Climate Risk Informed Decision Analysis (CRIDA)

Collaborative Water Resources Planning for an Uncertain Future

UNESCO
United Nations
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ICIWaRM
International Center for Integrated
Water Resources Management
under the auspices of UNESCO

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Collaborative Water Resources Planning for an Uncertain Future

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FOREWORD

by Blanca Jiménez-Cisneros, Director of UNESCO IHP

Over the last decade, climate change is accelerating and is now affecting every country on every continent. It is disrupting national economies and affecting livelihoods, particularly through the impact on water and water-related hazards. For each degree of global warming, an additional 4% of the global land area will face a water resources decrease of more than 30%. The impact of water-related hazards is also felt more in developing than in developed countries, both in terms of economical and human losses, reinforcing inequality and poverty.

Adequate planning for water resources management is therefore at the heart of disaster risk reduction, as defined by the Sendai Framework, and has been also integrated in the UN Sustainable Development Goals. The Paris Agreement highlights the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, and the role of sustainable development in reducing the risk of loss and damage. Comprehensive risk assessment and management is specifically proposed as a mechanism to address these challenges. The agreement also requests the UN agencies to support their Member States in order to enhance action on adaptation, highlighting adequate planning for policy making, as well as the identification of adaptation strategies.

Although global assessments of climate change impact can provide a rough indication of trends and expected impacts, the local conditions define how vulnerable the communities are to these water security threats. Adaptation to this climate stress is therefore a local process that requires the design of tailored solutions.

In this context, the UNESCO International Hydrological Programme presents therefore the Climate Risk Informed Decision Analysis (CRIDA). This approach provides a crucial framework to enable water managers and policy makers to assess the impact of climate uncertainty and change on their water resources and work towards effective adaptation strategies.

This multi-step process embraces a participatory, bottom-up approach to identify water security hazards, and is sensitive to indigenous and gender-related water vulnerabilities. By engaging local communities in the design of the analysis, the information provided by scientific modeling and climate analysis can be tailored and thus provide more useful answers to the challenges they are facing. They are also providing a more informed starting point to assess the different options for adaptation, and design robust adaptation pathways, in line with the local needs.

The CRIDA approach advocates hereby to move away from the 'one size fits all' approach, and to pursue locally embedded solutions to the specific threats to water insecurity due to climate and other global changes. Therefore, this reference document is also an invitation to become part of a global water community that engages with the local stakeholders to identify their water security vulnerabilities, and to support their capacities to address their water management challenges under climate change

Blanca Jiménez-Cisneros,

Director of the Water Sciences Division

Secretary of the International Hydrological Programme (IHP)

UNESCO

FOREWORD

by Will Logan, Director of ICIWaRM

Of all the sub-disciplines related to water science and policy, Water Resources Management is surely one of the most challenging. From hydrometeorology to surface water hydrology, from agricultural engineering to groundwater flow and transport, and from ecohydrology to aqueous chemistry—the water professional is inevitably faced with poorly constrained parameters, incomplete datasets, over-simplified models, and the need for "just one more sampling point".

But water resources management takes all that, and adds the exasperating human element—institutions and infrastructure, policies and politics, demographics and demagogues, cooperation and conflict. The hard science and engineering run up against the soft science and culture. And as the water management truism states, "the soft parts are hard." The hard parts are not so easy either.

Every situation is different, and integrated water resources management has distinct meanings in different political and cultural environments. It may mean elimination of waterborne diseases and poverty reduction in regions lacking safe drinking water and sanitation, or interannual water storage mechanisms to "flatten out the hydrograph". Or it may emphasize ecosystem restoration and recreational opportunities in a society that has solved most of its basic health and safety challenges, and where most of the "hard" infrastructure was built out decades earlier.

But sound management of water resources in the face of uncertainty is important in any context. The 2017 US Global Water Strategy recognized sound water management as one of four interconnected strategic objectives—with safe drinking water/sanitation/hygiene, cooperation on shared waters and strong governance, financing, and institutions. And developing methodologies to help humans and rivers to coexist may be our moral imperative as well. As the UN High-Level Expert Panel on Water and Disaster said back in 2007, "National and international hydrological institutes must...identify underlying analytical and data requirements to meet climate changes that are likely to be highly uncertain and so as to support structural and non-structural measures for disaster risk deduction."

However, this may be easier said than done. Climate scientists may provide thousands of scenarios about possible future climates that lead to wide ranges of future hydrologic conditions. For example, climate projections used in the International Upper Great Lakes Study to recommend lake regulation protocols between the US and Canada showed that lake levels—a key planning parameter—could go either higher or lower in the future. Further complicating this uncertainty are demographic and land-use changes, as well as active stakeholder groups advocating for their interests under potentially water-insecure conditions. Water planners and managers need guidance that helps them move away from what we do *not* know about the future to what we *do* know. In other words, it may not be known what future flow will result from a 100-year return period storm event, but it may be easier to estimate the annual expected damages that will likely be unacceptable in 2050. Is this a possible paradigm shift that can help decision making under deep uncertainty?

The goal of Climate Risk Informed Decision Analysis, or CRIDA, is to help address this conundrum. By integrating hydrologic and climate science with systems modeling, economics, stakeholder collaboration, risk informed decision making and flexible pathways forward, CRIDA can help the water resources planner to navigate through an uncertain world toward imperfect but robust and socially acceptable solutions. Which is all we can ask of them.

No single institution can provide all the answers all of the time. The International Center for Integrated Water Resources Management (ICIWaRM), under the auspices of UNESCO, is one of many institutes and centers worldwide that are integrating new ideas into tried-and-true water planning and management approaches. We are especially grateful to our colleagues from other UNESCO "category 2" centers, such as IHE-Delft (The Netherlands), ICHARM (Japan), CAZALAC (Chile) and ICWRCG (Germany), who have freely shared their ideas and feedback. Our relationships with the Alliance for Global Water Adaptation (AGWA), Deltares, Rijkswaterstaat, The World Bank, and UNESCO IHP have been particularly fruitful.

We are also grateful to CRIDA's authors, contributors and reviewers as well as to those who have provided support for them.

In conclusion, I am delighted that ICIWaRM, in partnership with UNESCO's International Hydrological Programme, has the privilege of co-publishing this important advance in water resources management and planning. I look forward in the coming years to seeing the CRIDA approach applied, tested, adapted, extended and perhaps occasionally stretched too far in a wide variety of human and natural environments around the world.

Will Logan

Director

ICIWaRM

PREFACE

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 hydrology into reliable, socially desired benefits. As needs have grown and interventions have increased, water resources managers worldwide have had to design more complex water management systems and make more complex tradeoffs. To address these complexities, technical, analytical, and governance procedures for water management have evolved to keep pace with growing societal demands. The uncertainties associated with climate change have added to those management complexities.

Uncertainty is not a new issue for policy makers, engineers, or scientists, especially in water management. But the increasingly visible and potentially extreme impacts of climate change, and other difficult to predict drivers that stress water services, have highlighted the need to reassess how we address a sequence of cascading uncertainties, caused by natural variability, and model and decision-related uncertainties associated with public needs, objectives and values. Few examples exist of best practices for uncertainty in the planning and design of water resources management systems. Estimating future climate impacts has proven to be particularly contentious and frustrating, and in many cases effective solutions have been largely dependent on the skills and experience of a few individuals rather than systematic and reproducible approaches to planning.

This guidebook focuses mainly on the early feasibility stages of project planning when vulnerabilities and future water demands are assessed and options are devised and formulated by both practitioners and stakeholders in a collaborative setting for project investment decisions.

At this stage of planning, impact assessment and evaluation, as well as uncertainties, are vague and qualitative because the information available is at a synoptic level. Normally, at a feasibility stage of planning, we understand fairly well what the looming problems are and can identify common methods and measures to address those issues. However, we are less certain as to which options are "best": most risk cost effective, resilient, or sustainable.

The approach outlined in this guidebook applies standard engineering design criteria to feasible options recommended through a multi-stage and typically iterative planning process. Additional analytical and planning decisions are then made throughout the planning process by planners and stakeholders consistent with established planning procedures, agency protocols, and decision maker needs.

CRIDA in context

Water resources planners have long planned and designed for the "known unknowns" – that is, that is, traditional visions of risk and uncertainty – usually by adding safety margins to critical design features. The understanding of the unknown future has been informed by what has happened in the past, including catastrophic events and their known socio-economic and environmental consequences. The unprecedented rate of global economic growth and the prospect of climate change have resulted in a need to plan and design for future "unknown unknowns." As a result, much effort has gone into tools and models to forecast future hydro-climatology on the basis of numerous climate models and speculations about future hydrologic responses. Unfortunately, these tools and models often led to greater uncertainty and a broadening of ranges of possible future scenarios and associated flood and drought frequency analyses, which are the traditional bases for hydrologic and hydraulic design.

Consequently, choosing 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. Planners remain confronted with basic questions: Should we invest to minimize risk? How much should we invest? How can we justify a particular decision, given all the uncertainties? How do we plan for an action that is neither too early nor too late? Perhaps most importantly, how do we convey the resulting analyses, built on a pyramid of uncertainties, to the public and political decision makers?

The contemporary approach to water management in the U.S. and much of the rest of the world was largely framed in the mid-twentieth century by a small group of specialists. The Harvard Water Program was commissioned in 1955 to improve the planning and design of water resources systems (Maass et al. 1962; Reuss 2003). The program consisted of representatives from operational agencies and academicians who integrated economic theory and engineering practices within a democratic decision-making framework. Using operations research and systems analysis techniques, the program developed new analytical tools for water resources planning that included considerations of risk and uncertainty. These approaches were formalized in the U.S. Water Resources Council's *Principles and Guidelines* for resource planning (U.S. WRC 1983).

The Harvard Water Program necessarily embraced an interdisciplinary approach, though today a larger set of disciplines is involved in water management. Unlike most climate-based vulnerability assessments, the Harvard Water Program advocated that the first step of any planning effort is the "community's unique political function to reach an agreement on the standards of the common life—the [planning] objectives." Objectives were translated into design criteria, and design criteria were transformed into proposed strategies, options and actions.

Similarly, the emphasis of CRIDA is using stakeholder collaboration in defining the planning objectives as the starting point of an analysis. That is, what are the specific water-related issues that need to be addressed and what are the intended outcomes? An objective, by definition, is a statement of a desired outcome, such as "reduce flood damages," "restore natural floodplain values," or "increase reliability of water delivery system." Perhaps most importantly, the Harvard Water Program's analytical techniques marked the beginning of formal, quantitative, multi-objective planning and risk analysis. Social and economic objectives included income generation, economic growth, and industrial production through the development of water resources and related land resources. Water resources management became a means to an end—the growth and development of a nation or region—and these socio-economic and cultural objectives have become paramount in the design of any modern water resources system located anywhere in the world.

Today, water resources managers must account for greater complexity in their technical decisions. Many aspects of that complexity have cascading, interacting waves of uncertainty: emerging socio-economic circumstances, demographic and urbanization trends, and eco-hydrological conditions. Globalization, population increases, and economic cycling and transformation also stress water resources systems with risks that are hard to estimate and balance. Even the science of the water cycle and our vision of "sustainable use" of water have been altered in profound ways since the Harvard Water Program began in 1955; many of the most important management insights from eco-hydrological science are less than 20 years old. As has been noted by Milly and colleagues (2008), the Harvard Water Program explicitly assumed that climate was fixed—an assumption that has not been widely viewed as deeply problematic until after the turn of this century. And all of these pressures, ideas, trends, and uncertainties are influenced by ongoing climate change.

Hence, today there is a need for quantitative and pragmatic guidance that centered on the needs of the water resources planner who transforms these societal objectives that explicitly guide the formulation of programs, projects, or activities in a manner that is consistent with standard engineering guidelines and practices. These conventional practices are associated with risk-informed decision making under a relatively stable climate regime yet provide a coherent approach and entry point to problems that require one to consider uncertainties such as climate change related consequences. The results of these analyses must then be presented to decision makers at a level of understanding that is not dependent on a complete, quantitative understanding of future probabilities that are inherently unknowable. Such guidance, however, must also consider the financial, technical, and institutional limitations and capabilities of planners and decision makers to complete master planning and pre-feasibility and feasibility studies.

The water resources community has made significant efforts to address these risks, though climate change and unconventional stressors have proven particularly challenging. Most efforts to incorporate shifting climate conditions have attempted to forecast climate states for a specific time period and then plan around those forecasts. These efforts have proven difficult and ultimately unsatisfying; decision bottlenecks can occur due to cascading uncertainties, a sense that these forecasts are biased or completely erroneous, and even political disagreements over the nature and extent of climate change. In most cases, the use of climate forecasts has not made significant changes to the Harvard Water Program paradigm of working towards one more or less knowable future—the most probable future. The time is now past for a "reinvigorated development of methodology…in the spirit of the Harvard Water Program" to support planners under a world of evolving uncertainties (Milly et al. 2008).

Sustainable Water Management for an Uncertain Future

In light of Milly and colleagues (2008) and subsequent analyses, the need for a more satisfying, complete, systematic approach has become clear. In November 2011, the World Bank and the Alliance for Global Water Adaptation (AGWA) organized and convened a workshop for international water resources practitioners entitled "Including Climate Change in Hydrologic Design." A principal challenge identified was the poor support for addressing and prioritizing climate change impacts despite an unprecedented wealth of tools and information. At the workshop, best practices and key principles were discussed and interagency working groups established. A World Bank Water Partnership Program event at the Vienna HydroPredict conference in September 2012 facilitated the exchange of ideas among groups, leading to formal approaches to operationalize decision scaling and bottom-up vulnerability assessment approaches, while parallel workshops with key groups were convened regularly by the World Bank, AGWA, Deltares, University of Massachusetts, Amherst, and the U.S. Army Corps of Engineers.

The first outcome was the World Bank's *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework* (Ray and Brown 2015), widely known now as the "decision tree approach." Building on some of the emerging insights from small workshops in 2015 under the longstanding cooperation between the U.S. Army Corps of Engineers (USACE) and the Dutch Environment and Infrastructure Ministry (Rijkswaterstaat), the CRIDA initiative was formally launched. The National Socio-Environmental Synthesis Center (SESYNC) and AGWA led a team effort to integrate environmental and water resources management issues and climate change concerns using these bottom-up vulnerability assessment principles with several of the CRIDA and decision tree approach contributors. The CRIDA working group linked and combined best practices and methods, including those that originated from the Harvard Water Program, particularly in the application of bottom-up approaches to uncertainty and risk reduction.

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Rijkswaterstaat – Rijkswaterstaat is the Executive Agency of the Dutch Ministry of Infrastructure and Watermanagement. Rijkswaterstaat is responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands - including the main road network, the main waterway network and the main water system.

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Introduction: Why CRIDA?

Climate Risk Informed Decision Analysis (CRIDA) is a methodology for water resources planning and management if significant uncertainty exists about future conditions. Longstanding techniques for incorporating "known" climate and hydrologic variability as well as economic, demographic, and financial uncertainty already exist within the guidelines of agencies such as the U.S. Army Corps of Engineers, the World Bank, and the Dutch Environment and Infrastructure Ministry (Rijkswaterstaat).

What has been missing is a coherent and consistent approach for dealing with anticipated but unquantified changes due to "unknown unknowns" such as climate change that impact project planning, socio-economic justification, resource management, and engineering design. Such uncertainties affect the selection of risk-reduction options by decision makers. Consequently, a process that incorporates unknown unknowns in planning for reliable and resilient solutions over the lifespan of a project becomes critical to selecting risk- and cost-effective solutions.

To address this need, CRIDA provides a collaborative process for risk-informed decision making: effectively assessing, managing, and communicating risks to stakeholders and decision makers, including successfully avoided risks and residual risks that cannot be avoided, quantified, or isolated.

The Role of Communications and Uncertainty for Decision Making

Describing risk usefully—what might happen, the scope of threats and opportunities, the threat of ineffective action—is a basic need for all stakeholders and decision makers. Risk-informed decision making is not new within the water resources planning community and has been practiced to varying degrees for centuries and quantitatively for centuries. In general, risk-informed decision making includes identifying the vulnerabilities, formulating options to reduce or eliminate vulnerabilities, and conveying the information so that stakeholders and decision makers can negotiate tradeoffs appropriately.

For institutions, risk-informed decision making is inherently about choosing management actions based on accepted protocols for planning and risk assessment. The U.S. National Research Council (NRC 2000) noted that

> Identifying sound, credible, and effective risk reduction priorities and solutions depends greatly on a well-informed public. The public should be knowledgeable about risk issues and should be given opportunities to express opinions and become involved in risk assessment and risk management activities. This involves risk communication: the effective understanding of risks and the transfer of risk information to the public, and the transfer of information from the public to decision-makers.

However, "deep uncertainty" with respect to factors such as climate change presents additional analytical and communication challenges. Decision making is difficult enough without trying to prepare for future uncertainties. Our existing risk communication framework has not been successful for the most part in demonstrating what additional or different interventions we need to make to increase resilience. Indeed, defining resilience itself is often problematic and conflictual. CRIDA amalgamates standard water resources planning processes and their embedded risk-assessment procedures while extending that framework to include cascading climate and other uncertainties. And only by pragmatically presenting and establishing an informed dialogue around risk and how uncertainty alters how we evaluate and manage performance can stakeholders and decision makers make effective tradeoffs.

Enhancing Existing Water Resources Management Principles

Water resources engineers and planners measure performance against the specific objectives for which a project or system was designed, which includes economic performance. A number of indices are in use to measure the performance of water resources systems in terms of reliability, resilience, robustness, and vulnerability of water resources subjected to climate extremes (e.g., Hashimoto et al. 1982). Reliability—the frequency over a long time period that a project delivers the design level of service—is opposed to failure, which quantifies frequency of service delivery below a design level. Vulnerability refers to the likely magnitude of a failure (e.g., maximum drought intensity) if one occurs. Resilience is often interpreted as a measure of how quickly a system is likely to recover from failure once failure has occurred. Vulnerability and resilience are effectively complementary notions. Inherently, the ensemble of drought management 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).

A key concept in a bottom-up vulnerability assessment is to identify the specific scenarios that pose a risk to desired system outcomes, which are quantified by the standard engineering measures of reliability, resilience, robustness, and performance vulnerability.

Outcome risk is reduced by a variety of risk-reduction management measures, including both structural and non-structural measures. They do not all reduce risk uniformly because they address different parts of the risk-management cycle (prevention, preparedness, response, recovery)—some protect property, while others are geared towards saving lives at the expense of property. For example, a flood warning and evacuation system has its own highly uncertain components that are very susceptible to cascading sequences of human error and technological breakdowns. Figure i.1 is a schematic that shows a hierarchy of typical flood damage risk reduction measures as steps. At the bottom of the ladder is residual risk or risk that is unknown because of uncertainties and risk considered tolerable by society. Future climate uncertainty and uncertainties in socio-economic growth and development trajectories will, in almost every case, widen the uncertainty bounds

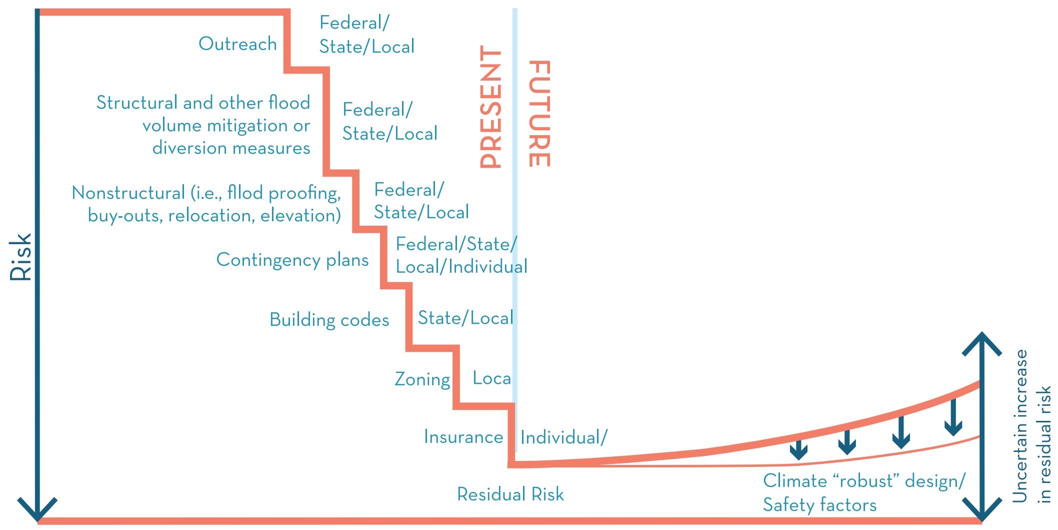


Figure i.1. Flood risk reduction management measures. Adapted from USACE (2012).

of residual risk. Structural measures with more conservative, humble engineering design factors can significantly reduce future uncertainties, thereby increasing robustness, reliability, and resilience.

Reducing Future Climate Risk from the Bottom Up

Unlike most attempts to consider future climate risks in water resources planning, the CRIDA process does not begin with climate models or a selection of future scenarios to be used in the planning and design of a project. Rather, CRIDA begins with the standard engineering procedures of identifying planning objectives and problems that need to be solved and then the planning team addresses how the uncertainties affect the choices of options and tradeoffs. Indeed, CRIDA follows a five-step planning process that is common to most infrastructure and water planning agencies. What differentiates CRIDA from other approaches is the application of a standard step-by-step planning approach in “bottom-up” risk assessment and management procedures to address the uncertainties of future climate and other unconventional stressors.

Bottom-up vulnerability assessment is meant to reflect the traditional manner in which water resources projects are considered, beginning with an assessment of existing vulnerabilities, problems and needs. Until about 2010, some climate scientists and resource management agencies advocated for “top-down” climate analyses that begin with a consideration of data generated by climate models, also known as General Circulation Models or GCMs (for discussion, see Brown and Wilby [2012], Kundzewicz and Stakhiv [2010], Nazemi and Wheater [2014]).

The preliminary stage of any vulnerability assessment is semi-quantitative, based largely on existing information, and typically includes such steps as:

- Estimating how much water is available to supply customers each year over a chosen planning period, based on some credible existing supply forecast.
- Estimating the water demand for each year over the same period, based on an existing demand forecast.
- Allowing for uncertainty in estimates and supply and demand forecasts.
- Comparing supply with demand (including uncertainty) and determining if a surplus or a deficit exists. If there is a deficit, the analyst should identify options to increase supply or reduce demand to achieve a secure supply of water.
- Considering how to ensure resiliency in a system now and in the future against a range of drought and non-drought hazards across the planning period.

Such *bottom-up* issues are typically completed using existing methods and procedures. In the event of a system failure, for example, the analyst might begin with questions such as the following:

- What happened and why?
- What were the specific pathways of failure and which sectors were most affected?
- What could have been done to prevent the damage using conventional options?
- What additional measures would be required to deal with future uncertain conditions?

A technical analyst might begin a vulnerability assessment by collecting as much available information as possible to answer first-order questions and organizing the answers as a starting point for stakeholder involvement. This process can be as simple as assembling relevant existing information into a report describing the hydrologic conditions, combined with a summary of future anticipated stresses on the system to provide a starting point for deliberations by stakeholders. While simple and straightforward, such approaches constitute the initial collaborative phase in the CRIDA process.

While the initial stage of standard risk assessment compiles relevant and sufficient information to define the management issues and performance criteria and measures important to stakeholders, a stress test provides details about the vulnerabilities of a system to specific conditions such as a change in rainfall variability. The responses to the stress tests can then be used to analyze system performance and modify the system design or operation as appropriate.

Figure i.2 illustrates sources of uncertainties that affect the analysis of risk. CRIDA provides a framework to align the risk analysis with decision making needs given these analytical

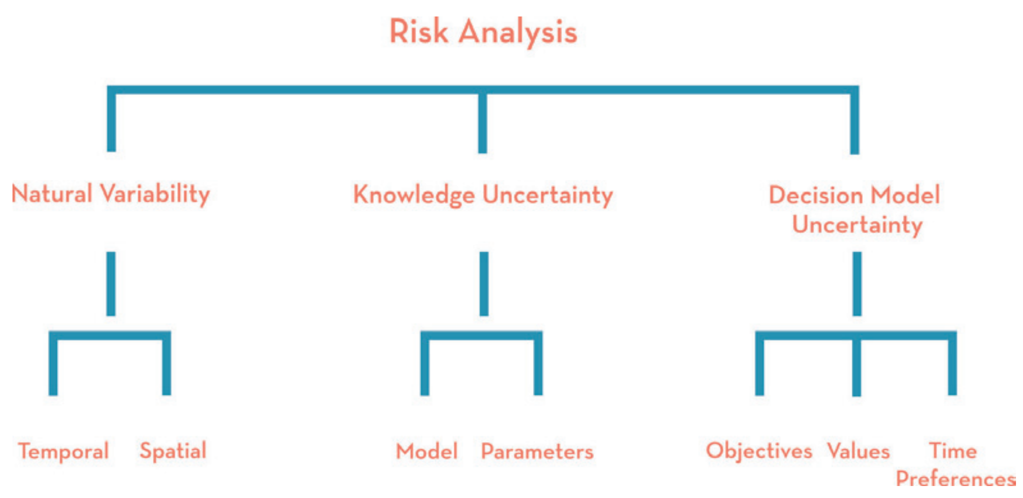


Figure i.2. Taxonomy of risk and uncertainty in decision analysis. Source: NRC (2000).

uncertainties through a process called “decision scaling.” Decision scaling guides an analyst to first focus on the level of service provided by existing infrastructure under existing conditions, rather than on the uncertainty under which the infrastructure will operate in the future (Brown et al. 2011). Decision scaling evaluates what is known about a system and how it performs under various conventional scenarios and design criteria for which the infrastructure was planned rather than what is not known. In other words, CRIDA offers an approach to initiate a vulnerability assessment and to incrementally plan towards future states that are known to lead to unacceptable performance.

This pragmatic approach still requires forecasts of the future, but decision scaling establishes the relative likelihood of unacceptable performance scenarios. Historic records and recent events can often inform vulnerabilities more effectively than climate models alone.

Who Needs CRIDA?

Worldwide, water resources and flood risk managers, asset and infrastructure managers, private companies, and national, provincial, and local government planning authorities all face similar challenges when developing plans and investments to revitalize or expand water infrastructure and networks to meet future needs or adapt to increasing uncertain future risks like those of climate change. They all seek ways to effectively assess and communicate future risks concerning the systems they are responsible for, and to achieve performance objectives. All such entities are more or less constrained by previous decisions, institutional regulations, available data, technical and production capacity, and budgets. Decisions on directions forward cannot be decided without support of key stakeholders and proper justification of expenditures.

Especially on the analytical level, these challenges can be tedious, ambiguous, and time and resource consuming. CRIDA adds value by offering a structured and stepwise approach to existing decision making processes in dealing with uncertain risks in a collaborative context.

The user of CRIDA is the “analyst,” who seeks guidance consistent with existing procedures to formulate and justify a water resources project, program, or activity that will be robust to uncertain futures. Moreover, the analyst needs to support a decision maker in the selection of an appropriate level of project robustness. The analyst is typically an individual with a technical background in water resources management. An analyst will recognize the need to find better approaches to incorporate uncertainty in decision making and then convey the key aspects of that uncertainty in the range of alternative viable approaches to decision makers and stakeholders. As such, the analyst plays a bridging role between stakeholders impacted by and attempting to influence decisions and decision makers. The analyst directly links governance and technical approaches. In most situations, analysts have little training for this role, particularly for the complex uncertainties surrounding non-stationary water management.

CRIDA Complements Existing Methods and Guidance

Risk and uncertainty analysis has been and remains a standard aspect of all steps in water resources planning processes. In the US, risk analysis has been important for more than 60 years since the publication of the Green Book (US Inter-Agency Committee on Water Resources 1958); subsequent guidance has been refined and is used to inform decision uncertainty. Choosing a particular action means asking questions about how important uncertainties will impact the project performance compared to an array of possible alternatives. The distribution of risks and uncertainties, how uncertainties influence the design of a project (robustness, resilience, and reliability), and the impact of uncertainty on costs remain important considerations.

CRIDA is most closely related to the World Bank's so-called "decision tree methodology" (Ray and Brown 2015) and the adaptive planning approaches developed in the Netherlands (e.g., Haasnoot et al. 2013) and applied in delta management (e.g., Bloemen 2015, Jeuken et al. 2014, Van Alphen 2015). CRIDA blends these approaches into a single whole.

CRIDA incorporates the basic elements of the World Bank decision tree approach guidance (Ray and Brown 2015) which progressively directs the user through a series of bottom-up vulnerability queries to assess resilience or robustness of an existing water management system to uncertain futures without prescribing any particular analytical procedure, tool, and/or planning process. By extension, the decision tree approach promotes the use of existing planning processes in the World Bank's client countries and guides stakeholders to deploy an array of available tools and methods to address local needs. At each decision point, the user either receives confirmation to proceed to the next level of analysis or exits the process.

CRIDA uses the same decision scaling framework but specifically applies it to a step-wise conventional planning process or planning cycle. CRIDA is more prescriptive in using dynamic adaptation pathways when flexible plans are recommended and in using incremental cost analysis (ICA) to compare robustness. CRIDA and the decision tree approach are complementary, with strengths and applications that are not exclusive and can lead to similar outcomes if applied within a conventional planning process paradigm.

CRIDA is also compatible with the UNESCO guidelines for Integrated Water Resources Management (IWRM, UNESCO 2009). IWRM and CRIDA share an emphasis on planning processes, the negotiation of multiple interests, and an emphasis on system stressors caused by social, environmental, and economic changes.

In contrast to Ray and Brown (2015) and IWRM, the CRIDA framework has three defining characteristics:

1. CRIDA's core approach to planning is consistent with approaches used by the majority of national water management agencies, including the Dutch Environment and Infrastructure Ministry and the U.S. Army Corps of Engineers. CRIDA respects those existing water resources management decision making processes and incorporates, within those steps, appropriate technical analysis to address unknown future uncertainties. As result, CRIDA can be adopted in a modular or stepwise fashion, as analysts develop familiarity and comfort with the approach.

2. CRIDA enhances the flexibility of a water resources system by examining a variety of adaptation pathways (Haasnoot et al. 2013) and formulating and evaluating the sequenc-

ing of combinations of measures designed to address future climate uncertainties. The adaptation pathways approach avoids "locking in" a single strategy by including alternatives that can be implemented when pre-defined "trigger points" are reached.

3. CRIDA relies on collaboration to integrate modeling, participation, and planning to address conflicts early in the planning process, to facilitate technical exchanges, and to promote multi-sectoral strategy development. Most importantly, the collaborative framework is geared to facilitate engagement between the analyst and decision makers to support decisions that build stakeholder buy-in for robust solutions to uncertain futures.

0

Getting Ready for CRIDA

The purpose of this guidebook is to explain how the CRIDA methodology can be applied to water resources planning and design for future uncertainties. The task of the authors has not been to design a "perfect" water resources management decision making process or to encompass all possible emerging issues around modern water management and economic development. The CRIDA approach follows accepted water design, planning, and investment procedures and cycles. At each step outlined below and fully described in chapters 1-5, guidance is provided for enhancing project resilience and robustness. CRIDA is flexible, allowing institutional, regional or sectorial innovations and the framework enables transparent and broad formulation of alternatives that consider both gray and green and hybrid infrastructure.

These steps align well with existing water resources planning processes where an analyst works collaboratively to iteratively formulate acceptable and effective alternatives in addition to a "null" alternative. The CRIDA framework complements this procedure to identify, quantify, and justify additional adaptive measures compared to a non-robust alternative. A collaborative framework facilitates the provision of complete, acceptable, and cost effective alternatives to the decision maker(s). Figure 0.1 illustrates how tasks discussed in this document complement the planning process.

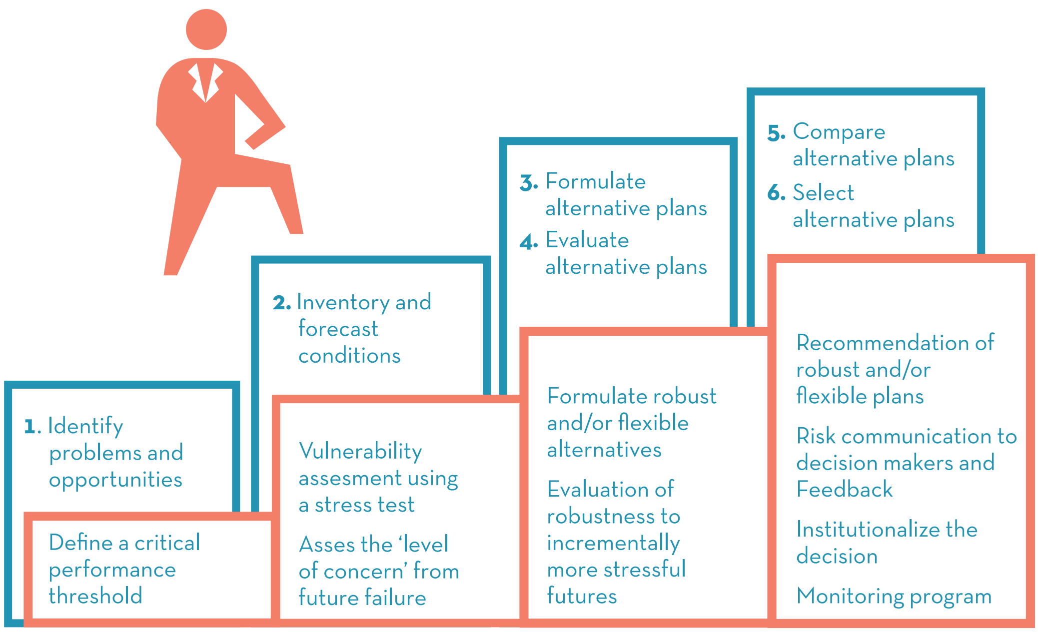


Figure 0.1. CRIDA tasks within a typical planning framework. Blue boxes show widespread planning framework steps; orange boxes show CRIDA steps.

Step 1 of the CRIDA approach involves structuring a collaborative process for supporting decisions by establishing the decision context. Key stakeholders can identify their critical thresholds of performance, based on accepted engineering standards or evolving scientific information that is relevant to the problem, which can then guide the technical analysis.

Step 2 consists of implementing a *bottom-up vulnerability assessment*, which refers to understanding the inherent vulnerabilities of the system in question. Step 2 begins with a screening approach to decide whether the problem(s) can be managed using existing "conventional" approaches. If a conventional approach is unsuccessful, then an analyst would prepare a stress test that imposes threshold conditions on the existing system such as reliability of service delivery or operational or structural failure. Stressing the system enables the identification of unacceptable levels of performance.

Step 3 comprises the formulation of actions to reduce the vulnerabilities identified in Step 2. The stress test serves to identify risk-reducing actions that improve performance related

Figure 0.2. CRIDA steps and outputs as an iterative processs.

to critical thresholds. Adaptation pathways can help to build flexible and robust plans based on these actions.

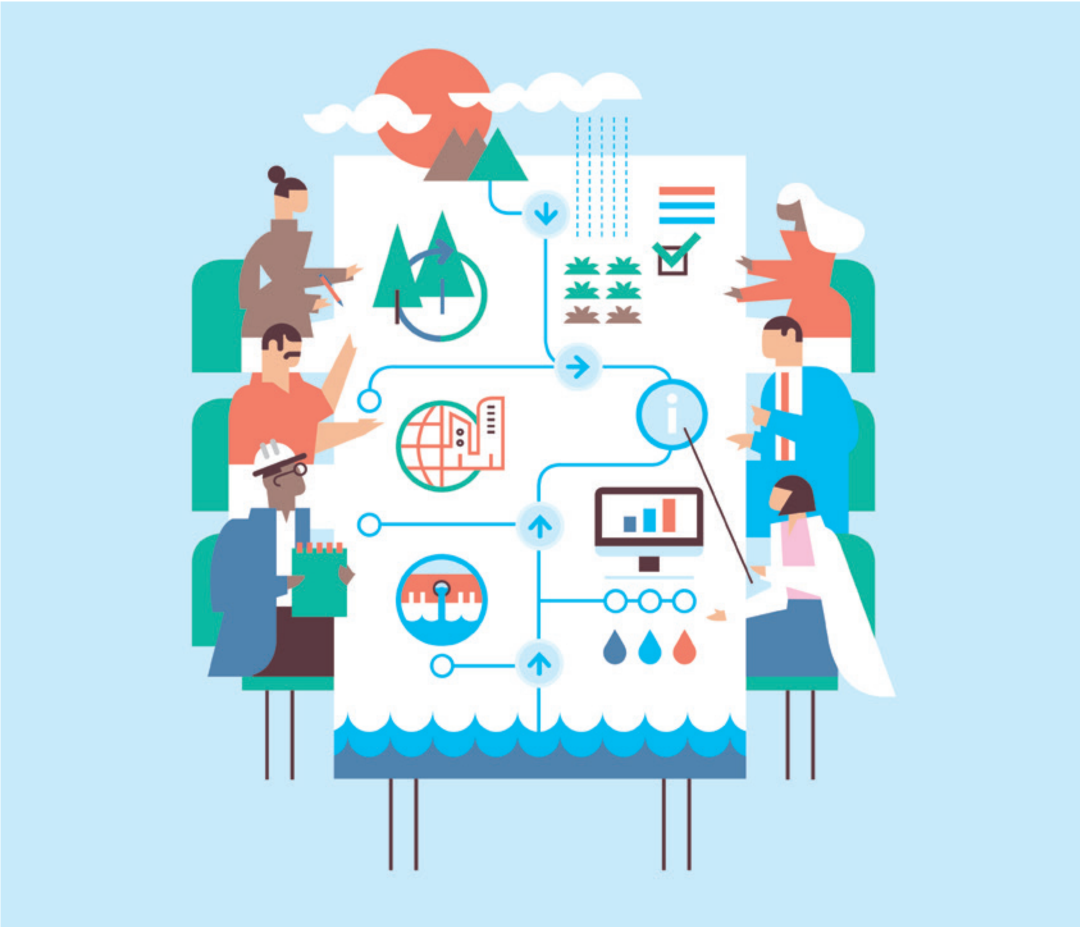
Step 4 involves assessment of the robustness or flexibility of the formulated plans and the integration of other decision criteria requirements.

Step 5 consists of institutionalizing the plan that was developed in the preceding steps, and providing general guidance on organizational, financing, and monitoring requirements.

These five steps can be applied at all levels of planning, study, or design with each level of analysis requiring a progressively greater degree of detail and consideration of uncertainties with corresponding influence on decisions to be applied within an agency's evaluation procedures and criteria. The application of decision scaling helps illuminate the influence of uncertainties on plan alternatives, tradeoffs, and the cumulative influence that uncertainties have on the decision processes.

1

The Decision Context: Structuring a Collaborative Process for Vulnerability Assessment



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Step 1

All good planning processes begin with a formal definition of problems and opportunities, an inventory of existing data, models, and reports, an assessment of the stakeholders to be engaged, and a clear geographic scope of the analysis (e.g. USACE 2000a, UNESCO 2009, Gregory et al. 2012). In early stages of planning, the analyst also sets the boundary conditions and conceptualizes and develops models or other tools that will be used to support a decision. Taken together, these elements begin to shape the decision context, which is critical to aligning the technical analysis to decision maker and stakeholder needs. Sometimes called decision scaling, the decision context structures the complexity of the analysis efficiently to recommend and justify a solution. In bottom-up procedures such as CRIDA, the decision context has additional importance because the analyst needs to define unacceptable levels of failure—critical thresholds—and to develop models for exploring solutions in subsequent steps.

The decision context is developed through interactive workshops conducted by a technical analyst who can support a structured engagement with stakeholders. Practical examples of collaborative decision support to modeling and decision making in water resources can be found in Bourget (2011). CRIDA emphasizes stakeholder engagement and the use of stakeholder-defined performance metrics to indicate vulnerabilities. Clear performance thresholds are a key element of the bottom-up vulnerability assessment conducted during Step 2.

The technical analyst applies the CRIDA process to construct a simplified system model (or to modify an existing model) to assess two issues:

1. The impact of drivers and/or uncertainties on system performance metrics given a specific sequence of extreme historical or plausible events, and

2. The relative benefits and costs for reducing undesirable negative impacts.

In other words, the analyst is exploring current and future risks: what are the current risks of system operations, and what risk management measures can reduce those risks.

Figure 1.1 graphically presents key inputs to a water resources decision model including technical, social, economic, and natural system variables. Often the human inputs are some of the most contentious, so finding a consensus solution cannot be overemphasized. Inputs and outputs from a water resources system model such as design parameters, performance metrics, and external drivers (including uncertainties) are also indicated.

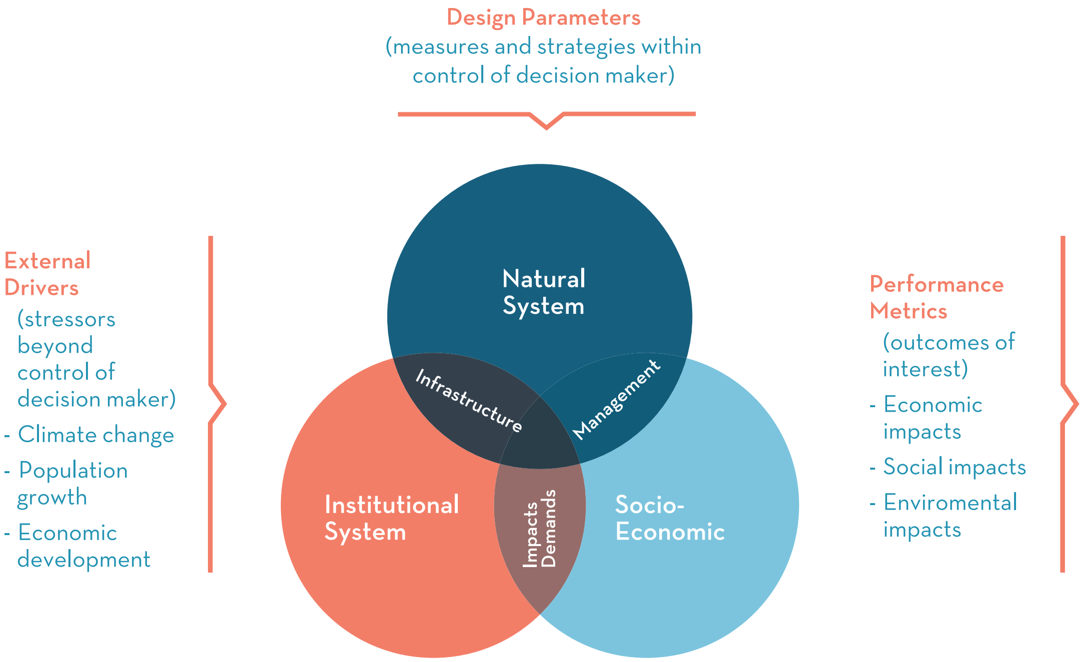


Figure 1.1. Key elements of a water resources system model. Adapted from Deltares (2015).

Outputs from Step 1

- Water resources system model
- External drivers
- Performance metrics
- Critical thresholds

1.1. DEFINING THE PROBLEM STATEMENT

Decision making is an innately uncertain process, even without climate change. A useful problem statement provides a foundation for actions and policies and establishes the scope of the analytical and collaborative process. Indeed, a well-bounded problem with clear objectives is more likely to be successfully solved. As USACE (2000a) explains, "The integration of economic, social, and environmental objectives allows for identifying broad and sustainable solutions. The problem statement should not preclude the consideration of all potential alternatives to solve the problem or achieve potential opportunities." Current and future conditions must be considered and because they are dynamic in nature, which are usually re-evaluated and modified in subsequent steps of the CRIDA planning process.

In almost any water resources project, multiple and competing interests must contribute to decision making. Therefore, it is important that scoping processes include stakeholder participation, especially if that occurs face to face with the analyst. A well-defined problem statement reflects the priorities of relevant stakeholders and agencies. Active stakeholder participation in the planning process is essential, but that participation must also be facilitated effectively.

Examples of constructive and unconstructive problem statements include:

- Constructive: In the dry season, water shortages affect our crop yields. Unconstructive: The irrigation system is inefficient (unconstructive).
- Constructive: The site has a growing economy and population, but there is an energy shortage. Unconstructive: We need hydropower dams.
- Constructive: We see increasing frequencies of flooding and worsening impacts from flooding. Unconstructive: We need more flood control levies because of climate change.

A problem statement that presumes a particular solution or course of action, such as "There is a need for flood management reservoir storage," limits the comprehensive examination of alternative adaptation strategies." A problem statement can also be overly broad or vague, such as "Water management in our basin shows institutional weakness."

Constraints on the planning process should be included within the problem statement because they usefully structure the range of acceptable solutions. Constraints can either be hard (i.e., they cannot be violated) or soft (i.e., they may require resources but can be overcome). Constraints are typically of two kinds: those based on the available resources, and those based on laws or policies that may structure planning, design, construction, and implementation outcomes.

1.1.1. Set Planning Objectives

CRIDA assumes that the analyst is oriented towards a shared stakeholder vision to solve the problem statement, which necessitates a bottom-up solution. Engagement with stakeholders to set objectives marks the single most essential difference between top-down and bottom-up methodologies. And the most essential aspect of a bottom-up solution is the process of defining a common set of objectives. The analyst must help stakeholders distinguish between effective and ineffective objectives. As USACE (2000a) notes,

> The planning objectives must be directly related to the problems and opportunities identified for the study and will be used for the formulation and evaluation of plans.... Objectives must be clearly defined and provide information on the effect desired (quantified, if possible), the subject of the objective (what will be changed by accomplishing the objective), the location where the expected result will occur, the timing of the effect, and the duration of the effect.

Effective objectives inform, define, and prioritize performance indicators and critical performance thresholds. They are the glue between technical applications and stakeholder definitions of success. From the analyst's perspective, useful objectives define vulnerability domains relative to future uncertainties and align objectives with project justification criteria.

Progress towards objectives is evaluated by performance criteria. When these criteria are identified in consultation with stakeholders, they can be used to represent system vulnerabilities through the establishment of performance thresholds.

Ideally, the main planning objectives are limited to one or two core targets. A low limit ensures clarity in the decision making process. The analyst can facilitate separating primary objectives (and their derived performance metrics) from secondary or "side" objectives (and their metrics). Thresholds will also need to be defined for all objectives since they limit the stress testing process. The development of such evaluation criteria will be discussed in more detail in the next section.

Box 1.1.

What Is a Good Model, and Where Do I Find One?

The objectives of a model in CRIDA are to identify the external drivers (Figure 1.1) that lead to unacceptable performance and to evaluate the impact of different design parameters on performance. Therefore, a model must establish a quantitative relationship between the external drivers and performance. This can be accomplished by sophisticated software packages or spreadsheets. The complexity of the modeling depends on the analytical requirements of the system being modeled such as needed detail, extent of the system, and the number of variables. For example, systems that abstract flows from large intra-annual reservoirs may be modeled using annual time steps. On the other hand, urban flood risk studies may require hourly time steps. Moreover, different decision makers have different information needs and confidence requirements. At a minimum, the model must be able to reproduce the objectives and performance that are evaluated.

Often the complexity increases over the planning phases (from strategic planning through pre-feasibility, feasibility, and design phases). The Iolanda Water Treatment Plant case study discussed in this document was developed using a Microsoft Excel spreadsheet. The use of an existing model may save resources, especially if one has already been validated and applied successfully to support related decisions, which can also promote support for outcomes. A "model" can be a *system* of models that integrates different components or stages.

Model calibration is important, but this is a difficult task when data are scarce. In CRIDA, the lack of data implies high analytical uncertainty—the analysis can continue but must adjust to such qualities. A good model will also be able to calibrate for key processes that drive the performance valves of interest. Seibert and McDonnell (2002) capture this sentiment when they state that models should be "less right, [but] for the right reason" than "right, [but] for the wrong reason." Precision and accuracy may be less important than clarity and utility.

Given these concerns, validation by stakeholders that key processes are being captured adequately is strategic, especially with limited data and high uncertainty. Collaborative modeling processes, such as Shared Vision Planning (Carrera and Mendoza 2017), provide an effective technique to facilitate stakeholder validation and buy-in of the model and to identify the necessary level of complexity for the decision.

Progress towards objectives is evaluated by performance criteria. When these criteria are identified in consultation with stakeholders, they can be used to represent system vulnerabilities through the establishment of performance thresholds.

Ideally, the main planning objectives are limited to one or two core targets. A limited number ensures clarity in the decision making process. The analyst can facilitate separating primary objectives (and their derived performance metrics) from secondary or "side" objectives (and their metrics). Thresholds will also need to be defined for all objectives since they limit the stress testing process. The development of such evaluation criteria will be discussed in more detail in the next section.

1.2. DEVELOPING RISK EVALUATION CRITERIA

One of the principal goals of water resources management has always been to transform variable, uncertain freshwater systems into dependable services such as water supply, flood risk management, ecosystem benefits, hydropower, and profitable agriculture. Attainment of these goals can be impeded by the diverse and sometimes contradictory services that water resources systems provide. The analyst must facilitate a prioritization of objectives to guide the wise use, design, and operation of water resources systems.

Performance metrics often measure a system's ability to deliver services. In CRIDA, these performance metrics are compared against minimum acceptable service levels —"thresholds"— to measure three basic variables: reliability (the frequency that system performance meets a target), resilience (the time it takes for a system to return from failed performance level to the target), and robustness (the range in which a system maintains target performance while facing external stressors). Compared to traditional economic decision criteria, these three variables form a standard for evaluating decision criteria when high climate uncertainty and variability are relevant. Performance metrics, thresholds, and decision criteria together constitute the decision and evaluation framework that guides CRIDA.

1.2.1. Set Performance Metrics

Performance metrics are critical elements of the CRIDA framework and act as the primary outputs of the system model. They quantify the outcomes as defined by the objectives and must be sensitive to external drivers and design parameters (Table 1.1). As a result, the choice of performance metrics deeply influences the resulting analysis.

What do good performance metrics look like?

Performance measures should have direct, monotonic relationships with external drivers such as climate, flow regime, and demographic change (Kjeldsen and Rosbjerg 2005). Table 1.1 shows key measures of performance, including ecological resilience. It may take time and effort before both the analyst and stakeholders are comfortable with a particular performance metric. The key is to keep performance metrics both simple and defensible. If needed, additional complexity can be added over time while prioritizing metrics in terms of their relative importance.

1.2.2. Enabling Ecosystems as Stakeholders

Ecological performance metrics are often important considerations in water resources studies whether or not the goal is the improvement of an ecosystem. Like climate itself, biophysical aspects of the landscape influence the timing, quantity, and quality of water resources available and cannot be disentangled. Every action that requires hydraulic structures affects

Topic of interest	External Driver	Design varibles to improve performance	Potential performance metrics
Water supply	Variability persistence and averages of the hydrologic input variables, target demand, upstream abstractions, temperature	Storage volume Target yield Demand management	Tied to benefits to relevant sectors in energy, agriculture, industry, and municipal use that benefit from water supply
Flood risk reduction	Intensity, duration, frequency, and spatial extent of rainfall events; permeability of catchment; antecedent moisture; operations; value and location of property and human settlements	Levee height Floodplain area Flood routing bypass Detention volume Management of risk (i.e., reduction of consequences) Runoff coefficient	Based on losses to productivity, property, and lives (they often have a probabilistic function to evaluate expected annual losses or expectations); or based on an area flooded or a specific level of loss or impact (e.g., a design flood)
Coastal risk reduction	Sea level rise, storm surge, and frequency of events; value and location of property and human settlements	Dune height and width Sea wall dimensions Wetland area Management of risk	Same as flood risk reduction

Ecology	Flow regime, environmental water quality, dam operations, nutrient composition, sediment transport	Floodplain area Indicators of hydraulic alteration Habitat connectivity	Often based on species indicators, habitat quality (that can be associated with flow levels or flooded areas), different flow regimes, species abundance, fishery productivity, reproductive success, floodplain connectivity, divergence from flow regime reference

Table 1.1. Common measures of performance by water resource topic of interest.

the natural habitat in some way. There are quantitative performance metrics, such as species diversity indices (e.g., European Commission 2005, Seaby and Henderson 2007), species productivity (e.g., Allen 1982, IUGLS 2012), environmental flow regimes (e.g., Richter et al. 1996, Poff et al. 2010), or floodplain wetlands-connectivity area (e.g., Ickes et al. 2005, USACE-HEC 2016). There are also qualitative metrics based on habitat quality (e.g., Rijkswaterstaat 2018, USACE-SWF 2011, Rosenfeld 2003, Verdonschot et al. 2012), and stream suitability indices (e.g., USACE-SAW 2003).

More recently, a growing body of work has explored how to integrate non-stationary perspectives and indicators into the management of aquatic ecosystems, such as Poff and Matthews (2013), Le Quesne and colleagues (2010), Matthews and colleagues (2011), Poff (2017), and Poff and colleagues (2016).

All of these approaches have proven useful in some contexts. In most cases, however, specific metrics are developed for regional or local needs based on regulatory interests or regional social and ecological characteristics and concerns. One approach to tracking ecological parameters includes the following steps:

1. First and foremost, the watershed community of stakeholders needs to establish a reference condition and/or develop a shared vision of success. What is desired? The reference condition does not have to reflect an undisturbed condition. Indeed, past states may no longer be possible. The reference condition can be any desired state arrived at through a stakeholder-driven process. Collaboration is important because ecosystem interests are diverse and are often based on values that must be taken into consideration for different plausible futures. A key question might be whether it is

possible to conserve an ecological system or whether ensuring ecological resilience to a different future is necessary (Poff et al. 2016). A reference condition is the desired state of the waterbody given intrinsic competing aspects of the basin community (Nestler et al. 2010).

2. Once a reference condition has been defined, key ecosystem performance indicators of the reference condition are prioritized and quantified through models and field data. Since these properties are used to evaluate the impact of different plans, it must be possible to model them (or qualitatively adjust as stream conditions change) with respect to an external driver.

Ecological considerations are often defined in an unsystematic and/or qualitative manner. The Eco-Engineering Decision Scaling (EEDS) methodology (Poff et al. 2016) demonstrates multi-objective decision scaling to negotiate simultaneous tradeoffs and risks for ecological and human-centered water management objectives. In this way EEDS can be seen as an application of the CRIDA approach by both setting main objectives and deriving a comprehensible set of performance metrics and thresholds. EEDS can also serve as a framework for defining and comparing green, gray, and hybrid infrastructure solutions.

1.2.3. Managing Ecosystems in a Dynamic Climate

The application of non-stationary, climate-dynamic approaches to ecosystems raises some novel issues and challenges where little clear guidance exists. Many species, ecosystems, and ecological processes have proven to be extremely sensitive to even small shifts in climate, particularly to changes in seasonality and season-linked behaviors such as migration and dispersal, flowering, breeding, growth and development, and hatching and fledging. Many of these behaviors and events are difficult or impossible to model, with complex and/or poorly understood linkages to air and water temperature, precipitation, and other climate variables for all but a handful of intensively studied species, such as plants and animals that are important for commercial agriculture and high-profile wild species such as salmonids. For many taxa, we have little or not guidance on the role of climate or climate change and how these elements should guide management decisions. The complexities associated with understanding the role of climate for individual species tends to scale up when looking at whole ecosystems.

At the same time, maintaining natural resource management regimes that ignore climate change presents quite substantial risks. "Conservation" has traditionally tried to define a past reference state (often associated with a past climate state, whether explicitly recognized or not) that may not be possible to achieve now or to maintain into the future as the climate continues to evolve. Even during the relatively modest climate shifts of the past 10,000 years (and before significant human impacts such as widespread agriculture or overhunting), ample evidence exists for major shifts in distribution and range, population sizes, and behaviors worldwide that are linked to climate change. From this longer-term perspective, trying to "maintain" or "conserve" a species, a community of species, a protected area, a larger ecosystem or ecoregional cluster to past conditions when climate probably plays an important role in defining a healthy state may actually have the perverse result of inhibiting effective auto-adaptation (e.g., natural adjustment) by many species and ecological processes to emerging conditions.

Box 1.2.

Non-stationarity (And Why It Matters)

Non-stationarity refers to an environment where observations from the past do not inform what might be observed in the future. Non-stationarity has special relevance to statistical analysis in water resources planning and design because variables derived from past hydrologic data observations, such as variability, persistence, and skewness, may no longer be representative of the future. The inability to adequately perform statistics, especially when data are already limiting to address rare extreme events, poses a problem for "optimizing" engineering design and for evaluation of expected benefits of projects over long life spans for a single projected future. Non-stationary climate concerns are further compounded by non-stationarity in non-hydrologic variables that will also affect water resources management, such as demographics, water demand, markets, interest rates, or land use.

One proposed alternative to waiting for field studies or experimental evidence to provide specific guidance on resilient species and ecosystem management is to include management targets that operate at multiple levels, such as populations (members of a single species living in one area), species (often many scattered populations across a whole range), communities of species sharing an ecosystems or habitat, or ecosystems (especially the ecological processes that help define specific ecosystems). While traditional approaches to natural resource management can generally provide good indicator guidance on populations, species, and ecosystems, effective non-stationary indicators for ecosystems and ecological processes are newer and may be less familiar with stakeholders representing biological targets.

A small but growing body of guidance has been emerging to develop non-stationary indicators. Le Quesne and colleagues (2010) suggested four clusters:

- The disturbance regime, which for aquatic ecosystems tend to be called the natural flow regime (Poff et al. 1997, Poff 2017). The natural flow regime is comparable to the fire regime for forests and grasslands and reflects the necessity for variation and variability in ecosystems over different timescales: daily, seasonally, and over short- and long-term multi-year periods. Sometimes called the "master variable" for aquatic ecosystems, the natural flow regime is an important cue and regulator for many ecosystem and species processes. Small shifts in the management or climate regime with the natural flow regime can have rippling impacts throughout the ecosystem, with diverse winners and losers. Climate change presents new management choices for how to conceive the natural flow regime (Poff and Matthews 2013, Poff 2017).

- Habitat complexity, which refers to the diversity of conditions that are available for species, especially during extreme events such as floods, droughts, and very high and low temperatures. Ecosystems that have been simplified in terms of water quality, sediment, and species diversity, for instance, will likely support less species resilience. Habitat complexity can be a useful target of restoration and other direct management interventions.

- Connectivity within and between ecosystems. During past climate shifts, many species responded by shifting their ranges over different timescales: daily and seasonally (such as upstream/downstream movement), across years, and even across decades or centuries, such as movement between basins. Species that are more restricted in range and mobility, such as from physical or temperature barriers to movement, will have more difficulty adjusting to new climate conditions. In many cases, hydrological and hydraulic barriers can be restored or modified. Connectivity is not a universal good, and high levels of gene flow between populations or the assisted migration of species to new regions will have many unintended consequences. Consultation with local or regional specialists is necessary.

- Metrics related to non-climate stressors, which can include many of the traditional concerns about ecosystems: overfishing, industrial pollution, invasive species, and untreated agricultural runoff and sewage. These forces can in conjunction with climate change reduce or limit the capacity of species to adjust or cope with climate shifts, especially extreme events.

These four ecological qualities for climate adaptation were also explored by Poff and colleagues (2016) in the EEDS framework, and these elements can help define critical thresholds, such as limits of change in the natural flow regime that might trigger deleterious impacts for a target species (e.g., salmon breeding). Rojas and colleagues (2018) have applied the EEDS approach at a national level in Mexico to indicate specific thresholds for environmental water reserves for particular basins; crossing these thresholds (for water consumption, for instance) could pose irreversible ecological impacts, which can guide the decisions for regional water managers and stakeholders in the future.

1.2.4. Avoiding Biased Analyses

Risk analysis is at the heart of CRIDA, and decision scaling is a structured method for untangling the many complexities associated with risk and uncertainty, including but not limited to climate impact uncertainty. A recent trend among resource managers and planners is to quantify the risks associated with various hazards and their potential consequences and then to evaluate risk reduction options.

Risk is typically expressed as a function of hazard and vulnerability (UNISDR 2013), which serves as a measure of anticipated consequences and can indicate some shift after the implementation of risk reduction. A traditional cost-benefit analysis can be used to support the selection of such appropriate mitigation measures (Baumann et al. 1998).

In the climate adaptation community, such analysis is often called a vulnerability assessment or VA. No single method exists for conducting climate vulnerability assessments. In general they do not provide the same degree of quantitative and analytical rigor for water investments in terms of evaluating cost effective risk reduction options as standard water resources project justification procedures used by the World Bank, U.S. Army Corps of Engineers, the Bureau of Reclamation (Stakhiv et al. 2016) or the Dutch Delta Program (Van Alphen 2015). The challenge for analysts is that "vulnerability" and "risk" are not interchangeable. In other words, reducing vulnerability always means that outcome risk is reduced, but reducing the outcome risk does not always reduce vulnerability (Sarewitz et al. 2003).

Understanding the relationship between vulnerability and risk has profound implications for the range of solutions proposed. An analysis that evaluates an adaptation strategy under only one measure of performance while ignoring others will often yield an extremely incomplete perspective and lead to biased decisions. For instance, dike or embankment construction and flood warning systems are common measures to reduce flood risk. As a result, flood damages enumerated in some currency value are a common flood risk reduction performance metric for both measures. An analysis that focuses on flood damage reliability to the exclusion of resilience and vulnerability is likely to bias selection of a dike construction strategy relative to other priorities such as flood insurance, reconfiguring flood control operating procedures, pursuing green infrastructure, and building capacity. Similarly, an analysis that focuses on resiliency and vulnerability to the exclusion of reliability is likely to bias against the selection of a dike-building strategy.

How the analyst frames risk is important to structuring the range of solutions available, especially economic analyses included in most project justifications. Stakhiv (2011) identifies four dilemmas in the manner in which the impact of extreme hydrologic risks are deducted or "discounted" (in the language of economics) in a typical analysis of water resource project alternatives. Widely used water project justification criteria are generally incompatible with the search for climate adaptation solutions intended to endure far into the future, especially under uncertain climate scenarios. The socio-economic effects of low probability–high consequence events, such as very extreme floods and droughts, can be discounted by selecting probability distributions that diminish the importance of low probability events (Haimes 2015, Botterill and Cockfield 2013). The economic consequences of such low probability events are further discounted when the economic discount rate—the interest rate used for discounted cash flow analyses such as cost-benefit ratio calculations—is too high for evaluating the impact of distant or rare future events.

1.2.5. Integrating Decision Criteria and Decision Rules

Stakeholder-defined performance metrics inform the criteria that decision makers use to evaluate a proposal, solution, or project. There are generally two stages of decision making in any planning setting, requiring a distinction between the criteria and rules used for decisions.

A planning group consisting of a spectrum of stakeholders typically possesses a wide variety of criteria, many of which may be in conflict. Each planning group devises its own problem statements, planning objectives, and performance metrics, typically derived from overarching goals established for that particular setting. To achieve its objectives, the planning group also establishes rules and criteria for assessing options and evaluating tradeoffs. These decision criteria enable decision makers to determine if a solution can proceed to the next stage of formal analysis.

In CRIDA, decision rules and decision criteria refer to distinct concepts. Decision rules are formal and explicit processes, usually derived from legislation and promoted by agency regulation and procedures, that guide how acceptable projects are justified for approval and funding. For instance, a finance ministry could require that a certain cost-benefit ratio be met as a prerequisite for funding and prescribe a discount rate to be used in project justification. Early discussions with financing authorities can help avoid difficulties as a project matures. In large institutions, procurement processes for engaging services, products, and partners may be strict for the definition of those products or services. For instance, green infrastructure is often very difficult for many institutions to address through traditional procurement procedures.

Decision criteria adjudicate acceptability for projects and are often quantified: cost effectiveness, cost-benefit ratios, or rates of return. Decision criteria may be estimated from performance metrics. Decision criteria can also have social, cultural, or political aspects that reflect the legal, customary rules, and procedures of key stakeholders. Regulatory constraints may be important criteria in some cases. If climate change is relevant, some criteria may relate to reliance, robustness, and resilience in order to cope with high variability and uncertainty.

Decision makers have ultimate authority over a solution, but the involvement of stakeholders allows decision makers to understand success from the perspective of their constituents. In many cases, decision criteria and decision rules overlap.

Performance metrics are used to formulate and evaluate alternative plans, while decision criteria and rules are used to select a recommended plan. The separation of these steps provides an additional level of transparency to stakeholders and decision makers and promotes a broad formulation of alternatives without the need to review decision criteria.

1.3. IDENTIFYING CRITICAL THRESHOLDS

Traditional planning seeks solutions that reach a desired performance level, while in CRIDA, a critical threshold is an unacceptable chronic level of performance or reliability that stakeholders want to avoid. Examples of traditional objectives include a specific output (e.g., a targeted production level) or flood protection defined by a design return period peak flood flow (e.g., a 1 percent flood event).

In contrast, CRIDA defines critical thresholds based on both formal documents and agreements and on stakeholders' experience. Both methods are used in combination.

- Based on formal documents and agreements. Critical thresholds can often be derived from legal guidance, by-laws, decrees, court precedents, policy documents, resource management guidelines. Examples include flood risk standards, regulatory frameworks, other design standards (e.g., minimum power generation), water supply, resource management concerns, private sector management scope, and energy service levels.

Box 1.3.

Impacts Defining Performance

A useful way to evaluate whether a stakeholder's defined level of unacceptable performance is a critical threshold is by the assessment of impacts. The critical threshold is a level of chronic unacceptable performance, which is often identified by a stakeholder because they intuitively understand the implications of failure in their system. The impact (ΔP) from unacceptable performance is the difference between the performance under expected climate states and the critical threshold defined (Figure 1.2). However, although the potential loss in performance (ΔP) may be critical to a specific stakeholder, it may not be critical to a decision maker or to a broader group of stakeholders. Loss of performance often needs to be evaluated in the context of economic, social, or environmental health of the system or with respect to a return to investment.

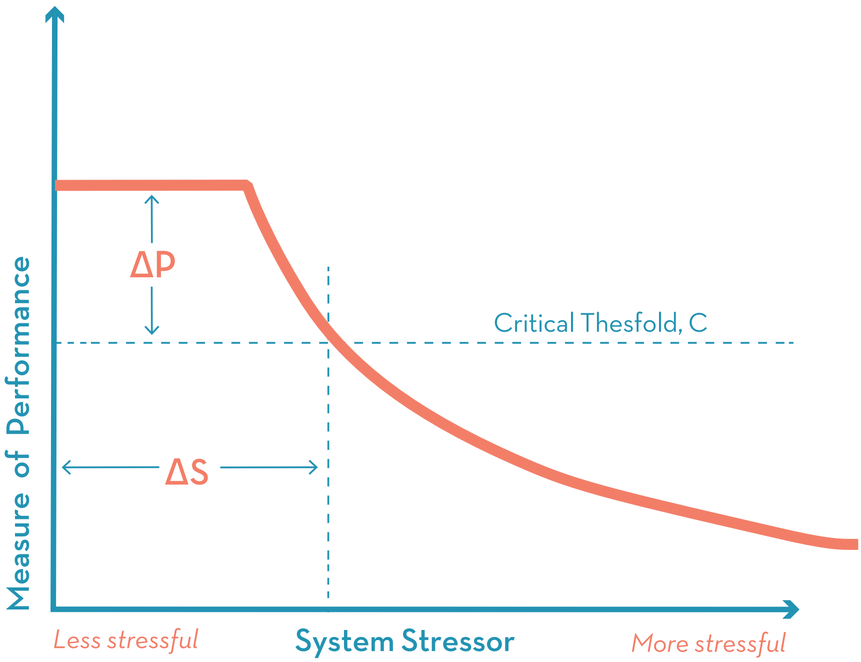


Figure 1.2. External stressors' impact on system performance, such as flood runoff performance like urban change or shifts in annual rainfall, can reach points where the change in performance (ΔP) and/or change in stressor (ΔS) reach a critical threshold (C) of unacceptable performance.

In general, the impact of lost or reduced performance might be evaluated with the following considerations:

1. Recorded or potential loss of life.
2. Reductions in quality of life, including health impacts, jobs, and subsistence agriculture.
3. Total economic losses, especially if they are a high portion of regional economic activity.
4. Losses in social equity with potential for social instability.
5. Lack of economically comparable substitutions to compensate for lost performance, such as the loss of reliable and inexpensive access to clean water.
6. Loss of an irreplaceable social, economic, cultural, religious, or environmental good.

These considerations and others might be linked to planning objectives or other institutional criteria. To be clear, when thinking about the future, these losses may never occur. However, in the decision context, the analyst begins to assign attributes of criticality if performance were to reach a critical threshold given a plausible future.

- Based on stakeholders' experience. Stakeholders are best positioned to discuss tolerance to failure and management-related values associated with failure. Stakeholders may refer to "breaking points" that require translation of such tolerance into terms relevant to climate conditions and/or water management. In some cases, thresholds cannot be clearly expressed as quantitative targets because they are qualitative or value driven. Modeling the systems in question may help elicit quantitative or semi-quantitative descriptors. The analyst should provide data on past critical events (for example, a time series of extreme climate events and their associated damage) or, if not available, on critical events for similar sectors and situations.

Many critical thresholds will be sensitive to different perspectives. Custom, culture, and evolving traditional practices can influence variable selection, though non-local stakeholders and analysts may not appreciate the importance of context and local groups may not clearly explain their concerns, particularly in the cases of unequal power relationships with "external" groups. Sometimes "ambassadors" capable of, for example, translating among the analyst and local stakeholders can help co-define objectives and performance thresholds. In transboundary basins, standards may need to be harmonized across jurisdictions and governance regimes (UNECE and INBO 2015).

The analyst may need help eliciting "narratives of failure" that can help define thresholds through questions such as "What keeps you awake at night?" For example, an operator of the Huay Luang Reservoir in Thailand described to one of the authors how severe extreme events, growing demand, and a centralized decision making process resulted in a near-empty reservoir at the beginning of several dry seasons. The reservoir operator had been saved from an empty reservoir only by unusually late rains. Stories about actual or narrowly averted failures can usefully frame a threshold. In the case of the Thai reservoir, the operator's anxiety resulted from chronic low reservoir water levels at the beginning of the dry season and the almost-realized risk of lost benefits. These thresholds then correlated to irrigated agriculture decisions.

1.4. DETERMINING DRIVERS OF CHANGE AND ESTABLISHING A SOLUTION-TESTING MODEL

One key aspect of the decision context is the development of a system model that can be stress tested to evaluate alternative actions and plans. Figure 1.1 is a representation of the possible components of such a model. The model must be able to modify external drivers to evaluate their impact on performance. Moreover, the performance indicators of the model system must adjust to shifts in design parameters. The model should be a solution testing and comparison tool. Further, design parameters should influence external driver impacts on the performance of all relevant plans or alternative solutions.

Model development is an iterative, collaborative process to explore how to achieve the objectives against the decision criteria. Developing a model collaboratively imposes a degree of rigor to match stakeholder needs with resource availability. Matching decision criteria with resource constraints forces different interests to better understand the nature of tradeoffs, benefits, and costs needed to reconcile conflicting objectives. Collaborative modeling bridges the gap between planning numerous options and choosing a single option that best meets the objectives and binding constraints. CRIDA's stress tests examine how system performance responds to changing external drivers.

The model's level of complexity is governed by the objectives, performance metrics, and decision criteria. There may be objectives or performance metrics that cannot be modeled due to resources, decision maker priorities, institutional scope, or relevance to the problem. However, decision makers' needs and the modeling or technical efforts must always be aligned.

Collaboration is essential for CRIDA to succeed. The following are some considerations to foster collaboration during the model development process.

Box 1.4.

Understanding the Context of Modeling

Analysts can begin with simple analytical procedures to incrementally understand the system being modeled. Analysis and models become more complex as required in support of decision making. The following are two examples of simple models that provided important decision making insights:

Grijsen (2014) used a simple empirical water balance model based on the Budyko Curve, which estimates the partition of evaporation and runoff as a function of aridity and biomes (Milly 1994), and then used linear regressions of runoff to estimate hydropower generation for a first-order evaluation of system performance sensitivity to hydrological shifts.

Tran (2017) used the Budyko Curve relationship for a first-order assessment of the relative contributions to reduced stream flow from changes in climate, and from changes in land use and upstream water withdrawals.

- Who is going to use the model, and how is the model going to be used? These questions emphasize how technical analyses are presented and visualized to inform decision makers and collaborate with stakeholders.

- How do external drivers impact system performance? Using iterative tests, the analyst should find monotonic relationships, so that a change in one direction (an increase or decrease) of a driver should lead to consistent directional change in performance. The interactive exercise should be geared to prioritize the external drivers to be modeled in a stress test that will evaluate the vulnerability domain of the system.

- Is the model correctly tailored to the performance metrics and decision criteria? In other words, the technical complexity and spatial and temporal resolution must be aligned with decision making needs.

- Have stakeholders been engaged early, so that the connections between data, technical requirements for objectives, and performance are clearly understood, and is there buy-in and validation on the technical analysis? The work of the analyst must be credible.

Box 1.5.

Developing a Decision Support Model to Address Present and Future Climate Stressors

In many parts of the world, unacceptable performance of existing water-based infrastructure is already strongly tied to stressful climate states (Figure 1.3). The water resources system in Ethiopia is vulnerable to climate change, and regional climate will likely become drier in eastern Africa (World Bank 2006). Here, the analyst may need to develop a system model that relates climate, via future water availability for irrigation and agricultural production, to gross domestic product (GDP). To design for a more stressful future climate, the analyst should include realistic design variables that reduce sensitivity of the economy to hydrological changes and a variable climate.

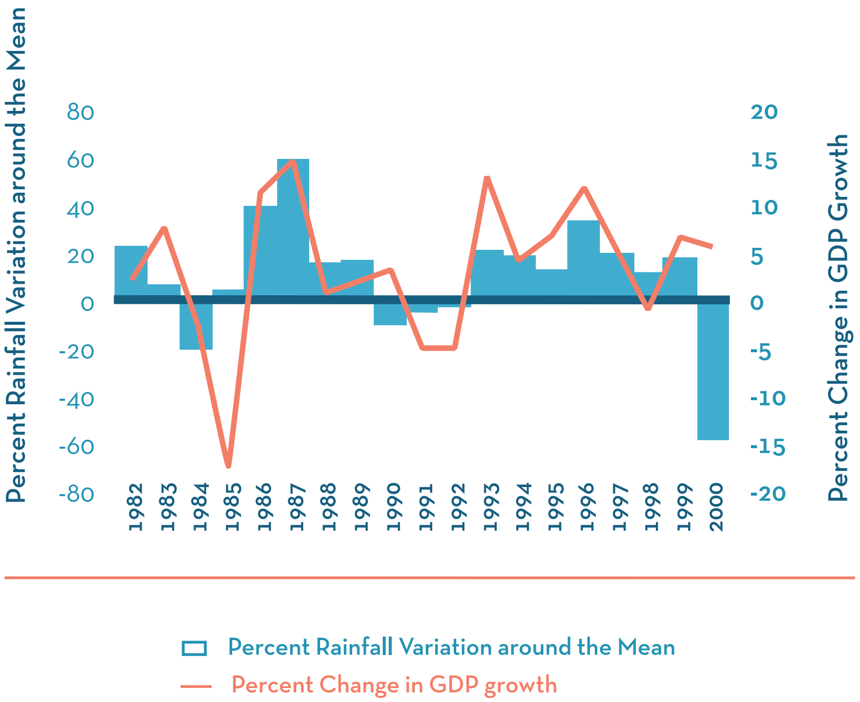


Figure 1.3. GDP and rainfall variability in Ethiopia. Adapted from World Bank (2006). This is an adaptation of an original work by The World Bank. Views and opinions expressed in the adaptation are the sole responsibility of the author or authors of the adaptation and are not endorsed by The World Bank.

Step 1

1.5.
BUILDING A SHARED VISION: STAKEHOLDER COLLABORATION

CRIDA's bottom-up processes bridge technical analyst and stakeholder perspectives to develop a shared vision of the existing state of water resources management and are designed to formulate solutions for alternative future states and test the feasibility and performance of alternative solutions across multiple futures. Stakeholders define success or failure via their preferred performance criteria, while the analyst establishes plausibility and facilitates exploration of stakeholders' risk tolerance to unforeseen conditions. The technical team also aligns the analysis with the needs of the decision maker.

Planning for uncertain futures ideally results in solutions that diverge from standard and traditional practices because these solutions should include estimates of robustness and flexibility. Decision makers will often consider robust, flexible solutions if they come at a reasonable cost and have stakeholder support. For example, at the U.S. Army Corps of Engineers, locally preferred plans are often recommended in addition to plans that maximize national economic development benefits. High-level support for variations from a standard plan is usually achieved only after collaboration between stakeholders and decision makers and the tradeoffs are made explicit: who benefits, by how much, and who bears the costs of increased resilience, robustness, and system reliability. Collaborative planning processes are always recommended and are especially helpful when there are multiple competing objectives and there is a great deal of uncertainty about the future. Shared Vision Planning (SVP) is one means to structure a collaborative process (Creighton 2010). SVP integrates planning procedures, a decision support model, and a structured stakeholder participatory process for water management. Other sets of tools have also been designed to support collaborative planning processes, including a UKCIP technical report (Willows and Connell 2003), public involvement techniques such as those from Creighton and colleagues (1998), and guidance on collaborative planning such as Nauta and colleagues (2016).

The scope of stakeholder engagement depends on the nature of the problem and the jurisdiction of the decision maker. For example, implementing an integrated river basin planning process without an empowered, established river basin organization with a clear and recognized mandate would be extremely challenging. Similarly, it may be difficult for a flood risk reduction agency to propose solutions to improve landscape management without an institutional mandate regarding forestry or urban management. The planner must recognize the "problem-shed": the decision making jurisdiction to identify the scope of stakeholder engagement. In general, those who have a stake in the decision should be considered in the problem statement or formulation of actions. See Bryson (2004) for stakeholder identification and analysis techniques.

Stakeholders can help the analyst understand failure concerning their interests, which is the foundation of defining a critical threshold. Stakeholders can also help identify whether certain actions are acceptable or would hinder other objectives or limit future options. Stakeholders can help validate the performance of models if their outputs coincide with what they have observed. Finally, buy-in can simplify decision making. This means that the level of stakeholder engagement depends on the scale of the problem and who can represent the relevant sectors. On one side of the spectrum, ministerial representatives from relevant sectors might be stakeholders in a transboundary application of CRIDA. On the other side of the spectrum, women may be critical stakeholders to help plan a Climate resilient water supply system that supports sustainable livelihoods, family health, or horticulture gardening. Similarly, in sub-Saharan Africa, women are almost 50 percent of the agricultural labor force and thus could be key representatives for that sector.

From the analyst's perspective, collaboration should be structured to ensure planning deliverables and milestones. The collaborative process often has rules of engagement that include conflict resolution procedures or explicit rules for workshop dynamics and planning. A specialized planning team may facilitate the collaborative process and perform technical tasks. Finding a group to support stakeholders or academic specialists can help the planning team to align the model with stakeholders' interests. Linked subgroups, meeting at regular intervals, can provide input to the analytical requirements and feedback to model development.

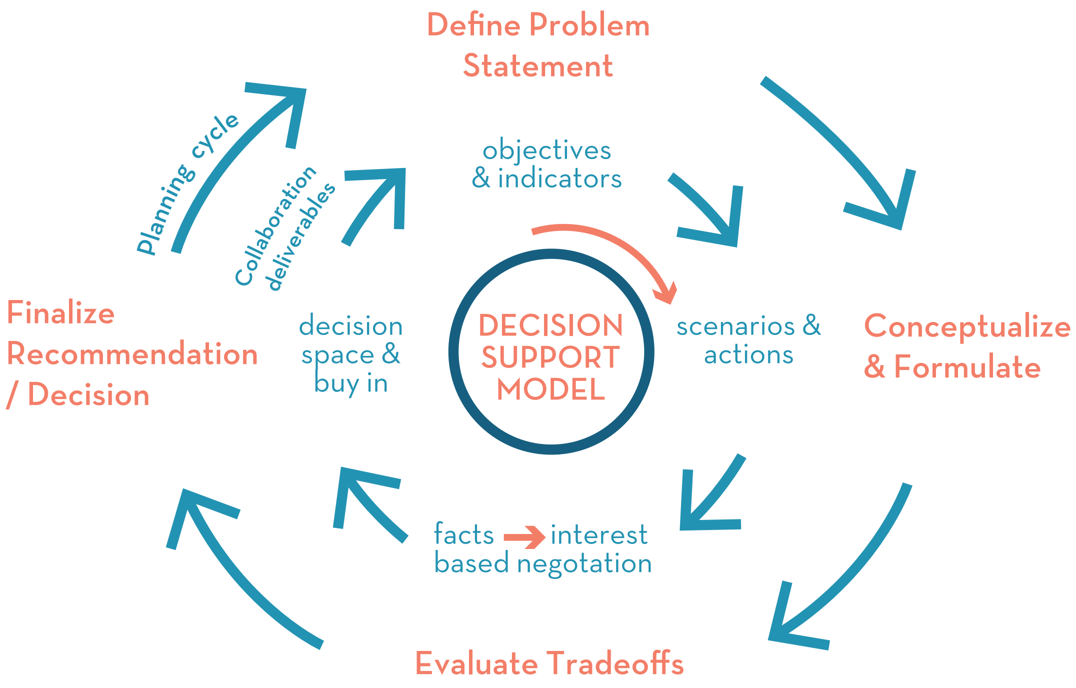


Figure 1.4. An example of a decision support model that integrates planning and stakeholder participation.

Decision makers should be briefed at key deadlines on overall progress of the effort. They provide direction, specify main and secondary decision criteria, and define the types of actions they are willing to consider. A preliminary model can be used in mock decision exercises to assist decision makers in preparing for their roles in selecting a plan or plans. This structure of collaborative planning teams and decision cycles is known as "circles of influence" (Creighton 2010, Bourget 2011, Cardwell et al. 2008).

The decision support model must be part of a collaborative planning process (Figure 1.4). While each planning phase has a corresponding deliverable and may correspond to a stakeholder workshop, they are still iterative engagements with a specific focus and clear milestones and deliverables. Successful implementation of the collaboration process requires early and often active support by decision makers, sometimes called "champions," combined with a competent facilitation and planning team and clear rules of engagement.

Figure 1.4 illustrates collaboration aspects of the planning process: establish a problem statement that defines unacceptable performance through critical thresholds; formulate an acceptable range of actions and alternatives for robustness; evaluate tradeoffs through a model; and facilitate buy-in for the decision making space.

Box 1.6.

The Decision Context of the Iolanda Water Treatment Plant

The Millennium Challenge Corporation (MCC) is an independent U.S. foreign aid agency that provides time-limited grants to promote economic growth, reduce poverty, and strengthen institutions. In Zambia, MCC is working with the Lusaka Water and Sewerage Company (LWSC) to rehabilitate the Iolanda Water Treatment Plant (IWTP) for increased drinking water production and improved reliability.

In recent years, droughts and increasing demand have led to more frequent system failures during which the IWTP is unable to meet its water delivery targets. Growing numbers of people in Lusaka obtain water from shallow wells with poor water quality. Waterborne illness and loss of life are a real threat to vulnerable populations. Moreover, there is concern that the future might be drier, further stressing the reliability of the IWTP.

MCC and the LWSC have identified infrastructure investments to reduce water delivery shortfalls for a standard period of analysis of 20 years given population growth trends and a stationary climate. However, MCC is interested in a retrospective analysis to determine and justify additional levels of investment that would improve the robustness of system performance in the event of significant climate change.

The investment must "meet demand for reliable treated water to Lusaka in the present and future in a cost effective manner" (the objective). However, the IWTP is a failing system under current climate conditions, with persistent delivery shortfalls (the performance metric) of treated water to the city of Lusaka. Any level of chronic shortfall is unacceptable (the critical threshold). Several climate change scenarios forecast lower rainfall and higher temperatures (external drivers), which could exacerbate shortfalls through electricity blackouts that shut down operations at the IWTP and/or reduce the volume of water available for treatment. It was unclear which of these two problems–loss of electricity or availability of water–would likely be the limiting factor in the future. Both the electricity and the untreated water for the IWTP come from a reservoir system that includes the Kafue and Itezhi-Tezhi Reservoirs, setting up a potential tension between water for hydropower and water for drinking. This case study uses a spreadsheet in MS Excel to model Kafue and Itezhi-Tezhi reservoir operations for provision of water and hydropower energy to the IWTP. The external drivers are inputs to the model, and the performance metric is the output.

Putting climate change uncertainty aside, analytical uncertainty is high due to limitations of the available meteorological and streamflow data: the stations that exist lie largely outside the basin, and the record length is poor. The analyst should thus pursue flexible, adaptive investments for robustness. However, the LWSC is an institution with limited capability to monitor and trigger adaptive plans (an institutional constraint). As a result, the recommended strategy developed through this case study is to formulate individual robust infrastructure investments that will be scalable to accommodate future funding availability and reduce the effect of an increasingly drier climate. More details can be found in Tkach and colleagues (2018).

Box 1.7.

Conceptualizing the Decision Context in the Waas River

A study was commissioned by Deltares to develop a framework for flood and drought resilience considering the uncertainties of climate change and different future public preferences. The site is the hypothetical Waas River, based on a reach of the Rhine River.

Over the last 25 years, two major floods have resulted in excessive damages in the order of 2,810 billion € while low flow levels in the dry season have led to 92 percent navigation reliability (problem statement). There is concern that the region will become more urbanized and wetter and drier in the wet and dry season, respectively (drivers). Decision makers want to reduce flood damages and social disruption from both extreme and nuisance flooding, improve navigation reliability, and protect environmental assets over the next 100 years or more (objectives). In addition, decision makers seek cost-effective solutions that include social preferences about the future (objectives). Some social groups believe in government control of water and nature for beneficial use while preserving the environment, others have a preference for enhanced outcomes for environment and equity objectives, while a third cluster wants to adhere to a liberal market, i.e. innovation, markets, and a private sector role. To balance these objectives, the technical analysis will require integrating hydrology, river hydraulics, and flood damage models in a multi-objective criteria decision support system (model requirements).

Through a collaborative process with stakeholders, performance indicators with their unacceptable levels of performance (critical thresholds) are identified for each of the perspectives. Table 1.2 provides an example of performance indicators representing different societal perspectives for a 25-year horizon.

Despite good data and technical capacity, there will likely be high analytical uncertainty given the uncertainty of the different future societal preferences and the diverse objectives and tradeoffs. The analyst will likely pursue system robustness through actions that can be updated with social preferences or as new conditions are observed, which suggests a flexible strategy. More details can be found in Haasnoot and colleagues (2012).

	Performance Indicators	Critical Threshold
Social	Urban area flooded (km^2/yr)	>0.5
Economic	Total flood damages (M €/yr)	>2000
	Agricultural damages (M €/yr)	>50
	Navigation reliability (%)	<93
Ecology	Wetland Habitat (km^2)	<12

Table 1.2. Examples of performance indicators and thresholds for the Waas River Basin.

2

Implementing a Bottom-up Vulnerability Assessment

ESTABLISHING THE LEVEL OF CONCERN 63

PERFORMING THE STRESS TESTS 66

DETERMINING RISK IN AN UNCERTAIN FUTURE 70

Step 2

In the second step of CRIDA, the analyst performs a stress test to explore future risks of a system failure through an inability to deliver services (e.g., water supply, hydropower, flood control) and/or a physical failure of infrastructure (e.g., dike overtopping, dam break) by performing a stress test. Failure is defined by the critical thresholds set in Step 1.

The outcome of the stress test is evaluated through an analysis that defines the "level of concern" (LOC). The LOC provides answers to two questions:

- Does credible evidence suggest a threshold will be crossed leading to unacceptable performance?
- Is the confidence level of the analysis sufficient to make a risk-informed decision?

The LOC provides further guidance for Steps 3 to 5 of the CRIDA process.

Input from Step 1

- Water resources system model
- External drivers
- Performance metrics
- Critical thresholds

Output from Step 2

- Stress test results showing the limits of performance
- An assessment of the plausibility that future stressors will lead to unacceptable performance
- An assessment of analytical uncertainty and how it affects the choice of options
- A measure of level of concern based on the assessment of plausibility and analytical uncertainty

2.1.
ESTABLISHING THE LEVEL OF CONCERN

To establish the LOC, the analyst will implement a bottom-up vulnerability analysis by applying a stress test. A stress test is designed to demonstrate the limits of performance in an existing system under a variety of plausible but uncertain future conditions. These conditions are typically derived from socio-economic projections of population and economic growth combined with water resources demand requirements. Water resources management options are then formulated to meet the projected demands along with an array of sustainability objectives.

A stress test can provide analysts and stakeholders with information to determine analytical uncertainty associated with future scenarios and the plausibility of assumptions and outcomes related to various scenarios. The LOC provides a qualitative determination, even if quantitative data are limited.

Typically, an analyst seeks a solution using engineering and economic guidance, but in addressing a future that may never be realized, the planner may face two types of deviations from standard practice which create a need for additional justifications. The first is a recommendation for an action that is *more robust*—encompassing significantly different and/or more stressful conditions than the present—than standard practices typically allow. For example, rising sea levels, the elimination of a snowpack reserve, or more severe floods and droughts may be anticipated. A more robust action is designed to encompass a broader range of uncertainties, which usually implies more costs (financial or other) than a decision maker or stakeholder might otherwise be willing to consider.

The second deviation is a recommendation for a plan that is *flexible* and can shift management, operation, or design towards consideration of emerging conditions. Pursuing several pathways simultaneously requires a long-term commitment and the institutional capacities to explicitly apply and maintain options. Pursuing flexibility, however, does not always result in timely problem solving, because of the often lengthy political approval processes associated with public infrastructure.

As shown in Figure 2.1, the relative risk of failure from potential impacts and the estimate of analytical uncertainty along the x and y axes of the LOC matrix will determine the broad strategy along with the appropriate degree of analysis. The amount of information and detail needed for the analysis to overcome uncertainties depends largely on the initial assessment of LOC. This quasi-quantitative assessment, when completed in conjunction with a stakeholder engagement system such as Shared Vision Planning, can define the degree of intensity required for the remainder of a CRIDA implementation. The LOC determines the overall strategy (Step 3), the evaluation of actions and plans (Step 4), and the development of a plan for implementation (Step 5).

The plausibility of surpassing a critical threshold provides a measure of urgency to either pursue robustness or defer action. Analytical uncertainty derives from factors such as the type

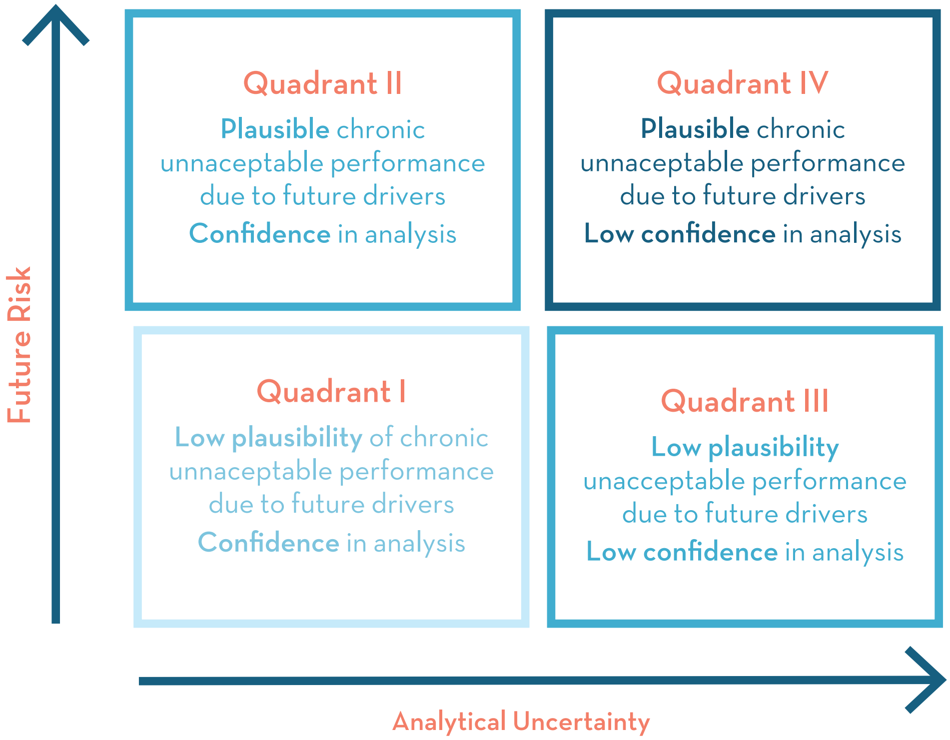


Figure 2.1. Establishing a "level of concern" in the planning process. Future risk in this document refers to the plausibility that a future driver is realized that surpasses a performance threshold. Analytical uncertainty results in a reduced confidence for the decision maker in making a decision given the available information.

of problem, available data, and geography. The level of analytical uncertainty is also affected by the risk aversion—or risk appetite—of the stakeholders and the decision maker.

The four quadrants of Figure 2.1 reflect the evidence acquired in the planning process. If the plausibility of future scenarios is judged to be low and the analytical uncertainties are small, then Quadrant I suggests that there is limited evidence for deviating from standard and/or accepted planning guidance and practices and the solution works with existing precautionary policies or safety margin requirements. This business-as-usual position is recommended when the stress test reveals low impact from future stressors. For most situations, Quadrant I is the starting position for the analyst and decision makers—and may be the endpoint as well for the CRIDA process if the LOC is low. This quadrant is also where no-regrets planning options are most sensible, based on conventional decision rules.

Quadrant II suggests decisive action to build robustness in response to plausible futures. In this case, the analytical uncertainty associated with the scenarios is acceptable and can be evaluated using existing risk analysis methods. For example, climate non-stationarity is not as important as other trends. The vulnerability assessment may indicate uncertain future stressors are credible and will likely have a high impact on system performance. Consequently, the analyst should develop actions or plans that satisfy standard procedure requirements and perform acceptably under potential futures. The analyst should also evaluate actions designed to address future risks greater than those considered by standard evaluation procedures.

An LOC in Quadrant III suggests the analytical uncertainty is relatively high even though future scenarios do not indicate a clear increase in risk. Hence, this situation provides evidence and justification to delay major project implementation, though the analyst may consider incremental low-regrets strategies that include monitoring and/or acquiring better information over time to address critical futures. Flexibility and the need to avoid rigid or path-dependent options may be important. In addition to continuing business-as-usual planning procedures, an analyst could propose adaptive actions to be prepared for implementation should a “trigger point” be reached in a monitoring program.

Box 2.1.

Setting Bounds for a Stress Test

Setting reasonable bounds for the stress test is an iterative process that will improve with experience. Some rules of thumb:

1. External drivers should be incrementally adjusted to show a transition from acceptable to unacceptable performance (i.e., surpassing a threshold).
2. The range of drivers should encompass observed and historical records.
3. The extreme drivers should exceed the magnitude of the majority of forecast data.
4. The driver values should be at least theoretically possible.
5. At least seven driver increments between the minimum and maximum values should be evaluated.

The LOC associated with Quadrant IV warrants both decisive and incremental action. In this case, there is a plausible risk of futures that will violate a critical threshold together with high analytical uncertainty. Decisive actions coupled with monitoring to facilitate an incremental and flexible response are justified. Generally, this high level of concern requires substantive institutional adjustments that include changes in planning procedures and decision criteria. A new evaluation and decision making paradigm is often required to accommodate this LOC and to address numerous unknowns

2.2. PERFORMING THE STRESS TEST

External drivers are manipulated in a stress test to determine when the performance of the water resources system model "breaks" (Brown and Wilby 2012). A breaking point is a value when previously designed performance outputs fall below critical threshold levels, such as because of increased demands or changes to resource availability. Often these drivers are hydrologic or climate related, but CRIDA recognizes that there are many potential drivers such as population growth or landuse change. Indeed, the stress test can help determine the relative impact of different drivers, which is often important to discuss with stakeholders and decision makers. In standard practice, non-climatic drivers are often treated as static inputs determined from traditional socio-economic forecasting or master planning methods.

There are two principal components of a stress test. The first is a water resources system model that connects external drivers to measures of performance. The second is an iterative and systematic manipulation of external drivers such as hydrologic or landuse variables to explore impacts on performance (Figure 2.2). The model's requirements are dependent on the main performance measures, decision criteria, and rules selected in Step 1. Many public agencies require a direct evaluation of system performance. Once possible options have been identified, evaluation and selection are ultimately based on other decision criteria.

As indicated in Figure 2.2, different drivers feed into an impact model and the stress test results illustrate performance sensitivity to external stressors. Prudhomme and colleagues (2010) refer to this process as sensitivity testing rather than the CRIDA stress test because the process is intended to reveal the domain of vulnerability.

The stress test is used to create a response surface, which is then regenerated repeatedly to evaluate the effectiveness of various policies or adaptation options in meeting planning objectives. The response surface can evaluate solution robustness. Depending on the number of stressors, a two-dimensional, three-dimensional, or higher dimensional surface may be needed. The benefit of a three-dimensional response surface is an ability to evaluate the impacts of combined changes in the drivers. If more than two drivers are evaluated, the analyst should determine which drivers the model finds most

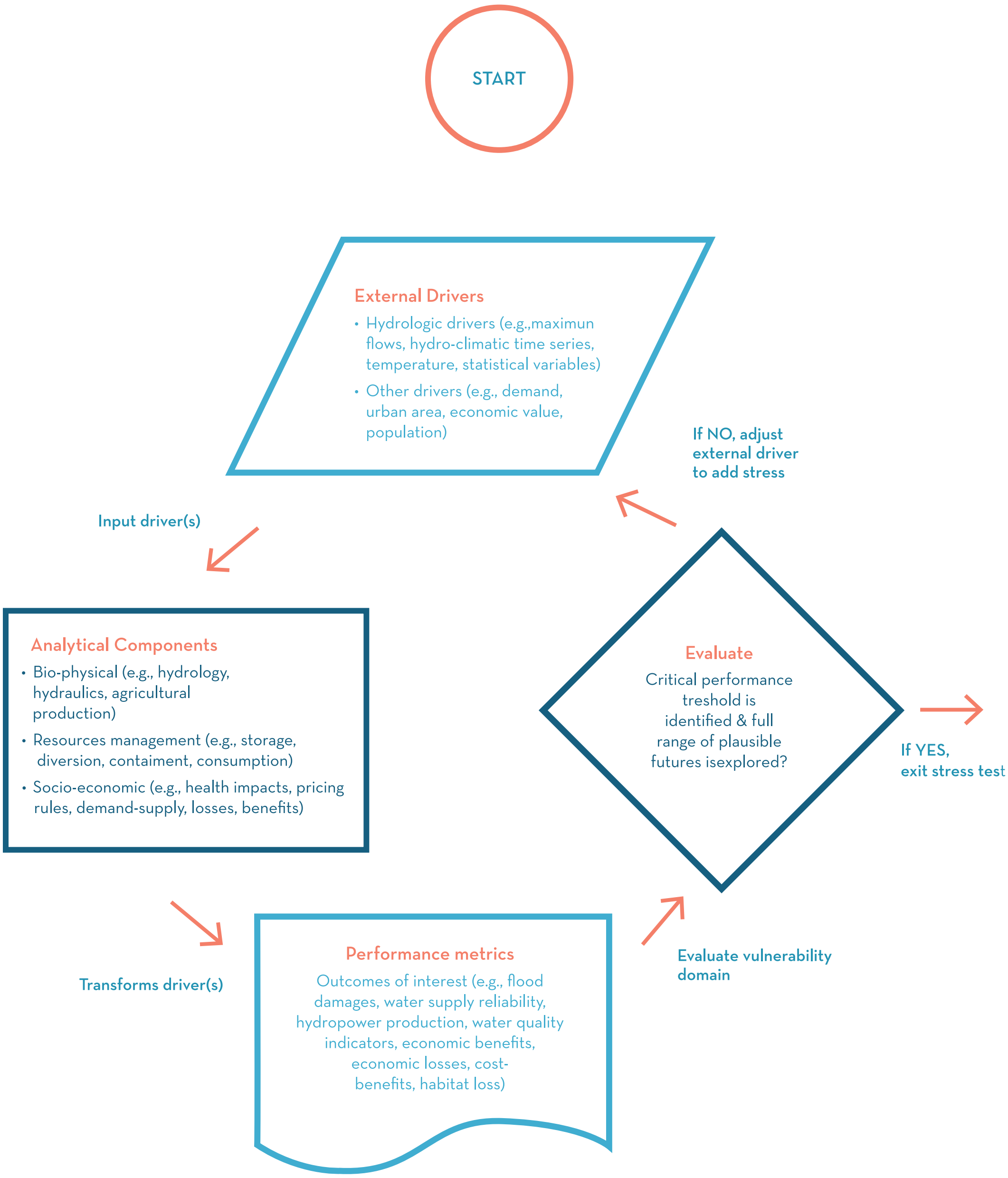


Figure 2.2. A stress test is the iterative adjustment of external drivers to locate unacceptable levels of performance, which defines the vulnerability domain

Box 2.2.

Modeling Changing External Drivers in a Stress Test

The stress test requires the manipulation of external drivers to generate different performance outcomes. The objective is to determine the drivers that lead to chronic unacceptable performance (threshold). For example, each realization of a driver time series or value would represent one value on the *x* or *y* axis in Figure 2.3.

To develop possible future climate states (or another external driver) to be used in a stress test, the analyst should take these steps:

1. Determine the climatic stressors that are relevant for the sector and region, which will be incrementally adjusted in a stress test.
2. Determine an appropriate method to generate synthetic future climate states to be used in stress test. The following sub-steps may be important:
   - Manually updating drivers and running models may be sufficient for systems that can be stressed by adjusting with a few variables or statistics. However, if there is significant scatter in the output a Monte Carlo method is recommended.
   - Bootstrapping a time series to incrementally recreate stressor scenarios applied with a Monte Carlo method are useful for more complex cases.
   - Weather generators are recommended instead of bootstrapping when maintaining realistic relationships between the various climatic variables is important (e.g., Steinschneider and Brown 2013).
3. Resample the historic climate record in order to fully explore the internal variability of the system.Independently modify multiple climatic stressors to the system.
4. Independently modify multiple climatic stressors to the system.

sensitive and then create multiple response surfaces. In a three-dimensional response surface, two dominant drivers are placed on the x and y axes. The response surface represents the sensitivity of a performance metric to the drivers' interaction. For example, if precipitation, temperature, and population growth are considered and the initial analyses suggest the system is most sensitive to changes in precipitation and population, then the analyst should create two to three response surfaces for changes in precipitation and population, with each response surface representing a different change in temperature state. However, two-dimensional response surfaces are easier to understand by most decision makers and stakeholders since they can show the variability in performance output by a time series or demonstrate the variability of performance output from one key driver in the context of different configurations of other drivers.

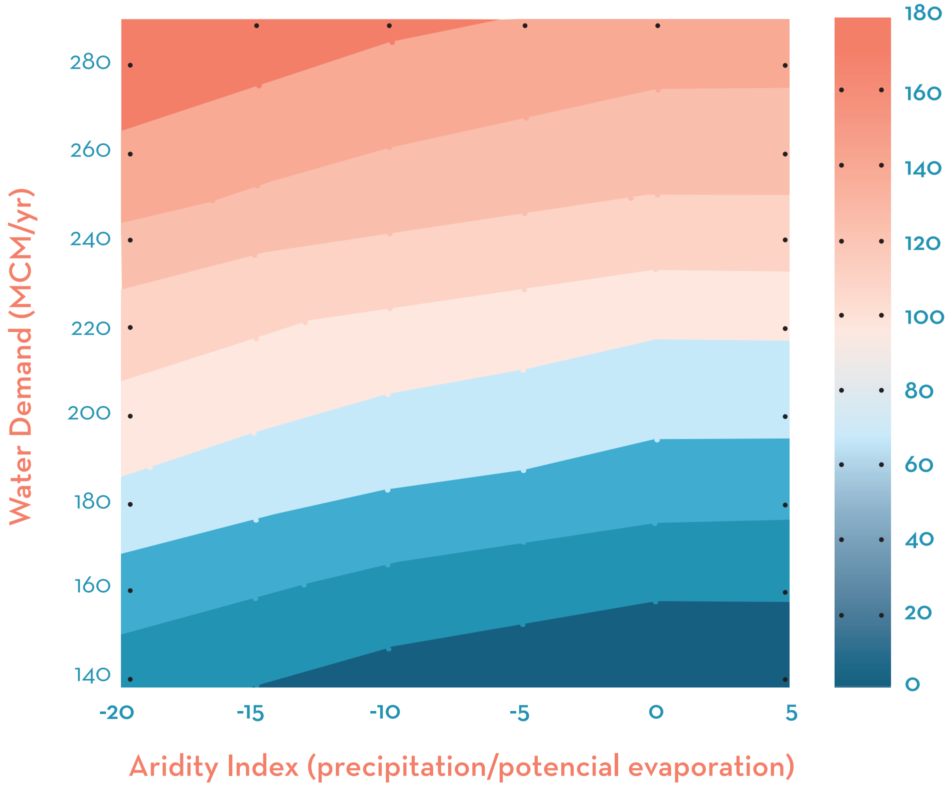


Figure 2.3. The response surface from a stress test of the Cebu water supply system in the Philippines. The color ramp represents water shortages estimated as the difference between water demand and supply. Each pixel in the plot represents a multi-year simulation run of system water provision under different configurations of stressors. These stressors are expected to shift in the future. This example illustrates that the Cebu system is more sensitive to changes in water demand than to aridity

Step 2

Figure 2.3 shows a three-dimensional stress test response surface for precipitation and water demand in the Cebu basin of the Philippines. Lessons from the response surface are derived visually; the system is more responsive to changes in demand than to changes in the aridity index. However, it is important to note the influence of the range of the x and y axes in determining the most dominant driver. If the ranges are not realistic, the stress test might overestimate the importance of a driver.

2.3. DETERMINING RISK IN AN UNCERTAIN FUTURE

Following the stress test, the impacts and plausibility of vulnerable future states are evaluated as well as the uncertainty of the analytical procedures to estimate the LOC (Figure 2.4). The impact is determined as the consequence of exceeding the critical threshold. The plausibility of exceeding the threshold is evaluated from an analysis of trend analyses, model projections, and system sensitivity.

The recommended intervention(s) should match the consequences or impact of reaching the threshold. If the LOC suggests the system will experience significant impacts within the planning horizon, then urgent implementation of adaptation responses is recommended. If the LOC indicates high uncertainty in the analysis, then the response could be more flexible and potentially include monitoring to shape later actions. The analyst may also chose to revisit the scope of the stress test or broaden the analysis. As an example, during an application of the stress test for water supply reliability in Cebu, Philippines, the analyst shifted the focus to future demand scenarios and away from climate change impacts. Similarly, the user may find that hydrologic variability is more important than mean hydrologic conditions.

The consequences of reaching a critical threshold are site specific. For example, an under-performing design that results in retrofitting a storm water system in a major urban area will likely have a higher retrofitting cost than the under-performing design of an agricultural irrigation system. In decision scaling, the context of the problem can matter in designating the consequences of failure.

In many ways, these discussions invoke risk and risk tolerance. A widespread definition of risk is the product of probability and consequence. Probability is a quantitative measure expressed from zero (event occurrence is impossible) to one (event occurrence of absolute certainty). Unfortunately, it is not possible to assign a probability to an uncertain future such as a climate change projection. However, uncertain future risk can be defined as a function of (1) the plausibility of a future state that violates a critical performance threshold, and (2) the level of impact of achieving a critical performance threshold. The use of plausibility is a qualitative measure that assigns a high, medium, or low expectation to an event occurring, as shown in Figure 2.4.

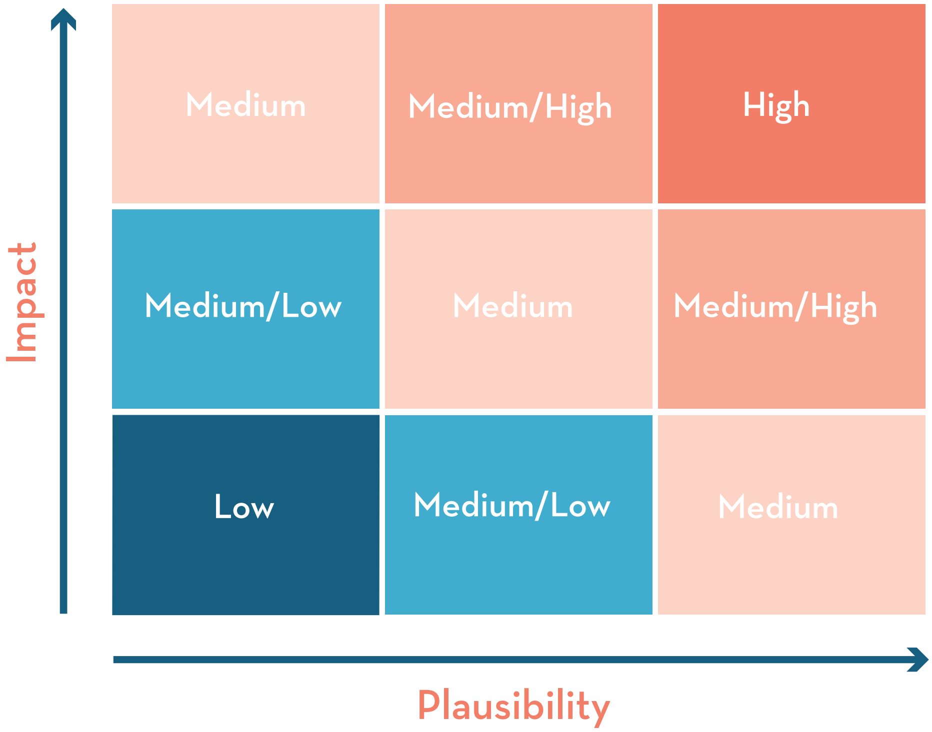


Figure 2.4. Assessing risk and risk tolerance through the future risk matrix. The analyst makes a determination for high, medium, or low risk depending on the decision context.

Step 2

2.3.1. The Plausibility of Future Impacts

After impact, the second component of a future risk matrix is plausibility. The question to be solved is the likelihood or plausibility of a system experiencing an identified impact within the planning horizon. Plausibility is inherently connected to analytical uncertainty, but focusing on the outcomes and impacts of uncertainties. Analytical uncertainty is more closely linked with data inputs. Given the uncertainty in both current and future climate conditions, the analyst may find assigning probabilities to stressor values difficult. However, evidence about the likelihood of future stressors can be found in observed data, trends, historical or paleo-information, and projection of the future. A wide range of information can be overlaid on a response surface and evaluated with respect to the critical threshold. Such a depiction of data is shown in red on Figure 2.5.

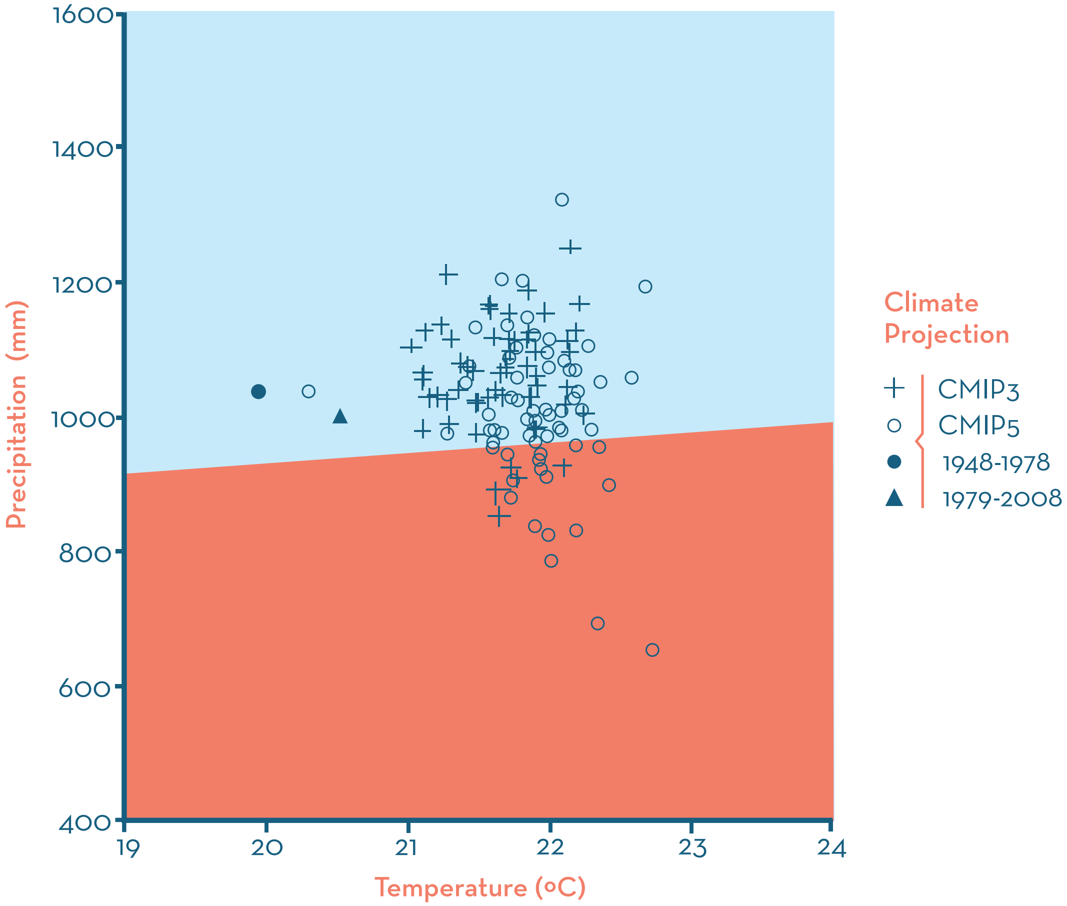


Figure 2.5. The climate response surface for a run-of-the-river hydropower project. A critical threshold was defined based on the costs for generating power. Red means that the threshold maximum regret costs cannot be met under the corresponding climate states as defined by precipitation and air temperature. The figure clearly shows that the system is much more sensitive to changes in precipitation. Note that global climate projections and average climatic observations of temperature and rainfall are overlaid to assess the plausibility of violating the critical threshold defined by the red domain. Adapted from Ray and Brown (2015). This is an adaptation of an original work by The World Bank. Views and opinions expressed in the adaptation are the sole responsibility of the author or authors of the adaptation and are not endorsed by The World Bank.

In general, evidence of change in specific stressors at different time horizons can determine the plausibility of outcomes that affect risk calculations. The integration of plausibility and impact determines plausible risk.

To assess the plausibility of violating a critical threshold, the following considerations may be useful:

1. The theoretical understanding of the physical impacts of a variable. Theoretical understanding is based on disciplinary consensus about expected changes in an external driver, such as rainfall intensities or water demand. For example, the intensification of the hydrologic cycle may support evidence for a different future state of a stressor by the climate science community. Likewise, the historical record may show a multi-decadal climatic oscillation associated with severe droughts. Non-climatic insights may be useful as well, such as evidence that economic development in a region causes migration to urban areas, plausibly affecting future urban demands for water.

2. Trends in observed meteorological, hydrological, demographic, and landuse data. Analyzing driver trends can help reveal both their importance as well as patterns, such as seasonal or interannual cycles. Such trends are more relevant to shorter-term planning horizons but add to the evidence of plausible futures and inform the direction of plausible change based on known change. For example, historical data may show an increase in the occurrence and magnitude of flood events, or local residents may have observed progressive reductions in snowpack. Likewise, analysis may show that settlements have grown and demands for water have increased over the last fifty years or that development has encroached on the floodplain over the last thirty years.

3. Models or paleo-data to make projections about the future. Such models can provide estimates of future populations or about future climate states over different time horizons. Paleo-data can be used to set boundaries on future states based on past patterns. Model projections provide values for external drivers into the future at different time horizons but they assume that the past heavily informs future patterns. For example, downscaled global circulation models (GCMs) may provide projections of future temperature and precipitation patterns, or birth and death rates combined with projected improvements in water delivery efficiency may provide projections of water demand in the future.

   There are several online tools that provide analysts with projections about different values of external drivers. The following are sources (not comprehensive) of different products of future projections of hydrologic or climatic variables:

   - CGIAR Research Program on Climate Change, Agriculture and Food Security: http://ccafs-climate.org/
   - IRI/LDEO Climate Data Library: http://iridl.ldeo.columbia.edu/
   - Intergovernmental Panel on Climate Change: http://ipcc-data.org/
   - KNMI Climate Explorer: https://climexp.knmi.nl/start.cgi

Box2.3.

The Use and Development of Climate Change Scenarios

In some operational agencies in the Netherlands, Denmark, Germany, UK, Switzerland, and other countries, climate scenarios are available for planners, companies, researchers, and consultants (Van den Hurk et al. 2014). For example, in the Netherlands the use of official scenarios is well instituted as they are applied in planning studies throughout the country.

Climate scenarios are defined by IPCC (2013) as "a plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that have been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models." Although such models are often informed by GCM projections, they are not necessarily the same models or scenarios. Many scholars have pointed to the flaws and pitfalls in replicating patterns, variation, persistence, extremes and trends in climate (Hallegatte et al. 2012; Steinschneider and Brown 2013; Barsugli et al. 2012; Stainforth 2010; Van Haren et al. 2013; Min et al. 2013; Brown and Wilby 2012).

In constructing plausible scenarios for future climate, pragmatic solutions are chosen to enhance their credibility as has been done by the Royal Dutch Meteorological Institute (KNMI) (Van den Hurk et al. 2014). Combining global GCM simulations with high-resolution regional climate model simulations should provide a better representation of smaller scale processes (so-called dynamical downscaling) than GCMs alone. Creating multi- or single-model ensembles increases the plausibility range. Including as much observational information as possible in time and space by use of statistical downscaling techniques (Bakker and Bessembinder 2012) will also improve the representation of variability and extreme events in the scenarios. Resampling these observations can further enhance the plausibility range.

Building scenarios by gathering, valuing, and combining evidence on climate change resembles CRIDA's LOC analysis. Indeed, good scenarios can support the CRIDA analyst in Step 2. Relevant climate statistics from scenarios can be used directly to drive the stress test (for example, Kwadijk et al. 2010). The same information can be used to establish the LOC by comparing the identified vulnerability range with the credible range suggested by the climate scenarios.

The quality and character of climate scenarios may vary from country to country and region to region, so the analyst should be well informed on potential limitations. Indeed, in a large number of countries, there are no good regional climate scenarios available and the analyst will have to rely on globally available data.

- SERVIR (a joint program of NASA and USAID): http://servirglobal.net/
- U.S. Army Corps of Engineers' Responses to Climate Change: https://www.usace.army.mil/corpsclimate/
- US Global Change Research Program: http://globalchange.gov/
- University of East Anglia Climatic Research Unit: http://cru.uea.ac.uk/
- World Bank Climate Change Knowledge Portal: http://climateknowledgeportal.worldbank.org/
- World Climate Research Program: http://cmip-pcmdi.llnl.gov/

4. System sensitivity—sometimes called elasticity—to assess the plausibility for failure during a stress test. The water resources model should be used to explore how the system responds to small changes in an external stressor and to what range of values. For example, does the performance collapse completely or slightly shift when the stress is increased? The performance of a system that is more sensitive to external drivers has a higher likelihood to be affected by shifts in that driver's variability. For example, the size of a reservoir that provides water to an irrigation district is directly proportional to the reliability of service. In other words, a smaller reservoir for the same district is more sensitive to reduced or more variable rainfall and higher evapotranspiration rates. Vulnerability may also derive from governance and funding arrangements. For instance, a water utility that recovers operation costs from fees and has access to investment loans is less sensitive to shifts in customer demand than a water utility that cannot readily recuperate its operating costs.

As a result, the analyst must integrate theory, observations, system sensitivity, and projections to make a determination of the plausibility that an external driver will achieve a state that results in chronic unacceptable performance. Figure 2.6 provides three conceptual variations that illustrate this determination process. In variation A, climate projections suggest that the climate will become more stressful, while short-term trends suggest climate is in fact becoming more stressful. GCM models support these forecasts, while modeling suggests that the system's performance is very sensitive. For this situation, the analyst is likely to determine that there is high plausibility that the critical threshold will be surpassed in the planning horizon. In the variation B, all the climate data components are the same, but the system is less sensitive within the evidence domain, so it may be categorized as having low plausibility for surpassing a threshold. Variation C is analogous to A, but the range of GCM forecasts is far broader. This figure could suggest that there is plausibility that the performance threshold will be surpassed but because of the broad domain of the forecast information, the analyst faces a higher level of analytical uncertainty, a situation discussed in the following section.

The following are rules of thumb to implement an assessment of plausibility informed by theory, short-term trends analysis, system sensitivity, and, if judged useful, GCM forecasts:

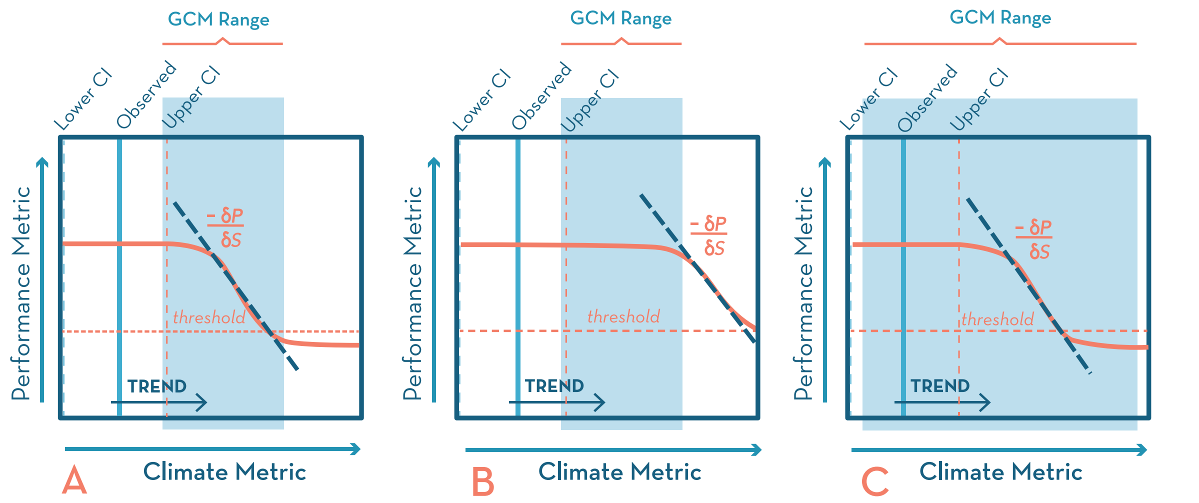


Figure 2.6. Examples of the climate and sensitivity components to assess the plausibility of surpassing a critical threshold.

1. Consider the operational lifespan of the project. A higher weight on a trends analysis should be used for short lifespans, while future projections are more relevant to longer lived projects. Data about climate oscillations will be relevant depending on the length of oscillation period.

2. Although climate projections are uncertain, they remain our best source of information about far-off events. The analyst should use *all* scenarios and consider the proportion of realizations that result in performance failure.

3. The plausibility of realizing a critical performance threshold is higher if the evidence that is relevant to lifespan and other considerations is consistent.

4. The plausibility of realizing a critical performance threshold is lower if the evidence that is relevant to lifespan and other considerations is inconsistent.

The analyst must take into account the impact or consequence of passing a critical threshold given the plausible realization of a stressor. Figure 2.4 illustrates how a determination of high versus low risk can be made. Outcomes that result in medium levels of risk should be discussed with stakeholders and decision makers because these can inform risk adverse or non risk adverse positions. For example, a high consequence and low plausibility analysis may result in pursuing a high risk strategy. Moreover, the risk from inadequate, non-robust, or inflexible designs matter, since the cost of retrofitting or rebuilding should also inform the discussion.

2.3.2. Analytical Uncertainty

Analytical uncertainty is the last part of the vulnerability assessment in CRIDA Step 2 and provides an indication of the risk of poor or ineffective analysis, which affects the selection of a strategic approach in Step 3 and how risk and uncertainty are communicated to stakeholders and decision makers. Analytical uncertainty depends on detecting ranges and directions and on the quality of underlying information. These criteria will also vary by the variable in question. For example, an analysis based on annual flood peaks has a higher requirement for good hydrological data and a sound probabilistic study than an analysis based on monthly streamflow.

Here, we present a list of guiding principles for the determination of high analytical uncertainty when assessing LOC. A determination of high analytical uncertainty is not a negative outcome or a result worthy of criticism. Ideally, a high analytical uncertainty guides the analyst towards flexible strategies, and an adaptation pathways map (discussed in Step 3) is developed to avoid limiting future options or making regretful or irreversible decisions now. However, flexibility is not always feasible.

The analyst can seek to try to reduce analytical uncertainty by obtaining more high-confidence data or by implementing stochastic scenario discovery procedures (e.g., Lempert et al. 2003). Ultimately, there are tradeoffs related to financial resources, scheduling concerns, and other factors. In general, big expensive projects that have very high social consequences might seek a scenario discovery approach if a flexibility strategy is not feasible or appropriate. In some cases, flexibility may still be inappropriate, as with limited governance capacity. In these cases, a robust strategy may be best.

Step 2

The following factors may suggest that the analyst faces high analytical uncertainty.

- The sources of evidence are inconsistent or have credible alternative interpretations.
- The range of projected or forecasted hydrologic variables (i.e., external drivers), such as annual rainfall from GCMs, leads to system performance ranging from critical to non-critical, containing both increasing and decreasing performance trends.
- The quality of modeled forecasts depends on many parameters, each with high levels of uncertainty. For instance, geographic factors such as large variations in elevation or low confidence in spatial resolution for a given variable may not promote reliable forecasts. Regions with rugged topography tend to increase analytical uncertainty in the downscaling of GCMs, especially in areas with limited data to characterize localized hydrological phenomena.
- The available data are not appropriate for the design requirements of a particular type of water resources analysis or design. For instance, the representative analysis of maximum annual peaks often requires a longer period of record than may be available (Diermanse et al. 2010, Haasnoot et al. 2015a). Likewise, the design of projects with a high potential for loss of life, severe damages, or excessive construction costs will require more data.

- Future upstream economic activities or landuse patterns are uncertain.
- The region of interest has a highly variable hydrology, such as arid areas in which the available stressor information is based on a few extremely rare events.
- There are highly diverse or conflicting interests that lead to disagreement about facts and key variables or fundamental differences in performance variables that are beyond the control of decision makers (Timmerman et al. 2017).

The determination of analytical uncertainty is used in the LOC matrix, but not all variables and parameters are essential to choosing a scenario for planning purposes. A sensitivity analysis can help address the relative importance of different sources of information and the effects of uncertainty on various options. Each part of Step 2 requires some degree of sensitivity analysis before proceeding.

Box 2.4.

Determining the Level of Concern in the Waas River

This case study is associated with Box 1.7. Here we assess the LOC around only two of the performance thresholds developed in collaboration with stakeholders and decision makers.

In a collaborative process, the Public Works Stormwater Division (PWSD) defines the current 75 percent return period peak flow event (1000 m^3/s) as a "damage threshold." An increase in the recurrence of this flow peak is unacceptable to effective performance of the PWSD. The local government defines a city recovery threshold as flood damages exceeding 2 billion €, which results from 15,000 m^3/s and that is expected once every 500 years. The occurrence of these flood damages at a higher frequency reduces the city's recovery capabilities. The consequences of surpassing these thresholds are high due to unacceptable political, social, and economic costs.

Assessment of Plausibility for Exceeding Thresholds

Multiple trend analyses were applied to the observed annual maximum discharge record. Linear regression analysis and the Mann-Whitney Wilcoxon test show that observed increases in maximum peak flows over the last one hundred years were not statistically significant. However, the Levene test of standard deviation indicates that the variance over the last fifty years has increased. Thus, in the near term there is little risk for violating a threshold. Figure 2.7 illustrates an increase in the exceedance probability between the first fifty years and second fifty years of data.

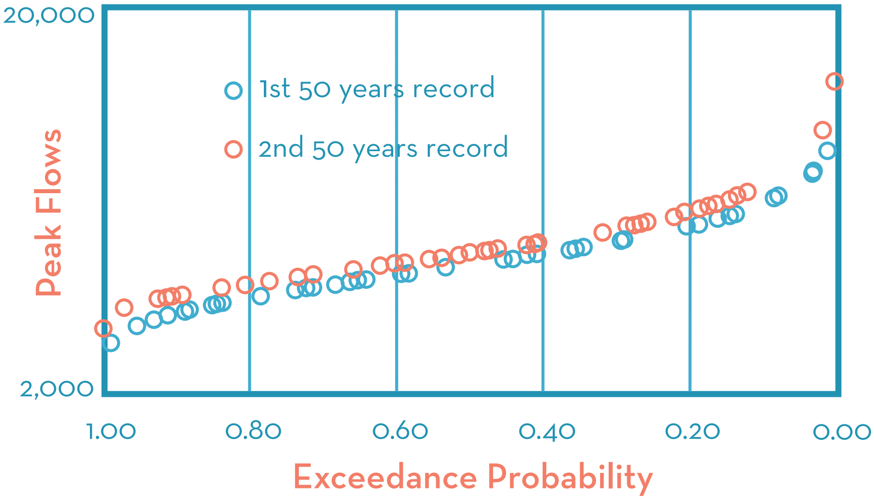


Figure 2.7. A log Pearson III fitting of one hundred years of maximum annual peak flows (in m^3/s) in the Waas River basin. A fitting was made for the first and second 50 years of observed data.

Expected damages from flood peaks are fairly sensitive to increases in the likelihood of those events. Namely, any change in flow likelihoods can be problematic, so the system is considered sensitive.

The theoretical understanding is credible. Upstream urbanization can plausibly see flow peaks that surpass thresholds from rainfall events of existing magnitude and frequency. These changes can be managed but a portion of the basin lies in a different country; transboundary governance issues apply.

Four climate scenarios developed by KNMI estimate futures that surpass critical thresholds (Table 2.1). G scenarios correspond with a moderate one-degree temperature increase while W corresponds with a warmer two-degree increase in temperature by 2050. L and H variations represent major changes in circulation. All scenarios show that that the damage threshold will be surpassed in the midterm (that is, by 2050). The recovery threshold is a greater concern for the long term (that is, by 2085).

KNMI Climate Scenarios

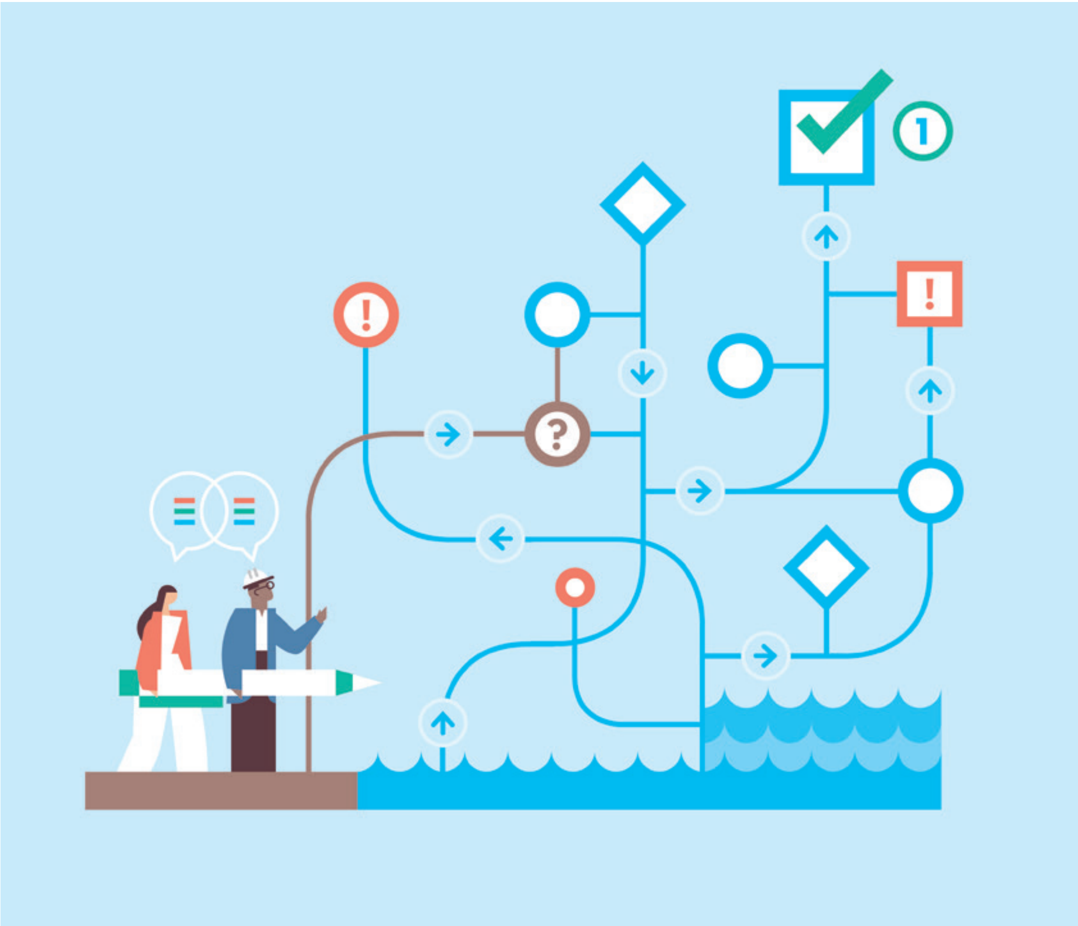
		GL	GH	WL	WH
Damage Thershold	Mid-term (2050)	X	X	X	X
	Long-Term (2085)	X	X	X	X
Recovery Thershold	Mid-term (2050)	X			X
	Long-Term (2085)		X	X	X

Table 2.1. Climate scenarios in the Waas River Basin. Scenarios that surpass thresholds are denoted by X

The analyst concludes that climate risks range from moderate to high. However, given the potential consequences of failure, a high-risk strategy is pursued. Moreover, given the limited number of climate projections used and their inherent uncertainty, the difficulty of assessing flood risk, and the contrasting stakeholder preferences (Box 2.1), the system has high analytical uncertainty. A framework that requires an initial robust action will be sought with significant flexibility to adjust as uncertainty recedes (Quadrant IV).

3

Formulating Alternative Plans



Step 3

IDENTIFYING A STRATEGIC APPROACH 85

FORMULATING DIVERSE COURSES OF ACTIONS 87

EVALUATING ROBUSTNESS USING THE STRESS TEST 91

DEVELOPING ADAPTATION PATHWAYS 96

In the previous two steps, the analyst explored decision making boundaries, tested risk tolerance, evaluated the LOC, and considered the data confidence and completeness. In Step 3, actions are formulated to reduce future risks and address the uncertainties identified in Step 2. All proposed actions are then stress tested to identify options that enable robust performance. In addition, this chapter will discuss how the analyst can develop flexible options and identify multi-sectoral opportunities and co-benefits to provide decision makers with a clear set of options.

Input from Step 2

- Stress test results showing the limits of performance of the existing system.
- An assessment of the plausibility that future stressors will lead to unacceptable performance.
- An assessment of analytical uncertainty and how it affects the choice of options
- A measure of LOC based on the assessment of plausibility and analytical uncertainty.

Output from Step 3

- Robust and flexible plans based on reducing relative risks and comparing alternative solution comprehensiveness, effectiveness, and stakeholder acceptability.

Once several broad actions and plans have been formulated, the analyst evaluates them in Step 4 to identify effective options for robustness and/or flexibility. Stakeholder involvement helps identify primary risks that must be reduced and residual risks that are broadly acceptable. The development of effective, efficient, acceptable, and complete plans is an iterative process through which decision makers identify potential cross-sectoral opportunities, such as using floodplains to reduce flood risks as well as recreational or ecosystem benefits.

3.1. IDENTIFYING A STRATEGIC APROACH

The analyst uses the expressed views of stakeholders and decision makers to identify alternative strategies for solving a particular set of problems. These strategies may include management options and institutional changes together with new or modified infrastructure investments. The LOC analysis in Step 2 provides insight for devising strategies that best match the assessed degree of risk, plausibility, and analytical uncertainty (Figure 3.1).

Typically, an analyst is concerned with the consequences of failure from under-designing a project or committing to excessive costs that cannot be easily justified. An institution's existing

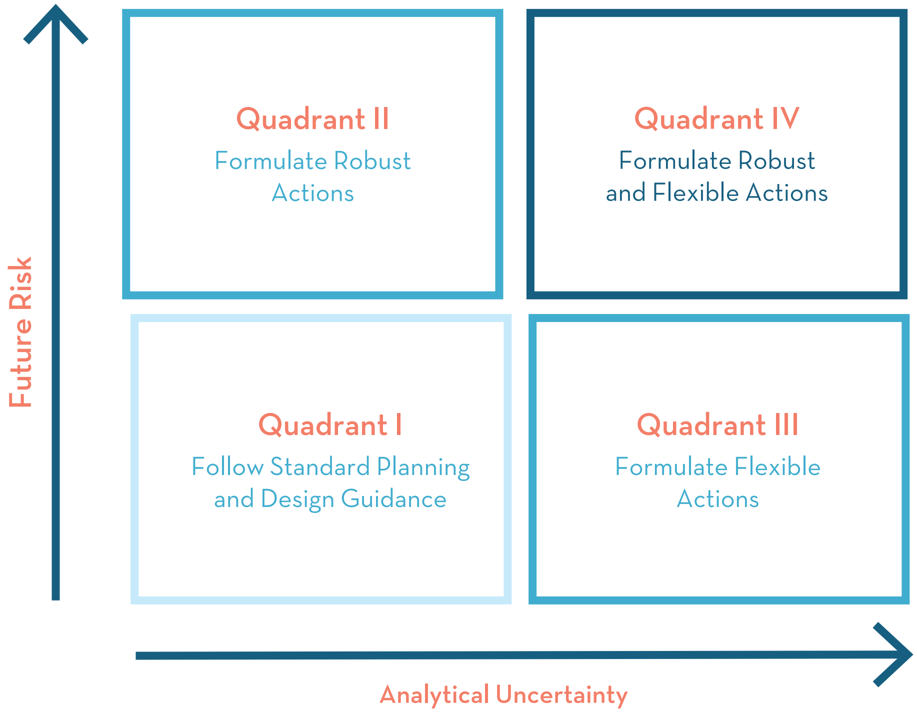


Figure 3.1. The decision matrix distinguishes levels of uncertainty relative to the severity of future risks.

practices 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 that may or may not address climate risks (Quadrant I, Figure 3.1). The stress test and identified LOC from Step 2 are used to determine whether these existing requirements are sufficient to address plausible stressors and whether moving beyond standard planning and design approaches is needed and justified.

Strategic recommendation for Quadrant I

When the analyst concludes from the LOC analysis that risk and uncertainty are fairly low, existing approaches, guidances, and regulations are judged to be adequate. In other words, conventional design practices should cover the anticipated range of plausible scenarios and analytical uncertainties. In most cases, the analyst will begin analysis with the assumption that Quadrant I is sufficient and that clear cause and justification must be found to deviate from standard planning towards more robust and/or flexible solutions. While many business-as-usual approaches do not include these insights, more institutions are beginning to provide guidance to address growing uncertainties. One recent example is U.S. Executive Order 13690, which provided a precautionary standard sufficient to address most future flood risks associated with an uncertain climate future (revoked in 2017, Executive Office of the President 2015).

Strategic Recommendation for Quadrant II

Robust actions to reduce future risks are recommended when analytical uncertainty is low and risks are well defined, high, and/or plausible. A more robust approach than presented in Quadrant I will likely require additional costs and effort. As a result, the following considerations may be relevant in assessing options:

- Consider a wide range of gray, hybrid, and green infrastructure to provide decision makers with a broad array of cost, effort, and management options and to reassure them that alternatives were considered.

- Given the added justification requirements, decision makers and stakeholders should collaborate with the analyst to identify a range of feasible and acceptable options. Co-developing solutions can also help generate buy-in for difficult tradeoffs.

- Formulate scalable or modular actions or options for those circumstances that require additional costs to build a level of robustness that might be difficult to justify, at least in initial project implementation. Considering increments or steps is a simplified approach to flexibility meant to offset later large expenses with initial or short term investments. For example, a pumping station may be designed to house ten diesel pumps, but only three pumps are initially installed. Likewise, consider the construction of a dike with a base to support a height of three meters but only constructed to a height of 2.5 meters. Allowing room for future growth is a simple adaptation pathway as discussed in Step 3.

Strategic Recommendation for Quadrant III

When there is high analytical uncertainty but little evidence of increasing risks in the future, decision makers face a difficult choice: 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 strategy (sometimes referred to as adaptive management) makes sense as long as the residual risks are understood and accepted by stakeholders. Delayed, sequenced, or incremental actions to expand the lifetime of existing infrastructure or enhance performance may be appropriate.

Quadrant III solutions are suggested when 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 2011). For example, developing new reservoir regulation operating rules is one means of altering institutional capacity, such as identifying different water allocation quotas for withdrawals and basin-scale management, as potential hydro-climatology shifts unfold.

Strategic Recommendation for Quadrant IV

When confronted by high analytical uncertainty and a high plausibility of significant climate change impacts, the analyst may need to emphasize a strategy that is both robust and flexible. The ability to increase robustness in the system and to provide flexibility to make enhancements as conditions evolve are difficult to achieve in a coherent manner, especially for large projects. Under this quadrant, the planner can consider a broader set of alternative actions than might be possible under others because the time horizon is often lengthened considerably. For instance, an adaptation pathways approach (Section 3.4) enables the analyst to consider solutions that may not be supported under current environmental, economic, or political conditions but might be appropriate in the future. In other words, current action may be required as well as the ability to monitor and make large adjustments as time passes. In general, the analyst should consider recommendations developed under both Quadrant II and Quadrant III.

3.2. FORMULATING DIVERSE COURSES OF ACTIONS

In addition to selecting the appropriate strategic direction (Figure 3.1), the analyst should formulate a wide range of actions that can reduce the likelihood of reaching critical performance thresholds. Alternative management scales, green infrastructure, non-structural and regulatory actions, as well as comparisons of single versus multipurpose solutions can foster a hypothesis-testing environment. While formulated actions need to be acceptable, effective, and complete (USACE 2000a), a broad and inclusive consideration of alternatives provides robust ideas and helps reassure stakeholders that the decision process was itself also robust and comprehensive.

Box 3.1.

Strategies to Formulate a Diverse Set of Robust Actions

Here, we suggest some strategies to develop robust plans that are robust to a wide variety of future scenarios, representing a compilation of suggestions from practice:

1. Rank groups of futures such as a set of climate change scenarios from less to more stressful and formulate increasingly robust actions to reduce the impact of each of these clusters. Evaluate the futures through an incremental analysis in Step 4.
2. Formulate actions that reduce risk across multiple steps or stages of a project, such as decreasing stressors at the source (e.g., reduce flow peaks), at the pathway (e.g., store and contain flood volume), and for receptor (e.g., zoning). The goal should be to formulate a diverse set of structural and non-structural portfolio of actions.
3. Develop robust actions ranked by efficacy and cost—that is, value. Expensive projects may be more efficient but funding might not be available for these interventions. Formulating both green and gray infrastructure projects is one mechanism to generate a range of solutions in this manner.
4. Consider completeness—that is, the other necessary actions or investments that are needed beyond the "core" solution. Encourage multiple interests to promote projects with co-benefits and thus diversify possible actions such as synergies in recreation, ecology, and flood risk reduction.
5. Formulate a wide set of options should be formulated that are increasingly more effective at reducing stressors.
6. Propose actions that must comply with regulations and/or be socially acceptable. Acceptability emphasizes satisfaction and stakeholder

buy-in. Collaboration is key given that plans that build robustness upon some baseline level of investment may incur additional costs such as higher taxes or reduced ecological quality. As a result, stakeholder and decision maker engagement is strategic. As part of this process, non-acceptable actions should also be formulated, especially if they are effective and efficient, both for comparison and because policies and preferences can change over time.

Any proposed set of alternatives should support the objectives identified in Step 1 and address the vulnerabilities and risks identified in Step 2. Engagement with stakeholders and familiarity with local geography, regional culture, regulations, and values are essential for developing robustness and flexibility in the alternatives. The involvement of experts from multiple disciplines is particularly useful at this stage, but continued collaboration with stakeholders remains essential to ensure that a clear, shared vision is maintained. The planning team may consider collaborating with stakeholders and decision makers on the following topics:

- Verify that the problem definition from Step 1, including the geographic or institutional scope for intervention, remains appropriate. In some cases, broadening the scope can lead to more effective actions.

- Develop diverse options in response to the problem definition that explicitly improve performance, increase resilience, and expand robustness.

    a. The collaborative process in Steps 1 and 2 can encourage stakeholders to express their preferences and move beyond a business-as-usual approach to change operations, shift to ecosystem solutions, alter demand, or otherwise innovate.

    b. Stakeholders should feel represented by the range of actions identified (Bourget 2011).

    c. Workshops that bring together stakeholders, designers, and multidisciplinary experts are useful to develop a comprehensive portfolio of potential actions (Prominski et al. 2012, Girling et al. 2006, Sanoff 1999).

- Encourage "complete" solutions when working with stakeholders and decision makers. In many cases, no single action is complete in the sense that it addresses all planning objectives, but two or more related options may possess synergies that address more objectives. For instance, combining or bundling solutions can provide a more robust approach even if these actions need to be sequenced over time rather than implemented simultaneously. The combination of non-structural and structural measures, or gray or green solutions are common complements.

- Identify cross-sectoral opportunities to satisfy multiple and diverse stakeholders and enhance robustness. Increasing reservoir volumes by including environmental flows, recreation, and sediment management while preserving the robust system performance is one example of generating broad support by finding co-benefits.

Box 3.2.

Formulating Robust Actions for the Iolanda Water Treatment Plant

Building on the case study introduced in Box 1.6, the LOC suggested a high risk that water supply shortfalls will increase over time at the same time that poor data quality suggests a combined flexible and robust strategy.

However, decision makers and plant operators acknowledge institutional weaknesses that would hinder an effective monitoring program, which would be necessary to implement an adaptation pathways plan. Moreover, financial and political considerations constrain significant investments in robustness. As a result, specific robust actions will be formulated that can also be scaled.

The stress test identified that the availability of hydropower to operate the water treatment plant and not the availability of water for treatment was the principal stressor to system performance with more climate change. As a result, actions were formulated to enhance energy availability:

1. The addition of generator capacity in excess of the current 125 kW need was identified as part of the baseline level of investment. This action can provide robustness and can be scaled.

2. The addition or improvement of treated water storage can also provide robustness but more storage is a costly action and not easily scalable.

3. Building a dedicated transmission line from the Kafue Gorge Dam Hydropower Plant to the Iolanda Water Treatment Plant can provide robustness but the action is not easily scalable and institutional coordination is poor.

4. Modifying reservoir operations is difficult to implement under current institutional arrangements.

5. Reducing demand through conservation and distribution efficiency is not a politically acceptable action since customers are already facing a failed utility and lack of water. Upgrading the electrical distribution system would also be institutionally challenging.

3.3. EVALUATING ROBUSTNESS USING THE STRESS TEST

The same stress test that was used to determine the future risks to the existing system is used now to test how these risks can be reduced by alternative system configurations. The stress test quantifies how performance reliability or resilience is improved over the status quo if risk reducing measures were to be implemented. There are three general types of impacts to performance (Figure 3.2).

- Enhanced performance, such as designing a reservoir sized for a higher demand. If funding is available and there are no detrimental impacts to other benefits, performance enhancements are preferred actions since stakeholders receive benefits regardless of the future.

- Increased failure resistance. Raising dikes, for instance, reduces flood risk failure in some cases.

- Reduced performance sensitivity or elasticity. Comprehensive control and monitoring systems, better demand management, more effective allocation adjustments, and broader operational scenarios are all examples of mechanisms to reduce sensitivity.

To perform the evaluation stress test, the analyst should first build the proposed actions into the systems models as described in Step 1. Changes to river profiles, dike heights, reservoir volumes, operation rules, and damage calculations allow the analyst to test system limits and model performance.

Second, the analyst should conduct a series of sensitivity analyses across a range of plausible futures to eliminate unacceptable actions and to determine how key variables affect the performance. An initial sensitivity analysis need not be a full-scale stress test and might only employ a few calculations (such as a single alternate climate state) to distinguish between effective and ineffective actions. Moreover, showing the results of a sensi-

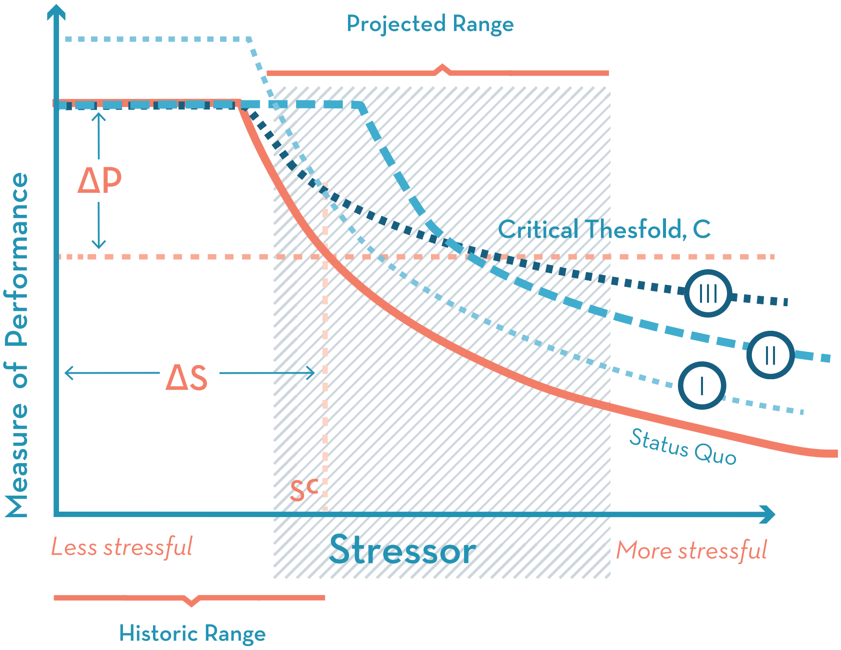


Figure 3.2. Evaluating plans using stress test outputs. As an example, a stressor might be the severity of rainfall shortage, measured as the mean monthly rainfall shortfall over a drought period or dry season in a catchment that drains into a reservoir. The measure of performance might be expected tons of marketable alfalfa harvested. Plan I might be increasing the size of the reservoir. Plan II might be improving the efficiency of water delivery. Plan III might be promoting a more drought resistant variety of alfalfa.

tivity analysis can spark powerful discussions with stakeholders. The format of the system models described in Step 2 is useful for educating stakeholders on the implications of their choices as it allows the analyst to effectively illustrate the impact of each action or combination of actions. In many cases, stakeholders will suggest changes to performance indicators, critical thresholds, or the range of potential acceptable solutions during these discussions.

Box 3.3.

Evaluating Waas Managemen Robustness via a Stress Test

The Waas Valley planners (see Box 2.4) have several proposed alternatives to lower flood risk including providing "room for the river" (i.e., additional floodplain space), using dikes, elevating critical infrastructure, and altering upstream operations. These proposals can be combined and developed to reach different levels of implementation. The stress test can assess improvements in performance by measure or combination of measures.

Figure 3.3 below illustrates three combinations of measures stress tested to evaluate damage reductions with respect to a no-action plan (blue dotted line).

The horizontal dashed line represents a critical threshold to be avoided. The *x* axis represents discharges from flood events, an external driver, an external driver, which are occurring with increasing frequency. The stress test provides an insight into how the system responds to the various proposed actions with respect to the key performance metric of damage.

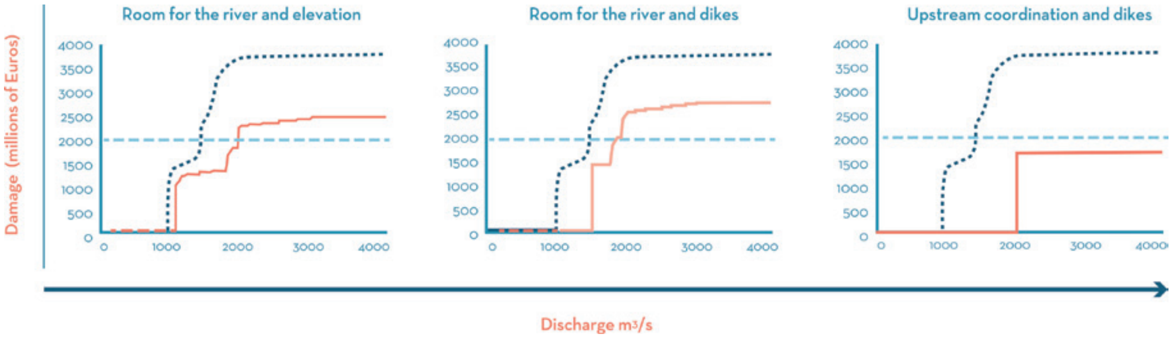


Figure 3.3. Damage curves versus discharge curves. The three strategies described here include (from left to right) "room for the river" in combination with raising the level of infrastructure, "room for the river" in combination with dikes, and upstream coordinated operations in combination with dikes. The blue dotted line represents a no-action plan.

3.3.1. Stress Tests for Multiple Objectives

Bottom-up vulnerability assessments can identify both satisfactory and unacceptable domains of performance for multiple criteria to highlight a more comprehensive analysis of robustness. The application of multiple criteria is especially important for environmental objectives, which are often framed in terms of maximizing socio-economic benefits while minimizing ecological impacts, which can lead to an asymmetry in evaluation and the need to choose between several alternatives.

The overarching set of planning objectives guide tradeoffs between options. Ideally, planning objectives should encompass notions of environmental sustainability and economic parameters. Performance criteria are quantitative representations of attainment of each objective.

In Step 1, the analyst selected a number of objectives. Not all objectives have the same level of importance, and the sensitivity of each objective may also be quite different. Such variations make multi-objective evaluation and tradeoffs complex. In practice, the ana-

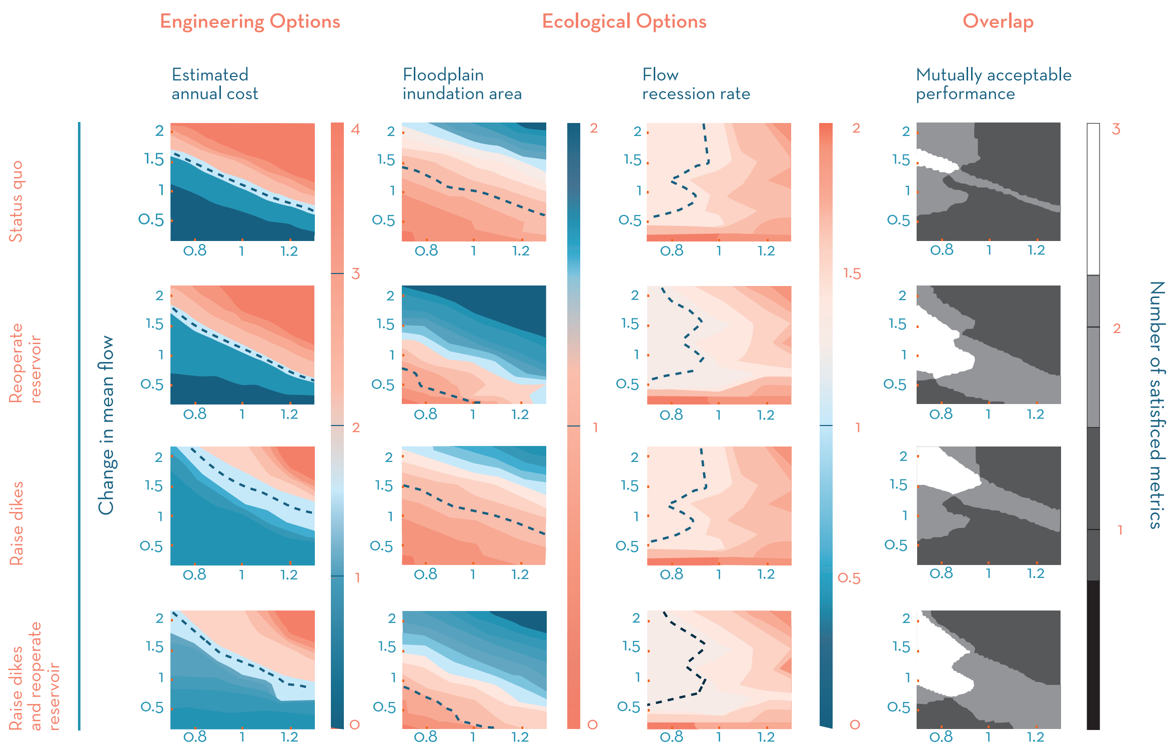


Figure 3.4. Using a stress test within the EEDS approach to map multiple objectives by tracking both engineering options (estimated annual costs) and ecological options (floodplain inundation area, flow recession rate). Adapted from Poff and colleagues (2016).

lyst should limit the number of primary performance metrics and quantitative analyses. Adding more qualitative steps or additional criteria analyses can occur later if necessary.

Poff and colleagues (2016) present a simple strategy to evaluate multi-objective metrics using a stress test. Their approach was developed to integrate ecological and engineering objectives during planning for flood risk reduction (Figure 3.4). Called Eco-Engineering Decision Scaling (EEDS), the approach is applicable beyond ecological applications.

Box 3.4

Finding Ecological and Engineering Win-Wins

A stress test was applied to evaluate performance of both flood risk reduction and ecologically suitable floodplain habitat for emerging climates in the Iowa–Cedar River watershed. The site was the Iowa Cedar River downstream of the Coralville Reservoir in the Iowa, U.S. Several proposals were under consideration and Figure 3.5 shows results from the stress tests conducted for the proposals to raise the dike height versus re-operating the infrastructure. The figures illustrate the development of win-win outcomes. Raising the dike builds robustness to a more extreme future, but a reservoir reoperation can be suitable for a wait-and-see strategy.

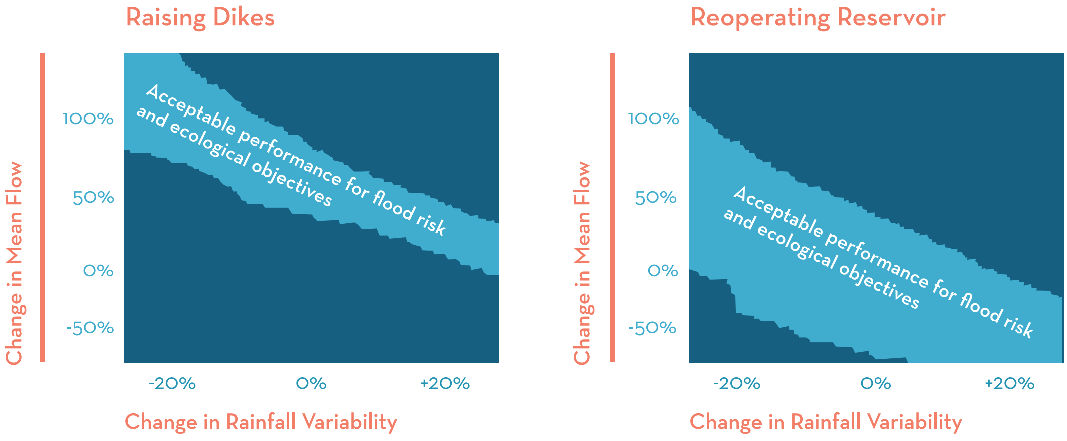


Figure 3.5. A two-dimensional stress test response surface for raising dike height and reoperating Coralville Reservoir for changing means in river flow and rainfall variability. Adapted from Poff and colleagues (2016).

Step 3

3.4. DEVELOPING ADAPTATION PATHWAYS

Developing long-term strategies requires that a set of alternative adaptation pathways be designed to address a span of decisions spaced over long time periods, such as decades. Adaptation pathways are an essential component of the CRIDA approach as the methodology explicitly acknowledges that some decisions concerning so-called known unknowns, such as future climate or socioeconomic uncertainties, can be addressed through a process of targeted monitoring and incremental decision making. Adaptation pathways defines processes to obtain better information and monitor anticipated threats to respond with greater certainty. Sometimes near-term "no regrets" options can be implemented and meet existing decision rules to become the building blocks for future pathways.

Decision protocols and decision rules change over time, and adjustments are constantly being made at all levels of governance that influence future decision making processes (Figure 3.6). In the United States, water resources evaluation principles and decision rules have evolved from the *Principles and Standards* (U.S. Water Resources Council 1973) to

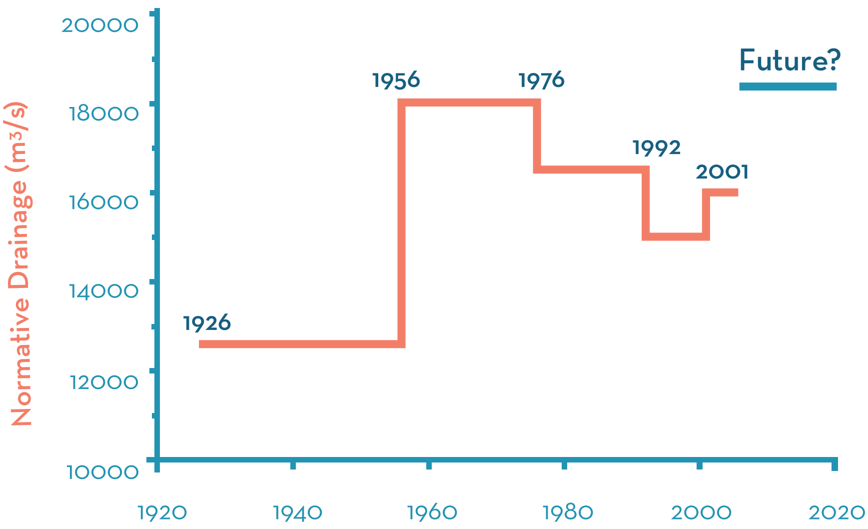


Figure 3.6. Change in policy objectives over time: Evolution of the design discharge of the Rhine River in the Netherlands. Adapted from Kwadijk and colleagues (2001).

the *Principles and Guidelines* (U.S. Water Resources Council 1983) to the Updated Principles, Requirements and Guidelines (CEQ 2013). Compared side by side, each edition results in the selection of a different option as a result of differences in decision rules even though the underlying analytical approaches are largely comparable.

Similarly, the European Union's Water Framework Directive (WFD), first implemented in 2000, has undergone continuous adjustments and modifications for floods, droughts, and water quality issues. Future decision rules and planning processes will adjust accordingly to meet future uncertainties and complexities in decision making. Hence, adaptation pathways provide a process or logic to effectively incorporate new perspectives into existing water resources guidance.

Action alternatives can be developed into distinct adaptation pathways, representing strategies that connect short-term actions with mid- and long-term actions (Haasnoot et

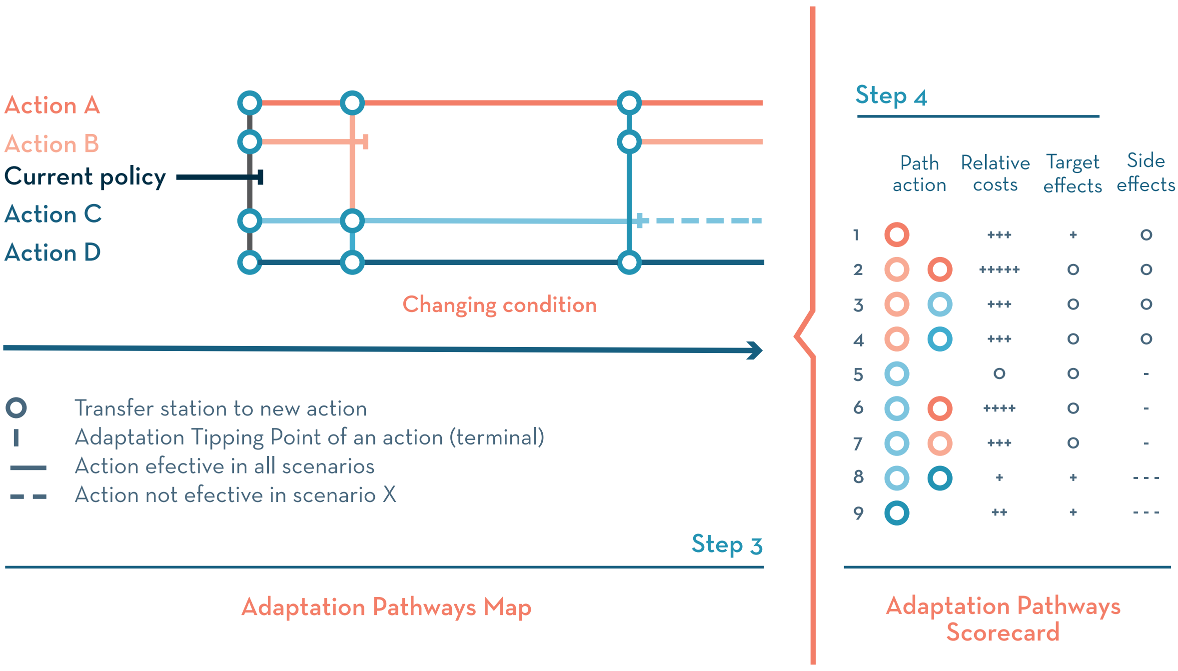


Figure 3.7. Adaptation pathways map and scorecard. Note that the map is the end result of CRIDA Step 3, while the scorecard is an evaluation component added in Step 4. Adapted from Haasnoot and colleagues (2013).

al. 2012). Organizing the timing and sequence of strategies is particularly useful when a more flexible approach is recommended as is shown in Quadrants III and IV in Figure 3.1. As a tool, adaptation pathways emphasize the importance of keeping future options available by avoiding regretful and irreversible decisions. Pathways make decisions transparent and explicit and illuminate decision points and options. Moreover, the pathways methodology specifies future actions that can be taken if initial efforts prove insufficient (Haasnoot et al. 2013).

There is a strong connection between the development of a set of pathways (Step 3) and their evaluation (Step 4). In practice, adaptation pathways are part of the same iterative process as considering alternatives, since evaluation leads to the selection of actions. For clarity, an adaptation pathways map (the focus of Step 3) and its scorecard (the focus of the next chapter, Step 4) are illustrated in Figure 3.7.

3.4.1. Developing an Adaptation Pathways Map

There are four stages in the development of an adaptation pathways map, which are discussed in the remainder of this section.

Stage 1: Define Actions and a Shelf-Life Indicator and Rank by Cost

The first stage in developing adaptation pathways is to define the primary shelf-life indicator (Box 3.5) and a set of different actions. This shelf-life indicator is the performance metric used in the adaptation pathways and, in principle, is the same metric used in Step 2. In cases involving multiple objectives, shelf-life is best determined by using the most constraining indicator.

The *x* axis of the adaptation pathways map normally illustrates the driver threatening the system, resulting in the need for adaptation. Two elements need to be specified in order to define the *x* axis: (1) a main system driver, and (2) the range of applicable values for the driver. Ideally, the stress test in Step 2 revealed a single dominant driver in the system, with the range of the driver informed by the LOC analysis in Step 2. However, if the stress test revealed multiple drivers that are difficult to order, the analyst will need to develop multiple adaptation pathway maps to reflect changes in the each driver. The main driver will remain on the *x* axis of each pathway map as this will most likely be the driver that requires monitoring in the future to identify trigger points. However, additional adaptation pathways maps will reflect selected change scenarios for the additional drivers. Between one and three scenarios are recommended, but the analyst should err on the side of fewer given the added uncertainty of a second driver.

Once the *x* axis has been established, previously selected actions are then grouped into recognizable categories along the *y* axis as shown in Figure 3.8. For example, flood and damage risk reduction actions may be initial categories if high water levels are most important, or in the case of droughts, water supply and water demand management actions. Additional categories could include green or hybrid solutions versus gray actions or downstream versus upstream actions, depending on how the main options can be presented best given the particular decision context.

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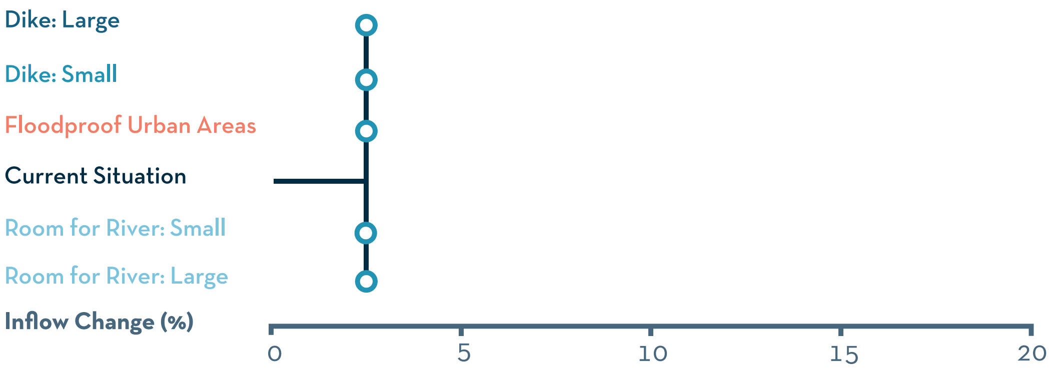

Figure 3.8. Adaptation Pathways, Stage 1: Define actions and the shelf-life indicator.

Box 3.5.

Why Do Pathways Have a "Shelf-Life"?

Bottom-up vulnerability assessment procedures such as CRIDA are based on the principle that the future is so uncertain that planners should first determine levels of unacceptable performance, i.e., critical performance thresholds, and the stressors that lead to them. These stressors have an uncertain temporal dimension: climate models forecast future stress scenarios that would manifest themselves at an unknown time in the future. The longevity of satisfactory project performance along a pathway is the project "shelf-life," an adaptation pathways term introduced by Haasnoot and colleagues (2012) coupled with a performance threshold. Like food that has become spoiled, most pathways have an expiration date when they will no longer function effectively.

Since forecasts of the start of a climate-related stressor are normally deeply uncertain, the shelf-life of a pathway's performance is also deeply uncertain. Using time as the x axis for a pathways map may promote a sense of false confidence, though decision makers often request (if not demand) insight into when specific impacts may occur. Most forecast models such as GCMs have general time elements as an abstract reference, such as year 2100. Assigning these temporal elements provides a limited framework to inform levels of urgency and priority and to establish a point of reference to other projects on different pathways, such as which project would likely fail first. However, the analyst (and decision makers) should remember that global change is not smoothly linear. In most cases, conditions will gradually increase in stress. A well-structured monitoring program can identify fundamental shifts in stressor values to help track and pace the rate of change.

Stage 2: Determine and Assign "Adaptation Tipping Points"

The term "tipping point" has several definitions in reference to climate change. In resilience theory, a tipping point is a stage when a driver shifts a system into an alternative stable state, such as a drop in precipitation that alters a forest into a grassland. In adaptation pathways, the emphasis is on decision making. Thus, an adaptation tipping point (ATP) refers to the period when an implemented decision must be reconsidered and potentially changed to track another pathway.

Defining tipping points confronts the same uncertainties associated with stress tests elaborated previously. However, the timeframe and uncertainties in scenarios and system performance often can only be addressed qualitatively through professional judgments

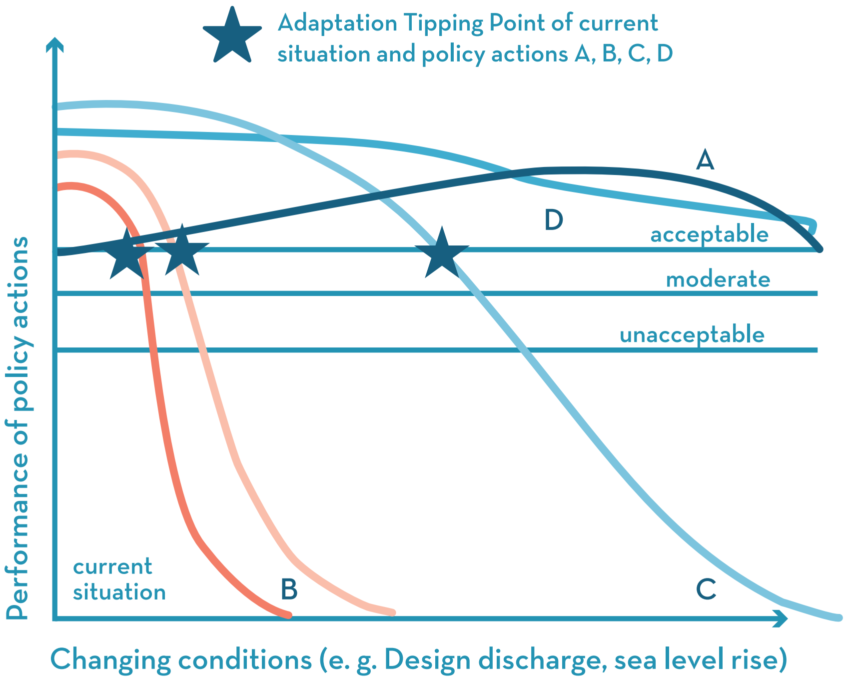

Figure 3.9. Adaptation Pathways, Stage 2: Determine Adaptation Tipping Points (ATPs). ATPs are determined for one system relative to policy actions A, B, C, and D under changing driver states. If an action performs below the acceptable threshold value, the action has reached its ATP. Adapted from Haasnoot and colleagues (2012).

or through modeling and analyzing multiple scenarios. Adaptation pathways inherently lay out plausible future conditions with reasonable tipping points that require decisions concerning alternative courses of action. Displaying these alternative pathways can help decision makers understand how their decisions may have consequences that favor or preclude certain future pathways.

The analyst should now have basic understanding of system climate vulnerability from the initial stress test. The next step is to identify the ATP for each stakeholder-approved action or measure. An ATP marks the transition of an action from acceptable to unacceptable performance based on the defined planning objectives. This point can be defined in terms of the physical driver (shelf-life condition) or time (shelf-life date). For example, Figure 3.9 illustrates the acceptability of system performance against a changing driver. The point at which performance falls below the acceptable threshold value is the ATP. Because an ATP is defined in terms of the driver, it is considered a shelf-life condition of the strategy. If the analyst has high confidence in the timing or pace in the driver, the analyst can also define the shelf-life date. The identification of the ATP, whether as a shelf-life condition or shelf-life date, is the key building block for creating an adaptation pathway map.

As explained in Section 3.3, the system model evaluates the performance of the system with each proposed action implemented and the new system is then stressed over a range of plausible future conditions for each driver. The result is a new response curve or surface

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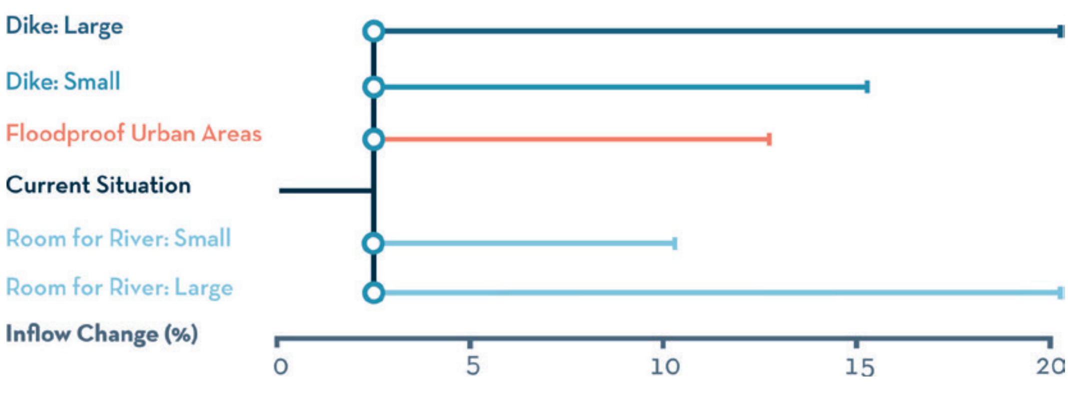

Figure 3.10. Adaptation Pathways, Stage 2: Assign ATPs to adaptation pathways map for each proposed action.

that should reflect a more robust system to the plausible future conditions. If the action is effective, then that action will delay the point at which the system no longer performs acceptably. Figure 3.9 provides a simple illustration of identifying ATPs for four policy actions. The current situation as well as proposed actions A through D are illustrated by the gray, red, yellow, green, and blue lines, respectively. The condition under which the performance of each system surpasses the acceptable threshold, identified with a star, is the ATP for each system. Note that in this example, actions A and D do not surpass the performance threshold and therefore do not have ATPs under the current range of plausible conditions.

Once ATPs are established, the analyst can present the information on a pathways chart (Figure 3.10). At this point, actions with delayed ATPs are shown on the top or bottom of the map, while actions with closer or more immediate ATPs are shown close to the current plan.

Stage 3: Identify Pathway Transfer Points

A pathways map can be drawn manually or using the pathway generator tool (see Box 3.6) based on expert judgment and/or model results. The preparation of an initial pathways map requires a team able to consider two different aspects of designing and implementing possible actions:

- Identify and draw any logical sequences of actions, starting with actions with early shelf-life dates and moving towards actions that would further extend the shelf-life date. Thus, a transfer point to the new action is activated once the previous action no longer meets threshold values of acceptable performance. All possible sequences are explored across the full suite of defined actions.

- The analyst can then also consider combinations of actions and present them as new actions with extended shelf-life dates. Combinations mimic investing in a package of actions at the same time. However, these actions would be implemented separately, as increased robustness is needed over time. Note that in some cases new actions would require new modeling analyses to estimate the added benefit for combining actions.

Stage 3 in Figure 3.11 illustrates how the adaptation pathways charts are updated with the transfer points for sequences and combinations of actions.

Stage 4: Refine Adaptation Pathways Map

The final stage is to refine the adaptation pathways to simplify the decision making process.First, remove unlikely or impractical transfer points. For example, the implementation of some actions may exclude others and some sequences of actions may be nonsensical, as when the lead, preparation, or financing time necessary in advance are too long, when there are large transfer costs involved, or when options are literally blocked by the preceding action in terms of location, budget, or other variables. Eliminating pathways

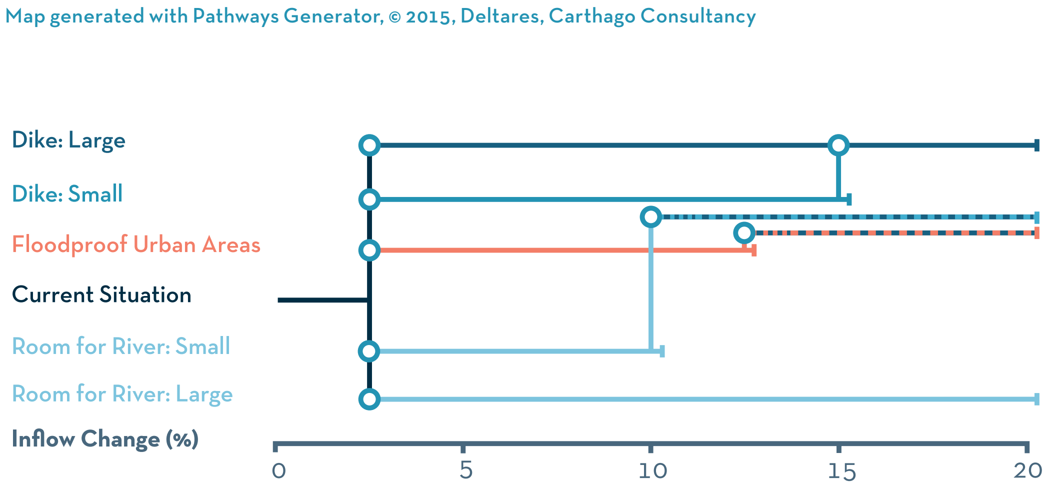

Figure 3.11. Adaptation Pathways, Stage 3: Identify pathway transfer points. Transfer points are shown by small circles, indicating points when shifts to other pathways should be considered.

Step 3

Box 3.6.

Making Adaptation Pathway Maps Using the Pathway Generator Tool

The analyst can use Deltares' Adaptation Pathways Generator software to develop the figures illustrated in this guidance. The analyst enters each action considered, the corresponding ATP, and all possible combinations defined in the development of the pathways into the program. The program then outputs a schematic diagram of the pathways, with the option of adding time in addition to the hydro-meteorological or socio-economic drivers to the *x* axis. The visualization of the pathways through the Adaptation Pathways Generator is an effective means to communicate the various adaptation plans available to stakeholders.

Everyone can download the software and find further guidance at https://publicwiki.deltares.nl/display/AP/Pathways+Generator.

that contain unlikely sequences simplifies the number of pathways for decision makers to evaluate.

Second, consider timing and urgency. At a minimum, timing is a necessary factor in most economic evaluations, such as for determining cost-benefit ratios and net present value (NPV), which will be discussed in Step 4. Knowing how much time is available to ensure financial, institutional, and technical capacity to implement a measure increases the likelihood of successful execution and can inform how flexible a pathway or group of pathways is.

However, depending on the driver, the level of uncertainty attached to timing can vary considerably. For example, anthropogenic drivers such as population growth and urbanization are relatively better understood (and may even be controllable with policies such as zoning) than climate variables. If these uncertainties are not well communicated, timing may provide a sense of false confidence to the stakeholders and decision makers.

However, if more detail on timing is still preferred, the analyst should use the best available information to guide scenario development while emphasizing the limitations of using timed scenarios to the decision maker. In some cases, timing can identify pathways that out- or underperform across scenarios, which can be referred to as "clear winners" or "clear losers," respectively.

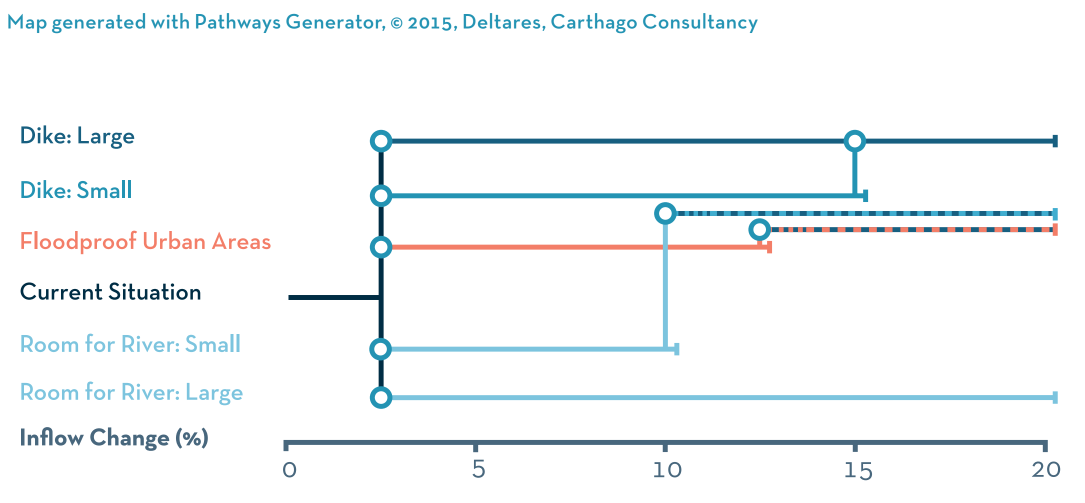

Figure 3.12. Adaptation Pathways, Stage 4: Refine adaptation pathways map. The process of refining pathways simplifies and clarifies the maps for decision makers and stakeholders; compare with Figure 3.11.

Box 3.7.

Using Adaptation Pathways for Indonesia's Coastal Development

Indonesia's master plan for National Capital Integrated Coastal Development (NCICD) required the consideration of multiple drivers and timing in the development of a flexible strategy using adaptation pathways (Figure 3.13). In this example, the analyst addressed coastal flood risk and considered two system drivers: sea-level rise and subsidence caused by massive groundwater pumping for industry, offices, hotels, and households. The analyst and decision makers agreed that both drivers have fairly low uncertainty: sea-level rise is a well-understood climate change variable, while groundwater depletion can be controlled by water supply policies. Both drivers increase exposure and vulnerability to coastal flooding. Therefore, the combined effect of both drivers was placed on the *x* axis of the adaptation pathways relative to sea-level rise and a conservative timing scenario was superimposed on the *x* axis. For subsidence, two different scenarios were considered: with and without continuation of groundwater pumping. Figure 3.13 illustrates the necessary pathways for the relative sea-level rise scenario under the scenario that pumping continues. In this example, under effective water supply policies that can be enforced, each plan selection has such an extended shelf-life condition that no transfer points are necessary before 2021. In effect, a plan can be identified that is robust without a need for flexibility.

The analyst is now able to evaluate a pathways strategy and a single robust action under all scenarios and inform the decision maker concerning the tradeoffs.

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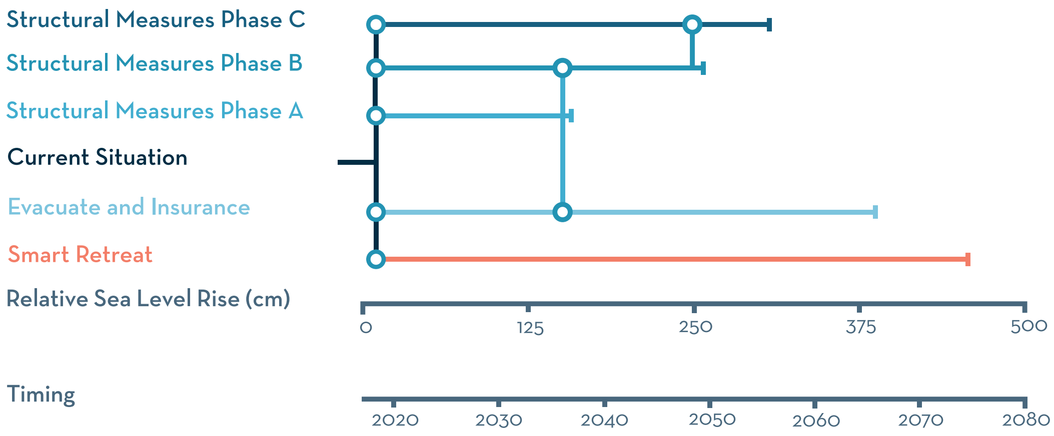


Figure 3.13. Adaptation pathways for relative sea-level rise scenario with continued groundwater pumping.

Step 3

4

Comparing and Recommending Plans

COMPLEMENTING STANDARD COMPARISON AND SELECTION PROCEDURES 109

INCREMENTALLY EVALUATE TO SELECT ROBUST AND/OR FLEXIBLE PLANS 113

COMPARING AND RECOMMENDING ADAPTATION PATHWAYS 121

Step 4

The role of planners for all types of projects is to provide decision makers with a handful of recommendations. The ultimate selection between those options is often based on non-technical criteria by decision makers, such as political interests. The analyst's responsibility is to provide a wide variety of options that reflect stakeholder interests as well as satisfy other needs, such as legal, social, and environmental requirements. In practice, the process is typically iterative and driven by decision makers who approve planning, funding, and financing. This chapter provides guidance to support decision makers when comparing and selecting a plan based on incremental benefits and costs.

Thus, in Step 4 competing plans are compared and a final selection for implementation is made. How does the analyst make a confident recommendation? Typical plan comparison and selection methods are applied within the context of an uncertain future scenario, but even if only one plan is formulated, it should be compared with a no-action alternative. When institutional preferred or pre-existing solutions already exist, these should also be compared under each scenario. However, most metrics for comparing and selecting plans do not consider greater levels of uncertainty, so they will likely favor less resilient choices. Here, the analyst will consider metrics that can help avoid biased comparisons and result in "brittle" or inflexible solutions.

This chapter provides guidance on the implementation of decision rules under the CRIDA process and is meant to help justify the selected plan or a set of plans to the decision maker that exhibit qualities such as robustness, flexibility, or both as formulated in Step 3. A method of incremental analysis is introduced that produces an unbiased comparison of plans across uncertain future scenarios.

Input from Step 3

- Robust and flexible plans based on risk reduction, comprehensiveness and completeness, effectiveness in meeting planning objectives, and stakeholder acceptability

Outputs from Step 4

- Comparison of plans against a baseline measure of performance
- Comparison of plans across different future scenarios
- Recommended plan(s) to the decision maker

4.1. COMPLEMENTING STANDARD COMPARISON AND SELECTION PROCEDURES

Alternative plans are compared as a normal part of any planning process (USACE 2000a, Eijgenraam et al. 2000). The most common plan evaluation approaches focus on economic valuation metrics, such as the application of discounted cash flow (DCF) methods that consider net benefits or net present values (NPV); the "best" plan in a comparison set commonly maximizes these values. Such approaches generally perform well within the context of a well known or assumed planning scenario.

The primary weakness of standard plan evaluation approaches is that they produce biased comparisons favoring brittle or inflexible plans. In other words, the riskiness of lower cost solutions is not properly accounted, such as when future conditions are not described probabilistically or forecasted accurately. Plans that are robust or flexible perform "better" (e.g., generate a higher return) over a broader range of potential future uncertain scenarios and are therefore less risky—despite the higher costs that they often carry.

CRIDA compares plans for robustness in contrast to some business-as-usual level of investment. The costs and benefits of robustness to uncertainty should be compared to the expected or baseline level of investment.

In CRIDA, more robust and/or flexible plans are developed in increments to demonstrate performance against incrementally more stressful futures. Plan comparison and selection procedures are then applied within the context of each plausible future scenario as informed by the LOC analysis conducted in Step 2 to produce an array of candidate plans, each successive candidate plan then representing a preferred action. The decision matrix (Figure 4.1) supports the analyst in choosing an approach for comparison based on the LOC analysis as explained in Step 2.

4.1.1. Quadrant I Comparison Procedures

Projects in Quadrant I exhibit minimal future risks and low analytical uncertainty. Standard evaluation procedures for justifying plans are suitable. For these plans, the assumption of stationarity or the existing understanding of uncertainty based on the past remains valid.

A decision maker may nonetheless seek alternate recommendations that are more robust—perhaps there is a very low tolerance for risk, for instance. The analyst may proceed to Quadrant III or make slight modifications to DCF methods as described in Box 4.1.

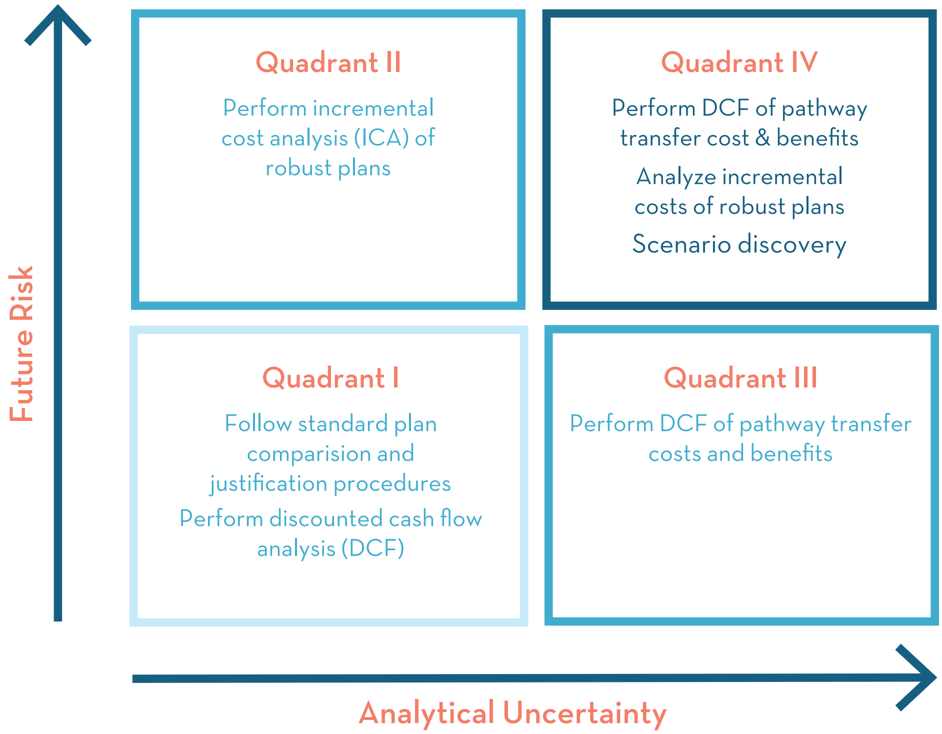


Figure 4.1. The decision matrix for comparing and justifying plans based on uncertainties in impacts and analysis.

4.1.2. Quadrant II Comparison Procedures

Projects in Quadrant II exhibit elevated risk to uncertain futures with a low level of analytical uncertainty. Plan comparison under this quadrant focuses on evaluating the additional robustness of plans above a baseline level of investment (as in Quadrant I) that is acceptable to decision makers using incremental cost analysis or ICA (USACE 1994). Different plan increments correspond to different unknown futures with a plausibility that is evaluated using the techniques in Section 2.3.1. Each increment may contain bundles of programs, activities, or projects (Step 3). For these plans, an assumption of stationarity is not valid.

4.1.3. Quadrant III Comparison Procedures

Projects in Quadrant III give cause for concern because of a high level of analytical uncertainty, but exhibit low risk from that uncertainty. Justifying a complementary comparison procedure to standard requirements may be difficult because of the low risk, but given the elevated level of analytical uncertainty, the planning team should develop adaptation pathways (Section 3.4) to ensure that plan recommendations do not constrain future flexibility and provide justification for monitoring of tipping points. Section 4.3 discusses procedures to compare and select the best pathways. DCF methods can be used to evaluate a baseline level of investment. Box 4.1 provides recommendations to enhance standard DCF methods in consideration of robustness. However, given the analytical uncertainty, the analyst should present preferred pathways to the decision maker.

Given the low evidence of risk in Quadrant III, the analyst will likely have limited incentives to compare across more than one future and will likely choose a future scenario that is most relevant or threatening. If more than one uncertain future scenario needs to be considered, ICA may be a useful metric.

4.1.4. Quadrant IV Comparison Procedures

Projects in Quadrant IV exhibit high analytical uncertainty and high impact uncertainty risks; this is a quadrant of highest concern. Plans should be recommended that are both robust and flexible. In Quadrant IV, the analyst should implement ICA to select an appropriate increment of robustness and also to create a pathways map.

If the number of uncertain futures that need evaluation is extremely high, a CRIDA analysis may be very difficult, especially for an expensive infrastructure project with high social and economic implications. Consequently, the analyst may consider the use of scenario discovery methods (see Lempert et al. 2006, Haasnoot et al. 2013), to develop a robust action (with or without flexibility) to benefit from additional uncertainty analyses. These methods are not within the scope of this guidebook.

Box 4.1.

Comparing Plans Across Different Scenario Futures: Avoiding Bias

If only one future scenario is considered, plans can be compared using DCF methods. However, when plans need to be compared with respect to different future scenarios that pose different levels of risk, a DCF analysis will be biased towards the least robust alternative. This is because discount rates applied to plan costs and benefits are often set by the institution for an entire class of projects. As a result, project- or plan-specific risks are not accounted for in the DCF analysis. This bias is exacerbated in the case of plans designed to return benefits over a long time horizon by reducing long-term risks such as slow-onset climate change impacts. To minimize this bias, the analyst may:

- Work with a decision maker for an institutional agreement to lower discount rates or designate different discount rates for different futures to improve the justification of benefits over a long time horizon, thereby enhancing plan selection with more reliable performance under rare and extreme events.

- Identify plans that are preferred across all future scenarios using DCF methods (i.e., find clear winners).

- Use ICA procedures in collaboration with decision makers to evaluate the incremental cost for additional robustness to performance under increasingly more stressful futures.

Standard DCF applications have a period of analysis that is usually shorter than the operational lifespan of some projects. This means that a project provides all the benefits as designed during the period of analysis (i.e., 0% depreciation), and once the life of the project exceeds the period of analysis there is a sudden loss of all benefits (i.e., a sudden 100 percent depreciation). The implication is that benefits from robust plans, which are meant to address rare events over longer timeframes, are muted. The analyst could present a complementary economic evaluation with an extended period of analysis for the DCF method required.

Evaluation methods that utilize probabilistic functions, such as expected annual damages, are derived by fitting mathematical functions to the occurrence of poorly understood and rare events. Plan comparison and selection is therefore sensitive to the statistical distributions used to estimate the probability associated with these events as well as the consequences associated with their occurrence. Stakhiv (2011) shows how use of the log-Pearson Type III function, currently required by U.S. water agencies to extrapolate maximum peak flow information, could result in a two-fold increase for a given design flood risk as compared to fitting the same data with a generalized extreme value function, which is routinely used by water managers in the United Kingdom and Japan. In this case, similar agencies in the U.K. and U.S. could come to different conclusions using the same data. To reduce bias from the selection of a probability distribution function, the analyst could complement analytic requirements with the following:

- Use more "thick-tailed" probability distribution functions (i.e., functions whose tails are not exponentially bounded) or transparently remove data points to enhance representation of rare and extreme events, or

- Include comparisons under specific or a range of extreme events or scenarios to test robustness.

4.2. INCREMENTALLY EVALUATING TO SELECT ROBUST AND/OR FLEXIBLE PLANS

Enhancements to a plan's robustness or flexibility are designed to withstand more stressful uncertain futures, which are compared on the performance (or benefits) provided per level of investment. As an example, consider a flood protection project that under current climate conditions maximizes protection using widespread planning evaluation and selection metrics with a $100 floodwall. Subsequently, plans are developed to include risks associated with two more stressful but plausible future climate scenarios. Under these potential futures, a larger $150 floodwall and the larger floodwall in conjunction with a $100 detention basin (e.g., $250 plan) are preferred. The additional cost of these two plans (i.e., $50 and $150, respectively) can now be weighed against the performance assurances they provide (Figure 4.2). The incremental benefit or performance assurance provided by the larger floodwall is measured as the difference between its performance and that of the smaller floodwall, with both evaluated under the incrementally more stressful future scenario. Similarly, the benefit assurance associated with the largest plan (i.e., larger floodwall plus detention basin) is identified by comparing its performance with that of an incrementally smaller candidate plan (i.e., larger floodwall without a detention basin plan) under the more stressful of the two potential climate scenarios.

Implicit in this incremental approach is the evaluation and selection of a preferred plan under the current climate scenario, referred to as the baseline plan because it serves as the first comparison point against which incremental cost and benefits (or performance) associated with more robust or flexible climate adaptation plans are benchmarked. The baseline plan may be a no-action or status quo alternative, if no additional action is justified now using the standard plan evaluation and selection methods. This plan is also referred to as the baseline level of investment because it defines a justifiable level of investment before future uncertainties are incorporated into the analysis. As a result, adaptation costs are identified explicitly and incrementally and not combined with costs that are justified under no-change scenarios.

4.2.1. Incremental Benefits of Avoided Losses

When the risk of a stressful future state is high, the analyst can determine the desired level of plan robustness by evaluating successively more robust approaches; often these plans will also be more expensive. Sources of increased stress can include deteriorated infrastructure, intermittent services, external stressors such as severe drought or floods, or economic disruptions. The first step by the analyst is to establish a baseline level of investment to rectify the most pressing problems using standard decision making criteria. Next, plans are developed that are incrementally more robust to extreme future conditions. When multiple plans with equal levels of performance are formulated, most institutions will likely proceed with the least costly plan. Such plans are cost effective since they achieve a given level of robust performance for the lowest possible cost.

Incremental benefits are generally defined as avoided losses in performance, such as reductions in risk of drought or flood damage, or reductions of system failure under incrementally

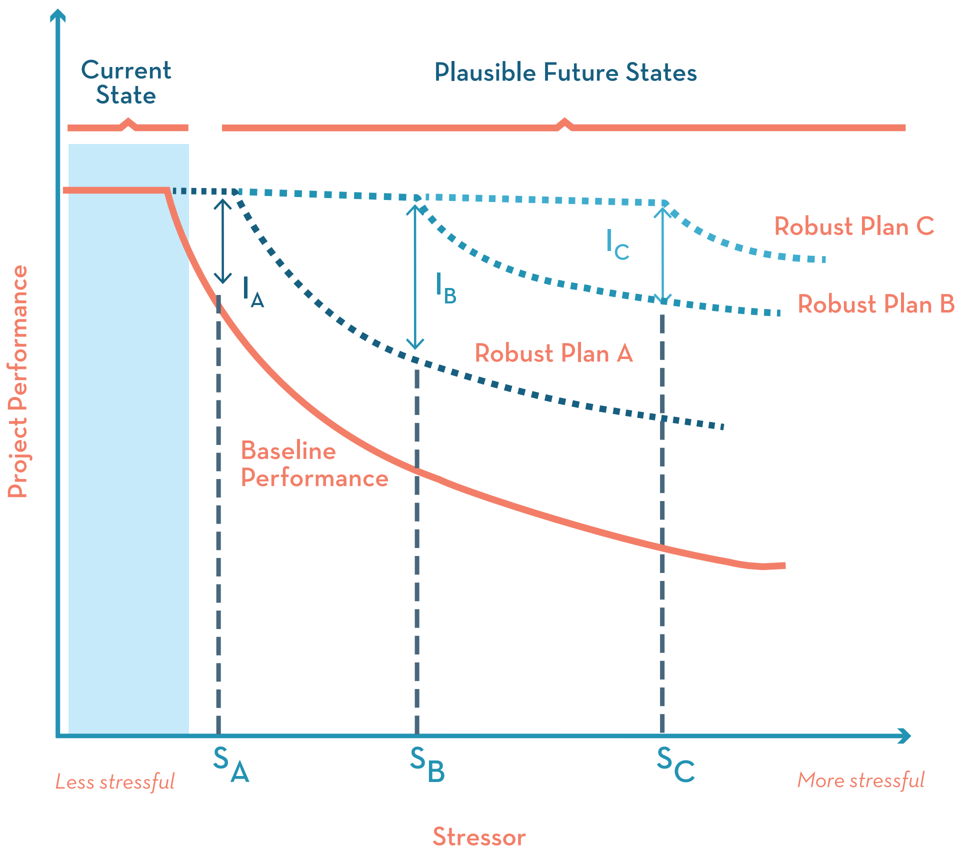


Figure 4.2. To evaluate a preferred plan for robustness, incremental benefits of each plan are computed by comparing one plan's performance to the performance of others, usually beginning with a plan that is the next least costly. Thus, the incremental benefits of Plan A (IA) are compared to the baseline, and the incremental benefits of the next most robust plan, Plan B (IB), is compared to Plan A. The more robust plans provide the desired level of performance under more stressful futures but are often more costly. The additional costs for incremental benefits are illustrated in Figure 4.3. Here, the plans are compared with respect to the baseline design performance. The same procedure can be applied to avoid surpassing the critical threshold.

more stressful future scenarios. The avoided losses are made with respect to a target future performance, which may be the baseline performance as designed or a critical performance threshold. The former will result in more robust solution that will likely come at higher expense. These incremental benefits are computed by comparing a more robust plan's performance to the performance of a less-robust plan, usually a plan that is the next least costly plan (Figure 4.2). Incremental costs are determined in a similar manner by comparing the difference between one plan and the next least robust option. The present value of benefits and costs can be calculated, provided that these valuations are performed for each plan and each future scenario. Thus, by disaggregating the baseline level of investment from the incremental costs and benefits of more robust plans, the level of investment in potential impacts can be defined explicitly for decision makers.

The level of investment needed to increase robustness is determined by explicitly comparing the incremental benefits and costs of successively more robust plans—plans that systematically reduce residual risks due to uncertain futures. Starting with the least robust plan (Plan A in Figure 4.3), decision makers can weigh each plan's additional costs against its incremental benefits. In this conceptual example, Plan B in Figure 4.3 has been selected, since its incremental costs can be justified most easily.

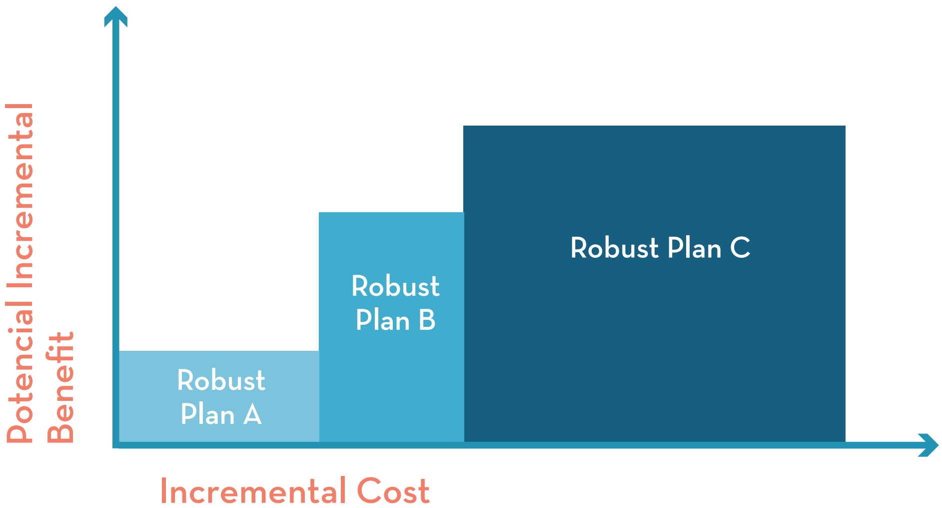


Figure 4.3. A comparison of Incremental Cost Analysis (ICA) for three plans that maintain baseline performance under three future scenarios. This conceptual example continues from Figure 4.2, where Plan B costs about 50 percent more than Plan A with an assurance that the damages avoided will be the same as those provided by Plan A but for a higher stressful future scenario, S_B. Plan C delivers the same performance assurance for an even more stressful future, S_C, but is twice as costly as Plan B.

Note that each increment represents a narrative about the future, such as levels of a stressor, a time horizon for a stressor scenario(s), or a qualitative assessment of likelihood. The benefits of each increment provided by plans, programs, or activities that result in costs above the baseline level of investment are the avoidance of chronic unacceptable performance under each narrative about the future. The number of plans and the number of increments is collaboratively developed with the decision maker as part of a risk-informed decision process.

Box 4.2.

Recommending a Robust Plan to Reduce Future Delivery Shortfalls from the Iolanda Water Treatment Plant

Upon examination of the various formulated plans in Box 3.2, the analysts determined that diesel generators could effectively reduce power shortages to avoid water treatment shortfalls for current and future drier climate states. In comparison to adding water storage, a dedicated power transmission line, reservoir re-operation, and demand management, the diesel generator alternative was the most acceptable solution. The generator demonstrated a good return on the baseline level of investment and was easily scalable, a necessary condition by the utility. This option was also the most realistic given that baseline conditions were already unacceptable and future funding was not certain. Iolanda required an immediate, robust solution.

Table 4.1 provides a summary of the ICA. An initial 125kW diesel generator is the baseline level of investment that prevents water treatment shortfalls under climate states that are 1 percent drier. An additional 125kW diesel generator capacity would add 30 percent to the baseline cost to ensure performance under a future climate that is considered to be up to 2 percent drier on average. The third increment of investment addresses a less likely drier future (up to 7 percent drier on average) by an additional investment of 250kW above the first increment at more than twice the cost of the baseline level of investment to avoid an additional 2 percent increase in shortfall.

The climate scenarios are based on a trends analysis and the proximity of the climate futures to the observed climate means. A trends analysis illustrates that the climate is getting drier at a fast pace, and a changing climate would first transition through 2 percent drier before a 7 percent drier future.

In the risk-informed decision analysis process, the analyst and decision makers (the utility and donor) pursue the new generator and also designed sufficient space in the powerhouse to install an additional 250kW in the future.

Table 4.1. An incremental assessment of shortfalls avoided by the Iolanda water treatment plant from a drier climate.

Increment	Additional diesel generation capacity above baseline	Climate change scenario	Incremental cost above baseline level of investment	Performance losses avoided if climate change scenario is realized
Baseline	125kW	Robust up to 1% drier climate*	-	-
1	+125kW	Robust up to 2% drier climate	Increase costs above baseline 30%	4% increase of shortfall avoided
2	+250kW	Robust up to 7% drier climate	More than doubles the cost from previous increment	An additional 2% increase of shortfall avoided

* This future climate scenario is within existing observed variability. This plan is considered to address current climate states.

Step 4

4.2.2. An Incremental Cost Analysis Shortcut: Selecting a Clear Winner

Occasionally, increasing levels of robustness or flexibility are achieved at no additional cost. In such situations, the same plan may be preferred based on standard plan evaluation and selection methods across multiple future scenarios. If no incremental cost is associated with the preferred plan under incrementally more stressful future scenarios then a "clear winner" exists across all the evaluated future scenarios and becomes the obvious candidate for selection.

4.2.3. Achieving Risk-Informed Decision Making

Risk-informed decision making should support the comparison and recommendation of an appropriate plan, program, or activity to enhance system robustness to more stressful futures that are deeply uncertain. Figure 4.4 illustrates the three components of risk-informed decision making: risk assessment (Steps 1 and 2), risk management (Step 3), and risk communication among the analyst, decision maker, and stakeholders. Risk communication is a cross-cutting component facilitated by the collaborative framework in CRIDA. In the previous steps, communication identifies hazards, vulnerabilities, and exposures with stakeholders. In Step 4, risk communication is central to the decision making process because risk decisions are most often political and social, especially when there are deep uncertainties about a future that cannot be quantified.

Figure 4.4. Risk informed decision analysis. Adapted from Yoe (2017).

An incremental analysis provides a risk-informed construct for the decision maker to hedge against unacceptable system performance under progressively more stressful futures. The selection of plan will be a function of policies, finances, and risk aversion. However, the decision maker will also make political, social, and environmental tradeoffs (Box 4.3). The analyst should be prepared to develop and provide assessments about the impact of each plan on environmental and social objectives in the future.

In risk-informed decision making, decision makers will often also seek input on the probability of a particular future, variable uncertainty, and other robust decision making criteria, such as to minimize possible loss from the worst case scenario (sometimes called a "minimax" criterion).

Box 4.3.

Selecting a Preferred Strategy for Flood Risk Reduction in Udon Thani, Thailand

In August 2017, an urban planning firm presented the leadership of Udon Thani, Thailand an ICA of four strategies to reduce current and future flood risks. The presentation to the mayor, department of public works, department of transportation, community groups, and environmental divisions was the result of five years of work using bottom-up vulnerability assessment procedures with a high collaborative component that allowed a very sophisticated risk communication process.

The four increments addressed progressively more stressful futures, and each increment had incremental costs at least an order of magnitude higher than the previous one. The first increment was the installation of "green streets" and small but strategic water gardens to address increases in the floods that had low property damages but high recurrence affecting the business community. The second increment was a far more ambitious plan formulated with stakeholders to connect several wetlands, develop urban recreation detention basins with recreation, and widen canals. This plan was very costly but could also serve to vitalize the downtown with restaurants and nightlife around canals and parks. The third and fourth increments were additional major components to progressively address increased runoff due to climate change and urbanization.

The analyst's recommendation was to start small with the first increment. The mayor, however, proposed a more ambitious and expensive increment because the development of green streets would create major traffic congestions (thereby jeopardizing future political will) and the conservation of remaining wetlands and land for flood risk reduction was time sensitive given the rapid urban growth of his city.

Probabilities

It is not possible to assign a probability to a future that is not informed by past observations of climate and other variables. In the formulation of plans (Step 3), future scenarios are clustered, and incrementally robust plans are developed to mitigate performance loss to progressively more stressful scenarios. Each scenario associated with an increment (e.g., Figure 4.3) can be cautiously assigned a likelihood descriptor based on the following considerations:

1. Future scenarios must be plausible based on theory, historic observations, and trends. Scenarios that are closer to the status quo are more likely than those that are more extreme because to reach an extreme state they have to attain some intermediary state. Each increment is thus associated with a qualitative statement of likelihood (i.e., from most likely to least likely).

2. The fraction of projections of the future that lie within increments can inform the designation of likelihood. It is important to note that these are not probabilities but rather meant to inform the decision maker about future risks using the limited information that is available about the future.

3. The development of incremental actions to mitigate potential future losses is an iterative and collaborative process around scenarios of concern at different plausible time horizons and actions that can mitigate their impacts.

Variable Uncertainty

It is possible to explore variable uncertainty using the stress test. Ray and colleagues (2018) implement a multidimensional stress test to compare different hydropower design alternatives. They explore the impact of a combination of uncertain variables from climatic to financial on a recommendation for a resilient hydropower design. In CRIDA, each increment would be iteratively developed, where each incremental action mitigates a significant portion (e.g., 90 percent of simulations or more) of the impacts from a possible range in a variable or combinations.

Supportive Robust Decision Making Criteria

Hashimoto and colleagues (1982) present different robust water resources decision making criteria, such as minimizing maximum regret (minimax regret), and system robustness criteria. These would be straightforward to incorporate by the analyst implementing a bottom-up vulnerability process such as CRIDA. The total cost, total losses avoided, and future scenarios associated with each increment would be applied in the procedures discussed by Hashimoto and colleagues (1982). It is important to note that a minimax regret approach is inherently pessimistic, dominated by the worst-case scenario and heavily influenced by the potentially arbitrary bounds of the stress test. Ray and colleagues (2018) illustrate the different outcomes from the comparison of plans using minimax regret and frequency of failure. As a result, the comparison of projects using such robustness criteria should complement the incremental analysis in a CRIDA process to support a risk-informed decision process.

4.3. COMPARING AND RECOMMENDING ADAPTATION PATHWAYS

Under high analytical uncertainty, adaptation pathways do not only help avoid compromising future adaptation possibilities; they are also an important risk communication tool. A pathways map provides the decision maker with an important visual to make a risk-informed decision.

For adaptation pathways projects, a single plan often consists of multiple decision points (Figure 4.5). To compare and select between the available paths at each decision point, each potential pathway is treated as a unique plan with plan benefits and costs compared with reference to a particular set of future conditions. Thus, within the context of a plausible future, the plan that conforms to the institution's standard decision making criteria can be identified as acceptable.

Flexible plans allow decision makers to select a course of action to adjust to shifting or emerging conditions while ensuring a near-term action does not rule out potentially critical future actions. Flexible plans cope with uncertainty by adapting to changing conditions. Adaptive management decreases the likelihood of buyer's remorse—spending too much or acting too quickly. In general, flexible plans require the analysis of fewer plausible future scenarios as part of the path comparison and selection process. A flexible strategy also increases the likelihood that a clear winner plan will exist. Within the context of a pathways project, the following conditions apply to clear winners.

- Include a narrow set of path choices at the decision point being evaluated. Ideally, the decision maker is provided one initial action or step that can be selected regardless of future path deviations. Typically less than three initial actions or steps can be clear winners when the final decision is based on political or social criteria.

- Economically justified under all evaluated future scenarios. If the same paths are preferred across different future scenarios, then the biases from DCF methods on different futures are not applicable.

When concern is about analytical uncertainty in Quadrant III, the strategy is about making certain that crucial paths remain available and accessible. In Quadrant IV, the planning team should use pathways and incremental costs to simplify the problem so that actions and plans can be addressed without expensive scenario discovery methods. However, for very expensive infrastructure projects with high consequences on life and property, scenario discovery methods may still be preferred. These two situations are discussed in more detail in the subsequent sections.

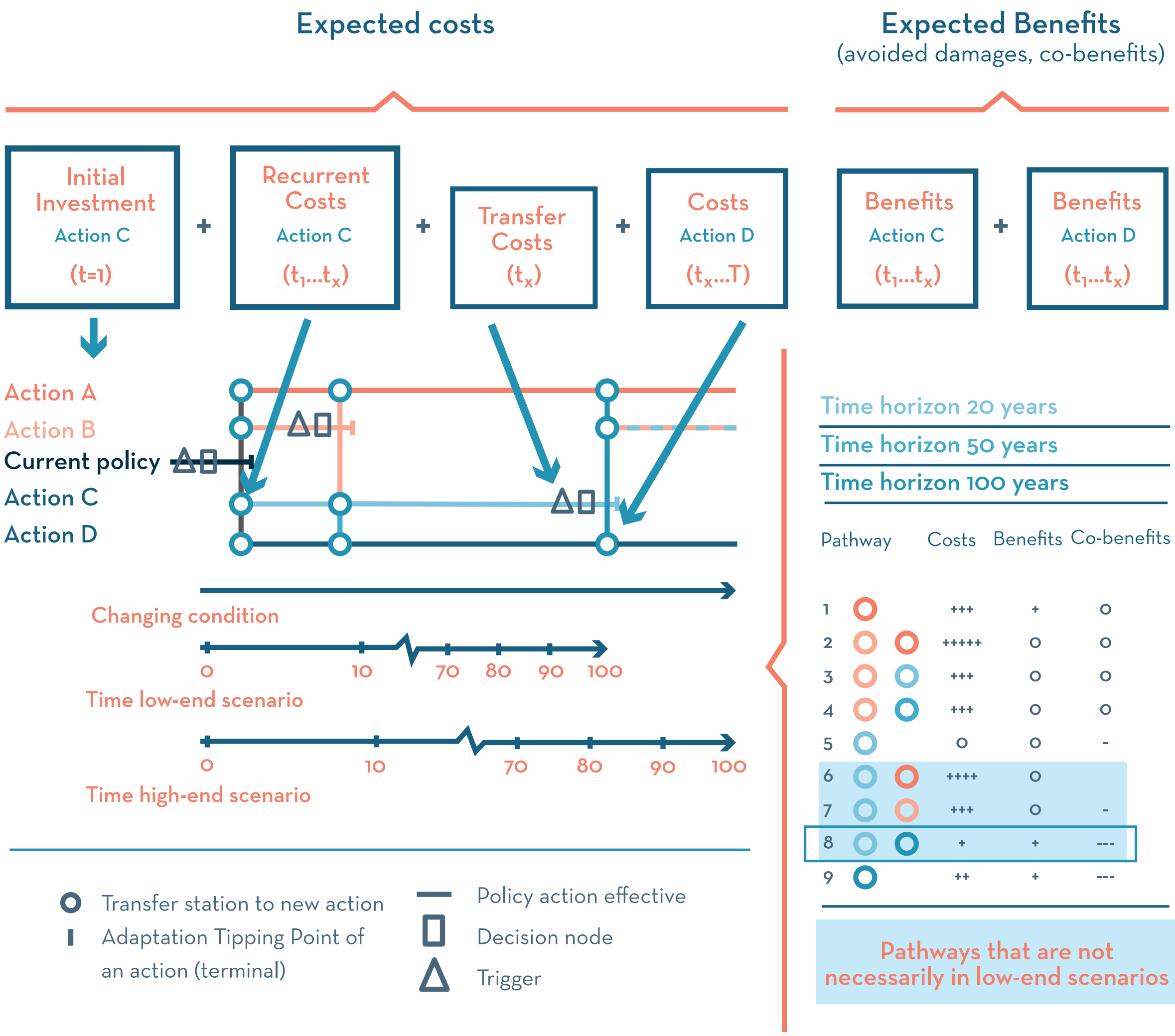


Figure 4.5. An adaptation pathways map with an economic evaluations scorecard. Note that the conceptual framework for the economic evaluation of the adaptation pathways is shown at the top in boxes of categories to incorporate in the evaluation. Source: Haasnoot copyright 2017.

4.3.1. Adaptation Pathways in Quadrant III

A Quadrant III strategy does not require quick and definitive actions to address uncertain future risk. Instead, the planner should consider a monitoring program, no-regrets actions, and ideally develop an adaptation pathways strategy. The analyst should also explicitly consider the costs linked to the delay of a given action, such as the expenses associated with implementing an action now versus the same action in the future.

Consider a hypothetical scenario of a floodplain rezoned to remain as an ecosystem rather than developed for urban or agricultural applications. Such a choice would address possible increases in future flood risk but may incur costs associated with not making this land available for other types of economic development. Investments such as dikes to address the problem under climate-stationary conditions might result in "sunk" costs (i.e., expenses that cannot be recovered) that limit future choices to adapt in a cost-effective way, thereby reducing future options and decreasing flexibility. The use of adaptation pathways can help navigate such issues.

Monitoring is an essential component of adaptation pathways because decision makers need to know when to shift from one path to another. Institutional arrangements that facilitate long-term monitoring, enable multiple decision points, and support the implementation of future actions are all important aspects of ensuring that adaptation pathways can be successfully implemented.

When an ATP is reached, the analysis of alternate paths should be updated. Periodic incremental updating also eliminates the need to lock in actions over long time horizons and allows decision makers the confidence to change paths at a later time without regret.

Each pathway represents a series of discrete investment actions made in response to changing conditions over time. A pathways map is an important visual tool for decision makers. In many cases, a flexibility strategy may begin by identifying no-regrets actions as a first point in a pathway. Showing pathways, tipping and transfer points, and incremental costs and benefits provides the basic ingredients used to perform an ICA. However, adaptation pathways as a methodology is distinct because the analyst makes the pathway transfer costs and loss of future options explicit to decision makers. Such insights can be powerful communication tools.

A DCF analysis of a pathways project will evaluate the initial investment, as well as recurrent, transfer, and implementation costs of future actions. This analysis also evaluates the accrual of plan benefits over the timeframe chosen for the evaluation (Figure 4.5). The following is a list of important steps the analyst should consider.

- Determine the timing of ATPs and transfer points for a limited number of scenarios. Section 3.4 includes more detail about urgency.

- Determine the timeframe and discount rate for the DCF analysis. These are often mandated by an institution's existing decision making rules. However, the time horizon for many future uncertainties can exceed the scope of traditional analyses. To make the future consequences of current decisions quite explicit, a time horizon of at least fifty to one hundred years is strongly recommended, especially since the operational lifetime of a project is often a century or more. Many institutionalized discount rates will bias project comparison and selection when multiple future states are considered. For the same reason, short time horizons bias the evaluation toward measures that are effective at solving short-term problems but lead to long-term regrets. Pathways projects reduce the chance of regret by deferring actions designed to deal with long-term problems.

- Incremental analysis procedures can reduce bias introduced through the use of institutionalized discount rates. In some institutional settings, the discount rate setting may be more flexible. When uncertainty about future conditions is very low, the discount rate associated with various pathways may be adjustable. The analyst may also explain to decision makers how sensitive a decision is relative to the choice of a discount rate and evaluation timeframe. In general, analysts should show the results of DCF analysis for at least three selected discount rates such as 3, 5, and 10 percent.

- Gather initial cost information as well as recurrent and one-time costs such as maintenance for each action along the pathway. "Transfer" costs are especially important. Transfer or transaction costs are defined by Haasnoot and colleagues (in preparation) as "the costs associated with switching or adding actions." Generally, they can be considered as the costs of delaying a decision and start-up costs for planning new options and designing an alternative system. Normally, transfer costs are included in the investment decisions of follow-up actions or not included at all when they fall beyond the planner's horizon. However, they are useful in making the relative flexibility of pathways more explicit. Two sources of transfer costs are especially important. First, there are the logistical costs associated with shifting from one action to the next. For instance, these logistical costs may include the relocation or removal of previously constructed features of a plan. Second, there are the sunk costs associated with investments that do not reach their expected life expectancy due to a need to switch to another investment (Arkes and Ayton 1999).

- Calculate the benefits that each action delivers over the selected timeframe and the evaluated future states. Non-monetary performance metrics may need to be translated to monetary units. Flood damages avoided (flood risk management actions), power production revenues (hydropower actions), or irrigation revenues (water supply actions) are examples of benefits.

- Calculate the DCF economic benefits for each pathway as well as the benefits from each combination of future scenarios and rank and present the results for each pathway. DCF analyses are often not comparable across future scenarios because discount rates may be scenario dependent. However, if certain pathways are performing clearly better than others across a range of scenarios, they are considered clear winners. An iterative process of optimizing the timing of investments or adding extra evaluation criteria to the analysis can also help to narrow down the choices.

The actual costs and benefits of actions and pathways ultimately depend on the occurrence of an uncertain future state. Deep uncertainties are associated with any particular future state, but actions and pathways that are robust to a range of plausible future scenarios can be constructed. It is important to settle on a plan through the selection of an incremental series of potential paths.

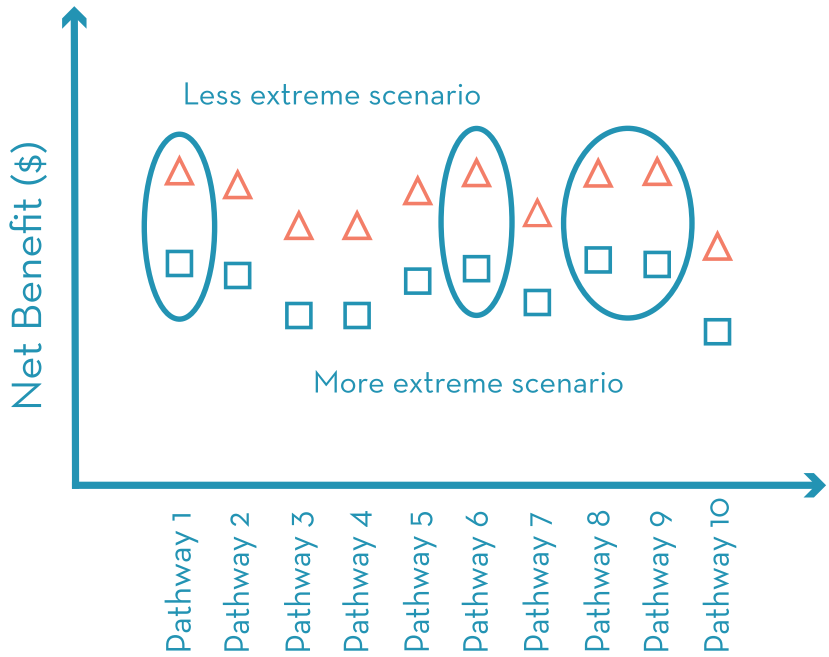


Figure 4.6. Net benefits of ten adaptation pathways under two future change scenarios using a single planning horizon. Triangles represent results from low-end forecast scenarios (less extreme) while the squares represent results from high-end forecast scenarios (more extreme). Pathways 1, 6, 8, and 9 are clear winners for both future scenarios. If these four winning pathways have the same first path, then a single recommendation can be made. If these four winning pathways have more than one first path, these can be further analyzed using other decision criteria as well as compared using ICA. Source: Haasnoot copyright 2017.

The evaluation of pathways adds extra work for the analyst when compared to traditional project evaluation. The fact that pathways are a sequence of actions implies that the cost and benefits of sequencing itself must be analyzed.

4.3.2. Adaptation Pathways in Quadrant IV

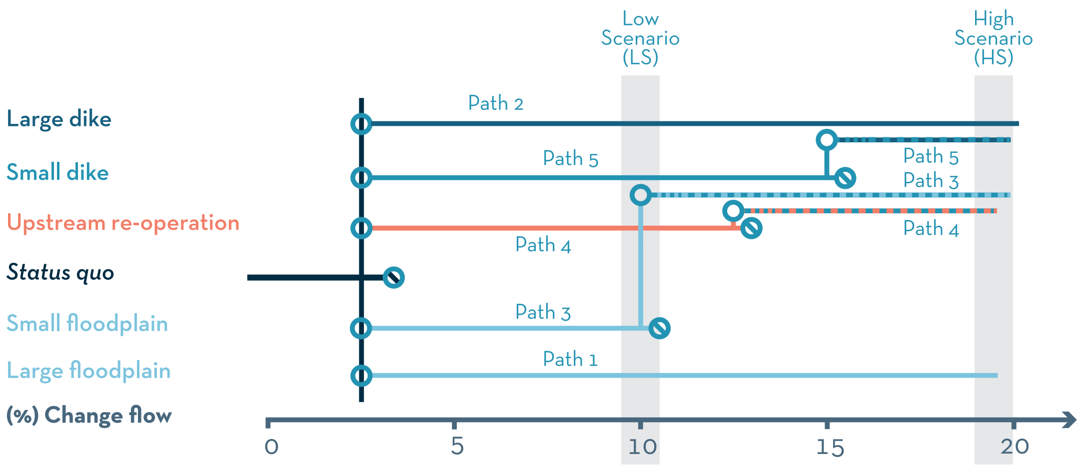
Plans in Quadrant IV of Figure 4.1 exhibit high levels of future risk and high levels of analytical uncertainty. In this quadrant, the analyst should recommend both short-term definitive actions to address uncertain future risks and the range of flexibility needed. To counter a project's high analytical uncertainty, robust initial designs are needed to decrease the project's high future risk. The procedures for evaluating and recommending these projects follow those outlined for Quadrant III. At each decision point, a path is justified through incremental analysis or the identification of a clear winner. For Quadrant IV projects, the potential paths at each decision point are generally associated with increasing robustness. Therefore, incremental analysis is often necessary to justify additional costs.

Box 4.4.

Recommending a Preferred Adaptation Pathway in the Waas River Valley

Pathways in the Waas River Basin were compared by estimating the cost-benefit ratios. Stakeholders concerned about environmental impacts and the preferences of urban developers also preoccupied decision makers. Figure 4.7 summarizes the analysis that compared five candidate pathways showing three decision rules required by decision makers: the cost-benefit ratio of each plan under two extreme future climate scenarios, an environmental impact score, and an urban developer preference score.

The cost-benefit ratio analysis indicates Path 4 is a clear winner because it is preferred under both climate scenarios thereby removing effects of a discounting bias. Path 4 is also a satisfactory choice for environmental and developer interests. Path 4 implements new reservoir operation policies upstream, and if flows are observed to permanently increase by 10 percent, a small dike is constructed along a riparian easement conserved for this purpose, which provides robustness even to extreme scenarios.



SCORECARD

	Paths				
	1	2	3	4	5
CBR HS	0.1	0.2	0.1	0.3	0.2
CBR LS	0.1	0.2	0.1	1	0.2
Developer	0	0.5	0.3	0.8	0.5
Environment	1	0	0.8	0.8	0.2

Figure 4.7. Recommended pathways for flood risk reduction in the Waas River Basin case study with a scorecard for each pathway. Cost-benefit ratios (CBR) for more extreme (HS) and less extreme (LS) climate scenarios, as well as urban developer and environmentalist preferences, are included.

The analyst evaluating Quadrant IV plans has at least two approaches available that may facilitate the selection of flexible paths. If neither approach leads to one or more preferred initial actions, it may be necessary to conduct a scenario discovery analysis (see below).

1. Implement a DCF analysis of adaptation pathways to identify clear winners. This approach is similar to Quadrant III, but analysts need robust designs and the definitive path is more urgent. As ATPs are reached, the DCF analysis of pathways may emphasize minimizing transfer costs while ensuring incremental benefits. Figure 4.5 illustrates the components of benefits and costs to consider in the DCF analysis of an adaptation pathway. The DCF analysis may also emphasize the timing of costs and benefits. The likelihood of identifying clear winners can be increased by analyzing different progressions of ATPs and varying robustness criteria.

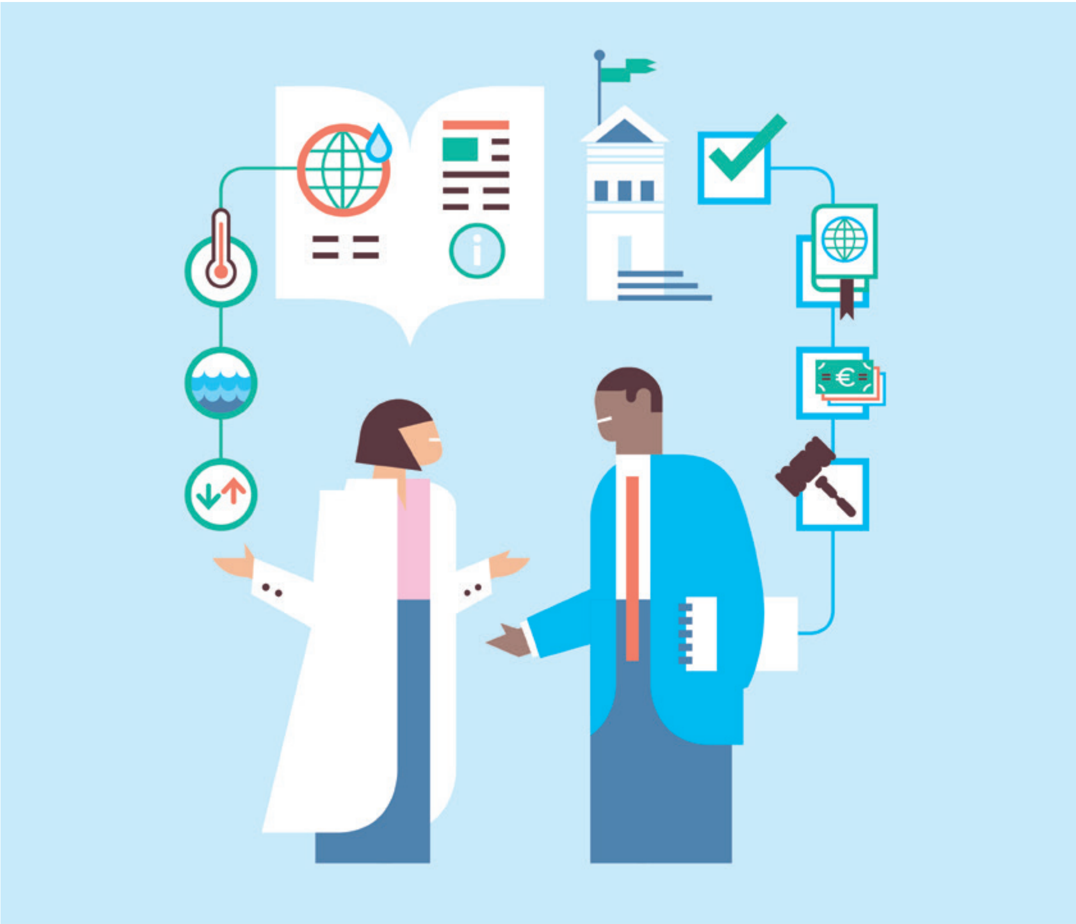
2. In the event a clear winner is not evident, ICA procedures can be applied to winning paths under each future scenario. The incremental analysis approach is best suited to

the selection of a suitable level of robustness. Thus, during the incremental analysis, the planner and decision makers must carefully consider the prospect of incurring excessive transfer costs or other regrettable consequences when selecting the incrementally justified plan.

In Quadrant IV, discovering an initial action or set of paths may not be possible due to extremely high levels of analytical uncertainty or conflicting interests that deeply impair an institution's normal decision making processes. For instance, a project may be expected to meet a large number of planning objectives or a large number of future scenarios and stressors may need to be explored. In this case, scenario discovery techniques—also called scenario and risk exploration—can be useful (Lempert et al. 2003, Kwakkel et al. 2015). Such detailed analytical requirements are usually only justified for high investment and high consequence decision making. These approaches are built on the premise that iterative Monte Carlo statistical sampling tools can uncover strategies that are economically efficient and highlight the decision components with the highest uncertainty. Although such methods can be computationally intensive, they can help subject matter experts or decision makers identify plans, select future scenarios, examine the sensitivity of the model, and discuss the plausibility of the scenarios. These outputs can then be adjusted and rerun. The analyst begins by running a simulation model multiple times with sets of input parameters representing many different futures that include climate models or weather generators. Lempert and colleagues (2003) and Kwakkel and colleagues (2015) can be consulted for more detailed guidance.

5

Institutionalizing the Decisions



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Step 5

For successful implementation, a decision concerning a complex situation must be institutionalized—integrated into management and policy documents so as to be fully adopted by the responsible individuals and institutions. Once the decision to proceed has been made, the relevant parties must align budgets, financing, policies, regulations, and/or laws. A decision-supporting monitoring plan is essential, especially for a staged and flexible decision making process. Step 5 requires sufficient competence in governance. The analyst remains integral by providing information and sometimes guidance on technical, institutional, and financing requirements.

Input from Step 4

- Comparison of plans against a baseline measure of performance
- Comparison of plans across different future scenarios
- Recommended plan(s) to the decision maker

Outputs from Step 5

- Implementation plan, based on institutional and financing requirements and LOC based on future risk and analytical uncertainty
- Adaptive management plan with integrated monitoring

5.1. FORMALIZING THE DECISION IN A PLAN

In Step 5, responsible authorities should make decisions regarding which plan, project, or course of action will be taken and how implementation proceeds. The nature and content of the plan depends on the institution's decision rules. Every institution applies rules unique to its business operations in the final selection of investments (Box 5.1). Typically, decision rules reduce future risks by focusing in an organization's areas of competence and by constraining financing and the implementation of actions. The formal decision rules of an agency or ministry responsible for project planning or project implementation are key to understanding solutions that can be implemented over a given time period.

By definition, adaptation to future risks requires change, though in some cases only a few incremental adjustments are necessary. In other cases, the expected impacts are so severe that dramatic and so-called transformational changes to infrastructure and institutions are required. The distinction between incremental and transformational change is important because the chosen path affects feasibility and governance. In general, transformational processes are more complex and disruptive and, therefore, more difficult to implement.

From a governance perspective, institutional change is challenging at both individual and organizational levels. Path dependency, a concept from systems theory, is often the greatest obstacle to significant change. Path dependency refers to history as an ongoing and powerful influence on a system's or individual's evolution. Every infrastructure network is set in a particular historical context of responsibilities, cultures, practices, and interactions. Over time, new elements are introduced, adjusted, or removed, and these changes can be represented as a path through time. However, the interdependence of these elements can create challenges to transformation. Transformational change by definition represents a breaking of many relationships—transforming the institution in significant ways.

Box 5.1.

The Role of Institutional Decision Rules

Institutions use different frameworks for making decisions. While water resources planning procedures may be broadly similar across institutions, individual institutions have their own variations. Risk and uncertainty have always been a significant part of evaluation protocols with guidebooks, manuals, and operating principles structuring planning for the major water sectors such as hydropower, navigation, municipal and industrial water supply, treatment, irrigation, and flood control.

Consider the different decision making frameworks of the Dutch Infrastructure and Environment Ministry, the U.S. Army Corps of Engineers (USACE), and the World Bank. Unlike the World Bank, neither the Dutch Environment and Infrastructure Ministry nor the USACE is currently engaged in poverty reduction as a primary goal in water resources development. Although these three institutions do not share commitment to poverty reduction, their basic criteria for project justification still centers on economic evaluation.

National economic development goals will always be a focus of water resources development plans in developing nations as will water security in the form of water-related disaster risk reduction and the provision of reliable services. For the Netherlands, Bangladesh, and other low-lying coastal nations that have little room for failure, water security is a top national security issue. Such variations in weighting decision criteria is easily accommodated within the CRIDA process.

For the Netherlands, a comprehensive report written by the Dutch Infrastructure and Environment Ministry (Slomp 2012) describes decision rules in the Netherlands. The Dutch apply a risk-cost-effectiveness approach as their basic decision criterion, which allows for tradeoffs between benefits, costs, and risk avoidance, depending on context. However, they always start with flood risk safety standards (Slomp 2012, Van Alphen 2015). Once Dutch safety standards are met, other management objectives (e.g., the environment, room for the river, social, social impacts) are included to select the most risk- and co-effective design.

The World Bank and USACE have a comparable approach: both start by selecting the project type and size that maximizes expected net present value (NPV). The NPV is a monetary estimate in current dollars based on the generation of net benefits over the life of a project. The differences in institutional approaches stem from the particular discount rate used for computing NPV and the allowable economic benefits and costs that can be incorporated into the cost-benefit analysis.

Participatory processes can strongly influence the final project selection. The Dutch Environment and Infrastructure Ministry and the USACE often require cost sharing with local partners. While both institutions are national in focus, locally preferred plans tend to be strongly favored. Similarly, the World Bank has historically focused on a return on client government approval as well as well-defined costs and returns (IEG 2010). In contrast, the USACE seeks to maximize a more conceptual form of economic worth calculated on the accumulation of national economic development benefits.

Transformation has two important implications for CRIDA. First, the current system is constrained by the infrastructure and institutional context, so that technically feasible options may not always be feasible from a governance perspective. Analysts, stakeholders, and decision makers may experience these constraints as a source of tension, conflict, or even anxiety. But creating a new “perfect” system is rarely a realistic option.

Second, transformational pathways require more effort and time in terms of governance than incremental actions that work to adjust the current system. Both incremental and transformational changes are part of the decision making options presented in Figure 5.1. Particularly for Quadrant IV, the scope required to reduce the effects of uncertainty becomes more ambitious, requiring more transformational changes from a governance perspective.

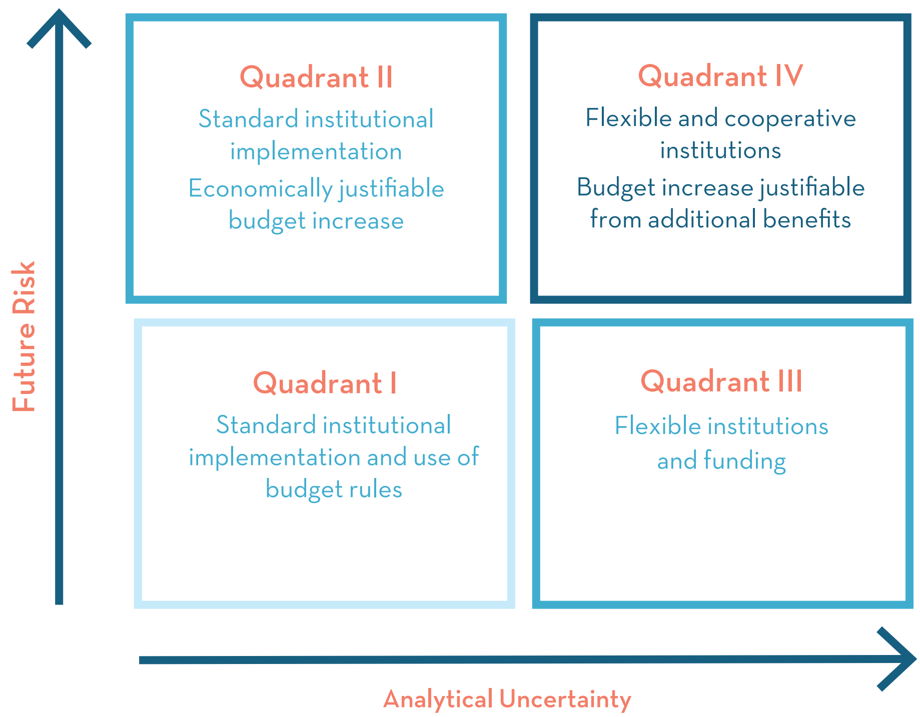

Figure 5.1. The decision matrix organizes the analysis of institutional and financing requirements.

Step 5

5.2. ADDRESSING THE CHALLENGE OF IMPLEMENTATION

If the analyst has identified a strategy to cope with high analytical uncertainty and medium to high future risk, a robust plan will be needed to implement the decision.

A robust plan typically contains the following elements:

1. A preferred strategy, including both short- and long-term actions.
2. Organizational, financial, and legal directives to implement the actions.
3. A monitoring plan to keep track of implemented actions and to trigger future action.
4. An implementation agenda, including budget, project lead, and preparation times.
5. An assignment of institutional responsibilities for implementing the components of the plan as well as scheduled updates of monitoring processes.

For implementation of staged decisions, the implementation agenda depends on a monitoring plan to trigger action. This includes designating a responsible party to monitor for windows of opportunity that may arise from other projects or processes. For instance, infrastructure maintenance and replacement cycles or spatial development planning can present opportunities to reassess risks or to combine benefits from other projects.

Instead of only a narrow focus on primary objectives, organizations should cooperate to find complementary benefits and co-manage options for adaptation over time. The use of mainstreaming or alignment processes as an implementation strategy has advantages. Costs can be reduced because more parties contribute, extra value can be created through multifunctional land use, and hindrances can be reduced by executing the works simulta-

Box 5.2.

The "ISA Framework" to Support Implementation

The feasibility of implementing proposed measures can be evaluated through a tool called the institutional and socio-cultural analysis framework (ISA Framework) as described by Van der Brugge and Roosjen (2015). The ISA Framework is useful for the examination of transformational processes playing out over long timescales and focuses on transformational pathways. The ISA Framework addresses two basic questions:

- What should change, and
- Who is able to enforce that change?

The ISA Framework assesses to what extent current institutional and socio-cultural conditions support or hamper adaptation measures.

neously. In some cases, financing through multiple sources can spread risk and improve the management of long-term risks.

Plan implementation may require changes in more domains than institutions and financing. Many governance frameworks exist that can help the analyst systematically evaluate implementation requirements (Box 5.2).

5.2.1. Windows of Opportunity

For mainstreaming risk reduction to be effective, investment strategies and timing must be synchronized across organizations and budgets. Synchronizing can promote synergies but may require flexibility in agency programming and coordination among various departments. The existence of windows of opportunities may not be known by all departments even within a single institution, especially large or dispersed organizations. A conscious effort to seek these opportunities can provide co-benefits for long term planning and operations. A window of opportunity might be a government-wide focus in the aftermath of a flood or drought event or the failure of a critical water infrastructure system. At these times of crisis, ministries often collaborate to solve specific water-related problems in coordination with legislative institutions. Such periods of high interest can be very effective windows of opportunity.

For transformational change, existing institutions may not to be well-suited for the new conditions and change or new institutional arrangements may be needed. The following are three examples in which new institutions enabled effective transformation:

- The North American Great Lakes. Large uncertainties concerning drivers for changes in climate and the effectiveness of measures to regulate the water levels of the Great

Box 5.3.

The Great Lakes–St Lawrence River Adaptive Management Committee

Two extensive U.S.-Canadian studies—the International Lake Ontario–St. Lawrence River Study (finalized March 2006) and the International Upper Great Lakes Study (finalized March 2012)—led the International Joint Commission (IJC) to advise the U.S. and Canadian governments about long-term management of the North American Great Lakes in light of transboundary stakeholders and complex climate impacts. This advice included decisions on improved regulation of lake outflows and on infrastructural investments as well as the adoption of an adaptive management strategy to address uncertain impacts and potential extreme water levels (International Joint Commission 2013). Despite the great efforts and extensive resources put forward to improve data, model quality, and assessments, large uncertainties remained. Indeed, a variety of hydrological parameters had data errors larger than the potential climate change signals. A process of adaptive management was recommended to establish a structured, iterative process of evaluation with the aim of reducing uncertainty over time and, if necessary, adjusting earlier management decisions. Therefore, the Great Lakes Adaptive Management (GLAM) Committee was created to provide information to the management authorities on the impacts of control structures and regulation plans on water levels and boundary flows that affect stakeholder interests such as recreation, shore protection damage, and wetlands. The GLAM is informed by an extensive monitoring and modeling program. The GLAM committee operates above the formally responsible parties in both countries.

Lakes, shared by the U.S. and Canada, led to the creation of the Great Lakes Adaptive Management Committee to allow for a flexible management approach, combining data analysis and operational decision making.

- A Dutch interagency approach to adaptation. When preparing the latest Netherlands adaptation plan for water management, special institutional arrangements were established to cope with (a) a long management and evaluation timescale (until 2100), (b) the multiple governmental departments and layers involved, and (c) the large uncertainties around the timing and scale of impacts. A new high-level commissioner was appointed to lead the program and facilitate cooperation be-

Box 5.4.

Aligning Agendas and Sectors in the Netherlands

Space and resources are scarce in the Netherlands so a shared view about investments for different sectors in a specific area is necessary. National and local governments have adopted an agenda for each region in the country. These agendas are updated every four years and are based on a joint vision of public investments in water and transport infrastructure among other development sectors. Decisions about what challenges and solutions are chosen arises from consultation between the central government and the relevant regions. Ultimately, the Multiannual program for Infrastructure, Spatial plans, and Transport (MIRT) schedules investment in programs and projects. MIRT decision rules ensure transparency and describe the tasks and roles of the parties and the decision making requirements for the government to reach a decision on a possible grant. By bringing together different sectoral investments in one spatial agenda, the chances for achieving synergy in time and space are increased.

For example, in the city of Nijmegen, a combined river widening and urban development project was realized by combining different investment budgets, which demonstrates the importance of choosing a broad and interagency adaptive strategy. Anticipating increases in river discharges in the future, authorities decided to make a backward dike realignment and to excavate a side channel. A pathway of perpetual dike heightening was thereby avoided if the area behind the former dike was developed as part of the city.

tween ministries. Moreover, a special act was adopted in Parliament to institutionalize the program with a fund for flexible budgeting over a time period beyond current governmental norms.

- Shared vision dialogues in the city of Udon Thani, Thailand. These dialogues led the city to develop green infrastructure plans to address the increase of droughts and floods due to climate change and rapid urbanization. An opportunity was seized due to existing development agency programs that were effectively leveraged and city leadership who were able to make decisions and think creatively.

Box 5.5.

Reducing Flood Risk with Green Infrastructure in Thailand

Fueled by intensifying economic links to China, Laos, and Vietnam, the city of Udon Thani, Thailand, is one of the fastest growing cities in Southeast Asia. The urban area sits within an agglomeration of distinct municipal authorities and has developed ambitious plans as an economic hub and gateway to the Mekong region. City managers aim to double Udon Thani's size and population in the coming decade. Growth has also led to increasing concerns about droughts and floods. Providing water during the dry season and managing increased flooding is a threat to the city's vision of being both an economic hub and a liveable city. The city is planning a green infrastructure strategy to enhance its robustness and to maintain adaptive capacity.

The city has a sophisticated flood risk reduction infrastructure operated and managed by the Public Works Department and constructed by the Department of Transportation as part of a ring road. The system has been incrementally enhanced through the addition of gates to restrict backflow from the Mekong, pumps, stormwater drains, additional routing canals, and a storm crew to clear debris and to start pumps before a storm. Several historic storm events led to public concern and to gradual updates to this infrastructure. The strategy has been effective in the past to route stormwater out of city boundaries. Future solutions need to enhance the capacity for temporary storage and peak reduction of stormwater because downstream communities are also concerned about additional routed water from the city. Increased upstream stormwater sources are due to rapid development in the peri-urban areas spanning different municipal authorities.

Several enabling conditions have facilitated a collaborative and risk-informed implementation.

1. The city leadership recognizes a paradigm shift is needed for alternative and coordinated approaches to resilience.

2. International donor programs support shared learning dialog, develop institutional capacity for resilience planning, and facilitate exchanges between city staff, local universities, and outside experts.

3. An operational water engineering agency provided capacity building in collaborative modeling techniques for decision support.

4. The mayor authorized funds and staff from the Public Works Department to develop stormwater models with USACE training and advice to evaluate green infrastructure renderings. The city sponsored sessions with key stakeholders to consider landscape features such as linear parks with stormwater routing capacity, wetlands and waterbody restoration for storage enhancement, and increased urban land-surface permeability.

5. Outside experts helped perform ICA to help discuss the additional cost for robustness to more stressful futures.

6. Committed city leaders allocated seed funding for a pilot green infrastructure canal section and participated in several collaborative planning processes, incorporating risk-informed decisions with politics, signed documents to institutionalize decision points, and provided hands-on direction at each workshop. In addition, an interested chamber of commerce is keen on the possibilities of green infrastructure for urban renewal, recreational opportunities, enhanced real estate value, social benefits (water canals to connect universities, a temple, sports stadium, and restaurants), and water supply.

7. There was a national requirement to update a zoning master plan that the city can use to negotiate with peri-urban municipalities.

The opportunity to interact with experts from outside Udon Thani and within the community and engage in a collaborative exchange around a common problem allowed the drafting of new ideas that had buy-in and that could be evaluated for robustness and flexibility in a systematic manner. The collaborative process is still ongoing, defined by specific design concepts, evaluated by sound engineering and economic tools, discussed in a two-way communication framework, and iteratively updated with city staff and leadership concerning financial, social, and political requirements.

5.2.2. Financing and Funding Plans

While *funding* refers to the allocation of resources (such as money), often with reference to applying resources from within an institution, *financing* more usually refers to the use of external resources for a program or project. As a result, financing comes with many conditions attached. Thus, financing often significantly shapes and structures implementation, serving as both a constraint and an evaluation criterion. In general, traditional financing approaches may have a neutral or even a negative effect on climate adaptation implementation strategies, and, in particular, on staged investments like adaptation pathways. In general, projects in Quadrants I and II are relatively easy to finance because familiar project justification procedures are used and projects are designed for routine levels of project uncertainty, such as existing levels of climate variability. Financing projects that will operate for decades, and explicitly incorporate uncertain climate change impacts is inherently more difficult to justify economically and financially. Non-economic criteria, such as public safety issues associated with increased risks of dike or dam failure, may have to be weighed more heavily in the overall decision making process.

Financing often influences the period over which risk is evaluated or shared. For example, a project's return on investment needs to be delivered within a certain period for it to be justified. Financing may also constrain the types of solutions that can be financed and procured. In the U.S., many public projects are funded through bonds that can more easily fund capital expenses (i.e., new or modified physical structures) than operating expenses (i.e., creating new management institutions, insurance schemes, shifts in operating regime, or capacity building). Financing methods such as green or climate bonds may add additional expenses and requirements to improve the "greenness" or environmental acceptability of a project. Finally, the availability of financing will be influenced by economic circumstances and changing priorities from both private funding sources and public budgets.

The analyst should learn early in the CRIDA process if the available financing choices are limited or predetermined, whether the project will be publicly financed, or if opportunities exist for public-private partnerships. The potential financial constraints should be uncovered early in Step 1's planning process and incorporated into Step 3 and Step 4 when selecting, comparing, and evaluating plans. With the help of financial experts, the analyst can support the decision maker in designing an integrated financial plan during Step 5, including the identification of potential cost-sharing partners and the institutions responsible for operations and maintenance. Flexible adaptive pathways may offer a less complicated solution while providing financial advantages by identifying piecemeal financing and the spreading of budgets over time. A deferred approach can provide the opportunity to buy time to search for additional financing. If the plans or pathways

Box 5.6.

External Financing Options: A Changing Landscape

Climate / Green Bonds

Green bonds (also known as climate bonds) are a type of loan marketed to investors as having some explicit environmental benefit and/or a climate mitigation (greenhouse gas emissions reduction or sequestration) or climate adaptation impact. Water Infrastructure Criteria for the Climate Bond Standard aim to standardize these to promote more robust practices around long-term water management. The criteria have been widely used and can be downloaded at climatebonds.net/standard/water/.

Multilateral, Bilateral, and UNFCCC Agency Climate Finance

Climate finance mechanisms and vehicles are a new category of development aid, and donor institutions (MDBs, the Global Environment Facility [GEF], the International Finance Corporation [IFC], many donor countries, UN institutions) must often provide an explicit accounting of the specific amount within a project that is focused on climate change, whether climate mitigation or adaptation (Ray and Brown 2015).

The Green Climate Fund

The Green Climate Fund (GCF) is a new international institution based in the Republic of Korea designed to support both climate mitigation and climate adaptation.

UNFCCC Loss & Damage Mechanism

As signaled in the 2015 in Lima and 2016 Paris UNFCCC conferences, a so-called "Loss and Damage Mechanism" has been developed by the UNFCCC national parties. These may be a useful source of funding for adaptation work.

selected contain divergent categories of measures, more than one financing source may be needed, an option sometimes called "blended finance."

5.3. MONITORING AND EVALUATING THE PLANS

Flexibility is an important requirement to enable institutional systems to deal with uncertainty. Uncertainty means the analyst is not sure about the timing and/or implications of impacts and, in severe cases, the analyst is unsure whether incremental or transformational changes are needed. Monitoring should be designed to provide information on the tempo and direction of critical developments so as to adjust strategies or measures when appropriate. Institutional flexibility is a prerequisite for keeping possible adaptation options open, responsive, and effective over time.

Without monitoring, adaptive planning changes from being proactive to reactive. Catastrophic events can communicate urgency, but primarily in a reactive way. Technical personnel often find communicating urgency to decision makers difficult without measured observations or projected data that provide distinct evidence of trends and clearly identified risks, ATPs, and decision making thresholds. Monitoring provides system managers with information to operate as well as a mechanism to update but it can also contribute to an adaptation pathways map or to initiation of a new planning study.

The goal of monitoring within the CRIDA planning cycle is to inform the responsible management institutions about when to act next. How to act, however, will vary depending on the outcome of the CRIDA decision cycle. If the decision maker opted to exit the process at Step 2 because the system was not yet vulnerable to climate change, then action by an analyst may entail a reassessment of system vulnerability. If the decision maker selected an adaptation pathway containing long-term options, then monitoring will reveal when the system reaches an ATP and when to implement the next action in the pathway (Haasnoot et al. 2015a).

In all cases, lead time to initiate implementation and to mobilize financing must be considered within the monitoring process. When an ATP occurs, the system of concern is experiencing chronically unacceptable performance. The ability to make an adaptation decision in time would require clear early warning signals that allow decision makers to formulate any changes in courses of action with sufficient lead time before an ATP (Figure 5.2). Lead times vary for different actions and include both sufficient time to prepare a decision and implement a measure. The analyst should ensure these lead times are well defined and taken into account in the monitoring plan.

As part of the CRIDA planning process, the analyst works towards establishing a formal monitoring program by communicating to decision makers the goals of the monitoring process, the parameters to be monitored, and the challenges monitoring may encounter. Communicating

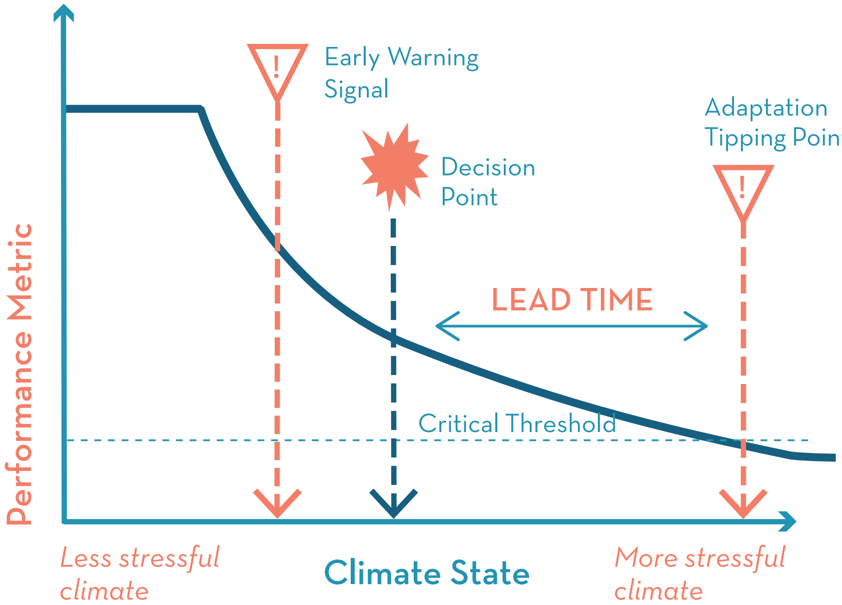

Figure 5.2. As expected performance changes due to more stressful climatic states or due to other stressors, the monitoring process and timing should ideally inform decision makers when to consider an alternative pathway, with sufficient warning to enable the necessary transfer shifts. The ability to identify an early warning signal due to a chronic reduction in performance is a difficult but necessary task to reevaluate the adaptation pathways plan to initiate a new course of action. Such an adaptive process provides system robustness because it allows for sufficient lead time prior to reaching the adaptation tipping point. The goal is to provide the lead time necessary to execute new actions, taking into account construction, financing, regulatory, or legislative considerations. Adapted from Haasnoot and colleagues (2015b).

these components for successful long-term monitoring programs ensures adaptive planning does not end in the initial phase of the CRIDA process and resources continue to be available for monitoring through implementation.

While the purpose of monitoring is clearly based on the CRIDA decision cycle, deciding which parameters to monitor is more complicated. Rosenzweig and colleagues (2011) categorized potential parameters to monitor as climate parameters, impact parameters, advances in science and technology, and the progress of adaptation plans.

At a minimum, the parameters used to identify ATPs should be monitored for a continued risk assessment of the system. Such parameters would likely relate to the climate and/or impact parameters and could include observed data as well as updated projections. Climate and hydrologic parameters (i.e., sea-level rise, subsidence, storm surge, precipitation, flood frequency, drought duration, or stream flow) represent the hazard side of the risk equation and are likely linked to the stress test completed in Step 2. Conversely, impact parameters are linked to the consequences side of the risk equation: the effects of hydro-meteorological changes impacting agriculture, flood risk, water supply reliability, and so on. These factors may have been considered to be drivers in the stress test, such as population growth or economic development, or they may have been built into the modeling of damages or consequences. Monitoring these two types of parameters allows the analyst to update risk assessments of the system. However, to detect early signals of change, the monitored indicators must show robust trends, which can be challenging especially in the case of extreme events (Haasnoot et al. 2015a).

Advances in science and technology may also alter the original decision, though such advances are unlikely to be monitored in any traditional scheme. Technological advances, such as in materials, may result in cost savings for alternatives and result in an economic reassessment of the developed pathways (Rosenzweig et al. 2011).

The final and perhaps most important monitoring category is tracking policies that will influence the analysis and evaluation of potential options. Monitoring policy ensures that the formulation of options, adaptive pathways, and associated decisions made as a result of the CRIDA planning process are actually feasible and implementable.

While the need for monitoring is apparent, the process of monitoring has challenges. First, identifying ATPs for some parameters is always difficult. For example, tracking statistically significant change in parameters with high variability such as annual maximum discharge is difficult given a small sample size and a short historical record. As shown by Diermanse and colleagues (2010), changes in peak discharge trends for the Rhine River cannot be detected in advance over the coming one hundred years due to high variability despite the considerable length of historic observations.

Identifying ATPs for certain monitoring parameters is not the only difficulty. Financially supporting the institutional capacity for a thorough monitoring process may also be problematic. Financing for monitoring should be considered before the completion of the CRIDA planning process and included in the operations and maintenance costs for the system. The financial and/or institutional capacity to implement a monitoring process should be a primary consideration before selecting a final adaptation pathway.

A Step Beyond: An Invitation to Join a Community of Practice

Bottom-up vulnerability assessment procedures for water resources planning and design under uncertainty began less as a well-defined and planned methodology than as an awareness among a group of loosely connected practitioners from academia, operational agencies, and development banks of the need to share new insights and experiences because the status quo was not working.

Existing planning and design procedures were often not suited to situations facing deep uncertainty, and many felt we were managing past the limits of our knowledge rather than embracing the fundamental questions about best practices that arose when considering what we did and not know about the future. We realized that the insights for shifting from constrained uncertainty to accrued confidence should be gathered, organized, and ordered for our own application and use.

CRIDA was one product from this community that built on (and with) the earlier work of groups such as the World Bank, Deltares, the Netherlands Environment and Infrastructure Ministry, the U.S. Army Corps of Engineers, and AGWA (the Alliance for Global Water Adaptation), among many others. A small but global community of practitioners and thinkers trying to describe resilient water management was thus formed, almost by accident.

As a project, CRIDA began in 2010, but many of the individuals working in this area started even earlier. The circle of individuals using and refining bottom-up methodologies has grown rapidly. CRIDA, like many of these approaches, has grown between institutions, proposing a paradigm shift in the evolution of water resources planning procedures for the broader community to consider and further enhance to their needs. The organic quality for all of the bottom-up methodologies is important to note. We have effectively crowd-sourced CRIDA and other approaches to motivated members of the larger water community. As authors, we have channeled the insights and guidance of many individuals and institutions.

We live in a time when the art and science of managing a dynamic water cycle through rigid frameworks requires revisiting old assumptions. Change is difficult, and champions are needed in leadership positions as well as from practitioners in the field to both illustrate success and to provide shared insights that might otherwise remain unpublished and lost. No single institution, discipline, region, or methodology is the single source of "resilience," and surely our knowledge of what works in a time of change and uncertainty will continue to evolve rapidly. In a time when water management practices are undergoing a profound change, we must gather excellence from many fields.

To stimulate debate, mobilize resources, and improve application through mutual learning, the World Bank, the Stockholm International Water Institute (SIWI), and AGWA launched a bottom-up knowledge platform in early 2018 to encourage and accelerate the exchange of new lessons and examples around resilient water resources management. Called AGWAGuide.org, this knowledge platform is designed to promote and gather advances and applications of bottom-up approaches to new audiences and challenges. Upon the publication of CRIDA, we will add UNESCO IHP to this team.

The UNESCO International Hydrological Programme (IHP) embraces the CRIDA approach to address climate change uncertainty, and to start identifying adaptation pathways using local knowledge. This bottom-up approach requires integration of local actors in all steps of the process, and is a key component to a successful transition to more robust water resources management. CRIDA is a participatory approach that touches on several of UNESCO's focus areas. Although it is rooted in the water and ecological sciences, aspects of the Local and Indigenous Knowledge Systems (LINKS) Programme could prove crucial to effectively embed CRIDA locally. But UNESCO also acknowledges the key role of women in the provision, management, and safeguarding of water, making gender equality in (future) water management and planning a global priority. CRIDA will therefore also benefit from gender mainstreaming to strengthen social inclusion in the decision making process, in support of the eradication of poverty and towards environmental sustainability.

Addressing water-related hazards and climate change is a key component of the UNESCO IHP's Global Network on Water and Development Information for Arid Lands (G-WADI)

Programme, and CRIDA is therefore adopted as one of the methodologies for resilient water decision making. Through capacity building of stakeholders in UNESCO Member States, case studies will be developed and documented from around the globe that apply the CRIDA approach for locally relevant applications. These case study examples will further strengthen the science base for CRIDA's propagation and adoption as a water planning and management tool, while simultaneously providing potential users with hands-on learning materials based on real-world applications.

We invite readers to join this virtual community of practice, to expand on and improve CRIDA, so that together we can all find greater confidence and a surer footing on the path of resilience.

Glossary of Terms

Actions, measures. Both terms are used interchangeably within CRIDA as neutral terms devoted to all adaptation responses. Most commonly, they are responses (e.g., infrastructure, spatial planning, capacity building) taken to decrease climate risks. Actions and measures may also be instrumental or policy steps necessary to make certain measures possible or to stimulate others to respond.

Adaptation pathway. A sequence of adaptation actions or measures to achieve objectives under changing future conditions. Within CRIDA these pathways are used in the context of planning and design. Adaptation pathways may be considered as part of an adaptation plan. Central to the adaptation pathways concept are **performance thresholds**. When a performance threshold is reached, known as an **adaptation tipping point**, additional actions are needed to reach the defined objectives. Also known as Dynamic Adaptation Policy Pathways (DAPP).

Adaptation tipping points. Sometimes called ATPs, adaptation tipping points are triggers to consider alternate **adaptation pathways**.

Analyst, the. A person representing the CRIDA target audience, who will apply the guidance to support decision making. The analyst may adopt different roles depending on the expertise required in each CRIDA step. A policy analyst may be distinguished from the system (hydrology, ecology, economy, governance) analyst or the stakeholder engagement specialist, but they are all part of the planning team. Analysts working at a decision making authority could also be called technical decision makers. Analysts are supported by external experts through a consultancy.

Climate risk. A climate-induced hazard with a certain probability for impacting communities and assets exposed to the hazard. These consequences can also be decomposed into vulnerability X exposure. CRIDA quantifies the climate risks within a certain climate state (future, present) but does not evaluate the probabilities that a certain climate state will occur.

Critical performance thresholds. Critical performance thresholds define an acceptable level of system performance. They inform the stakeholders when the system does not meet its objectives anymore and will fail due to changes in external conditions.

Decision criteria. See **evaluation criteria**.

Decision rules. See **evaluation criteria**.

Decision scaling. A method for developing robust strategies by understanding **performance thresholds** using a **stress test**.

Discounted cash flow analysis. A financial method to evaluate the benefits and/or costs of a project, program, or activity, which uses a discount rate to incorporate the time value of money and the risk premium of a decision.

Evaluation criteria. Categories used to assess and compare alternatives or measures, including effectiveness, efficiency, flexibility, and feasibility. Evaluation criteria are often measured through **performance metrics**.

External driver / external stressor. Independent inputs to a water resources system that result in changes in performance, such as urbanization, rainfall, or demand.

Flexibility. The ability to increase the resilience and robustness of a system with increasing insights and with little or no regret for past decisions.

Integrated Water Resources Management (IWRM). Defined by the Global Water Partnership as a "process that promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems."

Performance metrics. Direct or indirect indicators of system performance in terms that can be related to planning and design objectives. Performance metrics are also important inputs to the monitoring framework. In a decision making process not all stakeholders around the table have the same weight or clear a priori quantifiable objectives. Therefore, CRIDA distinguishes between a small number (one to three) of primary or key performance metrics linked to main objectives (which should be reached) and other performance metrics linked to secondary objectives (that should ideally also show positive scores).

Performance threshold. See **critical performance thresholds**.

Planning. In CRIDA**,** planning is a procedure that starts with a problem or opportunity definition, including the formulation of at least one alternative to a "no action" proposal and the justification of a recommended set of alternatives.

Resilience. The ability of a socioecological system to recover quickly and without significant permanent damage.

Robustness. The ability of a system to remain functioning under a large range of disturbance magnitudes. In addition to being a characteristic of a system, robustness can also be a characteristic of decision making itself (e.g., robust decision making), meaning a plan is performing well across a large range of uncertainties.

Scenarios (ex-post and ex-ante). A future state of the world as defined by a specific value or range of values for each uncertain parameter. Ex-post scenarios are based on observations rather than forecasts of the future, while ex-ante scenarios are based on forecasts rather than observations.

Shelf-life. The point at which an action or measure no longer meets the defined system objectives, sometimes also referred to as a use-by date or condition or an **adaptation tipping point**. The shelf-life of the action or measure is often defined in terms of a hydro-meteorological driver (i.e., change in precipitation) or a socio-economic driver (i.e., change in demand). However, where there is a high understanding of the expected changes in the driver, timing can also be used and referred to as the shelf-life date. A synonym for both is the term adaptation tipping point, which can be expressed both in time and condition change.

Stress tests. Stress tests within the framework of CRIDA are a procedure in which a water system is exposed to *ex-post* scenarios to identify system vulnerabilities, especially as defined by the **critical performance thresholds.** The conditions at which the system starts to fail are also called **adaptation tipping points. Decision scaling** is a particular advanced method for performing a stress test using performance thresholds and is a key part of Step 2 in the CRIDA approach.

Sustainability. Meeting economic, environmental, and social objectives now and in the future, as defined by the Brundtland reports (1987). Given the uncertainties associated with changes in future pressures and needs, a sustainable plan, project, or policy should also have characteristics such as robustness, resilience, flexibility, and/or adaptability.

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