing of the Compact have exacerbated drought conditions. Over concern that these trends will continue, all seven signatory states agreed in April 2019 to a contingency plan that would reduce water allocation to each of them during drought conditions, helping to stave off more draconian cuts should water levels continue to fall.

The new drought contingency plan represents a shift in the Colorado River Compact from a rigid framework to a more adaptive management policy. The plan is based on shortage sharing among the states with an emphasis on reducing the number of water users exposed to risk during drier periods—an effort to boost conservation and manage demand. In part, the new agreement is designed to use smaller-scale cutbacks in order to avoid larger federally imposed restrictions. Predetermined triggers will set the contingency plan in motion. In this case, cutbacks begin when water levels at the Lake Mead reservoir drop below 328 meters above sea level. Through adaptive management, water managers and state agencies hope to ensure continued performance and supply from the Colorado River to the approximately 40 million people it serves.

This is a prime example of adaptive planning, modifying existing agreements to account for climate uncertainty. Countries looking to improve the adaptation components of their NDCs or NAPs could adopt similar modifications or include adaptive planning mechanisms within new policies and plans.

set of adaptation activities across sectors, ensuring orchestration, coordination, complementarity, and synergies. Policies should, as a result, aim to put in place the levers and tools needed to adapt to dynamic, uncertain change in the water-climate system. The demands of climate-resilient water management therefore provide a guide to integrating climate and water policies:

- Make the need for radical changes in approaches to decision-making for water management under climate change explicit through setting of goals for managing water under "deep uncertainty," especially in policy frameworks, regulatory systems, infrastructure investments, and planning processes.
- Use water management to build resilience to climate change through coordination across four action domains: governance and participation; information and learning; system diversity and connectivity; and infrastructure and technology.
- Embed robustness and flexibility in water-relevant decision-making across all action domains. Robust decision-making, used for threats and opportunities that can be identified with high confidence, must work alongside ways of retaining flexibility to respond to multiple potential futures.
- Reinforce water governance and intensify reform processes to strengthen inclusion in decision-making and to promote self-organization through decentralization. Build multi-level water governance in which institutions at higher levels empower robust and flexible decision-making at lower levels.
- Invest in information management, data collection, analytical capabilities and hydro-meteorological monitoring to provide decision-makers at all levels with the new information they need to incorporate dynamically changing risks into water management.
- Disseminate information at all levels, support training and skill development for use and application of water and climate knowledge, and ensure broad participation to stimulate learning on water and adaptation, and improve knowledge sharing among different groups in society.
- Develop opportunities to expand and reinforce diversity across water-related systems, through support for diversity in the economy, conservation and restoration of ecosystems, and institutions and infrastructure, as a means of increasing flexibility and redundancy in management options for responding to unexpected events and changes.
- Identify vulnerabilities to water-related impacts of climate change for critical "action tracks" including agriculture, rural livelihoods, cities, water supply, and public health, and measures to reduce risks through infrastructure development (including both engineered and nature-based solutions), applications of technology, and water management. Apply systems-oriented methods for decision analysis that use participation of stakeholders to develop robust solutions for high-confidence risks and flexible solutions for low-confidence risks.
- Ensure inclusion of those most vulnerable to climate change in all action domains for climate-resilient water management, with the goal that adaptation does not exacerbate inequalities, for example, based on wealth, ethnicity, social status, or between women and men. Promote equality by balancing use of local and scientific knowledge in adaptation planning and action, linking local adaptation practices to decision-making, and application of rights-based approaches to action on adaptation.
- Require economic analysis of water investments appropriate to decision-making under uncertainty. Recognize that assuming future water risks can be discounted is not appropriate under climate change, and instead evaluate investments over longer periods of time and include robustness and flexibility in analysis of cost-benefit and returns.
- Combine climate finance and more general financing for water resources to expand the pool of finance available to accelerate mainstreaming of climate-resilient water management, including public and private investment. Complement scaled-up financing with expansion of access to insurance products for residual risks of water-related disaster losses.

Hence, while the story of water and climate change is complex, the action needed on water in climate change adaptation can be made practical. Using structured frameworks for policy and action based on principles of building resilience, people and societies can be equipped to make the adjustments needed to withstand and recover from the menace of the shifting water cycle under climate change. Through water, we can prepare.

8. Recommendations

Climate change is changing the water cycle, with impacts that are cascading through economies, food systems, ecosystems, and communities, and affecting the eventual success or failure of sustainable development. Every decision we make now about water management is also a chance to build resilience to climate change.

Longstanding practices for managing water resources and the delivery of water services will not necessarily meet our needs for effective climate change adaptation; climate change has humbled many of the hard-won guidelines, truisms, and strictures from decades past about sustaining water, managing risks, and matching water institutions and infrastructure to the climate. New evidence, practices and strategies for resilient water management have arisen, however, that provide a solid footing for adaptation.

Water-related adaptation to climate change should be coordinated through the four system-wide action domains of water governance and participation, information and learning, system diversity and connectivity, and infrastructure and technology. Building on this basic organizing framework for action on climate-resilient water management, we recommend the following:

1. Make system-wide action on climate change adaptation an urgent priority for water governance

Traditionally, and in popular perception, action on water management has been reduced to isolated pieces of physical infrastructure. In a changing climate, planners, funders and community, sector and political leaders must think differently about water. Their goal must be to build climate-resilient water management across sectors, groups of water users and scales. To do so, we need to:

a. Reform or reinforce multi-level water governance (regional, national, provincial, local) as the foundation for action, to strengthen self-organization and ensure that higher-level institutions empower decision-making at lower levels;

b. Use watersheds and basins as a critical unit of management for adaptation on water, but recognize that, pragmatically, action must be coordinated across hydrological as well as political, administrative and sectoral boundaries;

c. Link stakeholder priorities to decision making for adaptation using bottom-up risk assessment methodologies in cross-sectoral planning that takes account of existing adaptive capacities and helps to build consensus on a vision for resilience; and

d. Ensure inclusion of those most vulnerable to climate change in all action, to avoid adaptation widening inequalities based on wealth, ethnicity or social status, or between women and men.

2. Prepare proactively for high-confidence impacts as well as increasing and dangerous uncertainty

The emergence of unfamiliar, novel, and “transformational” water regimes is well under way in many regions as a result of progressive climate change. The basic, centuries-old premise that past experience is a reliable predictor of future water risks is dead. We face new uncertainties, and the depth of those uncertainties is increasing. Highly optimized, “single-solution” infrastructure plans and designs may be maladaptive and dangerous in future, or force destructive tradeoffs. Adaptation should thus respond decisively to impacts in which there is high-confidence, but avoid action that is difficult to undo, modify or adjust over time. Therefore, we must:

a. Design infrastructure options that perform well across a wide range of possible future climates while retaining flexibility in water-related adaptation, especially for long-lived infrastructure, investments, and institutions;

b. Embed the core concepts of robustness and flexibility across all action domains for climate-resilient water management, using risk-based approaches to identify and manage uncertainties; and

c. Ensure that water-related policies, regulatory systems, infrastructure investments, and planning processes explicitly acknowledge and structure decision making to respond to "deep uncertainty" resulting from climate change, such as in situations where it may not be possible to distinguish between highly divergent futures.

3. Validate the business case for adaptation investment under dynamic, uncertain water futures

Longstanding practice has assumed that we can optimize water management decisions through cost-benefit analyses in which low-probability and future water risks are heavily discounted or ignored. As water regimes shift in dynamic and uncertain ways, a fixed view of risk can lead to bad investments or decisions that cannot be easily reworked or modified. New methods of economic analysis are emerging for evaluating investments in water management with the aim of enabling clearer trade-offs about future choices and that can make costs and benefits under climate change transparent to decision-makers. This requires that we:

a. Recognize that assuming future water risks can be automatically discounted is no longer appropriate and ensure economic analysis of water investments are suited to decision making under uncertainty;

b. Evaluate investments in water management over longer time periods (e.g., extending evaluations to the operational lifetime of an investment) and across non-traditional costs and benefits to enable inclusion of robustness and flexibility in analysis of returns;

c. Plan for what might occur after an investment's operational lifetime ends to reduce the risk of inadvertent maladaptation; and

d. Scrutinize water investments using real options analyses, decision trees and multi-objective resilience assessments to help reconsider costs and benefits as knowledge, risks and the climate changes.

4. Invest in water and climate information systems

Governments, communities, development organizations, and businesses have little control over how the climate is changing, but they do control their own decision-making processes, and they can ensure that decision-making is able to consistently support resilient water futures. As water regimes shift, they need to be able to adjust or replace strategies as baselines and risks of scarcity, extreme events, and pollution conditions change. As uncertainty grows, the need for high-confidence and up-to-date information on water and climate—and the skills to use it for resilient solutions—is greater than ever before. To provide this, we must:

a. Invest in monitoring, remote sensing technologies, and data management and analysis to provide decision-makers with high-confidence water information that they need on dynamically changing risks and that informs management for resilience;

b. Disseminate information at all levels, support skills development for use and application of data, and promote broad participation to stimulate learning on water and adaptation across society;

c. Apply data to prioritization of action in places or sectors with high current and future vulnerability to water-related impacts of climate change; and

d. Adjust decision-making processes to account for limitations or low confidence in data, based on the sensitivity of risks and outcomes to the scarcity or unreliability of data, by giving priority to flexibility and making strategic goals more conservative.

5. Align water finance and climate finance to accelerate climate change resilience

Climate finance refers to funding formally directed to climate change mitigation and adaptation, loss and damage, and other specific targets of climate change action. Yet, because shifts in water regimes caused by climate change have system-wide impacts, all water financing should now be aligned with climate finance and climate-resilient water management. The aim should be to align systemic risks to systemic solutions and use financing to accelerate action to build resilience to climate change. To do so, we must:

a. Combine climate finance and public and private financing for water to expand the pool of funds available to accelerate mainstreaming of climate-resilient water management;

b. Alert the investor community of systemic risks posed by water and climate impacts and of effective, achievable risk assessment mechanisms for use in considering potential investments that can be easily scored and communicated;

c. Align project qualification and assessment processes for water and climate finance based on their substantially overlapping investment risks;

d. Evaluate how to reduce financial risks related to transboundary water cooperation at the project development stage, given the potential for conflict as water regimes shift; and

e. Expand access to insurance products, to manage residual risks of water-related disaster losses, and to broaden the pool of investors sharing shifting risks.

6. Use water as an enabler of adaptation in other sectors and for policy coherence

Water is by its nature systemic, and changes in water regimes interconnect impacts of climate change felt across society. Consequently, water-related action makes adaptation to address diverse vulnerabilities across sectors and groups more effective. Well-designed water-related adaptation, backed by coherent policies, can synergize solutions and catalyze progress towards climate change resilience, such as through the action tracks – on food security and rural livelihoods, finance, cities, infrastructure, nature-based solutions, and locally-led action – launched recently by the Global Commission on Adaptation. To take advantage of these synergies, we should, inter alia:

a. For food security – assess water productivity in agriculture at watershed and basin scales, and take action to introduce water-efficient technologies, changes in governance and economic incentives to improve water productivity and reduce water consumption in agriculture;

b. For rural livelihoods – integrate climate-resilient water management approaches, given the high vulnerability of smallholder farmers to water-related impacts of climate change, into strategies, plans and investments for adaptation in rural communities in developing countries;

c. For cities – integrate water management across action to build resilience in cities – relating to energy, disaster response, public health, water supply, sanitation and environment – rather than treating it as the concern solely of utilities;

d. For infrastructure – assess and reduce water-related climatic risks for the many types of infrastructure (e.g., transport, energy and agricultural) that, although not classified as water infrastructure, may be affected by the water-related impacts of climate change;

e. For nature-based solutions – integrate ecosystems and their services as natural infrastructure in decision making on water-related planning and investment, including for surface water and groundwater, to complement built infrastructure and enhance flexibility in managing basins for resilience; and

f. For policies – ensure, at national level, that trade-offs related to water among sectoral policies and in Nationally-Determined Contributions under the Paris Agreement are addressed in adaptation planning and in reconciling the water needs of climate change mitigation and adaptation; and, at global level, build coherence among the Paris Agreement, SDGs, and Sendai Framework by using water as a common point of interlinkage.

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The International Water Management Institute (IWMI) is a non-profit, research-for-development organization that works with governments, civil society and the private sector to solve water problems in developing countries and scale up solutions. Through partnership, IWMI combines research on the sustainable use of water and land resources, knowledge services and products with capacity strengthening, dialogue and policy analysis to support implementation of water management solutions for agriculture, ecosystems, climate change and inclusive economic growth. Headquartered in Colombo, Sri Lanka, IWMI is a CGIAR Research Center and leads the CGIAR Research Program on Water, Land and Ecosystems (WLE). www.iwmi.org

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Founded in September 2010, the Alliance for Global Water Adaptation is a worldwide member-based NGO comprised of regional and global development banks, government agencies and ministries, diverse nongovernmental organizations (NGOs), utilities, academia, and the private sector focused on the practice and policies around resilient water resources management. AGWA's work covers a number of areas related to climate change adaptation, including developing best practices for climate risk assessment and reduction, evidence-based policy, and resilient finance, economics, engineering, and natural resources management. AGWA is focused on how to help experts, decision makers, and institutions in the water community work more effectively.

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The Global Commission on Adaptation seeks to accelerate adaptation action and support by elevating the political visibility of adaptation and focusing on concrete solutions. It is convened by over 20 countries and guided by more than 30 Commissioners, and co-managed by the Global Center on Adaptation and World Resources Institute.