

Climate risk-informed decision analysis (CRIDA): 'top-down' vs 'bottom-up' decision making for planning water resources infrastructure

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ABSTRACT

Climate risk-informed decision analysis (CRIDA) is a guidebook that lays out an evaluation framework and decision procedures to deal with climate uncertainties that are consistent with traditional agency water resources planning frameworks. CRIDA guidelines complement existing institutional guidance on recognizing circumstances when more complex risk-based climate analysis may be needed, above those required by standard planning procedures. The procedures are based on the concept of 'decision-scaling' judgments to qualitatively assess levels of future risk and analytical uncertainty stemming from climate change-related uncertainties, and as a guide for choosing specific analytical approaches and appropriate levels of analysis. CRIDA addresses how much detail is appropriate for a given problem setting, depending on infrastructure type and function, whether it is new design or rehabilitation of existing infrastructure, modular design or long-life infrastructure. CRIDA was structured to resolve the contentious issue of deciding under what circumstances a 'top-down' climate scenario-driven analysis ought to be conducted versus a more traditional 'bottom-up' vulnerability assessment, based on conventional agency project feasibility procedures. The procedures for such vulnerability assessments and planning procedures are well-represented in classical approaches, such as those included in the 1983 U.S. Water Resources Council's 'Principles and Guidelines'. These commonly used procedures promote normative evaluation protocols and decision rules that generate alternative solutions which minimize risk-cost outcomes.

Key words: 'Bottom-up' water resources planning frameworks, Decision-scaling, Non-stationary climate analysis, Risk-based decision analysis

INTRODUCTION

For millennia, water resources management has been strongly linked to the economic, social and environmental development of civilizations and, later, nations. Harnessing water resources has transformed variable and often destructive hydrologic flood extremes into reliable, socially desired benefits (municipal water supply, irrigation, hydropower, navigation and environmental flows) and has ameliorated the ruinous effects of droughts. As needs have grown and interventions have increased, water resources managers worldwide have designed more complex water management systems and made more elaborate trade-offs among social, economic and environmental goals. To address these complexities, a wide array of technical, analytical and governance procedures for water management have evolved to keep pace with growing societal demands and the intricacies of public decision-making. However, large uncertainties associated with climate change have added to those planning and management complexities by challenging the foundations of hydrologic and hydraulic analyses associated with the assumptions of a stationary climate (Milly *et al.*, 2008).

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The water resources engineering profession has always dealt with risk and uncertainty, as it is inherent in the randomness of natural hydrological phenomena that serve as the basis for design criteria and engineering standards. However, in addition to resorting to empirical relationships based on physical properties, as well as statistics and probabilities to characterize the uncertainties that were known, engineers primarily accounted for the 'known unknowns' by stressing design redundancies and safety factors as a way of dealing with residual risks – i.e., those risks which could not be easily quantified or which represented acceptable or 'tolerable' risks (Institute for Water Resources, 2010).

Hence, while risk and uncertainty analysis are not a new issue for policy makers, engineers or scientists associated with water management, climate change has highlighted the need to reassess the sequence of cascading uncertainties caused by the climate models themselves, together with natural variability, future scenario uncertainties and decision-related uncertainties associated with public needs, objectives and values. Added to these largely intractable climate model uncertainties, is the more fundamental problem of dealing with hydrologic non-stationary.

In a changing world, planning, decision-making and designing water resources management require long-term projections of hydrological time series that include trends due to anthropogenic intervention and climate change (Kjeldsen & Rosbjerg, 2005; Barsugli *et al.*, 2012; Bayazit, 2015). Climate variability is a random variation from a long-run average distribution, whereas climate change is a trend or a shift in the long-run distribution.

Estimating future climate impacts has proven to be particularly contentious and analytically frustrating. In many cases, effective solutions have been largely dependent on the skills of experienced individuals rather than being based on protocols and standards for systematic and reproducible approaches to planning under climate uncertainty. In general, a simple well-understood model is generally preferable to a sophisticated one with large uncertainties (Matalas & Fiering, 1977; Fiering, 1982; Rogers, 1997). For water resources planning studies, stationarity is still a useful concept, as a starting point for stress tests and vulnerability analyses to make reliable predictions for engineering design (Stakhiv, 2011; Brown & Wilby, 2012; Slater *et al.*, 2021). Observations of past patterns and information are key elements for a successful prediction for hydrological processes (Lins & Cohn, 2011; Bayazit, 2015).

Water resources management decisions made today will have long-term effects because the projects have lifetimes in the order of 50–100 years. Therefore, planners must attempt to account for those impacts in the future (Thompson *et al.*, 2013). This may require an adjustment to or adaptation of frequency analysis, concepts like return period and risk, and hydrological design methods to the conditions of a changing world (Salas *et al.*, 2012; Salas & Obeysekera, 2014). Synthetic hydrologic series for specified future time periods can be generated by sampling uncertainty from variability due to climate change in a probabilistic way (Brown *et al.*, 2012). These are used to estimate the frequency distributions of decision variables under alternative water management strategies, showing the extent of a system's ability to meet the design requirements (Brown & Wilby, 2012). Uncertainties of future demand due to population growth and development in river basins can also be considered in a comparable manner. The combination forms the basis of a complete risk-based decision-making process, such as required by the U.S. Water Resources Council's 'Principles and Guidelines' (U.S. Water Resources Council, 1983).

A bewildering array of various climate modeling approaches, analytical techniques for non-stationary hydrologic analysis and planning evaluation approaches were devised to deal with the key issues. These center on climate change impact analyses, mainly for devising greenhouse gas reduction mitigation strategies. In turn, this array of methods has created additional challenges with associated uncertainties (Slater *et al.*, 2021), that include the following:

1. Downscaling a multitude of climate scenario precipitation and temperature outputs and transforming into hydrological outputs (runoff and flood and drought frequencies).

2. Dealing with non-stationary climate signals with standard frequency-based hydrologic analysis is currently the basis for project economic justification and design.
3. Adapting existing planning evaluation approaches that are not readily suited for dealing with large magnitude climate uncertainties.
4. Designing and economically justifying robustness and resilience for water projects under conventional economic project evaluation and justification procedures and criteria.

It should be recognized that many water infrastructure design procedures and standards already encompass and compensate for a considerable portion of climate and weather extremes and hydrologic uncertainties through various design redundancies and ‘safety factors’ (Matalas & Fiering, 1977; Ayyub, 2018). This historically conservative engineering approach implicitly and explicitly incorporates many, but not all, aspects of ‘robust’ and ‘resilient’ design features called for by many advocates of climate vulnerability assessments (Lempert & Groves, 2010; Hallegatte *et al.*, 2012; Lempert, 2019).

TRADITIONAL WATER RESOURCES PLANNING PARADIGM UNDERPINS CLIMATE ADAPTATION ANALYSIS

Most modern water resources planning is based on the tenets of operational hydrology and rational planning introduced by the Harvard Water Program (Maass *et al.*, 1962; Fiering, 1967). The U.S. Water Resources Council’s (1983) ‘Economic and Environmental Principles and Guidelines for Water and Related Land Resources Planning Implementation Studies (P&G)’ stand as a representative example of such traditional and proven water resources planning and evaluation protocols that were derived from the principles and concepts of the Harvard Water Program.

These procedures represent a unique combination of decision theory, public choice theory and benefit–cost theory (Stakhiv, 1986). As such, they encompass most, but not all the basic risk analysis requirements needed to assess infrastructure vulnerabilities that evolve primarily from uncertainties associated with climate change as expressed via hydrologic and hydraulic uncertainties, as well as future socioeconomic drivers. Risk and uncertainty analysis, in all aspects and dimensions of planning – social, environmental, economic, hydrologic and hydraulics, have been a core requirement of U.S. federal planning for the last five decades.

Many leading water resources infrastructure management institutions, such as the U.S Army Corps of Engineers (2000, 2019), World Bank (2020, 2021), Wright (2015), Asian Development Bank (2015, 2021), and the Netherlands Rijkswaterstaat (2016; Van Alphen, 2015), have developed comparable elaborate protocols for evaluating the socioeconomic and environmental feasibility of a variety of water projects that are consistent with the ideas and principles of the P&G. These protocols and guidelines undergo constant revisions and updating to accommodate new planning objectives (e.g., sustainable development goals, gender equity and environmental justice), updated economic and financial decision criteria, as well as new methods and techniques for hydrologic analysis, watershed modeling and climate uncertainty analysis.

Water resources project planning is essentially a three-tiered process. The process begins with a feasibility phase to determine if there is a real need for a project, and then lays out options for further study. This is followed by an advanced planning phase, where options are evaluated according to publicly derived planning objectives and evaluation criteria, and legally prescribed normative decision rules. Finally, if a project option is technically feasible as well as economically, socially and environmentally justified, it is selected and authorized to proceed to the design phase.

Project planning emphasizes procedures and rules that result in economic–social–environmental trade-off analyses that seek to maximize project net benefits. The overall aim is to maximize economic performance and

service reliability over the life of a project (Yoe, 2017). On the other hand, once a particular project alternative has been selected, engineering design strives to ensure that a catastrophic project failure is avoided by emphasizing measures that minimize the risk of hydraulic failure. Both the planning function and the subsequent design function require very specific, but different types of information about future climate and hydrologic loadings.

At all levels of planning and evaluation, a great deal of hydro-meteorologic information is required but use of available data is complicated by the fact that global warming is likely to result in a non-stationary climate regime (IPCC, 2021). Much effort has gone into tools and models to forecast future hydro-climatology based on a wide array of climate models and speculations about future hydrologic responses. Unfortunately, this has often led to greater uncertainty and a broadening of ranges of potential future scenarios and associated flood and drought frequency analyses (Koutsoyiannis *et al.*, 2008). Such scenarios are the traditional bases for hydrologic and hydraulic design. Consequently, any choice for a particular subset of future scenarios to plan, design or invest has become an increasingly subjective enterprise, centering on which climate scenarios to consider, and what hydrological analytical tools could be employed to deal with these cascading uncertainties (Slater *et al.*, 2021). Planners are confronted with the basic question of how much investment can be justified to minimize risk or how much is too much or too little investment?

Hence, there is a need for quantitative and pragmatic guidance that builds on and extends conventional planning and design procedures and practices that are internally consistent and can encompass future climate uncertainties and non-stationary. Existing conventional practices, associated with risk-informed decision-making under a stationary climate regime, provide a coherent approach and entry point to problems that require one to consider '*known unknowns*' such as climate change-related consequences. The results of these analyses must then be presented at a level of understanding to decision-makers that is not dependent on a complete, quantitative understanding of future probabilities that are inherently unknowable (Dessai & Hulme, 2004; Pielke & Wilby, 2012; Wilby & Murphy, 2019). Such guidance, however, must also consider the financial, technical and institutional limitations, and capabilities of planners and decision-makers to complete master planning, pre-feasibility and feasibility studies.

'TOP-DOWN' VS 'BOTTOM-UP' CLIMATE IMPACT ANALYSIS

In the context of this discussion, 'bottom-up' impact analyses, vulnerability assessments and 'stress tests' are meant to reflect the traditional manner in which water resources projects are considered. These begin with an assessment of vulnerabilities in existing water infrastructure and problems and anticipated needs at a site-specific or watershed level. Use of historical climate and hydrologic data is typically the first step. This approach contrasts with methods advocated by many climate scientists and resource management agencies who advocate that climate-based analyses begin with a consideration of data generated by climate models, e.g., general circulation models (GCMs) and scenarios for greenhouse gas emissions (Kundzewicz & Stakhiv, 2010; Brown & Wilby, 2012; Nazemi & Wheaton, 2014). The latter approach would be considered 'top-down'.

The 'top-down', or GCM-centered, approach was originally designed for devising climate mitigation policies, i.e., strategies for reducing greenhouse gases and not intended for site-specific adaptation analysis (Anagnostopoulos *et al.*, 2010; Conway *et al.*, 2019). Since the advent of the UN Intergovernmental Panel on Climate Change First Assessment Report (IPCC FAR, 1990), climate science has evolved exponentially and has better-defined pathways of future plausible climate scenarios.

On the other hand, traditional 'bottom-up' planning approaches must factor in multiple drivers of change to produce contextualized information that is relevant for decision-makers. Therefore, the best that can be offered in terms of derivations that certain climate scenarios will materialize is an inherently judgment-based statement of 'plausibility' (Mendoza *et al.*, 2018). Bottom-up approaches focus on water resources problems and how they

affect communities, through consideration of potential future risks on various population sectors and the residual risks associated with solutions. In a typical water resources management study, climate change is but one additional risk factor among a myriad array of other vulnerabilities, rather than the principal factor of future changes. Use of traditional planning processes developed over the past century that focus on climate change and its manifestations remain invaluable and should not be discarded (Stakhiv, 2011). This is especially relevant when it has been shown that most climate model simulations provide widely divergent outputs (Koutsoyiannis *et al.*, 2008; Knutti & Sedláček, 2013; Giuntoli *et al.*, 2015; Eisner *et al.*, 2017; Pechlivanidis *et al.*, 2017).

For example, Giuntoli *et al.* (2015), among many others involved with the Inter-Sectoral Impact Model Inter-comparison Project's (ISIMIP) multi-model ensemble comparisons, found that results from different impact models simulating the same systems under the same climate change conditions showed considerable variability. Unfortunately, the trend has been for many leading climate scientists and international institutions to advocate the most extreme scenarios, such as the RCP 8.5 (Representative Concentration Pathways) scenario as part of 'robust' planning solutions for major infrastructure (Ritchie & Dowlatabadi, 2017; Hausfather & Peters, 2020).

Hausfather & Peters (2020) called on policy makers to 'stop using the worst-case scenario for climate warming as the most likely outcome – more-realistic baselines make for better policy'. This is an important acknowledgment because these scenarios drive not only global and national climate mitigation and adaptation policies, but virtually all future infrastructure planning. As such, they skew the outcomes towards expensive and ultimately infeasible solutions. These scenarios are required in many national climate change assessments and strategic planning documents, so that economic development scenarios, project planning and regulatory decisions can be developed and compared against a uniform and consistent baseline. The basic question confronting planners in which baseline does one plan for an uncertain future 50–100 years hence.

Though a new set of future scenarios designed for global and national mitigation policy formulation have been developed – the shared socioeconomic pathways – offering a broader view of what a world 'with and without' future climate policy options might look like (O'Neill *et al.*, 2014; Nature Editorial, 2019), they are still far from being useful for water planners at the site-specific, project level (Hausfather & Peters, 2020). Thus, when water resources planners are forced to use highly unrealistic scenarios by their respective governments, as part of comprehensive river basin planning strategies or site-specific project planning, they are placed in a very difficult position of analyzing and planning for implausible and extreme scenarios, resulting in very costly and mostly unrealizable strategies, plans and project designs for future population needs (Shortridge *et al.*, 2017).

A commonly encountered display of future climate uncertainty for major river basins is exhibited in Figure 1. This figure represents the Mekong River Basin annual precipitation derived from three different climate models, based on two high-emission scenarios, RCP6.0 and RCP8.5, resulting in six climate scenarios that had been 'approved' by the Mekong River Commission (MRC, 2018) for comprehensive basin planning purposes. These scenarios represent the typical wide disparity among results in the various climate change scenarios and the models that generate the temperature and precipitation projections based on the scenarios, which are in use today that influence policies, vulnerability assessments and decision-making.

From a project planning or design perspective, when viewing Figure 1 it is quite difficult, if not impossible, to draw any sensible insights, much less conclusions about vulnerabilities and specific water management impacts for a particular project, project site or watershed in the Mekong basin from an ensemble of selected climate scenarios that represent the high end of possible greenhouse gas emissions scenarios. Clearly, there is a wide divergence in projected precipitation among the three climate models for the same scenarios, ranging from a 30% precipitation decrease for the GISS model/RCP8.5 scenario to a +40% precipitation increase for the GFDL/RCP8.5 scenario. Practically speaking, it is hard to imagine any combination of economically feasible

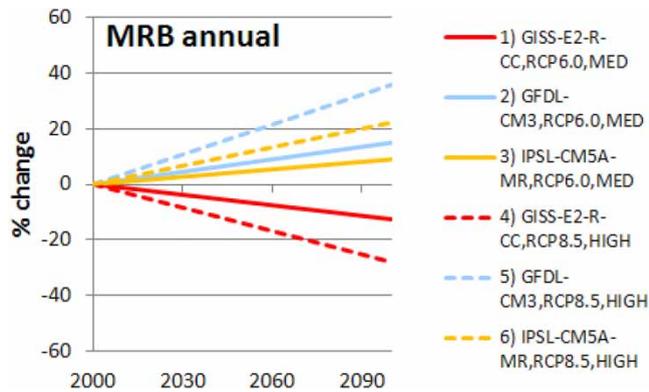


Fig. 1 | Projected change to annual precipitation relative to baseline period (1986–2005) in the whole Mekong River Basin (MRB) under six recommended climate change scenarios (MRC, 2018).

solutions that can resolve water resources problems for the Mekong basin across such a wide range of disparate ‘worst-case’ scenarios.

This situation is a common one for most analyses relying on a ‘top-down’ approach, i.e., one beginning with climate models and emissions scenarios provided by the IPCC, and then working to downscale the information to the geographic levels of interest. Though this approach was originally used as the basis for national-level ‘climate policy’ decisions largely for mitigation purposes (Dessai & Hulme, 2004; Kundzewicz & Stakhiv, 2010), the top-down analytical model was soon extended for many other adaptation purposes, including agriculture, forestry and water resources, inappropriately so, according to many (Koutsoyiannis *et al.*, 2008; Anagnostopoulos *et al.*, 2010; Pielke & Wilby, 2012).

Presently, it is impossible to predict which climate scenario will emerge to be the dominant one in a particular region – especially in the monsoon-driven climate of the Mekong River basin. Similar wide disparities among climate model outputs have been shown for many river basins around the world (Giuntoli *et al.*, 2015; Eisner *et al.*, 2017; Hattermann *et al.*, 2017; Kettner *et al.* 2018).

Recognizing these considerable uncertainties and disparities among various climate scenarios and models, it is quite impossible to design a functional water management project, or system, based on such vague and inconsistent climate information. Nor is it likely that applying ‘robust decision-making’ (RDM) methods can overcome such widely divergent climate model outputs (Daron, 2015; Herman *et al.*, 2015; Giuliani & Castelletti, 2016). Robust strategies are understood as those which satisfy performance criteria against most sets of future conditions (Bhave *et al.*, 2016; Wilby & Dessai, 2010). Project alternatives that meet ‘performance criteria’ across many different climate scenarios, i.e., ‘robust’ solutions, generally cannot meet normative economic efficiency criteria (i.e., benefits > costs) that are used by most water management institutions (Tol, 2003; World Bank, 2010; Stakhiv, 2011; Dennig, 2018).

Hence, there is an incongruity between the aims of ‘RDM’ that develop ‘robust’ solutions which cover a wide range of climate scenarios, and those of traditional decision frameworks that aim for economically optimal solutions. Traditional decision frameworks focus on the most likely or most plausible scenarios, both socioeconomic and climate based. This critical step, of assessing plausibility, relies on professional judgment, to a large degree, based on the known trends and circumstances within a particular watershed, area or region (Mendoza *et al.*, 2018). Once discrete projects/solutions are formulated, the decision rules applied are those that maximize net benefits or minimize the risk-cost, typically used by most public engineering institutions.

ALTERNATIVE APPROACHES TO DECISION-MAKING UNDER UNCERTAINTY

There is an additional discontinuity between the detailed risk analysis methods currently required for traditional hydrologic analysis and project benefit–cost analysis (BCA), with the inability to derive legitimate probabilistic information from an ensemble of highly divergent climate scenarios. While vulnerability assessments and bottom-up frameworks are useful in testing the robustness of planning alternatives, this approach requires some sense of the likelihood of selected future scenarios, usually with either uniformly sampled scenarios or ensemble projections treated probabilistically (Shortridge & Zaitchik, 2018).

Dessai & Hulme (2004) covered three important concepts in their paper ‘Does climate policy need probabilities?’ The first being the notion of whether probabilities can be legitimately assigned to various climate change scenarios and outcomes. The second questioning whether climate change scenarios even belong in the realm of probabilistic computation. The third issue raised was whether ‘top-down’, climate scenario-driven analysis can be applied to contemporary resource management issues. They proposed a ‘bottom-up’ variant to deal with typical resource planning and management climate adaptation policies, because they included an array of very complex interacting social, economic and resource capacity issues and vulnerabilities. Figure 2 best encapsulates their ‘top-down’ and ‘bottom-up’ dichotomy, which is an appropriate starting point for climate adaptation.

Borgomeo *et al.* (2018) assert that under conditions of climate uncertainty, decision-making is a three-way tradeoff between risk, cost and robustness. The incremental costs of meeting added robustness/reliability criteria can be quantified based on either risk attitudes of the public (‘tolerable risk’) or existing institutional, legislative or engineering standards and/or community criteria. In fact, most engineering design standards are routinely adjusted to meet contemporary notions of ‘tolerable risk’ (see Stakhiv paper, this volume).

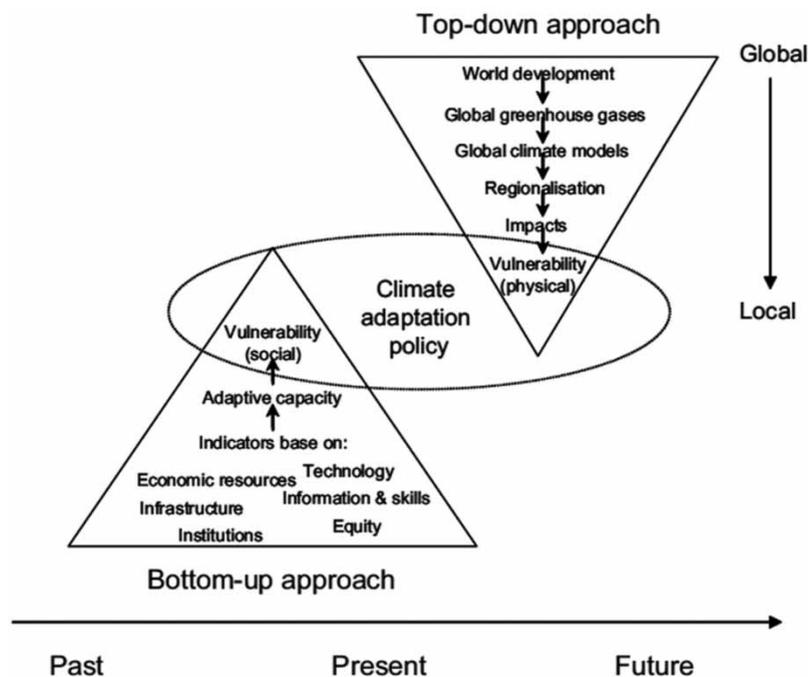


Fig. 2 | ‘Top-down’ and ‘bottom-up’ approaches used to inform climate change adaptation (based on Dessai & Hulme, 2004).

For water resources agencies, ‘robustness’ has two fundamental performance dimensions: reliable service delivery (municipal water supply, irrigation and hydropower) over time and safety – i.e., avoiding catastrophic project failure (e.g., levee breaches, dam failure, pipeline ruptures, etc.). The incremental costs of robustness are those that reduce ‘residual risks’ in the future, either in performance and/or safety, which can readily be derived using standard approaches for formulating cost-effective solutions based on existing conventional procedures and engineering standards (Stakhiv, 2011).

There are, however, two fundamental but very different and mostly incongruous aspects of climate risk-based decision-making that must be resolved within current practices. The first is that perceived climate non-stationary requires a different or modified suite of hydrological methods and models for conventional project justification approaches required by such evaluation protocols as the P&G and many other agency procedures that require BCA (Read & Vogel, 2015; Salas *et al.*, 2018; Serago & Vogel, 2018). The second is that climate change scenarios cannot be credibly assigned probabilities. The question is whether non-stationary can be treated independently of determining the probabilities of multiple climate scenarios?

Many alternative evaluation approaches that have been proposed, attempt to deal with climate change scenarios as a qualitative, judgment-based ‘plausibility’ issue, without specifically dealing with either scenario probabilities or explicitly with hydrologic non-stationary (Dessai & Hulme, 2004; Slater *et al.*, 2021). While climate scenario probabilities are not essential to formulating projects, some standardized approaches to hydrologic non-stationary would be useful for existing project evaluation procedures, as described, for example, in Salas *et al.* (2018).

Analyzing the risk of disastrous extreme hydrologic events (floods or droughts) lies at the heart of BCA and project justification. Hydrologic frequency analysis of observed conditions provides the evidence to estimate the probabilities of harmful outcomes, alongside extensive stochastic simulations of water systems to sample spatial and temporal variability (Borgomeo *et al.*, 2018). However, since there is now pressure to evaluate water investments in the context of a moving non-stationary climate framework (Milly *et al.*, 2008), different analytical frameworks have been proposed to overcome the difficulties of dealing with non-stationary and assigning probabilities to climate scenarios (Slater *et al.*, 2021).

However, Kroll *et al.* (2015) noted another underlying problem of trying to quantify non-stationary in flood flows, for it is not just related to climate change, but is shown to result from a variety of anthropogenic processes including changes in land use, climate and water use, with likely interactions among those processes making it very difficult to attribute trends to a particular cause, at a particular site. Serago & Vogel (2018) developed a simple statistical model which can mimic observed flood trends and the frequency of floods in a non-stationary world.

It is argued that decision analysis methods based on probabilistic risk analysis of historical hydrological observations alone may no longer be adequate to identify a water investment capable of meeting a performance or service standard (Borgomeo *et al.*, 2018). Others, such as Lempert (2019) and Dennig (2018) argue that the applicability of BCA, based on probabilistic characterizations of uncertainty, can no longer be relied on as an approach to ranking decision alternatives in the face of large uncertainties, especially those associated with climate change. For BCA to provide decision support under these circumstances, it needs to be reframed to account for the large uncertainties facing many types of decision challenges.

Stakhiv (2011) advocated changes in BCA procedures from a somewhat different standpoint, considering anticipated large climate uncertainties in the analytical process, and the need to formulate more robust water projects and systems. He argued that current economic procedures need to be revised to counter what he termed the ‘triple discount dilemma’ common to most agency procedures. In other words, current economic evaluation criteria and decision rules are set up in such a way as to discount (minimize) the effects of low probability–high consequence catastrophic events that may be more common during a future non-stationary climate. The

socioeconomic effects of uncertain, low probability–high consequence events, such as extreme floods and droughts, can also be discounted by the choices of probability distributions that diminish the importance of low probability events (Haimes, 2009; Pindyck, 2010; Botterill & Cockfield, 2013).

In addition, e.g., high economic discount rates of 7–10% used by the major public engineering organizations, such as the Corps of Engineers and World Bank, coupled with a decision rule that optimizes project outputs only to the level that maximizes net benefits, often resulted in projects that provided protection against floods in the 50–100-year range of return periods. The trend towards optimization, as part of systems analysis, coupled with the built-in ‘triple discount dilemma’, ultimately led to ‘brittle’ solutions (Fiering, 1982) – i.e., projects that were neither robust nor resilient (able to quickly return to design project performance levels after a failure).

In the search for more ‘robust’ decision-making approaches, an expanded approach that employed multi-scenarios based on a multiple models approach, using ‘ensemble’ climate projections favored by many climate scientists and hydrologists, generated scores of different precipitation and runoff simulations for river basins around the world (Lehner *et al.*, 2020). These, however, have not been as useful in clarifying future states of hydrologic runoff in given river basins, nor in reaching robust conclusions about the utility of these methods (Eisner *et al.*, 2017; Hattermann *et al.*, 2017; Krysanova *et al.*, 2017).

Hence, approaches that advocate ‘RDM’ which undertake evaluations of these ensembles also propagate a ‘top-down’ cascade of uncertainties that are difficult to unravel and comprehend by the average water resources planner working in any major water agency or department (Shortridge *et al.*, 2017). Nevertheless, they are part of a suite of newly developed approaches to deal with climate uncertainty as part of either policy setting, strategies for river basin development and investments and project planning (Groves *et al.*, 2014).

Daron (2015), Lehner *et al.* (2020) and Bhawe *et al.* (2016) challenge the utility of RDM practices, especially for developing nations, where data are sparse, and there are disagreements over which scenarios should be used for analysis. Conventional forecast-driven approaches to climate change adaptation create a cascade of uncertainties that can overwhelm decision-makers and delay proactive adaptation responses. One of the significant limitations and shortcomings of robust planning frameworks is the tendency to favor static alternatives to be implemented in the near-term, which could result in costly overdesign, particularly in the case of long-life infrastructure (Borgomeo *et al.*, 2018; Herman *et al.*, 2020). Clearly, there exist solutions that are insensitive to a wide array of climate scenarios, but they are either often considered economically infeasible under current benefit–cost criteria, or would likely be either socially or politically infeasible, requiring massive regulatory interventions and widespread behavioral adjustments at the national and local levels.

The added problem is that there are always uncertainties and residual risks associated with technological solutions – particularly non-structural solutions for floodplain management that are based on floodplain delineations and depend on uncertain flood warning triggers and timely evacuations during a flood (Haimes *et al.*, 1995). RDM seeks to identify those areas of residual risk that fall outside the range of stationary climate analysis. Risk ‘tolerance’ and residual risks are politically determined criteria, via public preferences (Institute for Water Resources, 2010).

Concurrently, several different and more pragmatic approaches called ‘adaptation pathways’ (Walker *et al.*, 2013), have been developed, which focus on defining a comprehensive set of alternative sequences of decisions and identifying the conditions that could guide decision-makers along the most appropriate sequence based on defining critical performance thresholds. Haasnoot *et al.* (2013) demonstrated this approach for flood control in the Netherlands, which included novel visualizations of different sequences of investments, that they called ‘pathways’. The pathways are combinations of different projects or measures that are implemented depending on which critical performance thresholds are exceeded. What is not and developed in this approach are the evaluation criteria which link the analytical procedures that transform future climate scenarios to defining when these

acceptable performance thresholds are breached. In other words, clearly identifying the thresholds for changing a course of action.

What the ‘adaptation pathways approach’ entails is the formulation of a core set of projects/actions that would be required, as a starting point, under any combination of scenarios, if only to keep pace with growing population demands and project rehabilitation requirements. Then, over a period of time, depending on new information and perhaps technological developments that alter future demand patterns (more efficient water saving devices, changes in industrial technologies, etc.), certain climate response pathways may be narrowed down to a better-defined strategy, with well-defined alternative adaptation pathways depending on the improved climate scenario information.

Another related approach, termed ‘decision-scaling’ (Brown *et al.*, 2012), has been described and applied in the Great Lakes region (Brown *et al.*, 2011) and the Niger River Basin (Ghile *et al.*, 2014). Decision-scaling provides techniques for extensively exploring plausible climate conditions to help identify key climate-related thresholds that distinguish different robust strategies. Both approaches – adaptation pathways and decision-scaling – belong to the subset of methodologies that rely on a ‘bottom-up’ approach. Decision-scaling is defined by Brown *et al.* (2012) as

‘... the use of a decision analytic framework to reveal the scaling of climate information that is needed to best inform the decision at hand. The methodology first identifies the climate conditions that are *relevant to the decision* and then uses that information to link to what is *credible* in available climate information’.

In other words, Brown *et al.* (2012) suggest that before launching into a ‘top-down’ multiple ensemble climate scenario robustness analysis, first look at what types of decisions and scales of analyses are required regarding the specific existing circumstances and vulnerabilities of a project or system of projects. These circumstances could vary at many different scales – from a strategic river basin plan, an infrastructure project, major dam spillway rehabilitation project, reservoir reregulation or capacity expansion of an irrigation project or water supply treatment plant. Then, identify those elements that require more detailed analysis simply to meet the projected demands and updated hydrological information since the projects were constructed. Finally, select the type of analysis and degree of specificity most appropriate to the nature of the problem that was identified. In other words, do not automatically begin with top-down, multi-scenario analysis. Brown & Wilby (2012) also propose several different quantitative approaches that link GCM scenarios with stochastic hydrologic ensembles as the basis for joining ‘top-down’ with ‘bottom-up’ analysis, if required.

Water resources management is inherently about incremental adaptation, adjusting to changes in climate, technology and population demands. As climate events are more closely monitored and models improve, and the variability, frequency and intensity of certain extreme events become more apparent over the next two decades, suggesting distinctive trends, then the sequence and timing of a suite of water resources projects that were designed for flexibility, robustness and resilience, can be evaluated with greater certainty. Then, the numerous permutations of alternative development pathways will be more readily apparent and can coalesce into a definable adaptation strategy.

CLIMATE RISK-INFORMED DECISION ANALYSIS

A dominant factor in the way ‘public engineering’ has evolved in the past two decades is linked to the advent of the six reports of the UN Intergovernmental Panel on Climate Change (IPCC, 2021), as well as national greenhouse gas reduction commitments required by the Paris Accords of 2015. These reports created a climate model-driven ‘top-down’ analytical paradigm which was unsuited for most water resources management problems – particularly those related to site-specific infrastructure design. Because climate models have been so

undependable for site-specific project planning, the water resources community banded together in 2010 to develop an alternative pathway for analyzing projects under climate uncertainty. Consequently, a number of practicing water management agencies and lending institutions, such as the World Bank, Corps of Engineers, Rijkswaterstaat, etc. formed an ‘Alliance for Global Water Adaptation’ (AGWA, 2020) <http://alliance4water.org/>.

The first outcome of this alliance effort was the World Bank’s *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework* (Ray & Brown, 2015), widely known now as the ‘decision tree approach’. Shortly thereafter, under the longstanding cooperation between the U.S. Army Corps of Engineers (USACE) and the Rijkswaterstaat (the Dutch national water management authority), the Climate Risk-Informed Decision Analysis (CRIDA) project was initiated (Mendoza *et al.*, 2018). (https://agwaguide.org/docs/CRIDA_Sept_2019.pdf). Meanwhile, the Asian Development Bank was also crafting its own set of guidelines for dealing with climate uncertainties within their planning frameworks (Watkiss *et al.*, 2020).

Both the World Bank ‘decision tree framework’ and the associated CRIDA planning methodology emphasize a ‘bottom-up’ analytical perspective to water resources project planning and decision-making, in view of the wide disparities in climate model outcomes. They are complementary analytical frameworks, since CRIDA also incorporates the ‘decision-scaling’ approach developed for the World Bank.

What differentiates CRIDA from other approaches is the application of a step-by-step approach that marries a conventional water resources planning and evaluation framework with decision-scaling rationale, emphasizing a ‘bottom-up’ methodology to risk assessment and management for those problems requiring a formal examination of potential climate-related uncertainties to justify the selection of a project alternative. The CRIDA version of decision-scaling focuses more on guiding the types of decisions that are made within a typical planning process, and what credible climate information might be needed for those decisions, and arrays those against the analytical uncertainties of the available information and anticipated future risks of project performance associated with climate change.

In CRIDA, it is the overall formal planning and evaluation process, i.e., the institutionally approved ‘evaluation and decision model’ that guides the determination of which analytical path is taken in dealing with model uncertainties versus those decision frameworks that are based on climate uncertainties as the introductory and encompassing step. Existing institutional frameworks, like the U.S. Water Resources Council (1983), which tie together national water resources management objectives, public and stakeholder preferences, and socioeconomic decision criteria, guide how agencies should approach particular water problems and the manner in which model and climate uncertainties are to be treated within an existing and politically approved decision-making framework.

At least since the 1970s, risk and uncertainty analysis have been a standard feature of all steps in routine water resources planning processes. The core component, when choosing a particular analytical pathway, has always been asking questions of how important individual uncertainties will impact project performance within an array of possible alternatives. Additionally, in this existing framework, the importance of the societal distribution of risks and uncertainties, how uncertainties influence the design of a project (robustness, resilience and reliability) and impact on costs constitute equally important considerations.

A report by the U.S. National Academy of Sciences (NRC, 2000) noted that ‘[T]he Corps’ [U.S. Army Corps of Engineers] risk analysis techniques and flood damage reduction studies will produce their greatest benefits if these techniques and studies *are executed within a comprehensive planning paradigm and framework designed to make the best social, economic, and environmental uses of the nation’s floodplain resources*’. In other words, the NRC recognized that any risk-based vulnerability assessment that is conducted outside a formal and approved societal objectives-based planning framework is incomplete and could lead to skewed or biased outcomes (National Research Council, 2009).

Outcome risk, i.e., uncertainty about either the consequences or severity of those consequences, is routinely reduced by a variety of risk reduction management measures, including both structural and non-structural measures. These measures do not reduce all risk uniformly because they address different parts of the risk management cycle (prevention, preparedness, response and recovery) – some protect property, others are geared towards saving lives at the expense of property. For example, a flood warning and evacuation system have its own highly uncertain components that are very susceptible to a cascading sequence of human error and technological breakdowns (Haimes *et al.*, 1995).

As an example, Figure 3 shows a stepladder hierarchy of typical flood damage risk reduction measures that are routinely employed as part of a strategy of flood risk reduction. At the bottom of the step ladder is ‘residual risk’, or risks that are unknown or highly uncertain, but are considered as ‘tolerable’ by society. Figure 3 shows that these residual risks will likely increase in the future, as climate change uncertainties become more apparent.

While economists value water for its abstract economic production values, water engineers measure performance against the specific objectives for which a project or system was designed, a wide array of services which contribute towards economic performance. A number of abstract performance indices were proposed to measure the performance of water resources systems in terms of robustness, reliability, resilience and vulnerability of water resources subjected to climate extremes (e.g., Hashimoto *et al.* 1982a). *Reliability* is the probability that no failure occurs within a fixed period, often taken to be the planning period. *Robustness* describes project designs and operating policies that may be sufficiently flexible to permit their adaptation to a wide range of possible demand conditions at little additional cost. *Vulnerability*, in this context, refers to the likelihood of a project service failure (e.g., due to maximum flood or drought intensity). *Resilience* is often interpreted as a measure of how quickly a system is likely to recover from failure once failure has occurred. Inherently, the ensemble of drought management measures (or flood control measures) that are implemented by any locality or region aims to increase system reliability, resilience and robustness, while decreasing vulnerability (Hashimoto *et al.*, 1982b).

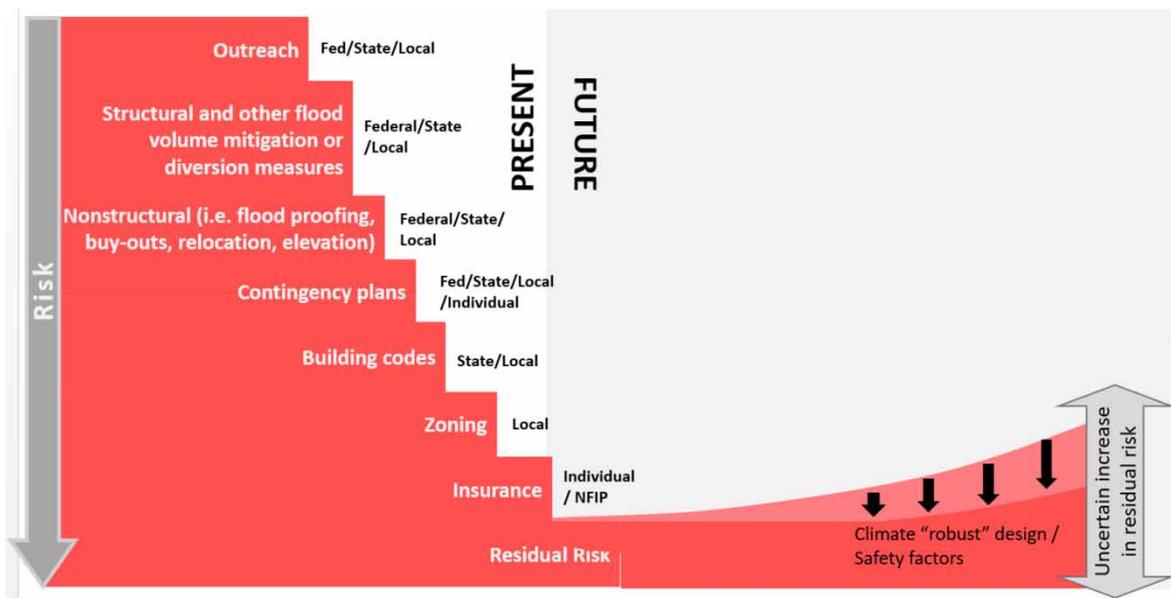


Fig. 3 | Buying down risk: flood risk reduction management measures.

Future climate uncertainty and socioeconomic growth and development trajectories will, almost inevitably, widen the uncertainty bounds of residual risk. Structural measures have proven to be the most reliable of all the measures, and more conservative engineering design factors can significantly reduce future uncertainties, thereby increasing robustness, reliability and resilience.

If certain destructive events occur frequently enough – e.g., a historic flood or drought; an infrastructure failure; or increased demands due to accelerated development programs (new irrigation projects, hydroelectric power or municipal water supply) – institutions will re-examine their portfolio of projects and water management systems, as well as policies and procedures. Such examinations may include operating rules to reassess performance to meet future demands under comparable hydro-meteorological conditions and/or a changing climate. Vulnerability assessments, or ‘stress tests’, are standard starting points for all inquiries often triggered by a flood or drought; whether expanding the capacity of a dam or navigation lock system due to anticipated growing capacity demands; or major repair and rehabilitation of existing water infrastructure systems that are approaching or have surpassed their design life (levees, hydropower, irrigation systems, dams, etc.).

DECISION-SCALING WITHIN CRIDA

The general concept of ‘decision-scaling’ as applied to climate-related uncertainties was likely first introduced by [Matalas & Fiering \(1977\)](#), though they did not have a term for the process they described to map the uncertainties associated with future climate scenarios against alternatives of optimal water resources system design. The authors also introduced the notions of robustness, reliability, regret and resilience as key attributes of any system design.

‘Part of the design problem is to identify the types of climate shift that might be anticipated and to determine if they are sufficiently precipitous with respect to flow characteristics to dictate a change in system design. It is not necessary for this purpose to know or to try to determine whether there is a true climatic shift, this may be an interesting scientific question, important in its own right, but it is virtually meaningless for the design of water resource systems’.

[Brown et al. \(2011, 2012\)](#) have substantially expanded on the concepts of decision-scaling as applied to water resources planning and decision processes under climate uncertainty. They explicitly focused on an approach for climate risk assessment that links bottom-up vulnerability assessment with multiple sources of climate information. To describe this methodology, they introduced the term ‘decision-scaling’, which refers to the use of a decision analytic framework to reveal the ‘scaling’ (choice of appropriate level) of climate information that is needed to best inform the decision at hand for different scales of water management problems.

The CRIDA approach, described in manual-like detail in [Mendoza et al. \(2018\)](#), is inherently based on a decision-scaling sequence of questions that try to categorize the nature of the problem at hand, within an agency’s existing procedural and analytical framework. At the core of the CRIDA approach is a traditional agency planning process. The Corps of Engineers, e.g., have wedded the CRIDA climate decision process with its version of planning, termed ‘shared vision planning’ ([Werick & Palmer, 2008](#); [Bourget, 2011](#); [Brown et al., 2011](#); [Palmer et al., 2013](#)). However, CRIDA focuses on the aspects of project planning that will be affected by climate uncertainties. It poses questions as to what types of potential climate shifts in a particular region may produce precipitous changes in hydrologic flows, and whether they are sufficient to dictate changes in standard approaches to design, so that planners can devise the most appropriate analytical approach to risk analysis under climate uncertainty. It elicits information about how concerned planners are about future risks and analytical uncertainties, depending both on the existing information and on the nature of proposed changes – new

construction, reservoir operations management changes, major rehabilitation of existing infrastructure or non-structural regulatory management changes.

There are two ways of viewing the CRIDA decision-scaling approach – both are complementary perspectives. The CRIDA approach is to view the problems more generically, in terms of qualitative ‘levels of concern’ about ‘future risks’ from climate uncertainties arrayed against known ‘analytical uncertainties’. This appraisal process can be viewed and simplified as four decision quadrants (Figure 4). Another complementary way of looking at the problem is from the more familiar perspective of categories of analysis typically used by water agencies for construction, operations, maintenance and long-range strategic planning (see Figure 5).

In CRIDA, performance metrics are selected to measure a system’s ability to reliably deliver services during the life of the project. These are then arrayed and compared against minimum acceptable service levels and thresholds to measure three basic variables: *reliability* (the frequency that system performance meets a target), *resiliency* (the time it takes for a system to return from failed performance to a target) and *robustness* (the range in which a system maintains target performance while facing external stressors) of services under the stress of future change. Compared to traditional economic decision criteria, these three variables form an enhanced level of consideration for decision criteria when high uncertainty and variability are important.

An initial vulnerability assessment, or ‘stress test’ of how a project or system performs under a variety of selected plausible scenarios or load factors, is always the starting point, and should always begin in Quadrant I (Figure 4), to determine whether the nature of the problem requires moving in a direction that deviates from standard planning procedures and accepted analytical techniques. In other words, explore the range of conditions under which a project will operate as designed, and determine which conditions will cause the project to perform unreliably or fail – either in curtailing delivery of services (water supply, irrigation, hydropower, etc.) or structural failure (spillway failure, overtopping, dam breach, etc.). Such procedures are enumerated in many engineering manuals of the Corps of Engineers or Bureau of Reclamation.

Even if the uncertainties are large enough to warrant additional and more detailed ‘stress tests’, further probing identified failure points and external loading factors (e.g., an expanded set of plausible climate scenarios), the underlying question remains – is the project robust enough, with its embedded safety factors and redundant design criteria to deal adequately under a foreseeable increase in climate variability? Are existing analytical tools and evaluation protocols sufficient to deal with the added levels of uncertainty?

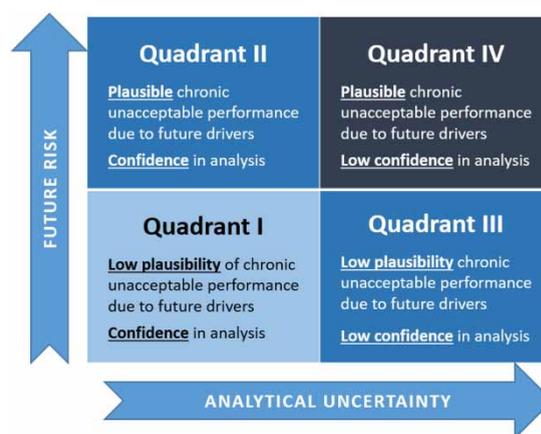


Fig. 4 | Categorizing future risk and analytical uncertainty to establish a ‘level of concern’ in the planning process (Mendoza et al., 2018).

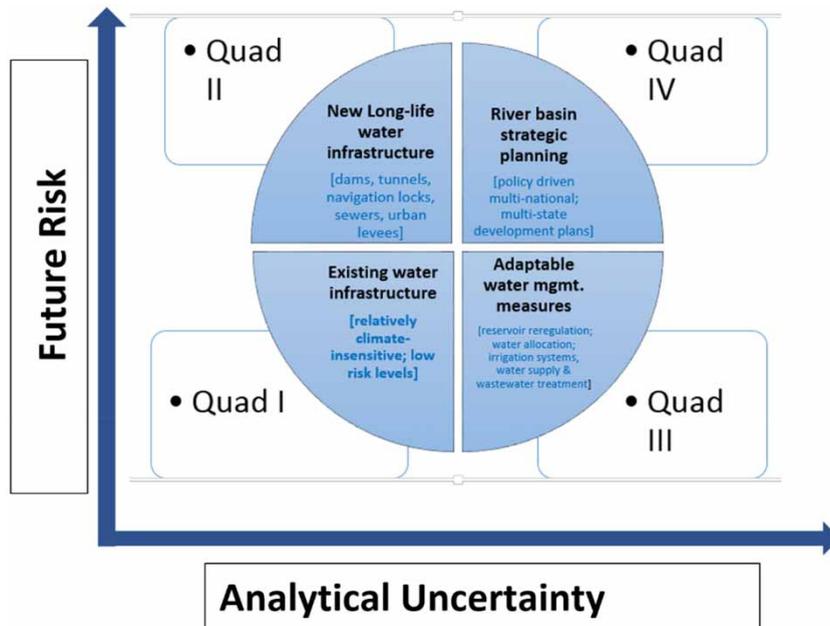


Fig. 5 | Decision-scaling perspectives based on water management functions.

Typically, an analyst is concerned with the consequences of failure from under-designing a project or excessive design costs that cannot be easily justified. An institution's existing practices and design standards often mandate precautionary policies and safety margins. In most cases, the analyst applies standard planning and design guidance as required by existing methodologies, regulations and guidelines (Quadrant I, Figure 4). The stress test should reveal whether there exists a qualitative 'level of concern' about future risks and analytical uncertainties related to either future socioeconomic changes and/or plausible climate scenarios and associated uncertainties. The analysts then determine whether the existing water delivery system or project can address future uncertain but likely plausible stressors, and whether moving beyond standard planning and design approaches is needed and justified.

In Figure 4, 'Future Risk' is the plausibility that a future driver (climate, population growth, demand increase, land use changes, etc.) can be identified that leads to chronic unacceptable failure, i.e., violates one or more selected performance thresholds, with associated adverse consequences. 'Analytical uncertainty' connotes a reduced level of confidence by the analyst in evaluating a project's performance over the life of the project, given the information available to evaluate and to adequately analyze the problem and potential solutions, so that a decision maker can formulate and choose an option with confidence.

The central focus of CRIDA is to determine if the problem encountered can be solved using standard existing 'bottom-up' methods, without necessarily resorting to highly uncertain climate scenarios – meaning whether one can stay within Quadrant I (Figure 4), or whether one needs to enlist other more tailored methods and mechanisms to effectively resolve a range of associated climate uncertainties. Among the decision uncertainties to consider include whether or which future climate scenarios to consider, and/or whether hydrologic 'non-stationary' needs to be factored into the planning and design of a water management strategy or action (e.g., Salas *et al.*, 2018). One of the key underlying questions is whether existing proven analytical methods combined

with robust engineering standards are sufficient to encompass the uncertainties inherent in climate variability and future change?

If the 'level of concern' is modest, and there is confidence in the plausibility of selected future scenarios, and the analytical uncertainties are small, then Quadrant I suggests that there is no need to deviate from standard, accepted planning guidance and practices. This default, 'business-as-usual' position is recommended when the stress test reveals minimal impact from future uncertain stressors that are likely to contribute to water resources system failure – either in the form of services or physical infrastructure failure. For most situations, Quadrant I is the starting position for the analyst and decision-makers and may be the endpoint for the CRIDA process if the 'level of concern' is low. This is where the classical 'no regrets' planning options are most sensible and are based on conventional decision rules embodied in agency procedures (Borgomeo *et al.*, 2018).

Based on preliminary stress tests, if the results show significant chronic project or system failures under a number of plausible socioeconomic and/or climate scenarios, then Quadrant II suggests decisive action would be required to build a new project or increase robustness (e.g. raise a dam for added flood storage or raise a levee to protect against higher flood levels) in response to plausible futures. Also, the analytical uncertainty associated with the scenarios is acceptable and can be evaluated using existing risk analysis methods. For example, climate non-stationary is not determined to be as influential as other socioeconomic trends that increase demands which exceed the capacities of the existing storage, treatment or delivery system. The vulnerability assessment may indicate uncertain future climate stressors are credible and have a potentially high impact on system performance. Consequently, the analyst should develop actions or plans that satisfy standard procedural requirements and perform acceptably under potential futures. In this quadrant, the methods advocated by Ray & Brown (2015) are appropriate.

A level of concern that places a situation in Quadrant III suggests that analytical uncertainty may be relatively high, but future scenarios do not indicate a clear increase in risk of impaired performance or system reliability. Hence, this situation may provide evidence and justification to delay major structural project implementation, suggesting consideration of incremental, low-regrets strategies that include monitoring and acquiring better information to address critical futures. In addition to continuing business-as-usual planning procedures, further analysis could suggest incremental adaptive actions be prepared for implementation should a trigger point be reached in a monitoring program.

The level of concern associated with Quadrant IV warrants both decisive and incremental action to increase the robustness of the system. There is plausible evidence and increased risks of future scenarios that will violate one or more critical performance thresholds, together with high analytical uncertainty. Under these conditions, decisive actions, coupled with monitoring to facilitate an incremental and flexible response are justified. Generally, this high level of concern may require substantive institutional adjustments that include changes in planning procedures and decision criteria. A new set of analytical tools, which may include 'top-down' climate scenario analysis (Ray & Brown, 2015; Salas *et al.*, 2018), coupled with an updated evaluation and decision-making paradigm is often required to accommodate this level of concern and address numerous unknowns.

It should be noted that analysis in Quadrants I, II and III essentially rely on standard procedures and analytical methods that can be found in dozens of engineering manuals of the various agencies and ministries that deal with water resources management. It is only in Quadrant IV that future operational risks and both climate and socioeconomic uncertainties are so large that methods specifically tailored for such circumstances should be employed. This is where decisions and analyses that fall within Quadrant IV are best served by the decision framework and methods and procedures found within the 'decision tree framework' proposed by the World Bank (Ray & Brown, 2015). This is also why the 'decision tree framework' and CRIDA are considered to be complementary risk-based planning and evaluation frameworks.

In particular, Quadrant IV, focusing as it does on large-scale strategic river basin planning, is where ‘RDM’ methods, such as those advocated by [Lempert \(2019\)](#), may be best suited. The Mekong River Basin Management Plan, noted previously, would be a candidate for such analysis, which would fully employ both a combination of ‘top-down’ and ‘bottom-up’ decision-scaling methods.

There is, however, a more conventional way of applying the decision-scaling perspective. [Figure 5](#) lays out a comparable and complementary way of viewing the types of typical water management issues that confront water planners from the perspective of familiar water management functions. The two axes are the same as for [Figure 4](#): the vertical axis is future risk and the horizontal axis is analytical uncertainty. For example, the way to overcome analytical uncertainty in Quadrant III is to delay decisions until better information is gathered through monitoring, e.g., and consider a series of incremental actions such as reservoir reregulation or reallocation of storage; incremental expansion of capacity by adding new water treatment units or raising a dam. Quadrant IV is essentially dedicated to large-scale strategic basin planning endeavors that encompass multiple future objectives, increased socioeconomic demands, coupled with a wide range of options and alternative technologies.

When there is high analytical uncertainty but little plausibility of increased future climate risk (Quadrant III), decision-makers face a difficult choice of taking potentially unnecessary (and expensive) actions or taking no action and risk future adverse consequences. In the first case, actions need to be justified based on the limits of analytical knowledge. In the second, the system remains vulnerable, but the risks may be tolerable. With either approach, a flexible adaptive management strategy makes sense – if the relative residual risks are understood and accepted by the stakeholders. Delayed, sequenced or incremental actions can be implemented and actions that expand the lifetime of existing infrastructure or enhance performance may be appropriate. In this instance, an ‘adaptation pathways’ approach is a reasonable decision framework as a starting point ([Haasnoot et al., 2013](#); [Kwakel et al., 2015](#)).

Quadrant III solutions are needed where the future conditions are reasonably well known but there are disagreements on which course of action to pursue because of uncertainties in key decision criteria. Accordingly, the analyst can embark on a series of enabling actions and adaptive management approaches, such as monitoring tipping points and strengthening institutional capacity to detect and implement transitions ([Wilby & Murphy, 2019](#)). An example could be the development of new reservoir regulation operating rules or identifying different water allocation quotas for withdrawals and river basin management, keeping pace with an evolving hydro-climatology, as in the case of the Great Lakes ([Brown et al., 2011](#)).

CONCLUSIONS

CRIDA ([Mendoza et al., 2018](#)) and its companion ‘decision tree framework’ document that is the basis of World Bank approaches to climate uncertainty ([Ray & Brown, 2015](#)), are complementary guidebooks that assist planning practitioners in deciding how to approach a wide range of climate uncertainties for different water resources planning and design functions. CRIDA provides a decision framework for addressing climate uncertainties within an agency’s existing institutional guidelines. The ‘decision tree framework’ focuses more on a decision-scaling process coupled with analytical approaches that tie together ‘bottom-up’ and ‘top-down’ climate evaluation perspectives.

For most aspects of water resources planning and management, climate adaptation-type analyses should be conducted from a standard ‘bottom-up’ risk management perspective because scenario-driven climate models do not provide the specific ground-level information needed for traditional water resources project evaluation and decision-making procedures. In a typical water resources management study or project justification analysis,

climate change is but one additional risk factor among a myriad array of social, economic, ecological and behavioral vulnerabilities.

For water resources planning studies, if the analyst determines that future risks due to climate uncertainties and/or analytical uncertainties are fairly well understood, climate stationary is still a useful concept as a starting point for stress tests and vulnerability analyses to make reliable predictions for engineering design (Stakhiv, 2011; Brown & Wilby, 2012; Slater *et al.*, 2021). Observations of past patterns and information are key elements for a successful prediction of hydrological processes (Lins & Cohn, 2011; Bayazit, 2015).

There are four important and major incongruities that water resources planners are asked to reconcile as part of their institutionally mandated project planning risk analysis approaches. First, estimating the likelihood/plausibility of climate scenarios. Second, linking these scenarios to non-stationary watershed hydrology, to quantify the reliability of future project service delivery and the risk of project failure. Third, applying the economic concepts of expectation requires calculations of expected annual damages (or benefits) that employ a selected probability distribution which best reflects a future uncertain climate state. Fourth, almost all benefit–cost decision protocols are based on discount rates and discounting, which further skews the analyses away from robust projects which can withstand more diverse climate uncertainties, by discounting risks and increased variability of distant future climate change, beyond 30–50 years. The sequential application of these largely incongruous steps as part of typical project justification procedures inherently skews the formulation of technically feasible and economically justifiable projects.

CRIDA and its reliance on ‘decision-scaling’ were devised as a practical way to address and bridge these risk incongruities, in a way that is compatible with existing institutionally acceptable water planning, evaluation and decision protocols. Decision-scaling is essentially a judgmental process that addresses several basic questions related to the degree of climate-related uncertainties that underlie a particular water resources problem. Decision-scaling helps to delineate and separate those aspects of analysis that require advanced methods that ought to be employed to deal with long-term climate uncertainties versus those that require additional analytical rigor using existing methods and analyses.

It turns out that except for mitigation-type policy analysis (prevention and reduction of greenhouse gases) and large-scale strategic river basin planning, the CRIDA approach shows that most existing planning protocols and analytical methods can be suitably modified to deal with hydrologic non-stationaries and climate uncertainties. Furthermore, most existing planning and design approaches are suitable for most water resource management issues because they already incorporate a number of built-in safety factors, redundancies and risk-avoidance measures that inherently are designed to accommodate most future uncertainties associated with climate change.

DATA AVAILABILITY STATEMENT

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

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