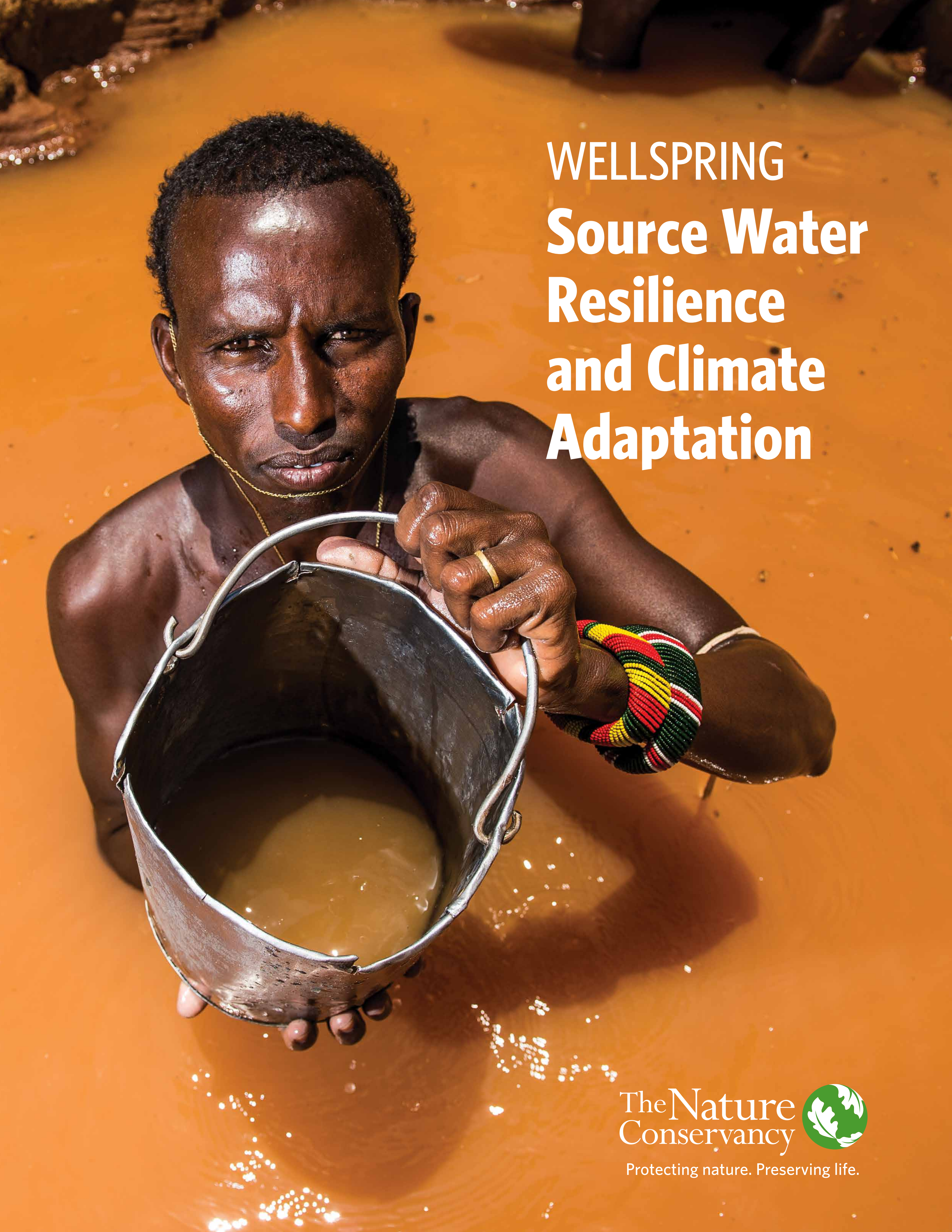

WELLSPRING

Source Water Resilience and Climate Adaptation

The Nature Conservancy

Protecting nature. Preserving life.

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COVER: Leparkeri, a Samburu warrior, stands inside a well he has dug along a dry river bed where he will water his livestock during the dry season, Kenya. © AMI VITALE

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Acknowledgements: Regina Buono, Kirsten Evens, Juanita Gonzalez, Tom Iseman, Will McGoldrick, Henk Ovink

Editor: Andrew Myers, Resolution Partners LLC

Designer: Miya Su Rowe, Rowe Design House

A special thanks to the Alliance for Global Water Adaptation (AGWA) and the Global Resilience Partnership (GRP), who made this report possible.

The Nature Conservancy is fortunate to have the support of visionary people and organizations whose generosity allows us to pursue our mission. We are grateful to the Enterprise Rent-A-Car Foundation for supporting our work to explore solutions to some of the world's most significant freshwater challenges.

Suggested citation: Matthews, J., Matthews, N., Simmons, E., & Vigerstol, K. 2019. *Wellspring: Source Water Resilience and Climate Adaptation.* Arlington, VA: The Nature Conservancy. https://www.nature.org/content/dam/tnc/nature/en/documents/Wellspring_FULL_Report_2019.pdf.

FOREWORD

source waters as leverage for resilience

by Henk Ovink

Special Envoy for International Water Affairs for the Kingdom of the Netherlands and Sherpa for the United Nations World Bank High Level Panel on Water

Last year was, once again, a disastrous year of climate extremes adding again more costs, deaths, and despair to the ongoing trend: an ever-growing increase in droughts, floods, and fires with environmental degradation, economic losses, deaths, refugees, conflicts, and inequality as a result. Climate change contributes to all of these disasters and exacerbates their impacts. In 2015, we set down a climate agreement and endorsed the United Nations Sustainable Development Goals (SDGs), but formal agreements alone will not change the world.

The climate crisis is a water crisis. Nine-in-ten natural disasters are water-related. Between 1995 and 2015, wind and water caused US$1.7 trillion worth of damage worldwide, according to UN estimates. The Organization for Economic Cooperation and Development (OECD) and World Bank estimate that by 2050, global flood damage will cost US$1 trillion a year. We face a challenging exchange: too much water and increasing extremes go hand in hand with far too little water; periods of drought align with flows of refugees and conflicts. We are building dams by the dozens and thus ruining the rivers and the sedimentation of our deltas, while at the same time in our coastal cities we are depleting our natural water supplies at a ruinous rate with sinking cities and retreating coastlines as a result, where sea level rise is jeopardizing these cities and deltas tripling their vulnerability.

The social challenges are as intense and severe. Worldwide, women and children walk for hours to visit wells — hours not spent on their economies, in their communities and their education. With proper water supplies, these women carry their communities towards more prosperity while their children go to school and progress even further and, with trustworthy sanitation, girls don't become dropouts but frontrunners, creating a virtuous cycle of economic and social development.

As the world's population grows another 50% in the next decades, the average welfare of citizens worldwide is also increasing. Rapid urbanization and economic growth are coupled with — and challenged by — the quickening impacts of climate change. All these processes are interlinked and add to the already large pressures on all of our resources — the raw materials and minerals, our natural (water) capital and the planet's ecosystems, the oceans and the atmosphere.

And yet, across the globe, we still focus resources on repairing the damage caused by past disasters rather than committing to prevention, preparedness and increasing our resilience. Our resources still focus almost exclusively on gray solutions — building walls and dams, digging reservoirs, and laying pipes. Investing in nature and protecting our water sources can bring significant added benefits in the form of increased resilience, a greater ability to adapt to our increasingly uncertain future and mitigating climate effects through CO_2 reduction.

Source Waters as a Solution

Our choices around climate change and water issues are often framed as prevention versus repair. This distinction is false; both are essential.

Clearly, we must slow the rate of negative impacts: to cut greenhouse gas emissions and to make efficient, wise, and careful use of our planet and all its resources. Yet at the same time, we need to prepare boldly, comprehensibly, and inclusively for tomorrow's extremes. Alternating between not responding to clear threats or reacting only after crises have occurred must be reversed to promote proactive, innovative, and transformative climate action. And for that a better understanding of the challenges and the complexity of water's dynamic relationship with economic, social, and environmental risks allows for better and more integrated and sustainable interventions.

With the 2030 Agenda for Sustainable Development (2030 Agenda), the United Nations established a comprehensive program of 17 interlinked Sustainable Development Goals (SDGs) that represent the necessary ambitions and promises the world must fulfill to shift towards a path to long-term sustainability and resiliency. Water itself is one of these SDGs, yet it also plays a role in almost every other SDG. Water cannot be seen as a single risk or reward factor that merely amplifies others. On the contrary, because water is linked to all other challenges, it has the unique capacity of being a crucial part of a broad range of solutions — real leverage to reach our goals.

Water — when understood best in its full complexity, valued comprehensively across social, cultural, environmental and economic values and managed inclusively at all scales and through all interests — can and should function as the necessary leverage for impactful and catalytic change and can help turn our risks into real rewards. In turn, we must match long-term comprehensive planning with short-term innovative implementation as well as ambitious climate adaptation plans with bankable transformation. Vulnerable cities, communities, and environments must be transformed into strong and resilient waterscapes. Resilient source waters are at the center of this work.

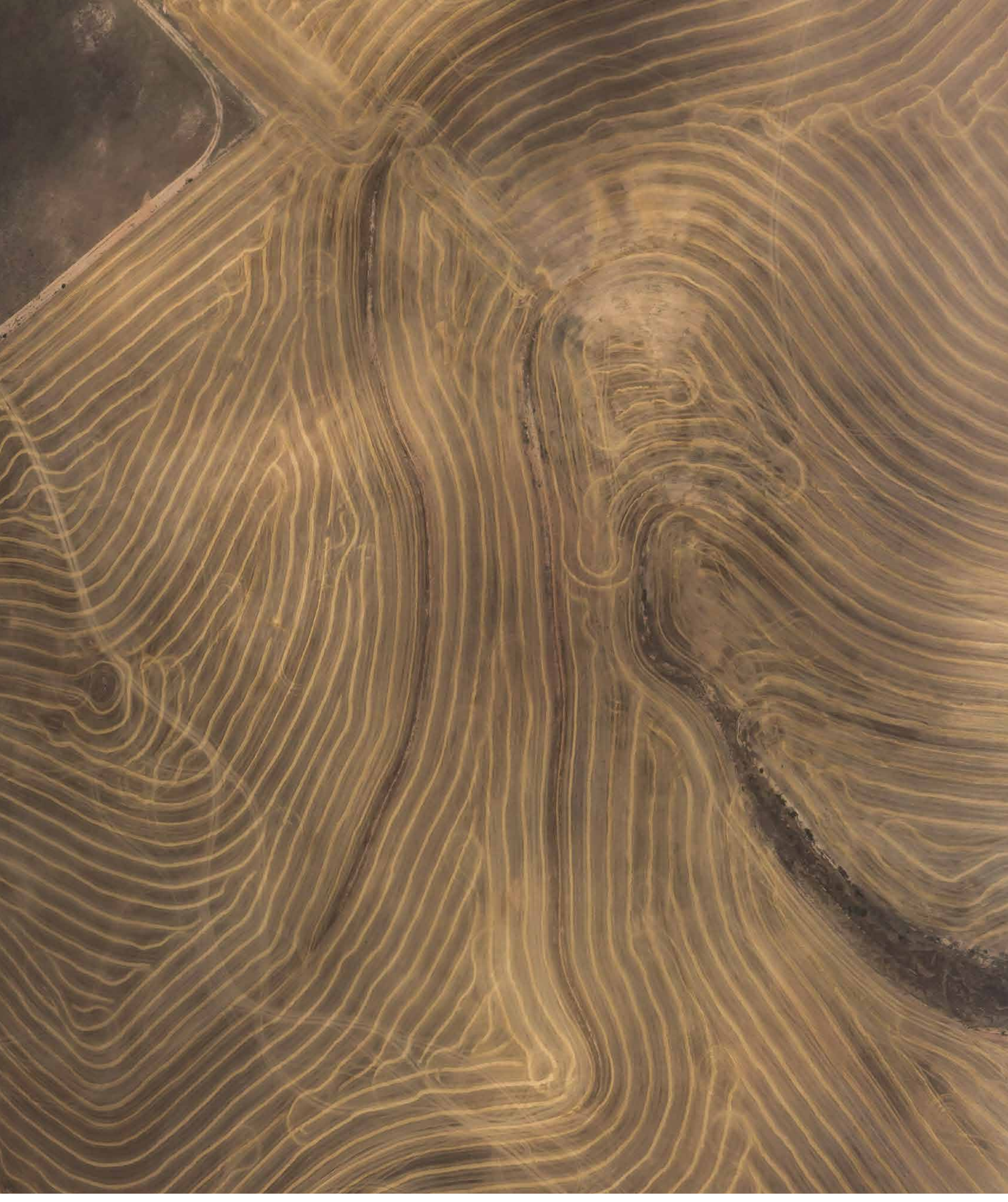
Clearly, we must also continue to accrue greater knowledge of the emerging water systems that sustain human and ecological communities and we must build greater capacity among both institutions and individuals. Result-driven, inclusive, and transparent collaborations are essential across all sectors, layers of government, and stakeholders. We must carry everyone over the river of change: activists and partisans, vulnerable communities, and insecure states, private and public institutions.

Can We Bridge the Gap?

The challenge is to bridge the gaps between plans and projects and between a siloed technocratic approach and an inclusive process that connects all stakeholders from day one. We cannot continue to repeat our past mistakes and make investments in isolation, only dealing with the disasters of yesterday, leading to increasingly worse disasters tomorrow. Our source waters are at the center of this dialogue as the natural capital that has brought us this far and that must carry us even farther now. We have to start funding and implementing these inspirational, innovative, and transformative projects, then scale them up and replicate them across our environments. Interventions by collaboration are needed to link everything together and, in doing so, to connect the Sustainable Development Goals with the Paris Agreement's climate ambitions to help the world and the system change from the ground up.

There is no time to waste: the Hurricane Harveys of this world will not stop. On the contrary: they are the new normal, becoming more extreme year by year. Climate change is a slow process — "even slower than Congress" we used to joke in The White House. But we have no time to waste. The process is slow and not always steady, but it is progressive. The need for fast results is an opportunity: ideal for setting up a good business case combined with political action. Long enough for the global ambition and short enough for the political reality of a single term. Ambitious enough to be attractive and short enough for targeted actions. This timing and these actions give me hope, if grounded in our longer-term plans and a collective and empowering approach. We can and we must act now. Resilient source waters are critical for that action.

Henk Ovink
The Hague, The Netherlands



Aerial view of drought-stricken, cultivated farmlands in Western province, South Africa. © FOUR OAKS/SHUTTERSTOCK

executive summary

Source Water Protection (SWP) has always been fundamental to water resources management. Source waters can deliver reliable and high-quality water services for drinking and domestic use, livestock and ranching, irrigation, energy, industrial development, and disaster prevention and recovery. As the pace of climate change quickens, SWP is now also becoming a critical component to ensuring resilience. Climate change presents a new range of threats, drivers, and uncertainties in how we interact with freshwater ecosystems, but recently developed approaches to cope with climate impacts will ensure that source waters can survive — and thrive — into the future.

As a body of practice, SWP recognizes that the water cycle is inherently connected to ecological and hydrological systems. As such, SWP practices have traditionally focused on integrating or restoring ecological and hydrological systems and processes and then linking these to formal water management systems, such as through Nature-Based Solutions (NBS). Resilient SWP adds another layer: a recognition that the water cycle is profoundly connected and sensitive to climate change. If managed with an eye to these drivers, resilient SWP can provide the flexibility needed to allow human communities to thrive even as we experience more volatility across our climate and social systems. Resilient SWP may also be more cost-effective than gray infrastructure alone in provisioning high-quality and reliable freshwater while also delivering a host of other important benefits, especially when considered over the long term.

Freshwater ecosystems can be a key component in providing resilience to communities, but they also need to be resilient themselves. Managing source waters for *resilience* at the same time as managing source waters *resiliently* should include the following elements:

1. Managing the governance, operations, and planning of source waters at catchment and basin scales, for both surface and groundwater.
2. Planning source water management over timescales that, at a minimum, reflect the operational lifetime(s) of the infrastructure interacting with target source waters. Timescales of decades to a century or more should be widespread.
3. Explicitly including the risks associated with climatic and hydrological uncertainties in decision-making processes for operations, planning, and finance.
4. Developing robust and flexible designs, plans, and management regimes that consider a wide range of interconnected drivers, such as climatic, demographic, and urbanization shifts.
5. Considering climate-influenced shifts in key variables, such as water timing, flow, and quantity; in the abundance, timing, and distribution of species; the composition of ecological communities; and the makeup and qualities of ecosystem processes.
6. Increasing the inherent capacity of source waters to adjust to climate impacts by restoring lost hydrological functions, formally integrating source waters into water management regimes, enhancing the services provided by source waters, and minimizing negative non-climatic influences such as pollution and overfishing.

introduction

In 2002, a mild drought in Rwanda reduced flows in the Rugezi River, which was the location of two run-of-the-river hydropower plants generating about 90% of the country's electrical capacity. Government leaders were faced with a dire short-term crisis, potentially crippling their economy, frightening domestic and foreign investors, and reducing the ability to meet critical electricity needs. Fortunately, the drought was over in a few weeks, returning generation back to more normal service levels. National decision makers recognized that more (and more severe) droughts were likely to occur in the future due to ongoing climate change, triggering a search to discover why power supplies had been so vulnerable to what was otherwise a historically modest drought.

One of the key findings by decision makers was that the wetlands upstream of the hydropower facilities had been badly degraded by a burgeoning population seeking new and fertile land for subsistence farms. Rwanda's source waters had been compromised, which had in turn compromised the nation's economic development. By converting wetlands into fields and degrading the wetlands' storage and flow regulation functions, profound changes in hydrology had occurred in the Rugezi River (Hategekimana and Twarabamenya, 2007).

Government leaders saw an integrated if complex set of solutions. Farmers in the Rugezi's marshes were resettled and the wetlands' function restored. Legislation to protect national water resources and to ensure that landless farmers had access to arable fields in less sensitive regions reduced pressure on national wetlands and riparian zones. The wetlands above the Rugezi's hydropower facilities were declared a Ramsar Wetland of International Importance. Moreover, the country diversified its energy generation systems away from an overdependence on hydropower and diversified hydropower generation away from a single basin. Rwanda had recognized the linkages between source water protection, land use, healthy ecosystems, and climate adaptation (Hategekimana and Twarabamenya, 2007; Matthews et al., 2011).

"Source Water Protection" (SWP) is now a widely used term to describe efforts to achieve human water security through sustainable ecosystem management (Abell et al., 2017). Although the terminology is relatively new, many of the strategies of SWP for maintaining or enhancing ecosystem services have been practiced for millennia (see examples in tables referenced in Appendix 2). Likewise, the preservation of environmental flow regimes, the restoration of hydrological functions, and the integration of ecosystems within water management infrastructure are well known approaches for securing freshwater.

Rwanda's insights about resilience and SWP — despite dating back to the first decade of this century — are still considered innovative. Rwanda identified an interlocking set of governance, legal, water management, social, economic, and planning opportunities that made the

Small stream wraps around the tea plantation and connects to the Rugezi Marsh — nearly 7,000 ha of protected area, Rwanda. © DOW MANEERATTANA/WRI

country's ecosystems and economy more robust. Few countries have approached climate change and water resources with such a comprehensive level of awareness. Many countries need to follow Rwanda's lead today. Here, we describe a new vision for achieving and managing resilient source water protection for communities and ecosystems in a changing climate.

> "Source Water Protection" (SWP) is now a widely used term to describe efforts to achieve human water security through sustainable ecosystem management.

Table 1: SWP Activities and the Types of Climate Change Impacts they can Help Address.

SWP ACTIVITY	EXAMPLES	FUNCTIONS MAINTAINED OR RESTORED	CLIMATE CHANGE IMPACTS POTENTIALLY ADDRESSED					
			Increased flood peaks	Less precipitation in dry season	Decreased snow pack	Increased water and air temperatures	Increased rainfall erosivity/soil erosion	Increased fire risk
Targeted land protection	Forest protection, grassland protection, wetland protection	Maintain ability of landscapes to filter and infiltrate water; slow down overland runoff; fog capture from forests	X	X	X	X	X	
Revegetation	Reforestation, afforestation, grassland restoration	Restore more natural hydrology; restore ability of landscape to filter and infiltrate water. slow down overland runoff	X	X	X		X	
Riparian restoration	Replanting riparian vegetation, fencing along streams to allow vegetation to grow and keep out animals	Restore ability of riparian vegetation to filter runoff before it reaches the stream; increased vegetation can decrease stream temperatures				X	X	
Agricultural best management practices	Cover crops, conservation tillage, nutrient management, irrigation management, soil management, agroforestry, crop switching, diversification of crop types	Reduce water use and/or consumption; restore or maintain soil health, including ability of soil to store moisture; reduce nutrient and chemical application or concentration in runoffs; increase filtration of pollutants at edge of field		X	X		X	
Ranching best management practices	Rotational grazing, fencing, prescribed fire, shrub control, silvopasture, pasture management	Restore or maintain vegetative cover and soil health; restore or maintain ability of vegetation to filter pollutants and slow down overland runoff; maintain or restore ability of top soil to store moisture	X	X	X		X	
Fire risk management	Prescribed fire, controlled burn	Reduce risk of catastrophic fires and subsequent risks of major soil erosion and water quality impacts; help maintain ability of landscape to filter and infiltrate water and to slow down overland runoff				X	X	X
Wetland restoration and creation	Restoration of previously existing wetlands or construction of new wetlands to address specific water issues, primarily water quality	Ability to store water and release it slowly over time; allow water to infiltrate; filter pollutants; slow down and decrease overland runoff	X	X	X			
Road management	Grading and drainage management, upgrading road material	Reduced erosion					X	

NOTE: This table provides an overview of how these activities might address climate change impacts; however, the ability of the activity to address specific impacts varies between specific applications and biophysical contexts.

Nature-Based Solutions: Integrating Ecosystems into Water Management Systems

Nature-Based Solutions (NBS) encompass a suite of ecosystem-related approaches to address pressing challenges facing humanity and our natural systems, including water security. NBS are defined by IUCN as "actions to protect, sustainably manage and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2018).

NBS can range in terms of how "natural" or engineered a solution is, from protecting a fully intact ecosystem such as an old-growth forest to implementing an engineered wetland. The U.S. Army Corps of Engineers, for instance, distinguishes between natural features (which are existing ecological processes and ecosystems) and nature-based solutions (which are somewhat broader and include designed and reconstructed and ecological analog approaches, such as "new" wetlands on brownfield sites) (Bridges et al., 2015). Here, we will follow the IUCN definition. What all NBS have in common is that they seek to maximize the ability of nature to provide ecosystem services that help address a human challenge, such as climate change adaptation or disaster risk reduction.

IUCN has developed eight general principles that may help provide a more tangible understanding of NBS:

1. NBS embrace nature conservation norms and principles;
2. NBS can be implemented alone or in an integrated manner with other solutions to societal challenges (e.g., technological and engineering solutions);
3. NBS are determined by site-specific natural and cultural contexts that include traditional, local, and scientific knowledge;
4. NBS produce societal benefits in a fair and equitable way, in a manner that promotes transparency and broad participation;
5. NBS maintain biological and cultural diversity and the ability of ecosystems to evolve over time;
6. NBS can be applied at a landscape scale;
7. NBS recognize and address the tradeoffs between the production of a few immediate economic benefits for development and future options for the production of the full range of ecosystems services; and
8. NBS are an integral part of the overall design of policies and measures or actions, to address a specific challenge.

Most of these principles integrate well with flexible approaches to resilience, especially if NBS assume that ecosystems will adjust and respond dynamically (and sometimes unpredictably) to climate impacts. Blending these principles with the strategies described here for resilient SWP is a powerful combination.

NBS can be critical elements of source water protection and often offer the most cost-effective approach to maintaining or improving water security for a watershed. NBS are especially useful to improve water quantity and quality through filtration and flow regulation. As described in the IUCN principles, NBS can be used alone or in conjunction with other solutions to produce the desired outcomes. For example, NBS such as protection or restoration of natural vegetation in the watershed can be combined with a smaller-scale gray infrastructure water treatment facility at the point of diversion to deliver clean, reliable water at a reasonable cost.

A young Rwandan boy fetches drinking water from the well in his two 10-liter yellow water containers while the women wait in line.
© SARINE ARSLANIAN/SHUTTERSTOCK

Beyond Rwanda: Converting Water from a "Climate Risk" into an Opportunity for Sustainability

The issues Rwanda faced in the Rugezi are not unique. For all countries, the language of climate change is largely the language of water-related crises: droughts, floods, fires, famines, typhoons, and hurricanes. The impacts of climate change manifest daily in the news with stories of extreme weather events, ecological loss, and human suffering. In most cases, the coverage of climate impacts tends to focus on risks rather than opportunities for positive change. But, as Rwanda's example shows, the reverse proposition may be true as well: Water, if managed well, can be a source of opportunity to enable a broader sustainability agenda for many countries. In particular, we can use SWP to connect ecosystems to our decisions beyond the "water sector" to build economic and ecological resilience.

> Water, if managed well, can be a source of opportunity to enable a broader sustainability agenda for many countries. In particular, we can use SWP to connect ecosystems to our decisions beyond the "water sector" to build economic and ecological resilience.

Between 2000 and 2010, deep concerns within the water management community about climate change began to coalesce into clearer focus (Gleick, 2000; Pahl-Wostl, 2007). In 2008, Milly and colleagues declared some of the core assumptions of more than a century of engineering and planning "dead" (2008). The premise that the past could reliably predict the future no longer made sense in a world experiencing abrupt climate change. The global climate system was entering a period of rapid shifts. Questions arose about our ability to predict the future well enough to design and operate long-lasting dams, irrigate fields productively with shifting seasons and manage freshwater fisheries and aquatic ecosystems without risk of collapse. Some long-standing standard practices in water management were at best ineffective and could even be potentially dangerous to communities, infrastructure, and ecosystems in the face of so-called “**deep uncertainty**,” a term that refers to the emergence of such large sources of uncertainty about the future that we cannot distinguish between the likelihood of widely divergent scenarios. In effect, Milly and colleagues (2008) identified the start of a crisis period in terms of defining what sustainability means in a time of social and environmental transformation (Pahl-Wostl, 2007; Rockström et al., 2009; Carpenter et al., 2011; Matthews and Boltz, 2012).

During that same period, however, we also saw the emergence of several disparate-but-powerful ways to account for a more complex, uncertain future. While water may be the means of expressing the negative impacts of climate change, resource managers and policymakers began to see how freshwater resources could also be the tool to reconcile and connect sectors, communities, and ecosystems to enable humans and other species to adapt and adjust to new climate conditions (Ringler et al., 2013; GWSP, 2014; Röckstrom et al., 2014).

We have new opportunities today, based on new insights about how climate change fundamentally alters our views of the role of water and freshwater ecosystems and our definition of sustainability (IWMI & AGWA, in press; UN Water, in press; GIZ, in press). *Wellspring* describes the challenges that climate change presents water and resource managers, but also sets out a new vision of resilience and sustainability to unite the interests of economies, ecosystems, and communities in a time of global change. For those who are already employing existing SWP practices, we will distinguish between traditional and resilient approaches to SWP. The practice of *resilient* SWP recognizes that hydrology, ecosystems, water management, and climate are intertwined, and that the integrity of ecosystems is necessary for the integrity of communities — and *vice versa* (Figure 1). Many regions are already facing serious threats from climate impacts, and these threats are likely to intensify and grow over coming decades and centuries. Restoring the functions of the landscapes and ecosystems that provide for and regulate our source water is one of the most reliable means society has for continuing to thrive and develop while alleviating poverty and promoting sustainable growth through a more effective vision of resource management (Poff et al., 2016).

> The practice of *resilient* SWP recognizes that hydrology, ecosystems, water management, and climate are intertwined, and that the integrity of ecosystems is necessary for the integrity of communities — and *vice versa*.

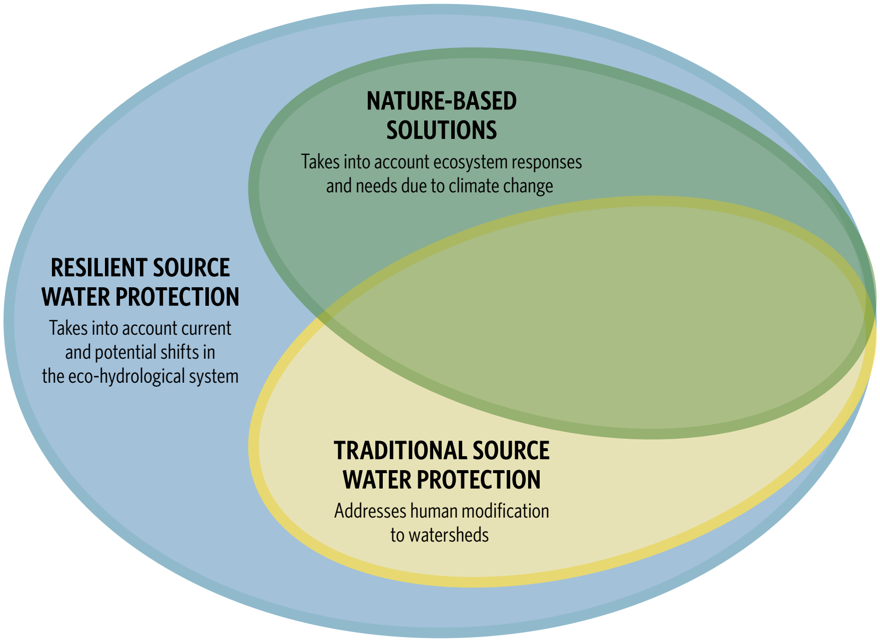


FIGURE 1: Both traditional SWP and resilient SWP have a strong emphasis on nature-based solutions. Resilient SWP differs from traditional SWP primarily by its focus on accounting for the shifting role of climate on both ecological and hydrological systems, especially how climate may alter water quality, quantity, and timing as the water cycle continues to shift with future climate change.

structure and approach

Wellspring is designed for those working in the fields of water resources management and natural resources conservation who want to consider new patterns of source water protection in light of ongoing climate change. Here, we present the insights and evidence to suggest what aspects of management should be continued, reprioritized, or shifted. Our hope is that readers will find strategic guidance that can impact institutional decision making. Climate change is generally described by the water community as a threat, but the threats posed by climate change are not equal in magnitude to all aspects of source water management and protection. In many cases, climate change also presents positive, proactive opportunities.

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Wellspring begins by describing the language of climate change, including some of the principles that define many of the core concepts of water resilience. We describe some of the negative impacts to water infrastructure and aquatic ecosystems before discussing the emergence of a coherent approach to resilient source water protection. We then summarize some of the members of the water community who have ownership over the spectrum of source water resilience decisions. Even when these actors have found consensus, however, arranging financing often remains a challenge, so we explore this topic as well. Finally, we address what for many — especially for many conservationists — remains an important component of our work: the sense of loss associated with climate change. Managing for resilience is not managing for conservation and reevaluating the meaning of sustainability — given the forces out of our control — requires courage and strength.

Moving toward “Resilience”

Climate adaptation — our ability to cope with and prepare for ongoing climate change impacts — has become a prominent and urgent issue for many policy makers at local, national, and global levels. As a result, in many countries, interest in climate change is expanding from the environment ministry to the finance ministry, as well as to other actors that focus on city planning, health, agriculture, energy, and poverty (OECD, 2013; World Bank Group, 2016). Reducing the rate of carbon emissions remains important to slowing down climate change, but now the extent and longevity of realized climate impacts are prompting new discussions: what does sustainable development look like if we have difficulty predicting the future? How do we design infrastructure or protect ourselves against weather events that are hard to foresee? How much can we use the past to predict the future and what other methods can we use to reduce emerging risks and take advantage of new opportunities?

One of the critical emerging points of discussion across the environmental, conservation, and economic development communities concerns how we manage natural resources in a sustainable manner in light of ongoing climate change. Concerns are especially acute with source waters, since freshwater resources are so critical to almost all aspects of modern economies. Protecting and managing source waters for a dynamic, changing climate can bind together ecological and social systems along a shared path of resilience (Holling, 1996; Folke et al., 2006; Davidson et al., 2016). Understanding how this statement functions in practice also means that we need a shared knowledge of terms such as "resilience" and "climate adaptation," as well as the tenets that have guided SWP efforts without reference to climate change.

Past SWP efforts have historically used two complementary narratives for guidance. One narrative has been borrowed from engineering: the past predicts the future, which is also called the **climate stationarity** assumption (Milly et al., 2008). The second narrative is borrowed from the conservation movement more generally, which could be paraphrased as the past defines success. Conservationists and resource managers as a whole typically define "baseline" targets based on some point in the past when the ecosystem was, in most cases, healthier and more intact. By using such baseline targets, managers can guide ecosystems back towards those more positive conditions. As discussed below, however, a baseline defined by past conditions may not make much sense in a time of rapid climate change. And while engineers, and water managers more generally, have made dramatic shifts in theory and practice away from the assumption of stationarity, the premise that past ecological states should be the primary basis for SWP targets has been far less questioned. Ecosystems are evolving in response to climate change, often in ways that are difficult to predict or manage (Parmesan, 2006). How does a baseline guide action in that context?

> **Protecting and managing source waters for a dynamic, changing climate can bind together ecological and social systems along a shared path of resilience.**

Attempting to use baselines from the past as management targets is unreliable and may even be counterproductive — the climate of even 50 years ago no longer exists. As species move around, adjust their movement patterns, or alter the timing of important biological processes such as migration, flowering, pollination, or breeding, we risk impeding their adaptive management behaviors if we operate based on outdated assumptions. During past periods of climate change, species often shifted their ranges radically. Ecosystems such as the Amazon's dense wet tropical rainforest have transformed into dry tropical savannahs like Brazil's cerrado ecosystem and back again. Protected areas can help buffer the impacts of climate change, but not stop or contain that change.

Given this context, clear definitions of three terms — climate adaptation, resilience, and transformation — are important to move forward. **Climate adaptation** is the most straightforward of these and refers to the specific actions we undertake to respond to or prepare for particular climate impacts. For example, raising flood dykes or storing water in aquifers are adaptation responses to increasing and decreasing precipitation patterns, respectively. Climate adaptation has a neutral, even technical connotation.

In contrast, **resilience** (or "resiliency," a term used primarily in the United States) is an unsettled and conflicted term. The word has long referred to the ability to recover from and/or resist a deviation, shock, or stressor by returning to the pre-disturbance state, much like releasing a stretched rubber band that can then go back to a relaxed condition. However, the number of definitions of resilience have proliferated in recent decades as the concept has been applied to new technical domains (cities, communities, ecosystems) and to new contexts (disasters, climate change, economic shifts).

Many of these new definitions are concerned with how a group, location, or ecosystem can be resilient when returning to the original state (*i.e.*, the unstretched rubber band) is no longer an option. What happens when the rubber band is stretched very far, distorting its shape permanently? Or if the rubber band breaks when over-stretched? In a broad survey of the term, Olsson and colleagues (2015) show a deep division between "bounce back" definitions of resilience and newer "bounce back with transformation" definitions, with the latter reflecting the insight that returning to the pre-shock or pre-disturbance state may not be feasible or even desirable. For decision makers and practitioners, such a definition of resilience encompasses both incremental adjustments to shocks and stressors as well as deep, irreversible, and permanent changes (Folke et al., 2006, 2010).

Bounce-back definitions correspond most closely to traditional approaches to SWP, while bounce-back-with-transformation definitions align with resilient approaches to SWP (and will be the basis for the usage of the term throughout the rest of *Wellspring*). Other authors have tracked how the expanded definition of resilience is permeating water resources management, driven by concern over climate change and the need for practitioners to develop more "resilient" targets and goals (Rodina, 2018; Burgess et al., 2019).

The third term, **transformation**, builds on the more recent and expanded definitions of resilience, but transformation is a relatively new term in the context of climate change. Transformation refers to conditions that have become so altered as a result of climate impacts that an ecosystem develops fundamentally new qualities and traits. In many parts of the world, transformation is already a daily reality. The Andes, Himalayas, and the Tibetan Plateau alpine ecosystems, which are key source waters for billions of people, are becoming temperate grasslands and even forests, completely altering the hydrologic regime. In the United States and Canada, Glacier National Park is going through a similar evolution as the last of its "permanent" glaciers disappear, thereby profoundly impacting the region's source waters through transitions such as the shift from a snowpack hydrology to a rain-driven hydrology (Luce, 2017). Other high-altitude ecosystems around the world are now or will be experiencing similar changes in coming decades.

> To be effective in the face of deep uncertainty, resilience must encompass approaches that allow us to persist, adapt, and transform in the face of uncertain climatic change stressors and shocks that create lasting, irreversible impacts.

However, change *per se* does not mean that new conditions are always "bad" or that climate impacts are always negative. Resilience in the face of transformation encompasses change that maintains some functional qualities (such as broad categories of species, basin flow patterns, the role of fire in the carbon cycle) while also developing or exhibiting new functional qualities (*e.g.*, community composition, the timing of ecosystem processes and flow regimes, temporary vs. permanent waters, etc.). As resource managers, we have active *choices* to make along the path of resilience generally and transformation in particular. We can generally slow or accelerate ongoing processes and guide the evolution to new conditions and qualities, sometimes even selecting for them when possible. Such choices and options are quite new for "conservationists," who historically have tried to "conserve" and limit change over time. To be effective in the face of deep uncertainty, resilience must encompass approaches that allow us to persist, adapt and transform in the face of uncertain climatic change stressors and shocks that create lasting, irreversible impacts.

These issues are complex and challenging, but there are a number of existing frameworks that institutions have developed that can be useful and relevant. The Global Resilience Partnership (GRP) for instance, has outlined the following key principles:

- **Embrace complexity.** It is essential to recognize the increasing complexity of development challenges, to identify their root causes and to understand how these can be addressed within the political, economic, ecological, and social systems in which they exist. Complexity further recognizes that

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systems are not linear and change may be disruptive and transformational.

- **Recognize the constancy of change.** Risks and stresses are becoming increasingly unpredictable, uncertain, and unavoidable due to the more complex, connected, and rapidly changing context of development. This needs to be recognized and requires systems that have the capacity to navigate dynamic and uncertain futures and that maintain diversity.
- **Strive for inclusive decision making.** It is increasingly important to put people and communities, especially women and marginalized groups, at the center of decisions and empower them to help develop equitable and sustainable solutions. This includes identifying the problematic structures and power relationships that created that marginalization in the first place and building on existing local and community-based solutions that fit the social and cultural context.
- **Enhance ecosystem integrity.** People, places, and ecosystems are intertwined and together support the multiple dimensions of human well-being. Approaches to development need to be transformed to ensure a good life for all while maintaining the integrity of the Earth's natural environments.
- **Promote flexibility and learning.** A rigid or fixed solution will not build resilience for change. Approaches need to be adaptive and responsive and we must constantly learn from what works and, crucially, what does not.
- **Stimulate and support innovation, synergies and opportunity.** Developing new solutions and innovations that engage with the complexity of development challenges will not only help build resilience, but will be essential to transforming to sustainable and just development.

CASE STUDY 1

Adapting the Colorado River Basin

Lead Author: Brad Udall, CO Water Center

The Animas River, a part of the Colorado River basin, runs through the James Ranch near Durango, Colorado. © ERIKA NORTEMANN

THE SITUATION

After two years of effort, the State of Colorado adopted the Colorado Water Plan in 2016. Among many goals, the plans called for the 80% of locally prioritized rivers to be covered by Stream Management Plans by 2030. Stream management plans identify shared environmental and recreational values and the associated biological and hydrological data to support these values. The plans then identify management actions that are needed to support the flows and land conditions necessary to achieve the environmental and recreational values.

THE ACTION

In 2017, the state provided US$5 million in grants to develop projects and plans to restore and protect watersheds and streams including the creation of stream management plans. A few places in the state had already begun to grapple with these issues prior to issuance of the Colorado Water Plan. In approximately 2015, stakeholders in the Roaring Fork Valley, which drains Aspen, began a process to write and implement such a plan. The initial plan was released by consultants in 2016. Importantly, the plan built upon a number of documents written over the previous decade.

For the Crystal River, a large tributary of the Roaring Fork, the plan assessed existing ecosystem function and looked at values such as the flow and sediment regimes, water quality, floodplain connectivity and riparian vegetation. The plan assessed stream morphology, channel structure, along with the biotic structure and performed an overview of existing water rights. These rights include agricultural and municipal rights, instream flow rights and trans-basin diversions. Planners constructed a model to understand the interplay of these rights and other factors of importance.

THE RESULTS

Planners used the model to investigate a number of alternative management strategies. Market-based strategies included non-diversion agreements, short-term water leasing. Conservation strategies included ditch lining, use of sprinklers and irrigation scheduling. An off-channel reservoir was considered to improve supply in dry times. Finally, the plan also considered various modifications to the river channel.

The plan identified a number of preferred management priorities. These included a non-diversion agreement with existing agricultural users, approximately 70% of the water use and conservation by the largest municipality in the drainage, Carbondale. In January of 2018, Colorado's Water Trust announced a 3-year agreement with a local rancher to keep water in the Crystal River during low flow periods.

REFERENCES

CWI (Colorado Water Institute). 1995–2019. "Newsletter on Stream Management Plans". http://www.cwi.colostate.edu/Newsletters.aspx.

Lotic Hydrological, LLC. 2016. *Crystal River Management Plan.* Roaring Fork Conservancy. Public Council of the Rockies. http://www.roaringfork.org/media/1352/crmp_noappendix_bleeds.pdf.

State of Colorado. 2019. "Stream Management Plans". https://www.colorado.gov/cowaterplan.

Tory, S. 2018. "New water agreement for Crystal River could open door to boost Colorado rivers". *The Aspen Times.* January 23. https://www.aspentimes.com/news/new-water-agreement-for-crystal-river-could-open-door-to-boost-colorado-rivers/.

climate threats to water infrastructure

Globally, we can see two broad and divergent patterns emerging with respect to gray infrastructure and climate change. First, countries with older infrastructure are beginning to adapt their aging water management systems to new or anticipated climate impacts. The United States, Australia, Japan, South Africa, Canada, former Soviet republics, and Europe built most of their stock of reservoirs, utilities, and other types of water infrastructure during the so-called "golden age" of dam building, which began around 1910 and ended roughly in the 1970s. These old-but-still-critical investments are showing clear signs of climate mismatches, such as the inability to cope with higher floods, lower mean annual precipitation, or extreme water temperatures.

For instance, in the United States, the Hoover Dam's massive Lake Mead reservoir has experienced a "drought" since about 2000 — reflecting decades of declining precipitation levels from the upper Colorado River basin (Lustgarten, 2016). A bleached white "bathtub ring" tens of meters high is now exposed around the perimeter of the Hoover Dam's Lake Mead, which clearly mark the climate conditions and flow patterns the Hoover Dam was designed for in the 1930s. Several water intake tunnels also now stand tens of meters above the water line.

To cope with these long-term trends, climate adaptation activities are well underway. Interventions to maintain the Hoover Dam's essential services have cost billions (Harvey, 2016). Regional groups such as the Southern Nevada Water Authority have promoted water-use reduction and water recycling programs in the nearby city of Las Vegas, Nevada (Ross, 2011). Major upgrades to the turbines were recently completed to maintain generation capacity, while dam operators invested in a huge underground "bathtub drain" tunnel formally referred to as Intake Tunnel 3, which can continue to supply nearby communities with water even if water levels fall below the second-tier intake tunnels (Wines, 2014), as is widely anticipated (Ross and Wolfe, 2015).

Major adjustments are also being made to the Colorado River's water governance and allocation agreement for U.S. states in the region. In mid-2019, the seven basin states signed a 'Drought Contingency Plan' (DCP) that will govern the operation of the basin until the end of 2026. The DCP puts in place large delivery reductions (up to 1.7 BCM/year) to selected Lower Basin users should Lake Mead drop to very low levels. The Colorado River basin is now shifting to a climate more typical of the mean of the past 1,000 years, rejecting a rigid set of assumptions about the amount of water that was reliably available when the Colorado River Compact was signed in 1922 and when the Hoover Dam was initiated in the following decade. The basin is not experiencing a "drought" so much as shifting to a new normal (Robbins, 2016b) Similar patterns are appearing with older water infrastructure globally. In late 2016 in northern California, the Oroville Dam — constructed in 1968 — transitioned

Construction cranes on the Three Gorges Dam in Yichang, China. © BRIAN RICHTER

from record drought to a period of intense rain, resulting in an uncontrolled and damaging release through its spillway that led to the evacuation of almost 200,000 downstream residents in February 2017 (Boxall & McGreevy, 2017).

The second pattern of gray infrastructure development is more widely seen in the developing world, especially in countries that have recently begun to intensify their use of water resources to provide electricity, clean water, and cheap transportation. This transition is most typical of countries experiencing rapid population growth and a shift from a subsistence or agricultural economy to a manufacturing and service economy, which includes much of Central and South America, Africa, and Asia. Most of these structures are being built in middle- and low-income countries such as China, India, Ethiopia, Turkey, and Vietnam, often on a more rapid timeframe than during the so-called golden age, with hundreds of new investments being deployed in single countries over a handful of years. We may be entering a "platinum age" of dam building.

Compared to developed economies, aquatic ecosystems in the developing world are relatively more intact and have a higher potential for retaining the integrity of their source waters. Unfortunately, in most cases, infrastructure in these countries is developed using the same past-predicts-the-future framework as was used throughout the 20th century. Indeed, the chief engineer for the Three Gorges Dam in China allegedly stated that his dam was designed to last "forever" (Matthews, Wickel and Freeman, 2011).

The majority of these new assets have not yet begun to significantly diverge from their ambient climate — they're too young. But the same climate mismatches we see in places like the Hoover Dam will soon be apparent in the developing world and, given the accelerating nature of climate change, probably in the very near future. In countries where large water infrastructure investments were made a little earlier such as in the 1950s to 1970s (Venezuela, India, and Zambia), quite advanced signs of climate-driven divergences from design specifications are already apparent. The Kariba Dam on the Zambezi in East Africa — one of the world's largest and completed only in 1959 — currently struggles to generate power for just a few hours each day (Singh et al., 2018). In countries with very rapid climate change such as Nepal, climate mismatches can be seen with infrastructure that is only a decade, or less, old (Matthews et al., 2011; UNECE & INBO, 2015).

Given the fundamental role of water infrastructure to modern economic development and growth, the developing world will likely need to spend hundreds of billions of US$ in the next two decades to upgrade, maintain and adapt water infrastructure to maintain the economic benefits of those investments. Negative climate impacts on operations in these countries will likely be magnified relative to wealthier countries as fewer resources will be available to compensate for economic and ecological damage or to undertake extensive redesign work as with the Hoover Dam.

> Resilient SWP is a powerful framework for how to envision long-term sustainable water planning, design, management and investment in an era of ongoing climate change.

But opportunities exist in parallel to these challenges: because the platinum age of new construction is ongoing, developing countries also have the highest potential to correct and learn from previous design gaps. Effective climate risk assessments such as bottom-up methodologies (described in more detail below) could produce more robust and flexible designs, while resilient SWP insights and interventions (see tables referenced in Appendix 2 for additional examples) could provide a more holistic and progressive set of water resource management solutions in place of or supplemental to traditional gray infrastructure projects. Resilient SWP is a powerful framework for how to envision long-term sustainable water planning, design, management, and investment in an era of ongoing climate change.

As with infrastructure, climate uncertainty is a very significant issue for ecosystems, particularly source waters. While most of the risks associated with gray infrastructure and climate change are about drops in efficiency, loss or disruption of income or services and more challenging tradeoffs versus other services or sectors (*e.g.*, irrigation vs. energy), catastrophic losses such as dam failures will probably remain rare. Especially for critical infrastructure and in wealthy nations, we should be able to modify and adjust many installations so that they match or track ongoing climate impacts. In contrast, climate change presents different risks for source waters.

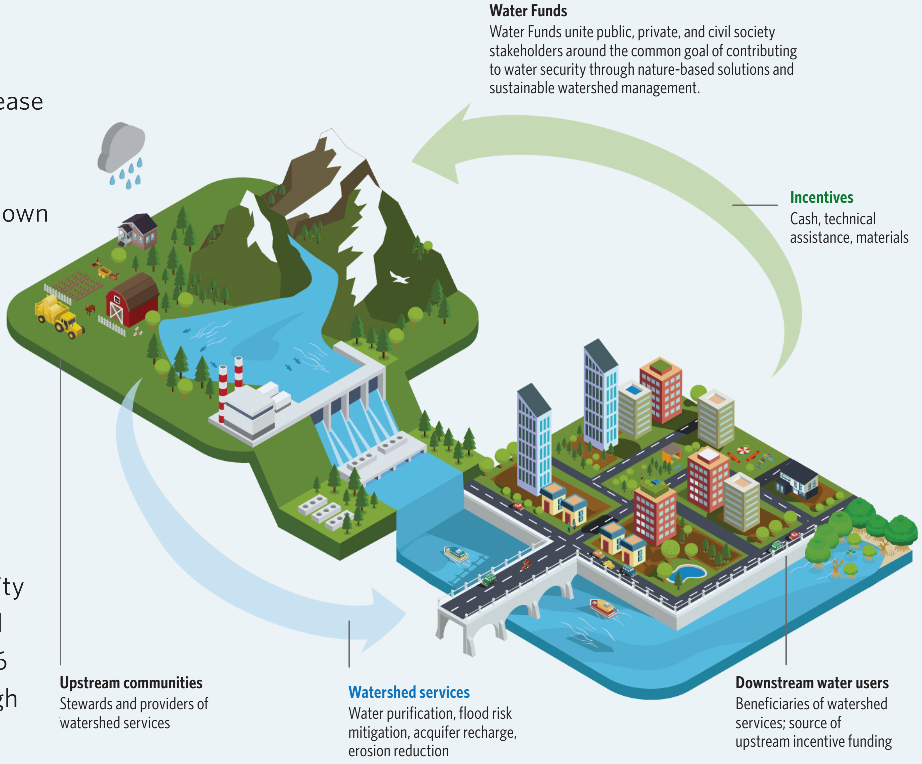
FIGURE 2 (AT RIGHT): Water Funds unite public, private, and civil society stakeholders around the common goal of contributing to water security through nature-based solutions and sustainable watershed management. Water Funds provide a framework for downstream water users (cities, beverage companies, utility providers, etc.) to address water security issues — including those related to climate change — at the source by investing in conservation projects that protect upstream lands, improving filtration, and regulating flows. Learn more at https://waterfundstoolbox.org/.

Water Funds: A Potential Framework for Resilient SWP

The Power of Nature

By 2045, the world's urban population will increase to more than 9 billion. Currently about 40% of the land around our world's water sources are degraded; nearly 36 hectares of forest are cut down every minute.

Healthy watersheds have been shown to provide diverse benefits to communities, ecosystems and cities, including carbon sequestration, habitat for local fauna, rich soils for sustainable agriculture and clean water for industry, energy, and consumption. Upstream forest protection, reforestation, and improved agricultural practices could improve water quality for 4-out-of-5 large cities around the world, and can deliver these benefits cost-effectively: 1-in-6 cities can pay for natural solutions solely through savings in water treatment costs.



The diversity and affordability of benefits underscores the urgency to mobilize the power of nature to meet water security challenges in a sustainable way. Water Funds provide a nimble, innovative solution.

Water Funds

The Water Funds model creates a governance and management structure that enables stakeholders around the world to work collectively to secure water for their communities. As an implementation mechanism, Water Funds protect our natural water systems by uniting civil society and the public and private sectors to manage the significant complexities associated with nature-based source water risk protection. They identify and implement mechanisms for the long-term financing of water security programs and work with people living upstream of cities to help them manage watersheds, improving the productivity and ecological resilience of their lands.

How Does a Water Fund Work?

A water fund is run by a governance board responsible for selecting those source water protection projects that will most effectively improve water security. They are also responsible for distributing funds to these activities and monitoring the project impacts after implementation (Figure 2). To date, there are a handful of water funds that consider climate change impacts specifically, but interest and momentum to evolve water funds to include robust and flexible approaches to water security and resilience are increasing.

Sustainable financing for source water protection projects comes from downstream users — communities, corporations, water providers, among others — and the landholders and civil society organizations working upstream receive these funds to implement the activities approved by the governance board. As an institutional platform, a water fund is an excellent tool to bridge science, jurisdictional, finance, and implementation gaps.

CASE STUDY 2

Monterrey Metropolitan Water Fund: Climate Change Disaster Risk Reduction in Mexico

Lead Author: Emily Simmons, TNC

THE SITUATION

In northern Mexico, the state of Nuevo Leon is characterized by a dry and semi-dry climate, but the region is also along the Gulf Coast making it very vulnerable to intense rainfall events during the hurricane season. For the city of Monterrey, this means that both droughts and flooding are a common occurrence.

The San Juan watershed is already highly stressed, supplying freshwater to more than 4 million residents of the Monterrey Metropolitan area. Water availability per capita is close to 290 liters/day, which is comparable to that of Middle Eastern countries including Syria and Saudi Arabia (Chaidez and Jesus, 2011). Climate change is projected to only worsen droughts in the area with longer dry spells and higher temperatures that increase evaporation (Sisto et al., 2016). When rain is needed, it often comes in the form of major tropical storms and, because Monterrey is built along the Santa Catarina River, a part of the San Juan River basin, flash floods continue to be a very high risk for the city.

When Hurricane Alex hit the area in 2010, Monterrey was heavily impacted by flooding, erosion, landslides, power outages and failed infrastructure. The accumulated damage across the region cost the state of a total of US$1.35 billion. The following three years Nuevo Leon experienced abnormally dry weather, but because the storage and regulation capacity of the reservoirs had been severely weakened from Hurricane Alex, water availability was extremely limited. Over 50,000 hectares of crops were damaged and more than 10,000 livestock were killed by the drought, which finally ended in 2013 just before Monterrey's water supply systems were about to collapse (Abell et al., 2017).

Years of poor land management, growing demand on the San Juan watershed, over-drawn aquifers and increasingly extreme hydro-meteorological events due to climate change, are the contributing factors that put Monterrey, Mexico on the map as one of the top 25 Latin American cities for water risk (TNC and LACC, 2016).

THE ACTION

During the same year that Hurricane Alex was developing, the Latin American Water Funds Partnership identified Monterrey as a leading city in Latin America with high potential of receiving improved water security from nature-based solutions and joined forces with key local partners from the private sector such as ARCA Continental, ALFA, Citibanamex, BANREGIO, CEMEX, Grupo Cuprum, Heineken, FEMSA, and from academia and civil society. After three years of thorough planning, fundraising, and strategic design the Monterrey Metropolitan Water Fund (FAMM) eventually emerged in 2013, becoming Mexico's first official Water Fund (Abell et al., 2017).

Not long after the FAMM began implementing conservation actions, the Governor of the State of Nuevo Leon, Jaime Rodriguez Calderon, recognized the opportunity that source water protection could provide for the area. In January 2016, he assigned both the Nuevo Leon Council and the FAMM to co-create a new water plan that would align sustainable development, climate projections, water demand, city planning, and more.

In 2018, they published the *2050 Water Plan of the State of Nuevo Leon* as a result of a two-year process of collaborative work with government institutions, universities, research centers, consultancy firms, and external consultants, and was peer reviewed by national and international water experts. Different public hearings to provide feedback on the results were also hosted and then published on-line. This process was unique in the Mexican context not only because of the number of studies done specifically for the purpose of creating the plan in collaboration with multiple experts, but also because of the long-term planning period considered. Having a document like this is an important legacy to improve the water governance of the State of Nuevo Leon.

Developing the 2050 Water Plan of the State of Nuevo Leon allowed the FAMM to align its own mission and goals to the Plan's key findings. These goals include:

1. Boost city resilience to extreme events (floods).
2. Boost resilience and system efficiency of the SADM utility system (Sistemas de Agua de Monterrey)
3. Promote a higher level of water governance in Nuevo Leon.

The updated mission of the FAMM is "to promote projects that increase the water security of the area in an efficient manner and increase the resilience of the city to extreme phenomena (floods)."

THE RESULTS

Based on the identification of a priority area for conservation to meet the FAMM's hydrological goals, some of the conservation projects implemented by FAMM from 2013 to December 2017 are:

→ Total Area of 5,478 hectares (ha) implemented
  - 1,347 ha reforested;
  - 2,796 ha receive payments for ecosystem services (PES);
  - 1,200 ha acquired for conservation;
  - 77 ha passive protection;
  - 58 ha soil conservation

→ SWP implementation strategies used: revegetation, reforestation, targeted land protection, soil conservation, PES.

These actions are aimed at improving the resilience of ecosystems, reducing runoff (floods) and favoring local water catchment and recharging aquifers. The hydrological modeling carried out by TNC, under different conservation scenarios, shows, for example, that by improving the green infrastructure on just 3,400 priority hectares, it would be possible to achieve an avoided runoff of 302 m^3/ha/year and reduce erosion by 40%. If the area is allowed to degrade, however, runoff would increase by 544 m^3/ha/year and water erosion could be 150% more severe, increasing the risk of flooding in the lower watershed (Hesselbach et al., 2019).

REFERENCES

Abell, R., Asquith, N., Boccaletti, G., Bremer, L., Chapin, E., Erickson-Quiroz, A., Higgins, J., Johnson, J., Kang, S., Karres, N., Lehner, B., McDonald, R., Raepple, J., Shemie, D., Simmons, E., Sridhar, A., Vigerstøl, K., Vogl, A. and Wood, S. 2017. *Beyond the Source: The Environmental, Economic, and Community Benefits of Source Water Protection.* Arlington, VA, USA: The Nature Conservancy (TNC). www.nature.org/beyondthesource.

Cháidez, N. and Jesús, J. 2011. "Water Scarcity and Degradation in the Rio San Juan Watershed of Northeastern Mexico". *Frontera Norte.* vol. 23, núm. 46, julio-diciembre, 2011, pp. 125-150. http://www.redalyc.org/articulo.oa?id=13619212005.

FAMM (Fondo de Agua Metropolitano de Monterrey). 2018. *Plan hídrico Nuevo león 2050.* Fondo de Agua, Monterrey, Mexico. http://famm.mx/wp-content/uploads/2018/10/Plan-Hi%CC%81drico-NL-2050.pdf.

Hesselbach M.H., Sánchez de Llanos, J.A., Reyna-Sáenz, F., García Moral, F.J., León, S.J., Torres-Origel, F. and Gondor, A. 2019. *Plan de Conservación del Fondo de Agua Metropolitano de Monterrey. México.* The Nature Conservancy.

Sisto, N., Ramírez, A., Aguilar-Barajas, I. and Magaña-Rueda, V. 2016. "Climate threats, water supply vulnerability and the risk of a water crisis in the Monterrey Metropolitan Area (Northeastern Mexico)." *Physics and Chemistry of the Earth*, Parts A/B/C, 91: 2–9. https://doi.org/10.1016/j.pce.2015.08.015.

TNC (The Nature Conservancy) and LACC (Latin America Conservation Council). 2016. "An opportunity for water security in 25 cities in Latin America". *Urban Water Blueprint.* Downloaded from: http://water.nature.org/waterblueprint/about/.

climate threats to source waters

The uncertainties around climate impacts on the water cycle are large enough that irreversible and catastrophic impacts on ecosystems are quite possible. Ecosystems are also, by their nature, far more complex than engineered water infrastructure. Not only may separate populations of the same species respond differently to the same impacts, but ecological communities will present a dizzying array of primary (direct) versus secondary and tertiary (indirect) responses to climate impacts, even as ecosystem processes (sediment flows, dissolved oxygen, temperature stratification) are also evolving. Our ability to predict future ecosystem states with confidence is extremely limited. Indeed, our ability to explain species assemblages in the relatively recent past (the early Holocene and late Pleistocene) remains largely elusive as well, when climate change was the main driver on ecosystem shifts and human impacts such as overfishing and pollution were limited or non-existent.

Paleoecological studies often show species gathered in ecological communities that seem strange or contrary to our current understanding of forests, wetlands, and rivers — a pattern referred to as **no-analog communities**, in the sense that there is no existing analog to groups of species we see gathered together versus in the past (Williams and Jackson, 2007; Velos et al., 2012). Today, researchers may have only rough data to understand the range of variation and variability a particular ecosystem has successfully endured in the past. Our ability to confidently predict responses to future (especially novel) stressors is especially difficult, even with taxa such as rice, wheat, or apples whose genetic and life-history characteristics have been explored in high resolution and experimentally.

Understanding climate threats to source waters, then, is less about knowing specific outcomes (low confidence) and more about trying to understand broad trends and categories of impacts (medium and high confidence). By using hydrological knowledge as our foundation, we can begin to make some informed statements about ecological or social outcomes. Some of the major types of climate impacts and their water management responses include:

1. **Extreme events.** Water-related extreme events include tropical cyclones (hurricanes and typhoons); flooding; very high temperatures for both air and water; grass, peat, and forest fires; and extreme drought (including multi-decadal droughts). In many ways, extreme events are the most often described type of water-related climate impacts as well as the most widely reported aspects of climate change — they represent major deviations from the norm. Extreme events *per se* are not new by any means and only recently have climate scientists begun to develop the tools to diagnose how recent climate change may be making "normal" extreme events more severe, frequent, or geographically different.
2. **Changes in "average" or "normal" climate conditions.** Shifts in mean climate are especially important for long-lived parts of the landscape, such as ecosystems, ecological communities, infrastructure, and highly organized systems such as cities. Processes and

systems that span 20 or more years may feel accumulating stresses that build over time until their weight triggers a tipping point or transition to a new set of conditions — sometimes even a set of new normal conditions. Significant changes in mean climate conditions are clearly visible in places such as high latitudes (Siberia, the Arctic) and at high altitudes, such as the Tibetan Plateau or the Andes, where climate change has been especially rapid and severe. Glaciers and snowpack in these regions are transitioning to wetlands, bare ground, or grasslands. In coming decades, grasslands may even become forests. For infrastructure, fixed operating regimes or design limits may be causing large changes in efficiency or service delivery, potentially altering the ability to operate or even, in the most extreme cases, resulting in design failure.

3. **Transformational change.** Perhaps the newest and least familiar term, "transformation" refers to the emergence of fundamentally novel conditions — a new normal — in a landscape or ecosystem. Transformation is the outcome of persistent trends in shifts in mean condition and/or extremely extreme events (items 1 and 2 above). While transformation has certainly occurred in the past, it is often a slow process lasting decades, centuries, or millennia. From a human perspective, transformation may be defined as the increasing unfamiliarity of a landscape, often following a series of extreme events or very advanced gradual changes. For riparian systems, transformation might look like a shift from a permanently flowing river to a temporary, ephemeral river, or *vice versa*. Shifts in the natural flow regime can ripple across species, populations and communities, altering or eliminating ecosystem processes around disturbance, nutrient and sediment flows and especially the timing of species behaviors, such as spawning, migration, and development rates.

In practice, these three categories can blend together or even shade from one to the other — shifts in extreme events can profoundly alter "normal" conditions, which can eventually lead to climate transformation. Because the implications of climate change are so unfamiliar to decision makers and stakeholders, these transitions can foster deep disagreements, such as the ongoing debate about whether the Murray-Darling Basin in Australia is in a long-term drought or entering a new climatic phase. Technical analysis of trends in observed data and projected modeling can inform but not authoritatively resolve these debates. A more effective approach is to develop a political consensus about current and potential risks relative to t he uncertainties in emerging climate patterns. Within 50 years we should know clearly if the Murray-Darling Basin is in a drought or some new normal, but what are the long-term consequences if we are overconfident and proceed down less resilient management paths now? Can we reverse weak or ineffective decisions and actions?

An irrigation pipe transfers water in a dry area of the Murray-Darling River basin, Australia. © ANDREW PEACOCK

Likewise, longstanding concepts such as ecological restoration and traditional approaches to nature conservation must reconcile with the implications of climate change and climate resilience (Sendig et al., 2015). Ecosystems do not automatically provide climate resilience to communities. Traditional conservation practices, for instance, normally define targets based on a past ecological baseline. However, that baseline — especially if it references a time more than 30 or 40 years ago — may be based on a retreating and irretrievable past, and a climate "lost" for the foreseeable future. For resource managers concerned about sustaining ecosystems and species against a wave of climate-driven impacts, such baseline-informed targets may be impossible or even counterproductive as goals. Indeed, some traditional approaches to SWP and water management more generally could exacerbate or trigger dangerous impacts on source waters by using past- or fixed-climate criteria to evaluate shifting-climate systems. Guidance on navigating through these challenges and contradictions follows, starting on page 28

CASE STUDY 3

Rio Grande Water Fund, New Mexico: Addressing Increased Wildfire Risk in the Southwest United States to Protect Water

Lead Author: Emily Simmons, TNC

THE SITUATION

In the United States, western states are experiencing an increase in catastrophic wildfires that can destroy livelihoods, ecosystem function, community infrastructure, wildlife habitat, and more. Scientists attribute these more frequent and severe burning events to the millions of acres of dense, fire-prone forests the region that are the product of historic land management practices, including suppressing naturally occurring (low-intensity) fires throughout the 20th century. In addition to the increased amount of fuel now available in forests, wildfire risk has also increased with higher temperatures and longer periods of drought caused by climate change. From 1970 to 2003, the burn area in southwestern states increased by 650% (Garfin et al., 2014). Climate change has also brought along warmer winters in the region which allow tree killing insects such as bark beetles to live year-round instead of dying off during the colder months. This has resulted in even more dry, dead forests — the perfect kindling and fuel for wild fire.

The season for southwestern wildfires generally ends when summer monsoons arrive, flooding after large severe wildfires can quickly become another type of disaster, especially for source watersheds.

After the 2011 "Las Conchas" — the largest wildfire that New Mexico had ever experienced to that date — normal monsoonal rain became a life-threatening torrent, washing ash, trees, and enormous amounts of sediment and rock debris from the wildfire area into the Rio Grande. Flows left a 21-meter deep sediment plug that nearly blocked the Rio Grande. Downstream, Albuquerque's water treatment facilities had to shut down because of the ash and sediment load, depriving the city of its surface supply of freshwater for 40 days.

Unfortunately, the impacts of wildfires and postfire flooding are expected to get worse if the climate continues to change. More than one third of all watersheds in the western United States are projected to have a sedimentation increase greater than 100% after a wildfire by the 2041–2050 period (Sankey et al., 2017). In addition to overwhelming amounts of debris and soil erosion, wildfires can often negatively affect water quality by changing turbidity and pH and increasing concentration of nutrients, chemicals and other runoff pollutants (O'Donnell, 2016). This can be detrimental not only to human health, but also aquatic habitat and biodiversity. The expected climate-change-induced extreme precipitation events will only exacerbate the problem.

THE ACTION

Recognizing that the Las Conchas wildfire and water crisis was not the first or the last fire emergency New Mexico would have to survive, The Nature Conservancy (TNC) began developing a plan that would unite stakeholders to address the immediate issues and adapt to the circumstances. By 2014, the result was the Rio Grande Water Fund, which launched with commitments from local governments, federal land management agencies, nonprofits, utilities, and private corporations.

TNC's Water Funds model is simply a finance and governance mechanism which allows downstream water users — like cities, businesses and utilities — to invest in upstream land management to improve water quality and quantity and generate long-term benefits for people and nature.

Today the Rio Grande Water Fund has more than 70 partners with the common goal of protecting New Mexico's source waters by reducing the risk of wildfire through forest restoration. The forest work of the Water Fund can help mitigate climate impacts:

"Prescribed burning, mechanical thinning and retention of large trees can help some southwestern forest ecosystems adapt to climate change. These adaptation measures also reduce emissions of the gases that cause climate change because long-term storage of carbon in large trees can outweigh short-term emissions from prescribed burning." (Garfin et al., 2014)

Properly thinned ponderosa pine (*Pinus ponderosa*) in northern New Mexico as a result from the Rio Grande Water Fund. © ALAN W. ECKERT

THE RESULTS

The Rio Grande Water Fund utilizes conservation activities such as forest thinning, stream restoration, flood control and prescribed wildfire management. It is expected to restore almost 300,000 hectares of fire-prone ponderosa pine and mixed conifer trees across the Rio Grande watershed stretching some 320 kilometers from Belen all the way to the Colorado border (Abell et al., 2017).

Through an economic lens, the cost of wildfire impacts on just one acre (0.4 hectares) in New Mexico can have a price tag of up to US$2,150, while thinning one acre of forest as a preventative measure costs only US$700 on average (Abell et al., 2017).

A Return on Investment (ROI) analysis completed for the Rio Grande Water Fund in 2016 found that forest restoration treatment dramatically reduces the potential financial impacts from severe wildfire and that the value of this reduction clearly outweighs the cost of program implementation (Kruse et al., 2016).

REFERENCES

Abell, R., Asquith, N., Boccaletti, G., Bremer, L., Chapin, E., Erickson-Quiroz, A., Higgins, J., Johnson, J., Kang, S., Karres, N., Lehner, B., McDonald, R., Raepple, J., Shemie, D., Simmons, E., Sridhar, A., Vigerstøl, K., Vogl, A. and Wood, S. 2017. *Beyond the Source: The Environmental, Economic, and Community Benefits of Source Water Protection.* Arlington, VA, USA: The Nature Conservancy (TNC). www.nature.org/beyondthesource.

Garfin, G., Franco, G., Blanco, H., Comrie, A., Gonzalez, P., Piechota, T., Smyth, R. and Waskom, R. 2014. "Climate Change Impacts in the United States: The Third National Climate Assessment." *Chapter 20*: 462–486. Edited by Melillo, J.M., Richmond, T.C., and Yohe, G.W., U.S. Global Change Research Program. http://nca2014.globalchange.gov/report/regions/southwest.

Kruse, S., Hartwell, R., and Buckley, M. 2016. *Taos County Return on Investment Study for the Rio Grande Water Fund.* Ecosystem Economics LLC 50 SW Bond Street, Suite 4, Bend, OR 97709, USA.

Littell, J. S., D. McKenzie, D. L. Peterson and A. L. Westerling. (2009). "Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003." *Ecological Applications*, 19: 1003–1021. https://doi.org/10.1890/07-1183.1.

O'Donnell, F.C. 2016. "The Influence of Restoration Treatments on Hydrologic Output in Fire-Adapted Forests of the Southwest." *ERI Working Paper No. 37*: 14. Ecological Restoration Institute and the Southwest Fire Science Consortium, Northern Arizona University.

Sankey, J.B., Kreitler, J., Hawbaker, T.J., McVay, J.L., Miller, M.E., Mueller, E.R., Vaillant, N.M., Lowe, S.E. and Sankey, T.T. 2017. "Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds." *Geophysical Research Letters*, 44: 8884–8892. https://doi.org/10.1002/2017GL073979.

Resilience Strategies: Managing for Climate Robustness and Flexibility

Uncertainty about future climate conditions is not a new problem for water managers generally or for SWP in particular, nor is uncertainty equally relevant for all types of water management problems (Figure 3). Climate change and our deeply interconnected social, ecological and economic systems, however, represent new types of uncertainty. A recent comprehensive study of uncertainty in water management applications points to an ongoing challenge in using climate projections, often without even a clear consensus on directional trends (that is, increasing or decreasing precipitation) between models (Kundzewicz et al., 2018). The lack of clear trends in climate model studies is common worldwide. Climate models have been widely criticized by the technical water community for providing unhelpful guidance on climate-related aspects of the water cycle (Kundzewicz and Stakhiv, 2010; Wilby, 2011). The low level of precision and sense of confidence in climate model projections limit using their outputs when high confidence in future conditions is deemed necessary, such as to avoid severe economic damage or disruptions. While the past may be a poor predictor of future climate, climate models alone are limited in their guidance. By themselves, they are not an easy replacement for a past-predicts-the-future approach. How can we be resilient without confident predictions of future climate and weather conditions? Do we need to make different kinds of decisions when our level of confidence in future climate scenarios is low?

> A broad consensus across the water management and environmental conservation communities has developed in the past decade that implementing resilience for freshwater systems includes two primary strategies: robustness and flexibility.

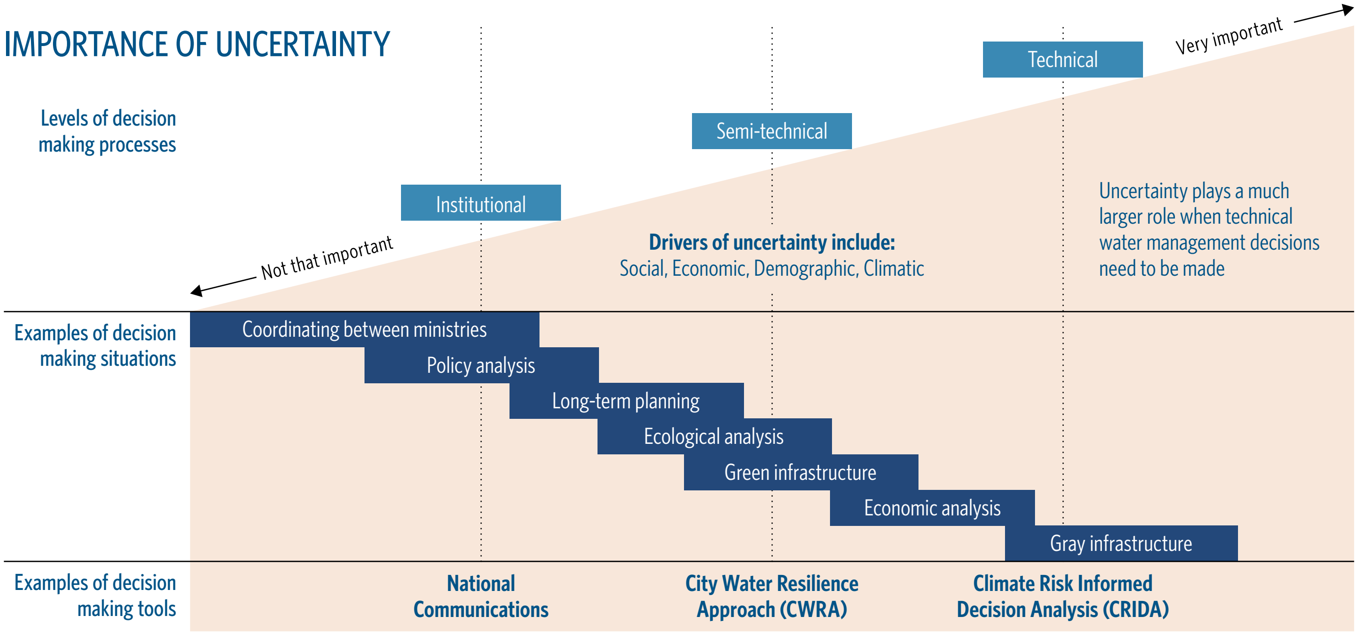


FIGURE 3: For decision makers and technical analysts, the level of uncertainty is critical to defining an effective resilient SWP strategy and solution set. However, future climate uncertainty is not equally important to all types of SWP problems. For more policy-oriented situations, decision makers, and stakeholders may be more tolerant of high levels of future uncertainty. When technical, quantitative solutions are necessary (as for infrastructure or economic analyses) and/or when the consequences of making an incorrect set of recommendations are high, the level of uncertainty of should be carefully considered. In these cases, high levels of uncertainty should result in a stronger emphasis on deferred actions or flexible solutions that can reduce the risks of making a regrettable choice. Note that for nature-based solutions, uncertainty levels are often relatively high because of the knowledge gaps about ecosystems and species and their potential responses to climate shifts, though uncertainty should not be an obstacle to their implementation.

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A broad consensus across the water management and environmental conservation communities has developed in the past decade that implementing resilience for freshwater systems includes two primary strategies: *robustness* and *flexibility* (García et al., 2014; Matthews, Mendoza and Jeuken, 2015).

When we have confidence in what the future might look like, robustness is clearly a good strategy for climate adaptation. When uncertainty is overwhelming and we cannot make good estimates of even the near-term future, flexibility is an optimal strategy. But today we are being challenged to integrate robustness and flexibility into an increasingly uncertain future. The combination of first producing a robust set of solutions followed by a flexible implementation plan has been proposed in a single methodology.

Robustness is a term borrowed from engineering and refers to imagining a wide vision of credible potential futures — not just a single future. Thus, we might foresee that a region will experience both more frequent and more severe droughts as well as more frequent and more severe flooding rather than just one or the other. Since our ability to predict the future with ongoing climate change is limited, we may need to plan for a series of alternate futures and try to encompass as many of these as possible in our work to maximize robustness.

For most water management applications, the real challenge is not just imagining what might happen in a speculative sense, but doing so using a quantitative cost-benefit analysis driven framework, which is how most economic, engineering, and finance analyses are prepared. So-called top-down risk assessment approaches to water resources management look at forces outside of a system, problem, or question and try to interpret the impacts. A more recent family of approaches, sometimes called bottom-up risk assessment, look at the intrinsic risks of a system — how it may fail or shift in reliability or efficiency because of its own limits (Figure 4).

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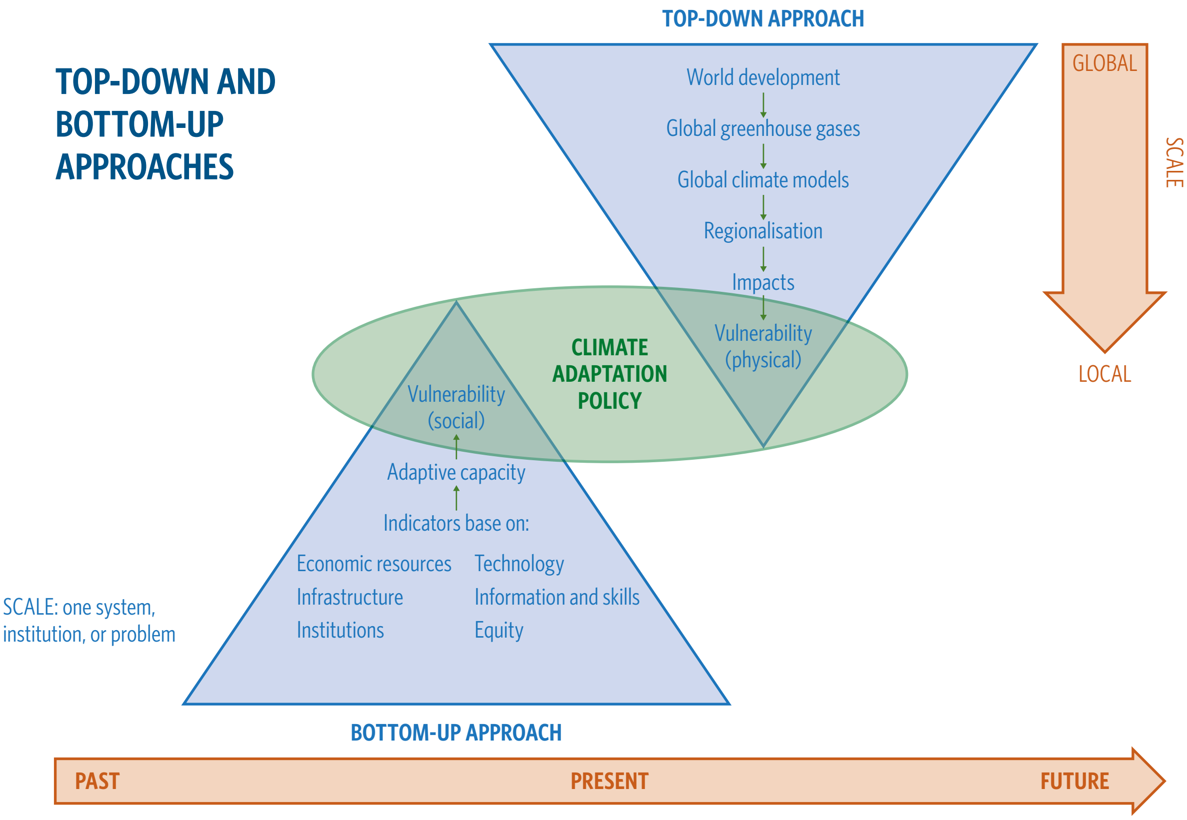


Dessai and Hulme, 2004

FIGURE 4: Two widespread approaches to assessing climate risks are top-down and bottom-up methodologies. Top-down approaches look at risks using externalities to the system or project in question, often beginning with global- or regional-scale impacts or risks and then reducing the scale of the variables in question to the system of interest. Global climate projections and water stress models are common top-down starting places. Perhaps less widely known, bottom-up approaches begin by trying to understand the project of interest as a system, which may mean developing a more formal model of how that system functions, such as in terms of governance, hydrology, decision making, or species life-history. Often this process reveals bottlenecks where the system could be vulnerable (or has already proven vulnerable) to shocks or stresses, such as when water supplies fall below a given level. Bottom-up approaches tend to provide higher levels of confidence, especially when quantitative analyses are involved. Both approaches can also be used to complement one another, as shown in this diagram. (Adapted from Dessai and Hulme, 2004).

Newer bottom-up methodologies such as decision scaling and robust decision making have been critical since about 2007 to help water managers interested in long-term sustainability avoid the trap of uncertainty or a predict-then-act approach (Ray and Brown, 2015). These methods build robustness by understanding the operational constraints of current ecosystems and hydrological and management systems combined with stakeholder definitions of success and failure to then provide quantitative guidance on how to maximize robustness (García et al., 2014; Brown et al., 2011).

In practical terms, robust approaches to SWP means ensuring that we buffer freshwater ecosystems from damaging change, whether from climate impacts or other drivers that damage connectivity, the disturbance regime, or complexity. Perhaps the single most important goal is avoiding irreversible damage to the integrity of freshwater ecosystems. Bottom-up approaches are effective at determining what boundaries or limits can be avoided and what aspects of ecological health can be restored, enhanced and maintained (Poff and Zimmerman, 2010; Poff and Matthews, 2013; Poff et al., 2016; Mendoza et al., 2018; Verbist, Rojas and Maureira, 2018).

Flexibility marks a stronger break with recent practice. Traditional water management practices assume that we can fully "optimize" our decision making on a single "best" and most comprehensive solution. Systematic approaches to flexibility began relatively recently with efforts such as the Thames Flood Barrier in the United Kingdom (Lumbruso and Ramsbottom, 2018) and the Dutch Delta Commission (Deltacommissie, 2008), which recognized that in some cases uncertainties around

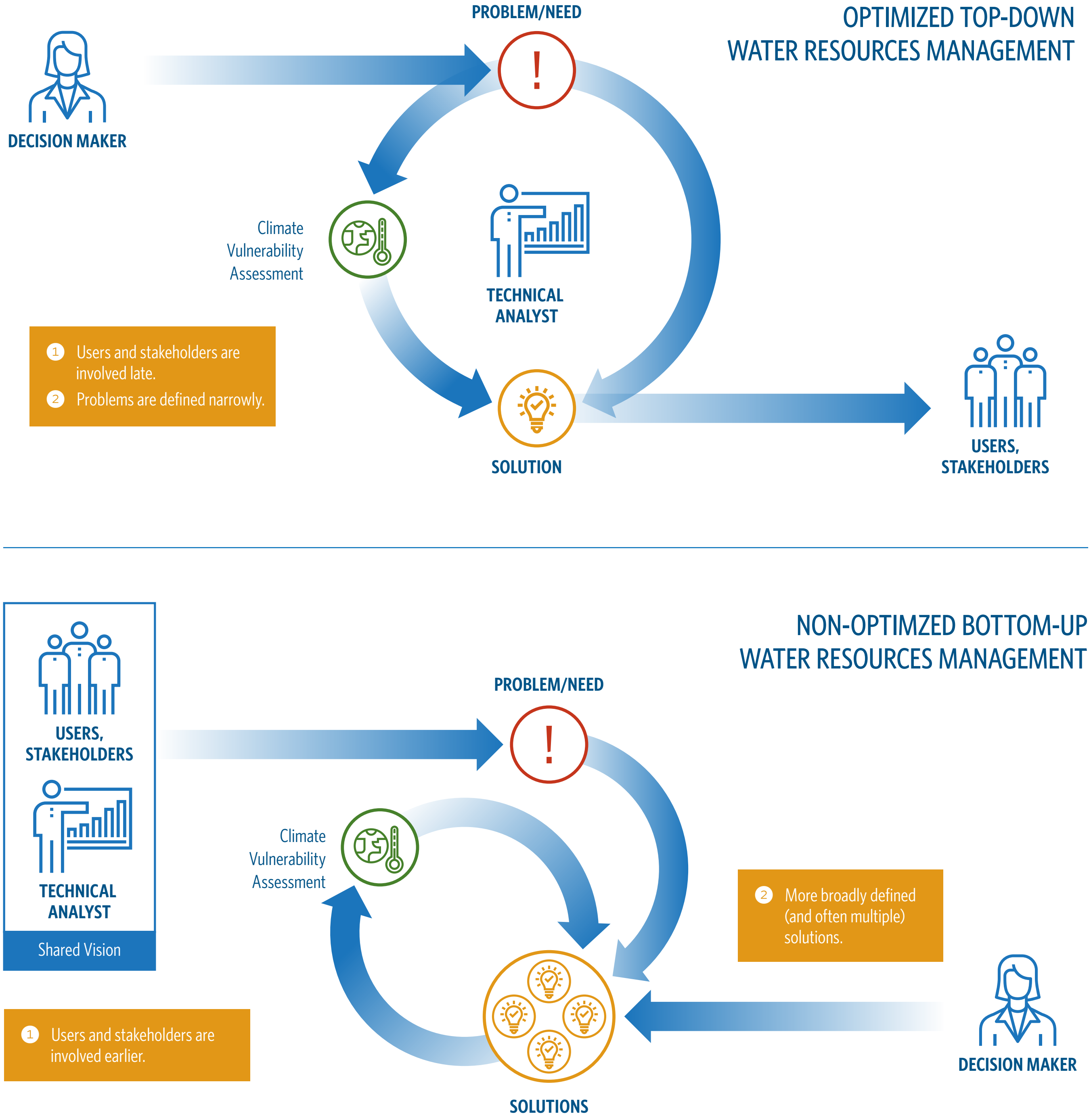


FIGURE 5. One of the most significant actions in response to climate change by the water community has been to shift from so-called top-down approaches to risk assessment and reduction (top image) to bottom-up approaches (bottom image). Top-down approaches have characterized most of water management decision-making processes in the 20th century and remain widespread. The majority of the authority in defining problems and goals resides in a decision maker, often associated with a funding agency or role, who assigns the development of solutions to a technical analyst or team of analysts. The evaluation of the solution with climate change metrics is often limited in scope, especially with regard to consideration of uncertainty, with most climate risks defined as external to the problem or project in question (*e.g.*, relative to a set of downscaled projections). After developing an optimized solution — often grounded in the assumption of a single vision of the future — stakeholders are presented with a single solution, with little or no ability to modify that solution. Bottom-up approaches represent the synthesis of a number of trends together. The technical analyst works with stakeholders to develop a shared vision and problem statement that can be translated into a set of performance metrics that express risk tolerance and success/failure; climate uncertainties are often considered here at the beginning of the process. In many cases, the analyst guides discussions around how the existing system operates and its intrinsic vulnerabilities, such as competition with other water users. A variety of solutions are proposed, which can be compared based on their performance against stakeholder objectives as well as their suitability in a wide range of potential climate conditions (*e.g.*, GCMs, paleoclimate, ecological models, trend data). The decision maker can select one — and often several — solutions from this portfolio in order to find the right combination of robust and flexible solutions. Bottom-up approaches are particularly effective in building consensus between stakeholders and decision makers in the face of complex or uncertain situations.

climate change and other types of drivers such as economic and social change made even evaluating the efficacy of a set of credible adaptation actions very difficult or impossible.

As an alternative, methodologies such as adaptation pathways and real-options analysis look at how to maintain future possibilities in a systematic way in order to not be trapped in a set of solutions that exclude relevant options or that might force more expensive or less suitable outcomes over time — avoiding a so-called path dependency (Haasnoot, 2013). Constructing a flood barrier, for instance, may be one response to current or near-term flood risks. A flexible approach might include ensuring that this flood barrier can be (1) raised higher over time if flood risk increases in the future, (2) moved if the floodplain expands, or even (3) be removed if flood risk declines. The use of wetlands as a floodwater absorption zone or a room-for-the-river strategy would also be considered flexible approaches, since they can be expanded, altered, or modified as conditions shift or confidence in a particular future grows. A flexibility strategy for resilience emphasizes the need for considering alternative futures and pathways for action, which can then be navigated over time.

Both robustness and flexibility can be implemented through governance channels, technical applications (such as for infrastructure design, planning and operations) and natural resource management practices. Resilient SWP is relevant to all of these aspects. The tables referenced in Appendix 2 describe flexible and robust interventions, respectively, around a range of water resources management actions and list out so-called low-regret actions, which could help a wide variety of potential climate impacts and threats with minimal negative side effects or tradeoffs.

In many cases, existing source waters are our first line of defense against negative climate impacts, even if they have been damaged or degraded, not least because they represent inherently flexible approaches. For example: source waters can often be enhanced, restored in function, or managed more easily than by trying to create a hard infrastructure replacement, which may have more limited operational parameters. Maintaining existing source waters delays irreversible interventions that may profoundly alter the hydrological landscape. Often, source waters will be revalued simply by formally integrating them within existing water management systems for their current adaptation benefits or services. For instance, in many cases wetlands can serve as both a sponge during floods and a reservoir during droughts, with those functions open to improvement or modification through resource management practices. Such interventions are more widely described by terms such as green infrastructure, green adaptation, or ecosystem-based adaptation (EBA).

Combining Robust and Flexible Solutions

Over a seven-year period, an international team including UNESCO, the Rijkswaterstaat, USACE, Deltares, AGWA and many others worked to bring together robustness and flexibility into an integrated methodology for resilient water management called CRIDA (Climate Risk Informed Decision Analysis) that also looks at ecological components of the landscape, including **green** and **hybrid infrastructure** approaches (Matthews, Mendoza and Jeuken 2015; Mendoza et al., 2018). These methods work by engaging with stakeholders and decision makers to determine a holistic definition of the problem to be solved and to find a clear set of performance indicators. Led by a technical analyst, the team assesses the level of confidence/uncertainty and the severity of potential threats before defining a core strategy (Figure 6). The team then develops and tests a set of robust solutions to credible threats and/or explores flexible implementation and planning approaches to cope with residual uncertainties. Under the CRIDA system, NBS and gray infrastructure are considered jointly, with a strong emphasis on measurable source water resilience.

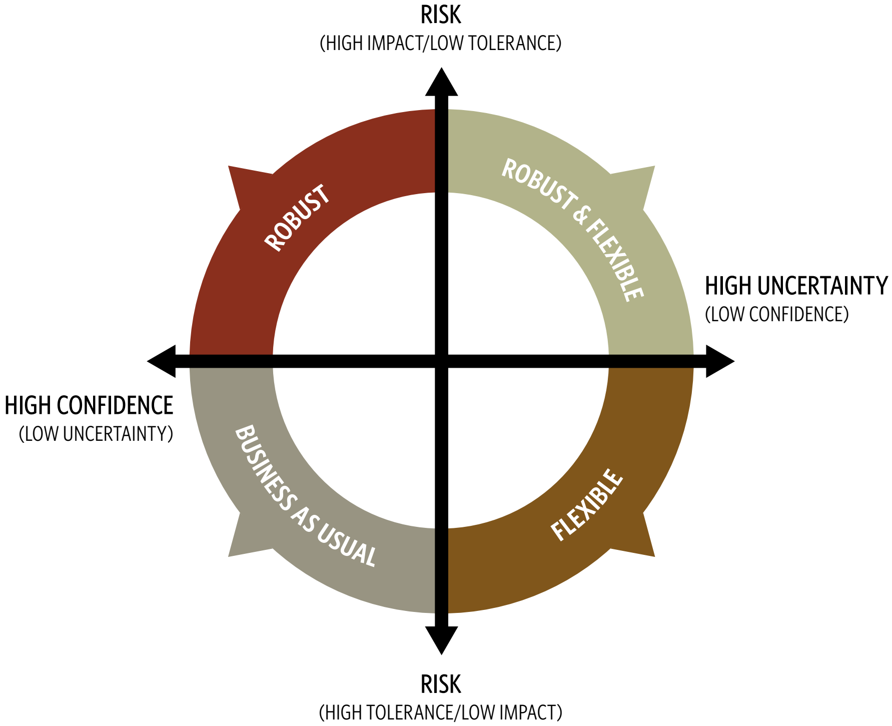
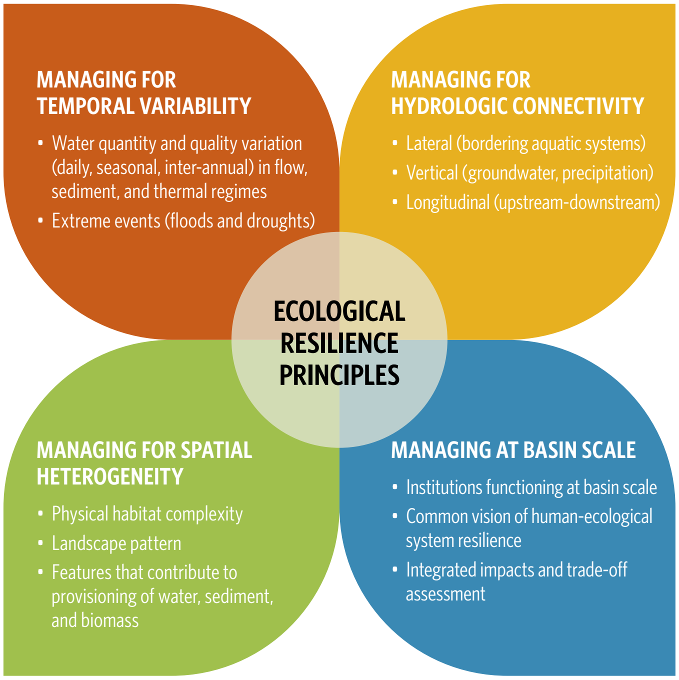


FIGURE 6: Robustness and flexibility are two broad strategies for coping with climate change impacts. A recent guidance on resilient water resources management suggests four potential pathways (Mendoza et al., 2018). When climate risks and the level of uncertainty are low, existing and traditional approaches to SWP may be sufficient. However, if climate risks are high in combination with low uncertainty about the nature of those risks, then a robustness strategy for SWP may be more appropriate. When negative impacts from climate change are relatively low but levels of uncertainty are high, then flexibility may be the most appropriate route. In many cases, though, the risks of dangerous impacts are high at the same time that the level of uncertainty is also high — suggesting that a combination of robustness and flexibility will ensure the most effective strategy for resilient SWP. Examples of robust, flexible, and no-regret actions are provided in Appendix 2. (Adapted from Mendoza et al., 2018).

Several principles have been suggested (Figure 7) that enable source water resilience, based on the capacity of freshwater ecosystems to respond to climate shifts now and in the past (Le Quesne et al., 2010; Poff, 2017; detailed in Grantham et al., in press). These include:

- **Managing for hydrologic connectivity.** Connectivity includes maintaining and/or restoring functional connections within and between ecosystems and habitats for the movement of nutrients, organisms, and ecological processes and functions. Grill and colleagues (2019) recently defined a promising set of metrics around connectivity.
- **Managing for temporal environmental variability.** For freshwater ecosystems, temporal variability is most often associated with the disturbance regime, also known as the natural flow regime or the annual hydrograph (Poff et al., 1997). The seasonal flow patterns in aquatic systems and water quality, play a critical role in maintaining ecosystem health. Distortions of the natural flow regime from shifts in climate or operational decisions can trigger rippling and profound effects across ecosystems (Poff, 2018).
- **Managing for spatial heterogeneity.** Spatial variation within freshwater ecosystems, sometimes also referred to as spatial heterogeneity, which broadly refers to ensuring that 1) hydrological and hydraulic aspects of freshwater systems are maintained and driven by ecological and hydrological processes rather than human modification intended to supersede or simplify natural functions (*e.g.*, natural meanders in contrast to “channelizing” a river, which reduces complexity); 2) that functional diversity can persist across the food web; and 3) that organisms are not trapped in one habitat, region, or ecological population or community.
- **Managing freshwater ecosystems at the basin scale.** Effective governance is critical for implementation, including the ability to develop a basin-wide “shared vision” of what resilient SWP can and should look like in practice.



Adapted from Grantham et al. (*in review*)

FIGURE 7: Defining ecological resilience in the context of climate change is not straightforward. One approach is to consider how ecosystems have responded to past episodes of climate change, such as the glacial-interglacial transition from the Pleistocene to the Holocene about 12,000 years ago. Building on the work of others, Grantham and colleagues (in press) suggest that ecological resilience means maintaining ecological functions even if the assemblage of species shifts. They identify four principles of ecological resilience that managers can use to aid ecosystems passing through these transitions. Three of these principles draw from insights into past enabling conditions for ecological transitions: temporal variability, hydrological connectivity and spatial heterogeneity. The fourth — basin scale management — reflects how we develop a common regional vision and coordinated actions for ecosystems, which of course is not associated with past major periods of climate-driven ecological change. (Adapted from Grantham and colleagues, in press.)

These key resilience principles for SWP reflect the enabling conditions necessary for source waters to compensate and adapt on their own to climate shifts, as they have largely done throughout history and prehistory. In the context of intensive human dependence and management of source waters, high uncertainty about emerging conditions and the need for a new climate-aware framework for water management, we have new choices for how we conceive the sustainability and resilience for SWP. Indeed, "natural" processes may now need more active human management in order to build, restore, and define resilience for SWP.

AT RIGHT: Employees from Stroud Water Research Center check a stream in Delaware's First State National Park for Ephemeroptera, Plecoptera, and Trichoptera insects — species that indicate healthy freshwater — as part of the National Parks Service 2016 BioBlitz event executed by The Nature Conservancy and partners. © DEVAN KING

CASE STUDY 4

Integrating Resilient SWP into Decision-Making Processes

Lead Author: John Matthews, AGWA

The five Great Lakes hold one-fifth of the world's surface fresh water, play a key role in influencing climate, and provide drinking water to nearly 40 million people, which is why The Nature Conservancy and its Canadian partners are working to protect more than 1 million acres, including 20 priority watersheds and 15 coastal areas across the area. © RON LEONETTI

THE SITUATION

Concerns over the use of climate models for water resources planning, design and operations reached a deep crisis in the late 2000s. One of the most important responses came through the application of so-called bottom-up approaches to risk assessment and reduction. These approaches emphasize the analysis of risk by: (a) engaging directly with stakeholders and decision makers early in a project design and planning process in order to define success, failure, and relevant performance metrics; and (b) developing a quantitative model of the system in order to test weaknesses. Bottom-up approaches are notable for their ability to cope with climate uncertainties more effectively than many traditional top-down approaches, which tend to define a set of risks without reference to the system in question.

THE ACTION

The U.S.-Canada International Joint Commission (IJC), an intergovernmental body to manage the North American Great Lakes, applied a bottom-up approach to climate adaptation concerns with Lake Superior with the support of Casey Brown at the University of Massachusetts, Amherst, in 2009 (Brown et al., 2012). The study provided quite positive and actionable results despite significant climate uncertainty and dozens of stakeholders. The approach can systematically deliver robust water management solutions through a methodology called decision scaling.

With a broad array of partners including Casey Brown and Patrick Ray, both of University of Massachusetts, Amherst, the World Bank undertook a significant revision of its approach to assessing climate risk to its water portfolio through what came to be known as the Decision Tree Framework (Ray and Brown, 2015). The application of decision scaling, while not referring to SWP, includes many of its basic approaches and assumptions, including understanding the resilience and hydrological context of resource management and infrastructure decision making.

An affiliated team recently published a companion approach that also uses decision scaling married to a flexibility methodology called adaptation pathways. The combined approach explicitly addresses ecological performance indicators. Called Climate Risk Informed Decision Analysis (CRIDA; Mendoza et al., 2018), the approach has been applied to a number of resilient nature-based solutions, including a national-level partnership that used the method on adaptive environmental flows at a basin scale (Verbist et al., 2018).

THE RESULTS

Bottom-up approaches have been proliferating rapidly and globally throughout the water community, including a massive multi-basin project for the greater Mexico City region that includes both built and nature-based solutions with more than three dozen regional stakeholders and partners. Led by the World Bank, the approach promises to create a profound shift in long-term decision making around water management. Although less than a decade old, bottom-up approaches promise to create a long-term reorientation around water risk assessment, including the integration of ecosystems within traditional decision-making processes.

REFERENCES

Brown, C., Ghile, Y., Laverty, M. and Li, K. 2012. “Decision Scaling: Linking Bottom-Up Vulnerability Analysis with Climate Projections in the Water Sector.” *Water Resources Research,* 48 (9). https://doi.org/10.1029/2011WR011212.

García, L.E., Matthews, J.H., Rodriguez, D.J., Wijnen, M., DiFrancesco, K.N. and Ray, P. 2014. *Beyond Downscaling: a Bottom-Up Approach to Climate Adaptation for Water Resources Management.* Washington, DC: World Bank Group. http://documents.worldbank.org/curated/en/204591468124480946/Beyond-downscaling-a-bottom-up-approach-to-climate-adaptation-for-water-resources-management.

Mendoza, G.F., Jeuken, A., Matthews, J.H., Stakhiv, E.Z., Kucharski, J. and Gilroy, K. 2018. *Climate Risk Informed Decision Analysis (CRIDA): Collaborative Water Resources Planning for an Uncertain Future.* Paris, France, and Alexandria, VA, USA: UNESCO-IHP, ICIWaRM.

Ray, P.A. and Brown, C.M. 2015. *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework.* Washington, DC: The World Bank. https://doi.org/10.1596/978-1-4648-0477-9.

Verbist, K., Rojas, P. and Maureira, H. 2018. *A Stress Test for Climate Change Impacts on Water Security: Case Study From the Limarí Watershed in Chile.* Paris: UNESCO.

aligning actors and actions for resilient source water protection

Most decisions involving SWP play host to diverse — sometimes disparate — stakeholders with their own agendas, worldviews, and planning and management processes. Actors from the public sector, private sector, financial institutions, environmental and development communities, and global policy makers have emerged as key drivers and supporters of effective action. Due to the complexity of climate stressors and solutions, no single entity, actor or decision maker can "fix" a particular system in isolation, and no single project implemented by an institution in isolation can spur or embody lasting institutional change. Resilience and adaptation must become normalized across sectors and institutions.

Best practices for finance, economic analysis, engineering, stakeholder engagement, regulatory frameworks, and natural resource management will all need some adjustment and learning over time. Fortunately, these insights are becoming more widespread as shown in the case studies in this publication (see also Appendix 2). Climate risk reduction, especially with regard to source waters, is becoming a new industry in itself (Flavelle, 2019), while groups that rate and evaluate financial risk such as bonds rating agencies have begun to include clear statements about the need to formally and explicitly assess climate risk exposure (Moody's, 2017). These events are likely signposts pointing to a more systemic approach to identifying and reducing climate risk, inclusive of resilient SWP. Unfortunately, we have many examples of failure as well. In early 2019, one of the largest utilities in the United States prepared to file for bankruptcy because of current and expected liabilities associated with climate impacts on the water cycle (Eckhouse and Roston, 2019).

The threat of climate change can align together even historically antagonistic groups around a common cause. The widespread awareness of shifting threats and high uncertainty about the future — even as new needs and tools appear — bodes well for progress. Everyone shares responsibility for ensuring resilient SWP, but consensus over what should be done, how those priorities should be implemented, and who should pay for supplemental actions often present real difficulties in finding common ground. This is especially the case when building resilience involves including new actors, existing actors playing new roles, and/or the need for significant changes in behavior.

In many cases, extreme events or natural disasters can spur the collaboration and change necessary, but long-term shifts in the status quo require deeper commitments across sectors. Finding consensus in many communities often revolves around adhering to Winston Churchill's admonition to "Never let a good crisis go to waste," where extreme weather events or the near-loss of essential services can prompt diverse groups to combine energies around a common agenda. Severe droughts, tropical cyclones, and floods are especially powerful opportunities for building consensus, as has occurred during recent droughts in Sao Paolo, Brazil and Cape Town, South Africa. In the Netherlands, major reorientations in policies occurred by witnessing disasters in other countries, such as Hurricane Katrina's impacts on New Orleans,

An aerial view of damage caused from Hurricane Katrina the day after the hurricane hit New Orleans, Louisiana. © JOCELYN AUGUSTINO/FEMA

Resilience and adaptation must become normalized across sectors and institutions.

Louisiana, USA, which influenced the national Delta Commission (Deltacommissie, 2008) to develop the Delta Act and related Delta Programme. The earlier example of Rwanda's Rugezi wetlands hydropower crisis also sparked a raft of revisions across multiple levels of governance.

Long-term and lasting institutional change often requires a much deeper commitment to foster shifts in staffing, decision-making processes, policies, and even legislation than is possible in the weeks and months after a severe disaster. Indeed, the ongoing influence from the Delta Commission in the Netherlands and Rwandan policy shifts both show how a progressive mindset can endure for years and build on a new post-disaster momentum rather than merely being a reaction to an individual event. Likewise, warnings by important thought leaders can create a disciplinary "crisis" that signals the need for a broader shift in strategy, such as the statement by Milly and colleagues (2008) that widespread water management practices were actually increasing climate risks within fields such as water resources engineering and planning.

However, the trends around disaster response indicate a lack of preparedness from sectors in preventing natural disasters in the first place. Careful preparation before such emergencies using the bottom-up risk assessment approaches described in the section on resilience strategies can help diverse groups find ready solutions to implement resilience when a crisis actually occurs. When sectors collaborate to find solutions that incorporate broad trends and categories of impacts rather than planning for specific outcomes, stakeholders can develop resilient SWP strategies that are proactive rather than reactionary. Bottom-up approaches can help diverse stakeholders, roles and disciplines determine what boundaries can be avoided and what aspects of ecological health can be restored, enhanced and maintained and provide quantitative guidance on how to maximize resilience.

CASE STUDY 5

Addressing Peru's Mounting Water Security Crisis with Natural Infrastructure

Lead Author: Alex Mauroner, AGWA

Cordillera Vilcanota mountain range glacier, Peru. © SERGEJF/FLICKR

THE SITUATION

In Peru, climate change has led to daunting challenges for the country's water security. Water supply is threatened due to large-scale glacial loss. Ecosystems and livelihoods are facing increasingly frequent extreme events such as floods, droughts and landslides. Several large-scale infrastructure projects have been proposed to help address these challenges, however, these dams, reservoirs and diversion systems are often subject to the same threats they are designed to address (*e.g.*, landslides, reduced rainfall, groundwater shortages) (Bennett, 2018).

THE ACTION

In June 2018, the United States Agency for International Development (USAID) and the Government of Canada announced an investment of US$27.5 million towards environmentally sustainable water infrastructure through the creation of the Natural Infrastructure for Water Security (NIWS) project. The goal of NIWS is to address climate and water risk through mainstreaming natural infrastructure. The NIWS project is being implemented by Forest Trends together with a consortium including CONDESAN, the Peruvian Society for Environmental Law (SPDA), EcoDecisión, and experts from Imperial College London.

NIWS has set out to provide a platform for more integrated management of water resources by bringing together local, national, regional, public, and private stakeholders. In November 2018, NIWS took action to this end by hosting Peru's first National Water Summit. Resilient SWP was identified as a key element to securing regional water security.

Peru had already been supporting national policies around natural infrastructure in the water sector for the past decade. Through a program known as the Ecosystem Service Compensation Mechanism, regulations allow utilities to allocate portions of user fees to investments in watershed health and climate change adaptation. Landowners around source waters are compensated for good land stewardship, providing financial incentive for long-term sustainability.

THE RESULTS

Coordinated stakeholder engagement and developing a shared vision around shifting source waters has been critical. The National Water Summit brought together representatives from 23 water utilities representing 14 regions of Peru. These representatives signed the Piuray Declaration, a commitment to protect the country's source water areas and surrounding ecosystems (Bennett, 2018), creating a framework for implementing resilient SWP at a national level. The Piuray Declaration also prioritizes gender equality in the water resources and sanitation sectors.

Financing natural infrastructure in Peru has been a multi-pronged approach and complements the national policy framework for resilience. Using portions of user fees, public water utilities have already set aside US$30 million for natural infrastructure and US$86 million for climate adaptation and disaster risk management (Forest Trends, 2019). Funds are already being used to compensate upstream land managers in exchange for care and protection of water sources. NIWS hopes that the Ecosystem Service Compensation Mechanism can serve as a long-term sustainable funding source for incentivizing sustainable management of source water areas.

REFERENCES

Bennett, G. 2018. "The Infrastructure Upgrade, Reimagined." Medium. https://medium.com/usaid-global-waters/the-infrastructure-upgrade-reimagined-681b23321e65.

Forest Trends. 2019. "Natural Infrastructure for Water Security in Peru." https://www.forest-trends.org/who-we-are/initiatives/water-initiative/natural-infrastructure-for-water-security-in-peru/.

financing source water resilience

One of the most practical of all obstacles for implementing SWP resilience strategies is the additional resource requirements presented by the new choices, options, and paths to address climate impacts. If change is required, who will pay for those changes? Most of our existing economic analysis and finance tools do not automatically select or promote resilient principles, such as robustness, flexibility, redundancy, broad stakeholder engagement, and valuing ecosystems. Benefits that may not accrue for years or even decades might not guarantee a sufficient return to be selected using tools that heavily discount uncertainty and risk. NBS solutions traditionally present significant barriers for financing — how can we pay for a wetland or for making "room for the river" instead of building a dyke or reservoir? Decision makers and stakeholders may support resilient SWP, but funding new types of work often presents significant barriers.

At the same time, if we can align the priorities of funding sources and resilient SWP, we can develop clear signals to groups who need funding about the expectations for defining the practice of climate adaptation and SWP as well as the confidence and credibility with investors who want to provision resilient actions.

Climate finance has been identified as one major resource. New institutions such as the Green Climate Fund (GCF) have been added to the portfolio of groups including the UNFCCC (*e.g.*, the Adaptation Committee), aid agencies and development banks that are designated channels for funding climate adaptation. Some such as the GCF are especially interested in NBS, while groups such as the World Bank, European Investment Bank, Inter-American Development Bank, and Asian Development Bank are working to more consistently include NBS generally, and resilient SWP options in particular, in their investment portfolios with clients (Browder et al., 2019). Many institutions have already recognized that NBS and climate resilience are natural synergies and that these priorities should be aligned within their lending and grant programs. In most cases, these institutions also recognize that climate adaptation and NBS projects require some extra effort as we mainstream these areas — that partner institutions need to build capacity and learn in order to fully implement these projects.

Not all approaches are equally useful with regard to climate finance in particular. Over the past two decades, groups such as development banks, aid agencies, NGOs, UN agencies and foundations have widely adopted criteria that refer to "**additionality**," which is a term derived from a policy stricture that climate adaptation must supplement "normal" (*i.e.*, not climate-change-related) economic development or resource management. In practice, such criteria often look like spending an "extra" volume of money for interventions that represent the difference between a world with and without climate change. This comparison of projects with and without climate resilience is often quite literal and specific, such as the difference between a flood dyke built for a world without climate change (*e.g.*, known floods) and a higher dyke to address more severe floods that may happen in the future (often associated with more uncertainty). The difference in design and cost between the mythical stable-climate structure and the climate-adjusted structure is the additionality. Labeling this extra component is the basis for obtaining climate finance approval and often the only aspect of a project that would be eligible for climate finance. In practice, identifying the precise value of additionality is challenging or impossible for water projects that involve governance and other non-infrastructure "soft" interventions and for NBS. The requirement for additionality presents especially significant obstacles for situations where uncertainties are high, which includes most source water interventions. Likewise, many governance approaches such as maintaining minimum environmental flows are important in a stable climate and even more important in a shifting climate by creating a formal stakeholder role and voice for source waters. Such low- or no-regrets measures typically do not qualify as "additional" and would not be eligible for many types of climate finance.

Realistically, the category of labeled climate finance is insufficient to meet the needs of emerging water investments globally — most, if not all, water projects should have some assessment of climate risks and solutions and most of these should probably also consider how SWP may be a key element. Thus, one of the challenges we face is how to fully mainstream resilient SWP across sectors and within institutions, with the recognition that existing sources of finance will be the main vehicle for funding rather than climate finance.

In recent years, for instance, the World Bank's Global Water Practice has created a climate risk assessment decision support system for all of its water investments based on bottom-up methodologies (Ray and Brown, 2015) and has published additional guidance on mainstreaming NBS internally and with its clients (World Bank and WRI, 2019). The Asian Development Bank is planning a similar project coordinated by its Environment and Safeguards and Climate Adaptation programs (untitled working paper now in preparation). Efforts to mainstream approaches such as climate resilience should ideally be coordinated with NBS and SWP programs as well, so that they are fully aligned and integrated. Indeed, one approach may be to require project teams to develop NBS and gray solutions in parallel so that the options can be more compared fully and consistently.

... if we can align the priorities of funding sources and resilient SWP, we can develop clear signals to groups who need funding about the expectations for defining the practice of climate adaptation and SWP as well as the confidence and credibility with investors who want to provision resilient actions.

The private sector has also been involved in resilient NBS. Beginning in 2014, a consortium of NGOs gathered many experts to crowd-source water resilience criteria to evaluate the thoroughness of climate risk assessments and the efficacy of adaptation responses to identified risks for a wide range of gray, hybrid and NBS water infrastructure investments funded though green and climate bonds (CBI, 2018). To date, almost US$8 billion have been evaluated against these criteria, including a massive room-for-the-river NBS bond issued by the Dutch government in May 2019 worth several billion euros (Anderson et al., 2019). Likewise, the bonds rating agency, Moody's, has been making strong statements about the need for assessing climate risks when assessing the financial soundness of bonds:

> Moody's analysts weigh the impact of climate risks with states and municipalities' preparedness and planning for these changes when we are analyzing credit ratings. Analysts for municipal issuers with higher exposure to climate risks will also focus on current and future mitigation steps [*i.e.*, climate adaptation steps] and how these steps will impact the issuer's overall profile when assigning ratings (Moody's, 2017).

Together, these trends suggest that finance can serve as a powerful signal to investors, planners, and decision makers that climate risks are serious and should be considered holistically. By reframing environmental risks as economic risks, we can ensure that resilient SWP scales up beyond individuals and institutions who already prioritize ecosystems and source waters in their actions.

CASE STUDY 6

Resilient Green Finance: SWP in Green and Climate Bond Criteria

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THE SITUATION

Much of the world's infrastructure is funded through a type of loan called bonds, especially for large public infrastructure projects. The investor community has become increasingly concerned about the climate risks that investments are exposed to, potentially reducing the ability of those investments to perform as designed. In addition, many investments are now being developed explicitly to reduce the exposure of communities to negative climate impacts. How can investors evaluate these claims for resilient infrastructure or infrastructure for resilience?

Beginning in 2007, bonds that are labelled "green bonds" or "climate bonds" were developed to alert potential investors that the investment had a positive environmental and/or climate adaptation or climate mitigation role. As the green and climate bonds market has grown from a few billion US$ annually to about US$200 billion in 2018, concerns over the credibility of these investments have grown.

THE ACTION

Beginning in 2014, a consortium of NGOs including the CBI (Climate Bonds Initiative), AGWA (the Alliance for Global Water Adaptation), WRI (World Resources Institute), Ceres, and CDP worked to develop a set of water resilience criteria. Created with the consultation of some 150 experts and investors from five continents and many areas of expertise, the criteria score the water resilience of both gray and nature-based solutions (CBI, 2018). These criteria particularly emphasize many of the core aspects of SWP, including the use of basin-scale management, modeling ecological and hydrological qualities through the lens of robustness and flexibility and the integration of adaptive governance and allocation systems (Gartner and Matthews, 2018; Matthews, 2018). Emerging markets such as China have seen explosive growth in the green and climate bonds market (Dai and Matthews, 2018).

THE RESULTS

The first iteration of the criteria, published in 2016, focused on the ecological and social resilience of gray water infrastructure; San Francisco Public Utility Commission issued the first bond using the criteria that year, while the nature-based solutions criteria were launched in 2018. To date, about US$8 billion in bonds have been issued against the criteria, spanning bonds from North America, Africa, Australia, Europe and Asia.

REFERENCES

CBI (Climate Bond Initiative), AGWA (Alliance for Global Water Adaptation), CDP (Carbon Disclosure Project), Ceres and WRI (World Resources Institute). 2018. "Water Infrastructure Criteria under the Climate Bonds Standard Background Paper: Background Paper". London: Climate Bonds Initiative.

Dai, L. and Matthews, J. 2018. "China's Green Bonds Finance Climate Resilience". New Security Beat. The Wilson Center. March 22. https://www.newsecuritybeat.org/2018/03/chinas-green-bonds-finance-climate-resilience/.

Gartner, T. and Matthews, J.H. 2018 "Forests and Wetlands Are Water Infrastructure. New Green Bond Helps Finance Their Protection". World Resources Institute, May 22. https://www.wri.org/blog/2018/05/forests-and-wetlands-are-water-infrastructure-new-green-bond-helps-finance-their.

Matthews, J.H. 2018. "Financing water resilience: the emergence of green and climate bonds for water." The United Nations World Water Development Report 2018: Nature-based Solutions. United Nations World Water Assessment Programme. Paris: UNESCO.

conclusions and recommendations

SOLUTIONS FOR RESILIENT SOURCE WATER PROTECTION AND CLIMATE ADAPTATION

Conservationists, resource managers, and policy makers can feel overwhelmed by the looming threat of climate change, especially as expressed in dire and frightening reports (*e.g.*, IPCC 2018). Moreover, the recognition that using the past to define and protect source waters may no longer be sufficient or useful is discomfiting. Transformational change is occurring now, whether or not we want it to. Those of us drawn to source water protection most often feel called to do good for communities and ecosystems together. To see and anticipate negative change can feed a deep sense of loss and even grief, especially if we fear that once-standard conservation practices may now have limited impact. The choices that we face today are different and arguably more difficult than those choices faced by our peers in decades past. But as stated by one of J.R.R. Tolkien's characters: "All we have to decide is what to do with the time that is given us" (1954). Grief can be focused into practical action based on faith in the deep resilience of ecosystems, species, and communities that have experienced climate change many times in the past.

Learning from Our Past

History — both human and ecological — should be a major source of solace and courage to move forward. Humans in many ways can be considered an aquatic species: our "habitats" have always been intimately linked with freshwater ecosystems, even in extreme environments such as deserts, high mountains, or the Arctic. Sometimes we have needed to modify or move waterways to colonize or remain in a particular locale, but source waters cannot be separated from Homo sapiens. Indeed, for millennia, human social and economic development has tracked the intensification of water management designed to reduce the effects of variability in weather patterns to irrigate, foster changes in land use, move and provision reliable water in sufficient quality and quantity as well as to capture the energy of falling water. Our link to source waters also makes us vulnerable to their modification and disruption, including through the process of climate change. As recently as 2,000 years ago, North Africa was the breadbasket for the Roman Empire, producing the grains that fed the millions living within the great cities of the Italian peninsula (McCormick et al., 2012). Some of the oldest human remains in North America are found on the edge of what is now one of the driest regions on the continent, though as recently as 7,000 years ago what are now seasonal and temporary ponds were once flowing rivers with migratory Pacific salmon (Grayson, 2011; Haig et al., 2019). The ancient Mayans in Guatemala (Douglas et al., 2015), Angkor Wat in Cambodia (Ortloff, 2009) and the Harappan civilization along the Indus in South Asia (Kathayat et al., 2017) also experienced shifts in climate that stranded their societies in a climate-economy-livelihoods-ecosystem mismatch, expressed primarily through changes in the water cycle, though these shifts were relatively minor compared to the current rate and extent of climate change.

With the exception of hunter-gatherers, all of these societies actively managed water resources through long-lived infrastructure, treating their climate as a fixed "utility" that would never adjust or alter. In time — and occasionally over very brief periods of time — the mismatch between their economies and infrastructure and their new climate became clear through water impacts. They likely either failed to modify their course or chose brittle, inflexible solutions that could not be easily adjusted when conditions altered, or unforeseen circumstances occurred.

Today, we have the gift of insight if not foresight. We can anticipate changes in ways that past civilizations could not. We can evolve and correct our errors. But making these changes in ourselves also means that we must reevaluate our past strategies in light of a dynamic water cycle and aspire to manage water — and source waters — for centuries rather than years.

Creating a Sustainable Future

Most observers now recognize that humans will need to navigate an extended and perhaps permanent period of uncertainty and volatility that includes significant risks to source waters (IPCC, 2018; WEF, 2018). Creating a sustainable future will require fundamental changes in how we envision and manage global systems, especially those relating to water (Rockström et al., 2018). Assumptions that future climate and hydrological conditions will be similar to the past no longer apply. We argue that using a resilience approach is fundamental to navigating this period of uncertainty, recognizing the interconnected nature of source water with climate, hydrology, ecosystems, economies, and societies.

This report sets out a new approach to source water protection that integrates resilience to allow communities, economies, and ecosystems to thrive in the face of a shifting climate. Wide ranging efforts applying source water protection over the last decade have yielded important lessons learned for developing resilient source water protection approaches:

A young woman picking tea leaves on a tea plantation in the Upper Tana Watershed where the Nairobi Water Fund is working to provide cleaner, more reliable water for downstream populations, Kenya. © NICK HALL

1. Water must be treated as a non-stationary asset associated with significant uncertainty for long-term management goals. For water managers, regulators and natural resource managers, monitoring and evaluation processes should be reassessed on a regular basis to capture trends and shifts that mark new transitions that herald new conditions. Economic valuation should reflect uncertainties in quantity, quality, and timing and consider sustainability over planning and operational lifetime scales, such as through lower discount rates.
2. Water resources should be viewed as an expression of climate, hydrology, and terrestrial and aquatic ecosystems. When possible, even localized projects should consider upstream-downstream impacts and interactions at catchment and basin scales as well as surface-groundwater interactions. System-level models should be used to help to assess and reduce climate-related risks through robust interventions.
3. Strengthen existing financing, management and stakeholder institutions through relationships and incentives that encourage adaptive, flexible management to cope with uncertainty and shifting conditions.
4. Welcome ecosystems into the water management circle. source water protection is ultimately about integrating communities and nature into a common management framework — aligning success and sustainability. Resilient nature-based solutions, green and hybrid infrastructure and green adaptation are all manifestations of the tools we have to realize a vision that links the current ecosystem and future adaptation services of ecosystems with poverty alleviation, economic growth and development and shared resilience.

appendices

Appendix 1: Terminology

Climate adaptation	The specific actions we undertake to respond or to prepare for climate impacts.
Deep uncertainty	The emergence of such large sources of uncertainty about the future that we cannot distinguish between the likelihood of widely divergent scenarios.
Ecosystem-based adaptation (EBA)	The conservation, sustainable management and restoration of ecosystems that can help people adapt to the impacts of climate change (IUCN, 2017).
Ecosystem transformation	Conditions that have become so altered because of climate impacts that an ecosystem develops fundamentally new traits. Transformation refers to what happens beyond the limits of adaptation.
Flexibility	The ability to 1) be easily modified, and 2) make adjustments to a solution or approach over time depending on the future impacts, perhaps more widely known in the water management or conservation communities as adaptive management.
Gray infrastructure	Human-engineered built structures and mechanical equipment, such as reservoirs, embankments, pipes, pumps, water treatment plants and canals. These engineered solutions are embedded within watersheds or coastal ecosystems whose hydrological and environmental attributes profoundly affect the performance of the gray infrastructure (Browder et al., 2019).
Green infrastructure	Ecological systems, both natural and engineered, that are planned and managed for their social, economic, and environmental benefits.
Hybrid infrastructure	The combination of green and gray infrastructure.
Nature-Based Solutions (NBS)	Actions to protect, sustainably manage and restore natural or modified ecosystems,that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN, 2018).
No-analog communities	Ecological communities inferred by paleoecologists, typically from the Pleistocene or early Holocene, that include an assemblage of species that has no current “analog” in extant ecological communities.

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Redundancy	Spare capacity purposefully created to accommodate disruption due to extreme pressures, surges in demand or an external event. It includes diversity where there are multiple ways to achieve a given need. For example, energy systems that incorporate redundancy provide multiple delivery pathways that can accommodate surges in demand or disruption to supply networks (Arup and The Rockefeller Foundation, 2015).
Resilience	The ability to recover from a deviation of stressor by returning to the pre-disturbance state.
Resilient Source Water Protection	A water-security strategy that recognizes that hydrology, ecosystems, water management and climate are intertwined, and that the integrity of ecosystems is necessary for the integrity of communities — and *vice versa*.
Robustness	Considering a wide vision of credible potential futures — not just a single future.
Source Water Protection (SWP)	Efforts to achieve human water security through sustainable ecosystem management.
Transformation	The emergence of fundamentally novel conditions — a new normal — in a landscape or ecosystem.

WELLSPRING: SOURCE WATER RESILIENCE AND CLIMATE ADAPTATION

appendix 2

Table 1: Examples of Flexible Approaches to Water Management

SWP INTERVENTION	RESILIENCE INNOVATION	WHERE TESTED	REFERENCES/ ADDITIONAL INFORMATION
Green and hybrid infrastructure systems	Formally integrating ecosystems such as riparian wetlands or aquifers into existing or planned water resources management systems.	“Room for the river” approaches that work with existing or anticipated flood inundation patterns. Developed in the Netherlands.	• van Meel, P.P.A., van Boetzelaer, M.E., and Bakker, P.C., 2005. • https://www.ruimtevoorderivier.nl/english/
Planned renormalizing of source water baselines	Given that the ecological and hydrological records could be weak indicators of how source waters may evolve as a result of climate change, planned renormalization of management baselines can help track shifting conditions over time.	In Pangani basin, Tanzania, and in countries implementing the European Union Water Framework Directive, renormalization is a process that has been implemented as a regulatory function by independent technical bodies. Typical baseline management periods in these and other applications of this approach often span five to 10 years.	• PBWB and IUCN, 2011. • European Commission, 2016.
Non-volumetric water sharing and allocation agreements	Water allocation agreements that define sharing as a percentage of available water resources, rather than as an inflexible quantity, are better able to manage both climate variability and climate change.	The India-Pakistan Indus Treaty is a non-volumetric water sharing and allocation agreement. In contrast to the 1922 Colorado River Compact in the U.S. (which does specify delivery volumes), the 1948 Upper Colorado River Compact uses a percentage system.	• UNECE and INBO, 2015.

SWP INTERVENTION	RESILIENCE INNOVATION	WHERE TESTED	REFERENCES/ ADDITIONAL INFORMATION
Allocation prioritization systems based on weather conditions or forecasts	Allocation systems that define staged allocation and usage patterns, such as drought stages triggered by precipitation, groundwater levels, or flow volumes.	San Antonio, Texas, USA, uses a drought stage usage system based on Edwards Aquifer groundwater levels. Users are prioritized based on factors such as economic importance, underserved communities, and ecological importance.	• City of San Antonio, 2017.
Contingency planning for black swan, rare, or exceptional events (or events that have not previously occurred, but that occur in credible projections) that would result in catastrophic impacts	Climate change is making some high-risk/low-probability events more likely, such as extreme precipitation and so-called super-droughts. Water resource planning needs to include contingencies for these types of events.	San Francisco/Bay area drought planning, which has spanned a portfolio of approaches, including diversification of their source waters and increased efficiency and storage measures.	• BARR (Bay Area Regional Reliability) Partners, 2017.
Dynamic adaptation policy pathways	A formal methodology for identifying alternative credible futures, strategies, and interventions to address those futures, and identifying decision-making “pathways” that can ensure that flexibility is maintained in the face of uncertainty and decision-making bottlenecks are avoided.	Netherlands inland/coastal flood risk and sea-level rise planning.	• Haasnoot et al., 2012. • Haasnoot et al., 2013.
Adaptive institutions	Agencies, institutions, and working groups that can help manage or consider and track emerging conditions and develop rapid responses, as well as consider how the parent or partner institutions may need to respond to emerging impacts.	The IJC supplemental commission for North American Great Lakes formed to address climate impact and adaptation issues, filling in important gaps that existed with existing shared U.S.-Canada institutions with the North American transboundary Great Lakes.	• International Joint Commission, 2015. • https://www.ijc.org/en/glam
Planned redundancy	Diversifying systems, which may come at some cost of efficiency during expected or “normal” conditions, but which may support reliability as conditions evolve or as unanticipated extreme events occur, so that operators are more flexible in the options they can draw on over time.	San Diego County Water Authority and its deployment of a desalinization facility to diversify freshwater sourcing. Recently, San Francisco Public Utility Commission (USA) has also expanded its source waters from the Sierra Nevada snowpack to more nearby reservoirs.	• Rygaard, Binning, and Albrechtsen, 2011. • https://www.sdcwa.org/sites/default/files/files/purified-water/purified-water-brochure.pdf

Table 2: Examples of Robust Approaches to Water Management

SWP INTERVENTION	RESILIENCE BENEFIT/RESULT	WHERE TESTED	REFERENCES/ ADDITIONAL INFORMATION
Overbuilt/increased safety margin systems	In some cases, expanding or adding operational or design safety margins can help adjust for more extreme operational conditions.	Adjustments to Hoover Dam (USA), USACE and UK Design guidelines.	• Patterson, Rosenberg and Warren, 2016.
Modular/expandable/ removable management systems	Overbuilding or pre-designing interconnections for facilities so that they can be built on, built over, connected (as through a network expansion), and/or removed as conditions change, can have a powerful robustness role in coping with uncertainty. In contrast to scalable approaches, modular solutions add (or remove) different functional tasks.	Hetch Hetchy Dam, California, USA, was designed to be expanded over time, and indeed some years after construction was completed to raise the reservoir levels. Groundwater recharge systems for urban stormwater can also serve as an "extra" reservoir for high storm flows.	• Null et al., 2014.
Increasing water supply sourcing	As with planned redundancy in the flexibility section, having multiple water supply systems can help maintain reliability and strengthen delivery options.	Las Vegas, Nevada, USA, has recently acquired unrealized rights to distant aquifers if Colorado River levels drop below sustainable levels (which appears likely) and has already been using local aquifers for storage during flood and high river periods for dry season withdrawals.	• SNWA, 2018a. • SNWA, 2018b.
Backup systems infrastructure	In highly optimized systems, there may not be a good plan for managing critical functions exposed to unprecedented climate impacts.	Intake Tunnel 3 at the Hoover Dam, Colorado River, USA, was designed as a "bathtub drain" at the bottom of Lake Meade's reservoir in case water levels fall below existing intake tunnels, which currently provide water supply for cities in southern Nevada.	• SNWA, 2018a. • SNWA, 2018b.
Scalable systems	Individual solutions that can be expanded (or reduced) as necessary are a variation on backup systems, so that solutions can shift in scale over time to match or track uncertain shifts in climate, demographic change, or other impacts.	The Dniester River in eastern Europe spans Ukraine and Moldova, which recently signed a water sharing agreement focused on a number of issues, including climate adaptation associated with flood control and data sharing, particularly early warning systems.	• UNECE and INBO, 2015.

SWP INTERVENTION	RESILIENCE BENEFIT/RESULT	WHERE TESTED	REFERENCES/ ADDITIONAL INFORMATION
Increased monitoring and evaluation linked to operational decision making	Developing systems that can provide regional guidance for both extreme events (*e.g.*, floods) as well as collecting and sharing data relevant to operations and management can support the identification of trends and trigger shifts in adaptive management.	The Dniester River in eastern Europe spans Ukraine and Moldova, which recently signed a water sharing agreement focused on a number of issues, including climate adaptation associated with flood control and data sharing, particularly early warning systems.	• UNECE and INBO, 2015.
"Planned failure"	Traditionally, many water management systems have focused on a low- or no-tolerance approach to failure. By defining a service threshold and having exceedance of that threshold still remain "acceptable" and tolerable, planned failure can ensure that unpredicted or extreme events are not catastrophic.	Urban stormwater in sponge cities in China and in Hull, UK. In both cases, cities have shifted from seeing any urban flooding as a catastrophic failure to allowing cities to shift movement, processes, and systems in response to expected floods as well as increasing flood frequency.	• Chan et al., 2018. • Jiang, Zevenbergen and Ma, 2018.

Table 3: Examples of Low-Regret Approaches of Water Management

SWP INTERVENTION	RESILIENCE BENEFIT/RESULT	WHERE TESTED	REFERENCES/ ADDITIONAL INFORMATION
Approaches such as Integrated Water Resources Management (IWRM), water-food-energy nexus and other basin/national planning that includes multiple sectors and multiple climate futures	Water spans many sectors, and water decisions span many spatial scales. Often, water governance and allocation are only marginally or implicitly recognized across the decisions and scales, which commonly occurs in the context of WASH, energy, agriculture, and urban management. Cross-sectoral integration and coherence approaches that recognize these implicit decisions can rationalize and make water decisions more explicit and achievable.	The Republic of South Africa's national freshwater climate adaptation plan takes a risk-based approach to looking at regional priorities and uncertainties across sectors in order to maximize robustness and flexibility.	• Sebesvari, Rodrigues and Renaud, 2017. • Pegasys, 2018. • Department of Environmental Affairs, Republic of South Africa, 2017.
The application of resilience indicators to monitoring and evaluation and planning systems	"Resilience" as a term is often weakly defined in practice in terms of how and what we count and manage, as well as how we integrate new information into our strategic vision of source water resilience and what can, and cannot, be achieved.	The City Water Resilience Framework is an approach being tested in a number of urban landscapes globally to support cities (and groups of cities influencing one another's source water management decisions) to explore specific indicators, which can guide both technical and strategic decision-making processes. Ecosystems and source waters are explicitly described, and the CWRF is informed by the bottom-up approaches described elsewhere.	• Arup and SIWI, 2019.
The integration of shared-vision approaches and bottom-up methodologies within project and planning development processes	Ensuring that stakeholders and partners have a shared vision for what success and failure look like in the context of non-stationary water management is critical to endure that source waters can be resilient and, in turn, provision resilience. Methods that can then translate these goals into a clear set of performance indicators for design, finance, and operations will be much more likely to succeed.	The World Bank underwent a major reassessment of how it assessed climate risk for many years before publishing the so-called Decision Tree Framework, which guides World Bank loan officers through a process with clients to build a shared vision linked explicitly to resilience performance indicators. Major applications of this work have been undertaken globally, perhaps most notably for source waters in Mexico City.	• Ray and Brown, 2015. • Ray et al., 2018.

SWP INTERVENTION	RESILIENCE BENEFIT/RESULT	WHERE TESTED	REFERENCES/ ADDITIONAL INFORMATION
Integration of green and hybrid infrastructure options within project development processes	Source waters are always a part of the landscape and should always be formally included in holistic water resources management decision making. In many cases, existing ecosystems can be enhanced, restored, or if necessary, even built anew to constitute green-gray or green infrastructure.	Udon Thani, Thailand, is a rapidly growing city that has worked to create a vision for growth that welcomes source waters into the city as it faces new challenges from flood control, water storage, and water allocation. Source waters have been envisioned as both a technical solution and as a means for improving quality of life.	• ICIWaRM, 2016.
Integration of DRR, climate impacts, and WRM approaches in risk assessment and preparation processes	The disaster-risk-reduction community has often had a limited engagement with climate adaptation/impacts (*e.g.*, around novel or shifts in the severity and frequency of extreme events) or with water management issues, including water as either the medium of a disaster (*e.g.*, a flood or drought) or water as the mechanism for recovery (*e.g.*, clean water). These groups are working more closely, recognizing in some cases, as well, the linkages that resilient source waters play in sound prevention and recovery processes.	The High-level Experts and Leaders Panel on Water and Disasters (HELP) program from the Netherlands, Japan, UNISDR, and others have been recommending significant shifts in focus, funding and programs. A UNEP/EC project in Lukaya Basin, Congo, has been implementing some of these concepts. WWF recently published a guide to preventing and recovering from floods emphasizing source waters and nature-based solutions.	• UNISDR, 2016. • Matthews et al., 2018. • WWF, 2016.
Early warning system integration within decision making, rapid responses	Early warning systems tend to support crisis responses, but they can operate over multiple timescales, such from such as short-term flood events or slow-onset droughts. These can also trigger effective responses to manage and buffer source waters as part of the response system.	Spanish drought early warning system is a model approach to integrating environmental flows and drought response.	• Zia and Wagner, 2015.
Ensuring that planning and risk assessment processes extend to (if not beyond) infrastructure operational lifetimes	Many water projects compare costs and benefits only over the finance period rather than the operational lifetime of an investment. The difference in evaluating sustainability can be many decades, thereby reducing the ability to examine impacts on and interactions with source waters.	Climate Bonds Initiative water infrastructure green and climate bonds criteria specify the need to align the evaluation of climate performance and ecological impacts over operational lifetimes.	• CBI, 2017. • CBI et al., 2018.

SWP INTERVENTION	RESILIENCE BENEFIT/RESULT	WHERE TESTED	REFERENCES/ ADDITIONAL INFORMATION
Application of economic evaluation instruments that encourage long-term risk assessment	Sustainability of water systems is often measured over very short timescales, which downplays the importance of uncertainty, or focuses on narrow sets of indicators and small non-hydrological spatial scales.	Explicit consideration of approaches that reverse or expand the sustainability considerations can strongly benefit source waters, such as the application of real options approaches, lower discount rates to place a greater emphasis on distant over short-term benefits, and the use of Incremental Cost Analysis to compare benefits among a set of options can all help support more holistic economic options for source waters.	• Yang and Blyth, 2007. • Mendoza et al., 2018.
The use of finance instruments that strengthen existing institutional frameworks	Finance systems to connect or pay for source-water services risk creating parallel or disaggregated governance and management systems for source waters and ecosystems more generally. Source-water finance systems ideally should blend, reinforce, or operate within broader basin, water management, or governance systems to ensure cooperation rather than competition.	World Bank investment for drought management with Mexico City, Mexico State, neighboring states, and the national government (forthcoming).	• World Bank, 2019.
Environmental allocations	Environmental allocations such as "water reserves" or "environmental flows" are key methods for giving source waters a place at the table in water allocation and governance decisions. While the terms of these allocations can vary widely, they generally reflect a desire to give voice to source waters legally and institutionally.	Significant work has been occurring recently to develop adaptive water reserves and to define a climate-aware generation of resilient environmental flow regimes for source waters in many countries.	• Poff, 2017. • Gawne et al., 2018.
Insurance to enable adaptation	Insurance programs are one strategic tool to ensure that shifting natural processes such as flood pulses can be maintained, even as their extremes shift over time. Insurance programs can identify and prioritize in advance of extreme events levels of risk tolerance and who will share (and pay for) those risks.	The Mississippi River overflow system for emergency-flood dyke breaches was developed in regions of the U.S. to ensure that during extreme floods that high waters would inundate agricultural regions rather than high-value regions, while also maintaining the source water benefits of flood pulses. In effect, farmers are paid for loss of agricultural activity when flood managers deem necessary by transferring flood damages intentionally.	• Simpson, 2018.

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references

Abell, R., Asquith, N., Boccaletti, G., Bremer, L., Chapin, E., Erickson-Quiroz, A., Higgins, J., Johnson, J., Kang, S., Karres, N., Lehner, B., McDonald, R., Raepple, J., Shemie, D., Simmons, E., Sridhar, A., Vigerstøl, K., Vogl, A. and Wood, S. 2017. *Beyond the Source: The Environmental, Economic, and Community Benefits of Source Water Protection.* Arlington, VA, USA: The Nature Conservancy (TNC). www.nature.org/beyondthesource.

Anderson, J., Gartner, T., Mauroner, A. and Matthews, J. 2019. "Conservation Finance Takes Off as the Netherlands Issues One of the Largest Green Bonds Ever." *Insights* blog, 21 June. World Resources Institute. https://www.wri.org/blog/2019/06/conservation-finance-takes-netherlands-issues-one-largest-green-bonds-ever.

Arup and SIWI (Stockholm International Water Institute). 2019. *The City Water Resilience Approach.* London: Arup. https://www.resilienceshift.org/publication/city-water-resilience-approach/.

Arup and The Rockefeller Foundation. 2015. *City Resilience Framework.* 100 Resilient Cities. https://assets.rockefellerfoundation.org/app/uploads/20140410162455/City-Resilience-Framework-2015.pdf.

BARR (Bay Area Regional Reliability) Partners. 2017. *Bay Area Regional Reliability Drought Contingency Plan.* Prepared by Brown & Caldwell for BARR. Walnut Creek, CA. http://www.bayareareliability.com/wp-content/uploads/2018/03/BARR-DCP-Final-12.19.17-reissued.pdf?9f00f0&9f00f0.

Boxall, B. and McGreevy, P. 2017. "Thanks to storm runoff, there's a lot of water over California's second-largest reservoir." *Los Angeles Times.* 12 February. https://www.latimes.com/local/lanow/la-me-ln-oroville-historic-spill-20170211-story.html.

Bridges, T., Wagner, P., Burkes-Copes, K., Bates, M., Collier, Z., Fischenich, C., Gailani, J., Leuck, L., Piercy, C., Rosati, J., Russo, E., Shafer, D., Suedel, B., Vuxton, E. and Wamsley, T. 2015. *Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience.* Washington, DC: US Army Corps of Engineers. ERDC SR-15-1.

Browder, G., Ozment, S., R. Bescos, I., Gartner, T. and Lange, G.-M. 2019. "Integrating Green and Gray: Creating Next Generation Infrastructure." Washington, DC: World Bank and World Resources Institute. License: CC BY 4.0. https://openknowledge.worldbank.org/handle/10986/31430.

Brown, C., Werick, W., Leger, W. and Fay, D. 2011. "A Decision-Analytic Approach to Managing Climate Risks: Application to the Upper Great Lakes." *Journal of the American Water Resources Association,* 47 (3): 524–534. https://doi.org/10.1111/j.1752-1688.2011.00552.x.

Burgess, R., Horbatuck, K. and Beruvides, M. 2019. "From Mosaic to Systemic Redux: The Conceptual Foundation of Resilience and Its Operational Implications for Water Resource Management." *Systems*, 7 (3): 32. https://doi.org/10.3390/systems7030032.

Carpenter, S., Stanley, E. and V. Zanden, J. 2011. "State of the World's Freshwater Ecosystems: Physical, Chemical, and Biological Changes." *Annual Review of Environment and Resources*, 36: 75–99. https://doi.org/10.1146/annurev-environ-021810-094524.

CBI (Climate Bond Initiative), AGWA (Alliance for Global Water Adaptation), CDP (Carbon Disclosure Project), Ceres and WRI (World Resources Institute). 2018. "Water Infrastructure Criteria under the Climate Bonds Standard Background Paper: Background Paper." London: Climate Bonds Initiative.

CBI (Climate Bonds Initiative). 2017. *Climate Bonds Standard*: Version 2.1. London: CBI. https://www.climatebonds.net/files/files/Climate%20Bonds%20Standard%20v2_1%20-%20January_2017.pdf.

Chan, F.K.S., Griffiths, J.A., Higgitt, D., Xu, S., Zhu, F., Tang, Y.T. and Thorne, C. R. 2018. "Sponge City in China — A breakthrough of planning and flood risk management in the urban context." *Land Use Policy*, 76: 772–778. https://doi.org/10.1016/j.landusepol.2018.03.005.

City of San Antonio. 2017. "City of San Antonio Drought Operations Plan." https://www.sanantonio.gov/sustainability/Environment/DroughtOperationsPlan.

Clark, P.U., Shakun, J.D., Marcott, S.A., Mix, A.C., Eby, M., Kulp, S., Levermann, A. et al. 2016. "Consequences of Twenty-First-Century Policy for Multi-Millennial Climate and Sea-Level Change." *Nature Climate Change*, 6 (4):360–69. Nature Publishing Group. https://doi.org/10.1038/nclimate2923.

Davidson, J.L., Jacobson, C., Lyth, A., Dedekorkut-Howes, C.L., Baldwin, J.C., Ellison, N.J., Holbrook, M.J., Howes, M., Serrao-Neumann, S., Singh-Peterson, L. and Smith, T.F. 2016. "Interrogating resilience: toward a typology to improve its operationalization." *Ecology and Society*, 21 (2): 27. https://doi.org/10.5751/ES-08450-210227.

Deltacommissie. 2008. *Working Together with Water: A Living Land Builds for Its Future — Findings of the Deltacommissie 2008.* The Hague, NL: Delta Commission.

Department of Environmental Affairs, Republic of South Africa. 2017. *National Climate Change Adaptation Strategy: Republic of South Africa.* 2nd Draft for Public Comments. https://www.environment.gov.za/sites/default/files/reports/nationalclimate_changeadaptation_strategyforcomment_nccas.pdf.

Dessai, S., Hulme, M. 2004. "Does Climate Adaptation Policy Need Probabilities?" *Climate Policy*, 4 (2): 107–128. https://doi.org/10.1080/14693062.2004.9685515.

Douglas, P.M.J., Pagani, M., Canuto, M.A., Brenner, M., Hodell, D.A., Eglinton, T.I., and Curtis, J.H. 2015. "Drought, Agricultural Adaptation, and Sociopolitical Collapse in the Maya Lowlands." *Proceedings of the National Academy of Science*, 112: 5607–12. https://doi.org/10.1073/pnas.1419133112.

Eckhouse, B. and Roston, E. 2019. "PG&E May Be the Business World's Biggest Climate-Change Casualty Yet." Bloomberg. 15 January. https://www.bloomberg.com/news/articles/2019-01-15/pg-e-may-be-business-world-s-biggest-climate-change-casualty-yet.

European Commission. 2016. "Common Implementation Strategy for the Water Framework Directive and the Floods Directive." *Guidance Document* No. 35. Luxembourg: Office for Official Publications of the European Communities. https://circabc.europa.eu/sd/a/5b969dc0-6863-4f75-b5d8-8561cec91693/Guidance%20No%2035%20-%20WFD%20Reporting%20Guidance.pdf.

Flavelle, C. 2019. "Corporate America Is Getting Ready to Monetize Climate Change." Bloomberg. 22 January. https://www.bloomberg.com/news/articles/2019-01-22/muggy-disney-parks-downed-at-t-towers-firms-tally-climate-risk.

Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T. and Rockström, J. 2010. "Resilience Thinking: Integrating Resilience, Adaptability and Transformability." *Ecology and Society*, 15 (4): 20. https://doi.org/10.5751/ES-03610-150420.

Folke, C. 2006. "Resilience: The Emergence of a Perspective for Social-Ecological Systems Analyses." *Global Environmental Change*, 16 (3): 253-267. Pergamon. https://doi.org/10.1016/j.gloenvcha.2006.04.002.

García, L.E., Matthews, J.H., Rodriguez, D.J., Wijnen, M., DiFrancesco, K.N., and Ray, P. 2014. "Beyond Downscaling: A Bottom-Up Approach to Climate Adaptation for Water Resources Management." Washington, DC: World Bank.

Gawne, B., Capon, S., Hale, J., Brooks, S., Campbell, C., Stewardson, M. and Everingham, P. 2018. "Different Conceptualizations of River Basins to Inform Management of Environmental Flows." *Frontiers in Environmental Science*, 6: 111. https://doi.org/10.3389/fenvs.2018.00111.

GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit). In press. "Water and Climate Change: Stop Floating, Start Swimming." Bonn, Germany.

Gleick, P. H. 2000. "The Changing Water Paradigm: A Look at Twenty-First Century Water Resources Development." *Water International*, 25 (1): 127–138. https://doi.org/10.1080/02508060008686804.

Global Water System Project. 2014. "Call to Action for Implementing the Water-Energy-Food Nexus." *International Conference: Sustainability in the Water-Energy-Food Nexus*, 19–20, Bonn, Germany, The Global Water System Project.

Grantham, T., Matthews, J.H., Bledsoe, B. In press. "Engineering for Ecological Resilience in Managed Freshwater Systems." *Water Security*.

Grayson, D. 2011. "The Great Basin: A Natural Prehistory." Berkeley, CA, USA: University of California Press.

Grey, D. and Sadoff, C.W. 2007. "Sink or Swim? Water Security for Growth and Development." *Water Policy*, 9 (6): 545–571. https://doi.org/10.2166/wp.2007.021.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H. and Macedo, H.E., 2019. "Mapping the world's free-flowing rivers." *Nature*, 569 (7755): 215–221. https://doi.org/10.1038/s41586-019-1111-9.

Haasnoot, M., Kwakkel, J.H., Walker, W.E. and ter Maat, J. 2013. "Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world." *Global Environmental Change*, 23 (2): 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.

Haasnoot, M., Middelkoop, H., Offermans, A., Van Beek, E. and Van Deursen, W.P. 2012. "Exploring pathways for sustainable water management in river deltas in a changing environment." *Climatic Change*, 115 (3–4): 795-819. https://doi.org/10.1007/s10584-012-0444-2.

Haasnoot, M. 2013. *Anticipating Change: Sustainable Water Policy Pathways for an Uncertain Future.* Edited by Eising, F. and Twente, N.L.: University of Twente.

Haig, S.M., Murphy, S.P., Matthews, J.H., Arismendi, I. and Safeeq, M. 2019. "Climate-Altered Wetlands Challenge Waterbird Use and Migratory Connectivity in Arid Landscapes." *Scientific Reports*, 9: 4666. https://doi.org/10.1038/s41598-019-41135-y.

Harvey, C. 2016. "'Climate change is water change' — why the Colorado River system is headed for major trouble." *Washington Post*. 19 August. https://www.washingtonpost.com/news/energy-environment/wp/2016/08/19/climate-change-is-water-change-why-the-colorado-river-system-is-headed-for-trouble/?noredirect=on&utm_term=.7b4ff003f5b4.

Hategekimana, S. and Twarabamenya, E. 2007. "The Impact of Wetlands Degradation on Water Resources Management in Rwanda: The Case of Rugezi Marsh." *Proceedings of the 5th International Symposium on Hydrology*. Cairo, Egypt.

Holling, C.S. 1996. "Engineering Resilience Versus Ecological Resilience." *Engineering Within Ecological Constraints*. Edited by Schultze, P., 31–44. Washington, DC: The National Academies Press.

ICIWaRM (International Center for Integrated Water Resources Management). 2016. "Shared Vision Planning for Green Infrastructure to Reduce Urban Flood Risk in Udon Thani, Thailand." https://iciwarm.info/shared-vision-planning-for-green-infrastructure-to-reduce-urban-flood-risk-in-udon-thani-thailand/.

Independent Evaluation Group. 2012. "Adapting to Climate Change: Assessing the World Bank Group Experience." Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/21106.

International Joint Commission. 2015. "Great Lakes." St. Lawrence River Adaptive Management Committee of the Great Lakes Boards of Control Directive. Ottawa, ON and Washington, D.C.: International Joint Commission.

IPCC (Intergovernmental Panel on Climate Change). 2008. *Climate Change and Water.* Technical Paper of the Intergovernmental Panel on Climate Change. Edited by Bates, B., Kundzewicz, Z.W., Wu, S., and Palutikof, J.P. Geneva, Switzerland: IPCC Secretariat.

IPCC (Intergovernmental Panel on Climate Change). 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Pachauri, R.K. and Meyer, L.A. IPCC, Geneva, Switzerland, 151 pp.

IPCC (Intergovernmental Panel on Climate Change). 2018. *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* http://www.ipcc.ch/report/sr15/.

IUCN (International Union for Conservation of Nature). 2017. "Ecosystem-Based Adaptation." Issues Brief. https://www.iucn.org/sites/dev/files/import/downloads/ecosystem-based_adaptation_issues_brief_final.pdf.

IUCN (International Union for Conservation of Nature) Commission on Ecosystem Management. 2018. "Nature Based Solutions." https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions.

IUGLS (International Upper Great Lakes Study). 2012. "Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels." *Final Report to the International Joint Commission.* Ottawa, ON and Washington, D.C.: International Joint Commission.

IWMI (International Water Management Institute) and AGWA (Alliance for Global Water Adaptation). In press. "Background Paper on Water and Climate Adaptation." Rotterdam, Netherlands: Global Commission on Adaptation.

Jiang, Y., Zevenbergen, C. and Ma, Y. 2018. "Urban pluvial flooding and stormwater management: A contemporary review of China's challenges and 'sponge cities' strategy." *Environmental Science & Policy*, 80: 132–143. https://doi.org/10.1016/j.envsci.2017.11.016.

Kathayat, G., Cheng, H., Sinha, A., Yi, L., Li, X., Zhang, H., Li, H., Ning, Y. and Edwards, R.L. 2017. "The Indian Monsoon Variability and Civilization Changes in the Indian Subcontinent." *Science Advances*, 3 (12): e1701296. American Association for the Advancement of Science. https://doi.org/10.1126/sciadv.1701296.

Kundzewicz, Z.W. and Stakhiv, E.Z. 2010. "Are Climate Models 'Ready for Prime Time' in Water Resources Management Applications, or Is More Research Needed?" *Hydrological Sciences Journal*, 55 (7): 1085–1089. https://doi.org/10.1080/02626667.2010.513211.

Kundzewicz, Z.W., Krysanovad, V., Benestad, R.E., Hov, Ø., Piniewskic, M. and Otto I.M. 2018. "Uncertainty in climate change impacts on water resources." *Environmental Science and Policy*, 79: 1–8. https://doi.org/10.1016/j.envsci.2017.10.008.

Le Quesne, T., Matthews, J.H., Von der Heyden, C., Wickel, A.J., Wilby, R., Hartmann, J., G Pegram et al., 2010. *Flowing Forward: Freshwater Ecosystem Adaptation to Climate Change in Water Resources Management and Biodiversity Conservation.* Washington, DC: World Bank.

Lumbruso, D., and Ramsbottom, D. 2018. "Flood Risk Management in the United Kingdom: Putting Climate Change Adaptation into Practice in the Thames Estuary." *Resilience: The Science of Adaptation to Climate Change*, 79–87. Amsterdam, NL: Elsevier.

Lustgarten, A. 2016. "Unplugging the Colorado River: Could the End Be Near for One of the West's Biggest Dams?" New York Times, 20 May. https://www.nytimes.com/2016/05/22/opinion/unplugging-the-colorado-river.html.

Matthews, J.H., Timboe, I., Amani, A., Bhaduri, A., Dalton, J., Dominique, K., Fletcher, M., Gaillard-Picher, D., Holmgren, T., Leflaive, X., McClune, K., Mishra, A., Koeppel, S., Kerres, M., Krahl, D., Kranefeld, R., Panella, T., Rodriguez, D., Singh, A., Tol, S., White, M., van de Guchte, C., van Weert, F., Vlaanderen, N. and Yokota, T. 2018. "Mastering disaster in a changing climate: Reducing disaster risk through resilient water management." Global Water Forum.

Matthews, J.H., Seimon, A., Mulligan, M., Sindorf, N., Burke, S. and Shields, C. 2011. "An Assessment of the Climate Change Vulnerability of Rwanda's Wetlands: Integrating Eco-Hydrological, Socio-Economic, and Institutional Perspectives." Kigali, Rwanda, and Washington, DC: Rwandan Environmental Management Authority and the Global Environmental Facility.

Matthews, J.H., Mendoza G.F. and Jeuken, A.B.M. 2015. "Designing for Climate Confidence: Moving Beyond Uncertainty in Sustainable Water Management." *Water Monographs*, 3: 20–29. https://alliance4water.org/resources/Designing_for_Climate_Confidence_WCCE.pdf.

Matthews, J.H. and Boltz, F. 2012. "The Shifting Boundaries of Sustainability Science: Are We Doomed Yet?" *PLOS Biology*, 10 (6): e1001344. https://doi.org/10.1371/journal.pbio.1001344.

Matthews, J.H., Wickel, B.A.J. and Freeman, S. 2011. "Converging Currents in Climate-Relevant Conservation: Water, Infrastructure, and Institutions." *PLOS Biology*, 9 (9): e1001159. https://doi.org/10.1371/journal.pbio.1001159.

McDonald, R. and Shemie, D. 2014. *Urban Water Blueprint: Mapping conservation solutions to the global water challenge.* The Nature Conservancy: Washington, DC. https://www.nature.org/content/dam/tnc/nature/en/documents/Urban_Water_Blueprint.pdf.

Mendoza, G.F., Jeuken, A., Matthews, J.H., Stakhiv, E.Z., Kucharski, J. and Gilroy, K. 2018. "Climate Risk Informed Decision Analysis (CRIDA): Collaborative Water Resources Planning for an Uncertain Future." Paris, France and Alexandria, VA, USA: UNESCO-IHP, ICIWaRM.

Milly, P., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P. and Stouffer, R.J. 2008. "Stationarity Is Dead: Whither Water Management?" *Science*, 319: 573–574. https://doi.org/10.1126/science.1151915.

Moody's Investors Service. 2017. "Climate change is forecast to heighten US exposure to economic loss placing short- and long-term credit pressure on US states and local governments." Moody's Investor Service. 28 November. https://www.moodys.com/research/Moodys-Climate-change-is-forecast-to-heighten-US-exposure-to.PR_376056.

Moody's Investors Service. 2017. "Environmental risks: Evaluating the impact of climate change on US state and local issuers." Report no. 1071949. New York: Moody's Investment Service.

Null, S.E., Medellín-Azuara, J., Escriva-Bou, A., Lent, M. and Lund, J. R. 2014. Optimizing the dammed: Water supply losses and fish habitat gains from dam removal in California." *Journal of Environmental Management*, 136: 121–131. https://doi.org/10.1016/j.jenvman.2014.01.024.

OECD (Organisation for Economic Co-operation and Development). 2005. *Bridge Over Troubled Waters: Linking Climate Change and Development.* Edited by Agrawala, S. Paris: OECD.

OECD (Organisation for Economic Co-operation and Development). 2013. *Water and Climate Change Adaptation: Policies to Navigate Uncharted Waters.* Paris: OECD Publishing. https://doi.org/10.1787/22245081.

Olsson, L., Jerneck, A., Thoren, H., Persson, J. and O'Byrne, D. 2015. "Why Resilience Is Unappealing to Social Science: Theoretical and Empirical Investigations of the Scientific Use of Resilience." *Science Advances*, 1 (4): e1400217-12. https://doi.org/10.1126/sciadv.1400217.

Ortloff, C.R. 2009. *Water Engineering in the Ancient World: Archeological and Climate Perspectives on Soceities of Ancient South America, the Middle East, and South-East Asia.* New York, NY: Oxford University Press.

Pahl-Wostl, C. 2007. "Transitions Towards Adaptive Management of Water Facing Climate and Global Change." *Water Resources Management*, 21: 49–62. https://doi.org/10.1007/s11269-006-9040-4.

Parmesan, C. 2006. "Ecological and Evolutionary Responses to Recent Climate Change." *Annual Review of Ecology and Evolution*, 37: 637–69. https://doi.org/10.1146/annurev.ecolsys.37.091305.110100.

Patterson, C., Rosenberg, T. and Warren, A. 2016. "Design, operation and adaptation of reservoirs for flood storage." Report – SC12001/R. Bristol, UK: Environment Agency. http://evidence.environment-agency.gov.uk/FCERM/Libraries/FCERM_Project_Documents/sc120001_report.sflb.ashx.

PBWB (Pangani Basin Water Board) and IUCN (International Union for Conservation of Nature). 2011. *Pangani River System – Future of the Basin Report.* Moshi, Tanzania. PBWB and Nairobi, Kenya: IUCN Eastern and Southern Africa Regional Programme. 39 pp. https://cmsdata.iucn.org/downloads/future_of_the_basin.pdf.

Pegasys. 2018. "Climate Adaptation Strategy." RSA. http://www.pegasys.co.za/portfolio-items/climate-adaptation-strategy-rsa/.

Pittock, J. 2010. "A Pale Reflection of Political Reality: Integration of Global Climate, Wetland, and Biodiversity Agreements." *Climate Law*, 1: 343-373. https://doi.org/10.3233/CL-2010-017.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., et al., 2010. "The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards." *Freshwater Biology*, 55: 147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x.

Poff, N.L., Casey, L., Brown, M., Grantham, T.E., Matthews, J.H., Palmer, M., Spence, C.M., Wilby, R. et al., 2016. "Sustainable Water Management Under Future Uncertainty with Eco-Engineering Decision Scaling." *Nature Climate Change*, 6: 25–34. https://doi.org/10.1038/nclimate2765.

Poff, N.L. and Zimmerman, J.K.H. 2010. "Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows." *Freshwater Biology*, 55(1): 194–205. https://doi.org/10.1111/j.1365-2427.2009.02272.x.

Poff, N.L. and Matthews, J.H. 2013. "Environmental Flows in the Anthropocence: Past Progress and Future Prospects." *Current Opinion in Environmental Sustainability*, 5 (6): 667–675. https://doi.org/10.1016/j.cosust.2013.11.006.

Poff, N.L. 2017. "Beyond the Natural Flow Regime? Broadening the Hydro-Ecological Foundation to Meet Environmental Flows Challenges in a Non-Stationary World." *Freshwater Biology*, 12: 1011–1021. https://doi.org/10.1111/fwb.13038.

Poff, N.L., Bain, A.M., Karr, J., Prestegaard, K., Richter, B.D., Sparks, R.E. and Stromberg, J.C. 1997. "The Natural Flow Regime." *BioScience*, 47: 769–84. https://doi.org/10.2307/1313099.

Ray, P.A., Taner, M.Ü., Schlef, K.E., Wi, S., Khan, H.F., Freeman, S.S.G. and Brown, C.M. 2018. "Growth of the Decision Tree: Advances in Bottom-Up Climate Change Risk Management." *JAWRA (Journal of the American Water Resources Association)*, 920–937. https://doi.org/10.1111/1752-1688.12701.

Ray, P.A. and Brown, C.M. 2015. *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework.* Washington, DC: The World Bank. https://doi.org/10.1596/978-1-4648-0477-9.

Rodina, L. 2018. "Defining 'Water Resilience': Debates, Concepts, Approaches, and Gaps." *Wiley Interdisciplinary Reviews: Water*, 6 (2): e1334–18. John Wiley & Sons, Ltd. https://doi.org/10.1002/wat2.1334.

Rijke, J., van Herk, S., Zevenbergen, C. and Ashley, R. 2012. "Room for the River: delivering integrated river basin management in the Netherlands." *International Journal of River Basin Management*, 10 (4): 369–382. https://doi.org/10.1080/15715124.2012.739173.

Ringler, C., Bhaduri, A. and Lawford, R. 2013. "The Nexus Across Water, Energy, Land and Food (WELF): Potential for Improved Resource Use Efficiency?" *Current Opinion in Environmental Sustainability*, 5 (6): 617–624. https://doi.org/10.1016/j.cosust.2013.11.002.

Robbins, J. 2019a. "Crisis on the Colorado: Running Dry: New Strategies for Conserving Water on the Colorado," *Yale Environment 360.* 31 January. https://e360.yale.edu/features/running-dry-new-strategies-for-conserving-water-on-the-colorado.

Robbins, J. 2019b. "Crisis on the Colorado: On the Water-Starved Colorado River, Drought Is the New Normal," *Yale Environment 360.* 22 January. https://e360.yale.edu/features/on-the-water-starved-colorado-river-drought-is-the-new-normal.

Rockström, J., Falkenmark, M., Allan, T., Folke, C., Gordon, L., Jägerskog, A., Kummu, M., Lannerstad, M., Meybeck, M., Molden, D., Postel, S., Savenije, H., Svedin, U., Turton, A. and Varis, O. 2014. "The Unfolding Water Drama in the Anthropocene: Towards a Resilience-Based Perspective on Water for Global Sustainability". *Ecohydrology*, 7: 1249–1261. https://doi.org/10.1002/eco.1562.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B.H., Liverman, D., Richardson, K., Crutzen, C. and Foley. J. 2009. "A Safe Operating Space for Humanity." *Nature*, 461: 472–475. https://doi.org/10.1038/461472a.

Ross, H.C. and Wolfe, S.E. 2015. "Life After Death: Evidence of the Hoover Dam as a Hero Project That Defends Against Mortality Reminders." *Water History*, 8 (1): 3–21. https://doi.org/10.1007/s12685-015-0151-9.

Rygaard, M., Binning, P.J. and Albrechtsen, H.J. 2011. "Increasing urban water self-sufficiency: New era, new challenges." *Journal of Environmental Management*, 92 (1): 185–194. https://doi.org/10.1016/j.jenvman.2010.09.009.

Sadoff, C. and Muller, M. 2009. *Water Management, Water Security and Climate Change Adaptation: Early Impacts and Essential Responses.* Stockholm, Sweden: Global Water Partnership.

Sebesvari, Z., Rodrigues, S., and Renaud, F. 2017. "Mainstreaming ecosystem-based climate change adaptation into integrated water resources management in the Mekong region." *Regional Environmental Change*, 17 (7): 1907–1920. https://doi.org/10.1007/s10113-017-1161-1.

Simon, C. and Duchhart, I. 2015. "Green Infrastructure as a tool for resilience: the case of Chota, Mozambique." *Conference: 4th IFLA Africa Symposium* – October 2015 (Track Landscape and Infrastructure). Nairobi, Kenya. https://www.researchgate.net/publication/284185790_Green_Infrastructure_as_a_tool_for_resilience_the_case_of_Chota_Mozambique.

Simpson, A.G. 2018. "FEMA Grows Its Flood Reinsurance Plan with $500 Million Cat Bond." *Insurance Journal*. https://www.insurancejournal.com/news/national/2018/08/01/496590.htm.

Singh, A., Lund, H.G. and Barr, J. 2018. "Challenges in Building Climate-Resilient Quality Energy Infrastructure in Africa." *Resilience: The Science of Adaptation to Climate Change.* Edited by Zommers, Z., Alverson, K. and Alver, 376. Amsterdam, NL.

SNWA (Southern Nevada Water Authority). 2018a. "Water Banking." https://www.snwa.com/where-southern-nevada-gets-its-water/preparing-for-the-future/water-banking.html.

SNWA (Southern Nevada Water Authority). 2018b. *2018 Water Resource Plan & Water Budget.* Las Vegas: SNWA. https://www.snwa.com/assets/pdf/water-resource-plan.pdf.

Tellman, B., Bausch, J. C., Eakin, H., Anderies, J., Mazari-Hiriart, M., Manuel-Navarrete, D., and Redman, C. 2018. "Adaptive pathways and coupled infrastructure: seven centuries of adaptation to water risk and the production of vulnerability in Mexico City". *Ecology and Society*, 23 (1):1. https://doi.org/10.5751/ES-09712-230101.

Tolkein, J.R.R. 1954. *The Lord of the Rings: The Fellowship of the Ring.* London: George Allen & Unwin.

Turpin, T. 2008. *Dam.* London: Reaktion Books. 256 p.

UNECE (United Nations Economic Commission for Europe) and INBO (International Network of Basin Organizations). 2015. *Water and Climate Change Adaptation in Transboundary Basins: Lessons Learned and Good Practices.* Geneva. https://www.unece.org/fileadmin/DAM/env/water/publications/WAT_Good_practices/ece.mp.wat.45.pdf.

UNISDR (United Nations International Strategy for Disaster Reduction). 2016. *UNISDR Strategic Framework 2016–2021.* Geneva: UNISDR. https://www.unisdr.org/files/51557_strategicframework.pdf.

UN Water (United Nations). In press. *Policy Brief: Climate Change and Water.* Geneva, Switzerland: UN Water.

van de Ven, F.H.M, Snepb, R.P.H, Koole, S., Brolsma, R., van der Brugge, R., Spijker, J. and Vergroesen, T. 2016. "Adaptation Planning Support Toolbox: Measurable performance information based tools for co-creation of resilient, ecosystem-based urban plans with urban designers, decision-makers and stakeholders." *Environmental Science Policy*, 66: 427–436. https://doi.org/10.1016/j.envsci.2016.06.010.

van Meel, P.P.A., van Boetzelaer, M. E. and Bakker, P.C. 2005. "Spatial planning key decision room for the river." *Proceedings of the 3rd International Symposium on Flood Defence.* Nijmagen, the Netherlands, 5/2005.

Veloz, S.D., Williams, J.W., Blois, J.L., He, F., Otto-Bliesner, B. and Liu, Z. 2012. "No-analog climates and shifting realized niches during the late quaternary: implications for 21st-century predictions by species distribution models." *Global Change Biology*, 18 (5): 1698–1713. https://doi.org/10.1111/j.1365-2486.2011.02635.x.

Verbist, K., Rojas, P. and Maureira, H. 2018. *A Stress Test for Climate Change Impacts on Water Security: Case Study From the Limarí Watershed in Chile.* Paris: UNESCO.

WEF (World Economic Forum). 2018. *The Global Risks Report 2018.* Geneva: WEF.

Wilby R.L and Vaughan, K. 2011. "Hallmarks of organisations that are adapting to climate change." *Water and Environment Journal*, 25: 271–281. https://doi.org/10.1111/j.1747-6593.2010.00220.x.

Wilby, R.L. 2011. "Adaptation: Wells of Wisdom." *Nature Climate Change*, 1 (6): 302–303. Nature Publishing Group. https://doi.org/10.1038/nclimate1203.

Williams, J.W. and Jackson, S.T. 2007. "Novel climates, no-analog communities, and ecological surprises." *Frontiers in Ecology and the Environment*, 5 (9): 475–482. https://doi.org/10.1890/070037.

Wines, J. 2014. "Colorado River Drought Forces a Painful Reckoning for States." *New York Times.* 5 January. https://www.nytimes.com/2014/01/06/us/colorado-river-drought-forces-a-painful-reckoning-for-states.html.

World Bank Group. 2016. *High and Dry: Climate Change, Water, and the Economy.* Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/23665.

World Bank. 2019. "Uruguay: Strengthening Creditworthiness of the Water and Sanitation Sector." http://www.worldbank.org/en/about/partners/brief/uruguay-strengthening-creditworthiness-of-water-sanitation-sector.

WWF (World Wildlife Fund). 2016. *Natural and Nature-Based Flood Management: A Green Guide.* Washington, DC: World Wildlife Fund. https://www.worldwildlife.org/publications/natural-and-nature-based-flood-management-a-green-guide.

Yang, M. and Blyth, W. 2007. "Modeling Investment Risks and Uncertainties with Real Options Approach." *International Energy Agency Working Paper Series.* Paris: IEA. https://www.iea.org/publications/freepublications/publication/ROA_Model.pdf.

Zia, A. and Wagner, C.H. 2015. "Mainstreaming early warning systems in development and planning processes: Multilevel implementation of Sendai framework in Indus and Sahel." *International Journal of Disaster Risk Science*, 6(2), 189–199. https://doi.org/10.1007/s13753-015-0048-3.

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