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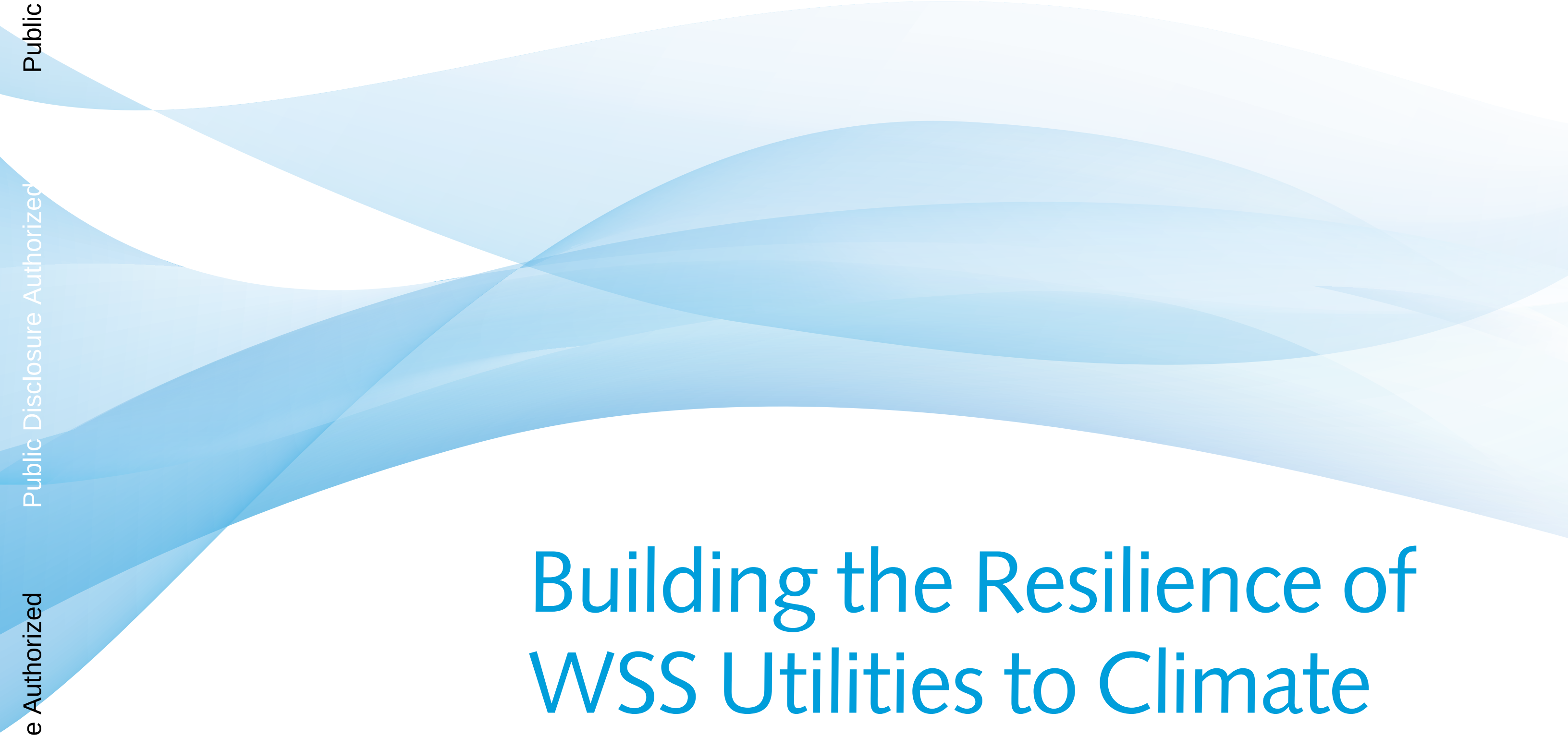

Building the Resilience of WSS Utilities to Climate Change and Other Threats

A Road Map

WORLD BANK GROUP

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Executive Summary

Water supply and sanitation (WSS) utilities are expected to become increasingly susceptible to the expected impacts of climate change. These impacts will materialize with more frequent or more severe extreme events, including floods and droughts; different rainfall patterns and temperatures; and seasonal shifts. However, many stakeholders, managers, and investors do not yet fully consider future climate conditions as a necessary input to business risk analyses and long-term planning. Yet it is critical to adequately consider climate risks and opportunities when planning for WSS services and water resources.

This failure to consider future climate conditions in planning exercises to date can be explained by multiple factors, including (i) lack of recognition that future climate trends will differ from historical data; (ii) limited knowledge about the potential risks to utilities' business operations over various timescales; (iii) inadequate access to relevant climate and weather information to incorporate into infrastructure design, operations and maintenance (O&M), and business continuity plans; and (iv) the perceived costs of making adjustments associated with planning for climate change.

Considering climate risks is likely to improve the service provider's resilience and result in increased reliability and operational effectiveness in both the short and long term. This may directly benefit the local economy, national resource security, and national economic growth.

WSS utility planners and engineers have dealt with natural climate variances and disaster planning as part of the design process for many years. However, the traditional methods for these plans have not considered the deep uncertainty surrounding many future conditions, which are further exacerbated by climate change. Deep uncertainty is uncertainty that occurs when parties to a decision do not know or cannot agree on models relating the key forces that shape the future, the probability distributions of key variables and parameters in these models, or the value of alternative outcomes. There currently is no established road map available to guide WSS utilities in planning for an uncertain climate future, or more generally for decision making under deep uncertainty, which can include issues such as population growth projections, local economic development, or changes in future demand. Thus, while this report frequently links deep uncertainty to climate change, the reader should understand that the term encompasses a much broader suite of uncertainties facing WSS utilities.

This document provides practical and workable guidance to incorporate uncertainty into the choices of WSS utilities, be it through design, planning, or operations. In applying the process presented here, a utility will be better prepared to deal with future conditions: it will be more resilient.

Overview

To help utilities incorporate resilience and robustness in their choices, this road map proposes a process in three phases that can inform the design of strategies necessary to WSS services provision. The phases proposed in this road map are adapted from the World Bank's Decision Tree Framework (DTF) (Ray and Brown 2015) to better suit the decision-making process and concerns of WSS utilities. The DTF and this road map build on the same methodologies to move away from a traditional "predict then act" approach. The main departure from the DTF is the recommendation to consider all possible uncertainties, including climate change, from the start. The road map builds on the understanding that climate change is most often an amplifier of existing uncertainties (many of which are threats), and, as such, should not be evaluated as a stand-alone impact.

Phase 1: Knowing the system. The process starts with participatory work in which an extensive team (including planners, operators, and other stakeholders) identifies the problematic and critical elements of the system; the potential threats that may affect these elements and the consequences of their individual or joint failure; the performance objectives the utility wants to achieve; and the available solutions. This scoping also identifies tools, data, and models to be used in the subsequent phases.

Phase 2: Identifying vulnerabilities. Next, analysts (internal experts or external consultants) use the information gathered in Phase 1 to stress-test the water system over a range of plausible futures and assess its performance under different conditions. This is done first for the system as-is (status quo) and then for the different possible solutions, and their combinations. Performance is measured against the objectives defined in Phase 1. The stress-test results in a concise description of the conditions most likely to cause the utility to fail to meet one or more objectives. These conditions are often summarized as scenarios that describe the combinations of factors that yield success or failure. Analysts also identify options that reduce vulnerability and improve the performance of both the system as a whole and of critical elements over the same range of futures.

Phase 3: Choosing actions. Analysts organize these options into robust and flexible strategies and examine the trade-offs among them in meeting the agreed objectives under the scenarios identified in Phase 2. The options should include careful monitoring for conditions of concern (i.e., tracking if the system is moving outside of the scenarios in which performance is acceptable).

As an integral part of all these steps, analysts present current vulnerabilities, options, and trade-offs to other teams in the water utility, the board, and possibly to external stakeholders to define an acceptable, actionable, robust, and consensual road map. Depending on the complexity of the project, one or more rounds of participatory work are needed with stakeholders to refine the objectives or the threats, or to adjust the options available to decision makers.

Applying the three-phase approach outlined in this document helps utilities understand their system and their investment plans more fully in terms of their robustness and resilience to climate change and other uncertainties. It enables utilities to assess these threats without first needing to predict future conditions. The road map helps the user to identify critical elements of infrastructure and possible future states of its operating environment, assess the potential impacts resulting from failure of those critical assets, and measure failures against articulated objectives, such as the level of service to be delivered to customers.

The approach reveals the strengths and vulnerabilities of investment plans concisely: as a specific set of conditions in which the investments identified can achieve reliable service or where additional actions may be necessary. It also helps utilities invest robustly by identifying near-term, no-regret projects that can be undertaken now, while maintaining flexibility in pursuing additional actions adaptively as future conditions evolve. These results can be achieved both with a qualitative exploration and a quantitative assessment, depending on the context and the resources available.

WSS utilities need to be willing to engage in long-term planning that accounts for the deep uncertainties they face and will continue to impact service provision in the future. This road map proposes a clear approach for WSS utilities to embark on this type of complex analysis that, in most cases, will differ greatly from previous approaches. By embracing such innovation, utilities also recognize that the analysis could produce controversial findings or recommendations different from their expectations. However, in applying this approach, they also embrace the opportunity to secure long-term resilience in the provision of WSS services for their customers.

Abbreviations

AR5	Fifth Assessment Report of IPCC
capex	capital expenditure
CMIP5	Coupled Model Intercomparison Project Phase 5
DTF	Decision Tree Framework
ENSO	El Niño-Southern Oscillation
GCM	global circulation model
GHG	greenhouse gas
IFC	International Finance Committee
IPCC	Intergovernmental Panel on Climate Change
LIC	low-income country
NGO	nongovernmental organization
OCVM	Organización de Cuenca del Valle de México
opex	operational expenditure
PRIM	patient rule induction method
RCM	regional circulation model
SEDAPAL	Servicio de Agua Potable y Alcantarillado de Lima
SUNASS	Superintendencia Nacional de Servicios de Saneamiento
USAID	U.S. Agency for International Development
WEAP	water evaluation and planning system model
WSS	water supply and sanitation
WUCA	Water Utility Climate Alliance
XLRM	Uncertainties, Policy Levers, Relationship, Metrics

Chapter 1

Reasons for Integrating Robustness and Resilience to Climate Change Impacts into Urban WSS Planning Exercises

1.1. Water Supply and Sanitation Utilities Have to Operate under Environments of Ever-Increasing Uncertainties and Complex Stakeholder Dynamics

By 2030, half of the world's population will be living in water stressed areas. Global driving forces, including climate change, water scarcity, population growth, and urbanization, are expected to affect water supply and sanitation (WSS) services around the world (World Bank 2017c).[1] Predictions generally differ on, for instance, how much demand will grow, how the urban shape of the city will develop, and how rainfall patterns may change. WSS service providers are already being challenged by events that lay outside the known historical records. For instance, in March 2017, Lima's water supply was interrupted for four consecutive days due to extremely intense rains, which had never been experienced before, leading to severe landslides that filled the river with mud. The main water treatment plant could not deal with the resulting turbidity and suspended solids levels. This example is far from unique given the increasingly severe floods and droughts being experienced globally, but in itself it shows the surprises that even well-organized utilities like *Servicio de Agua Potable y Alcantarillado de Lima* (SEDAPAL, Lima's WSS utility) are facing.

Climate change is creating new challenges for water utilities. While an overwhelming body of scientific evidence clearly shows that past historical records by themselves may no longer be a reliable guide to current and future climate, the exact impacts of climate change on local climate, including local extreme weather-related events, are highly uncertain (see box 1.1). For instance, the once in 50-year storm may already be occurring at a higher frequency than available historical data suggest, while the next drought may be significantly different in intensity or duration than the historical drought of record. The best science, however, can rarely specify the exact nature of these changes. Climate change is creating a situation in which the engineering standards and status quo of years past have become less reliable guides to address future requirements. Statistical approximations that have been the foundation of engineering design to date have become less accurate and appropriate because they rely solely on historical data that do not encompass a changing future. Therefore, to ensure the uninterrupted delivery of their mandate, utilities need to start planning for an uncertain future.

Assessments of many future conditions, including climate change, technological change, economic growth or demographic trends, cannot be viewed as accurate predictions or forecasts, but should instead be considered candidate scenarios for the future. For example, the likelihood estimates for long-term land use patterns or global economic growth are neither well characterized nor verifiable. These are examples of uncertainty for which responses have been codified through the application of national design standards. These standards are based on

BOX 1.1. What Is Resilience?

Climate change response has increasingly centered on resilience, and the needed modifications to infrastructure design practices, investment analysis processes, and policy decisions regarding financing and disaster risk management. Fundamentally, resilience is "*the capacity of any entity—an individual, a community, an organisation, or a natural system—to prepare for disruptions, to recover from shocks and stresses, and to adapt and grow from a disruptive experience*" (Rodin 2014, 3).

The modern concept of resilience builds on insights from three fields: engineering, ecology, and operations research. The engineering application of resilience focuses on combining strength with flexibility or redundancy. The ecological application appreciates the occurrence of large changes, through which the system can absorb large shocks without collapse (i.e., regaining stability). Systems thinking considers feedback loops and time delays, which can create chains of cause and effect that differ significantly from what people might naturally infer.

Resilience helps integrate consideration of disasters and shocks into a broader theory of system function and change. This connection matters because extreme events will be one of the primary ways in which the effects of climate change are felt. In addition, such extreme events may help catalyze desired changes in an urban system. Drawing on its ecological roots, resilience notes that some systems may in fact thrive on shocks. For instance, many forests in the western United States require periodic fires to clear out undergrowth and allow new trees to grow. Without such fires, the system loses resilience because trees become too old and build up fuel with potential for catastrophic firestorms. Ecologists capture this idea through the concept of the adaptive cycle, which has four phases. The system begins with rapid growth and then reaches a period of stasis. A disruption then releases the system so that it can reorganize and begin another period of change or growth.

In managing risks in an urban water services setting, resilience should be viewed as an all-encompassing goal, much beyond climate change per se. Resilience should be part of a risk governance process. In this process, a broad group of decision makers managing the city's risks can deliberate around the feature(s) of resilience identified as most suitable for a service provider, its stakeholders and other water users. For this reason, this guidance note does not advocate for a specific definition of *resilience*. Instead, it describes an effective process that cities and WSS service providers can follow as they strive to increase resilience.

likelihood estimates, irrespective of their predictive ability. Design guidance on climate change is rarely available, especially in low-income countries (LICs), yet as a factor that exacerbates uncertainty in other areas key to the planning process, the influence of climate change cannot be ignored. In this sense, more systematized approaches are needed to address the deep uncertainties surrounding climate change.

Acknowledging that WSS utilities and urban water systems face deep uncertainty allows planners to work towards identifying resilience strategies. **Deep uncertainty is uncertainty that occurs when parties to a decision do not know or cannot agree on models that relate the key forces that shape the future, probability distributions of key variables and parameters in these models, or the value of alternative outcomes** (Lempert 2003). Most projections of future socioeconomic conditions (population, prices) are deeply uncertain, and many projects have nonmonetary impacts (e.g., lives saved or regional equity), which cannot be valued in an uncontroversial manner. Unfortunately, in many places around the world, little attention is given to uncertainty about future trends, and even less toward climate change in combination with other uncertainties.

Water management is often conflictual because different users have different priorities. Building consensus about the decisions that a utility makes about service provision is important in successfully realizing its functions. Even without deep uncertainty about future conditions, a WSS utility needs to continuously negotiate with other users. Uncertainty about future trends is also linked to disagreements among stakeholders and limits consensus-building efforts. Contention in planning can threaten the ability to implement projects as planned. People or groups with different (and sometimes competing) values, priorities, or interests often have very different views of the likelihood of different events taking place. Deep uncertainties are therefore also a threat to the ability to build consensus on the right policies or project design to address climate change. Since the existence of a large consensus is a critical determinant of project success, deep uncertainties are an important threat to water utilities' master planning efforts and their assumptions for future system performance.

The process to create a plan is often as important as the plan itself. Unfortunately, experience shows that plans are often done by small technical teams working in silos, with limited effort to reach out to stakeholders. Yet, some cases in which such outreach was explicitly carried out show that it pays dividends to make consensus-building across stakeholders part of planning. For instance, the Louisiana Coastal Protection and Restoration Authority is in charge of developing a Coastal Master Plan for a Sustainable Coast. Updated every five years, the master plan provides a 50-year blueprint for coastal restoration and flood risk reduction projects coastwide. Thanks to an intensive participatory process aligned with the methodologies presented in this road map, the Louisiana House joined the Louisiana Senate by approving—unanimously for the first time—the 2012 and the 2017 plans, which immediately became operational upon approval.[2]

1.2. Reliable WSS Service Provision is Essential for Economic Well-Being and Growth, yet Providers Often Have Limited Resources and Need to Spend Effectively

WSS services are essential for well-being and growth. WSS utilities in LICs are under tremendous pressure to increase coverage and service levels, which often relegates increasing the resilience of (new and) existing assets to a secondary priority due to budget constraints.

While more investments are urgently needed to improve basic WSS access in LICs, maintaining or enhancing resilience of new and aging infrastructure to natural disasters, especially in the context of climate change and variability, are critical for development. If a disaster strikes, a WSS system that is still functioning can sustain the lives and livelihoods of people, and ultimately revitalise other sectors. Therefore, systems that are built well for the first time, for instance planning for safe failure[3] or with added safety margins, and that are well maintained, are more likely to recover quickly to provide the desirable level of service after a crisis and avoid serious development impacts - for instance, a cholera crisis due to treatment failures leading to deteriorating water quality. In cities especially, the performance of firms is also affected by the availability of water. The World Bank (2017c) finds that when urban water services are disrupted, whether by climate, inadequate infrastructure, or both, firms suffer significant reductions in their sales and employment. Small and informal firms are particularly vulnerable and are also a major source of employment in LICs. The impact of WSS services and their performance therefore extends beyond the widely documented effects on human health.

Planning for resilience is not easy, despite the apparent benefits of increasing resilience. There are several institutional and regulatory, system planning, and engineering and design challenges that most utilities face in the implementation of resilience measures. For instance, most utilities do not have incentives to integrate resilience measures in their planning processes due to lack of financial and technical resources on the one hand, or tools/human capacity to measure the success of resilient measures on the other. Similarly, risk assessments are often not properly used in the planning of infrastructure systems and networks as investment options are chosen without due consideration for different types of risks and scenarios. As a result, master planning efforts have commonly been separated from crisis response, instead of integrating potential crises in the recommendations of the master plan, leading to duplication in teams allocated to these efforts and lack of coordination among them. In addition, design codes and standards are seldom updated to reflect changing average temperatures and precipitation rates, extreme conditions, or natural hazards and therefore do not reflect the shifting planning environment utilities are facing.

In LICs, WSS utilities are frequently financially constrained. Dealing with all risks (e.g., as is done in the Netherlands) is extremely costly and therefore becomes prohibitive for most utilities. For instance, in the context of climate change, the traditional approach of increasing the factor of safety to allow for greater variance of storm events while still providing adequate services becomes cost-prohibitive and ineffectual. Factors of safety will certainly still be necessary but cannot be the sole solution for climate adaptation. A balance needs to be struck between improving the robustness of a system (Lempert 2003) and avoiding excessive opportunity costs. Yet, utilities with resilient systems (see box 1.1) will incur damage less often and thus have more resources freed from emergency management (e.g., financing expensive water tankers or reconstruction), which can be used instead for other much needed investments in water or other sectors, since many utilities in LICs are state-owned.

It is extremely dangerous – and can be very costly – to disregard risks, because doing so may lead to large losses and stranded assets, for both the utility and the local economy. For example, in Lima, SEDAPAL developed a US$2.6 billion infrastructure investment plan in 2012 to secure the city's supply to 2040. The investments aimed to prepare the city to provide reliable service under one scenario of population increase and economic growth, without any sensitivity analysis around what would happen if the population did not grow as expected, or if climate varied (Kalra et al. 2015). Yet, socioeconomic changes may take different turns than expected: industries may move in or out of the town based on surrounding infrastructure (e.g., ports, taxes). Although on average wealthier people consume more water, the right conservation education program may lead people to start consuming less and introduce water saving measures in their households. Climate models for Lima show a wide range of plausible precipitation changes, from plus 40 percent to negative 20 percent from the historic mean. A joint study by the World Bank and SEDAPAL (Kalra et al. 2015) finds that if climate were a little drier than the current one, the foreseen investments would not be able to meet the projected demand. And if demand were higher than the projection used, even a wetter climate would not be able to secure reliability. In other words, the costly plan has turned out not to be robust to future changes. Planning for a narrow vision of risk therefore may lead to stranded assets, budgetary lock-ins, and avoidable political tensions.

SEDAPAL is not alone in this approach. A complementary study to this report—referred to from hereon as the Global Study - (World Bank, forthcoming) finds that **climate resilience strategies are largely designed in response to the historical manifestations of a single type of disaster.** The traditional approach to climatic event risk has been to take statistical recurrence of past events for a single type of disaster, determine the plausible impacts of that risk overtime, and based on the identified level of risk, plan to maintain the impacts within an acceptable limit. Yet, droughts and floods are already by definition rare events and therefore occur infrequently in existing historical records. Due to climate change, relying on historical climate data for designing investments can lead to catastrophic outcomes. In fact, climate change may cause new and different risks to occur in combination. The greater the number of risk factors that occur simultaneously, the more uncertain and potentially serious the impacts will be. Therefore, utilities that are vulnerable to multiple factors are at the greatest risk, will have to implement the largest number of mitigation measures, and will benefit most from planning for and considering multiple future scenarios.

Moreover, the Global Study finds that most WSS utilities separate crisis responses and master planning efforts (World Bank, forthcoming). Many utilities have put in place emergency plans to manage disruptions from both extreme events and other system shocks (e.g., how to recover quickly from disruptions). When available, best practices to manage disruptions from extreme events and other system shocks include, for instance, identification of the most critical and vulnerable elements of the system, ensuring that they never fail, and contingency planning in case they do fail. For instance, many utilities rely on conjunctive water use and withdraw emergency groundwater volumes when rainfall is scarce. But in the face of new and more serious stressors, traditional, reactive, narrowly focused plans may no longer suffice. These types of emergency response measures must therefore be integrated from the onset in master planning, so that the decisions made by the utility already account for potential disruptions, are less vulnerable to them and can recover more quickly.

Moreover, partly because of the need to combine short- and long-term pressures, **climate change cannot be dealt with in isolation from other threats.** Specifically emphasizing climate change can bias the focus on future decades when near-term choices are in fact critical, not only for short-term service provision but also to be better prepared for long-term changes. However, investments that enhance climate resilience often focus on increasing storage capacity, which requires the construction of large infrastructure that may remain stranded if climate were not as dry as predicted. Conversely, operational improvements in efficiency and demand management can substantially accrue benefits that delay or even fully avoid future major capital investments when managing climate change concerns.

1.3. Principles for Resilient WSS Services Planning

The picture laid out in the previous sections shows the importance for a shift in paradigm regarding the way WSS utilities incorporate uncertainty in their decision-making process to truly build resilient water systems. Business as usual is already failing service providers in LICs, and not only because the climate is changing. **WSS utilities must mobilize new solutions**. Although all new investments should consider resilience, utilities do not always have the financial ability to diversify water sources or invest in larger drainage canals or in a second water treatment plant. Planning for resilience is an opportunity to manage the trade-offs utilities face.

First, **to preserve an efficient service delivery, water utilities need to shift from a mostly reactive plan, to a mostly proactive set of actions that combine preparedness, emergency responses, efficient operations, and longer-term capital investments**. Proactive sets of actions should include both near term choices (e.g., reducing leaks; improving financial stability; optimising the system's operation; providing incentives for efficiency gains, operation and maintenance, or improved metering; and demand monitoring) and longer-term choices, such as infrastructure measures. An ongoing World Bank study with Lima's water utility SEDAPAL shows that when aiming to increase resilience to future droughts, adding storage alone will not secure an acceptable level of reliability, despite the large upfront cost. Instead, actions like continuing to invest in losses reduction and establishing measures to curtail demand effectively upon activation of the first drought triggers are generally more cost effective and easier to get consensus on. (Kalra et al. 2015). To avoid maladaptation and a bias on future decades, it is critical to avoid falsely assuming that short-term operational choices do not have an impact on longer-term reliability.

The U.S. Water Utility Climate Alliance (WUCA)[4] is working toward the integration of near- and long-term choices when addressing the issues that a utility may face. These issues could range from excessive debt, stranded assets, overdependence on technology, or additional storage versus valuable institutional changes such as pricing, demand management, or regional cooperation. WUCA defines “no regret” for water utilities as those strategies that provide benefits under current and potential future climate conditions. They are those strategies that reduce current stressors while making the utility more resilient to future changes (Heyn and Winsor 2015).

WSS utilities should favor a flexible, dynamic approach that helps avoid lock-ins. Because of the large uncertainty related to future conditions, it is wise to avoid investments that may lead to lock-ins. The most robust strategies are the most flexible and adaptive. A water utility’s climate plans will evolve over time in response to new information. When building a map of how a utility’s planning efforts will navigate many possible futures, planners must contemplate if actions are irreversible and if they can be connected across time. Many low-regret short-term actions (e.g., conservation incentives, self-insurance, pricing, and maintenance) are reversible and easily paired with challenging capital-intensive projects. In some cases, these capital-intensive projects can be eliminated because of the successful implementation of low-regret short-term interventions. Flexibility is crucial to avoid overinvestments and stranded assets, and it helps more efficiently allocate the available budget across a utility’s priorities. Flexible strategies help avoid the frequently high cost of unplanned learning: when organizations respond to events as they occur but devote little attention or resources to understanding how to make the learning process more durable and effective (NRC 2009).

Building demand management and capacity flexibility into the water utility is critical for improving robustness and resilience, particularly when future conditions are difficult to predict. Gaining efficiency first and delaying investments builds flexibility and resilience. When a utility is vulnerable to a threat—whether because protection is too expensive or not feasible for any other reasons— knowing it early allows utility actors to monitor the situation and respond on time (and efficiently) if the threat ever materializes.

1.4. New Methodologies Are Available to Help Decision Makers Make the Right Choices and Manage Unavoidable Trade-Offs

To deal with these new challenges, utilities need a robust decision-making framework to increase their resilience while dealing with the deeply uncertain changes in current stressors and new failure mechanisms brought about by climate change. The guidance in this document builds on state-of-the-art methodologies, referred to as “Decision Making Under Deep Uncertainty” (DMDU[5]). These approaches are increasingly being used in planning exercises around the world, and water utilities are sometimes at the forefront of associated innovations. A World Bank guidance note on the application of these methodologies, the Decision Tree Framework (DTF), was also published in 2015 and has been applied in several projects focused on water utilities and water resources management.

(Ray and Brown 2015) The objectives are to identify trade-offs among strategies, identify robust options and provide decision makers with clear, transparent information. Moreover, the methodologies advocate for a heavily participatory process, which helps build consensus. In the end, decision makers can make consensual, informed choices.

DMDU's key concept to improve the resilience of water utilities is to shift the focus from seeking highly precise predictions towards discovering future consequential scenarios. Planning for multiple scenarios avoids costly surprises and helps reach consensus. People can agree on a strategy or a project for different reasons. Exploring different futures enables the inclusion of all possibly diverging views of what the future may look like. This helps avoid gridlocks and leads to a better understanding of how to prioritize those beneficial actions across plausible futures.

To build consensus on prioritized portfolios of actions, stakeholders must explore the consequences of candidate actions carefully for a diverse suite of metrics, or ways to measure a project's performance (e.g., cost, reliability, equity, and resilience). For instance, a city may prioritize equity, a utility may prioritize reliability, and nongovernmental organizations (NGOs) may prioritize environmental impacts. If the resilience-enhancing process considers all three measures and transparently presents the trade-offs, the three entities will have an informed dialogue to find a compromise. In some cases, they may find that certain options perform better than expected across all three metrics.

Developing robust projects or strategies that augment a utility's resilience requires carefully defining diverse metrics for success and failure, considering several alternative options, and assessing the performance of these options under many possible future conditions. The most robust strategies perform well (although not necessarily optimally) under a wide number of future conditions—and can include all stakeholders' views on what the future may look like (and according to several metrics of success)—and therefore create the largest consensus.

These methodologies are proven and applicable. The sector is gaining some experience in how to approach the challenges of climate change and managing trade-offs under uncertain future conditions. The World Bank (forthcoming) compiles emerging responses to climate change through identification of good engineering practices and case studies of 20 cities from around the world. Within the World Bank, the DMDU approach is being implemented in an increasing number of projects (see box 1.2). In the Water Global Practice, this approach has been identified as a powerful tool in Danilenko, Dickson, and Jacobsen (2010). They suggest that WSS utilities should use robust DMDU approaches to choose between available strategies to adapt to climate change.

Danilenko, Dickson, and Jacobsen (2010) do not dive deep into how urban water utilities can apply these approaches. This road map operationalizes their work. It details a three-phased approach that water utilities can follow when they plan for resilience and robustness.

BOX 1.2. World Bank Projects Using Decision Making under Deep Uncertainty Principles

Mozambique Rural Road (IN PAD OF P158231). DMDU principles were applied to a road network model. The model was used to prioritize roads based on criticality and flood risk and to identify robust interventions on these roads given uncertainty on future flood risk and vulnerability, costs, and traffic. Working paper in preparation.

Cutzamala Project, Mexico (forthcoming). DMDU principles were applied through the DTF to evaluate the vulnerability of the water system to climate and demand changes, especially regarding its ability to deliver water to Mexico City, and identify options to address this vulnerability.

Mwache Multipurpose Dam, Kenya (2016). DMDU principles were applied through the Decision Tree Framework (DTF) to assess the performance of the project under the effects of climate change. Alternative demand and supply management options to mitigate long-term risks and inherent trade-offs to identify robust adaptation options were evaluated.

Sacmex, Mexico City (under final revision). DMDU principles were applied through the DTF to develop a proper accounting of water inflow and outflow in Mexico City using a lumped model that distributes water available from all sources to each *delegación* to explore the sensitivity of the water allocation (and associated aquifer abstraction) to decreases in water available from the Cutzamala system.

Evaluating SEDAPAL's Investment Plan to 2040, Lima (2015). This study serves as an example of application throughout this document and allowed the *Superintendencia Nacional de Servicios de Saneamiento* (SUNASS), Lima's WSS regulatory agency, to confidently (and contrary to many people's expectations) approve the first tranche of no-regret investments of the SEDAPAL master plan (Kalra et al. 2015).

Preparing for Future Droughts in Lima, Peru: Enhancing Lima's Drought Management Plan to Meet Future Challenges (forthcoming). Building on the preceding study, the World Bank supported SEDAPAL in reviewing the performance of its current drought management plan under uncertain future conditions. It finds that it is extremely important to continue investing in efficiency measures now, before considering extra storage capacity, which will help only if the climate were to become much drier than current conditions.

Upper Arun Hydropower Investment Project, Nepal (2015). DMDU principles applied through the DTF to evaluate the robustness to climate change of design options for the Upper Arun investment. The study per se was not directly adopted by the government, but, following engagement during the course of the analysis, the International Finance Committee (IFC) has asked for a similar study of another dam (Bonzanigo et al. 2015).

box continues next page

BOX 1.2. continued

Addressing Climate/Disaster Risks of Multi-Modal Transport Network in Vietnam (ongoing). Network criticality and the DMDU approach are being used to assess the climate and natural hazard vulnerability of the national transport networks, including roads, railroads, and inland waterways. The project will identify the most robust intervention to increase resilience. The underlying model will be integrated into an open source tool deployed to the Ministry of Transport in Vietnam.

Dar es Salaam (2017–18). DMDU principles were used to identify the drivers of future risks for the urban transport network and to prioritize interventions to increase the resilience of the Bus Rapid Transport.

Lake Victoria (2017–18). DMDU principles were used to test the sensitivity of port infrastructure and lake transport operations to changes in Lake Victoria levels, and to identify adaptation options.

Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors (2015). DMDU principles are used to evaluate the impacts of climate change on hydropower and irrigation expansion plans in Africa's main rivers basins (Niger, Senegal, Volta, Congo, Nile, Zambezi, Orange) (Cervigni et al. 2015). *Shock Waves: Managing the Impacts of Climate Change on Poverty.* DMDU principles are used with others to calculate the impacts of climate change on poverty by 2030 and the main drivers of these impacts (Rozenberg and Hallegatte 2015).

Notes

1. Several of the following paragraphs rely at times verbatim on World Bank (2017b).
2. See the RAND website for more information, https://www.rand.org/jie/infrastructure-resilience-environment/centers/water-climate-resilience/projects/louisiana-coastal-plan.html.
3. A type of failure (of a component or function) that has no effect on the system's ability to reach a safe state.
4. In January 2007, the San Francisco Public Utilities Commission hosted the first national Water Utility Climate Change Summit, attended by more than 200 water and wastewater utility executives, government officials, climate change experts, and environmental leaders. The purpose was to help participants better understand the impacts of climate change on water-related infrastructure and water resources. Shortly after the summit, WUCA was formed to provide leadership and collaboration on climate change issues affecting U.S. water agencies. The organization comprises 11 of the nation's largest water providers. WUCA members supply drinking water to over 50 million people throughout the United States. Its mission is to collaboratively advance water utility climate change adaptation. Today, WUCA is dedicated to enhancing climate change research and improving water management decision making to ensure that water utilities are positioned to respond to climate change and to protect water supplies. See WUCA's website, www.wucaonline.org.
5. See the DMDU Society's website, www.deepuncertainty.org.

Chapter 2

Three Phases to Improve WSS Utilities' Climate Resilience

Each utility faces its own challenges and will be affected by context-specific climate change impacts and other risks. The portfolio of solutions available for increasing water utilities' robustness and resilience includes capital, financial, institutional, socioeconomic, and operational measures. Some measures, particularly those that improve the overall efficiency of an agency, would also help address climate-related risks because they increase the utility's overall health—and hence, its ability to deal with crises. Such measures indeed set the foundation of any further effort to build resilience. For those utilities that access finance from the markets, the stability of financial debt payments is crucial for the resilience of a water utility. Unfortunately, its effects on a utility's ability to reliably sustain the required level of service are often ignored.

Water utilities need to prioritize robust investments specific to their context. Not all possible solutions may be needed or available to all utilities, and the budget, or political priorities, may constrain the final choice(s). The three phases defined in the following methodology help guide the prioritization of actions to increase the robustness and resilience of an urban WSS utility to future changes, in line with DMDU methodologies (see box 2.1).

Phase 1: Knowing the system. The process starts with participatory work in which an extensive team (including planners, operators, other stakeholders) identifies the problematic and critical elements of the system, the potential threats that may affect these elements and the consequences of their individual or joint failure, the performance objectives the utility wants to achieve, and the available solutions. This scoping identifies tools, data, and models to be used in the subsequent phases.

Phase 2: Identifying vulnerabilities. Next, analysts (internal experts or external consultants) use the information gathered in Phase 1 to stress-test the water system over a range of plausible futures and assess its performance under different conditions. This is done first for the system as-is (status quo) and then for the different possible solutions, and their combinations. Performance is measured against the objectives defined in Phase 1. The stress-test results in a concise description of the conditions most likely to cause the utility to fail to meet one or more objectives. These conditions are often summarized as scenarios that describe the combinations of factors that yield success or failure. Analysts also identify options that reduce vulnerability and improve the performance of both the system as a whole and of critical elements over the same range of futures.

Phase 3: Choosing actions. Analysts organize these options into potential robust, flexible strategies and examine the trade-offs among them in meeting the agreed objectives under the scenarios identified in Phase 2. The options should include careful monitoring for conditions of concern (i.e., tracking if the system is moving outside of the scenarios in which performance is acceptable).

BOX 2.1. Options when Choosing a Methodology

Multiple methodologies have been developed to stress-test strategies, and analysts must select those that are robust to deep uncertainties or adaptable to a changing future. A review of methodologies can be found in Herman et al. (2015) and Dittrich, Wreford, and Moran (2016). For instance, decision scaling (Brown et al. 2012) uses a weather generator to stress-test water projects against a wide range of future climate and hydrological conditions and adapt them so that they perform well in a large number of scenarios. Robust Decision Making (Lempert et al. 2004) also stress-tests strategies but combines climate conditions with socioeconomic conditions to identify the combination of factors that can make a project fail. Adaptation pathways (Haasnoot et al. 2013) look for tipping points in climate conditions that would make a project fail over time and propose pathways to adapt before the tipping point is reached. Multi-Objective Robust Decision Making uses emerging tools to better understand key trade-offs for different candidate actions as well as their robustness. It has been used to address a water agency's system and financial resilience, among other applications. For instance, it has been used to integrate long-term infrastructure investments, near-term operational strategies, and medium-term financial instruments (Herman et al. 2015).

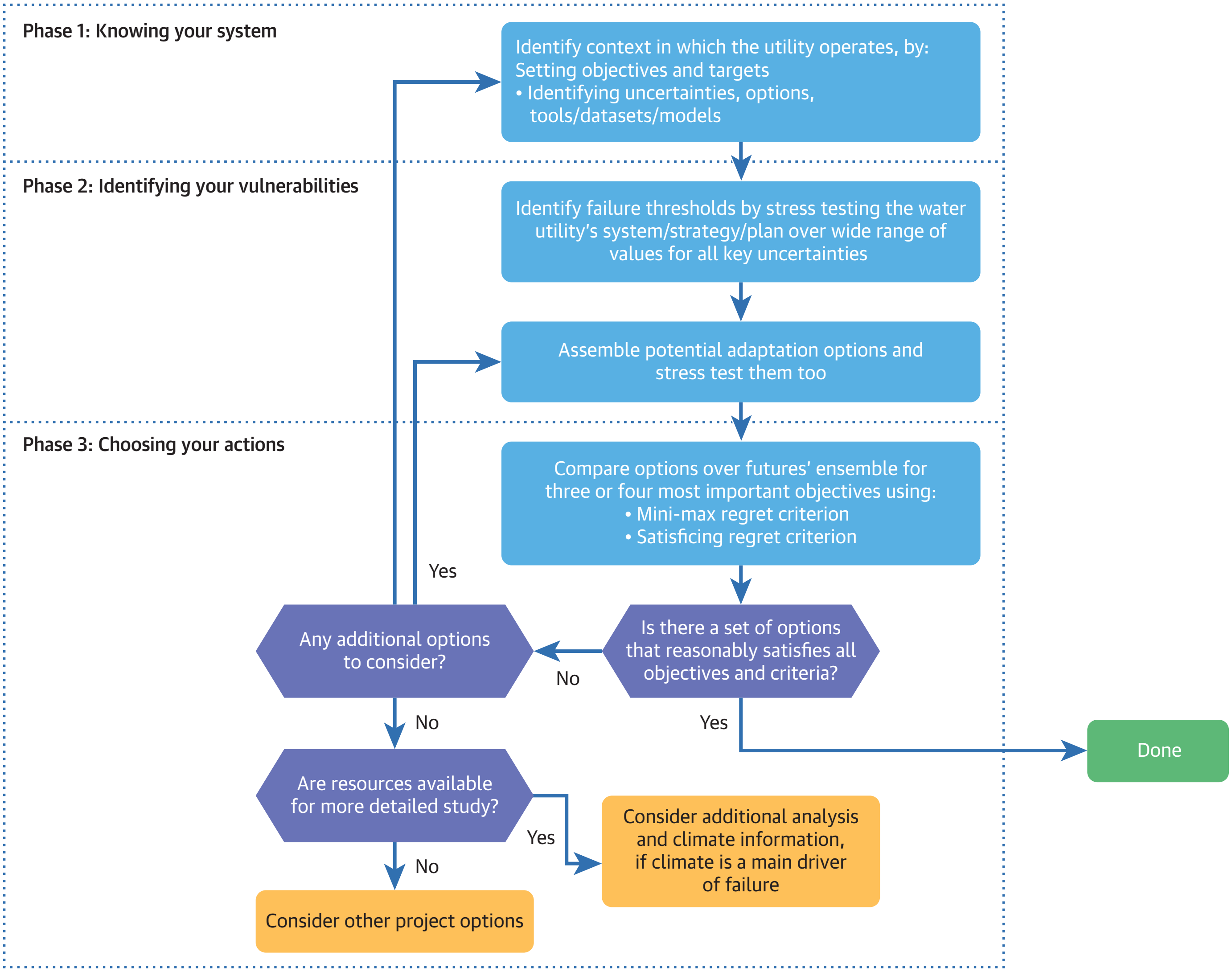
Depending on the importance of various factors, the complexity of the problem, or the resources available, one methodology can be more appropriate than the others. Most often, a combination of methodologies serves the client better than one methodology alone. It is important to maintain sufficient flexibility during the project to adapt to changing needs, which are bound to occur as the planning problem becomes better understood.

Future project leaders and analysts should be agnostic to the DMDU technique, embedding methodological exploration and development into the project budget and timeline, and seeking opportunities for drawing from multiple methodologies.

As an integral part of all these steps, analysts present current vulnerabilities, options, and trade-offs to other teams within the utility, the board, and possibly external stakeholders to define an acceptable, actionable, robust, and consensual road map. Depending on the complexity of the project, one or more rounds of participatory work is needed with stakeholders to refine the objectives or the threats, or to adjust the options available to decision makers.

These three phases are summarized in figure 2.1. Applying this process will help the WSS utility manager (or decision-makers) reconcile short- and long-term priorities, and make decisions to increase the utility's resilience, despite deep uncertainties about future conditions (be these related to climate, demand, or budget).

FIGURE 2.1. **Process: To Improve the Resilience of a WSS Utility**



Note: These phases are meant to be regularly revised. The idea is to update the plan regularly, as more information arrives and priorities shift. WSS = water supply and sanitation.

2.1. Important Considerations

Assessments are local, and one size does not fit all. Utilities across the world vary in size, capacity, and responsibilities. Though the level to which risk and uncertainty are considered in the planning process varies, each utility manages risks of failures in its own way and already has processes in place to do so. It is important to build on what operators and planners feel comfortable with, rather than introducing completely different systems. The framework presented here acknowledges that WSS utilities in different countries or cities will have diverse starting points, values, and approaches. Hence, it does not prescribe specific methodologies and models, but rather a suite of questions and available tools that would help plan for resilience. The choice of which tools to apply depends on the data and model availability, the resources available, and time constraints specific to each water utility and particular adaptation exercise. A brief review of different methodologies aligned with the steps proposed in this guidance document is provided in box 2.1 below. Though each has its specific focus, it is worth noting that they all advocate for stress-testing available actions, strategies and plans and selecting those that are robust and resilient to deep uncertainties or allow for enough flexibility to adapt to a changing future. In general, a combination of methodologies serves WSS utilities better than one methodology alone. It is important to maintain sufficient flexibility during the project to adapt to changing needs, which are bound to occur as both the water utility managers and the analysts better understand the problem at stake.

The **process** itself is also important. Historically, attention has often focused on choosing the right tools rather than implementing the right processes, leading to final decisions that may ultimately have been political. Promoting stakeholder participation and inclusion early on, by bringing the right actors on-board throughout the process, helps ensure that their views are included, their concerns addressed, and that the final result is an approved alternative for all key decision makers - and important stakeholders for the sector. The steps proposed in this document suggest a way to integrate more participatory elements with the purely analytical evaluation of the options to encourage a focus on the process as well as the new individual actions.

The process presented in this document can be applied at different scales, from utility-scale resilience to individual project-scale robustness. This document is designed to engage WSS utility managers on ways to ensure the utility as a whole increases its resilience in a robust way. However, the same process can be repeated at any planning stage, from system planning engagements to the individual project level, including to evaluate a combination of projects.

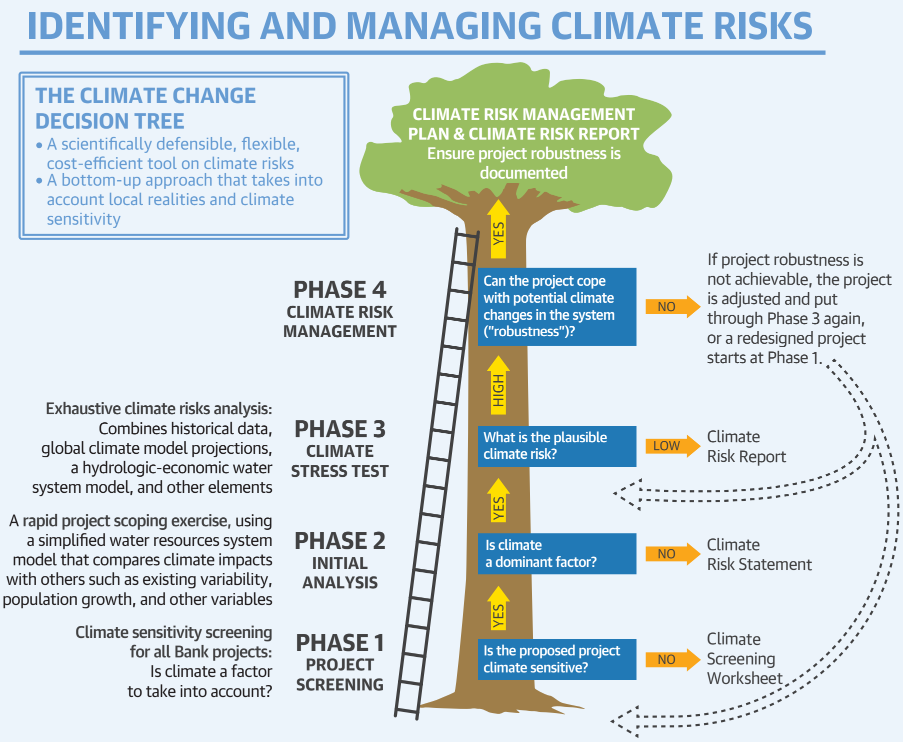
Because of the contextual specificities, these phases describe the basic components of the process. In detailing the process and its different phases, the present document provides an overview of the challenge and basic components of proposed solutions. This methodology can be applied widely, but its application will always be extremely context specific. A serious party willing to engage in this resilience-building process would have to invest time and resources to convert their areas of interest into specific analytical assessments, even if the process is only carried out in a qualitative way. Section 3 lists the skills necessary for a full assessment.

To accompany the reader through the three phases, the authors have chosen the example of a recent World Bank–SEDAPAL collaboration, in which the team applied the same process (Kalra et al. 2015). SEDAPAL approached the World Bank out of concern that its Master Plan to 2044, which includes 14 capital-intensive infrastructure options, did not include climate change considerations.[1] Box 2.2 describes the similarities between the methodology proposed in this document and the DTF.

BOX 2.2. The Phases' Correspondence to the Decision Tree Framework

The Decision Tree Framework (DTF) (Ray and Brown 2015) was developed in 2015 by the Water Global Practice at the World Bank to help task team leaders from all sectors evaluate the climate change risks for their projects and the tools needed for an appropriate assessment (which is compulsory for all projects) (see figure B2.2.1). It responds to a corporate mandate to screen all World Bank projects for vulnerabilities to climate change. The DTF focuses on a project-level assessment and provides a simple screening process to determine whether there is the need to proceed to a full climate risk management exercise, or if it is possible to exit the process at an earlier stage. It offers a series of concrete steps to address eventual climate change risks for a project. As requested at the time, the framework focuses on direct climate risks, and not climate as a potential risk multiplier (although in its application, other risks are usually considered).

FIGURE B2.2.1. Identifying and Managing Climate Risks



The DTF is organized in four phases of increasingly technical complexity: (i) climate sensitivity screening for all projects; (ii) rapid project scoping exercise; (iii) exhaustive climate risk analysis; (iv) and climate risk management. The process presented in this document is consistent with, and builds on, the DTF, but it customizes its principles to urban WSS utilities. This document recognizes that for most water utilities,

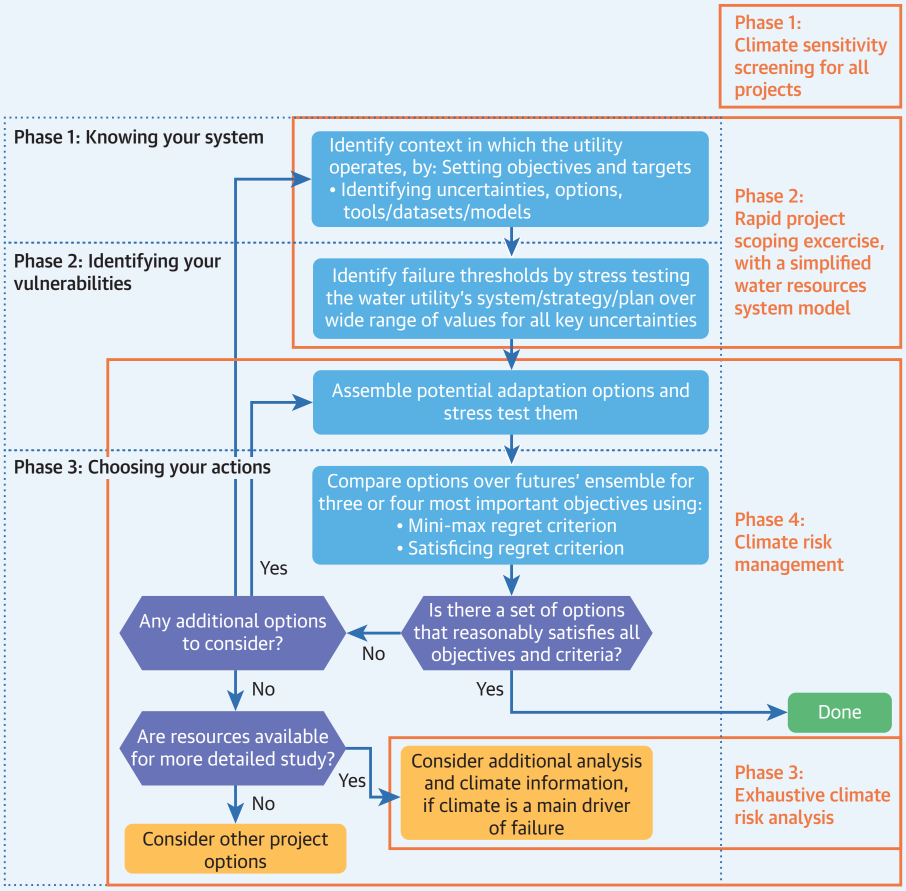
box continues next page

BOX 2.2. continued

climate change will be a risk multiplier: it should not be addressed in isolation, but through an integrated perspective of the utility's challenges and objectives. This document argues that from the beginning, a utility should evaluate all risks together, and then rank them, to design appropriate risk management solutions (as outlined in section 2.1). The two approaches (the DTF and the one presented in this document) build on the same Decision Making under Deep Uncertainty (DMDU) methodologies and analytical framework.

Figure B2.2.2 sketches general overlaps and differences between the DTF's phases (outlined in orange) and those proposed in this guidance document (outlined in blue dotted line). This guidance document skips Phase 1 of the DTF and assumes that all water utilities will be sensitive to climate change in some way and warrant a further deeper dive. Phase 2 of the decision tree is similar to Phase 1 of this document and aims to develop a better understanding of the context in which a utility operates. Although Phase 2 of the decision tree mostly focuses on climate change, the questions are similar

FIGURE B2.2.2. The Phases' Correspondence to Decision Tree Framework



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BOX 2.2. continued

to that of Phase 1 in this guidance document. Phase 2 of this document joins Phases 3 and most of Phase 4 of the DTF, by identifying the vulnerability of the current system and of possible options. Phase 3 of this document then supports the user in choosing the most robust strategy, which is the last step of Phase 4 of the DTF. The choice and prioritization of the options, when decision makers choose a course of action, is considered a key step and therefore deserves its own phase in this document. If climate is the main driver of the remaining vulnerabilities, and resources are available, the utility should invest in a deeper study on the manifestations of climate change in its region (Phase 3 of the framework offers a valid methodological approach for a deep climate change screening).

2.2. Phase 1: Knowing the System

The first phase of the analysis identifies the context in which the WSS utility operates and helps answer questions such as:

- What are the utility's objectives?
- What uncertainties may make it difficult to achieve them?
- What are the options for addressing these uncertainties?
- What tools, data and models are available to help address these questions?

This problem framing phase can be organized into four categories of concerns: (i) the utility's objectives and the metrics for evaluating the extent to which these objectives are met; (ii) the uncertainties that might affect meeting these objectives; (iii) the options available for managing these uncertainties; and (iv) the tools, datasets and simulation models that can be used to support the decision process. Lempert et al. (2003) organize these factors into a 2 × 2 matrix they call the XLRM matrix, in which *X* stands for "Uncertainties"; *L*, "Policy Levers"; *R*, "Relationship," i.e., data and models; and *M*, "Metrics"[2] (see box 2.5, figure B2.5.1 for an example of the matrix as applied in Lima).

This process is usually carried out through a one-day scoping workshop, which should convene all interested stakeholders. For this phase, planners should aim to be as inclusive as possible and avoid setting finite boundaries on the discussion, as the goal is to take all possible surprises and priorities that may jeopardize the achievement of a consensual and robust plan into account. This phase ideally occurs at the very beginning of the planning stage of a project or of the planning process for the utility.

2.2.1. Setting Objectives and Success Metrics

The initial rounds of discussion should define the objectives for the water utility and its service provision as the first step in the process. Often, the expected level of service to be delivered by a water utility is measured as service reliability. What is the acceptable level of service disruption? Does the utility need to ensure 100 percent reliability under all cases? Or is 80 percent sufficient while the remaining 20 percent can be covered by an emergency plan? What is an acceptable recovery time? Should it always be the same or does it depend on the type of disruption? Different objectives can be set at this stage, which can scope beyond the utility service. Other stakeholders may add their own priorities, for instance securing water for other uses, or safeguarding environmental flows.

Defining the objectives and targets for a plan or a project) is very context specific and always challenging. A good entry point for this discussion can be to define unacceptable failure scenarios, and to translate this definition into quantified thresholds associated with some metrics. For instance, a water utility may fail to fulfil its agreed targets if the treatment plant is out of service for more than 24 hours, or if the conjunctive water use system set up is not able to buffer the treatment plant's partial failure, so more than X percent of the city needs to be supplied by water trucks. In practice, the definition of "failure" can vary significantly across utilities, or even departments within the same utility. In the United States, utilities often define failures as getting close to the margin of safety unless it is a legitimate physical component failure, which directly and immediately impacts operation. Rarely do these failures lead to loss of services over prolonged periods. In other places, like Lima, it is normal to assume the sporadic loss of water resources leading to the need to hedge with local storage tanks, emergency groundwater withdrawals, or other options. This flexibility with the concept of failure allows planners to define the reliability objectives that most suit their context and to explore specific solutions.

One important advantage of the proposed approach is that people do not need to agree on a unique criterion (say for example a cost-benefit ratio). The objective of this phase is indeed to identify several metrics, which is helpful as utilities have multiple objectives that cannot be easily incorporated into a single metric. The list of criteria may for instance include reliability, affordability, social and environmental considerations, the utility's financial sustainability, acceptable level of service, or overall cost.

Different aspects of the same criterion can and should also be considered. For instance, stakeholders may have different opinions on what reliability means. These can all be included in the analysis. Through the planning process, stakeholders can understand more explicitly how assuming different levels of service to meet demand changes the parameters of failure and fundamentally shapes the perceptions of needed capacity investments. For instance, accepting low levels of service for a short duration, where active conservation measures can be employed, can substantially reduce the need for major capital investments.

In this initial discussion, flexibility must be integrated into the result metrics. For instance, having an ambitious target of 100 percent reliability can be extremely costly and lead to overinvestment. A more flexible target could aim for 80 percent reliability and put in place a contingency plan for the remaining 20 percent. It is important to consider whether metrics distinguish easily reversible from irreversible failures. For example, multiple small violations in a factor of safety threshold (e.g., dropping below 25 percent active storage) may be readily addressed through demand management. The design and implementation of investments should be entirely driven by these objectives. Building in flexibility to adjust targets when unforeseen events happen helps ensure the continued tracking of these objectives and contributes to the robustness and resilience of the utility under a broad array of challenging circumstances.

2.2.2. Cost and Benefit Metrics and Financial Risk Measurements

When identifying metrics, planners should avoid solely focusing on the average balance of expected cost and benefits. Instead, these measures could be complemented by other metrics representing, for example, financial impacts (e.g., debt balances, see box 2.3), or distributional impacts (e.g., what parts of the city benefits the most from the project). Given their long-term nature, water utility climate change adaptation planning efforts should also carefully document the effects of discounting[3] when evaluating impacts of concern.

BOX 2.3. Financial Stability

Though the stability of financial debt payments is crucial for the resilience of a water utility, this issue is often ignored. Financial stability is particularly important for utilities that plan to secure financing from commercial banks for service expansions. The ability to obtain commercial finance is key to the longevity of a utility since it ensures funding sources that are not dependent upon guarantees from multilateral finance institutions or other soft financing.[a] Most of the factors at play in determining a utility's creditworthiness are within the financial control of the utility, with some exceptions.

Although the institutional structure for water utility financing can vary significantly across global contexts, they all share the challenge of providing seriously capital-intensive services. Annualized debt payments and financial ratings can significantly shape access to financing for investments and ongoing support for operation and maintenance (O&M). The financial implications of extreme floods (loss of capital investments, migration, stability of crises management, or insurance costs) and droughts (revenue losses from restrictions, volatile source water pricing, emergency capacity expansions, water quality and network pressure failures, or costs of financial self-insurance) must be explored and measured. It is worthwhile to track the volatility and variability of revenues beyond average annual financial debt payments. Rare but plausible swings in revenue (e.g., worst 1 percent of annual revenues distribution) are difficult to manage and warrant risk mitigation strategies. Measures that can help maintain the stability of financial debt payments include self-insurance, index insurance, drought surcharge, or tiered pricing structures tied to restrictions, among other financial instruments.

a. Soft financing: financing with no interest or a below-market rate of interest and lenient terms often offered to developing countries.

The government may need to approve additional funding requests, or donors may also be interested in nonmonetary impacts, such as environmental, social, or health impacts of certain investments, or distributional impacts, such as the project's impact on a variety of users.

The vulnerability analysis should includes an objective focused on an economic metric, which integrates climate and non-climate variables into either a cost benefit or cost effectiveness criterion. By integrating economic variables, the combination of uncertain factors that could make the option(s) nonviable can be identified and the option(s) modified accordingly to reduce these vulnerabilities. Such integration allows planners to design the project(s) and complementary social or environmental interventions in parallel. Often, the negative social and environmental impacts are estimated once the decision on a project has already been made and the conversation focuses on deciding how to compensate for them and whether the residual impacts are acceptable. Instead, planners can use this integrated approach to include these impacts in the decision-making process, which allows the design of a more flexible solution from the start.

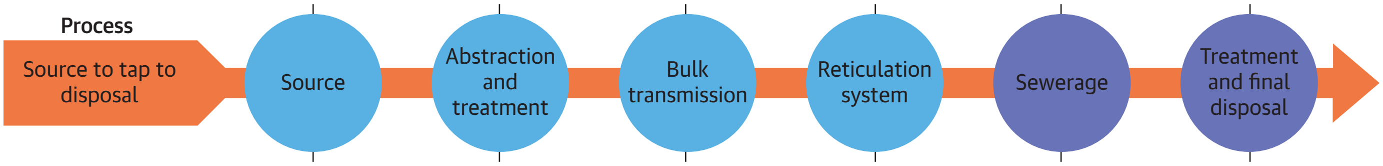
An analysis that tracks multiple metrics simultaneously makes it easier to add specific actions or to adjust project design to correct for negative outcomes. For instance, stricter water quality regulations may have negative impacts on industries in the area and may become socially acceptable only if accompanied by complementary actions to incentivize the installation of better treatment plants in these industries.

The concepts of success and failure should therefore be as broad as possible, much beyond the common measure of level of service, to include possible unintended side effects. Inclusive and transparent tracking of multiple metrics aids consensus building. It also facilitates a common understanding of the train of logic that informs planning choices, which is useful for the reproducibility of analysis and to identify the provenance of concerns.

2.2.3. Identifying Uncertainties

During the initial discussion, the extended team should identify the main (near- and long-term) causes of possible failures in the water system. The definition of the sources of uncertainty is one of the most critical inputs in the process. This step can include both threats (e.g., increase in demand, contamination, or natural hazards) and opportunities (e.g., increase in water availability) that the current system would be unable to deal with. All threats, including those that cannot be easily mitigated or that seem unlikely to materialize, should be identified and discussed with stakeholders at this stage. Discussion can be driven by a simple schematic of the WSS system (see figure 2.2) (World Bank, forthcoming), but must look beyond the infrastructure to include the institutional, operational, and financial aspects. The list of uncertainties should be very comprehensive at this stage. This list of uncertainties typically includes at least water availability and quality, costs and economics, demand, socioeconomic context (including how people and firms would accept interruption of services), and feasibility considerations. As part of Phase 2, the initial factors to be carried forward in the analysis will then be identified among this broader list.

FIGURE 2.2. Schematic of a WSS System



Note: This diagram is limited only to the infrastructure side. It is advisable to include also the operational, institutional, and (for some utilities) financial aspects. WSS = water supply and sanitation.

2.2.4. Identification of Possible Options

In the initial round of discussions, planners should identify options and alternatives to manage the uncertainties identified. These options can be policy decisions or levers (e.g., water quality regulations), infrastructure projects (e.g., reservoirs and pumping stations), or operational measures (e.g., monitoring systems, tracking rainfall or system losses). At this stage, it is important to consider and evaluate novel combinations of proactive actions that integrate preparedness, emergency responses, efficient operations, financial stability, and longer-term capital investments. Drawing knowledge from the different teams within a water utility, and even from external actors, helps broaden the scope of options considered to include more transformational or less traditional actions, such as the use of green infrastructure instead of traditional "hard" infrastructure (World Bank 2018).

When the possible investment has already been identified (e.g., the project is a new reservoir to cope with water scarcity), then possible alternatives should include different design options for that specific project. It is also important to include options that can be reversed, such as pricing and demand management, or setting the foundations for possible future enlargements: these options will make the portfolio of investments more flexible to changing future conditions. One of the main advantages of DMDU methodologies is that they help select and sequence these investments to build the resilience of the utility while avoiding budgetary lock-ins and stranded assets.

Box 2.4 and appendix C provide an initial list of possible options, categorized by type (e.g., operational or capital solutions) for dealing with different climate impacts based on good engineering practice and case studies of utilities around the world (World Bank, forthcoming). The list can help guide the initial discussion on available options and be complemented according to stakeholders' knowledge of the context. When discussing available options, participants should think, for instance, of their feasibility, the implementation time, their cost and possible externalities. Having information on these qualitative attributes for the selected options enriches the discussion of trade-offs in Phase 3, which includes performance considerations.

BOX 2.4. Options to Increase Resilience in WSS Utilities

This box introduces a noncomprehensive list of options, based on a global assessment of select water utilities across the globe. The global assessment identifies five broad categories of robustness and resilience building measures: capital, socioeconomic, institutional, operational, and financial. A more detailed list of options can be found in appendix D, table D.1. However, this list of options is still not exhaustive (World Bank, forthcoming).

Some measures, particularly those that improve the overall efficiency of a utility, address all climate-related risks and set the foundation of further efforts to build resilience. Ideally, utilities will provide high-quality WSS services at the lowest cost to consumers necessary to maintain that level of service. Other measures are hazard- and location-specific: clearly, an inland water utility is not concerned by sea level rise. Importantly, each WSS utility faces its own challenges and will be affected by context-specific climate change impacts (one, or multiple) and other uncertainties. Therefore, planners must select the combination of measures that will most impact their organization.

Capital measures are typically the costliest. These measures tend to consist of significant interventions such as new infrastructure construction and large-scale rehabilitation of assets. As such, capital measures are frequently organized in order of importance or efficacy for the specific utility. Frequently, a master plan is developed by the utility in collaboration with external engineering consultants. This can be a straightforward method to plan activities and identify sources of funding prior to undertaking a large-scale project. The major upside to capital measures is that they can impact the functionality of the utility for years or decades to come, essentially constituting a permanent solution. At the same time, if incorrectly designed or part of a poor planning process, they have locked in significant funds that could have been better used elsewhere.

Socioeconomic measures may include smart metering or educational outreach campaigns for the community, integrated water resources management, or setting up water trading systems to deal with growing demand. Such measures may be particularly impactful in areas with recent access to new types of infrastructure which may be used inefficiently by their residents. T As they rarely rely on the construction or repair of infrastructure, these measures tend to be among the least expensive options. This category also includes social protection and compensation. Indeed, it is sometimes cheaper to compensate farmers for lost production than to provide them with the water they need to save that production. Schemes through which high productivity users (e.g., urban users) are given priority and low productivity users (e.g., small farmers) are compensated can also be explored.

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BOX 2.4. continued

Institutional measures are another type of soft intervention available. Activities may include changing design standards or coordination among multiple governmental entities to align efforts and maximize results for uncertainty mitigation. Though scheduling and agreeing to actions may be challenging across multiple organizations, it is not necessarily expensive since regulations, thought products, and new approaches are the typical outputs from institutional measures. In addition, new or modified regulations can be a very cost-effective approach to improving utility operations.

Operational measures are essentially the day-to-day tasks of the utility. These include operating infrastructure and performing regular maintenance and repairs, as well as commercial activities. Modifications to the status quo can often have significant impacts on many aspects of a utility's operations. For example, developing a regular leak detection schedule could help reduce nonrevenue water and decrease the amount of water wasted while also increasing the efficiency of the utility's billing. If operational changes are implemented and maintained over time, they can be just as effective as capital projects. Water utilities vary among cultural contexts in terms of expected operational reliability and level of service. In LICs, care should be taken when defining operational measures so that the attainable levels of service and reliability of their water services increase over time.

2.2.5. Identification of Tools, Dataset and Models

The final activity in Phase 1 is the identification of available data and models that can be used to assess the performance of options under future conditions. In many cases, the project analysis can be done using existing tools and models. DMDU techniques will use these tools and models differently, but they seldom require the development of new tools. For instance, analysts using the DMDU method to evaluate a utility's resilience to future changes will use water system planning models, such as the Water Evaluation and Planning System (WEAP) and historical hydrological data: the same tools used for a traditional analysis. However, the model structure may not allow an adequate representation of the infrastructure's operations, potential levels of water abstractions or ensemble simulations of diverse uncertainties. Therefore, a careful evaluation is necessary to assess which aspects identified in this phase the model can capture. The scoping exercise must identify the tools that can be made available to the analysts' team, whether they include models, data, or pre-existing knowledge of the system, which is often the main source of information available in LICs.

In some cases, data or models will not be available. The utility may not have invested in the development of a water supply operations and planning model. In some cases, the processes under consideration may be too difficult to model, for example, the impacts of reforesting an upper watershed on water quality and availability downstream. Globally, many regions are strongly limited by the scarcity of data or the expense that collecting good data represents. Task teams must decide if they want to allocate resources to develop the required models and collect data or manage without them, meaning that more variables would remain uncertain in the decision-making process, or the analysis would be more qualitative. The result of this first phase can be organized in a matrix that summarizes the results of the problem-scoping work (box 2.5). This matrix will be used as a basis for the analytical work to be carried out in Phase 2.

BOX 2.5. Phase 1: Scoping of a Problem with SEDAPAL, Lima

After the scoping workshop, the team reduced its long list of possible priorities to the elements that could be modeled and the metrics that mattered the most to the client. The objective was for the water utility *Servicio de Agua Potable y Alcantarillado de Lima* (SEDAPAL) to provide reliable water supply to Lima by 2040. The options available were 14 different infrastructure projects. The threats identified were climate change, fast demand growth, budget availability, and political infeasibility of some of the components. The tools and data required for the project were a WEAP model, with which the team assessed the performance of the system, and an interactive decision tool for the water utility to evaluate their options. At the beginning of the collaboration, SEDAPAL did not have an up-to-date and comprehensive model of its system. The interactive decision support tool was developed over the course of the project as a useful way for SEDAPAL and external stakeholders to access the results of the study and use it for future planning exercises. (Kalra et al. 2015)

The objectives and metrics for success were defined during several meetings with SEDAPAL. Figure B2.5.1 presents a matrix summarizing these elements. For instance, currently they are able to meet about 80 percent of the current daily demand on average. After different iterations, they decided that meeting 90 percent of the demand at least 90 percent of the time, thereby allowing for some variation in the supply, was a satisfactory performance.

FIGURE B2.5.1. Metrics Used with SEDAPAL

Uncertainties/Threats	Options
• Future water demand • Future stream flow • Project feasibility	• 14 infrastructure projects • Available budget for infrastructure • (Efficiency and demand management)
Models and data	**Metrics**
• WEAP model • Interactive, analytic decision support tool	• Objective: no service interruption longer than 24 hours • Cost of plan relative to the initially planned investment cost

2.3. Phase 2: Identifying Vulnerabilities

Using the key factors identified in Phase 1, the project team now identifies the specific future conditions in which the utility would meet and miss its objectives. This is accomplished by stress-testing various options over a wide range of uncertainties. Stress-testing can range from exploring a few qualitative scenarios to detailed modelling of thousands of scenarios when teams have sufficient modeling and data capabilities. During the stress-test, uncertainties are jointly sampled to create hundreds or thousands of scenario worlds. Next, the metrics of interest are computed within and across these scenarios for the portfolios of actions being considered. These stress-tests help to answer a series of specific questions:

- What are the critical elements in the system?
- How do the selected options perform across a wide range of potential future conditions?
- Under what specific conditions do these options fail to meet decision makers' goals?
- Are those conditions sufficiently likely that utility managers should choose a different option?
- What are the options' trade-offs between meeting the goal and their performance on other metrics (e.g., cost, impact on other users)?

In this phase, it is helpful and appropriate to use the current utility management approach - or the status quo or 'no project' option - as the comparative baseline against which the proposed actions are evaluated and justified. Using the status quo as a comparative will also provide an understanding of how the system as-is would perform in different plausible scenarios. Since this process is iterative, the utility may have developed new options in Phase 3 and find it helpful to return to Phase 2 to stress-test these options.

To realize the stress-test, Phase 2 includes two main sets of actions: (i) the identification of critical elements and the development of plausible futures, and (ii) the characterization of vulnerabilities. These are described in more details in the rest of this section.

2.3.1. Identification of Critical Elements and Development of Plausible Futures

First, analysts and utility experts identify the **critical elements** in the system: these are the elements for which failure would lead to the worst consequences. For the identification of critical elements, a utility should consider all the assets and resources whose failure could affect service delivery. Identifying the critical elements (and, consequently, the nonessential or redundant elements) is a first step toward the development of robustness-enhancing alternatives. The system diagram in figure 2.2 can be a useful starting point. Traditionally, utilities have carried out such exercises to rank the different system elements in terms of their criticality, but they generally focus mostly on what would happen if one element of the system failed. The Basin Organisation of the Mexico Valley, the organization in charge of supplying 25 percent of Mexico City's water, carried out this exercise to prioritize the use of its limited maintenance budget. Analysts assumed the total failure of the individual elements of their systems and the consequences that may have to the delivery of water to the city. It is also important to test partial and combined failures. The rest of the analysis may then focus on increasing the robustness of the identified elements to augment the overall resilience of the water utility.

In parallel, analysts and utility experts identify the magnitude of the uncertainties identified in Phase 1 through a range of possible high and low values or qualitatively come up with best- and worst-case scenarios. For instance, different demand growth scenarios indicate a range between 0 percent and 100 percent change from today's demand by 2030; and global circulation models (GCMs) predict a range of negative 40 to 40 percent precipitation change from historical trends. There is disagreement on the discount rate, so the team picks a range from 6 percent to 12 percent. Based on the ranges, analysts **develop multiple cases, or plausible futures**, which are combinations of uncertainties, within the bounds of these ranges. The system will be stress-tested using these plausible futures. For instance, each case will contain a certain demand, an assumption on precipitation, and an idea on institutional feasibility. The cases are artificial states of the future world, designed to stress the system; at this stage, no explicit consideration of their probability is needed. Developing cases to stress-test the options has the added advantage of filling data gaps, a frequent problem for utilities in LICs. This methodology does not pretend to draw probabilities from faulty or inconsistent data, but to develop credible scenarios that would help identify the breaking points of the options.

2.3.2. Characterization of Vulnerabilities

Once the critical elements have been identified and the uncertainty ranges have been developed, there are two general ways in which a utility may conduct the vulnerability analysis proposed here: through modeling or through qualitative techniques (or a combination). The former provides more comprehensive and quantitative results but may be harder to implement. Both approaches have the same goals and can produce useful results.

When models are available—or resources are available to develop them—analysts use them to evaluate the performance of each option for many futures by running the model for each generated scenario. Based on the ranges, analysts develop hundreds of cases.[4] Sometimes the model runs hundreds or thousands of scenarios to ensure the uncertainty space is well sampled and a sufficiently broad assessment of vulnerabilities is possible. In other contexts, for instance when facing resource constraints, carefully considering a few dozen futures may be appropriate. A model does not always need to be very complicated, but the team needs to be aware of its limits: critical elements may be missing. To avoid this, the model runs can be complemented with nonmodeled or qualitative information and narratives.

This analysis results in a database. Each record in the database includes the model inputs, representing the uncertain future conditions, and the model outputs, representing the metrics for each option, in addition to any qualitative information. Analysts may then apply data visualization or statistical classification algorithms (often called "scenario discovery" algorithms[5]) to the database to identify the combinations of a small number of the uncertainties that best distinguish the futures in which the options meet and miss the objectives.

The resulting clusters of futures represent scenarios that can be used to understand and communicate the utilities' potential vulnerabilities. The combinations of uncertainties that describe the scenarios represent the driving forces of success or failure. For instance, such an analysis might suggest that a dam can fail to meet its reliability objectives (as listed in the matrix) if average annual rainfall decreases more than 20 percent and water demand increases more than 10 percent. Thus, these two conditions are the key driving forces of the dam's vulnerability scenario. Other uncertainties (e.g., construction time or discount rate) are less critical to the dam's vulnerability.

This process provides a quantitative answer to the question of which combinations of uncertainties are real threats that will likely / status quo cause failure. In several past cases, some very credible threats were found not to matter as much as expected, while issues that were not considered initially could threaten the project or service (see example from SEDAPAL in box 2.6). For instance, in the analysis performed by the RAND Corporation for the protection of New Orleans against hurricanes, the magnitude of sea level rise (a very controversial issue) was found not to affect the preferred solution, while it was heavily dependent on the response of homeowners to incentives to elevate their houses, an uncertainty that was added to the list of factors considered during the consultation process (RAND 2010).

BOX 2.6. Phase 2: Identifying SEDAPAL's Main Vulnerabilities

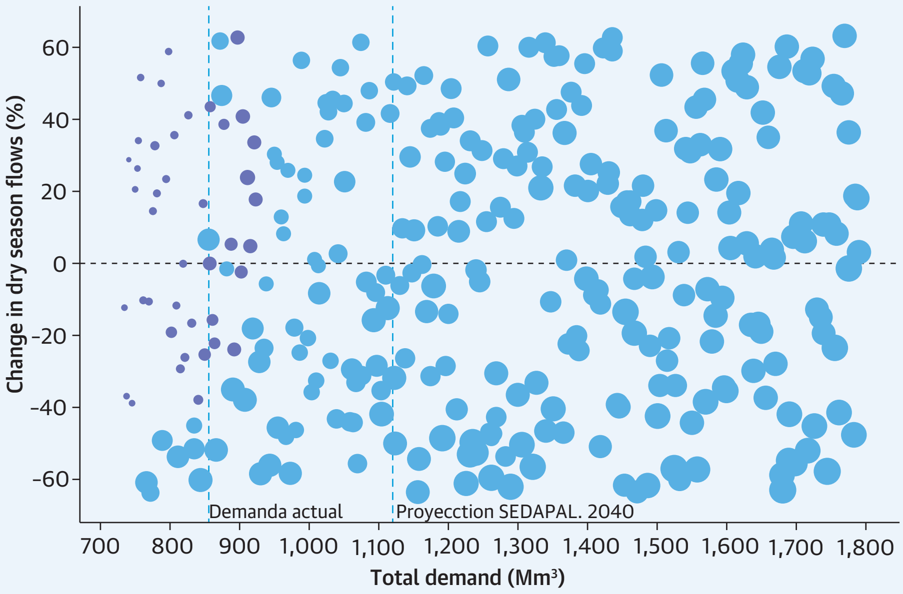
The first step of the vulnerability analysis of the SEDAPAL planning process was to compare the future performance of its system with and without the implementation of the master plan. The team developed 300 cases of future climate and demand and calculated the unmet demand for each one. Figure B2.6.1 shows the performance of the system under these 300 futures. Each dot indicates a plausible future, with the futures in which the reliability target is met in purple and those where it is not met in blue, while their size represents the magnitude of the unmet demand. The two vertical dotted lines indicate the current situation (on the left) and the one projected future demand that SEDAPAL had considered (on the right). Results show that the current system is vulnerable to even a small increase in demand, and that a much drier climate would also lead to failure. With the master plan implementation, reliability increases even under a much drier climate if demand does not exceed the projected levels, or if climate becomes wetter. But the analysis also shows that even with the full implementation of the master plan, the system would fail to meet its reliability target in many plausible futures (blue dots in panel b). This is the case even if demand were to remain lower than expected, particularly if the future were drier than expected.

box continues next page

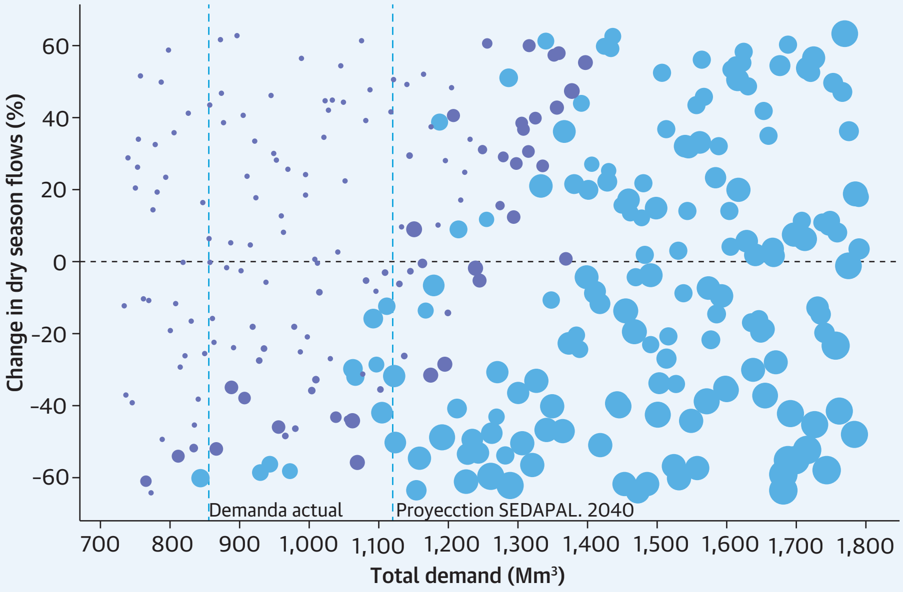
BOX 2.6. continued

FIGURE B2.6.1. SEDAPAL System Performance under 300 Futures

a. Without master plan



b. With master plan



Note: On the y-axis, the changes in dry season flows and, on the x-axis, the demand.

When models are not available, too costly, or impossible to develop, a qualitative version of the previous exercise can be performed through a scenario building exercise (box 2.7). Even in the absence of a model, a full XLRM analysis should be developed to describe what modeling would be ideal, what uncertainties matter, what options or levers are important, and what measures are relevant. Some scenarios can be qualitatively developed based on contrasted assumptions on the uncertainties identified in the previous phase. For instance, what would an optimistic and a pessimistic rainfall scenario look like? What would an optimistic and pessimistic scenario on cost overruns look like? This would allow an initial exploration of the uncertainty space. Experts can rank each uncertainty by its degree of uncertainty and its potential importance to the decision. They can then cluster these factors into a small number of key driving forces, using their judgment. Analysts can judge how well the options perform in each scenario and use these results to understand and communicate the utilities' potential vulnerabilities and the options' potential strengths or limits.

Finally, whether models are available or not, analysts and decision makers can compare the failure scenarios with evidence from the analysis to determine if the scenarios are sufficiently plausible to hedge against. They can compare trade-offs between robustness, feasibility, cost, and other factors and select those options that best balance their needs. For instance, a 100 million cubic meters of extra storage capacity may eliminate vulnerabilities to drought and increasing demand but may also be much costlier than reducing system inefficiencies and could significantly impact downstream users.

BOX 2.7. Denver Water and Scenario Planning

There are cases in which models could be available, but softer methods such as scenario planning, which usually involves considering a few scenarios only, are preferred for governance reasons. For example, after experiencing both the driest year and the worst Colorado wildfire on record in 2002, coupled with an increased understanding of climate impacts, Denver Water management was convinced that it needed to start planning for more changes and simultaneous crises. After exploring more quantitative techniques, the utility ultimately decided to apply scenario planning for long-term water supply planning as an incremental change from traditional methods, which were easily understood at the utility governance level. Thanks to this exercise, Denver Water is now building additional flexibility in its investment portfolio, which will allow the utility to be prepared and react appropriately in the future. One no-regret option identified as part of this process is for water service providers and legislators to team up to create a state legislation aiming to phase out the sale of less efficient bathroom fixtures. The bill was signed into law in 2014.[a]

[a] See WUCA's website, https://www.wucaonline.org/assets/pdf/pubs-uncertainty.pdf.

Fully qualitative applications—albeit an option—are relatively uncommon. In applying this process, teams tend to use models already available within the utility. Whenever there is no model, it is generally possible to develop a simple one to help the utility explore the consequences of different investment options. In either case, the analysis should not focus on the infrastructure elements alone, but should include institutional, socioeconomic, and operational measures as well. Moreover, it should evaluate the WSS system in its entirety to ensure that the analysis does not miss propagating impacts and potentials solutions.

2.4. Phase 3: Choosing Actions

One key step of this approach is, of course, choosing among different options. Once the model has been run, or qualitative scenarios have been tested, results are collected in a database of outputs, which includes the performance of each option under each of the futures explored. Using the results of the vulnerability analysis carried out in Phase 2, analysts now organize the options into modified or new strategies that are robust: that is, that achieve the utilities' objectives over a wide range of plausible futures.

The proposed approach helps identify trade-offs and clearly identifies the strengths and limits of each action, or combination of actions. However, it leaves the selection of the actions to the decision makers or to the broader stakeholder group. The experts will not propose "the" optimal solution because, in the context of uncertainty and multiple objectives, there is no such thing as an optimal solution.

This phase helps identify how the utility might augment or modify its current or proposed infrastructure and management to reduce its vulnerabilities. It answers questions such as:

- Are there low- or no-regret options that help achieve objectives no matter what future occurs?
- Are any combinations of options robust over all plausible futures?
- If not, what are the trade-offs among the options?
- Can the utility defer some actions and implement only if conditions warrant?
- Can the utility make its plans more robust by monitoring and adjusting over time?

How a team responds to these questions and turns them into actionable solutions depends on its decision-making criteria. The more common criteria are summarised below.

2.4.1. Identifying No- or Low-Regret Actions

Some near-term choices can be qualified as "no-regret": they would work well under all future conditions, are easy to implement and help improve service delivery as soon as they are put in place. If these actions are available, the utility should prioritize them. Sometimes no-regret actions are easy to identify and do not require sophisticated analysis. Box 2.8 shows what no-regret actions Maynilad Water took to combat increasing turbidity in its source water. In other instances, the no-regret option(s) may not be as clear and analysis can

BOX 2.8. No-Regret Action to Address Increased Turbidity in Maynilad, Manila

The CEO of Maynilad Water (Manila, Philippines) reported that the utility's biggest concern to date is water quality variation due to increased precipitation intensity. This is one of the most important drivers for the utility to consider climate change resilience measures. To improve water quality and reduce sedimentation caused by runoff, Maynilad supports the rehabilitation and reforestation of the La Mesa Watershed. Maynilad and SMART-Philippine Long-Distance Telephone Company have agreed to plant 30,000 trees annually under the Ipo Watershed Reforestation Program. Planting trees in the watershed area will lead to greater soil stability and prevent sediment runoff into the source water. Regardless of any changes in precipitation levels, this will reduce the amount of soil in the water, which directly impacts turbidity and other water quality metrics. As a result, the significant cost of treating highly turbid water will be greatly reduced.

help identify them or a timeline to implement them (see figure B2.6.1 for an example from SEDAPAL).

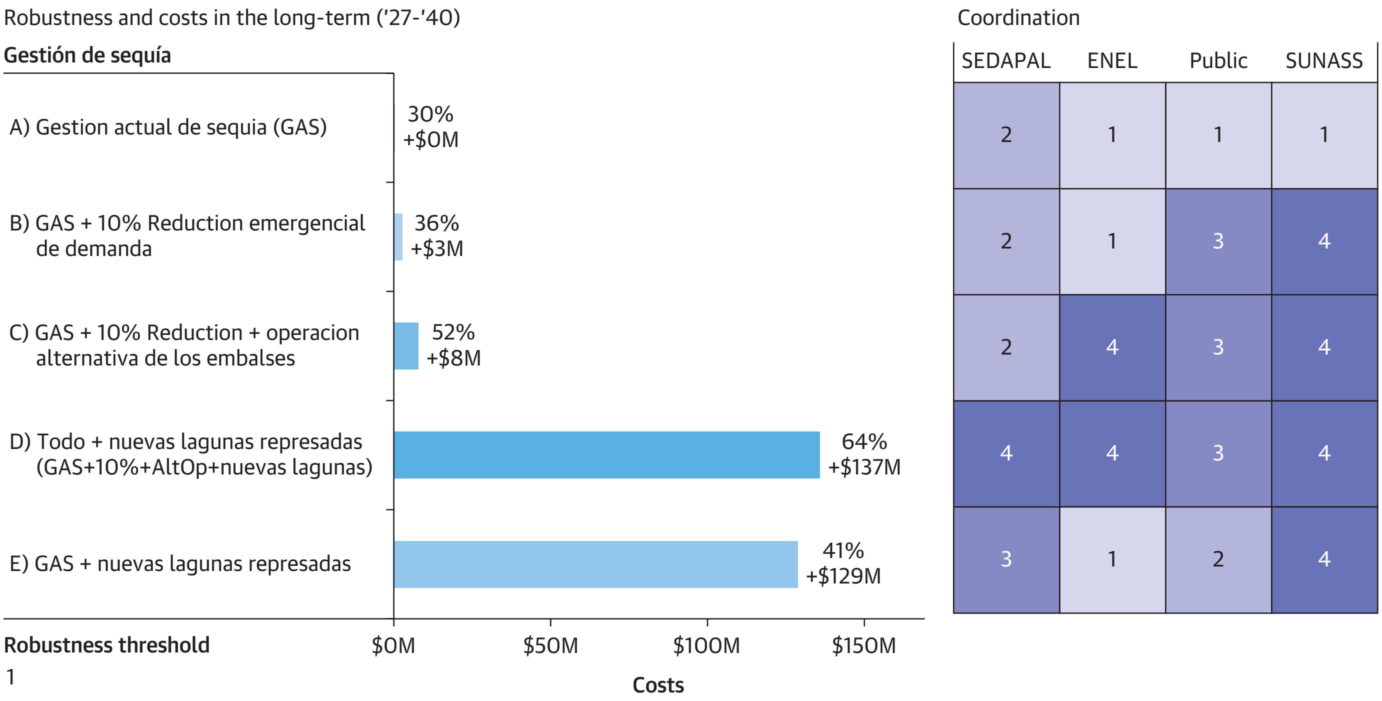
The benefits of identifying a portfolio of no-regret actions for the short term is that they tend to be easier to implement from a socio-political perspective. They also improve the resilience of the water utility under a wide range of future conditions while reducing the risk of infrastructure lock-ins if the future is less extreme than the full range considered in the analysis. These options are often accompanied by strong monitoring systems, which enable the water utility to adjust its plan of action when new information becomes available (e.g., when the triggers are met).

2.4.2. Evaluating Trade-Offs between Options

The definitions of *success* and *failure* by different metrics allow the decision to implement a project or plan to better account for multiple perspectives and constraints, such as the political economy of the project or noneconomic objectives like conflict prevention or regional balance. At the same time, the traditional benefit-cost ratio (or return on investment) remains as one of the criteria that can make the project fail. This way, the challenge of having to aggregate all costs and benefits into a unique metric is avoided whilst maintaining the economic-performance criterion in the analysis. Consider for instance the choice between two options to increase resilience: investing in reducing system losses or building a new reservoir. While a cost-benefit analysis would produce a ranking, there may be important trade-offs between these choices. For instance, it may be that the new reservoir is cost-effective and provides greater resilience, but it leads to much higher environmental and social costs, while reducing network losses does not lead to the same resilience levels but is a much more acceptable intervention and brings many near-term benefits. A constructive discussion among stakeholders with divergent views is more likely if these trade-offs are identified and made explicit. These could also be different units within a water utility.

Sometimes additional robustness implies an additional cost (e.g., build a reservoir). In that case, the decision can be informed by the trade-off between vulnerability and cost (how much more does it cost to make the project more robust? How much loss is avoided per extra dollar spent?). However, most often, the additional costs can be accounted for through other dimensions of the definition of a successful or failed project. For instance, if the definition of *failure* includes a cost-benefit ratio—or a return on investment—then the additional cost of robustness is acceptable if the project's net present value remains positive. Figure 2.3 shows an example of visualisation of plausible additions to the drought management plan for SEDAPAL, Lima's water utility. The figure shows trade-offs between the three main metrics considered during the evaluation stage. It shows for instance that for only US$ 8 million and a relatively low coordination requirement (score: 13), robustness to drought can nearly double by being able to implement emergency demand control measures that can reduce demand by 10 percent when a drought hits and by changing the operation of some reservoirs (robustness to from 30% to 52% of futures). Instead, adding extra reservoirs without first having developed the demand management plan would cost US$ 129 million to the utility, and can secure robustness in only 41 percent of the droughts considered. (Groves et al., forthcoming).

FIGURE 2.3. **Trade-Offs between Robustness, Cost, and Coordination Effort, SEDAPAL, Lima**



SEDAPAL	ENEL	Public	SUNASS
2	1	1	1
2	1	3	4
2	4	3	4
4	4	3	4
3	1	2	4

Source: Groves et al., forthcoming.

Note: The left column lists the options; the middle column shows the change in reliability (%) and the cost ($); the right column shows a qualitative evaluation of what level of coordination efforts would be needed to implement the different options, both internally within SEDAPAL, and externally with other stakeholders.

Care should be taken to carefully document the benefits and costs of improving robustness against scenarios for future conditions. Moreover, given the multiplicity of concerns captured via different metrics, planners should make sure that improving robustness for one aspect of a system is not decreasing it elsewhere. A common way of measuring robustness is to interactively explore acceptability thresholds for key performance metrics and track how frequently they are met or not across sampled scenarios.

2.4.3. Choosing Robust Solutions

DMDU proposes to compare the performance of the different options through a robustness rather than an optimality criterion. The traditional framework using optimality typically ranks alternative decision options based on the best estimate probability distributions. In general, there is a best (i.e., highest ranking) option. The shortcoming of the optimal solution is that it is only optimal for the predicted future and in a few sensitivity tests,but may be poor otherwise. A robustness criterion, in contrast, seeks solutions that are good (though not necessarily optimal) no matter what the future. There are several specific definitions of *robustness*, but all are structured around the satisfaction of certain criteria. For instance, a robust strategy can be defined as one that performs reasonably well compared to the alternatives across a wide range of plausible future scenarios (box 2.9). Different stakeholders should discuss what "reasonably well" could mean - in other words, what definition would satisfy them. Stakeholders can also evaluate trade-offs between robustness and other decision criteria like costs and feasibility. Often there is no single robust strategy; rather, decision makers can choose among set of reasonable choices.

BOX 2.9. Choosing a Decision Criterion Is a Question of Risk Tolerance

The choice among decision criteria is fundamentally a question of risk tolerance. Non-probabilistic decision criteria are easy to use and appropriate when reliable probability distributions are not available. Non-probabilistic decision criteria are often used in DMDU analyses of water projects. One of the most common non-probabilistic decision criteria (and highly risk averse) is mini-max regret. To use a mini-max regret criterion, analysts would calculate the regret associated with each option in each future, including the "do nothing" option. In order words, this is the difference between the option that performs best in that future, which will have zero regret for that future, and the other options being evaluated. Analysts would then choose the option with the smallest maximum regret compared to the other options, across all futures.

Another less risk-averse non-probabilistic decision criterion is satisficing regret. A decision that satisfices is one that works "well enough." To implement the satisficing regret criteria, analysts choose a level that represents an acceptable

box continues next page

BOX 2.9. continued

amount of regret. For instance, it might be "good enough" to achieve a net present value under uncertainty within 10 percent of the best possible net present value a project could achieve without uncertainty. Again, analysts would then calculate each option's regret in each future, by looking at its performance for each future (output of Phase 2). They would then choose the option with an acceptable regret (satisficing) in the most number of futures. In the simplest case, each future carries similar weight: the satisficing space is "counted" as the number of scenarios in which the performance of the system is satisfactory. Alternatively, analysts might assign weights to scenarios according to their likelihood (however derived), without taking the step of formalizing the probability of possible future scenarios according to a well-characterized probability density function.

The satisficing regret criterion selects a design option that performs well over a wide range of plausible futures, while the mini-max regret criterion selects a design option that performs well in the worst cases. For instance, consider a situation in which a team stress-tests alternative design options over a set of climate projections given by the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble. The satisficing regret criterion would select a design option similar to what one would get focusing on the mean value (e.g. expected net present value) and assuming an equally weighted probability distribution over all the scenarios of the CMIP5 ensemble. However, the mini-max regret criterion would select a design option similar to what one would get by assuming an equally weighted CMIP5 distribution and demanding a very high confidence level (i.e., confidence against the 1/100 event).

Analysts can use both the satisficing regret and the mini-max regret criteria as simple, straightforward approaches to addressing resilience. If these two criteria recommend similar design options, one can be confident that a more detailed analysis would also give similar results. If the two criteria suggest different design options, one can then (i) choose the option recommended by mini-max regret as the more risk averse option; (ii) choose the option recommended by satisficing regret as the less risk averse option; or (iii) conduct a more sophisticated DMDU analysis that considers a range of risk aversion and can include imprecise probabilistic information. The two metrics would also usually be calculated for a do-nothing option, which can then be compared to options to increase resilience.

Calculating satisficing regret in this example is based on one indicator, net present value. However, satisficing regret need not be based on a single indicator: its only requirement is to identify scenarios under which a system fails. This failure can be based on multiple indicators, which may reflect different priorities. However, it is not always possible to calculate an aggregate regret. For instance, if the decision makers aim to minimize costs while keeping reliability above a certain level and preserving flows to protect ecosystems, the regret scenarios may not be compatible.

There are also some cases in which the analysis shows that decision makers cannot reach the stated objectives with the available budget. This is a very important finding of the proposed approach: decision makers should be able to report that their mandate is inconsistent with the budget and that objectives need to be revised (e.g., slower increase in access, or lower reliability) or resources increased. This approach allows to phase investments in a robust way: decision makers could, for instance, start with feasible actions within the available budget, having clearly identified how those actions would contribute to meeting the objective and what vulnerabilities would remain if no extra budget were made available.

2.4.4. Identifying the Right Triggers for Phased Investment Actions

A strategy is particularly robust when it is explicitly designed to evolve over time in response to new information. A DMDU analysis often simulates the evolution over time of the climate and other biophysical systems but also of the policy as it responds to a wide variety of future contingencies.

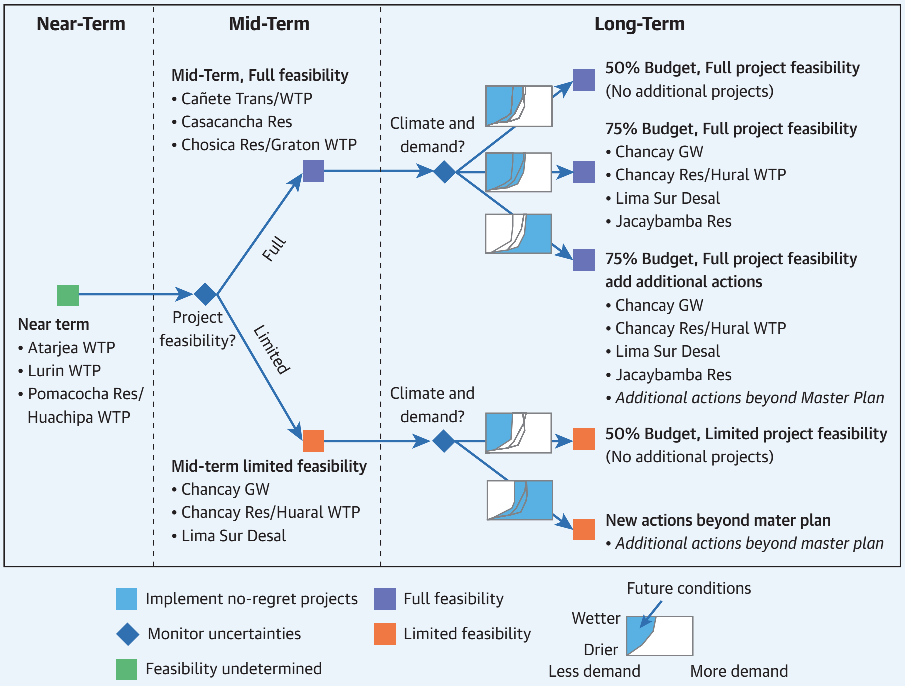
These analyses help define which indicators should be used to monitor and evaluate the situation and identify whether a scenario of failure is becoming more likely. **The approach provides thresholds beyond which further action is needed, thus facilitating the design and acceptability of adaptive planning.** For instance, the Lima study on water supply options identifies portfolios of projects for the medium-term based on better information on project feasibility, and for the long-term based on trends in climate and water demand (box 2.10, figure B2.10.1). Beyond project design, the analysis therefore produces indicators that can be monitored over time to assess portfolio or project progress and identify when adjustments are needed (which is rarely done through traditional monitoring and evaluation). However, planners have to assume strong knowledge of both the performance of actions against the objectives and of the appropriate timing for their implementation. For example, implementing too many major water supply infrastructure investments too early can lead to stranded assets for a long time and high opportunity costs. The concept of “action triggers” can provide a helpful guide to actions. This concept warrants that an action be implemented when a threshold of acceptable failure risk is exceeded. For example, in many systems in the United States, demand management actions are often tied to a specific storage level or stream flow but not linked to the broader seasonal hydroclimatic and demands context. In contrast, a risk-of-failure trigger can account for forecasts of supply and demand in a seasonal context (e.g., early spring water deficits are different than early fall). These triggers can be formulated across different types of management actions and for different time scales of concern (e.g., weekly operations in demand management and annual-scale infrastructure actions). Consequently, the identification of these can help avoid fixing too many interventions ahead of time, thus it helps avoiding lock-ins and stranded assets. Actions are triggered in the context of the dynamic risks a system is confronted.

Phase 3 is intended as one part of an iterative process. If needed, analysts and decision makers iterate earlier steps to examine more options or modify certain features, explore a wider range of uncertainties and consider additional metrics. For instance, they may

BOX 2.10. Phase 3: Phasing the Implementation of SEDAPAL's Master Plan

The description of intermediate results in box 2.6 shows that the full implementation of the master plan led to higher reliability. However, it comes at a high cost: US$2.48 billion. Moreover, not all proposed infrastructure may be equally feasible. Therefore, the analysis divides the investments into three phases, near-, medium-, and long-term. In the first phase, the utility should implement no-regret investments, which, in this case, are those that would be cost-effective not only under all plausible scenarios of climate and demand change but also regardless of the additional infrastructure that may be implemented later (e.g., if all or only some infrastructure is implemented). In the medium-term, more information about what projects are feasible will be available, and this information becomes the medium-term trigger that will help exclude some options. Indeed, a few were unlikely to be approved (see blue diamond named "project feasibility?" on figure B2.10.1). If all projects can be implemented (arrow marked with "full," pointing up), the analysis suggests a set of investments; if not (arrow marked with "limited," pointing down), another. Finally, in the long term, when more updated information on the climate and demand changes are available, the utility can implement the third phase of investments based on that future state of the world. The final tree, shown in figure B2.10.1, indicates that SEDAPAL could save 25 percent of the budget because two projects

FIGURE B2.10.1. Triggers Identified for Phasing SEDAPAL's Investments, Lima



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BOX 2.10. continued

are redundant: there are no added advantages in implementing them (third purple square in the right column). Moreover, in case of extreme climate and high demand scenarios, the existing master plan will not be able to eliminate SEDAPAL's vulnerabilities. Therefore, SEDAPAL may want to consider additional investments. In discussion with them, it was decided that the utility needs to scale up its demand management portfolio.

change their objectives because the initial ones were too ambitious and cannot be met, or because they were not ambitious enough. They may also change the list of options available, because they realize that the initial list does not include any satisfactory solutions. Multiple rounds of analyses may be needed to arrive to a final list of options. As Lempert et al. (2013) describe, this approach can be used to time investments and develop flexible plans designed to evolve as new information becomes available. These steps can be used to design individual projects and portfolios of projects or to compare different exclusive alternatives.

2.4.5. Dealing with Remaining Vulnerabilities

Broadly framing system concerns helps utilities be prepared to manage the residual risk—the risk that cannot be eliminated—by identifying it in a transparent manner. When the preferred set of actions is selected, the analysis provides the conditions that will cause this set of actions to fail, and the consequences of that failure. Typically, the analysis will provide results such as, "the set of actions identified will not be sufficient should five consecutive years of drought hit and if demand increases by more than 50 percent." It then becomes possible to discuss the plausibility of these conditions and what addtional actions can help deal with these residual risks. Using again the Lima example, the analysis shows that even if all infrastructure options were implemented, the system would remain vulnerable to a demand even slightly higher than forecast in a drier climate than the current one. Therefore, the team recommended that the utility explore other softer options, such as demand management and efficiency improvements.

Another important recommendation emerged from the system's sensitivity to demand: the importance of investing in improved planning to understand use efficiencies and demand growth dynamics. Perverse incentives can encourage significant overestimation of demand growth to gain access to capital investment. Understanding demand growth rates (including forecasts about population and economic growth, location specificity and consumption growth rates) are particularly challenging in LICs. Improved planning to understand use efficiencies and demand growth dynamics can help clarify priority investments and link to broader system factors that shape regional changes (e.g., shifts in sectoral demands, price-based incentives, and opportunities for coordination).

If climate change were the main driver of the remaining vulnerabilities, the water utility would have two options, as illustrated in the bottom left part of figure 2.1. If resources were available, analysts could invest in exploring plausible future climates in depth (see appendix A for a deep dive into specific methods). Tariq et al. (2017) provides an example of when and how one could consider more extensive analysis of climate information. The authors use "(imprecise) probabilistic climate projections to inform the choice among robust adaptive policy pathways" (Tariq et al. 2017). The study uses alternative sets of climate information to provide a bounding set of probability distributions for the future 90th percentile 24-hour rainfall, which is used to quantify the trade-offs between inaction and two alternative adaptive plans (admitting all caveats of the analysis). Therefore, they explored the uncertainty space related to climate change and the potential impact it may have on the project in much more detail. When doing similar exercises, analysts should remain aware of the limitations of downloading climate scenarios (from another source) and running a hydrological model. Often, these exercises ignore the uncertainties intrinsic to downscaling efforts, the missing extremes, and the weak representation of human processes in hydrological modeling.

Notes

1. Many other examples of application of these processes can be found on Deep Uncertainty Society's website, www.deepuncertainty.org.
2. Ray and Brown (2015) rename them the 4 *C*s: choices, consequences, connections, and uncertainties. Nonetheless, both terminologies are in use and refer to the same factors.
3. Discounting is the process through which changes in value are accounted for over time, under the assumption that a dollar today will be worth less tomorrow. In this case, the depreciation of certain investments over time or the need to value nonmonetary impacts would require a clear understanding of how discounting plays into the planning process.
4. An efficient way to develop scenarios quantitatively is by using the Latin hypercube sampling method, which is similar to but more efficient than Monte Carlo sampling in that it covers the uncertainty space with fewer scenarios.
5. The data mining algorithm PRIM (patient rule induction method) is a common tool (Friedman and Fisher 1999).

Chapter 3

Conclusions

While more investment is urgently needed to improve WSS access in LICs, there is growing awareness that maintaining or enhancing the resilience of new and existing or aging infrastructure to natural disasters, especially in the context of climate change and variability, is critical for development. This guidance document provides WSS utilities with (i) a justification of the importance of urban WSS systems becoming more robust and resilient to climate change and other uncertainties, and (ii) a planning and decision making approach that can be followed to improve robustness and resilience while reconciling near- and longer-term priorities.

Though climate change impacts the ability of utilities to provide the service levels they aspire to, it can provide opportunities for utilities to readjust priorities and reduce costs in the long-term. This can be done by combining performance improvement (a well-run utility is better able to respond to climate change), the identification of cost-effective solutions to future states of the world (including a mix of soft and hard interventions), and decisions that allow for adaptation over time. It is recognized, however, that incorporating climate change into planning is still a challenge, even in upper-income countries. This can lead to inappropriate solutions that may result in expensive lock-ins.

This document provides an entry point into integrating climate change in utility planning efforts through the application of state-of-the-art methodologies to deal with uncertainty. These are laid out clearly in three phases and are being applied by a growing number of water utility and water resource managers around the world. The Decision Tree Framework (DTF) also contains a compendium of many existing methodologies that could be used to support water utilities to build their resilience.

Applying the three-phase approach outlined in this guidance document helps utilities understand their system and their investment plans more fully in terms of their robustness and resilience to climate change. It enables utilities to assess climate change and other threats without first needing to predict future conditions. It helps highlight critical elements of infrastructure, identify possible future states of the world and assess the potential impacts of climate change resulting from failure of those critical assets, while measuring these against articulated levels of service to be delivered to customers - or other objectives.

The approach reveals the strengths and vulnerabilities of investment plans concisely. It produces a specific set of conditions in which the identified investments can achieve reliability or where additional actions may be necessary. It also helps utilities invest robustly by identifying near-term, no-regret projects to prioritize now, while maintaining flexibility and pursuing additional actions adaptively as future conditions evolve. These results can be achieved with a qualitative exploration or a quantitative assessment, or a combination, depending on the context and the resources available.

WSS utilities need to be willing to engage in long-term planning that accounts for the deep uncertainties they face and will continue to impact service provision in the future. This road map proposes a clear approach for WSS utilities to embark on this type of complex analysis that, in most cases, will differ greatly from previous approaches. By embracing such innovation, utilities also recognize that the analysis could produce controversial findings or recommendations different from their expectations. However, in applying this approach, they also embrace the opportunity to secure long-term resilience in the provision of WSS services for their customers.

Appendix A

Skills and Resources Required for Applying the Phases

The phases described in previous chapters may be new to the utility and may require a different skill set than those normally available in the water supply and sanitation (WSS) sector. Moreover multiple methodologies have been developed to stress-test strategies and to select those that are robust to deep uncertainties or adaptable to a changing future. Depending on the importance of different factors, the complexity of the problem or the resources available, one method may be more appropriate than the others. Most often, a combination of methodologies serves the client better than one methodology alone. This chapter shows that the approach can be as simple or complex as budget and human resources allow. For these reasons, recruiting a consultant or choosing among specific methodologies can be a challenge.

Nevertheless, the consultants should possess certain skills, which are detailed below. It is the commissioner's role to ensure that the level of effort and time required are reasonable. This section briefly outlines the skills and resources that have been used in applying this approach around the world.

Skills needed. Demonstrated experience in carrying out studies similar to Robust Decision Making, Decision Scaling, Adaptation Pathways, Robust Optimization or other Decision Making under Deep Uncertainty (DMDU) methods.[1]

Some skills which the team of analysts (or individual consultant) would need to show are common to both qualitative and quantitative approaches:

- Demonstrated experience with workshop organization and participatory approaches
- Demonstrated experience with scenario building and planning
- Familiarity with global circulation models (GCMs) and the strengths and limitations of their use
- Demonstrated experience with the basic foundations of DMDU
- Strong data visualization skills to communicate technical results to policy makers

Other skills are more specific to the quantitative evaluation of system resilience:

- Demonstrate experience with scenario building, including familiarity with GCMs and strengths and limitations of their use, and hydrological modeling
- Demonstrated experience with system models, especially running them hundreds of times or demonstrated experience with scenario planning (the latter is particularly critical when models are not available)
- Demonstrated experience in economic analysis
- Demonstrated experience with coding tools, such as python, R, or similar
- Demonstrated experience with data mining algorithms like PRIM (patient rule induction method)

Time required. Between six months and one year in most cases. Some rapid appraisals can take less time while very comprehensive evaluations, such as planning efforts with many different investments and several stakeholders, may take longer.

Budget resources. If the utility is hiring a firm, the cost typically ranges between US$100,000 and US$300,000, depending on the context, scope, and data and model availability. If individual consultants are hired instead of a firm, the cost will be lower (US$50,000 to US$80,000). Some large master plan analyses, such as the Coastal Master Plan of Louisiana, can cost more than US$1 million. It is important to put this amount in perspective: even in the extreme cases, the cost of such studies is close to 0 percent of the cost of the investments informed by a master plan. In this sense, if such a study increases the efficiency of public spending by 0.1 percent, it pays for itself. Moreover, the budget for infrastructure project design usually amounts to more than 5 percent of the investment costs, and could easily include these analyses of plans, or even of projects (e.g., at the prefeasibility or feasibility level). To define the scope of the analysis, the Uncertainties, Policy Levers, Relationship, Metrics (XLRM) matrix is a good starting point, even if developed informally with the client. It also provides a sense of the problem, possible options, available data, and modeling capacity.

Finally, one of the important criteria for the success of the approach (for a consensual and informed decision to be taken) is the willingness of the client utility to go through a transparent and open process, in which inconvenient facts are discussed often. To yield a successful project, trust must be built between the analysts, utility staff and other partners, for instance, the World Bank team. This may require carrying out the phases in two stages, first in a closed format and then with external stakeholders, so that the utility staff may feel able to speak more freely about the threats to its system.

Ensuring the client's commitment to the process is critical. It will often be the case that technical teams of external consultants and researchers perform an analysis for a client or stakeholder (i.e., Servicio de Agua Potable y Alcantarillado de *Lima* [SEDAPAL]). The technical team produces analysis and findings and the stakeholder receives them. As noted in the literature on decision support notes (NRC 2009), this allocation of roles puts the relevance of the analysis to stakeholders' needs at risk. The analysis may not answer the questions that the stakeholder is asking; the stakeholder may not buy into the methodological process or findings; or the stakeholder may not be able to take intellectual ownership of the methodology, tools and outcomes. Experience shows that success is most often linked to the *inclusion of the client's technical staff as core part of the analytical team*. The staff's involvement ensures that the analysis focuses on the right questions, that the results are important and practical for the client, and that the client seeks to take ownership of the methods and tools developed in the analysis and employ them in future planning activities.

Note

1. See the Deep Uncertainty Society's website, www.deepuncertainty.org.

Appendix B Climate Change and WSS Utilities

Water supply and sanitation (WSS) utilities face changing local climate variability; in fact it has already changed. Climate change impacts and will continue to impact the water cycle through temperature and precipitation changes and sea level rise. Beyond simply changing mean conditions, climate change is exacerbating the variability of extremes. Table B.1 summarizes some of the impacts of the associated hazards on WSS utilities. While each of these impacts can be considered in isolation, there can be complex interactions between the hazards as well. In one given location, it is plausible that projected changes in precipitation due to climate change could lead to droughts and increased water scarcity, while also increasing hazards for extreme floods in the wet season. Moreover, sea level rise may both increase saline intrusion and exacerbate the effect of storm surges. Or, as demonstrated in several cases, the combination of water scarcity and increased precipitation intensity can result in both an increased need for water storage and a faster loss of storage capacity due to accelerated sedimentation rates.

TABLE B.1. **Impacts of Hazards on WSS Utilities**

Climate Effect	Hazard	Impact on WSS sector
Decrease in precipitation	Drought	Reduction in raw water supplies, reduced flow in rivers, less dilution/increased concentration of pollutants and minerals in water, challenge to hygiene practices, lack of water for urban water activities such as firefighting, urban irrigation and industry, soil compaction, possible population displacement
Increase in precipitation and severe weather	Flooding	Pollution of groundwater resources, inundation of wells, inaccessibility of water sources, flooding of latrines, damage to infrastructure, landslides around water sources, sedimentation and turbidity, challenges to sustainability of sanitation and hygiene behaviors, water-borne diseases, possible population displacement, destruction of property
Increase in temperatures	Heat waves	Damage to infrastructure, increase in pathogens in water leading to increased risk of disease and mortality, intensification of urban heat island effect, impact on water quality
	Melting and thawing of glaciers, snow, sea ice, and frozen ground	Seasonality of river flows affected leading to a reduction in water availability in summer
Sea level rise	Flooding and saline intrusion into freshwater aquifers	Reduction in availability of drinking water, with high impacts on quality
Other	Earthquakes	Earthquakes can physically damage WSS facilities and disrupt critical lifeline operations, possible population displacement, destruction of property

Source: Adapted from Resilient WSS Sector COP paper, June 2017; and World Bank, forthcoming.
Note: WSS = water supply and sanitation.

In addition to changing existing stressors, climate change has compounding impacts that present a **new set of possible failure mechanisms** in addition to the traditional risks faced by water utilities. For instance, a utility may face heat extremes, landslides and sedimentation, or encounter invasive species in their watershed that have not previously been of concern. Box B.1 presents one way to understand future climate changes and these interacting impacts through global circulation models (GCMs).

BOX B.1. Understanding Future Climate Changes with Global Circulation Models

When it comes to predicting future climate changes, global circulation models (GCMs) have been used to understand how the global climate system will evolve to future changes in radiative forcing.[a] The international climate science community has established a process to compare climate models and the experiments performed with them, and the full ensemble of results are publicly available to users worldwide. There are however several issues when using GCM outputs for investment planning. First, while there is vast agreement in the scientific community regarding the warming trends of the planet, as demonstrated in many different GCMs, the uncertain nature of atmospheric conditions and patterns means that the implications of this trend at the local level varies significantly from one model to the next. In fact, in difficult-to-model geographies, different GCMs can project both positive and negative climate change impacts in the same region. Second, there is greater confidence in temperature projections than precipitation projections, and there is greater confidence in gradual changes in average conditions than in extreme weather events such as storms. Most GCMs disagree on the extent of future changes in precipitation and extreme weather events, and climate modeling experts caution users against picking an apparent "best performing" model. Third, GCMs generally operate at a spatial resolution of 150 square kilometers to 300 square kilometers, and therefore fail to fully resolve physical features at smaller scales. It is possible to downscale GCM outputs at the regional level, but this process often adds more uncertainty to future changes in climate. Therefore, it is imperative to use a large range of scenarios when assessing the future climate changes that can affect a WSS utility (see appendix C on how to address these challenges).

a. Radiative forcing is the difference between the sunlight or heat entering the Earth's atmosphere and the amount radiating back out to space. In a sense, radiative forcing measures how much the Earth is heating up and whether it faces an energy imbalance.

Appendix C Global Circulation Models, Challenges, and Solutions

Why Future Climate Change Is Uncertain

The Intergovernmental Panel on Climate Change (IPCC) is regarded as the most comprehensive and authoritative international body for assessing the science related to climate change (World Bank 2017b). In its most recent assessment of climate change, the Fifth Assessment Report (AR5), the IPCC states: "*Temperatures are projected to continue to increase during all seasons, with heat waves projected to become more intense and more frequent around the world. In the coming decades, wet regions around the globe are expected to become wetter, and dry regions are expected to become drier.*" (Stocker et al. 2013)

According to the IPCC, climate models are the primary tools available for (i) investigating the response of the climate system to various forces (natural and anthropogenic); (ii) making climate projections on seasonal to decadal time scales; and (iii) making projections of future climate over the coming century and beyond. Climate projections are based on the laws of physics and considered well-known compared to, for instance, other projections of the economy and demographics. Climate modeling is, however, limited by three key factors:

- Uncertainty arising from an incomplete understanding of Earth system processes and incomplete representation of these processes in climate models
- Uncertainty about future concentrations of greenhouse gases, arising from uncertainty over the scale of future global emissions of greenhouse gases by human society, and thus the scale of future radiative forcing. This becomes a dominant source of uncertainty on time scales of 50 years or more
- Natural climate variability resulting from (often physically chaotic) processes within the climate system that cause changes in climate over relatively short time scales, for example, the El Niño-Southern Oscillation (ENSO) (Houghton, Jenkins, and Ephraums 1990)

However, this uncertainty should not stall or halt action on increasing resilience to climate change. Informed investment decisions must be made even in the face of uncertainty. Strategies and options are, therefore, required against a wide variety of possible future conditions. The specific characteristics of climate change—both observed and projected—vary by region. Therefore, WSS utility managers and investors must be aware of future projected climate changes as they apply them to their local and regional context (USAID 2017).

Climate Models and Projections of Future Climate

Over the past 40 years, there has been considerable scientific study of the evolution of the Earth's climate and the processes involved, as well as of how the climate may continue to evolve. The IPCC's AR5 (Planton 2013) reviews over 10,000 research publications. Confidence is very high regarding models' ability to reproduce the global-scale annual mean surface temperature increase over the historical period, including the more rapid warming in the second half of the 20th century, and the cooling immediately following large volcanic eruptions. Climate and Earth system models are based on physical principles, and they reproduce many important aspects of observed climate. Both aspects contribute to confidence in the models' suitability for their application to detection and attribution studies and for quantitative future predictions and projections (Flato 2013).

To construct scenarios of future climate change, there is a need to understand how the climate system has evolved and will evolve over time due to changes in forcing (predominantly anthropogenic radiative forcing). The climate science community has developed a range of climate models, which range from simple one-dimensional models to complex and very computationally intensive global circulation models (GCMs). GCMs are essentially three-dimensional representations of the coupled ocean-atmosphere-cryosphere and biosphere systems. Regional climate models (RCMs) are used to produce higher spatial resolution data and are used in downscaling the results from experiments performed with GCMs over specific regional domains. The added value of RCMs is mainly seen in the simulation of topography-influenced phenomena and extremes with relatively small spatial or short temporal character, such as large-scale monsoon patterns (Stocker et al. 2013). Different climate modeling centers operate different GCMs and RCMs, which are broadly similar but often differ in the parametrization details of key elements of the coupled climate system.

Climate Models' Relevance to Water Utilities

In the context of future climate change, GCMs have been used to perform climate change experiments that help us understand how the global climate system has evolved in response to changes in historic forcing (including radiative, volcanic, and other natural mechanisms) and how the climate system will evolve to future changes in radiative forcing. The international climate science community has established a process that compares climate models and the experiments performed with them. The fifth stage of the Coupled Model Intercomparison Project (CMIP5), was used for the evaluation in the IPCC AR5 (Taylor, Stouffer, and Meehl 2012). CMIP also undertakes a review of GCMs, setting out guidance for experimental design and needed attributes. The full set of results from CMIP5 are publicly available to users worldwide.

For the historic component, the results from the climate simulations are not directly comparable to observations because the results are not synchronized in time with observations. Nonetheless, comparisons have revealed that there are large differences between climate model outputs and observed climate.

For any specific variable of interest and location, there is only one observation and many model results, making comparisons difficult to interpret. Often, errors are discarded as biases. The present generation of GCMs is not able to fully resolve observed variability, means, extremes, and some major climate processes (e.g., ENSO, Asian monsoons, or attitudinal range). These are the most useful information for a utility operator because they directly affect water availability. Furthermore, data at specific geographic locations are unreliable. Even if experiment results provide close agreement with observed data, there is no guarantee that the future response will be correct (due to internal model feedbacks and sensitivity to an increase in forcing). Therefore, climate modeling experts caution users against picking an apparent "best performing" model based solely on historical accuracy, since this unlikely to adequately reflect the ability to reliably reproduce changes in future climate.

In general, there is greater confidence in projections for larger regions than for specific locations. There is also greater confidence in temperature projections than precipitation projections, and there is greater confidence in gradual changes in average conditions than in extreme weather events such as storms. The current state of science and credibility for climate models reproducing relevant climatic features is given in table C.1. Over the next few decades the largest source of uncertainty is likely to be natural variability, followed by uncertainty related to the response of the climate system to past changes in radiative forcing. In the second half of this century, uncertainties in future levels of anthropogenic emissions also become a significant source of uncertainty. When looking at climate science, there is a high degree of certainty that current climate change has already changed (i.e., has become different than that suggested by the historic record) and will change more in the future.

The spatial resolution at which the current suite of climate models (CMIP5) generally operates (150-300 square kilometers) prevents them from fully resolving physical features at smaller scales such as the utility level. For instance, a watershed supplying a water utility may include high altitude mountainous terrain with sharp features at scales smaller than the grid size of the GCMs. These mountainous features may significantly affect the intensity of local extreme rainfall events, and thus the climate-related risks to the facility. But GCMs with large

TABLE C.1. Likelihood of Climatic Changes

Phenomenon and direction of trend	Likelihood of further changes	
	Early 21st century	Later 21st century
Warmer or fewer cold days and nights over most land areas	Likely	Virtually certain
Warmer or more frequent hot days and nights over most land areas	Likely	Virtually certain
Warm spell and heat waves. Frequency or duration increases over most land areas	Not formally assessed	Very likely
Heavy precipitation events. Increase in the frequency, intensity, or amount of heavy precipitation	Likely over many land areas	Very likely over most of the midlatitude land masses and over wet tropical regions
Increases in intensity or duration of drought	Low confidence	Likely
Increases in intense tropical cyclone activity	Low confidence	More likely than not in the western North Pacific and North Atlantic
Increased incidence and/or magnitude of extreme high sea level	Likely	Very likely

Source: Stocker 2013.

grid size cannot resolve how the local terrain affects these extreme events. In addition, there is often an apparent need to link the outputs of climate models to hydrological models of the hydraulic facilities' watershed, while these latter models generally require time series of climate variables at finer spatial (and temporal) resolution than provided directly by the GCMs.

There are several ways to address these challenges. Often it is possible to find "downscaled" climate projections for a specific region. Statistical downscaling involves perturbing the historically observed local temperature record with the coarser spatial resolution outputs from the climate models. As one very simple example, if a climate model indicates that the annual temperature across some region of the world will be 2 degrees Celsius hotter in 2050, then the daily, observed temperature record for some local areas in the region might be increased by 2 degrees Celsius. Dynamic downscaling, on the other hand, involves linking the coarse grid GCM results to a finer scale RCM for the region in question. While dynamic downscaling can often resolve the effect of physical features at smaller scales (e.g., mountainous terrain), the use of one RCMs only (in part due to higher computational resources), and therefore the full envelope of results from the recommended use of multiple models cannot be produced. However, while the benefits of downscaling are many, it does not correct inherent biases or other deficiencies in the GCM ensemble. As summarized by Deser et al. (2012) "*It is worth noting that downscaled information derived statistically or dynamically from global climate model output will add local detail but remains dependent on the overlying larger-scale field and cannot mitigate the uncertainty of projected climate trends due to natural climate variability*." As another option, one can use stochastic weather generators, which use the local historical climatological record in a particular location and impose trends or shifts in the climate parameters of concern (e.g., temperature or precipitation mean, variance, persistence, and skew).

Stochastic weather generators and downscaled GCM projections have advantages and disadvantages in providing a set of climate projections for water planners. The climate models offer greater insight into physically based climate parameter covariance, but users should only use climate projections that scientists have made available for the location. It is not recommended that users generate new climate projections in any but the most sophisticated and well-funded planning efforts. Thus, users may have less control over the range of climate variables explored by any set of climate projections. In addition, users of climate model projections may be prone to overconfidence, that is, believing these physically realistic models are more accurate than they actually are.

Weather generators allow users to more precise control over the climate parameters explored, leading to greater flexibility and understanding. However, to assess a plausible range of variation, results must ultimately be compared to the climate model outputs. Simple weather generators such as those that explore only changes in average annual temperature and precipitation, may miss complex variations and correlations among climate parameters at multiple spatial and temporal scales. These varations and correlations are represented in the GCM projections with varying degrees of fidelity, but they may prove important to water project performance.

Best Practice Recommendations in Assessing Climate Change Risks

Given the uncertainty in determining future climate change, it is not possible to obtain high confidence projections of future climate. Therefore, relying on mean values and confidence intervals for future climate suggested by any single climate projection or any single best- or central-estimate probability distribution is not appropriate. For instance, it is not possible to give accurate estimates of the fifth and 95th confidence bands for many climate parameters, such as precipitation, temperature, and wind in any specific location.

Therefore, the recommendation is to use the full range of most current CMIP model experimental runs and their percentage change values to inform climate stress-tests on proposed utility projects and basin plans. That is, once the climate- and non-climate-related vulnerabilities are identified, the full range of projected changes across the CMIP ensemble can be used to assess whether the risks are of concern, based on whether the climate information produced indicates that the problematic climate changes are likely or not to occur. Whether or not they are downscaled, it is important to use a full range of GCM projections. The examples cited throughout this document demonstrate how to use this climate information without reliable probability distributions and confidence intervals to evaluate risks and improve climate resilience.

A climate stress-testing approach based on weather generation algorithms can be used to generate scenarios of change efficiently, while downscaled projections from the most current GCM ensemble can be used to infer the probability of the changes. The former can provide more controlled experiments regarding sensitivity to specific climate variabilities. The latter can provide insight into physically-based nonlinear relationships between climate parameters responsive to large-scale oceanic and atmospheric climate processes. However, most climate resilience efforts to date have used only one or the other of the two options, which in most cases proves entirely adequate. The road map thus recommends using whichever method is most convenient: stochastic weather generators whose range of plausible variation is measured against the CMIP ensemble or the projections in the CMIP ensemble directly.

Climate projections provide limited and often biased explorations of the effects of internal climate variability, especially precipitation variability (Rocheta, Evans, and Sharma 2014), with amplified carryover effects for runoff estimates (Fekete et al. 2004). Perhaps most importantly, GCMs have the least capacity to generate the variables that are most important for water resources projects, such as local hydrologic variability and extremes (e.g., floods and droughts). Those extreme events are at the tails of climate variables distributions and by percentage will change more rapidly than the mean in a changing climate (Dai, Trenberth, and Karl 1998). While the CMIP ensemble is the best widely available source of climate information for general guidance on climate resilience, there may be situations in which planners find it useful to directly consult climate scientists, who may be able to refine the information available in any particular case.

Appendix D Resilience Options Implemented by WSS Utilities around the World

TABLE D.1. Options for Climate Change Resilience Implemented by WSS Utilities

Type of resilience measure	Resilience action	Addresses climate impact: droughts and water scarcity	Addresses climate impact: precipitation intensity	Addresses climate impact: sea level rise and saline intrusion	Addresses climate impact: storm surge and coastal flooding	Primarily benefitting process	Co-benefits
Operational	Additional monitoring and staffing during tropical storms to improve emergency response	X	X	X	X	Pumping stations and WWTPs	Preparation for all emergencies
Capital/ operational	Afforestation and catchment management	n.a.	X	n.a.	X	Sources	Environmental, general benefits associated with watershed management
Capital/ operational	Artificial recharge of aquifers	X	n.a.	X	n.a.	Sources	Drought management, additional water resources
Capital	Assessment of appropriate investments projects for tackling future water shortages	X	X	X	X	Institutional	Financial efficiency and resource efficiency
Capital	Backup power supply to key assets	X	X	X	X	Pumping stations, WTPs, and WWTPs	Protects against wider power network outages; preparatory for all emergencies
Institutional	Citizen education on solid waste management to reduce blockages or loss of capacity in drainage systems	n.a.	X	n.a.	X	Sewer/ drainage networks	Environmental and health benefits associated with improved solid waste management; floodwater management
Institutional	City regulations require grey water reuse system on all large new developments	X	n.a.	n.a.	X	Sources	Reduction in potable water consumption and the associated reduction in energy and chemical usage Reduction in sewer connection size/capacity required for new developments
Institutional	City requires households and new build structures to have rainwater harvesting facilities; this water is injected into local groundwater	X	n.a.	n.a.	n.a.	Water sources	Increased quantity of water available Reduction in storm water flows for collection/treatment

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TABLE D.1. continued

Type of resilience measure	Resilience action	Addresses climate impact: droughts and water scarcity	Addresses climate impact: precipitation intensity	Addresses climate impact: sea level rise and saline intrusion	Addresses climate impact: storm surge and coastal flooding	Primarily benefitting process	Co-benefits
Socioeconomic	Citywide land use and zoning (e.g., increase urban density, low water impact developments) to reduce consumption or mitigate other risks	X	X	X	X	Consumer	Urban development good practice, reduced development costs, improved storm water management
Institutional/ capital	Climate risk screening as part of the coastal risk assessment regulatory requirement: involves raising plinth levels, ensuring sufficient pump heads, etc.	n.a.	X	X	X	Sanitation assets	Useful information for all potential scenarios
Institutional/ capital	Climate risk screening as part of the coastal risk assessment regulatory requirement: involves raising plinth levels, ensuring sufficient pump heads, etc.	n.a.	n.a.	X	X	All sanitation assets	Reduced flood risk
Capital	Conjunctive use: groundwater storage of surface water for use during periods of drought	X	n.a.	n.a.	n.a.	Sources	Flood management
Capital	Construction of desalination plant	X	n.a.	x	n.a.	Sources/ treatment	Additional water resource
Socio-economic	Customer water saving awareness campaigns	X	n.a.	n.a.	n.a.	Consumer	Resource efficiency, societal awareness
Capital	Decrease evaporation losses from surface water sources by artificial aquifer recharge and storage	X	X	n.a.	n.a.	Sources	Flood management
Intuitional/ operational	Establish communication procedures between relevant municipal and private sector operators to reduce water levels in the system in advance of storm events	X	X	x	x	Drainage/ sewer network and WWTPs	Preparatory for all emergencies, improve response for nonclimatic effects

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TABLE D.1. continued

Type of resilience measure	Resilience action	Addresses climate impact: droughts and water scarcity	Addresses climate impact: precipitation intensity	Addresses climate impact: sea level rise and saline intrusion	Addresses climate impact: storm surge and coastal flooding	Primarily benefitting process	Co-benefits
Operational	Identify critical customers (e.g., hospitals) and develop emergency supply plans	X	X	X	X	Consumer	Emergency planning
Operational	Improve interconnections at transmission and distribution level between sources	X	n.a.	n.a.	X	Transmission	Improved resilience for any event; supply continuity for routine maintenance
Operational	Improved aquifer modeling	X	X	X	X	Water sources	Useful information for all potential scenarios
Capital	Increase dam capacity to provide additional water resources and enable the blending of sources	X	X	X	X	Sources	Financial efficiency and resource efficiency
Capital	Increase reservoirs capacity to assure water supply	X	X	n.a.	n.a.	Distribution	Improved network storage, potential for reduced peak flow requirements
Operational	Automatic closing of gates on reservoir to isolate intake when salinity thresholds are above trigger levels; capacity designed to withstand increased periods of closure in future years	X	X	X	n.a.	Water sources	Protection against other chemical spills/sources of contamination
Operational	Increased monitoring of river water quality	X	X	X	n.a.	Water sources	Protection against other chemical spills/sources of contamination
Institutional/ capital	Increased urban green space or sustainable urban drainage systems	n.a.	X	n.a.	X	Sewer/ drainage networks	Reduced drainage and treatment requirements; social/environmental benefits; floodwater management
Capital/ operational	Increased water quality monitoring and adapted WTP and chemical dosing to handle increased flows	n.a.	X	X	n.a.	WTPs	Financial efficiency and resource efficiency, decreased flood risk
Operational	Increased water quality monitoring during periods of drought	X	n.a.	n.a.	n.a.	Treatment	Financial efficiency and resource efficiency

table continues next page

TABLE D.1. continued

Type of resilience measure	Resilience action	Addresses climate impact: droughts and water scarcity	Addresses climate impact: precipitation intensity	Addresses climate impact: sea level rise and saline intrusion	Addresses climate impact: storm surge and coastal flooding	Primarily benefitting process	Co-benefits
Institutional	Increased design requirements for sewers and storm water systems to account for climate change increasing storm surges, runoff, etc.	n.a.	X	X	X	Sewer networks	Utility and drainage efficiency, lower maintenance costs, improved responses for nonclimatic effects
Capital	Injection of treated wastewater into a system of dedicated coastal wells	n.a.	X	X	X	Water sources	n.a.
Operational	Inspection of the outlet gates during heavy rainfall and flooding events at WWTPs with discharge outlets to inland rivers	n.a.	X	X	X	WWTPs	Preparation for all emergencies, useful for nonclimate-related emergencies
Capital	Installation of additional treatment (membranes) to handle increased salinity levels	X	n.a.	X	n.a.	Water sources/ water treatment	Additional water resource
Institutional	Integrated emergency planning with city or national agencies	X	X	X	X	All water supply assets	Valuable for any emergency event including nonclimatic responses
Capital	Modifications to water treatment plants to adapt to a changing raw water envelope	X	X	X	n.a.	Treatment	Additional water resource
Capital	Network of underground tanks to collect rainwater	X	X	n.a.	n.a.	Drainage networks	Helps prevent contaminate water directly entering the sea untreated, additional sources
Operational	Premonsoon preparation: rehabilitation and maintenance; emergency planning	X	X	X	X	All sanitation assets	Improved system efficiency and operations
Socioeconomic	Provide financial incentives to customers to use less water	X	n.a.	n.a.	n.a.	Consumer	Financial efficiency
Operational	Provide increased storage at both household and network levels to serve poor and vulnerable customers in periphery areas	X	X	n.a.	n.a.	Distribution	Emergency planning

table continues next page

TABLE D.1. continued

Type of resilience measure	Resilience action	Addresses climate impact: droughts and water scarcity	Addresses climate impact: precipitation intensity	Addresses climate impact: sea level rise and saline intrusion	Addresses climate impact: storm surge and coastal flooding	Primarily benefitting process	Co-benefits
Capital	Purchase of mobile water treatment plants for emergency drinking water supplies	X	X	X	X	WTPs	Valuable for any emergency event
Capital	Raising pumping station elevations above projected flooding levels	n.a.	X	X	X	Pumping stations	Improved resilience for any event
Operational	Reduce leakage through metering/leakage detection and reduction programs	X	n.a.	n.a.	n.a.	Distribution	Increased revenue/ decreased production costs
Operational (and capital for the development of an alternative source)	Reduce overpumping reliance on coastal aquifer: requires provision of alternative sources and regulations limiting abstraction	X	X	n.a.	n.a.	Water sources	Resource efficiency
Socioeconomic	Reduce water use through regulated and enforced behavioral change (garden watering, filling of pools, water control officers)	X	n.a.	n.a.	n.a.	Consumer	Resource efficiency
Socioeconomic	Reduce water use through technical regulations on equipment and fittings (low flush toilets, metering taps)	X	n.a.	n.a.	n.a.	Consumer	Resource efficiency
Institutional	Regional collaboration-sharing of assets (e.g., mobile water treatment plants)	X	X	X	X	All water supply assets	Valuable for any emergency event
Capital	Reinforcement and twinning of key water abstraction infrastructure	X	n.a.	X	n.a.	Intake and raw water transmission facilities	Improved continuity of supply during routine maintenance
Capital	Retrofitting combined sewer overflows from backflow from SLR, with weirs, duckbills, etc.	n.a.	X	X	X	Disposal/ outfalls	Useful information for all potential scenarios

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TABLE D.1. continued

Type of resilience measure	Resilience action	Addresses climate impact: droughts and water scarcity	Addresses climate impact: precipitation intensity	Addresses climate impact: sea level rise and saline intrusion	Addresses climate impact: storm surge and coastal flooding	Primarily benefitting process	Co-benefits
Institutional	Screening and planning processes to incorporate risks associated with SLR	n.a.	n.a.	X	X	Significant assets in sanitation system	Disaster risk mitigation, reduced flood risk
Institutional	Screening of assets for climate change risk	X	X	X	X	All water supply assets	Valuable for all assets
Institutional	Screening of new/ rehabilitated assets for long-term storm surge vulnerability	n.a.	n.a.	n.a.	X	All water supply assets	Useful information for all potential scenarios
Capital	Separate sewerage and drainage systems	n.a.	X	X	X	Sewer/ drainage networks	Reduced treatment of wastewater
Operational/ socioeconomic	Smart metering programs to improve leakage reduction and provide customers with improved consumption data	X	n.a.	n.a.	n.a.	Distribution	Financial efficiency, reduction of NRW
Operational	Use of reservoirs to temporarily 'bank' water from other sources	X	X	n.a.	n.a.	Sources	Resource efficiency
Socioeconomic	Use water markets to decrease nonpotable water uses	X	X	n.a.	n.a.	Consumer	Economic prioritization of resources
Capital	Wastewater reuse: wastewater effluent retreated to irrigation potable standard and utilized for irrigation	X	n.a.	n.a.	n.a.	Treatment/ disposal	Additional water resource
Capital	Water reuse: wastewater effluent retreated to potable standard and reintroduced to supply	X	n.a.	X	X	Sources	Increased quantity of potable water supplies available with potentially lower energy requirements
Institutional	Water screening and planning processes to incorporate risks associated with SLR	X	n.a.	X	x	Significant assets in water delivery cycle	Useful information for all potential scenarios

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TABLE D.1. continued

Type of resilience measure	Resilience action	Addresses climate impact: droughts and water scarcity	Addresses climate impact: precipitation intensity	Addresses climate impact: sea level rise and saline intrusion	Addresses climate impact: storm surge and coastal flooding	Primarily benefitting process	Co-benefits
Socioeconomic	Community educational outreach campaigns	X	n.a.	n.a.	n.a.	Consumer	Financial efficiency
Socioeconomic	Integrated water resource management	X	X	X	X	All water supply assets	Financial efficiency, interagency collaboration
Socioeconomic	Water trading systems	X	X	X	n.a.	All water supply assets	Financial efficiency, interagency collaboration
Institutional	Modification of design standards	X	X	X	X	All water supply assets	Improved functionality
Institutional	Alignment among different entities on risk and uncertainty across areas	X	X	X	X	All water supply assets	Improved functionality, financial efficiency, interagency collaboration, public perception
Operational	Billing efficiency improvements	X	X	n.a.	n.a.	Consumer	Financial efficiency, improved data quality
Operational	Recurring leak detection program and NRW reduction campaign	X	n.a.	n.a.	n.a.	Distribution	Efficiency
Operational	Systemic monitoring systems	X	X	X	X	Distribution	Improved system efficiency and operations

Source: Adapted from World Bank, forthcoming.

Note: n.a. = not applicable; NRW = nonrevenue water; WTP: water treatment plant; WWTP: wastewater treatment plant.

Glossary

Climate change compared to weather. *Climate change* refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forces such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use (Pachauri and Meyer 2014). *Weather* refers to the state of the atmosphere with regard to temperature, cloudiness, rainfall, wind, and other meteorological conditions. The difference between weather and climate is therefore the measure of time.

Risk compared to deep uncertainty. *Risk* refers to uncertainty that can be quantified with probability distributions. For example, the likelihood of experiencing a car crash is easily calculable from ample historical data. But many future conditions cannot be reliably quantified and are called deep uncertainties (Knight 1964). Here, *deep uncertainty* is defined as uncertainty that occurs when parties to a decision do not know or cannot agree on (i) models that relate the key forces that shape the future, (ii) probability distributions of key variables and parameters in these models, or (iii) the value of alternative outcomes (Lempert, Popper, and Bankes 2003).

Failure. *Failure* is one of the most subjective terms used and is heavily reliant on the context. However, it can be broadly defined as when the level of service drops to a point at which it adversely affects users. This is discussed in greater detail throughout the document.

Level of service. The level of service defines the way in which utility managers and operators want the system to perform over the long term. It includes technical, managerial, and financial components. It is therefore a fundamental part of how a utility's system is operated. Level of service objectives commonly include statements about (i) how much water the water supply system will typically be able to supply; (ii) how often and for how long water restrictions might occur; and (iii) the possibility of needing an emergency water supply due to a prolonged drought. The objectives provide a basis for water supply security planning, helping to balance the need for water with the cost of supplying it.

Regret. The concept of *regret* is defined by Savage (1950) as the difference between the performance of a strategy in a future state of the world, given some value function, and that of what would be the best-performing strategy in that same future state. In other words, regret is a measure of how big a mistake one can make when making choices under uncertainty. A metric for measuring the robustness of one adaptation project is calculating the maximum regret of implementing the project or the worst performance of the project across all scenarios (for instance its lowest net present value), and comparing it to the maximum regret of not implementing the project (highest possible net present value of the project across all scenarios). A no-regret action provides benefits under all future conditions.

Reliability. The probability that supply is sufficient to fulfil demand fully, or to an acceptable agreed level, for instance, 99 percent of the time.

Resilience. The capacity of a project or system to absorb the shocks or stresses imposed by climate change and other factors, and in the process to evolve into greater robustness. Projects planned with resilience as a goal are designed, built, and operated to better handle not only the range of potential climate change and climate-induced natural disasters but also contingencies that promote an efficient, rapid adaptation to a less vulnerable future state.

Robustness. A robustness criterion seeks solutions that are good (though not necessarily optimal) no matter what the future (Lempert et al. 2006). There exist several specific definitions of *robustness*, but all incorporate some type of satisfying criteria. For instance, a robust strategy performs reasonably well compared to the alternatives across a wide range of plausible future scenarios. Often there is no single robust strategy but a set of reasonable choices that decision makers can choose among; they may evaluate the trade-offs between robustness and other decision criteria, such as costs and feasibility. Utilizing robustness as a decision criterion is significantly different from what most utilities (and decision makers in all sectors) do. The traditional approach ranks alternative decision options on the basis of what is believed to be the most credible probability distribution s. In general, there is a best (i.e., highest ranking) option. The shortcoming of the optimal solution is that it is only optimal for a single predicted future, but may perform poorly if that future does not occur.

Stress. Stresses are factors that make the effective operation of a utility or project more difficult. Stress can be induced by many factors including limited financial resources, poor management capacity, or impacts from climate change.

Vulnerability. The propensity or predisposition to be adversely affected. Vulnerability encompasses such concepts as sensitivity or susceptibility to harm and lack of capacity to adapt.

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