Official Journal of the World Water Council
Water Policy

 Water Policy Vol 23 No S1, 31 doi: 10.2166/wp.2021.265

Water-related infrastructure investments in a changing environment: a perspective from the World Bank

Diego J. Rodríguez[a,*], Homero A. Paltán[a], Luis E. García[b], Patrick Ray[c] and Sarah St. George Freeman[d]

[a] World Bank Group, Global Water Practice, Washington DC, USA
[b] Independent Consultant, Washington DC, USA
[c] Department of Chemical and Environmental Engineering, University of Cincinnati, Cincinnati, USA
[d] Civil and Environmental Engineering Department, University of Massachusetts Amherst, Amherst, USA
*Corresponding author. E-mail: drodriguez1@worldbank.org

ABSTRACT

At present, there is a global deficit in infrastructure and the World Bank Group (WBG) is one of the major sources of financing to reduce this gap worldwide. The WBG has policies and protocols for approving investments taking into consideration financial and economic indicators while ensuring social and environmental safeguards. In recent years, these safeguards have been updated to include the effects of climate change and robustness and resilience to support climate-informed project investment decision-making. A series of tools for screening projects for climate vulnerabilities and identification of risk management options have been developed to help project teams comply with these requirements. One of these tools is the hierarchical four-phased Decision Tree Framework (DTF) that, beyond screening, helps to analyze plans and project vulnerabilities, climate-related or otherwise, using a decision scaling approach, and explore risk management options, if necessary. The four phases of the DTF are (i) project screening, (ii) initial analysis, (iii) stress test, and (iv) climate risk management. This paper reviews applications of the DTF from the climate change screening phase to non-climate uncertainty screening and decision-making for project investments and prioritization. A peek into work in progress for incorporating resilience in the decision-making process, both for projects and through projects, is also provided, as well as next steps, looking forward.

Key words: Climate change, Climate-informed investments, Decision-making, Development, Infrastructure, Uncertainty

HIGHLIGHTS

- Since 2010, the World Bank Group has developed several tools that facilitate climate risk assessment and evaluation to inform decision-making.
- The Decision Tree Framework (DTF) integrates them within a bottom-up approach which accounts for various uncertainties that challenge the water sector while narrowing the gap between science and its practical applications.
- The DTF permits the consideration of resilience aspects beyond the physical dimensions of water infrastructure including the integration of human, economic, and institutional-governance systems.
- The DTF pilot studies suggest its practicality, flexibility, and scientific coherence for its application in the wide diversity of water projects across various geographies.
- Apart from its progress, the DTF still needs to adequately refine the incorporation of green infrastructure, water quality risks, energy efficiency and renewable, sea-level rise, and others.

1. INTRODUCTION

Managing water is a key factor in reducing poverty and promoting shared prosperity, playing an important role in achieving the sustainable development goals (SDGs) (Merrey & Awulachew, 2015; United Nations, 2019). Our ability to manage water is at the same time facing a critical point in human–water relations that merits urgent attention and action (Wilby, 2019). The contributions and limitations of both gray and green water infrastructure for this purpose have been highlighted around the world over the years, so has the social and economic benefits of closing the investment gap for building new, and maintaining existing, water infrastructure. This is needed to confront the challenges posed by climate variability and projected changes, growing populations, intensification of water use activities, increasing pollution, and rising social and economic costs caused by floods and droughts (Rodríguez *et al.*, 2012; Cervigni, *et al.*, 2015; Value of Water Campaign, 2017; UN Water/WBG, 2018).

Never has this been more evident than in present times. Important uncertainties in the changing conditions of the natural and climatic system, as well as human, social, economic, and institutional factors, are likely to alter the principal characteristics for which a project was originally designed, jeopardizing its success. The hydrological response of a catchment to accelerated changes in the historic climatic conditions, alongside land-use changes and population growth, casts a shadow of doubt about the reliability of long-cherished traditional hydrological methods based on erstwhile stationarity working assumptions. In what cases are these methods still applicable? When are new approaches and methods needed? What are the desired characteristics of new methodologies? Recognizing and assessing these uncertainties is only the first step. They must be incorporated into the institutional decision-making investment process framed by financial, economic, social, and environmental conditions of existing policies.

Aware of these circumstances, since the 2010s the World Bank Group (WBG) in collaboration with its partners has been working to quantify these uncertainties and incorporate them in the decision-making process for water-related investments. With its current portfolio of annual water investments on the order of US$41.5 billion, the WBG is presently an important multilateral source of financing and investment for water projects globally. It benefits, therefore, from an excellent opportunity to incorporate the latest developments in investment decision-making under uncertainty (climate and other), applied to water-related infrastructure and planning, and transmit them to its client countries for application at the local level.

Section 1.1 of this paper overviews the WBG's framework for water-related project financing and how this framework has been gradually incorporating climate change, robustness, and resilience considerations. Section 2 summarizes some of the tools available for implementing major climate change-related commitments. Section 4 describes in more detail the origin, evolution, and potential of one of these tools for decision-making under uncertainty - the Decision Tree Framework (DTF) (Ray & Brown, 2015). Section 4 reviews piloting applications of the DTF as it has evolved from the climate change screening phase to non-climate uncertainty screening and decision-making for project investments and prioritization in planning, incorporating robustness and resilience in the decision-making process, work in progress, and next steps. Section 6 includes potential DTF roles not yet developed.

1.1. World Bank Investment Project Financing

The WBG's Investment Project Financing Policy calls for the assessment of a proposed project based on various country and project-specific considerations, project objectives and technical, economic, financial management and procurement, environmental and social considerations, and related risks. The environmental and social considerations (known as Safeguard Policies for Investment Project Finance operations) included environmental assessments and action plans as well as safeguards related to natural habitats, water resources management, pest management, indigenous peoples, physical and cultural resources, involuntary resettlements, forests, and safety of dams, as well as other considerations for each specific project, related to location in international waterways and in disputed areas, as applicable.

Echoing the conclusion of the IPCC in its 2007 Fourth Assessment Report, that warming of the climate system is unequivocal, and that the effects of climate change are already visible in terms of higher average air and ocean temperatures, widespread melting of snow and ice, rising sea levels, floods becoming more common in some regions, while in others droughts becoming more intense, the WBG made climate change the central theme of its 2010 World Development Report '*Development and Climate Change*' (World Bank, 2010). Among key conclusions were that climate change threatened all, but particularly developing countries, and that these countries were more exposed and less resilient to climate hazards. Nevertheless, it also concluded that reducing climate risk was affordable. However, further climate change is unavoidable and decision-making processes needed to evolve to tackle a riskier and more complex environment. This brought to the forefront the need for alternative frameworks for decision-making to address uncertainties that are difficult to evaluate and to minimize vulnerabilities not just to a single but to a range of possible risks. The 2010 World Development Report put forward a policy prescription, stating that this approach should be complemented by decision support techniques that looked for 'robust' (encompassing a wider range of unanticipated variability) rather than just economically optimal strategies, where costs, benefits, and the trade-offs inherent in climate policies were assessed under all scenarios.

In 2016 the WBG's Climate Change Action Plan 2016–2020 was published (World Bank, 2016), supported by five strategic shifts for the Bank's climate work: (i) support for the implementation of plans, (ii) convergence of the WBG's climate and development agendas into strategies and operations, (iii) shaping national investment policies and programs to maximize the impact, (iv) rebalance the WBG climate portfolio increasing the focus on adaptation and resilience, (v) and facilitating transformation from business as usual to achieving global climate commitments. The activities under the Climate Change Action Plan were organized around four priorities: (i) support transformational policies and institutions, (ii) leverage resources, (iii) scale-up climate action (in renewable energy and energy efficiency, sustainable mobility, sustainable and resilient cities, climate-smart land use, water and food security, green competitiveness, and other actions such as early warning systems, climate and health, and others), and (iv) align internal processes and work with others.

By 2017, the Bank priority areas included climate change and infrastructure alongside gender, social and political fragility, and public–private partnerships. The Environment and Social Framework or ESF (World Bank, 2017a) was launched, offering broader and more systematic coverage of environmental and social risks, including climate change. The ESF will progressively replace the current Safeguard Policies for Investment Project Finance operations, with the two operating in parallel for about 7 years (World Bank, 2018a). The Adaptation and Resilience Action Plan (World Bank, 2018b) prioritizes adaptation and resilience, elevating them to an equal footing with climate mitigation actions. Besides boosting adaptation financing and mainstreaming the incorporation of climate risk in planning, design, and implementation, the Plan includes developing a new resilience rating system for development and infrastructure projects on the ground and creating incentives for governments, project developers, and investors to select higher-resilience options.

Over the past few years, the WBG has also made important climate change-related corporate commitments, establishing targets to integrate climate change into operations and strategies. Guidance notes have been produced and periodically revised and adjusted as necessary to help operational teams move toward a climate-smart portfolio and maximize the project's climate adaptation and mitigation co-benefits (the portion of financing in a project that contributes to climate adaptation and/or mitigation).

Currently, the WBG aims to implement four major commitments related to climate change: (i) climate and disaster risk screening; (ii) greenhouse gas (GHG) accounting; (iii) shadow price of carbon application (to GHG emissions and reductions); and (iv) climate adaptation and mitigation co-benefits tracking. Guidelines for designing climate-informed projects around the four major climate change commitments applicable to the WBG's Water Global Practice would include three interconnected steps:

1. Gain insight into climate change vulnerability context and GHG emissions associated with the project, identifying current and expected climate and disaster risks, emission implications, and opportunities to improve the project.
2. Informed by the results of step 1, design project components to be climate-prepared, particularly for adaptation and resilience.
3. Ensure that the mitigation and adaptation co-benefits are articulated according to the Joint Multilateral Development Bank agreed methodologies for tracking climate change adaptation and mitigation finance. Adaptation co-benefits are assigned to a project only if it incorporates the project's climate change vulnerability context, the intent to address the identified vulnerabilities is explicitly stated, and a clear and explicit link between the identified vulnerabilities and specific actions is established.

To address each of these steps, the guidelines provide a wide list of tools and resources that the project team can use. For the purpose of this paper, only the following will be discussed in the next section: the Climate Change Knowledge Portal (CCKP), the WBG Climate and Disaster Risk Screening Tools (CDRST), and the DTF.

2. TOOLS AVAILABLE FOR IMPLEMENTING MAJOR CLIMATE CHANGE-RELATED COMMITMENTS

The first two tools, described below, provide a rich guide to initially identify whether a project is vulnerable to climate variability and other hazards, and the level at which a project may be impacted. Yet they do not provide by themselves a detailed description of risks, nor do they provide enough bases for risk management or to design strategies to increase the robustness or resilience of a project. This can be done with the third tool – the DTF – described in following sections.

2.1. Climate Change Knowledge Portal

This web-based platform (http://sdwebx.worldbank.org/climateportal/) runs on a Google Maps interface so the user can query any location, country, or region on the globe. Historical climate conditions are derived from the global network of weather stations which have been quality-corrected as well as complemented with gridded global historical products. Future conditions are calculated from global circulation model (GCM) outputs from several models utilized in the IPCC's 5th Assessment Report. Examples of statistics derived from the main climate variables shown in this platform include projected changes in maximum daily temperature, monthly maximum temperature, largest 5-day cumulative rainfall, annual maximum daily rainfall, and others. Similarly, the tool provides projected impacts in various indicators describing change in the energy, agriculture, health, drought, and water variables. The change in these variables can be visualized and downloaded for various future climatic scenarios and decades in the 21st century. An example of an output of this tool is shown in Figure 1.

The standardized spatial resolution is 2° (about 200 km). The tool has also aggregated these results at the basin level for various major rivers of the globe. Although information provided by the CCKP cannot be taken as precise predictions of future climate change, water-planners may be able to use them to get an initial idea of the range of future climate, as part of a first-order examination of the projected change of the historic climate conditions which could be anticipated for a specific water project.

2.2. Climate and Disaster Risk Screening Tools

These specific tools are intended to support Bank Project Teams to understand if and why further studies and consultations may be required during the design of climate-vulnerable projects but may be of use also for

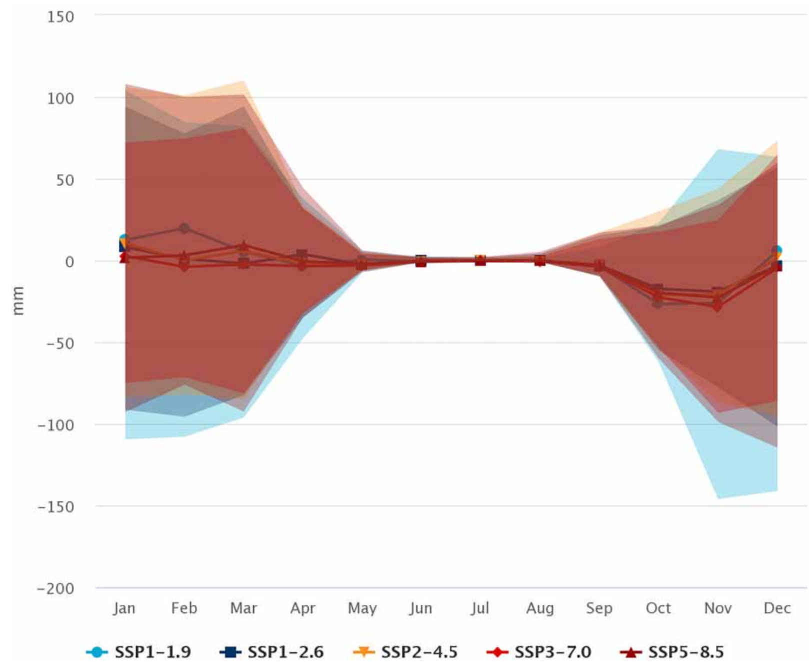

Fig. 1 | Projected precipitation anomaly for a catchment in Southern Africa, 2060–2079.

other decision-makers. This set of screening tools is best applied at the early stages of project evaluation, as they consider climate and disaster risks at the high level (in both the short and long term, and at the country and project scales). The aim of these screening tools is, thus, to ensure that decision-makers properly incorporate anticipated climate variability and particularly extreme events that are the basis of potential natural disasters, in the development and design of policies, programs, and projects. At a country-level scope, the user can apply this tool to examine the way in which climate, and other natural hazards, may affect national strategies and policies or institutional reforms during their design phase. At the project level, the tool provides specific instruments to systematically explore risks and support investments in the health, transportation, energy, coastal flood protection, agriculture, and the water sector.

The CDRS for water projects can be accessed via its online WBG platform (https://climatescreeningtools.worldbank.org). First, it allows the user to detail the basic characteristic of a water project, namely title, type, location, and others. From here, the user can evaluate the project's perceived or qualitatively estimated exposure to the range of climate and geophysical conditions and hazards which are given by the location of the project. The climatic conditions and hazards, which can be identified, include extreme temperatures, extreme precipitation and flooding, drought, sea level, storm surge, and extreme winds. This climatic information is given by the CCKP platform. The user is then able to categorize the estimated level of exposure of a project. Next, this set of tools permits the exploration of potential impacts by combining exposure to multiple hazards and the vulnerability of the project, which depends on the user understanding of the project. In this stage, the users can rate the expected level of impact to one or various sources of present or future hazards. Then, the tool permits one to assess and rate the proposed project's capacity to adapt to the range of impacts identified. Lastly, these data are used to develop a summary report which identifies the overall estimated risk of a project (see Figure 2).

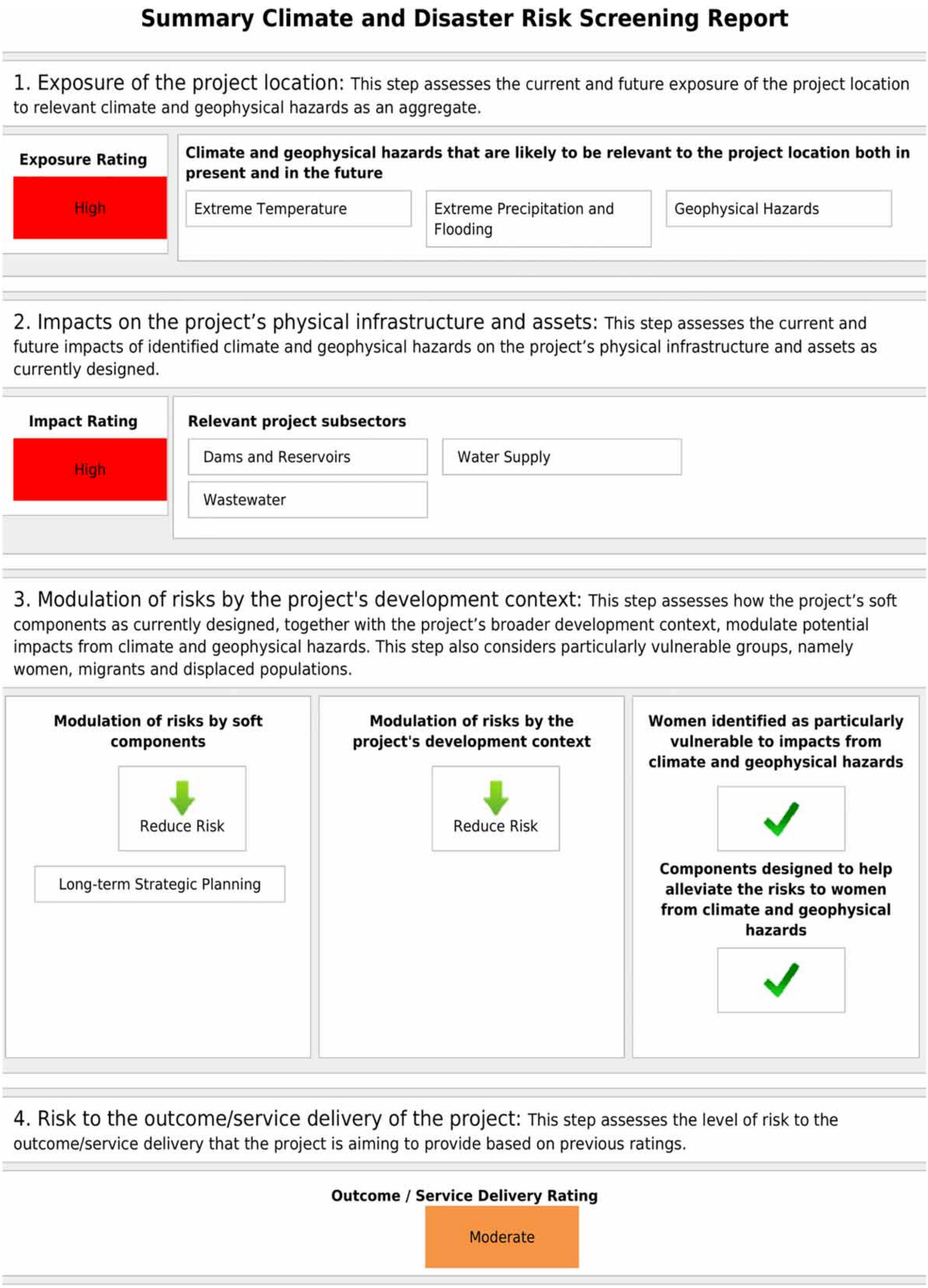

Fig. 2 | Summary climate and disaster risk screening report as output of the Climate and Disaster Risk Screening Tool.

2.3. Decision Tree Framework

This tool goes beyond the CDRST and provides the Project Teams with additional specific questions to ask when screening water-related projects. Its application basically starts after the CDRST (or any other suitable screening method) indicates the project is vulnerable to climate change. If so, it goes into a rapid project scoping exercise to assess the importance of the project's vulnerability to climate change *vis-à-vis* other vulnerabilities. Here, vulnerability thresholds are defined on a project-by-project basis and depend on their design, characteristics, historical tipping points, or others as agreed by stakeholders. If the vulnerability to climate change is deemed significant, it calls for an exhaustive climate risk analysis or stress test, using a bottom-up approach, defined later in this chapter. In the WBG version, it uses the decision-scaling approach (Brown *et al.*, 2012) for robust-based planning of water systems but it can conceivably also use other existent bottom-up approaches. The DTF uses a stress test as a simple way to identify the vulnerabilities of a system, which also permits the evaluation of their response when modifications are performed. If the results of the stress test indicate that the project needs modifications, a further step is needed to verify if its robustness, or other selected performance metrics, can be improved. The results of this analysis will indicate if the project can be adjusted or if more complex methodologies of decision-making under deep uncertainty are needed in search for an adequate performance of the selected metrics, or even if other options should be explored. Section 4 below describes in more detail the characteristics of the DTF.

3. ORIGIN, EVOLUTION, AND POTENTIAL OF THE DTF

3.1. Early initiatives to communicate climate data science

In 2009, the report 'Water and Climate Change: Understanding the Risks and Making Climate-Smart Investment Decisions' (Alavian *et al.*, 2009) was published by the WBG. It was an effort to assist countries with incorporating adaptation to climate variability and change in their work programs. The report also provided the first version of a tool that could be used to assess exposure and screen the investment portfolio on a regional basis.

According to a prevalent trend at the time, the WBG followed traditional approaches that downscaled the results of several GCMs under given IPCC scenarios to project streamflow series as input for project design. These approaches (often referred to as 'Top-Down') rely on the initial understanding and manipulation of data derived from GCMs to infer responses at the local scale. Yet, scientific literature has widely recognized the limitations which may occur when manipulating and making decisions solely with these data. These limitations are typically a result of the large uncertainties which are inherited from the configuration and characteristics of GCMs (Stainforth *et al.*, 2005, 2007; Teng *et al.*, 2012; Hartmann *et al.*, 2013), whose original purpose was to simulate climate conditions at a global scale and not hydrology at a local scale. This led water managers to face a wide range of possible scenarios of future climate conditions. If one scenario was chosen over the rest, it may lead to the project being vulnerable to the occurrence of a combination of other *likely* climatic possibilities and the cumulative uncertainties may not, in fact, be adequately characterized.

Acknowledging these fundamental limitations of climate projections, in 2012 the WBG Independent Evaluation Group in its Report 'Adapting to Climate Change' (IEG World Bank/IFC/MIGA, 2012) identified that 'climate model information has generally been unable to inform quantitative decision making' in various previous water resources studies. As such, the report concluded that climate models 'have been more useful for setting context than for informing investment and policy choices'.

Furthermore, in 2014 the International Development Association (IDA), which is the WBG's fund to fight extreme poverty, acknowledged the need for climate change risk assessment under its Seventeen Replenishment IDA17: 'Maximizing Development Impact, Special Theme 3: Climate Change'. It called for 'mainstreaming climate and disaster risk management in IDA countries' strategies, policies and investments' and to 'screen all new IDA operations for short- and long-term climate change and disaster risks and, where risks exist, integrate appropriate resilience measures' (IDA, 2014). This now applies as well to all World Bank projects.

Also, existing research suggests that changes in population dynamics, economic circumstances, demand patterns, land-use change, and others all have important effects on the future characteristics and outputs of water resources systems, and they are equally uncertain decision variables (Groves *et al.*, 2008; Lambin & Meyfroidt, 2011; Stakhiv, 2011; Buytaert & Bievre, 2012). Failing to incorporate these variables, along with an incorrect representation of climatic outputs and their uncertainties, may in turn importantly affect the description and assessment of the characteristic of design risks and costs in water planning and investment design.

3.2. Incorporating decision-making under uncertainty and risk-based approaches

Both the IDA17 call and the acknowledgment of IEG were congruent with the recommendations of the WBG's 2010 World Development Report. There was a need to develop an accepted process for climate change risk assessment in order to reduce the vulnerability of people, their assets, and livelihood to climate-related risks.

This fueled a paradigm change from the traditional method of Predict, then Act approach, to a Flexible and Robust Decision-Making (RDM) approach. Thus, several applications of the RDM methodology (Lempert *et al.*, 2006) were made by the WBG, among them, to various existing projects under preparation in Africa (Cervigni *et al.*, 2015) and to Peru in the 'Strategy for Implementing Lima's Long-Term Water Resources Master Plan' (Kalra *et al.*, 2015).

A summary of existing decision-making methodologies able to deal with climate-related uncertainty, namely cost–benefit analysis under uncertainty, cost–benefit analysis with real options, robust decision-making, and climate-informed decision analysis, was later compiled by Hallegate *et al.* (2012) to help decision-makers identify which method was more appropriate in a given context, as a function of the project's lifetime, cost, and vulnerability.

Conceivably, some questions from the practitioner's point of view can be posed: would these methodologies be applicable in all the cases? If not, in which cases should they be applied? Were there other simpler analyses that could be applied in some simpler cases and if so, what were their characteristics? Looking to respond to these types of questions, a series of analytical approaches have been developed which tend to look at the intrinsic characteristics of a water resources project or system and describe them in terms of exposure, sensitivity, and their adaptive capacity to withstand stress (García *et al.*, 2014; Ludwig *et al.*, 2014; Rosenberg & Madani, 2014; Brown *et al.*, 2015). These approaches are commonly referred to as 'bottom up' since they first assess the characteristics of the existing system and its sensitivity to a wider range of climate inputs and identify the parts of the system that are most vulnerable, and the specific attributes of those vulnerabilities. From here, these approaches look to examine the response, or sensitivity, of a system to a series of climate projections or other variables that stakeholders consider may affect the expected outcomes of their project.

Thus, bottom-up approaches permit analysts to include potential sources of risk such as change in population dynamics or economic conditions, as previously mentioned. Several methodologies of the bottom-up approach exist in the current scientific literature. They include the scenario-neutral approach (Prudhomme *et al.*, 2010), the information-gap theory (Hine & Hall, 2010), the risk informed decision-making (Ayyub *et al.*, 2010), and the decision scaling approach (also known as the Climate Informed Decision Analyses) (Brown *et al.*, 2012). In these approaches, the level of complexity as well as the resources needed to inform decisions is scaled (adjusted) according to the unique characteristics of a project and other relevant factors, as well as the issues and decisions that may arise in the process that are generated by stakeholders. As such, during the various stages of this process, water resources managers as well as local stakeholders can interact in order to identify not just the potential risks, but also agree on the appropriate level of analyses required to understand the vulnerabilities of the system. So these approaches, instead of beginning with the examination of climate projections and hazard calculations, looks to consult relevant stakeholders, explore data available, and others which lead to an informed evaluation of the system characteristics.

Using these approaches allows not only diagnosis of the potential impacts of climate and other variables in a water project, but also generation of adaptation options, which would reduce the effect of the relevant stressors in a system (Hamlet, 2011). Often these approaches permit water planners to assess the chances of success, or failure, of a specific project under current or plausible future conditions (Rosenberg & Madani, 2014). From here, water managers are in the position to propose modifications to the project in order to test the response of such modification to the identified stressors. At this stage, decision-makers and stakeholders would be able to formulate and design more risk–cost-effective resilient and robust solutions for a project.

Since 2011, the WBG has conducted a series of studies, which included components of these risk-based and/or bottom-up approaches. For instance, Rodríguez-Iturbe & Valdés (2011) presented a simple framework, which aimed to understand and predict floods and monthly flows at the catchment level, in various dry and humid ecosystems in rivers of Venezuela and Kenya, and in Arizona and Florida in the USA. This framework proposed 'no-regret' actions in order to produce positive results regardless of the existence of hydroclimatic changes. At the same time, this framework proposed to treat rainfall as a stochastic process to address random fluctuation in rainfall and its impacts on soil moisture seasonality.

In 2012, the Executive Secretariat of the Niger Basin Authority (NBA) and the WBG implemented jointly a climate risk assessment (CRA) initiative for the Niger River Basin (Grijsen *et al.*, 2012). The proposed approach followed a risk-based framework which identified a series of potential climate hazards by analyzing response sensitivities of selected performance indicators (related to hydro-energy generation, irrigated agriculture, navigation, flooding, and the sustenance of environmental flows) to shifts in runoff. The approach translated shifts in future climate variables into runoff changes following an elasticity approach (e.g., what is the runoff response to a $\pm 10\%$ change in precipitation of the existing system?). The study also looked to assess the ability of this water system to tolerate climate variability in terms of the elasticity of performance indicators – both on its operational characteristics, as well as its overall designed capacities and structural reliability. In this case, the results suggested that the impacts of climate changes on the water resources of the Niger River Basin would be mild to modest. It should be noted that historical streamflow records presented more critical situations than those projected by GCMs, diminishing the usefulness of the projections for exploring system vulnerabilities to climate change in a stress test framework. A similar elasticities approach to examine runoff response to climate variables was later applied to assess the climate vulnerability of the Tina Hydropower Project in the Solomon Islands (Grijsen, 2016).

In a more comprehensive effort in 2013, the WBG completed a study which looked to exhaustively assess the impacts of climate risks and development alternatives on water and agriculture in the Indus Basin of Pakistan (Yu *et al.*, 2013). A multi-modeling framework was developed to understand the interdependencies between climate, water, food, and the economy. The results showed that the most sensitive parameters to climate in this basin are inflow from stream tributaries, crop water requirements, and depth of groundwater. This framework also helped to explore the implications of possible adaptation investments scenarios. The results, for instance, indicated that investments in canal efficiency and crop yield would minimize the impacts of future climate risks and meet the food self-sufficiency objectives of the country. The importance of the effect of non-climate factors, such as mandatory distribution of water volumes among provinces, was also highlighted.

3.3. Structure and process of the DTF

As above-mentioned, a tool capable of addressing climatic and non-climatic uncertainties in water resources planning and project design, while building on state-of-the-art scientific methods and the practical experiences from the studies mentioned above, was needed. But mainly, able to answer what should be an obvious question of a hypothetical Bank Task Team Leader or likewise mid-level decision-maker or water engineer in any WBG Client Country:

> '*I know that my plan or project is vulnerable to the effects of climate change, which might be to some extent uncertain, and I am convinced of the importance of taking them into account in my plans and designs. How best to do it in a manner commensurate with the perceived vulnerability of the investment and the corresponding justifiable effort and cost?*'

Thus, the WBG, in partnership with organizations such as the Alliance for Global Water Adaptation (AGWA), the U.S. Army Corps of Engineers, the University of Massachusetts-Amherst, and the Stockholm International Water Institute (SIWI), among others, started in 2011 to develop an updated framework for analysis – hopefully meeting those characteristics – that in 2015 resulted in what is now called the DTF.

For its development, similar decision support tools used by other institutions were reviewed and many consultations, internally and externally in international technical meetings, were held. The resulting DTF is a bottom-up tool for decision-making under uncertainty that encompasses a step-by-step decision-making approach resembling the attributes of a branch of a tree. It looks to deepen or scale up the level of analysis only when needed by the perceived vulnerability of the project at each step. This characteristic in turn helps decision-makers to make better use of their human and financial resources and make use of known and proven hydrology and water resources methodologies.

To improve the effectiveness of water resources management planning and project design under climate variability and change, it incorporates into the analysis the climate science insights provided by constantly improving models. It then compares its effects *vis-à-vis* other non-climate uncertainty. It also offers transparency that lets the decision-maker or engineer know what is going on at each step and allows them to make the decisions.

In addition, the DTF also looks to maximize the utility of previous WBG diagnostic tools such as the CCKP and the CDRST. Also, while using up-to-date scientific knowledge to assess and manage climatic and non-climatic risks in water planning and projects, it is flexible in that sense, and it can conceivably use many methodologies or models according to the characteristics and needs of the problem at hand and the requirements of the user. The DTF is, therefore, designed in such a way that the process can be followed mainly within the capabilities available to water managers and increase their confidence about the overall assessment of climate risks while increasing their capacity to manage them. A graphic overview of the DTF is presented here in Figure 3.

One of the principal characteristics of the Decision Tree process is that it is hierarchical, meaning that the continuity of the process is assessed in each phase of analysis. The DTF involves four main phases. Phases 1 through 3 correspond to the risk *assessment* stage of analyses. Lastly, Phase 4 provides the elements necessary to *manage* risk. As such, the four hierarchical phases of the DTF process are: Screening (Phase 1), Initial Analysis (Phase 2), Climate Stress Test (Phase 3), and Climate Risk Management (Phase 4). The above steps are described in more detail in Supplementary Material, Information 1, and graphically in Supplementary Material, Information 2.

4. SUMMARIZING THE IMPLEMENTATION OF THE DTF

From its inception, the DTF was designed to be applied to all types of water infrastructure projects at the earliest stages of study (pre-feasibility or feasibility) so that whatever recommendations for risk management could be provided in advance of the more detailed and definite design stages. The DTF was not conceptualized as an independent tool but as an integral component of the pre-feasibility or feasibility studies, consistent with existing planning and evaluation protocols. Therefore, its added level of effort and cost should be commensurate with the

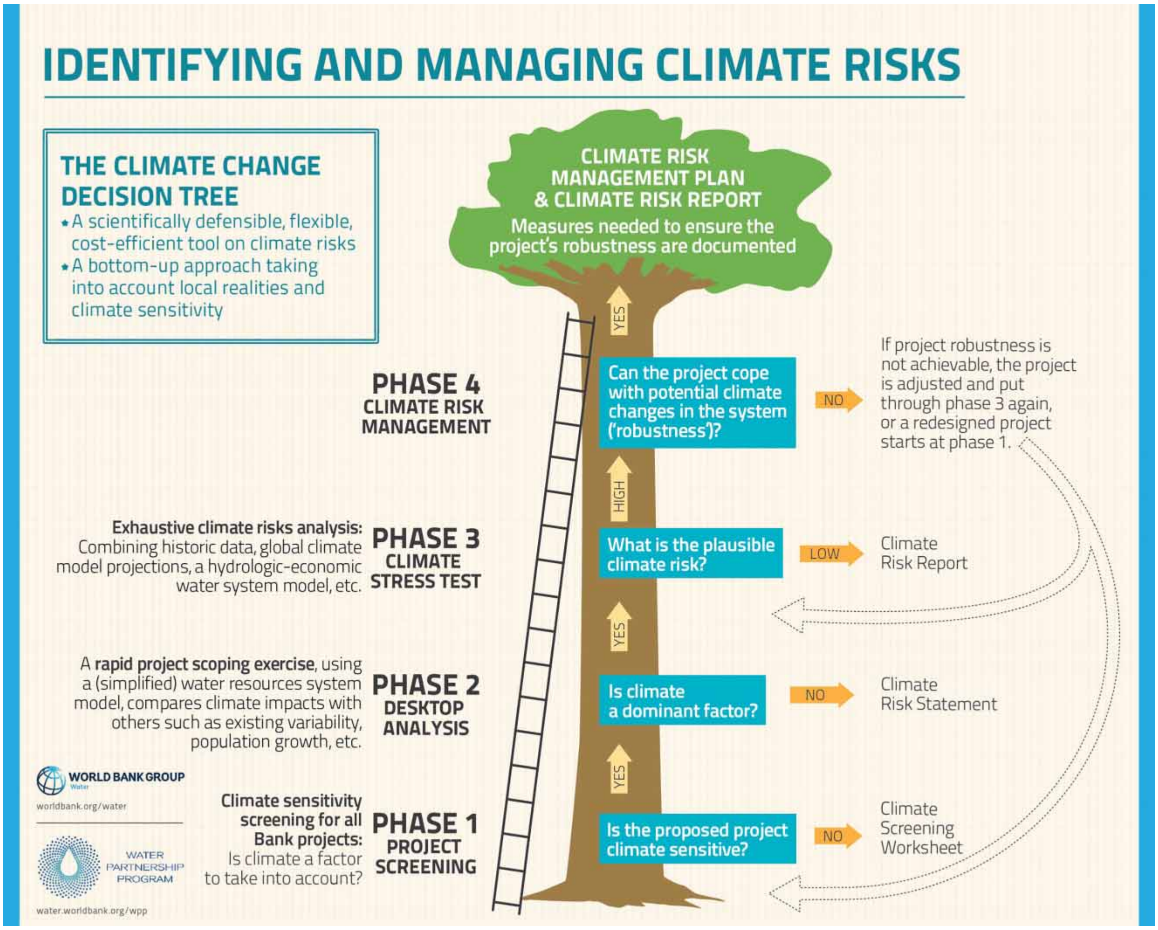

Fig. 3 | Decision Tree Illustration. *Source: Water Partnership Program (WPP), Water Security for All: The Next Wave of Tools. Annual Report 2013/2014.* World Bank Group.

effort and cost of these study stages. For the same reason, the DTF was originally a tool for analysis once the plans and pre-designs have been elaborated.

Since its launch by the WBG in 2015, the DTF has been able to successfully disseminate the climate component of a project *vis-à-vis* other potential risks while providing management strategies. The DTF has been piloted in 10 WBG projects and one more is currently still in implementation. These are: (1) the Upper Arun Hydroelectric Project (UAHP) in Nepal, (2) the Mwache Multipurpose Reservoir in Kenya, (3) the Poko Hydroelectric Project in Indonesia, (4) the Cutzamala Water System (CWS) in Mexico, (5) the Evaluation of the SACMEX Urban Water Resilience in Mexico City, Mexico, (6) the Kabeli-A Run of River Hydroelectric Project in Nepal, (7) the Lower Nzoia Irrigation and Flood Control Project in Kenya, (8) the Multipurpose Water Resources System in the Chancay-Lambayeque Basin in Peru, and (9) the qualitative design of Resilient Strategies for the Malanje and Lubango Water Utilities, Angola. Current activities include concluding stages of the Modeling of Water Security and Resilience for the Valley of Mexico, Mexico.

The DTF has also been the basis for the preparation of WBG sector guidelines such as (1) the Resilience Guidelines for Water Supply and Sanitation Utilities and (2) the Hydropower Sector Climate Resilience Guidelines (World Bank, Mott MacDonald, 2017). The latter is now being tested in the field in collaboration with the International Hydropower Association (IHA) and the European Bank for Reconstruction and Development (EBRD) in three to five pilot projects. At present, the projects that the WBG is targeting are the Kabeli-A in Nepal and the Mpatamanga in Malawi.

4.1. From assessing uncertainties to investment decision-making

As shown in previous sections, the WBG in collaboration with its partners and the support of world-class researchers has made significant advances in facing the practical challenges posed by climate change in water-related plans, investment design, and operations.

The WBG – as do other similar institutions – has specific policies and rules for project financing and is favoring the use of decision-making under uncertainty approaches to incorporate climate- and non-climate-related uncertainties into its decision-making framework, where the DTF is an important resource.

As previously discussed, the WBG's Safeguard Policies for Investment Project Finance operations have evolved with an increasing attention to social and environmental issues (through the ESF) and within these, climate change, and within this, adaptation and resilience resulting in guidelines for designing climate-informed projects around four major climate change commitments, which include climate and disaster risk screening, and adaptation and mitigation co-benefit tracking.

Although the DTF is included as a tool for the climate and disaster risk screening first step, its usefulness goes beyond that. It supports project teams to also assign co-benefits by specifically assessing the project's vulnerabilities to climate change and suggesting linked risk management actions. As mentioned in the Pakistan Indus Basin study (Yu *et al.*, 2013), non-climate factors (such as land-use change) may, in some cases, be equal or more important than those attributed to climate. Beyond the climate change realm, the DTF also helps the project team to assess other non-climate-related vulnerabilities and their relative importance among themselves and, in comparison, with those attributed to climate. It will also help the project team to assess and compare the project behavior in relation to its intended delivery reliability and other indicators such as cost, robustness, and resilience, when subject to uncertain climate and non-climatic stressors.

As such, examples of piloting applications of the DTF as it has evolved from the climate change screening phase to non-climate uncertainty screening and decision-making for project investments and prioritization are reviewed below.

4.2. Climate change and non-climate uncertainties

The UAHP in Nepal (see Supplementary Material, Information 3) was the first pilot where the DTF was applied (Bonzanigo *et al.*, 2015). The objective of the study was to assess the vulnerability of the pre-feasibility 335 MW design of the UAHP to changes in the initial (climate and other) conditions under which the proposed design was based; and to recommend adaptation strategies through iterative CRA and climate risk management. Using visual aids, such as interactive parallel plotting (see Figure 4), proved to be useful to illustrate this type of comparative analysis results for decision-makers.

4.3. Vulnerabilities, trade-offs, and risk management actions

The Mwache Multipurpose Reservoir study in Kenya (HRG UMass, 2017a) aimed to assess the risks of Mwache's Dam 2015 design, associated with climatic and demographic change as well as to evaluate adaptation and risks management options from a water supply perspective. It also examined trade-offs between domestic, irrigation, and environmental uses, and the climate change stress test was expanded to include demographic stressors.

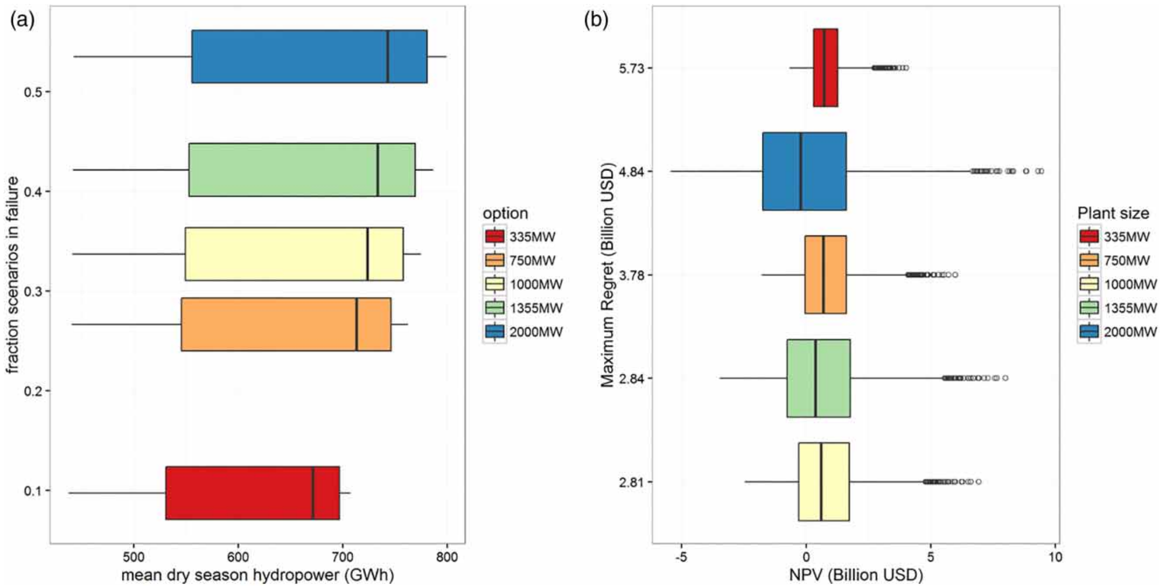

Fig. 4 | Comparative analysis for different plant size scenarios in the UAHP, Nepal: (a) fraction of scenarios in failure is determined by the NPV that is less than 0; (b) maximum regret vs. NPV. *Source:* Ray *et al*. (2018).

In Phase 2 of the analysis, the DTF was able to detect that the project, in its original design, was sensitive to climate uncertainty, hydrological model uncertainty, natural climate variability, and long-term demand changes. For instance, water demand was estimated to increase by up to 200% by 2030 due to demographic expansion. Also, the climate models were found not to agree in the same direction of change when projecting precipitation changes. Therefore, Phase 3 was deemed necessary.

The stress test in this stage was done using a simple rainfall–runoff model (with a storage component accounting for soil moisture and groundwater) and a water resource system model which included the effects of sedimentation. Stakeholders identified safe yield (the amount of water that can be delivered annually with a 95% reliability ratio, or 80 MCM/year) and overall and critical reliability (reliability was defined in this context as the percentage of intervals during the simulation period that the reservoir can meet the prespecified demand; critical reliability was defined here as the percentage of intervals during the simulation period that the reservoir can meet at least 60% of the prespecified demand). This stage later showed that the risk of the Mwache Dam failing to meet the safe yield target was low. Yet, the reliability of the system under various climatic conditions was found to decrease as domestic water demand increased.

Lastly, Phase 4 was triggered to assess the performance of the system under four different reservoir capacities. This stage found that larger designs, despite minimal benefit increases in terms of average safe yield, significantly improved the resilience of the system to drought conditions. Here, resilience was defined as the ability of the system to recover from delivery failures and it was measured by the probability that a successful period will follow a failure period. This phase also found that modifications in the operating rules could importantly help to increase resilience. Changing the allocation rules between domestic, irrigation, and environmental uses could be important to achieve the goals of the individual uses and may increase their reliability by up to 10%.

4.4. Prioritization of investments and trade-offs between objectives

The study of the CWS in Mexico (HRG UMass, 2017b) was developed given the growing concern for the vulnerability of the Mexico City water system to shocks, and the capacity of the system to adjust to the climate and demographic change. The CWS (Supplementary Material, Information 4) is a highly complex inter-basin water transfer to the Mexico City Metropolitan Area (MCMA) which has about 23 million inhabitants. Drinking water supply and irrigation are also provided to local users in the Cutzamala basin. This CWS involves seven reservoirs: El Bosque, Valle de Bravo, Villa Victoria, Tuxpan, Colorines, Ixtapan del Oro, and Chilesdo – the first three providing storage. Pumping stations (with about 1,100 m of elevation difference), open channels, tunnels, pipelines, aqueducts, and a single water supply treatment plant are also part of the system, which delivers around 15 m^3/s to the MCMA.

Built between the late 1970s and the early 1990s, the CWS is operated by the Valley of Mexico River Basin Organization (OCAVM in Spanish) of the National Water Commission of Mexico (CONAGUA in Spanish), delivering bulk water volumes for the city of Toluca, and the Water System of Mexico City (SACMEX). Local uses in the Cutzamala basin have priority. Reservoirs minimize spills and maximize storage to assure the reliability of water supply. Reservoir levels are also influenced by water quality considerations and recreational/tourism use preferences.

Although authorities were confident that the CWS had been reliable up to the time of analysis, supply shortages during the 2009 and 2013 droughts raised concerns about future worsening conditions due to climate change and other uncertainties, so several new investment options had been proposed to strengthen reliability, as shown in Table 1.

With support from the WBG, the development of an integrated water resources management plan to enhance the reliability and resilience of the CWS and enhance its confidence was initiated. The WBG, OCAVM, and the Hydrosystems Research Group of the University of Massachusetts (HRG UMass) applied the DTF (see Supplementary Material, Information 4) to identify vulnerabilities to changes in climate and evaluate the possibility of greater water supply delivery from the system. Using a broad set of performance indicators including yield, cost, robustness, and resilience, the proposed interventions of Table 1 were evaluated both individually and combined as optimized portfolios. Two additional options (the last two rows of Table 1) – a pressurized tunnel at Villa Victoria and a pressurized tunnel plus storage expansion – were also evaluated, as well as a preliminary

Table 1 | New investment options.

Intervention	Brief Description of Intervention
Villa Victoria	Extra storage and canal
Bosque-Colorines Canal	Increased capacity of canal between Bosque and Colorines reservoirs
Temascaltepec reservoir	Additional reservoir with larger storage capacity
Platform at Bosque	Decreased dead storage level at Bosque reservoir
Tuxpan Pump	Pumping groundwater below Tuxpan during dry season
Tuxpan Irrigation	New larger capacity canal for irrigators at Tuxpan
Villa Victoria Pressurized Tunnel	New pressurized tunnel (20 m^3/s) to connect pumps to Villa Victoria and Villa Victoria to Los Berros
Villa Victoria Pressurized Tunnel and Storage Expansion	50 MCM extra storage in Villa Victoria and the pressurized tunnel (above)

Source: HRGU Mass (2017b).

evaluation of optimizing reservoir and canal operations and the effects of deferred maintenance of canals and pumps.

As stated in the (HRG UMass report 2017b), the Temascaltepec reservoir provided the greatest increase in the maximum reliable yield, robustness, and resilience of the system. However, it was the costliest and would take the longest to develop. The best-performing investment portfolio that did not include Temascaltepec consisted of the Villa Victoria, Bosque Platform, and the Tuxpan Pump interventions. However, 'the Villa Victoria Pressurized Tunnel in conjunction with an expansion of the Villa Victoria's current capacity yielded significant improvements in all performance metrics considered' falling just short of the approximate yield increase which would be provided by an investment in Temascaltepec (HRG UMass, 2017b). At substantially less costs per m^3/s, it becomes the best performing intervention that does not include Temascaltepec and it does perform better for a wider range of futures than the current system, thus improving the robustness of the system to future climate change.

The analysis also preliminarily evaluated the effects of optimized reservoir and canal operations (Figure 5). The results indicate that changing the operational rules of the system provided benefits that are comparable or superior to many of the investment portfolios. Specifically, there is a potential to somewhat increase the reliable yield of the system without investment in additional infrastructure. Also, a preliminary analysis also indicated that lack of proper maintenance of canals and pumps will be reflected not only in less delivery capacity and more frequent and longer failures but also in less ability to recover from shocks (HRG UMass, 2017b).

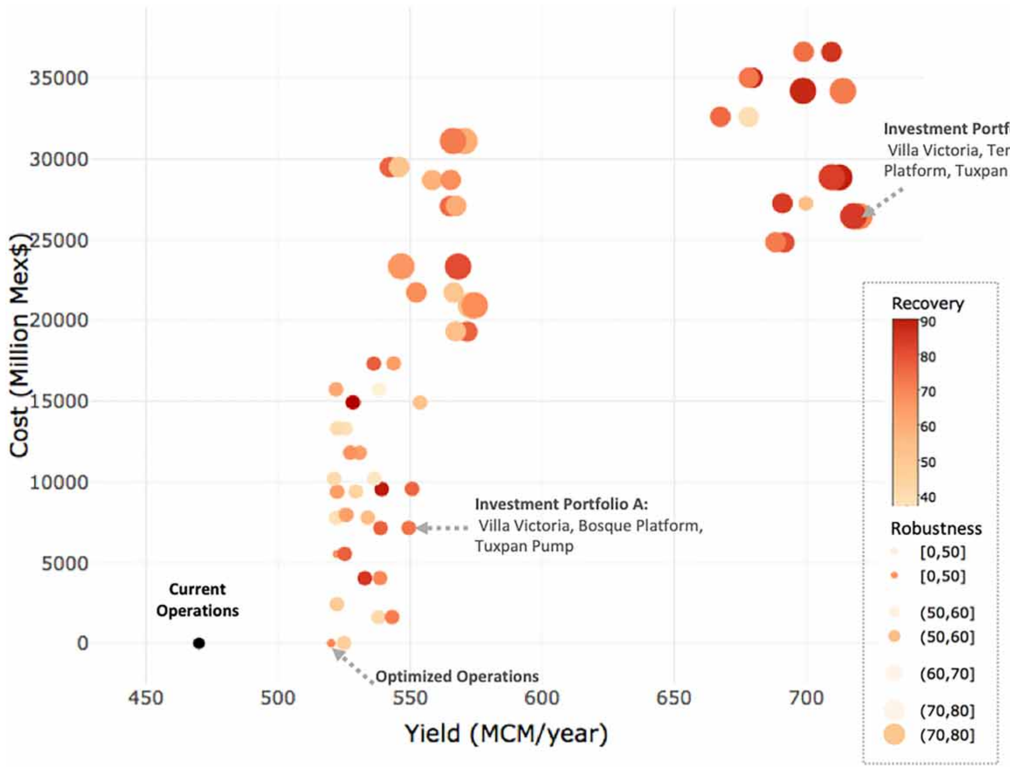

Fig. 5 | Evaluation of investments in the Cutzamala System options against their performance in terms of water yields, cost, resilience (recovery), and robustness levels.

The example highlighted in Figure 5, with the use of visualization tools, is of importance to inform local authorities on how best to select and prioritize new investments considering not only the financial domain but also other metrics such as reliability, resilience, robustness, and performance during drought. The DTF helps to understand trade-offs between yield, robustness, resilience, and economic performance metrics. This is a useful feature in Phase 4. As some of these objectives may be conflicting, the use of visual aids such as spider-plots of trade-offs between key performance indicators like those shown in Supplementary Material, Information 5, for example, may help stakeholders' decisions and evaluate the consequences of such decisions.

5. DESIGNING CLIMATE-INFORMED PROJECTS AROUND WBG'S FOUR MAJOR CLIMATE CHANGE COMMITMENTS

Guidelines drafted to help project teams comply with this mandate, previously described in Section 2, offer the DTF as one of the WBG's tools to 'help task teams allocate climate risk assessment efforts in a way that reflects various projects' sensitivity to climate-related (and other long-term) risks. When more in-depth analyses are needed, methodologies for decision making under uncertainty (DMU) are suggested. These DMU methodologies help identify specific project vulnerabilities and solutions that may help alleviate these, despite the large uncertainty about future climate and other dynamic factors.' This is no different from what the DTF has been used for up to date. The difference is that previously the DTF has been applied once plans or pre-designs have been elaborated and, in this case, the tool would be involved in the preparation process *before* Board approval. That, together with the new emphasis on resilience and co-benefit tracking, poses new stimulating challenges to the application of the DTF that the WBG has started to confront with research partners.

5.1. Incorporating resilience in the decision-making process, work in progress, and next steps

Resilience is a concept that intuitively makes one think about shocks and an ability to recover. While it is a concept that is not uniform and is still under construction, some of its first definitions were introduced many years ago, evolving from the disciplines of psychology and psychiatry in the 1940s (Manyena, 2006). Some of the simplest definitions of resilience in this domain applied to individuals refer to it as 'the capacity of human beings to survive and thrive in the face of adversity'. It involves 'being able to recover from difficulties or change – to function as well as before and then move forward'. The equivalent of 'bouncing back' (Lynde, 2015) is derived from the Latin word *resilio*, meaning 'to jump back' (Manyena, 2006). That is why in water resources it is usually connected to the occurrence of extreme hydrometeorological or seismic events during the life cycle of structures and services.

However, the shock or disturbance may be of such nature that it does not affect the infrastructure *per se*, but its ability to deliver a certain service level for which it was designed. So, a complementary popular conceptual definition of resilience associates it to 'the ability of human communities to withstand external shocks or perturbations to their infrastructure and to recover from such perturbations' (Bocchini *et al.*, 2014). Two key aspects are introduced here. First, resilience is a property not only of structures or infrastructures but mainly of communities. Second, resilience is not only about being able to withstand a certain disturbance, but also about having the institutional framework, resources, and means for a prompt, efficient, and effective recovery (Bocchini *et al.*, 2014). At the same time, recently the concept of resilience has also been enriched by also adding the characteristics of the recover. In fact, resilience could also be seen as a catalyst of change, toward building back better or safer after a shock or disruption event (Wilby, 2020).

As a response, several efforts have been underway at the World Bank toward building resilience to weather-related disasters, as well as to plan and design of water-related infrastructure based on resilience indicators, to guarantee that this infrastructure will keep providing the required level of service in the face of shocks of different nature (World Bank, 2013, 2017b, 2017c; World Bank/GFDRR, 2015). The IPCC or the Rockefeller Foundation definition of resilience has been favored by some sectors, this is 'the capacity of individuals, communities, and systems to survive, adapt, and grow in the face of stress and shocks, and even transform when conditions require it. Building resilience is about making people, communities and systems better prepared to withstand catastrophic events – both natural and manmade – and able to bounce back more quickly and emerge stronger from these shocks and stresses' (Rockefeller Foundation, 2015).

Yet, the overall universal difficulty to define resilience is also translated at the World Bank sphere (World Bank, 2017b). Furthermore, encompassing concepts of resilience including robustness and adaptability have also been suggested (World Bank, Mott MacDonald, 2017). But in most of the pilot DTF applications mentioned in Section 4.4, a simpler concept based on Hashimoto *et al.* (1982) was used. This refers to the concept of recovery, or how fast a system recovers from a failure once failure occurs. This concept facilitated the operationalization during Phase 3 of the DTF according to the services provided by the infrastructure. This went from simpler, single structure–single use cases to more complex multi structure cases such as in the Cutzamala study in Mexico, where resilience was evaluated for the whole system. Nevertheless, the focus has been on the infrastructure and its ability to provide the services.

But the resilience framework for water resources systems is much more complex, as reviewed by Wang & Blackmore (2009). Regarding resilience to climate change, the WBG considers two types of projects: (1) those that when screened show vulnerability to climate change but after modifications the risk is managed and (2) those that are specifically designed to increase robustness and resilience to long-term climate changes (World Bank, 2017b). The first type of projects needs to *be* resilient and the second type needs to *build* resilience. In order to address these aspects, the project resilience rating system was developed as part of the recently launched WBG's Adaptation and Resilience Action Plan mentioned in Section 2, which has a strong focus on people's resilience and sees projects as instruments that contribute to people's resilience ('resilience *through* projects'). These projects, however, must themselves be resilient and able to deliver their services to the population ('resilience *of* projects'). A new resilience rating system has been recently released by the World Bank to support clients scaling up climate adaptation actions both at the infrastructure level and at the user level (World Bank, 2021).

Up to now, the DTF has been used as a tool for type (1) projects. An example is the Cutzamala system study for Mexico City described previously. However, the DTF pilot applications presently in progress in Nepal (testing the application of the Hydropower Sector Climate Resilience Guidelines in a run-of-river hydroelectric development), Kenya (resilience of an irrigation and flood control project in the lower Nzoia river basin), and Peru (resilience of the Chancay-Lambayeque water resources system at the basin level) are a good opportunity to explore interrelated project resilience performance indicators at three levels: infrastructure, beneficiaries of the services, and the river basin community.

To be applied for type (2) projects, modifications and upgrades to the DTF will need to be made. A reference is the pilot work that has continued in the MCMA after the Cutzamala study with the collaboration of the Rockefeller Foundation and the HRG UMass, aiming to transform the way water infrastructure investment programs are designed to obtain 'freshwater resilience' for the city. This concept emphasizes that freshwater ecosystems (think lakes, rivers, and aquifers) can handle changes, particularly climate, and still continue to deliver their essential services. This is the fundamental principle of resilience: being able to respond and adapt to shocks and stresses and to transform when conditions require it.

Using the approach called 'Freshwater Resilience by Design' (Brown, 2017, 2018), the work focuses on multiple objectives (economic/service, social/equity, and environmental) consider multiple futures (climates, population growth and demographic change, economic growth and change, and societal preferences change) and links 'urban investment program and policies with investments and policies in the connected river basins, and the evaluation of benefits and costs in each location' (Brown, 2017, 2018). This approach also incorporates aspects of projects and activities that strengthen the resilience of the communities and users.

Adding resilience and robust design considerations to any project in order to reduce risk and uncertainty typically increases the costs. These vulnerability-reducing design features often conflict with traditional economic project justification and decision rules (e.g., maximize net benefits, maximize the internal rate of return, and benefit–cost ratio greater than one) and trade-offs must be considered, as was done in the study of the Cutzamala system (Supplementary Material, Information 4). Moreover, in urban water investment projects such as water and wastewater, for example, that are complex in nature and depend not only on physical factors but also on social factors, it is difficult to estimate the benefits when focused on increasing resilience. Initial work being discussed with RAND aims to develop a framework for the economic assessment of the resilience benefits. That is, 'the net benefits associated with the absorption of shocks and stressors, the recovery path following a shock, and any co-benefits that accrue from a project, even in the absence of a shock' which may be positive or negative for a given project (Bond *et al.*, 2017).

Regarding multiple objectives and consideration of both climate and non-climate factors, the need for a multidimensional stress test was posed for hydropower investments facing climate, geophysical and financial uncertainty (Ray *et al.*, 2018) and updates to the DTF have been proposed, such as (1) replacing its 'climate change stress test' with a multidimensional stress test and (2) 'the addition of a Bayesian network framework that represents joint probabilistic behaviour of uncertain parameters' as sensitivity factors to aid in the combination of conditions under which a water system fails to meet its performance targets, and better understand the relative magnitudes of the varied risks faced (Ray *et al.*, 2019). The use of a multidimensional stress test is being piloted in the analysis of the Kabeli-A Run of River Hydroelectric Project in Nepal, in collaboration with the IHA and the EBRD.

5.2. Lessons learned and the way forward

The DTF has been operationally piloted in various water projects to both enhance the assessment of climate and non-climatic risks and provide guidelines to manage such risks. Toward this end, these efforts have promoted a highly participatory approach in situations dealing with hydropower, water supply, irrigation, flood control, and river basin planning, both individually and in multi-use schemes, involving both single major hydraulic structures as well as complex multi-structure systems. Co-creation and validation workshops organized with stakeholders in each pilot study as well as training courses were useful to reinforce stakeholders' understanding of their systems, define their performance metrics, and evaluate their risks and risk-management options.

The first pilot study was a faithful application of the methodology described in the WBG's DTF book (Ray & Brown, 2015). From there on, successive pilots needed to include methodological enhancements to cover non-climatic uncertainties in more depth, economic considerations, regard for ground water, nature-based solutions, environmental and other trade-offs, operation rules, maintenance, robustness, resilience of infrastructure (Ray *et al.*, 2018), and prioritization of investment options. Although initially intended as a tool for project screening, the DTF is now being applied to assess multiple-investment basin plans and prioritize investments considering multiple metrics, including robustness and resilience.

Thus, being able to assess and manage risk in a systematic and flexible way, the DTF has been an important contribution to the WBG's efforts to mainstream assessing and managing the risk posed by the climate change and other important uncertainties. Nonetheless, as the pilot studies suggest, there are challenges and improvements that have yet to be addressed.

Looking forward, immediate necessities that need to be explored include those concerning the integration of important components of the hydrological cycle. For instance, the application of the DTF to complex urban systems evidenced that it still needs to improve its capabilities to integrate groundwater processes with surface water. This would require the integration of models which help to include the interaction of groundwater in flood and drought occurrences. In line with this, current efforts in Mexico City look to incorporate these principles within a machine learning approach to simulate infrastructure, physical, and decision processes under a resilient framework. Yet, the DTF also offers the opportunity for its application without the need of application of sophisticated models, particularly in areas where data are scarce, non-existent, or highly uncertain. Indeed, a previous initial experience of applying the DTF in two water utilities in Angola, which met these characteristics, suggests that its adjustments toward a more qualitative type of exercise are also promising.

At the same time, the DTF has not yet been used to assess and manage water quality risks. Also, the consideration of the way future land-use changes, human activities, and social factors may affect the performance of a water resource project still needs to be further deepened. In line with this, the DTF would also require incorporating and addressing issues concerning seawater intrusions and salinization of soils. A similar improvement yet to be considered relates to the inclusion of processes that would enhance the management of risks and resilience building in coastal zones, such as projected sea-level rise or the occurrence of cyclones and tropical storms. Also, modeling in detail the effect of maintenance or lack thereof as well as the definition of adequate indicators for resilience or equity as well as for non-climate stressors has been challenging.

6. CONCLUDING REMARKS

Important benchmarks in the development and consolidation of the DTF are the robustness policy prescription of the WBG's 2010 World Development Report, the IDA 17 climate and disaster risk screening requirement, the Climate Change Corporate Commitments incorporating the Water Global Practice, the development of the CCKP, and the CDRST. The DTF unites them as a practical assessment and managing tool that also provides a way to integrate the use of traditional hydrologic and water resources methodology. At the same time, the DTF allows the addition of various of the latest advances in decision-making under uncertainty and bottom-up approaches, as well as new information provided by the latest climate science modeling.

Although not finished yet, the pilot phase with the incorporation of research and knowledge advances is considered positive. Further insights on the practicality and flexibility of this approach are expected from the pilot studies under process, the project and community resilience screening indicators being developed through the WBG Adaptation and Resilience Action Plan, the results of the freshwater resilience concept application in Mexico City, and the results of the Hydropower Resilience Guidelines testing and validation. In particular, achieving a better understanding of which types of projects (hydropower, irrigation, municipal water supply, and flood control) require a better-defined set of specific analytical steps in order to assure uniformity of outcomes.

The flexibility of the DTF offers the opportunity to incorporate advances from the academic/research community – not only to overcome some of the noted needs but also to use the framework beyond considering the physical dimensions to integrate human systems, such as those aspects of resilience related to economic, social, and institutional-governance. In line with this, incorporating and adjusting various indicators analyzed by Hallegatte *et al*. (2016) and the proposed collaborative work in resilience benefits would enhance the understanding not only of physical infrastructure resilience but also of the socioeconomic resilience of water projects. Similarly, this approach still needs to refine the incorporation of green infrastructure as risk management alternatives. Including a reasonable representation of human and natural systems would enhance the application of this framework for resilient and robust decision-making in natural and socially sensitive areas.

Efforts have been made to deepen understanding of the financial mechanisms and investment strategies of water projects under uncertain conditions. But other issues, like the role of water funds and governmental bodies in financing strategies, and economic evaluation procedures that stem from the DTF need yet to be incorporated.

Similarly, the role of resilient and robust water infrastructure projects to build resilience to sustain city, river basin, and country-level development and water security goals, recently introduced, is still incipient. This task would need to include an integrative assessment and management of risks of additional systems where water systems constitute an important component such as in health, food, commerce, transport, and international trade.

Equally important for institutions is not to forget the need for giving increasing attention to narrowing the gap between the science and its application in the field. In the operational dimension, mainstreaming still has a way to go. The technical level of the methodology is considered high but, even as modifications and additions are being considered and introduced at the upper end, there have been suggestions about lowering the level of its description so that it can be adopted and applied more easily. The methodologies are well sustained scientifically but would benefit from being translated to a practitioner language that makes sense to the technician and the decision-maker in the field, especially in the developing world.

DISCLAIMER

The findings, interpretations, and conclusions expressed in this review paper are those of the authors and do not necessarily reflect the views of the World Bank, its Board of Executive Directors, or the governments they represent.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Alavian, V., Maher Qaddumi, H., Dickson, E., Diez, S. M., Danilenko, A. V., Hirji, R. F., Puz, G., Pizarro, C., Jacobsen, M. & Blankespoor, B. (2009). *Water and Climate Change: Understanding the Risks and Making Climate-Smart Investment Decisions*. The World Bank, Water Sector Board, Bank Netherlands Water Partnership Program, and Norwegian Ministry of Foreign Affairs, Washington, DC.

Ayyub, B. M., Prassinos, P. G. & Etherton, J. (2010). Risk-informed decision making. *Mech. Eng. Mag. Sel. Artic. 132*(1), 28–33.

Bocchini, P., Frangopol, D. M., Ummenhofer, T. & Zinke, T. (2014). Resilience and sustainability of civil infrastructure: Toward a unified approach. *Journal of Infrastructure Systems 20* (2), 04014004.

Bond, C. A., Strong, A., Burger, N., Weilant, S., Saya, U. & Chandra, A. (2017). *Resilience Dividend Valuation Model: Framework Development and Initial Case Studies*. RAND Corporation, Santa Monica, CA. Available at: https://www.rand.org/pubs/research_reports/RR2129.html.

Bonzanigo, L., Brown, C., Harou, J., Hurford, A. & Ray, P. (2015). *South Asia Investment Decision Making in hydropower. Decision Tree Case Study of the Upper Arun Hydropower Project and Koshi Basin Hydropower Development in Nepal*. World Bank Report No. AUS11077, June 17, 2015.

Brown, C. (2017). *Freshwater Resilience by Design, Presentation in the World Water Week*. SIWI, Stockholm, Sweden.

Brown, C. (2018). *Freshwater Resilience by Design*. Presentation in the Resilient Water Decisions Workshop, World Bank, Washington, DC.

Brown, C., Ghile, Y., Laverty, M. & Li, K. (2012). Decision scaling: linking bottom-up vulnerability analysis with climate projections in the water sector. *Water Resour. Res. 48*(9).

Brown, C. M., Lund, J. R., Cai, X., Reed, P. M., Zagona, E. A., Ostfeld, A., Hall, J., Characklis, G. W., Yu, W. & Brekke, L. (2015). The future of water resources systems analysis: toward a scientific framework for sustainable water management. *Water Resour. Res. 51*, 6110–6124. doi:10.1002/2015WR017114.

Buytaert, W. & De Bievre, B. (2012). Water for cities: the impact of climate change and demographic growth in the tropical Andes. *Water Resour. Res. 48*(8), 1–13. doi:10.1029/2011WR011755.

Cervigni, R., Liden, R., Neumann, J. E. & Strzepek, K. M. (2015). *Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors. Africa Development Forum*. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/21875.

García, L. E., Matthews, J. H., Rodriguez, D. J., Wijnen, M., DiFrancesco, K. N. & Ray, P. (2014). *Beyond Downscaling: A Bottom-Up Approach to Climate Adaptation for Water Resources Management*. Available at: https://openknowledge.worldbank.org/handle/10986/21066.

Grijsen, J. C. (2016). *Tina River Hydropower Development Project, Solomon Islands Climate Risk Assessment*. World Bank.

Grijsen, J., Brown, C., Tarhule, A., Ghile, Y. & Taner, M. (2012). Climate risk assessment for water resources development in the Niger River Basin. *Water Partnersh. Progr. (WPP)/TWIWA, HydroPredict 12*.

Groves, D. G., Yates, D. & Tebaldi, C. (2008). Developing and applying uncertain global climate change projections for regional water management planning. *Water Resour. Res. 44*(12). doi:10.1029/2008wr006964.

Hallegate, S., Shah, A., Lempert, R., Brown, C. & Gill, S. (2012). *Investment Decision Making under Deep Uncertainty, Application to Climate Change*. The World Bank Sustainable Development Network, Office of the Chief Economist, Washington, DC.

Hallegatte, S., Bangalore, M. & Vogt-Schilb, A. (2016). *Socioeconomic Resilience: Multi-hazard Estimates in 117 Countries*. The World Bank.

Hamlet, A. F. (2011). Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. *Hydrol. Earth Syst. Sci. 15*(5), 1427–1443. doi:10.5194/hess-15-1427-2011.

Hartmann, D. L., Tank, A. M. G. K. & Rusticucci, M. (2013). *Climatie Change* 2013: The Physical Science Basis, IPCC Fifth Assessment Report, IPCC, AR5, 31–39.

Hashimoto, T., Stedinger, J. R. & Loucks, D. P. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res. 18*(1), 14–20.

Hine, D. & Hall, J. W. (2010). Information gap analysis of flood model uncertainties and regional frequency analysis. *Water Resour. Res. 46*(1). https://doi.org/10.1029/2008WR007620.

HRGUMass (2017a). *The Decision Tree Initiative: Water Resources Development and Allocation for the Mwache Dam*. Final Report. World Bank.

HRGUMass (2017b). *Including Climate Uncertainty in Water Resources Planning and Project Design-Decision Tree Initiative. Pilot Studies of the Cutzamala Water System*. Mexico-Draft Final Report. World Bank, Washington, DC.

IDA (2014). *Report from the Executive Directors of the International Development Association to the Board of Governors, Additions to IDA Resources: Seventeenth Replenishment, IDA17: Maximizing Development Impact*.

IEG World Bank/IFC/MIGA (2012). *Adapting to Climate Change: Assessing the World Bank Group Experience*. Phase III of the World Bank Group and Climate Change, Washington, DC.

Kalra, N., Groves, D. G., Bonzanigo, L., Molina Perez, E., Ramos, C., Brandon, C. & Rodriguez Cabanillas, I. (2015). *Robust Decision-Making in the Water Sector; A Strategy for Implementing Lima's Long-Term Water Resources Master Plan*. Climate Change Group, Office of the Chief Economist, Washington, DC.

Lambin, E. F. & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci. U. S. A. 108*(9), 3465–3472.

Lempert, R. J., Groves, D. G., Popper, S. W. & Bankes, S. C. (2006). A general, analytic method for generating robust strategies and narrative scenarios. *Manage. Sci. 52*(4), 514–528.

Ludwig, F., van Slobbe, E. & Cofino, W. (2014). Climate change adaptation and integrated water resource management in the water sector. *J. Hydrol. 518*(PB), 235–242. doi:10.1016/j.jhydrol.2013.08.010.

Lynde, D. W. (2015). *Resilience Definitions and Concepts*. Available at: https://dmh.mo.gov/docs/mentalillness/resilience.pdf.

Manyena, S. B. (2006). The concept of resilience revisited. *Disasters 30*(4), 433–450.

Merrey, D. & Awulachew, S. B. (2015). Critical roles of water in achieving the proposed SDGs: a nexus perspective (water-energy-food-climate change). In: *Presented at the Workshop on 'Capacity Development in Advancing Water and Sustainable Development'*, February 24–25, 2015, United Nations, New York City, NY.

Prudhomme, C., Wilby, R. L., Crooks, S., Kay, A. L. & Reynard, N. S. (2010). Scenario-neutral approach to climate change impact studies: application to flood risk. *J. Hydrol. 390*(3–4), 198–209.

Ray, P. A. & Brown, C. M. (2015). *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework*. World Bank, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/22544.

Ray, P. A., Bonzanigo, L., Wi, S., Yang, Y. -C. E., Karki, P., García, L. E., Rodriguez, D. J. & Brown, C. M. (2018). Multidimensional stress test for hydropower investments facing climate, geophysical and financial uncertainty. *Global Environ. Change 48*, 168–181.
Ray, P. A., Taner, M. Ü., Schlef, K. E., Wi, S., Khan, H. F., Freeman, S. S. G. & Brown, C. M. (2019). Growth of the Decision Tree: Advances in Bottom-Up Climate Change Risk Management. *JAWRA Journal of the American Water Resources Association* 55(4), 920–937.
Rockefeller Foundation (2015). *Resilience Webpage*. Rockefeller Foundation, New York. Available at: https://www.rockefellerfoundation.org/our-work/topics/resilience/.
Rodríguez, D. J., van den Berg, C. & McMahon, A. (2012). Investing in Water Infrastructure: Capital, Operations and Maintenance. Water Papers, World Bank, *Water Partnership Program*.
Rodríguez-Iturbe, I. & Valdés, J. B. (2011). *Uncertainty and Climate Variability in the Design and Operation of Water Resources Projects: Examples and Case Studies*.
Rosenberg, D. E. & Madani, K. (2014). Water resources systems analysis: a bright past and a challenging but promising future. *J. Water Resour. Plann. Manage. 140*(4), 407–409. doi:10.1061/(ASCE)WR.1943-5452.0000414.
Stainforth, D., Aina, T., Christensen, C., Collins, M., Faull, N., Frame, D. J., Kettleborough, J. A., Knight, S., Martin, A., Murphy, J. M., Piani, C., Sexton, D., Smith, L. A., Spicer, R. A., Thorpe, A. J. & Allen, M. R. (2005). Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature 433*(7024), 403–406. doi:10.1038/nature03301.
Stainforth, D. A., Allen, M. R., Tredger, E. R. & Smith, L. A. (2007). Confidence, uncertainty and decision-support relevance in climate predictions. *Philos. Trans. Royal Soc. A365*(1857), 2145–2161.
Stakhiv, E. Z. (2011). Pragmatic approaches for water management under climate change uncertainty. *J. Am. Water Resour. Assoc. 47*(6), 1183–1196.
Teng, J., Vaze, J., Chiew, F. H. S., Wang, B. & Perraud, J. -M. (2012). Estimating the relative uncertainties sourced from GCMs and hydrological models in modeling climate change impact on runoff. *J. Hydrometeorol. 13*(1), 122–139.
UN (2019). *The Sustainable Development Goals Report 2019*. United Nations, New York.
UN Water/WBG (2018). *Making Every Drop Count: An Agenda for Water Action. High-Level Panel on Water Outcome Document*. Available at: http://www.unwater.org/high-level-panel-on-water-outcome-document/.
Value of Water Campaign (2017). *The Economic Benefits of Investing in Water Infrastructure*. Supported by a diverse group of more than 33 leaders in the US water industry, including American Society of Civil Engineers, Boston Water and Sewer Commission, Water Environment Federation, and others. Available at: http://www.TheValueofWater.org/resources.
Wang, C. -H. & Blackmore, J. (2009). Resilience concepts for water resource systems. *J. Water Resour. Plann. Manage. – ASCE 135*. doi:10.1061/(ASCE)0733-9496(2009)135:6(528).
Wilby, R. L. (2019). A global hydrology research agenda fit for the 2030s. *Hydrol. Res. 50*(6), 1464–1480. https://doi.org/10.2166/nh.2019.100.
Wilby, R. L. (2020). Resilience viewed through the lens of climate change and water management. *Water 12*(9), 2510.
World Bank (2010). *World Development Report 2010: Development and Climate Change*. © World Bank. License: CC BY 3.0 IGO, Washington, DC. Available at: https://openknowledge.worldbank.org/handle/10986/4387.
World Bank (2013). *Building Resilience: Integrating Climate and Disaster Risk into Development: Lessons from World Bank Group Experience*. The World Bank, Washington, DC.
World Bank (2016). *World Bank Group Climate Change Action Plan 2016–2020*. World Bank, Washington, DC.
World Bank (2017a). *The World Bank Environmental and Social Framework*. Washington, DC.
World Bank (2017b). *Operational Guidance for Monitoring and Evaluation (M&E) in Climate and Disaster Resilience-Building Operations*. Washington, DC.
World Bank (2017c). *World Bank Resilience M&E (ReM&E) Good Practice Case Studies*. Washington, DC.
World Bank (2018a). *Annual Report 2018*. Washington, DC.
World Bank (2018b). *Adaptation & Resilience Action Plan, Key Messages*. Washington, DC.
World Bank/GFDRR (2015). *Investing in Urban Resilience, Protecting and Promoting Development in a Changing World*. Washington, DC.
World Bank Group (2021). *Resilience Rating System: A Methodology for Building and Tracking Resilience to Climate Change*. World Bank.
World Bank, Mott MacDonald (2017). *Hydropower Sector Climate Resilience Guidelines*. Final Report (Beta Version). Washington, DC.

Yu, W., Yang, Y. -C., Savitsky, A., Alford, D., Brown, C., Wescoat, J., Debowicz, D. & Robinson, S. (2013). *The Indus Basin of Pakistan: The Impacts of Climate Risks on Water and Agriculture*. The World Bank.

First received 16 November 2021; accepted in revised form 16 November 2021. Available online 1 December 2021