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Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework

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Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework

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FOREWORD

The Water Research Foundation (WRF) is a nonprofit corporation dedicated to the development and implementation of scientifically sound research designed to help drinking water utilities respond to regulatory requirements and address high-priority concerns. WRF's research agenda is developed through a process of consultation with WRF subscribers and other drinking water professionals. WRF's Board of Trustees and other professional volunteers help prioritize and select research projects for funding based upon current and future industry needs, applicability, and past work. WRF sponsors research projects through the Focus Area, Emerging Opportunities, and Tailored Collaboration programs, as well as various joint research efforts with organizations such as the U.S. Environmental Protection Agency and the U.S. Bureau of Reclamation.

This publication is a result of a research project fully funded or funded in part by WRF subscribers. WRF's subscription program provides a cost-effective and collaborative method for funding research in the public interest. The research investment that underpins this report will intrinsically increase in value as the findings are applied in communities throughout the world. WRF research projects are managed closely from their inception to the final report by the staff and a large cadre of volunteers who willingly contribute their time and expertise. WRF provides planning, management, and technical oversight and awards contracts to other institutions such as water utilities, universities, and engineering firms to conduct the research.

A broad spectrum of water supply issues is addressed by WRF's research agenda, including resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide a reliable supply of safe and affordable drinking water to consumers. The true benefits of WRF's research are realized when the results are implemented at the utility level. WRF's staff and Board of Trustees are pleased to offer this publication as a contribution toward that end.

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EXECUTIVE SUMMARY

OBJECTIVES

While water agency managers are accustomed to adapting to changing circumstances, climate change adds a layer of complexity to already substantial challenges (Anderson et al. 2007; Groves et al. 2008a; Miller and Yates 2006; Yates and Miller 2011). Utilities face three key planning challenges as they seek to identify and manage climate change risk. First, the potential impact of climate change must be reflected in the planning tools used for evaluation and management of water resources. Second, the planning framework must appropriately address the profound uncertainty that climate change introduces. Lastly, to develop a successful risk-management strategy, the framework must evaluate dynamic strategies that consist of near-term actions and deferred actions that could be implemented as conditions warrant. As future conditions become increasingly less certain, there are implications for the success of long-term plans (Groves and Lempert 2007; Lempert, Popper, and Bankes 2003). Accordingly, decision processes responding to these changes are necessarily evolving away from a deterministic prediction-based paradigm to one based on vulnerability identification and adaptation planning (Brekke et al. 2009; Freed and Sussman 2006).

This report highlights Robust Decision Making (RDM), a quantitative, iterative analytical framework that responds to the above challenges and needs of water utilities. The primary objective of this report is to present guidelines for RDM by means of simplified examples (Chapter 2), followed by detailed implementations of RDM guidelines in two pilot studies: Colorado Springs Utilities (CSU) (Chapter 3) and New York City Department of Environmental Protection (DEP) (Chapter 4). These primary objectives are bookended by an introductory chapter (Chapter 1), which includes (along with portions of this Executive Summary and the Appendices) a review of climate vulnerability assessment so far, and a concluding chapter (Chapter 5) that brings together lessons learned.

BACKGROUND

In the past decade, several utilities began to explicitly address climate change in their planning processes to varying degrees and using different approaches. Experience has accumulated, especially among larger water utilities, in identifying the potential risks posed by climate change, quantifying the potential impacts on water systems as they are currently configured and operated, and modifying plans to mitigate future climate impacts. This experience has been documented as case studies in reports funded by the AwwaRF/Water Research Foundation (Miller and Yates 2006; Yates and Miller 2011), the Water Utility Climate Alliance (Barsugli et al. 2009; Means et al. 2010), the Association of Metropolitan Water Agencies (Cromwell et al. 2007), and the United States Environmental Protection Agency (EPA) (EPA 2010, 2011, 2012).

The narrative that emerges from the accumulated experience is that much of water utilities' early focus was on risk identification. Activities were concentrated on understanding climate change science, developing methods for downscaling climate projections, and producing guidelines on possible climate change impacts of relevance to utilities. The latter range from the very general (Cromwell et al. 2007; EPA 2010) to more detailed (Miller and Yates 2006; EPA 2011). In moving from risk identification to risk assessment, the language of vulnerability assessment has been favored, in recognition of the fact that several assessments tend to be qualitative, whereas "risk" implies a more quantitative (probabilistic) focus. For example, EPA (2011) summarizes the vulnerability assessments for four utilities to illustrate the range of approaches that the utilities have adopted, and how the specific choices differ (for selection of emissions scenarios, global general circulation models, downscaling methods, modeling tools, and specific analytical methods).

In light of the deep uncertainties that climate change adds to the many non-climate uncertainties, moving from risk identification to vulnerability assessment, and then to risk management, requires an adaptive planning approach (EPA 2011), embedded within sound Integrated Water Resource Management (IWRM) practices (Yates and Miller 2011).[1] Given the significant challenges in implementing IWRM in the context of adaptation to climate change, decision science and analytical methods have been proposed for guiding vulnerability assessment and adaptation planning. For example, Means et al. (2010) provides an overview of the benefits and limitations of five leading decision support methods: classical decision analysis, traditional scenario planning, RDM, real options, and portfolio planning. Of these five, all but RDM require assigning probabilities to uncertain dimensions of the decision problem. Yates and Miller (2011) also focus on decision analytics, demonstrating its application through detailed case studies for a different set of utilities. Their work, alongside a body of work from the RAND Corporation and its partners, highlights the central role of iteration in decision support for water utilities. At a much broader national level, the National Academy of Sciences (NAS) has championed adaptive and iterative risk management as the most useful framework for dealing with climate change (NAS 2011). These confluences are reflected in this report's focus on RDM, an iterative, quantitative framework for vulnerability assessment and risk management, as applied to water utilities.

APPROACH

The study was undertaken with four guiding tasks in mind in order to develop a research methodology that may assist other utilities in evaluating, selecting, and prioritizing climate change adaptation strategies:

1. Synthesize knowledge on climate risk identification and assessment.
2. Develop a vulnerability assessment and management framework.
3. Pilot test the framework for the New York City water supply system.
4. Pilot test the framework for Colorado Springs Utilities within a formal IWRM plan.

The synthesis of knowledge is reflected in the literature referenced throughout and in cases summarized in the Appendices. The second task resulted in the development of the guidelines for RDM, found in Chapter 2, while the pilot tests are covered in Chapters 3 and 4, as well as in the Appendices.

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[1] A widely used definition of IWRM from the Global Water Partnership states that "IWRM is a process which 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" (Hassing et al. 2009).

RESULTS AND CONCLUSION

RDM is implemented in a sequence of steps detailed in Chapter 2: Participatory Scoping, System Evaluation Under Uncertainty, Vulnerability Assessment, Developing Adaptation Options, and Risk Management (through trade-off analysis amongst the adaptation options). The RDM application for CSU focuses on the stages through vulnerability assessment, while the application for DEP takes implementation through all the steps, including Risk Management.

System evaluation for each pilot used different, existing models that have been developed over several years by the respective utilities. Other steps of RDM used common tools in both studies: most importantly, the Participatory Scoping step (organizes the key factors of analysis in terms of the key uncertainties, options [or levers], performance metrics, and relationships), and the statistical analyses for the Vulnerability Assessment step.

Interestingly, future hydro-climatology and demand for water emerged as common key uncertainties for both pilot utilities. Water quality and regulatory regimes were additional factors important for DEP, given its focus on continued delivery of unfiltered water from rural, upstate New York. At CSU, imported water sources and associated infrastructure were additional factors of interest. Performance metrics distilled through the XLRM metrics clearly reflected these common and individual preferences. In both pilots, alternatives were evaluated against a baseline comprised of the existing plans.

CSU's Vulnerability Assessment evaluated tens of thousands of futures. Despite this large number, this project did not consider all plausible risks that were identified in the CSU planning process. Several key findings relevant to long-term planning were highlighted:

- CSU's current system is generally robust to a wide range of plausible current hydrologic conditions. Even when faced with different combinations of plausible risks, reliability remains high. If CSU successfully implements its build-out infrastructure plan, its system will remain highly reliable over the coming 50 years if it faces hydrologic conditions similar to the recent past.
- However, if hydrologic conditions are more consistent with some global climate model future projections and estimates of paleoclimatic conditions,[2] then future reliability and resilience could decline significantly.
- The CSU build-out system is generally reliable provided that combined total annual mean streamflow is greater than about 103 thousand acre-feet per year (kafy), regardless of demand uncertainty and the other risks evaluated. If flows are lower than 95 kafy, the CSU system will perform poorly under all demand projections and risk assumptions. For intermediate flows, the risk factors could play an important role in determining future reliability—particularly reductions in diversions from the Colorado River.

For the DEP application, 252 futures were evaluated and four adaptation alternatives were compared: (1) increasing capacity of the Catskill Aqueduct, (2) making operational chang-

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[2] Paleoclimatic conditions are those from hundreds to thousands of years ago, derived from tree rings, lake sediments, and other natural sources.

es, (3) augmenting supply, and (4) implementing all three of these options simultaneously. Key findings for the DEP system were:

- DEP's system may not be able to meet specified water quality or water reliability targets under many plausible future conditions based on the preliminary analysis presented, even with the investments already planned for the Baseline system.
- Higher-than-expected demand may be an important determinant of when DEP's system would no longer meet specified water quality targets.
- Turbidity thresholds and changes in climate can lead to a wide range of outcomes, even with the same level of demand. The complex interaction between turbidity and climate suggests that it is worthwhile for DEP to continue research efforts in this area.
- From a risk management perspective, the adaptation options considered in this analysis may not be sufficient for addressing specified water reliability goals in the long term future; DEP may wish to consider a wider range of options.
- Inability to adequately characterize the uncertainty in future climate, specifically with respect to extreme event frequency and intensity, underscores the preliminary nature of the analysis and its conclusions. However, the methodological framework is robust and could be re-applied as climate science is able to provide better estimates of future conditions in order to obtain more precise conclusions.

APPLICATIONS AND RECOMMENDATIONS

This project offers practical guidance to the water industry on how to address climate change risk at a time when many agencies across the United States are updating their long-range plans. The type of approach presented in this study, to assess and identify climate change risk and then evaluate and prioritize risk management strategies, can directly influence the approach and scope of agency Capital Improvement Plans, Strategic Plans, or Integrated Resource Plans.

In both pilots, the participatory scoping stage was found to be a very important stage. The formal and structured deliberation using XLRM proved useful for distilling key uncertainties, response strategies, performance metrics, and possible adaptation options.

The RDM applications documented here point to priority areas for investing resources that can reduce uncertainty in the future. For example, the DEP study noted the importance of developing better population/demand and turbidity-flow relationships and of obtaining better estimates of future climate, especially with respect to extreme event frequency and intensity, which at present add large uncertainty to the potential impacts and adaptation potential of various strategies. While DEP recognized that these three issues were important prior to the project, the full RDM analysis quantitatively revealed the importance of these issues compared to other uncertainties analyzed as part of this project.

Implementing RDM poses challenges (Groves and Lempert 2007). One of these, which equally applies to any other framework, is that the state of knowledge of the relationships of some key factors to the decision problem may not be mature; for example, the flow-turbidity relationships that are so important for DEP. The challenge that is specific for RDM (and all iterative approaches in general) is the need for substantial computing and analytical resources. A third challenge is that there is no guarantee that the key vulnerabilities identified by the analysis will be easily interpretable or a useful basis for developing risk mitigation strategies. However, as the state of knowledge of water resource systems improves, the RDM framework can be applied with updated knowledge, providing new insights and possible solutions in keeping with the spirit of iterative, adaptive planning. This makes RDM an important addition to the IWRM toolkit.

CHAPTER 1: INTRODUCTION AND MOTIVATION

1.1 CHALLENGES IN ADDRESSING CLIMATE CHANGE AND OTHER UNCERTAINTIES IN LONG-TERM WATER RESOURCES PLANNING

Water agencies have always faced uncertainty when planning for the future. Traditional planning methods are based on the assumption of *hydrologic stationarity*—that future hydrologic conditions will be statistically similar to those recorded in the recent historical record (beginning typically sometime in the early 1900s). Scientific evidence is mounting, however, that future climate and hydrologic conditions will be significantly different from those in the past due to the continued accumulation of greenhouse gases (GHGs) in the atmosphere, and the associated changes in climate (Bates et al. 2008; Milly et al. 2008; IPCC 2007). The timing, magnitude, spatial patterns, and dynamic feedbacks that climate change will have on future hydrologic conditions are highly uncertain.

This climate and hydrologic uncertainty, coupled with growing urban demands, new environmental requirements, and water quality regulations poses challenges to the success of water agencies' plans (Miller 2008; Groves et al. 2008c; Lempert and Groves 2010). Warming from climate change will increase landscape and agricultural irrigation requirements (Brown, Foti, and Ramirez 2013). Persistent shifts in precipitation patterns due either to natural variability or climate change will affect yields of existing water systems (Brown 2010). Managing these uncertainties will require many water agencies to invest in new infrastructure and revise management procedures to ensure supply reliability and regulatory compliance (Kessler 2011).

Without knowing the statistical properties of future conditions, the application of standard reliability analyses is less appropriate than in the past (Brown 2010; Craig 2010; Connell-Buck et al. 2012). Likewise, more classical decision theoretic methods such as traditional optimization based approaches can be difficult to articulate for policy-relevant water resource decision problems. Inherent non-linearities, un-structured and often sparse data; fluctuating policies; complex economic, social, and natural conditions; and spatial and temporal complexities make problem formulation difficult.

Many water managers and planners have begun using Integrated Water Resource Management (IWRM) tools and principles to help guide planning in the face of considerable uncertainty, including climate change. While there are many definitions of IWRM, Bromley (2005) suggests that it is "simultaneously a philosophy, a process, and an implementation strategy to achieve equitable access to, and sustainable use of, water resources by all stakeholders at catchment, regional, national, and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits." A more recent definition from the Global Water Partnership states that "IWRM is a process which 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" (Hassing et al. 2009).

Typical of many descriptions of the climate change risk management process (Lopez et al. 2009; EPA 2010, 2011), the Water Research Foundation (WRF) Project 3132, *Climate Change and Water Utility Planning, Decision Analytic Approaches*, outlined a structured, four-step, iterative process meant to help utilities examine climate risk and adaptation alternatives in the face of uncertainty (Yates and Miller 2011). While informative, the steps outlined in the report were generic and prescriptive. Moreover, they did not provide specific guidance for how to assess uncertainty or evaluate risk under conditions of deep uncertainty, which pervade long-term climate adaptation planning efforts.[3] In contrast, the approach to vulnerability assessment and risk management described in this report is designed to address deeply uncertain planning challenges. It explicitly uses iteration to support an exploratory analysis of vulnerabilities and identification of robust risk management strategies.

Generally, the past decade has seen considerable interest by the water utility community in exploring the potential impacts of climate change. This period has been referred to by David Behar, Climate Program Director of the San Francisco Public Utilities Commission and former director of the Water Utility Climate Alliance, as an era of assessment, as there are very few examples of water utility actions or adaptations directly linked to "climate change" (Wald and Schwartz 2012). The next era will be one of action, as water utilities grapple with large infrastructure investment decisions, and include climate change in their risk management and decision processes.

To begin considering climate change and other uncertainties in long-term water plans, many utilities develop future projections reflecting, for example, possible changes to hydrology and demographics.[4] Although it would be desirable to develop probabilities for each projection and employ this information using traditional reliability analysis, there is no single accepted, valid approach for doing so (Groves et al. 2008a). Instead, these projections are often used to stress-test plans developed based on historical conditions—an analysis that can be performed without ascribing any particular confidence intervals to the accuracy of the projection forecasts. In some cases, an agency can use this information to begin formulating contingency plans. However, in many cases it is not clear how to use this information in agency decision making as they grapple with questions such as:

- Should we prepare for the worst projection or the middle projection?
- Are these the best projections to use for our planning?
- What if there are other important projections that we did not consider?

Many recent research efforts have sought to define approaches for addressing climate change uncertainty and taken steps towards defining best practices. For example, the WRF Tailored Collaboration project, the *Joint Front Range Climate Change Vulnerability Study,* involved six utilities. The study focused almost entirely on identifying climate change vulnerabilities to the six utilities' water supplies by selecting appropriate global climate models (GCMs), developing adjusted historical climate projections, and employing hydrologic simulations (Woodbury et al. 2012). WRF Project 3132, *Climate Change in Water Utility Planning: Decision Analytic Approaches* (Yates and Miller 2011), summarized several case studies of water utilities that involved vulnerability assessments. In two cases, the Inland Empire Utilities Agency (IEUA) and

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[3] Deep uncertainty occurs when stakeholders and decision makers do not agree on how likely or desirable future conditions might be (Lempert et al. 2006).

[4] Utilities and other agencies often refer to projections of a single variable or set of variables as "scenarios." In this report we reserve the term "scenario" to describe a unique combination of futures that describe conditions most relevant to the future performance of a water management system.

Palm Beach County Water Utilities Department (PBCWUD), the utilities underwent a comprehensive risk assessment and management process.[5]

Uncertainties about climate change and other trends pose new challenges to implementing IWRM. New tools and approaches are needed, a premise which was a central tenant of the original Request For Proposal 4262 from WRF, *Vulnerability Assessment and Risk Management Tools for Climate Change: Assessing Potential Impacts and Identifying Adaptation Options*. An imperative of WRF Project 4262 is to provide "a mix of generalized guidance and tools across a wide array of circumstances and capabilities; and apply them to climate change challenges." The approach that we have developed and applied in this study is designed to systematically address both vulnerability assessment and risk management.[6]

1.2 A FRAMEWORK FOR EVALUATING CLIMATE VULNERABILITY AND DEVELOPING ADAPTATION STRATEGIES

This report describes a framework for supporting a broader IWRM process under climate change and other uncertainties through the identification of key vulnerabilities and risk management. The framework is referred to as "Robust Decision Making" or RDM (Groves and Lempert 2007; Lempert, Popper, and Bankes 2003) and is tailored to water planning based on experience gained through a variety of prior efforts (Lempert and Groves 2010; Groves et al. 2013a, b).

The process has a few central attributes:

1. **Supports an iterative and participatory dialogue.** Broad participation across the utility and strong leadership are imperatives throughout the process; the process should develop analytic results that support dialog with stakeholders and decision makers, that in turn provides new insights into what analysis ought to be performed next.
2. **Identifies a wide-range of uncertainties and plausible futures.** Climate change is only one of the many uncertain factors that affect water utilities. The many combinations of different uncertainties could lead to a wide array of plausible futures that should be explored.
3. **Explores across a spectrum of possible future climates.** Climate science is still maturing, but is informative. Climate projections based on a number of methods should be used. These include climate model outputs, regional climate modeling experiments, "downscaling," paleo-records, climate narratives, etc.
4. **Identifies key vulnerabilities.** From simple conceptual models to complex computer models, the process should help illuminate a water utility's vulnerability to climate and

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[5] The IEUA study was performed by RAND researchers (Groves et al. 2008a, b, c) led by Dr. Groves, and was designed to evaluate the use of new methods for decision making under uncertainty for water planning. The PBCWUD study was led by Dr. Yates, who worked with RAND and others to implement similar analysis that included Multi Criteria Decision Analysis (MCDA). MCDA is an analytical component of a highly participatory IWRM planning process, which included the consideration of climate change in infrastructure investment decisions that were being explored by the PBCWUD.

[6] We contend that risk management that considers climate change is synonymous with climate change adaptation planning; therefore we will use climate risk management exclusively in this report to mean both.

other uncertainties. This information is the best guide to the development of adaptation strategies.

5. **Seek robust strategies.** Given the large uncertainty of future climate and other factors, decision science methods should be brought to bear that can be used to develop adaptation strategies for water utilities that are robust across an array of performance metrics. Robust strategies in this context would be those that will achieve utility goals across a broad range of futures rather than those that are optimal under a single set of assumptions about the future. A variety of different performance metrics and methods can be used, ranging from simple approaches such as benefit/cost analysis to more complicated algorithms that account for competing and multiple interests, such as Multi Criteria Decision Analysis (MCDA).

RDM is different in some important ways from traditional planning approaches. First, RDM deemphasizes the sometimes arduous development of a few choice scenarios to reflect uncertainty. Rather it relies on computer simulation models to evaluate large ensembles of futures, and from the analytic results, it identifies a small set of scenarios that are relevant to risk management decisions. Second, because future climate and other long-term trends are so uncertain and agencies have only limited opportunities to prepare for the next 50 years, the RDM framework does not try to identify optimal strategies. Instead, it focuses on strategies that seek to be robust, strategies that are shown to perform sufficiently well under a wide range of alternative assumptions about the future. Third, rather than analytically identifying a single "preferred alternative," RDM highlights the tradeoffs among strategies. This information then informs a dialog about choices that necessarily requires the inclusion of subjective information about how severe risks might be and the willingness to invest to mitigate these risks.

This framework has been applied in a variety of water planning contexts in the United States and abroad. Descriptions of some of these can be found in the Appendices:

- IEUA (Groves et al. 2008a, b, c; Lempert and Groves 2010)
- California Central Valley (Joyce et al. 2011)
- California Sierra Nevada Mountains (Groves et al. 2013a)
- Applications in the United Kingdom (Dessai and Hulme 2007; Matrosov et al. 2013)
- Metropolitan Water District of Southern California
- Palm Beach County Water Utilities Department (O'Neil and Yates 2011)
- Colorado River Basin Study (USBR 2012; Groves et al. 2013b)

This study demonstrates the framework through two pilot projects with two utilities—Colorado Springs Utilities (CSU) and New York City Department of Environmental Protection (DEP).

1.3 ORGANIZATION OF THIS REPORT

Chapter 2 describes the methodological framework, focusing on the key steps required to implement the RDM process. Chapters 3 and 4 summarize the two pilot studies. Supporting materials are presented in the appendices. Chapter 5 provides concluding remarks. More details from the analyses undertaken for each of the pilot studies can be found in the Appendices.

CHAPTER 2: THE ROBUST DECISION MAKING FRAMEWORK

This study presents an analytic, objective framework to support long-term climate risk management. Specifically, it helps (1) define climate and other uncertain factors that may play an important role in the future performance of a water utility's management system; (2) identify uncertain factors to which the utility is most vulnerable; and (3) compare the tradeoffs among robust strategies—those that reduce vulnerability and manage future risks over a wide-range of plausible assumptions about the future.[7] Long-term climate risk management strategies should seek *robust* rather than *optimal* strategies, as our ability to predict future water management conditions is severely limited—particularly in the era of full- or over-allocation of water resources and a non-stationary, changing climate. In practice, this means developing water management strategies that are flexible and are comprised of near-term decisions that keep options open, so that acceptable outcomes are possible even if our best assumptions about future conditions do not hold.

The robust water management strategies identified by RDM are typically designed to be adaptive and evolve over time in response to new information, such as evolving water needs or supplies (Lempert and Groves 2010).[8] RDM helps structure an iterative evaluation of the performance of leading strategies against a wide array of plausible futures. It then supports a systematic identification of the key vulnerabilities of those strategies (Bryant and Lempert 2010; Groves and Lempert 2007). This information informs the development of adaptation responses to the identified vulnerabilities (Lempert and Collins 2007; Lempert, Popper, and Bankes 2003). Successive iterations develop and refine strategies that are increasingly robust. Final decisions among strategies are made by considering the key tradeoffs among a few robust strategies.

Importantly, RDM can help long-term water planning processes even when stakeholders and decision makers may have strong disagreements about which risks are most likely and which outcomes are most important (Groves and Lempert 2007; Lempert and Popper 2005). To do so, RDM follows an interactive series of steps consistent with the "deliberation with analysis" decision support process described by the National Research Council (2009). We call this "Dialogue with Analysis" for the water planning context (Figure 2.1). It begins with stakeholders, planners, and decision makers working together to define the water management questions and develop the scope of the analysis to be performed. Subsequent steps involve data collection, modeling, and analysis, along with deliberations based on this information in which choices and objectives are

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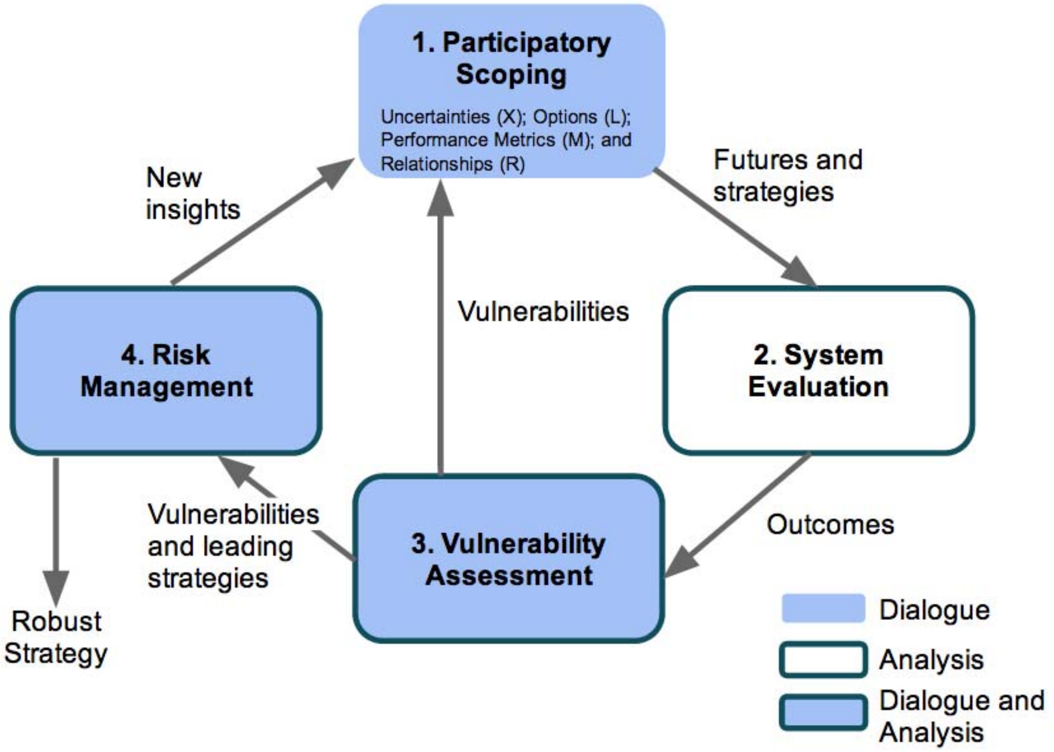
[7] RDM can accommodate different ways of thinking about future uncertainty (Lempert et al. 2007). Future assumptions could reflect different futures defined by combinations of specific projections of factors important to planning. For example, the California Water Plan Update 2013 developed nine land-use projections that differ due to population growth and housing density (DWR 2012). Future assumptions could also refer to different weighting schemes for a larger set of climate projections. Tebaldi and Sanso (2009) and Dettinger (2006) provide two approaches for weighting climate information.

[8] Two of the case studies summarized in Appendix C used RDM to develop adaptive, robust strategies—IEUA and the Colorado River Basin Study.

revisited.[9] RAND's RDM Lab (www.rand.org/rdmlab) provides information on the methodology and applications across a wide range of policy problems.



Based on Lempert et al. 2013a.

Figure 2.1 The Robust Decision Making framework for water planning

2.1 PARTICIPATORY SCOPING

The first step in RDM is dialogue—stakeholders, planners, and decision makers work together to structure the analysis. This step identifies the key uncertainties that a utility will likely confront and the metrics that describe how well the utility's future goals would perform. This step can also be used to define alternative adaptation decisions, such as investments or programs, and select or develop the relationships or models that will be used to estimate how the system will perform in the future.

Lempert, Popper, and Bankes (2003) introduced the "XLRM Matrix" as a useful tool for structuring dialog about these elements. The XLRM Matrix can be thought of simply as four boxes that document for an RDM analysis the uncertain factors or uncertainties (Xs) that define futures; the management decisions, options, or levers (Ls) that comprise alternative strategies; the performance metrics (Ms) used to describe outcomes; and the relationships or models (Rs) used to simulate a water management system (Figure 2.2).

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[9] The pilot studies summarized in Chapters 3 and 4 are documented more fully in the Appendices to provide examples of how RDM experimental designs can be configured.

A facilitator can use this matrix to record stakeholder or decision maker concerns about future possible risks and ideas for managing these risks. Its primary value comes from requiring each idea to be disaggregated into the core elements that can be clearly classified into one of these boxes. In this way, the XLRM dialogue helps develop a common language; distinguish between those things that are outside the control of the utility and those that it can directly or indirectly influence; and develop meaningful performance metrics.

For example, stakeholders may express concern that future extended droughts (an "X") will lead to reductions in available surface supplies for irrigation (an "M"). They may follow-up by stating that they would need to develop additional groundwater pumping capacity (an "L") to enable them to replace surface supplies with groundwater. They may finally express concern that pumping costs (an "M") will be higher than the costs of diverting surface flows, particularly if groundwater levels decline with increased use (an "R"). These reasonable conditions and concerns are articulated, disaggregated, and recorded in an XLRM Matrix as shown in Figure 2.2.

Uncertainties (X)	**Decisions, Options, or Levers (L)**
• Climate conditions • Historical conditions • Extended drought	• Current infrastructure • Expanded groundwater pumping capacity
Relationships or Models (R)	**Performance Metrics (M)**
• Surface/groundwater hydrology model	• Available surface supply • Costs of obtaining supply

Figure 2.2 XLRM Matrix reflecting an example stakeholder concern

Through the scoping dialog, stakeholders, planners, and decision makers can add additional information to the XLRM Matrix. The matrix ensures that all concerns are captured while minimizing redundancy of concepts that would occur if each concern were simply compiled into a long list. This step can also be revisited throughout a planning process. The first use may focus on uncertainties, metrics, and relationships. After an analysis of current vulnerabilities, stakeholders may then structure a dialogue around additional adaptation options.

While developing an XLRM Matrix is initially a qualitative process, quantitative information about the uncertainties and performance metrics is also required. First, ranges of plausible values or assumptions for the uncertain factors must be established. Different sources of information can be used for this purpose. Plausible ranges for climate or hydrologic variables, for example, can be derived from historical records, paleoclimate records, and GCM projections (Groves, Yates, and Tebaldi 2008; Brown, Foti, and Ramirez 2013). Second, performance metric thresholds are needed to define in which futures a particular management strategy would meet a utility's goals. For example, a utility may establish a goal that its system meets all demands in nine out of ten years without drought restrictions.

The XLRM Matrix and supporting information provides the information needed to organize the systems evaluation in Step 2.

2.2 SYSTEM EVALUATION UNDER UNCERTAINTY

RDM seeks to evaluate the performance of water management strategies under a broad range of plausible futures, without an initial focus on the likelihood of the different futures. Predicting the uncertain future can often lead to bias and gridlock, and it may not bring water managers closer to agreement on how best to proceed or understand the merits of a chosen strategy. Using simulation models to define outcomes under a broad-range of assumptions about the future is increasingly considered best practice in climate change planning and decision support (NAS 2011; Lempert et al. 2013b).

In this step, which is largely analytical, the analysts first use the uncertainties defined in Step 1 to develop a set of futures to be evaluated. A model (or suite of models) estimates how each strategy would perform for each future. The entire set of simulation model runs is called the experimental design.

The experimental design is typically defined such that each uncertainty is sampled broadly and uniformly. Figure 2.3 shows how an RDM sampling approach differs from a probabilistic and traditional scenario approach. The top pane shows an assumed likelihood distribution for a hypothetical uncertain factor (blue curve). A Monte-Carlo, probabilistic sampling approach would sample proportionally to a specified likelihood distribution. For the illustrative case shown in the figure, more samples (eleven) are taken from the left half of the distribution, reflecting the higher assessed likelihoods for that portion of the uncertain factor range. In contrast, only five samples are taken from the right half of the factor range. Since the derived weights will influence the results of the analysis, there needs to be agreement on the shape of the distribution. In many cases, discussions about the nature of these distributions can take a significant amount of time and even jeopardize the acceptance of the analysis by diverse groups.

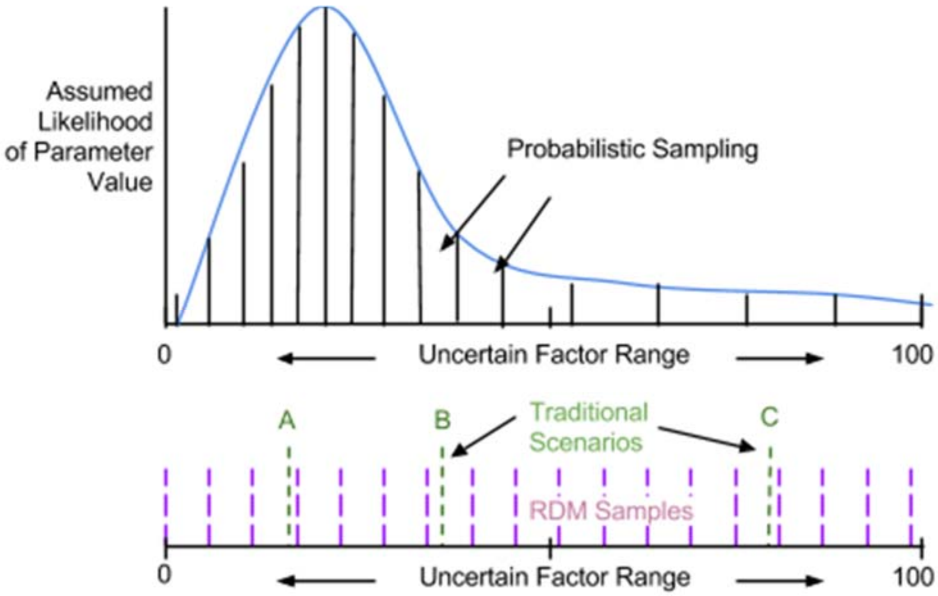

Figure 2.3 Example of a probabilistic, traditional scenario, and RDM sampling approach

The bottom panel shows the sampling across the same factor range for a traditional scenario approach (green, short-dashed lines) and an RDM sampling approach. Note that the traditional scenario approach generally uses a small number of samples which may or may not be uniformly distributed across the range. Similarly to the probabilistic approach, a traditional scenario approach requires important decisions be made about what values to specify for the small number of scenarios. This also can be contentious as individual stakeholders may advocate for the analysis of those scenarios that they believe will justify their preferred strategy.

Traditional scenario planning and probabilistic planning use samples to describe what the future will bring. RDM uses samples in a fundamentally different way. The samples are used iteratively to stress test strategies across a wide range of possible future conditions without making judgments about whether one future is more likely than any other. Thus, analysts sample uniformly across the range of plausible values to ensure that all viewpoints about the future are represented, but are not judging whether one sample is more likely than another.[10] This understanding helps analysts design hedging options to protect against those vulnerabilities.

In some cases, the experimental design can be full factorial, where each combination of different uncertain factors is included. For example, a full factorial design for 12 climate projections and 3 demographic projections would include 36 futures (i.e. 12 x 3 = 36). When many variables are included in the experimental design, a full factorial design can become very large. For example, the number of futures in a full factorial design for six factors, each with three values, would result in $3^6 = 729$ futures, and thus is potentially computationally expensive. In these cases, a Latin Hypercube sampling scheme (McKay, Beckman, and Conover 1979) can be used to help uniformly sample across the factor space without requiring all combinations of uncertain factors to be included. To develop a simple Latin Hypercube sample, for example, one first uniformly samples across each uncertain factor by the total number of samples to be developed, say 50. Next, one randomly selects one of the 50 selected values for each of the uncertain factors—these selected values comprise one future. After selecting a value, it is not eligible for selection again. This random sampling process is then repeated 49 more times to develop 50 futures.

Thus, both vulnerability assessment and risk management analyses can require the generation of large databases of results. In some applications, a small number of laptop computers are sufficient to handle the computational requirements. In other cases a large computer cluster or multi-processor server is required. The computational requirements depend upon (1) the computing time needed to simulate the management system for a single future, (2) the number of futures developed to reflect uncertainty, (3) the number of strategies evaluated, (4) the number of iterations of analysis performed, and (4) the amount of time available to evaluate cases. It is common to make tradeoffs between the number of futures and number of strategies when computationally intensive models are needed to evaluate future performance. Fortunately it is usually not difficult to distribute the required runs across many different computers.

This step produces estimates of system performance based on the metrics or goals defined in Step 1. These outputs could include simple metrics such as water demand by user-type, water supplied over time and across the management system, and unmet demand. They can also include more derived metrics such as reliability (e.g. the percentage of years in which a specific share of water demand is supplied) or safe yield (e.g. the level of yield that is available in nine out of ten years). The outputs can also include environmental and financial metrics such as minimum in-stream flows and costs of service provision.

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[10] Note that a probabilistic analysis could also sample uniformly, but then weight the futures proportionally to an assumed likelihood distribution.

2.3 VULNERABILITY ASSESSMENT

In Step 3, which combines analysis with dialogue, the stakeholders, analysts, and decision makers work together to evaluate the simulation results from Step 2 and define the key vulnerabilities of a utility's plan. This step defines "vulnerable conditions"[11]—combinations of external, uncertain factors that lead a utility to not meet its management goals.[12] This information helps facilitate discussions about how to develop strategies that are more robust, how to compare alternative robust strategies, and what future conditions ought to be monitored to inform adaptation of an agency's long-term plans (Groves and Lempert 2007; Lempert and Groves 2010).[13]

Specifically, analysts first evaluate the results from the simulations in Step 2 and determine in which futures the management strategy or strategies do not meet the agency's management goals. Next, a *scenario discovery* process is used, often with stakeholders and decision makers, to define a small number of scenarios, or vulnerable conditions, to which the strategy is vulnerable. The information about vulnerable conditions can help define new management options that can be used to test strategies more robust to those vulnerabilities—shown by the iterative arrow that returns to Step 1 in Figure 2.1. Alternatively, the vulnerable conditions provide information for comparing the tradeoffs among different strategies—shown by the outbound arrow to Step 4 in Figure 2.1.

The vulnerability analysis helps decision makers recognize those combinations of uncertainties that require their attention and those they can more safely ignore. Recall that the uncertainties include numerical, statistical, or conditional characteristics that are evaluated in Step 2. In water management studies, these may include aspects of the future climate, e.g. changes in daily, monthly, and seasonal temperatures and precipitation; uncertainty in future population, per-capita demand, demand patterns; the regulatory or legal environment; environmental conditions; energy concerns; etc. (Groves et al. 2008a).

If the number of uncertainties is small, visual inspection might suffice to elicit the vulnerable conditions. If the problem is multidimensional, with many different uncertainties that interact in complex ways, then quantitative statistical methods or data mining algorithms can help find the combination of uncertainties that give rise to those vulnerable conditions. In this case, the analyst must choose the most appropriate analytical method or methods. With many factors, statistical algorithms such as the Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999) have been used in a variety of applications. Other algorithms such as Classification and Regression Tree (CART) (Bryant and Lempert 2010) or principal component analysis combined with PRIM (Dalal et al. 2013) have also been used.[14]

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[11] In the RDM literature, these vulnerable conditions are often called "policy- or decision-relevant scenarios," as they represent the scenarios that lead to a set of decisions that perform poorly. Thus they are the conditions in which alternative decisions are needed.

[12] Management goals are defined by the performance metrics and thresholds established in Step 1.

[13] For example, the Colorado River Basin Study (USBR 2012) used this approach to define dynamic portfolios of management options and the streamflow conditions that would trigger investments in new supply augmentation or demand reduction options.

[14] Lempert, Bryant, and Bankes (2008) compare the use of PRIM and CART to identify vulnerabilities. Dalal et al. (2013) describes how, in some cases, transforming the database of scenario inputs using principal component

The basic approach of all of these methods, regardless of their complexity, is to distill the large amount of information generated in Step 2 down to what is most relevant to decision makers and stakeholders. This requires not only defining conditions that lead to vulnerabilities, but also ensuring that they are easily *interpretable*. Usually, the smaller the number of uncertain factors used to describe the vulnerable conditions, the higher the interpretability.

Often an agency is vulnerable to more than one set of vulnerable conditions. For example, a first set of vulnerable conditions might define a specific combination of urban demand growth and climate conditions that would lead the agency to miss its water reliability goals. A second set of vulnerable conditions might occur under less extreme growth and climate conditions if a new instream flow requirement were also implemented. A first set of vulnerable conditions could be defined as:

- Urban demand growth > 3 percent per year and
- Average annual precipitation < 95 percent of the historical average

A second set of vulnerable conditions could then be defined as:

- Urban demand growth > 2 percent per year and
- Average temperature rise of 2 degrees C and
- Implementation of new instream flow requirements

There are no "correct" definitions of vulnerable conditions, and there is a natural tension between how broad or how narrow the definitions should be. Broad definitions of vulnerable conditions will result in a higher number of futures from the full population that are vulnerable, or do not meet the goals of the utility. This results in high coverage, where coverage is defined as the ratio of the number of futures represented by the vulnerable conditions that do not meet utility goals to all futures that do not meet utility goals. Problematically, a broad definition of vulnerable conditions will likely include a number of futures that are not vulnerable or do meet utility goals. This results in low density, where density is the ratio of futures that are represented by the vulnerable conditions and do not meet utility goals to all futures that are represented by the vulnerable conditions. The example below illustrates these key points.

In contrast, narrow definitions of vulnerable conditions are more focused and will thus define fewer of the vulnerable futures. They have lower coverage but higher density. Ideally, all the futures represented by the vulnerable conditions would not meet agency goals (i.e. 100 percent density) and the vulnerable conditions would describe all the futures that do not meet agency goals (i.e. 100 percent coverage).

An Illustrative Example

To illustrate how the vulnerability assessment process works, we present a simple hypothetical example (Figure 2.4). This example focuses on the long-term planning of a small water

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analysis can lead the PRIM algorithm to identify more interpretable vulnerabilities—those with higher concentrations of bad outcomes, for example.

utility whose raw water supply comes from a river intake that fills its supply reservoir. Through a participatory scoping exercise, the utility concluded that it wants to achieve “raw water storage above 75 percent of capacity, 90 percent of the time or more,” which the utility refers to as its safe yield. The utility has a water systems model, which simulates daily demand and supply and tracks water storage in its system. The utility’s record of water demand shows an annual average value of between 65 and 105 million gallons per day (mgd) over the past 30 years. This variability and the uncertainty of supply were used to determine the safe yield defined above. The utility is concerned about how climate change might impact its system, uncertainty about future demand, and the prospect of new wholesale customers. It has been provided ten climate change projections by its university partner, all suggesting warming but with a range of precipitation changes to wetter and drier conditions. The utility also has developed projections of future demand from a growing population, ranging from a low of 75 to a high of 120 mgd. The possibility of new wholesale customers is characterized by the size of the potential contract as large, medium, or small. There is disagreement about the likelihoods of the future contract sizes.

Uncertainties (X)	**Decisions, Options, or Levers (L)**
• Climate conditions • Demand for existing customers • Contract size for a new wholesale customer	• Current infrastructure • Other adaptation options to be determined
Relationships or Models (R)	**Performance Metrics (M)**
• Small Water Utilities Water Systems Model	• Safe yield

Figure 2.4 XLRM Matrix for simple numerical example

Following RDM, the utility developed an experimental design to evaluate a wide range of futures using its systems model. It used a Latin Hypercube sampling approach to specify twenty futures that uniformly sample across the ten climate projections, projections of future customer demand between 75 and 120 mgd, and three sizes of possible wholesale contracts (Small, Medium, or Large). The utility evaluated the performance of its existing system across these 20 futures and calculated the key performance metric (safe yield) for each future.[15] This information, along with the experimental design parameters, was compiled into a spreadsheet that is summarized in Table 2.1. As an example, Future 1 included a projection of total demand of 103 mgd, climate projection 7 (warmer and drier), and a large expansion of the wholesale customer base (L). For that future, the safe yield was calculated to be 91 percent.

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[15] The safe yield (SY) of the water system was found by counting the number of days (d) in the 30-year simulation where the reservoir storage fell below 75 percent of capacity, and dividing that number by the total number of days (N) in the simulation (N = 10,950 days). Thus, SY= (1-d/N)*100.

Table 2.1
Summary of sample experimental design and performance metric

Future	**Projections**			**Performance Metric**
Number	Demand (mgd)	Climate Change	Wholesale	Safe Yield (%)
1	103	7	L	91
2	101	9	M	85
3	119	1	L	89
4	105	2	L	91
5	77	3	M	94
6	96	6	M	89
7	113	8	L	77
8	105	4	L	90
9	89	10	M	91
10	81	6	M	92
11	115	4	L	87
12	111	7	S	91
13	110	3	M	91
14	84	8	L	88
15	96	1	S	93
16	91	4	M	89
17	84	2	M	92
18	85	5	S	91
19	90	1	M	90
20	107	9	L	79

Note: (L)arge, (M)edium, and (S)mall denote assumed size of future wholesale customers. Mgd=million gallons per day.

Figure 2.5 shows the result of each future with respect to each of the uncertain factors, where the climate projections are on the horizontal axis, water demand estimates are on the vertical axis, the size of symbol indicates the wholesale type; and the value under the mark is the safe yield result for that combination of factors.

Using PRIM, the utility then identified the vulnerable conditions that define their key vulnerabilities. In this case, the utility defined them as:

- Demand ≥ 95 million gallons per day (mgd)
- Climate projection: 6-10 (warmer/drier projections)
- Wholesale type: Medium or Large

These vulnerable conditions define a subset of futures, which in this case includes 5 of the 20 futures (i.e. support = 25 percent). Of the five futures that are described by the vulnerable conditions, four of them are vulnerable, or do not meet the goals set for safe yields. Thus the density is 80 percent. Four of the seven futures that fail to meet the safe yield goal are described by the vulnerable conditions, for a coverage of 57 percent. In summary, the statistics that define the quality of the defined vulnerable conditions are:

- Support: 5 of 20 = 25 percent (the ratio of futures described by the vulnerable conditions to the total number of futures)
- Density: 4 of 5 = 80 percent (the ratio of vulnerable futures to all futures described by the vulnerable conditions).
- Coverage: 4 of 7 = 57 percent (the ratio of vulnerable futures described by the vulnerable conditions to all vulnerable futures).

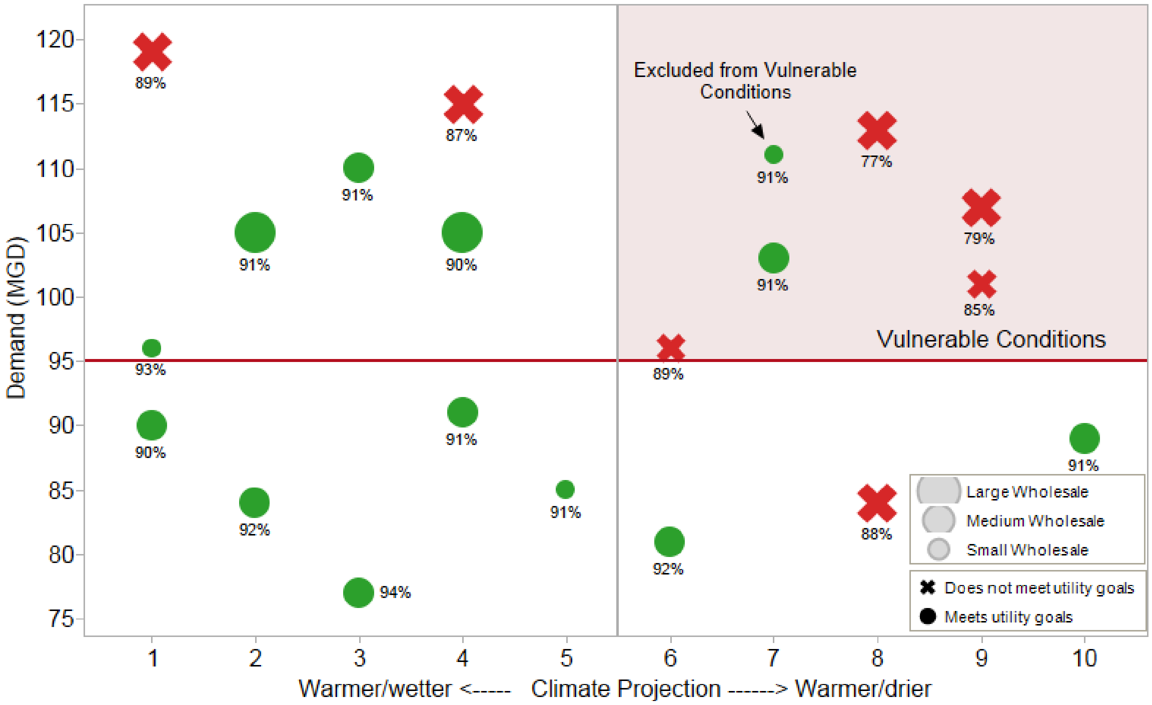

Figure 2.5 Graphical representation of the outcomes of the twenty futures with thresholds for the identified vulnerable conditions

Had the utility considered a simpler definition of vulnerable conditions based on only two criteria, climate and demand, as for example:

- Demand ≥ 95 mgd
- Climate Projections: 6-10 (warmer/drier projections),

then the density of the vulnerable conditions would be lower—only four of six futures consistent with the criteria would not meet the safe yield goal (67 percent density). The number of futures not meeting the safe yield goal would remain the same—four of seven.

This concise description of the utility's primary vulnerability was then included in a dialogue over what strategies could be implemented to improve reliability under these specific conditions.

2.4 DEVELOPMENT OF ADAPTATION OPTIONS TO ADDRESS VULNERABILITIES

The vulnerable conditions defined in Step 3—vulnerability assessment—identify the specific uncertain future conditions in which the system does not meet the goals of the utility. If the analysis has only considered a baseline strategy, then this information can be used to inform another dialogue with stakeholders and decision makers about additional water management options necessary to reduce these vulnerabilities (returning to Step 1). Alternative strategies would then be evaluated across all the futures and analyzed to see how effective they are in reducing vulnerabilities (Steps 2 and 3).

If alternative strategies have already been evaluated, then the information on vulnerabilities can be used to develop adaptive strategies—those that evolve over time in response to observed conditions, returning to Step 1 (Lempert and Groves 2010; Groves et al. 2013b). The results for assessing vulnerabilities can also provide the information to evaluate the key tradeoffs among the alternative strategies in Step 4.

2.5 RISK MANAGEMENT THROUGH TRADEOFF ANALYSIS AND DELIBERATION

RDM helps to structure an assessment of different strategies to manage future risks associated with uncertainties. The vulnerabilities identified in the previous step serve as the foundation for evaluating potential modifications of a proposed strategy that might reduce these vulnerabilities (Step 4). RDM supports this step through the use of interactive visualizations that help decision makers and stakeholders understand the tradeoffs in terms of how alternative strategies perform in reducing vulnerabilities. This information is often paired with additional information about costs and other implications of strategies, so that meaningful deliberations over different strategies can occur (Groves et al. 2013a).

At this point—when deliberating about key tradeoffs among different strategies—the decision makers and stakeholders can bring in their assumptions regarding the likelihoods of the vulnerable conditions. For example, if the vulnerable conditions are deemed very unlikely, then the reduction in the corresponding vulnerabilities may not be worth the cost or effort. On the other hand, the vulnerable conditions identified may be viewed as plausible or very likely, lending support for a strategy designed to reduce these vulnerabilities. Finally, if there is substantial disagreement about the likelihood, the strategy can be modified to add adaptivity—that is, to monitor key factors affecting the vulnerable conditions and defer or trigger some choices based on observable outcomes over time.

Based on this tradeoff analysis, decision makers may decide on a robust strategy (the outward arrow from Step 4 in Figure 2.1) and begin implementation. They may also decide that none of the strategies under consideration are sufficiently robust and return to the decision structuring step (the arrow back to Step 1 in Figure 2.3); this time with deeper insight into the strengths and weaknesses of the strategies initially considered.

CHAPTER 3: COLORADO SPRINGS UTILITIES—CLIMATE RISK ASSESSMENT IN AN INTEGRATED WATER RESOURCE PLAN[16]

CSU is a community owned water provider serving about 380,000 customers, located along the Front Range Corridor of the Rocky Mountains. The City of Colorado Springs is somewhat typical of other large cities in the western United States, which long ago outpaced the ability of local water supplies to meet demand and turned toward importing distant water supplies into its service area. This involved the development of water supplies across the Continental Divide on the Western Slope of the Rockies and their conveyance to the Eastern Slope drainages flowing towards Colorado Springs—a distance of over 100 miles. Importation required the development of significant storage, conveyance, and treatment infrastructure, which operates within a regulatory context defined by the priority of water rights and environmental requirements on both sides of the Continental Divide (Figure 3.1).

To ensure that it can maintain a balance between future water supplies and demands, CSU is evaluating both supply side and demand side management options. On the supply side, for example, CSU is currently investing in the first phase of a nearly one billion dollar pipeline project—the Southern Delivery System or SDS—to "meet the community water needs through 2050." CSU also initiated a new process to create an Integrated Water Resource Plan (IWRP) in the fall of 2010, about the time that this WRF project began. The IWRP will be a long-term strategic plan to provide a reliable, sustainable water supply to customers in a cost-effective manner. CSU seeks a holistic approach to water resource planning that focuses on water supply while also considering water demand, water quality, infrastructure reliability, environmental protection, water reuse, financial planning, energy use, regulatory and legal concerns, and public participation.

Our study team and CSU sought to coordinate this WRF pilot with the IWRP to enable this WRF pilot to inform an ongoing planning process and provide a unique opportunity to evaluate the application of the RDM framework in the context of an IWRP. Development of the IWRP followed a three-phase approach. Phase 1 defined the issues, risk factors, and vulnerabilities of CSU's water enterprise. While highly participatory, it was internally focused and conducted in collaboration with this pilot study. Phases 2 and 3, currently in process, are intended to be more publicly oriented, with Phase 2 focused on Strategy Identification and Evaluation; while Phase 3 will develop the strategic IWRP itself. Our study team has contributed primarily to Phase 1, as CSU was unfortunately delayed in undertaking Phases 2 and 3 during the project period of performance. CSU has reviewed the results and is considering how best to incorporate them into the ongoing IWRP process.

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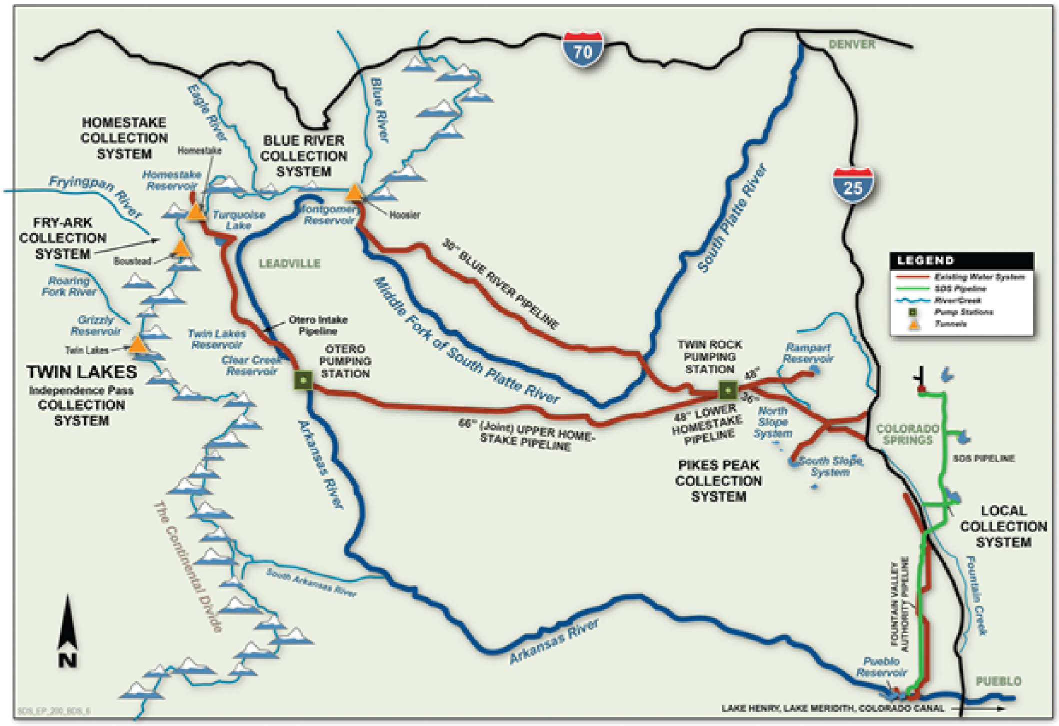
[16] This case study was developed primarily by Jordan Fischbach (RAND Corporation), Edmundo Molina-Perez (RAND Corporation), and David Yates (NCAR), with assistance from David Groves (RAND Corporation).



Source: CSU 2012

Figure 3.1 Colorado Springs' water system

3.1 PARTICIPATORY SCOPING FOR THE COLORADO SPRINGS UTILITIES INTEGRATED WATER RESOURCE PLAN

At the onset of this pilot the IWRP team began implementing elements of the RDM framework described in this report as part of the IWRP's Phase 1 activities. CSU used the XLRM Matrix to structure a dialogue with staff and develop futures, performance metrics, and a modeling system capable of evaluating a large ensemble of futures.

This participatory scoping evolved over a series of months in coordination with the IWRP. The XLRM Framework was first introduced to the planning team and then used to structure dialogues primarily around uncertainties and performance metrics. Concurrently, CSU's technical staff and consultants modified their simulation model to evaluate different hydrologic conditions and water demands, and developed a data management system capable of archiving for later analysis the results from the model simulations. The final XLRM Matrix is summarized in Figure 3.2 below and described in greater detail in Appendix A. Each element is discussed in further detail in the following sections. The CSU water system model that is at the center of understanding how uncertain conditions like climate and demand influence the performance of the CSU water delivery system is described first.

Uncertainties (X)	**Decisions, Options, or Levers (L)**
• Hydrology conditions • Historical conditions • Paleo-informed conditions • Climate-informed conditions • Demand conditions • 2016 demand • Estimated buildout demand (range) • Other system risks • Transbasin diversion reductions • Storage capacity reductions • Delivery system capacity reductions	• Current infrastructure • Expected buildout infrastructure (buildout demand only)
Relationships or Models (R)	**Performance Metrics (M)**
• CSU Operations and Yield MODSIM Model • WEAP as a Hydrology Model • Hydrology Data Management System	• Reliability Index • Vulnerability Index • Resilience Index • Sustainability Index

Figure 3.2 XLRM Matrix for CSU pilot study

3.1.1 System Models

CSU uses a modeling system called MODSIM to simulate the performance of its raw water system under different specifications of future demand, hydrology, and infrastructure. CSU refers to this as their Yield Model. MODSIM was developed by CSU and is a generalized river basin water allocation model to aid in decision support. On the raw water supply side, CSU has three primary sources: undepleted natural inflows, limited natural inflows due to intake and pipe capacities, and altered flows that are depleted or otherwise altered by regulation. The CSU MODSIM model represents about 40 inflow nodes on a monthly timestep, whose flows are then distributed throughout the supply network to the demand nodes of the water delivery system. A representation of monthly water demand at each treatment plant is the ‘pull’ that forces water deliveries that are managed through representative rules of the water delivery system.

The CSU MODSIM model considers different types of seasonal and annual hydrologic conditions by running a 59-year, observed hydrologic sequence for the period 1950 to 2008 against various levels of water demand for the main collection points of their raw water supply. The CSU Yield model uses this time series directly, by evaluating system performance through simulation of the actual sequence of historic years (e.g. 1950, 1951, ... 2008). A Yield Model simulation can thus reflect alternative system conditions, such as levels of demand, reservoir operating rules, new supply-side infrastructure, etc. CSU has, in the past, evaluated system performance statistically within the context of the historical hydrology and assumed that hydrologic conditions were stationary.

There is good reason that CSU relied on the historic hydrology when exploring the vulnerabilities of its raw water system. CSU’s water supplies are tightly coupled to both internal and external forces, as a major portion of CSU’s water is managed through “exchange.” Exchange water is reclaimed water that is reused through a complex accounting system to generate potable supplies and through direct reuse as non-potable supply. Thus, the time series of the natural and regulated inflows are uniquely coupled across time. Consequently, it is not possible to generate new, raw water inflows simply through hydrologic simulation. This category of inflows regarded as ‘altered’ is a key reason that CSU relied on the historically observed record in their Yield Model, as the altered flows are highly dependent upon factors outside CSU’s control. In addition to representing the water supply at the inflow nodes, the other important supply is the exchange potential, which is estimated from the natural and altered flows and the state of the water supply system for a given future.

3.1.2 Uncertainties

The IWRP discussions produced a broad list of potential future risks to CSU’s raw water supplies and delivery capability. These risks were classified into two broad categories: (1) long-term threats to water delivery, and (2) near-term operational outages. The former includes uncertainty regarding future hydrology, water demand growth, unplanned infrastructure limits within the system, and regulatory or legal issues that could constrain relied-upon water imports, particularly across the Rocky Mountains from Colorado River tributaries (“West Slope” supplies). The latter includes transient, operational risks that could substantially affect deliveries in a given year or season but are not necessarily long-term threats. These include potential infrastructure outages (e.g., transformer failure leading to pumping loss) and disaster risk (e.g., wildfire leading to temporary water collection, storage, or delivery system outages).

While this study is primarily focused on long-term climate risk management, the pilot analysis considered the short-term risks alongside the long-term risks to better understand the interplay of the two potential drivers of vulnerability.[17] Thus in consultation with CSU, the study team identified a subset of key uncertain drivers in this pilot study, both near- and long-term, focusing on uncertainty related to future demand and hydrologic conditions, along with potential curtailments to diversions from the Colorado River Basin, and potential long-term reductions in storage or delivery capacity relative to planned levels.

3.1.3 Demand

The IWRP team will eventually consider a range of demand projections for CSU reflecting plausible conditions 50 years into the future. In this pilot study we considered CSU’s demand estimated for 2016, reflecting current conditions, and a range of future buildout demand estimates representing plausible conditions 50 years from now. Total demand in 2016 was assumed to be about 90 thousand acre-feet per year (kafy).[18] CSU considers 138 kafy to be a moderate buildout demand projection at this stage of the planning process, but also acknowledges that buildout could be higher under alternative assumptions (Basdekas, 2012). This pilot study, therefore, considers a range of future demands from about 138 kafy (53 percent increase) to 165 kafy (84 percent increase). For each annual demand assumption, the demand model reflects a fixed pattern of monthly water use, which was assumed to remain unchanged in both the 2016 and

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[17] The RDM approach can also be useful to structure a short-term vulnerability analysis focused solely on the short-term risks—for example, if operational risk related to wildfires increases with a warming climate—but such considerations were outside the scope of this initial analysis.

[18] Water agencies use different units of measurements. For this report, we use the units favored by the agency.

buildout demand projections and reflects higher levels of use in the summer months corresponding to outdoor turf and amenity watering.

3.1.4 Hydrology Projections

For the IWRP process and the WRF study, CSU has extended this method of exploring hydrologic variation by developing alternative hydrologic projections. The WRF team helped translate these climate projections to the hydrology datasets required by CSU's water system simulation Yield Model. The first set was based on resampling the observed historical flows to re-create more severe dry spells as suggested by paleoclimate reconstructions. To do this, the years of the historic record were resequenced using a non-homogenous Markov Chain, with the corresponding monthly values of each year used as the inflow hydrology of both the natural and regulated inflows. In this way, the exchange potential is directly determined.

The second set of data modified the historical hydrologies so that the flows were consistent with projected hydrologic conditions from downscaled, bias-corrected GCM projections. These climate change projections were based on the downscaled CMIP3 Climate and Hydrology Projection archive found at http://gdo-dcp.ucllnl.org/. These data include translations of climate projections over the contiguous United States using a statistical downscaling technique known as Bias Correction Spatial Disaggregation (BCSD). The BCSD CMIP3 data include projections from 16 climate models, each with several "ensemble members" that make assumptions about GCM configuration and future GHG concentrations. This results in a total of 112 climate projections of average temperature and total precipitation on a monthly time-step for the contemporary period of 1950 through 2000 and the future period 2001 to 2100.

Problematically, these GCM data yield projections of future precipitation and temperature, yet the Yield Model needs inflow data to the raw water collection system. Thus, we needed to develop a procedure that would reflect how climate change would impact the inflows into the CSU raw water system, recognizing the dependence of the Yield Model on the historic inflow data. To do this, we developed a simple hydrologic model of the Arkansas and South Platte Rivers using the Water Evaluation and Planning system (WEAP) (Woodbury et al. 2012). This model was used to simulate flows for the contemporary period of 1951 to 2000 and the future period for all climate projections. The climate forcing dataset for both periods was from the CMIP3 archive mentioned above. These simulated flow data for the Arkansas and South Platte Rivers were then mapped to the Yield Model inflow nodes, where the full set of 112 altered flow sequences were derived. Details of the method can be found in Appendix A. In summary, the climate projections include:

- **Observed Historical** (Historical): 1 time series projection
- **Paleo Informed** (Paleo): 52 time series projections selected by CSU to reflect longer-than-observed dry spells, and which were subjectively selected based on poor system response.
- **Climate Informed** (Climate): 112 hydrologies consistent with BCSD CMIP3 climate projections (see Appendix A)

We developed statistical characterizations of these hydrology projections for use in the vulnerability analysis. Separate summaries were developed for the West Slope (sum of flows at all Colorado River tributary inflow points), East Slope (sum of all flows at Arkansas River Basin and local collection points), and as the sum of both. Each projection is described with statistics reflecting characteristics across the 59-year projection for each summary point, including:

- Annual mean (kafy)
- Annual mean of driest N-year period (kafy; examined 3- and 5-year periods)
- Number of dry years
- Maximum consecutive dry spell length (years)
- Maximum aggregate deficit—the cumulative flow shortage accumulated in all dry years across the 59-year sequence

Dry years are defined as years below median annual flows from the historical record (49.6 kafy and 62.2 kafy for the East and West Slopes, respectively, or 124.8 kafy for the combined basins). The median was used in order to remove high-flow outliers that could skew the dry year count.

Figure 3.3 shows several of these characterizations—annual mean and maximum dry spell length—for the East Slope (y-axis) and West Slope (x-axis). Each point in the scatter plot summarizes one 59-year projection, with colors indicating the source of the projection. A linear best-fit line is also included to illustrate the correlation between East and West Slope hydrology statistics, with a much higher correlation in mean flows than for dry spell length (mean flow R^2=0.71, spell length mean flow R^2=0.12).

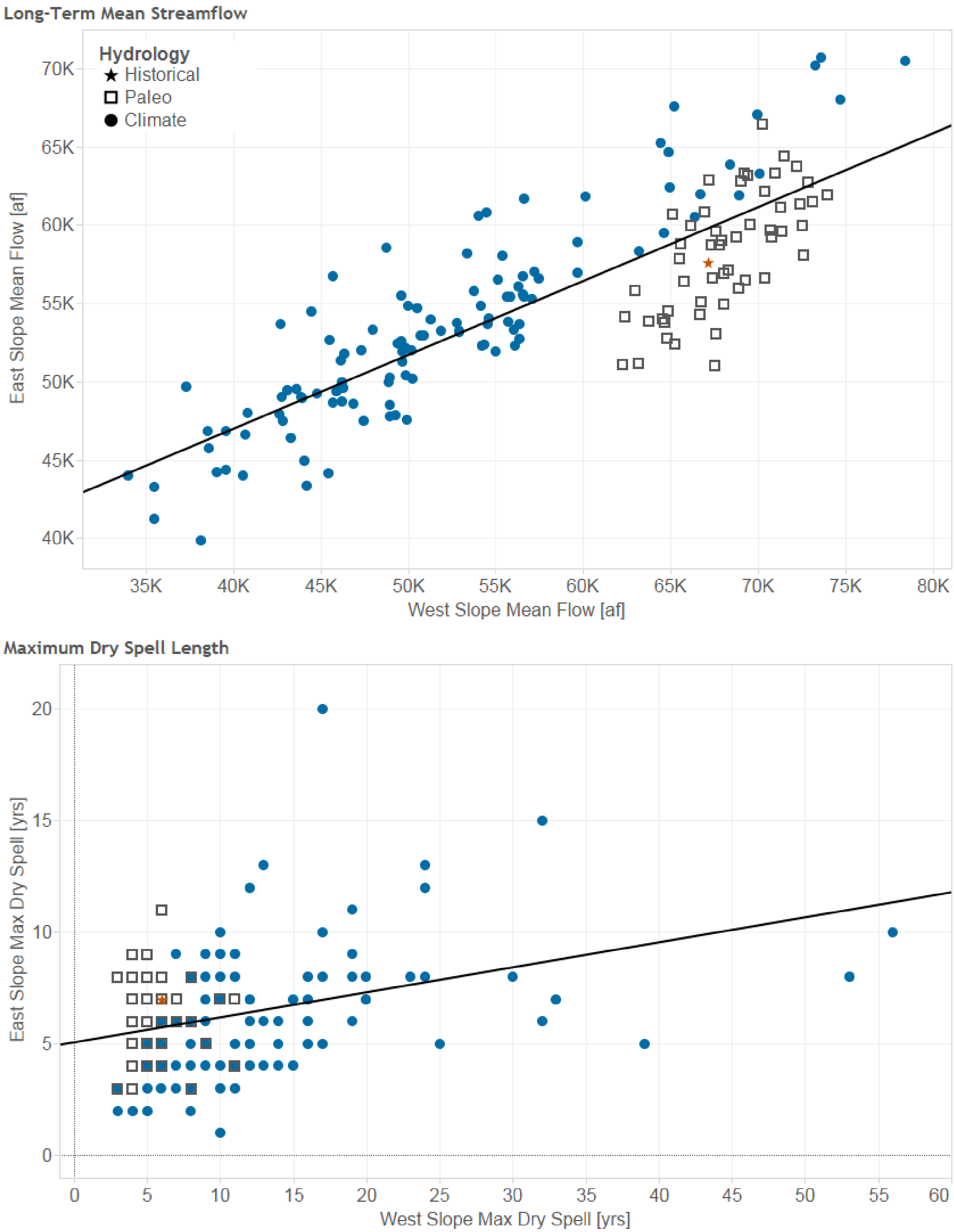
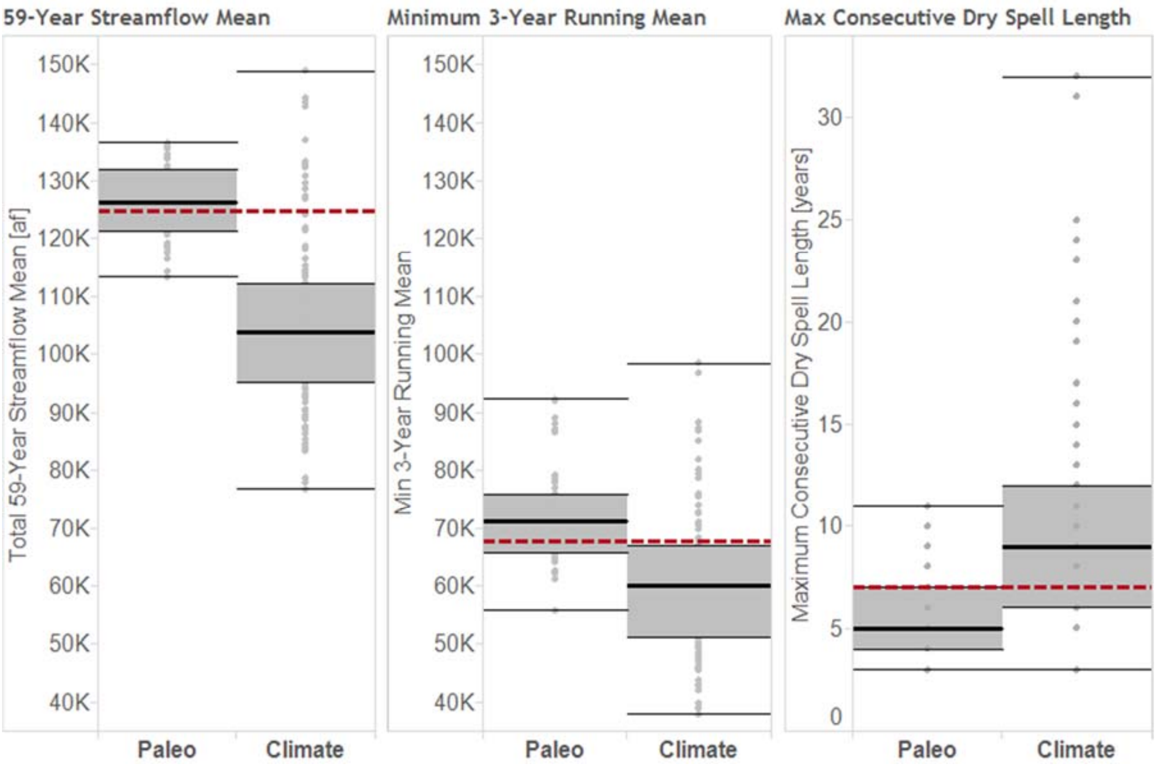


Figure 3.3 Mean streamflow and maximum dry spell

Figure 3.4 presents three different summaries of the hydrologies—59-year mean, minimum 3-year running mean, and maximum consecutive dry spell length—of East and West Slope flows for the Paleo and Climate hydrologic projections. These figures show that the Climate projections vary across a wider range for all three statistics, with most projections showing substantially lower flows and longer droughts relative to the Historical projection (dashed red line). The Paleo hydrology projections, however, are more evenly distributed around the Historical mean flow value, and include only a subset of projections with greater drought lengths than the Historical maximum.



Note: The shaded area of each boxplot show the interquartile range (25th to 75th percentile), while the bolded line shows the distribution median. The "whiskers" show the minimum and maximum of each distribution. Dashed red lines show the values from the observed Historical projection.

Figure 3.4 Statistical summaries of total streamflow for the CSU hydrology projections

3.1.5 Water Importation and Infrastructure Risk

The vulnerability analyses described below also considered a subset of importation and infrastructure risks drawn from the broader working set developed for the IWRP process. The severity of each risk factor varies across a range of plausible values which, when implemented, are applied for all 59-years of a simulation. By applying the plausible values in all years, we represent system performance effects from a long-term or permanent reduction relative to current expectations.

We evaluated risk factors related to regulatory, legal, and environmental changes that could reduce the important transbasin diversions from the Colorado River; risks to the amount of storage for three major system components; and delivery capacity restriction for the two major delivery systems. The risk factors and ranges evaluated are as follows:

- Regulatory/legal/environmental changes that reduce transbasin diversions from the Colorado Basin: 0 to 50 percent
- Colorado Canal system storage reduction: 0 to 25 percent
- Turquoise Reservoir storage reduction: 0 to 25 percent
- Pueblo Reservoir storage reduction: 0 to 25 percent
- SDS capacity reduction: 0 to 20 percent
- Otero Delivery system capacity reduction: 0 to 20 percent

3.1.6 Decision/Options/Levers

CSU's IWRP process will eventually consider alternate infrastructure investments in order to improve long-term system performance. However, additional infrastructure and policy options were not implemented or tested in the systems model in time for this pilot study. As a result, this analysis only considers two sets of infrastructure assumptions:

- 2016 infrastructure conditions: SDS Phase 1 is in operation with 2016 demands.
- "Buildout" infrastructure: evaluated with buildout demand.

Buildout infrastructure represents CSU's current infrastructure improvement plan over the next 50 years. The IWRP process is designed to improve upon this plan by understanding the vulnerabilities of this plan and developing refinements to make it more robust. As a result, the pilot WRF study is primarily an analysis of the potential limitations or vulnerabilities associated with this initial plan.

3.1.7 Performance Metrics

This pilot study focuses on the main performance metrics under evaluation for the IWRP—CSU's ability to consistently and reliably deliver water to its customers across a wide range of futures. Potential delivery shortfalls or shortages that would require CSU to implement mandatory water use restrictions are used to measure the ability to meet deliveries in each time period.

CSU has further identified three additional metrics, based on the annual shortage totals, to describe how well the system would perform over time (Sandoval-Solis, McKinney, and Loucks 2011). Each metric captures different shortage challenges, summarized for each 59-year projection:

- Reliability: percent of months in which the system meets all demands and no shortage occurs. A reliability of 100 percent means that no shortages occur in a simulation (McMahon et al. 2006).
- Vulnerability: percent of demand unmet if a shortage occurs. This measures the average depth of shortage across the projection on a percentage scale for those years in which a shortage occurs (Hirsch 1979; Cai et al. 2002). To bring this onto the same scale as the other indices, in this pilot we use the inverse ("1-Vulnerability"), which measures the average percent demand met when shortages occur.
- Resilience: percent of time in which a shortage month is followed by a non-shortage month. This measures the probability of recovery, or the system's ability to recover from a previous shortage (Moy et al. 1986).

Sandoval-Solis et al. (2011) further identify an overall sustainability index, based on the unweighted geometric mean of these indices:

$$Sustainability = (Reliability * (1 - Vulnerability) * Resilience)^{1/3}$$

This pilot uses all four index-based metrics to assess CSU's water delivery performance across the futures. We particularly focus on *Reliability* and *1-Vulnerability* as readily understandable measures of the frequency and depth of shortage, respectively. By contrast, *Resilience* and *Sustainability* are more difficult to interpret, and the analysis shows that as additional uncertainty is considered, the performance with respect to these metrics degrades significantly.

3.1.8 Experimental Design

The WRF team performed the vulnerability analysis in several stages to best understand how different future uncertainties would affect the performance of the CSU system.

First, we evaluated the current system under current demand across the paleo-informed hydrologic conditions and risk factors. To evaluate risk factors we developed 148 projections of individual risk factors using a Latin Hypercube sampling procedure.[19] This sample provides an assessment of the current level of system performance under hydrologic conditions and risks that are plausible today. Next, we evaluated buildout conditions and expected demand across the entire spectrum of plausible future hydrologic conditions as represented by the Historical, Paleo, and Climate projections, without risks. Lastly, we developed a smaller set of 60 projections,[20] combining the individual risk factors with varying demand, and combined these with all hydrologic projections to evaluate the buildout infrastructure under hydrologic, demand, and other uncertainties. In total, we evaluated 17,813 futures (Table 3.1). Each future took approximately 2 minutes to evaluate on a single processor with MODSIM and the data management system, yielding a total of about 600 central processing unit hours to complete this experimental design.

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[19] For each parameter included in the hypercube, the sampling was conducted so that approximately half of the sample produced either the lowest demand assumption or zero risk for each parameter, with the other half distributed quasi-uniformly according to the hypercube method. In this way, we could consider potential combinations of demand and risk without always assuming that the risks would be nonzero.

[20] We reduced the size of the sample across risk factors and demand to reduce the number of simulations required for scenario set 3.

Table 3.1
Experimental Design for CSU Vulnerability Analysis

Set	Infrastructure	Hydrologic Projections (#)	Demand Projections (kafy)	Risk Factors	Total Futures
1	Current	Paleo (52)	Current (90.3)	None (1 projection) and varying (148 samples across risk factors)	7,748
2	Build-out	Historical (1), Paleo (52), Climate (112)	Moderate buildout (138.4)	None	165
3	Build-out	Historical (1), Paleo (52), Climate (112)	Uncertain buildout (138.4-165)	Varying (60 samples across demand and risk factors)	9,900

Upon examination of the results for Future Set 3, the WRF Team determined that the MODSIM model was producing inconsistent results when demand was set higher than 154 kafy. Further investigation revealed the current model had been calibrated using constraints that limit flows to certain demand nodes. These constraints, while appropriate when overall demand is less than 154 kafy, lead to unrealistic flow restrictions at higher levels of demand. The model thus requires additional calibration to be valid at demands higher than 154 kafy. As a result, cases with demand levels above this threshold were removed from the final pilot analysis, reducing the number of samples in future demand/infrastructure by 14 and yielding a net total of 7,755 futures.

3.2 COLORADO SPRINGS UTILITIES WATER SYSTEM EVALUATION UNDER UNCERTAINTY

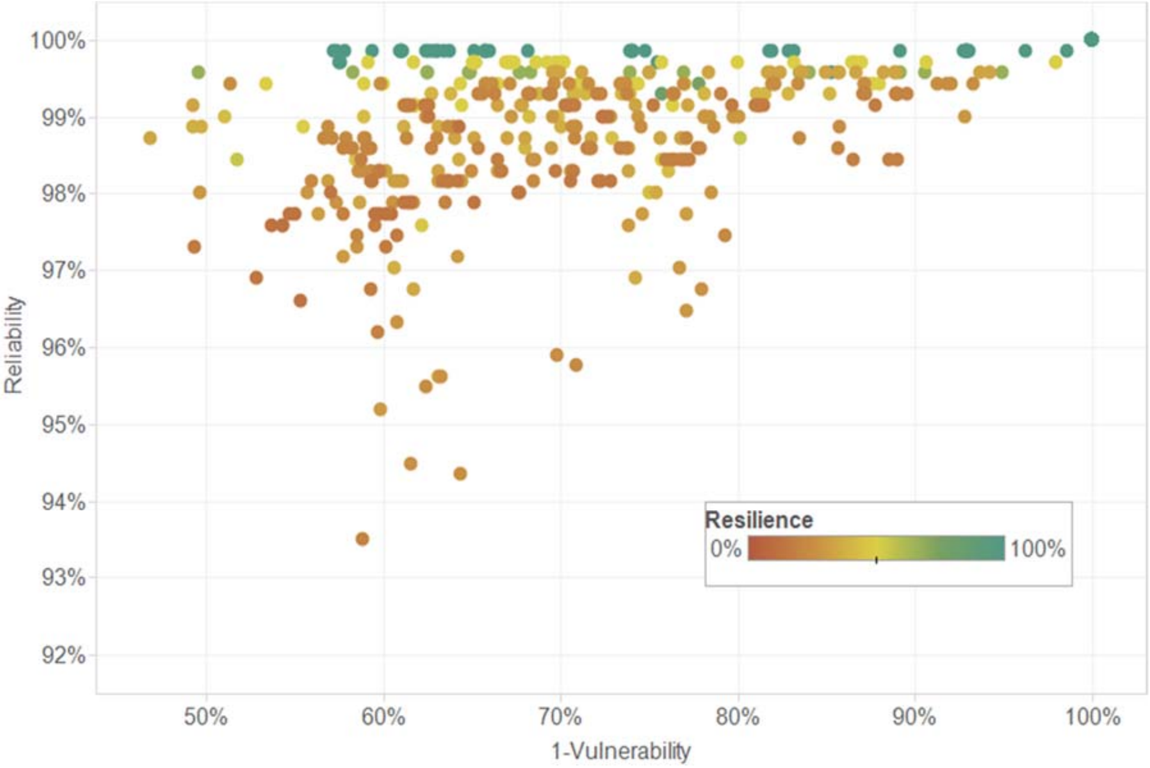
The WRF team evaluated the performance of the CSU's system under each set of futures described above.

3.2.1 Current System

First, we considered if the current system—represented by infrastructure and demand conditions as expected in 2016—might be vulnerable to shortages from stressing hydrologic conditions not in the observed Historical set, with or without additional risk factors included.

Figure 3.5 shows the results for 2016 conditions. Each point in the scatterplot shows the result from one future with one paleo-informed hydrology projection for Reliability (y-axis), 1-Vulnerability (x-axis), and Resilience (color range). Best-case water delivery results, represented by the green point in the upper-right corner of the graph, would have no delivery shortages. All three indices at this point equal to 100 percent. Ninety-five percent of the 7,748 futures show no delivery shortages.

Figure 3.5 shows that, according to the simulations, CSU's system generally performs well across a range of assumptions with 2016 demand and infrastructure. In general, the system remains reliable across the range, with shortage occurring in less than 7 percent of months (93 percent or greater reliability) in all cases considered. In the simulations, CSU occasionally experiences shortages that exceed 20 to 40 percent of demand (1-Vulnerability of 60 to 80 percent in Figure 3.5), and the Resilience index suggests that these shortages might extend for several months once triggered. CSU indicated during discussions that a 20 percent demand shortage typically necessitates watering restrictions and other temporary demand management measures for drought periods, while a 40 percent demand shortage could require CSU customers to curtail outdoor water use. Nevertheless, shortage remains relatively uncommon in 2016 conditions even when including either longer consecutive dry spells than observed historically or when introducing the risks described above.

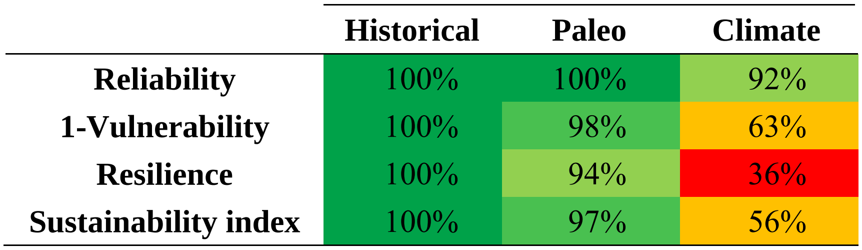


Note: There are 7,332 overlapping points at Reliability = 100% and 1-Vulnerability = 100%.

Figure 3.5 Evaluation of current CSU system under current demand, paleo hydrologic projections, and other risk factors (Future Set 1)

3.2.2 Future System with Hydrologic Uncertainty

We next evaluated how the buildout infrastructure would perform under buildout demand and a broad range of plausible future hydrologic conditions (i.e. Historical, Paleo, and Climate projections). Figure 3.6 summarizes the average results for each set of hydrologic projections to show major differences among the hydrology projections.



	Historical	Paleo	Climate
Reliability	100%	100%	92%
1-Vulnerability	100%	98%	63%
Resilience	100%	94%	36%
Sustainability index	100%	97%	56%

Note: This table shows the average results for each subset of projections. Colors are scaled from 0 to 100 percent.

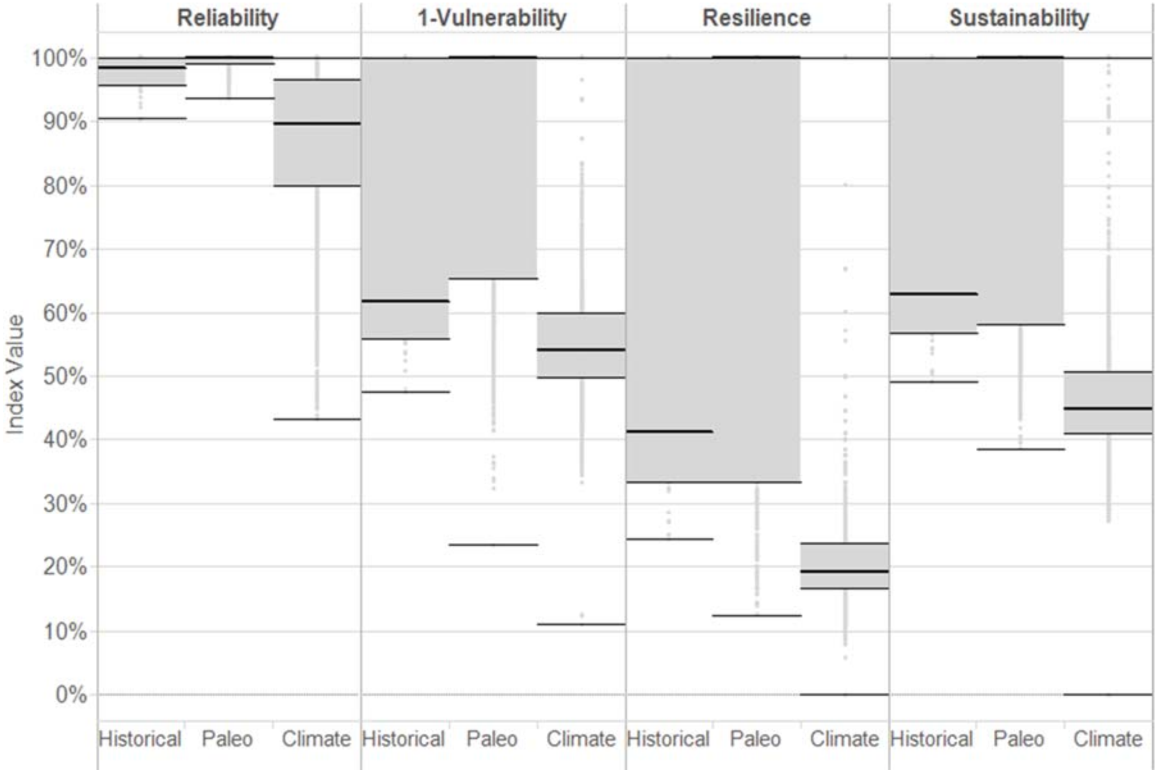
Figure 3.6 Average results of buildout conditions assuming moderate buildout demand and no additional risks

With no additional risks included and fixed ("most probable") demand, results in the buildout condition are essentially perfect for historical hydrology and similarly excellent across the paleo projections. These results suggest that without climate change, the system would continue to meet growing demand reliably under these assumptions. The system performs substantially less well under climate change hydrologic conditions. While average Reliability exceeds 90 percent, performance of the 1-Vulnerability, Resilience, and Sustainability metrics in much of the climate-informed hydrology is poor—average values being 63 percent, 36 percent, and 56 percent respectively. CSU would expect an average shortage level of nearly 40 percent of demand when shortages occur.

3.2.3 Future System with Hydrologic and Demand Uncertainty and Additional Risks

The last set of futures evaluated varies hydrology together with projections of demand and other future risks. The results for the four indices across all of these assumptions are summarized in Figure 3.7 below, once again divided out across each hydrology type. Compared to the results for the previous set of futures (summarized in Figure 3.6), this figure shows that higher demand and additional risk factors do not notably increase the frequency of shortage (Reliability) in historical and paleo-informed projections. In both, the Reliability index remains above 90 percent across entire range. In terms of Vulnerability, the average depth of shortages (when they occur) does shift somewhat with the new varying assumptions with a long distribution tail extending below 50 percent in the historical projection and below 30 percent in the paleo-informed set. Resilience, and the final Sustainability index, also decline across these ensembles, though as previously discussed, the Resilience results are more difficult to interpret and may in part be due to modeling artifacts.

The CSU system performs much worse when demand and other risks are evaluated with the Climate hydrologic projections (Figure 3.7). Notably, the Reliability index declines substantially in many climate-informed projections, with an ensemble median of about 90 percent, 25th percentile of 80 percent, and a lower quartile (bottom 25 percent of cases) extending below 50 percent. The climate-informed hydrologies show a similar increase in average shortage: the ensemble includes a wide range of average shortage outcomes from 10 to 100 percent, with a median value of 55 percent across the projections. The combination of more frequent shortage and deeper shortages in the climate-informed ensemble suggests that CSU's infrastructure plans could become vulnerable if more adverse conditions occur.



Note: the shaded area of each boxplot shows the interquartile range (25th to 75th percentile), while the bolded line shows the distribution median. The "whiskers" show the minimum and maximum of each distribution.

Figure 3.7 Summary of results across futures for the buildout condition with varying demand and risk assumptions, by hydrology source

To understand the relationship among the frequency of shortages (Reliability) and how deep the shortage is (Vulnerability), Figure 3.8 shows the results for each simulation as a single point on a scatter plot, where each point represents one future from the third set of futures, showing the combined results for Reliability (y-axis) and Vulnerability (x-axis). The points are colored by the hydrology source. The graph also delineates a reliability threshold, based on the historically-experienced reliability of about 80 percent (Basdekas 2012). CSU indicated that shortages occurring more frequently than this threshold do not meet planning objectives.

All of the cases with low reliability (below the 80 percent threshold) also include high average shortage volumes—greater than 40 percent (1-Vulnerability of 60 percent). In addition, this graph shows clearly that CSU experiences reliability below 80 percent only when facing hydrologic projections from the Climate hydrologies.

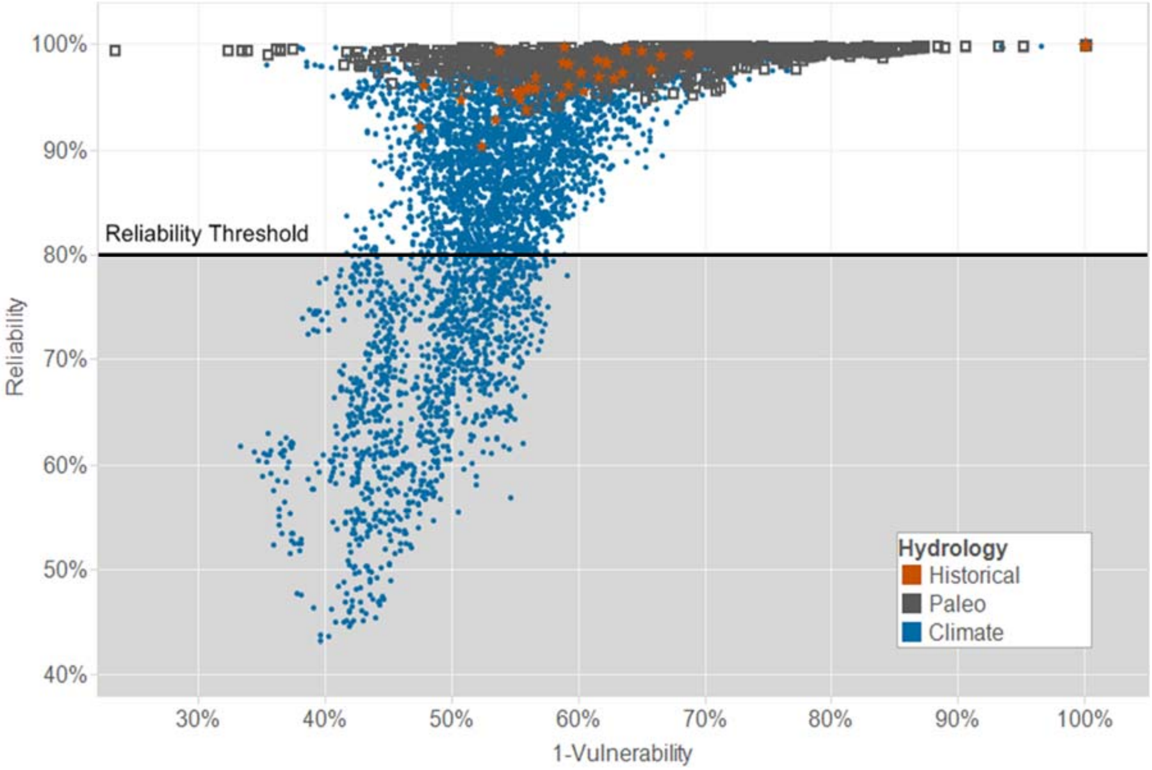


Figure 3.8 CSU reliability and 1-vulnerability results across futures

3.3 COLORADO SPRINGS UTILITIES VULNERABLE ASSESSMENT

The participatory scoping activity described above highlighted a range of different factors that might stress the CSU system in the future. An analysis of the simulation results for a large ensemble of futures confirmed that the system would not meet CSU's goals under many plausible futures. Understanding the specific factors and corresponding ranges of plausible conditions can provide important insight into CSU's vulnerabilities and how best to manage the identified risks.

While the visual inspection of the simulation results shown in the preceding section provides a first look at what conditions lead to vulnerable outcomes, a statistical analysis is needed to understand how different factors work together in causing the CSU system not to meet its goals. We used PRIM clustering analysis to identify key factors leading to vulnerabilities from the 9,900 futures evaluated for CSU's future (buildout) infrastructure and demand—the 3rd set of futures in Table 3.1. For this vulnerability assessment, we focused on outcomes in which CSU would not meet its 80 percent Reliability goal, as these cases are also associated with large average shortages (Figure 3.8). We considered different characterizations of hydrology for the sum total of the East and West Slope collection points, including long-term mean flow, minimum three-year drought flows, and consecutive dry spell length, as well as demand and the infrastructure risks considered.

Overall, Reliability falls below 80 percent in 17 percent of the futures evaluated. Starting from this point, we identified two sets of vulnerable conditions:

- Vulnerable Conditions #1: These conditions are defined when long-term mean streamflow falls below 95 kafy, which is approximately 76 percent of historical observed total streamflow (see Figure 3.4). When these conditions occur, Reliability falls below our assumed CSU threshold in 79 percent of the cases (79 percent density). These conditions describe 80 percent of all vulnerable futures (80 percent coverage).
- Vulnerable Conditions #2: These conditions are defined by long-term mean streamflow and the additional risk of curtailed transbasin diversions. When streamflow is below 103 kafy (83 percent of the historical average) and transbasin diversions are reduced by more than 42 percent, Reliability falls below the 80 percent threshold 72 percent of the time (72 percent density). These conditions describe an additional 6 percent of all the vulnerable futures (6 percent coverage), exclusive of those already accounted for in the first set of vulnerable conditions.

Overall, the two sets of conditions have a balanced density and coverage of 79 percent and 80 percent, respectively. That is, these conditions describe 80 percent of all futures in which the Reliability goals are not met, and the Reliability goals are not met in 79 percent of these futures. This is thus a useful set of conditions for CSU to be concerned about.

The results from both conditions are summarized in Figure 3.9. This figure shows the Reliability results for each future (coloring) in terms of the key uncertainties that define the vulnerable conditions—long-term mean flow (x-axis) and transbasin diversion reductions (y-axis). Regions with Reliability above 80 percent are colored grey to green, while those below the target threshold are colored in increasing shades of red. The thresholds identified in the PRIM analysis are shown as dashed black lines for each set of conditions, and the area included in the vulnerable conditions is shaded yellow.

Figure 3.9 shows that most of the vulnerabilities identified in this analysis are associated with a potential reduction in long-term mean flows, emerging from the climate-informed projections. A reduction in transbasin diversions—which could occur if the Colorado Basin were to enter a prolonged shortage period—is also a concern, but only with relatively high levels of curtailment of the West Slope diversions. Predominantly, what emerges from the vulnerability analysis is that CSU could be vulnerable if overall streamflow at their collection points falls into the lower quartile of the climate-informed hydrology projections considered in this analysis. These conditions are relatively extreme, but remain plausible given current climate projections for the Rocky Mountain region.

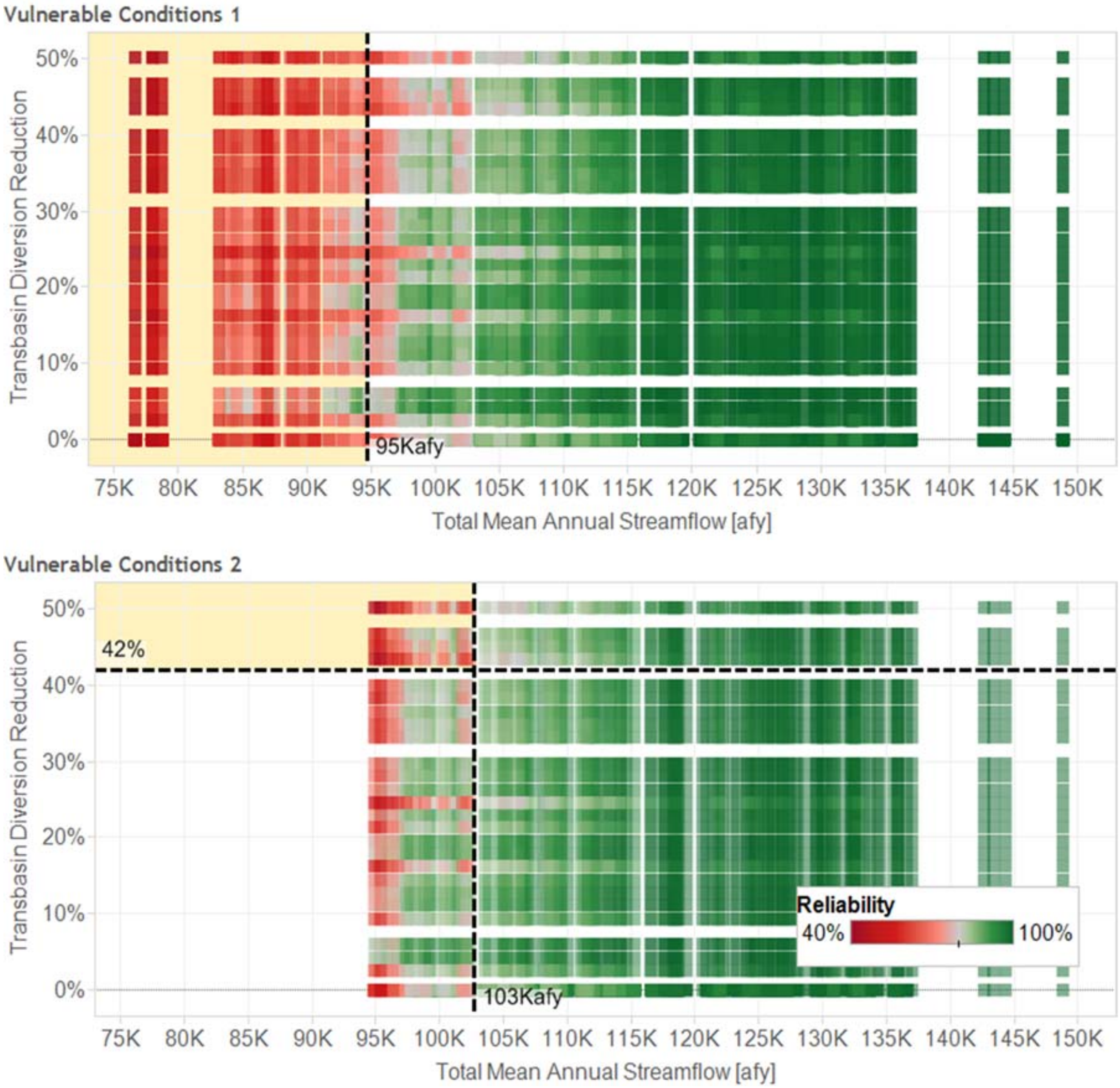


Figure 3.9 Two key vulnerable conditions for CSU based on the reliability across futures

3.4 SUMMARY OF FINDINGS AND NEXT STEPS

The vulnerability analysis provided several key findings relevant to CSU's long-term planning:

- CSU's current system is generally robust to a wide range of plausible current hydrologic conditions, as suggested by the set of paleo sequences evaluated. Even when faced with different combinations of plausible risks, reliability remains high.
- If CSU successfully implements its buildout infrastructure plan, its system will remain highly reliable over the coming 50 years if it faces hydrologic conditions similar to those of the recent past.
- If hydrologic conditions are more consistent with some GCM projections and paleo conditions, then future reliability and resilience could decline significantly.

- The CSU buildout system is generally reliable provided that combined total annual mean streamflow is greater than about 103 kafy, regardless of demand uncertainty and the other risks evaluated.
- If flows are lower than 95 kafy, the CSU system will perform poorly under all demand projections and risk assumptions.
- If flows are less than about 103 kafy, but higher than 95 kafy, then the risk factors could play an important role in determining future reliability—particularly reductions in diversions from the Colorado River.

These results are not definitive. They clearly depend upon the ability of CSU's model to realistically evaluate conditions under a much wider range of assumptions than have been previously considered. The IWRP process that CSU is currently undertaking will need to carefully examine some of the more extreme results to ensure that the model is projecting reasonable future outcomes. The analysis also only evaluated a subset of paleo-informed hydrologic conditions, and so there might be others that place greater stress on the water system.

CSU can now use this information about vulnerabilities to inform a dialogue with its stakeholders and planners about strategies that may be used to manage these identified risks. Based on the analysis performed, such strategies would need to help CSU function under long periods of lower flows and less availability of Colorado River water.

CHAPTER 4: CLIMATE VULNERABILITY ASSESSMENT AND RISK MANAGEMENT FOR THE NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION[21]

New York City (NYC) has developed an ambitious program, called PlaNYC, to ensure the long-term sustainability of the City's natural and built environment in the face of population growth, aging infrastructure, and climate change (CoNY 2011). Climate change adaptation is a core objective of DEP's strategic and capital planning efforts. DEP is engaged in three major strategic efforts: developing new sources and conveyance to allow extended repair of a leaking aqueduct that supplies 60 percent of the NYC water supply; evaluating the impacts of population growth and sea-level rise on sewer/wastewater systems; and identifying potential impacts of climate change on the water supply system and evaluating adaptation options (DEP 2008). The pilot study described in this chapter, developed in partnership with DEP staff, furthers ongoing efforts to assess and manage climate risks to the system.

The NYC water system supplies drinking water to almost half the population of the State of New York—more than 8.4 million residents of NYC and one million people in Westchester, Putnam, Orange, and Ulster Counties—plus the millions of commuters and tourists who visit NYC throughout the year. Overall consumption averages about 1.1 billion gallons per day. The water supply system that meets these needs consists of the Croton, Catskill, and Delaware surface water systems and a groundwater system of wells in southeast Queens (Figure 4.1). The three surface water collection systems include 19 reservoirs and three controlled lakes with a total storage capacity of approximately 580 billion gallons. The reservoirs were designed and built with various interconnections for flexibility to meet quality and quantity goals and to mitigate the impact of localized droughts or storm events. Due to excellent water quality and the extensive watershed protection efforts of DEP and numerous stakeholders, a key part of the DEP system—the Catskill and Delaware system (CAT/DEL)—remains unfiltered in accordance with the United States Environmental Protection Agency's (EPA's) Surface Water Treatment Rule and are regulated under a Filtration Avoidance Determination. Maintaining source water quality and unfiltered status saves DEP billions of dollars in treatment plant capital and operating costs.

The NYC water system faces many challenges: competing demands for water, managing water quality, negotiating tradeoffs among water quality and reliability, and managing longer term changes in climate, demand, and regulatory requirements. For this study, we focus on the goals of maintaining water supply reliability into the future and minimizing low water quality events which could jeopardize DEP's availability to operate the CAT/DEL without filtration, per EPA regulations.

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[21] This case study was developed primarily by Nidhi Kalra (RAND Corporation), Ben Wright (Hazen and Sawyer), and Edmundo Molina-Perez (RAND Corporation), with assistance from David Yates (NCAR) and David Groves (RAND Corporation), and in collaboration with many DEP staff members.

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Figure 4.1 New York City’s water supply system

4.1 PARTICIPATORY SCOPING WITH DEP

Stakeholder engagement played an important role in this pilot project. We organized two workshops and regular discussions with DEP according to the Participatory Scoping step of RDM.[22]

The first workshop was held at DEP's offices in Kingston, New York in February 2011. This workshop included DEP staff and technical stakeholders involved in existing ongoing planning studies. This initiated a dialogue over the next several months, resulting in a documented XLRM Matrix that guided an initial demonstration analysis. The XLRM Matrix included current, planned, and potential future water management strategies; the objectives the strategies aimed to achieve; the climate, demand, and other uncertainties that would affect the ability of the strategies to meet their objectives; and the models to simulate these interactions. This process also prioritized the modeling and data gathering activities that would be needed to support the RDM pilot study. In addition to defining the analytical problem, this scoping step built a common understanding of the problem and relationships between stakeholders and analysts. The value of this step cannot be overstated, particularly in analyses involving participants who are geographically dispersed and bring different skills to the effort.

In June 2011, we conducted a second workshop by teleconference that demonstrated RDM and focused on the system evaluation and vulnerability assessment steps in our analyses (Steps 2 and 3 in Figure 2.1). This step helped validate the model, introduced stakeholders to visualizations of hundreds of cases and the use of thresholds to separate them into acceptable and unacceptable cases, and refined the scope of the analysis.

A third engagement coincided with a broader project advisory meeting in July 2012 to present results on the vulnerabilities of DEP's baseline strategy and initial results on the benefits of adaptation options. These results are the focus of this report.

Figure 4.2 shows the final XLRM Matrix used to develop the vulnerability assessment and risk management analyses. In brief, four different types of uncertainties were identified, including those related to future climate, demand, and regulation, as well as the specific relationship between flow and turbidity which may vary in the future. The vulnerability assessment (Step 3) evaluated a baseline system that included a few infrastructure elements that are planned or under development. The risk management analysis (Step 4) evaluated four adaptation strategies comprised of additional water management strategies. The pilot analysis focuses on two key performance metrics—water reliability in terms of the percentage of days in which drought restrictions are needed, and water quality in terms of the percentage of days in which water is so turbid that alum must be added to the water to maintain quality.[23] A set of three different models

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[22] The NYC water supply system has many stakeholders beyond DEP. While the study team was only able to engage with DEP for this project, every effort was made to incorporate the concerns of other basin stakeholders.

[23] As noted above, water supplied from the CAT/DEL reservoirs is of consistently high quality and does not need to be filtered before distribution to the public. However, heavy rain events occasionally cause the water to become turbid. DEP addresses this problem by adaptive system operations. If the system becomes overwhelmed with turbidity, alum is added to the water, which precipitates out some of the material suspended in the water, so that it is fit for consumption and complies with regulatory standards.

was used to calculate system performance under the different futures and strategies. Appendix B provides additional information on the XLRM factors. We evaluated the robustness of the DEP system against four uncertainties—future climate, demand, regulatory regime, and flow-turbidity relationship.

Uncertainties (X)	**Options (L)**

• Climate time series projections (14: one historical plus 13 climate models derived)
• Demand levels (3 levels)
• Regulatory regimes (2 sets)
• Flow-turbidity relationships (3)
	• Planned system
	• Adaptation strategies (4)
	  • Catskill Aqueduct
	  • Operational changes
	  • Supply augmentation
	  • Augmentation + reduced operational constraints + operational changes

Relationships or Models (R)	**Performance Metrics (M)**
• Rainfall-runoff models • System simulation model • Reservoir water quality models	• Water reliability (percent drought days) • Water quality (percent alum days)

Figure 4.2 XLRM Matrix for DEP pilot study

4.1.1 Uncertainties

Climate

DEP has developed 145 climate projections that reflect 29 GCMs, three emissions projections (A1B, A2, and B1), and two future time periods: 2045 to 2065 and 2080 to 2100. This study used a subset of 13 of these projections for the 2045 to 2065 time period, selected to capture a range of stressors to the system while also avoiding redundancy and reducing run time. We focused on the 2045 to 2065 time period, as that was deemed most relevant to decisions that DEP might make in the near-term.

It is important to acknowledge that the climate projections utilized and available at the time of this study do not adequately quantify future changes in extreme rainfall frequency and intensity, despite qualitative evidence in current trends. The inability of current climate science to adequately characterize the uncertainty in future climate with respect to extreme event frequency and intensity, underscores the preliminary nature of the analysis and its conclusions because of the importance of extreme events to the reliability and quality of water supplied from the NYC system. However, the methodological framework is robust and could be re-applied when climate science provides better estimates of future climate to obtain more precise conclusions.

Water Demand

DEP's current estimate of residential water use is 78 gallons per capita per day (GPCD) with approximately 380 mgd of non-residential and unaccounted for water (Siskind and Keniff 2010). Future demands may be very different from the present because of changes in domestic use characteristics, economic growth, the emergence or decline of commercial or industrial water users, or other uncertainties. For this study, we specified three total demand levels, designed to span the plausible range of future demand:

- 1,120 mgd: lower-than-projected demand, consistent with current demands;
- 1,250 mgd: DEP's official 2030 demand projection; and
- 1,450 mgd: A higher-than-projected demand estimate corresponding to a 10 percent increase in GPCD and a 0.5 percent annual growth rate.

Regulatory Regimes

CAT/DEL provides approximately half of NYC's annual supply and is also consistently the highest quality supply, but it is also the most heavily regulated of DEP's three systems. The two primary requests of DEP from downstream stakeholders are to (1) increase downstream releases during periods of low flow, and (2) reduce peak flows during high flow events for flood control. Both conditions have the potential to negatively affect DEP's water supply objectives. For example, increased releases during dry periods reduce stored water available for DEP withdrawals, which if a drought were to occur could lead to more severe water restrictions.

To explore the impact of alternative regulations on DEP's water system, two regulatory regimes were modeled. The first reflects current agreements. The second would lead to more downstream releases and increase flood control. See Appendix B for more detail.

Flow-Turbidity Relationships

Little research has been undertaken on the potential impact of climate change on sediment loads of streams and rivers (IPCC 2007). While there is a general consensus that increasing rainfall intensity will increase watershed sediment loads through erosion, the precise relationship between turbidity and the magnitude and frequency of a storm event is not well understood (Nearing 2001). Changes in rainfall intensity and frequency, antecedent dry periods, and water temperatures alter how turbidity is mobilized and how quickly it settles out of the water column, influencing whether a rainfall event results in a minor or major turbidity event. Climate change adds an additional layer of uncertainty because seasonal weather variations are expected to become more severe and extreme rainfall is expected to increase, but it is not currently possible to either quantify these changes or quantify how these changes will influence turbidity mobilization.

To account for some of this uncertainty three variations in the flow/turbidity relationship were used in the modeling analyses: historical, 10 percent higher flow triggers (i.e. lower turbidity response than historical), and 10 percent lower flow triggers (i.e., higher turbidity response than historical).

4.1.2 Options and Strategies

DEP has plans to implement several investments in the system by 2020. For our initial analysis (not shown), we compared a baseline that includes these additional investments. We found that the planned investments consistently improve system performance over a wide range of futures. This experiment validated the model and the analytical process in the eyes of stakeholders, and facilitated concrete discussions about the final scope of the pilot study. We used the planned near-term system with these investments as the baseline water resource management strategy, rather than the present-day system.

Options for reducing supply and water quality vulnerabilities focus on measures that improve system resilience by adding new supply or increasing sub-system delivery capacity. The adaptation options modeled in this study are consistent with the options considered as part of the NYC Water for the Future project for short-term supply reliability improvements during the 6- to 15-month Delaware Aqueduct repair project (DEP 2013):

- **Catskill Aqueduct**: Reduce hydraulic constraints on Catskill Aqueduct to increase aqueduct capacity from 595 to 640 mgd.
- **Operational changes**: During turbidity events, allow transfer of a maximum of 240 mgd of Croton system water into the Delaware Aqueduct to increase the peak delivery capacity from the Croton system. Also during turbidity events, allow greater drawdown of West Branch and Rondout Reservoirs to obtain more water from the Delaware system when the Catskill system is offline to avoid the use of alum.
- **Supply augmentation**: During periods of drought or high turbidity, augment the DEP water supply with 50 mgd from the DEP groundwater system and an additional seasonally available supply (100 mgd maximum, annual average of 50 mgd) from interconnections with adjacent water utilities.

Each adaptation option was modeled as a stand-alone strategy, and all three were modeled together for a total of four combinations of adaptation strategies.

4.1.3 Performance Metrics

Water reliability was quantified using the DEP drought condition trigger, which is an indicator of hydrologic stress in either the Delaware or Catskill subsystems and adjusts modeled demand levels to indicate voluntary and mandatory use restrictions during drought conditions for the DEP service area. The drought condition can have a value of “normal,” “watch,” “warning,” or “emergency.” This metric is described in detail in Appendix B. While no explicit threshold for acceptable frequency of drought conditions currently exists, the study team determined that it would be useful to distinguish future conditions in which the system experiences worse drought than it has in the past. Therefore, the threshold for acceptable reliability was set at the percent of drought warning and emergency days under baseline conditions and historic climate—two percent.

We measure water quality as the percent of days in which alum must be applied—an undesirable condition and also an indicator of poor water quality in the system. While DEP’s goal is zero alum usage, it was decided an absolute threshold may be impractical for a long term simulation; therefore a threshold of 1 percent was selected as a suitably low value that would have a low probability of negatively affecting DEP’s filtration avoidance determination.

4.1.4 Models and Relationships

This study relied on downscaled GCM data developed by DEP based on the delta change factor methodology (Anandhi et al. 2011). Climate adjusted streamflows were modeled using the downscaled GCM data and DEP’s rainfall-runoff modeling tool. Streamflows were then routed through DEP’s existing systems modeling framework, the Operations Support Tool (OST), to calculate water reliability and water quality performance for each water management strategy under unique sets of assumptions about climate, demand, and other factors. These models and relationships are described further in Appendix B.

4.2 NEW YORK CITY SYSTEM EVALUATION

To implement a vulnerability assessment with respect to water reliability and quality, we first estimated the performance of the planned management system under 252 different futures. These futures are a full factorial combination of the 14 climate projections, three demand levels, two regulatory regimes, and three flow-turbidity relationships.

To provide context for this analysis, Figure 4.3 plots summaries of the climate information corresponding to the fourteen climate projections—the difference in annual average temperature (vertical axis) and the percent difference in average annual precipitation (horizontal axis). Note that each of the climate projections derived from GCMs suggests warming (between 1.5 and 3.5 degrees C). All but one projection suggest increased precipitation, up to 12 percent over the historical levels.

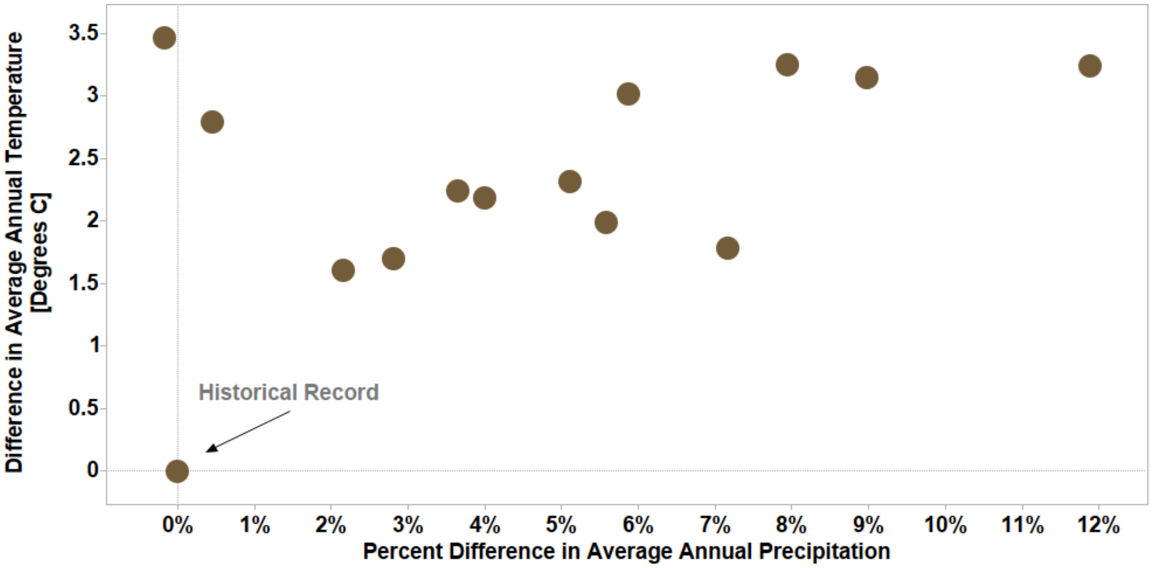


Figure 4.3 Annual temperature and precipitation in fourteen climate projections relative to the historical record

To summarize how the DEP system would perform, Figure 4.4 shows each of the 252 simulation results in terms of the two key metrics—supply reliability (vertical axis) and water quality (horizontal axis). Supply reliability is expressed as the percentage of drought days for the 76-year simulation period. Water quality is expressed as the percentage of days in which alum would need to be added to the Catskill supply to reduce turbidity. The performance thresholds for each metric are also indicated. Circles indicate results in which both supply reliability and water quality goals are met. Xs indicate results in which one or both goals are not met.

As one of its most salient features, Figure 4.4 shows that the Baseline strategy meets both performance targets in less than half of the futures (115 out of 252). In 60 out of 252 futures the Baseline strategy fails both metrics; in 78 out of 252 futures it fails the water reliability target but meets the water quality target; in no futures does it meet the water reliability target but fail the water quality target.

Figure 4.4 suggests that under many plausible futures, DEP will not be able to meet its water quality and water reliability targets even with the investments planned in the Baseline system. It is important to note, however, that we have not yet made any statements about the likelihood of the various futures in Figure 4.4. Before concluding that DEP should seriously consider augmenting the Baseline strategy, we must examine the conditions that lead the system to meet or fail to meet its goals and explore whether adaptation options might be robust to a wider range of conditions. We perform this analysis first for water reliability and then for water quality.

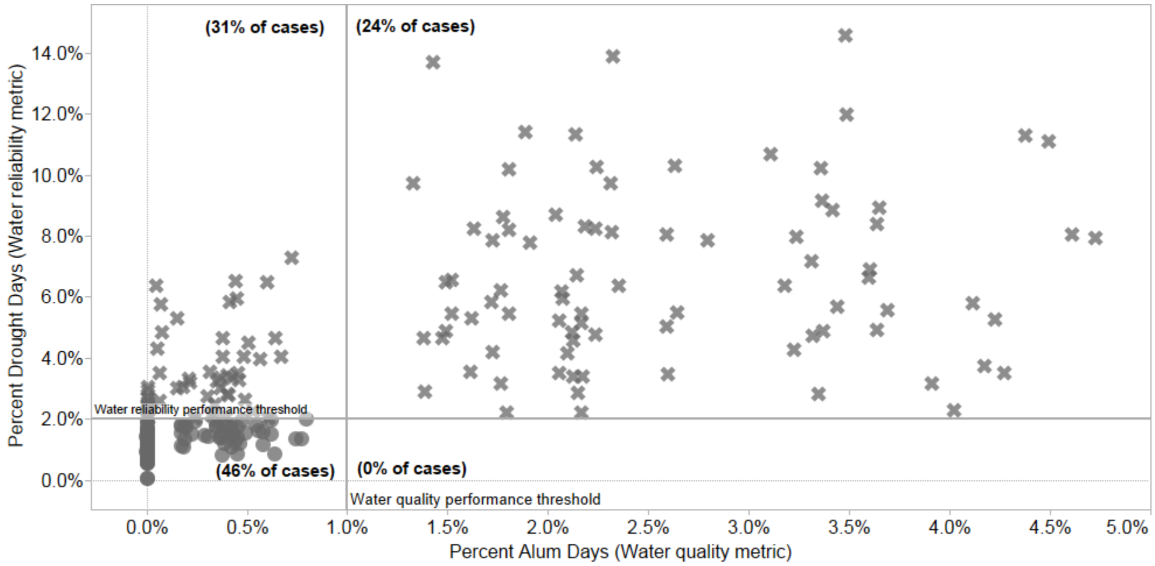


Figure 4.4 Supply reliability and quality performance of baseline management system under 252 plausible futures

4.3 NEW YORK CITY VULNERABILITY ASSESSMENT

4.3.1 Water Reliability Vulnerabilities

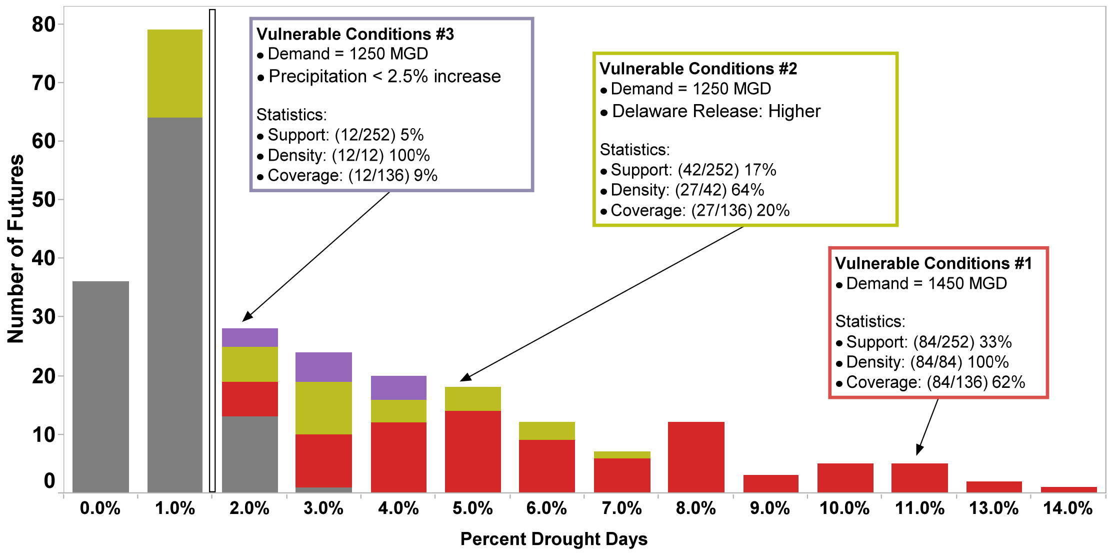
We next used PRIM (described in Chapter 2) to identify the future vulnerable conditions in which the baseline management system fails to meet the specified water reliability goals. In this case, we seek to distinguish the 46 percent of futures in which the goals are met from the 54 percent of futures in which the goals are not met. The PRIM analysis was used to evaluate which uncertain factors and ranges on those factors correspond to the results in which the reliability goals are not met.

To use PRIM, we first assembled a database in which each individual record contained information about the climate, demand, regulatory regime, and turbidity assumptions—the uncertain parameters from the experimental design. We tested two different ways of characterizing the climate projections: (1) by annual changes in temperature and precipitation (see Figure 4.3); and (2) by seasonal changes in temperature and precipitation. The results presented below are based on the more simple annual characterizations. Each record of the database also contained information on whether the reliability and quality goals were met.

The PRIM analysis identified three sets of conditions that result in DEP's reliability goals not being met:

- Vulnerable Conditions #1: These conditions are defined only by future demand. When demand is at the high end of the range—1,450 mgd—the percent of drought days always exceeds 2 percent (100 percent density). These conditions describe 33 percent of all the futures (33 percent support) and 62 percent of all vulnerable futures (62 percent coverage).
- Vulnerable Conditions #2: These conditions are defined by demand and regulatory requirements. When demand is at its middle value—1,250 mgd—and downstream release requirements are high, the percent of drought days exceeds the 2 percent threshold 84 percent of the time (84 percent density). These conditions describe 17 percent of all the futures (17 percent support) and 20 percent of all the vulnerable futures (20 percent coverage).
- Vulnerable Conditions #3: These conditions are defined by demand and annual precipitation. When demand is at its middle value—1,250 mgd—and precipitation is less than 2.5 percent wetter than the historical average, the percent of drought days always exceeds 2 percent (100 percent density). These conditions describe 5 percent of all the futures (5 percent support) and 9 percent of all vulnerable futures (9 percent coverage).

Figure 4.5 shows a histogram of reliability results for the 252 futures evaluated. The histogram is colored to signify the results that are described by the three vulnerable conditions (red, yellow, and purple) and those that are not (gray). Results to the right of the vertical line exceed the 2 percent threshold. The gray shaded portion that is to the right of the vertical line indicates futures that exceed the 2 percent threshold, but that are not described by the three vulnerable conditions. Similarly, the yellow shaded region to the left of the vertical line indicates futures below the threshold that happen to correspond with vulnerable condition #2.



Vulnerable Conditions #3
- Demand = 1250 MGD
- Precipitation < 2.5% increase

Statistics:
- Support: (12/252) 5%
- Density: (12/12) 100%
- Coverage: (12/136) 9%

Vulnerable Conditions #2
- Demand = 1250 MGD
- Delaware Release: Higher

Statistics:
- Support: (42/252) 17%
- Density: (27/42) 64%
- Coverage: (27/136) 20%

Vulnerable Conditions #1
- Demand = 1450 MGD

Statistics:
- Support: (84/252) 33%
- Density: (84/84) 100%
- Coverage: (84/136) 62%

Figure 4.5 Outcomes in terms of percent of drought days across the 252 futures colored by vulnerable condition

These results suggest that demand, climate, and regulatory requirements have a significant effect on whether the Baseline system meets its water reliability targets. Although the turbidity threshold is uncertain, it has much less of an effect for this metric of success. All together, these three vulnerable conditions describe 90 percent of all vulnerable futures and only a few non-vulnerable futures (13 percent). As such, they provide a good explanation of the baseline system's water reliability performance.

We can now ask, "What might cause these vulnerable conditions to occur?" The first condition that leads to poor water reliability is high demand (1,450 mgd) in the 2045 to 2065 time period. This could occur with sustained increases in population or per capita demand, or some other major change to demand patterns (e.g., rapid growth of a new industrial sector). DEP should continue to track changes in population and water use patterns across several sectors (residential, commercial, industrial, etc.) in order to evaluate trends over time that could lead to very high demand.

The second set of vulnerable conditions relates to demand of 1,250 mgd and increased operation of the Delaware system for non-water supply purposes. Demand of 1,250 mgd is consistent with the city's projections of future population growth and with trends in per capita water use. While there is no pending action to change Delaware release requirements, there has been significant pressure on DEP to adjust operating rules for non-water supply objectives (e.g. flood control and dry weather releases). DEP actively works with other Delaware River stakeholders and has been open to accommodating reservoir operations revisions so long as there is no measurable impact on DEP's ability to provide a reliable water supply to its customers. Whether DEP can manage the additional stresses of higher release requirements even with stable demand depends on the future climate.

Third, the system may not meet water reliability targets under 1,250 mgd demand projection when increases in annual precipitation are less than 2.5 percent. This level of precipitation increase is necessary to accommodate projected demand while maintaining historical rates of drought. We evaluated the change in annual precipitation projected by 70 climate models for the 2045 to 2065 time period under the three climate projections considered in our study. In 26 of these, the annual precipitation increase is less than 2.5 percent. Together, the evidence for future demand and climate characteristics suggest that DEP may face challenges in continuing to meet its historically low levels of drought condition days, and that DEP may want to consider augmenting its Baseline water resource management strategy to make it more robust.

4.3.2 Water Quality Vulnerabilities

We repeated the vulnerability analysis to identify conditions that would lead DEP's Baseline system to fail to meet its water quality goals. In this case, the vulnerability analysis was particularly straightforward. If demand is 1,250 mgd or below, less than 1 percent of days require alum use (Figure 4.6, top). When demand is 1,450 mgd, however, alum use ranges from greater than 1 percent of days to about 5 percent. Visual inspection, rather than PRIM in this case, revealed that the primary driver of high alum use was the turbidity threshold and not climate or regulation. In general, lower turbidity thresholds lead to higher alum use (Figure 4.6, bottom). In both plots, the red vertical reference line separates the futures in which the baseline system fails to meet its 1 percent target from the futures in which it does. While climate did not drive additional alum use in this analysis, detailed review of the model output revealed that many of the climate change projections increased the number of high turbidity events, but that they were not of sufficient duration to cause an alum event. Turbidity is driven primarily by extreme rainfall; unfortunately climate projections available at the time of this study did not adequately quantify future changes in extreme rainfall intensity, despite qualitative evidence in current trends.

The relationship between high demand and alum use is indirect. When turbidity is high in the Catskill system, DEP can avoid applying alum and instead wait for turbidity to subside naturally. DEP can continue to meet water demands by drawing more heavily from the other two subsystems in the meantime. However, as demands increase, the length of time DEP can avoid using the Catskill system becomes shorter. DEP may then have to draw water from all three subsystems simultaneously because of competing operating rules and hydrologic or hydraulic constraints, leaving it with no choice but to apply alum. The relationship between the turbidity threshold and alum use is intuitive. A lower threshold implies that lower flows are needed to create turbidity and so turbidity occurs more frequently.

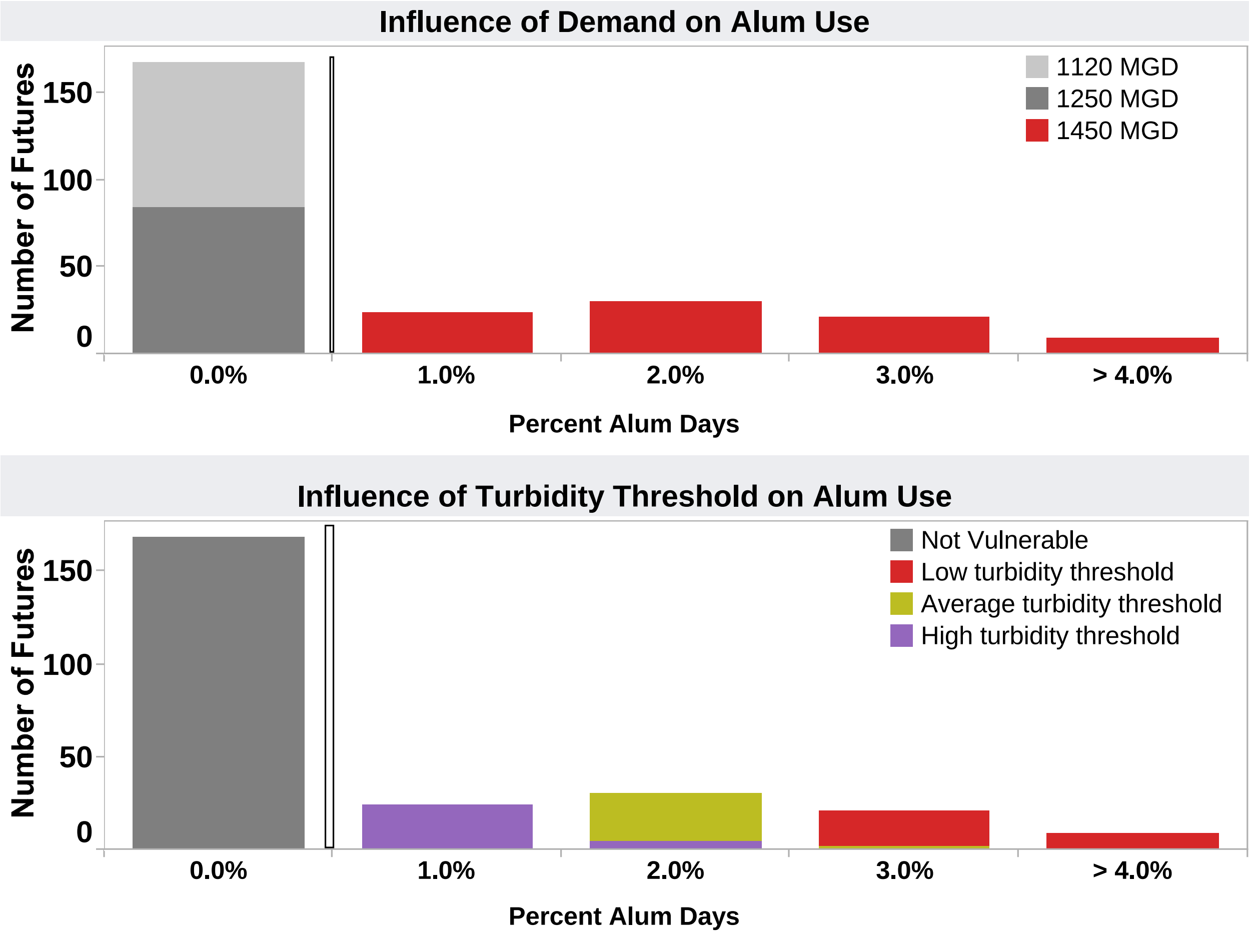


Figure 4.6 Percent alum days colored by demand (top) and turbidity threshold (bottom)

We next consider evidence that would lead to the conditions under which the Baseline system fails to meet water quality targets, namely demand of 1,450 mgd. As noted in the water reliability analysis, it would seem beneficial for DEP to continue to track socioeconomic and related water trends, given that this level of demand could occur with sustained increases in population, changes in per capita usage, or some other major change to demand patterns.

While turbidity thresholds and precipitation do not affect whether the Baseline system meets or fails to meet the 1 percent performance threshold, the turbidity relationship may exacerbate or reduce the need for alum. The relationship between precipitation, flows, turbidity, and alum use is not well understood and is complex. Turbidity is a function of physical features such as channel depth and composition. This analysis suggests that it is worthwhile for DEP to continue to invest in efforts to better understand and model turbidity, as it will continue to have significant implications for the long term performance of the water system. Of particular interest is whether projected extreme weather event changes in the future could result in more frequent or longer turbidity events that will stress the current management strategies under lower demand levels.

4.4 NEW YORK CITY CLIMATE RISK MANAGEMENT

We considered four adaptation options described above: (1) increasing capacity of the Catskill Aqueduct, (2) making operational changes, (3) augmenting supply, and (4) implementing all three of these options simultaneously. To reduce total runtime, we ran each of these adaptation options on a subset of the original 252 futures. We removed variability in the turbidity threshold, which the above analysis shows is not a major predictor of water reliability performance. In particular, we chose the 84 futures with a low turbidity threshold that results in high turbidity and alum use, as this condition is the most stressing to DEP's water system.

Figure 4.7 summarizes the percentage of drought days across the 84 futures for the five management strategies. The reference line indicates the 2 percent drought days performance threshold. These results clearly show that only options that include augmenting the water supply improve water reliability across the futures evaluated. The improvement is small, but it is statistically significant.[24] These modest changes suggests that the adaptation options considered here may not be sufficient for addressing NYC's water reliability goals in the long term future, and that DEP may wish to consider a wider range of options.

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[24] A paired t-test indicates that the true difference in the means of the drought days of the Augment Supply option and the Baseline differ at a significance level of 0.01. A 95 percent confidence interval suggests that the Augment Supply option drought days are 0.5-0.7 percent less than the Baseline. The same is true for a comparison of All Options and the Baseline.

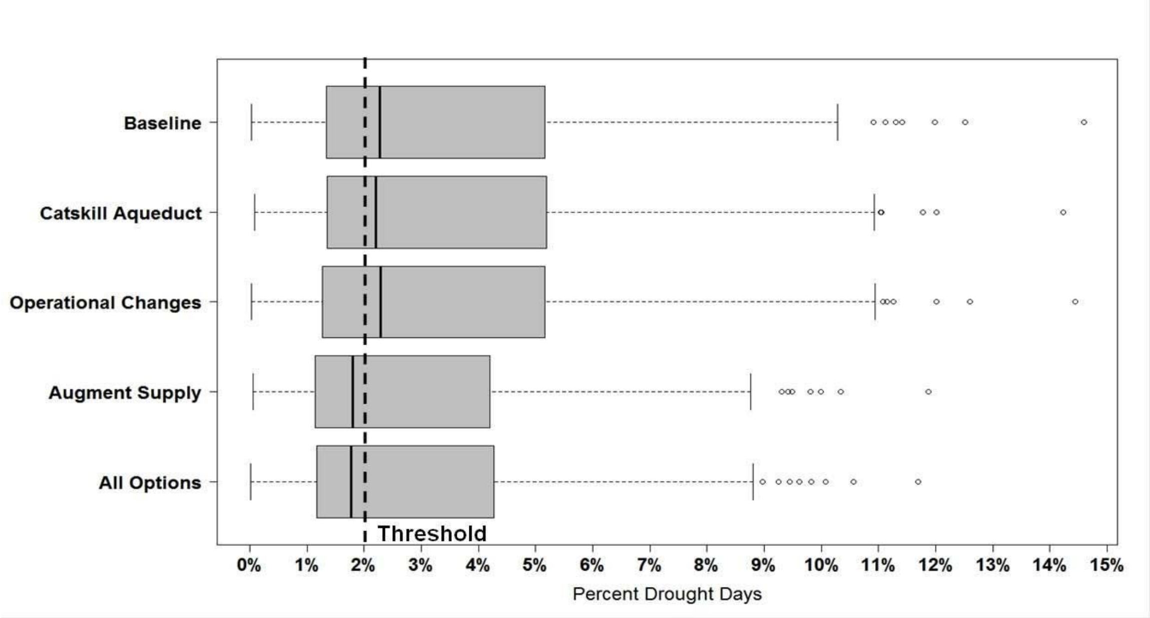

Figure 4.7 Water reliability results across the futures in terms of percentage of drought days for the baseline management strategy and four alternative strategies

We also evaluated how the four adaptation strategies affect water quality. Figure 4.8 summarizes the percentage of alum days for each of the 84 futures, separated by the level of demand, in light of the strong effect on the water quality results (see above). The dashed vertical reference line indicates the 1 percent water quality performance threshold.

Figure 4.8 shows that for the low demand cases (1,120 mgd) all strategies lead to very low alum use. For medium demand (1,250 mgd) there is some alum use projected for the Baseline, but alum use is all but eliminated with either the Operational Changes or Augment Supply strategies. Increased capacity in the Catskill Aqueduct has no significant effect. For high demand (1,450 mgd), all futures lead to alum use greater than the threshold. The Catskill Aqueduct again has no significant effect. The other options, however, do decrease the use of alum across the futures, although not enough to fall below the water quality threshold.

While none of the four adaptation options result in acceptable performance (less than 1 percent alum use) in the 28 futures where demand is high, the adaptation options other than the Catskill Aqueduct capacity may enable DEP to meet its water quality targets under a much wider range of conditions than the current system. Conversely, the system with adaptation options may only perform unacceptably at the highest levels of demand and when turbidity is more easily triggered. As better quantitative data on extreme events becomes available along with improved modeling tools for turbidity, it would be worthwhile for DEP to rerun the analysis of certain adaptation options to evaluate this hypothesis. An RDM analysis can also help inform analysts on areas of iteration and further investigation, consistent with the iterative nature of the process shown in Figure 2.1.

The above analysis suggests that operational changes and supply augmentation, individually or in combination, may help DEP meet its water quality targets in cases where the Baseline system alone cannot. Further, despite not being able to achieve full mitigation, these options may provide some improvement to drought resilience for the system. However, these efforts are not without cost and may have feasibility limitations.

Revising operations to allow transfers of 240 mgd of Croton system water into the Delaware Aqueduct and to allow greater drawdown of certain reservoirs is a relatively low cost option and offers some improvement—0.3 percent fewer alum days on average. DEP would incur some additional costs for pumping the extra water from the Croton system, but no additional costs for drawing down the reservoirs. However, there may be some regulatory hurdles for this option because water pumped from the Croton system would bypass the new treatment plant, which may require special permits.

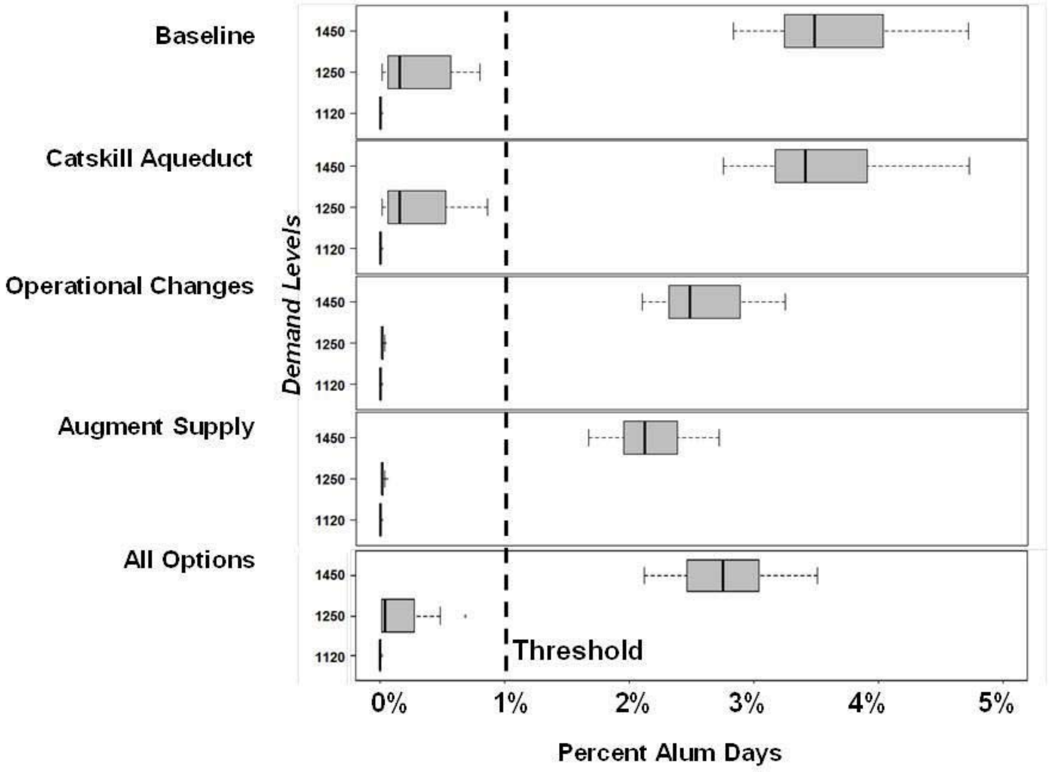

Figure 4.8 Water quality results in terms of percentage of alum days for the baseline management strategy and four alternative strategies by demand level

On the other hand, augmenting supply offers greater benefit—0.4 percent fewer alum days if undertaken alone and 0.5 percent if undertaken in combination with operational changes. Yet supply augmentation is likely to be very expensive—potentially on the order of tens to hundreds of millions of dollars in capital and operating costs. The DEP groundwater supply is contaminated with MTBE and requires expensive treatment. Importing water from outside of the DEP watershed, an alternative means of augmenting supply, could also result in additional costs to purchase water from other utilities and perhaps would require building interconnections. There may also be social, political, or other challenges to purchasing water from other utilities. However, some of these adaptation options may be implemented, at least on a temporary basis as part of the Delaware Aqueduct repair, which may reduce costs and improve feasibility of implementation on a permanent basis for dealing with future extreme events.

4.5 INFORMING FUTURE DEP DECISIONS

In the previous sections, we assembled information on tradeoffs to support a choice among adaptation strategies. In this policy context, decision makers should consider four factors:

1. The risks of doing nothing;
2. The extent that risks are reduced through different adaptation options;
3. The cost or level of effort to implement the adaptation options; and
4. The decision makers' expectations of the likelihood of different futures and predicted outcomes.

The results presented up to this point provide information relative to the first two factors. That information alone is insufficient to support a decision among different strategies. Information about costs and level of effort for implementing the different options, along with future expectations concerning the vulnerable conditions is also required. The RDM methodology provides a means for considering this information not at the beginning of a decision analysis, as is common in a traditional analysis, but at the end. The advantage of this approach is that the preceding analysis first identifies which conditions are relevant to the decisions—these are the vulnerable conditions. This helps focus the sometimes-difficult process of defining likelihoods for future conditions upon only those conditions that matter. Furthermore, the implications of different stakeholder and decision maker expectations can be made explicit. This information can then help support the necessary deliberations needed to finalize a decision. In this case study, we can intuit that if the vulnerable conditions seem likely to occur, DEP would first consider revising operations, a potentially low cost option as compared with more expensive supply augmentation.

In a more general RDM analysis, we would combine the empirically derived information about vulnerabilities and the conditions that lead to them with subjective information about how probable the key vulnerabilities are likely to be. Together this information can provide guidance on how much to invest to reduce vulnerabilities. Here, we would calculate how likely the vulnerable conditions of 1,450 mgd demand would have to be in order to justify the investment in augmenting supply to meet water quality targets. Fortunately, DEP is unlikely to experience 1,450 mgd demands anytime in the near future. The significantly more modest 1,250 mgd demand level is only projected to occur by 2030. Even for a city the size of New York, a 200-300 mgd jump in demand is extremely unlikely to occur suddenly. Therefore, as future trends in demand growth become better defined, DEP should pursue developing a more comprehensive set of adaptation options to expand water supply or restrict demand as necessary.

4.6 KEY FINDINGS AND SUMMARY

This analysis indicates that there are a number of combinations of plausible conditions under which DEP's water supply system may fail to meet its water reliability or water quality objectives, or both. Many of these vulnerable conditions are consistent with future projections of demand, climate, and other factors. In particular, it may be difficult to meet water reliability goals in the future given increased water needs from projected consumptive demand or greater downstream releases, unless future climate change results in substantially more precipitation in the future. While many climate models project overall increases in precipitation, many do not project sufficient increases to offset anticipated needs. Water quality goals—as measured by alum use—may be difficult to meet if demand is higher than projected. The challenges may be exacerbated if turbidity events become more severe, if future climate results in less average precipitation, or with other factors that are not yet well understood.

As a result, DEP may wish to consider adaptation options to make the system more robust. Of the four adaptations considered here, only supply augmentation seems to provide some improvement to DEP's ability to meet water reliability goals in the future. Both supply augmentation and operational changes significantly improve the ability of the system to address water quality challenges. Added model runs would help quantify these benefits in a wider range of futures with varying turbidity thresholds as better information on extreme precipitation under climate change becomes available. Operational changes, which offer modest reductions in alum use, are inexpensive and offer a first defense against potentially high alum use if DEP determines that demand is likely to be higher than current projections. Overall this analysis quantified some important characteristics with respect to vulnerability of the DEP water supply. This pilot RDM study provided the following key findings:

4.6.1 Vulnerability Assessment

- DEP's system may not be able to meet specified water quality or water reliability targets under many plausible futures based on the preliminary analysis presented here, even with the investments already planned for the Baseline system.
- Specific combinations of demand, climate, and regulatory requirements, in particular, help determine whether the Baseline system meets its water reliability targets. They provide a good explanation of the Baseline system's water reliability performance.
- The conditions under which DEP's system would not meet specified reliability goals are plausible and consistent with the best available evidence utilized in this analysis. This suggests that DEP should consider adaptation measures that would make the system more robust. It is important to emphasize that even though the tested futures are plausible, the actual probability of any one future occurring is unknown.
- Higher-than-expected demand may be an important determinant of when DEP's system would not meet specified water quality targets. However, turbidity thresholds and climate characteristics can contribute to a wide range of outcomes, even with the same level of demand.
- Higher-than-expected demand could occur with sustained increases in population or per capita demands. DEP should continue monitoring these trends. The complex interaction between turbidity and climate suggests that it is worthwhile for DEP to continue research efforts in this area.

4.6.2 Risk Management

- The adaptation options considered here may be insufficient for addressing specified water reliability goals in the long-term future based on this analysis; DEP may wish to consider a wider range of options.
- Adaptation options considered here may enable DEP to meet its water quality targets under a much wider range of conditions than the current system. It may be valuable for DEP to iterate upon the analysis to confirm this.

- Despite the fact that there are a number of potential futures in which DEP's water supply may fail to meet supply reliability and water quality objectives, because of the criticality of demands, consistent monitoring of changes in demand over time can provide signposts for actions. Demand is a critical component of the system, influencing the effectiveness of management strategies to maintain both water quality and reliability goals; while not modeled in this study, managing future demand (i.e. maintaining demand growth within an acceptable range) may be the most cost-effective adaptation option available to DEP.

CHAPTER 5: CONCLUSIONS

This report described many challenges that climate change poses for water utilities engaged in long-term planning. It proposed a framework for conducting climate vulnerability assessments and developing climate risk management strategies based on RDM. Lastly, it presented two pilot studies in which this framework was applied.

This study purposefully applied the framework in two very different planning contexts. As a result, each application focused on different aspects of the planning framework. The CSU application used the RDM framework to directly inform the beginning stages of its ongoing planning process. Specifically, CSU used the XLRM Matrix to organize numerous workshops and conversations on the scope of the IWRP. Additionally, rather than developing a few scenarios or trying to estimate probabilities of different scenarios, it developed the data and modified its simulation models to support the evaluation of its system under a large range of diverse futures. The pilot study then used this information to demonstrate how to implement a climate vulnerability assessment. The CSU pilot study did not evaluate alternative strategies to reduce remaining climate risks.

The pilot with DEP, in contrast, was a distinct effort that differed from DEP's other planning activities. DEP staff participated in several workshops to develop an XLRM Matrix for the purposes of the study and assisted with the overall modeling effort. The vulnerability assessment considered two performance metrics—reliability and quality—that are related yet reflective of different system processes. The RDM analysis also evaluated some preliminary alternative strategies for managing the climate risk identified through the vulnerability assessment.

5.1 LESSONS LEARNED

The application of the RDM framework for this study yielded a number of important lessons summarized here.

5.1.1 Participatory Scoping

In both pilot projects, the XLRM Framework was widely viewed by the planners as a helpful approach to organizing thinking about uncertainties, metrics, and strategies. In the NYC case, it was used primarily by the study team to organize and communicate the different analyses. For CSU, it was embraced by CSU planners and formally used as the organizing framework for CSU's IWRP (see Appendix C). In both cases, it helped organize concerns about climate change and other uncertainties and focus stakeholder concerns.

It is not always possible to address all concerns raised during the participatory scoping in the subsequent analysis. For example, lack of data, poor understanding of key processes, and low fidelity of available models may preclude simulating certain possible effects. Likewise, the complexities of the real-world water system cannot always be represented by the models used to explore known system vulnerabilities. For example, risks around infrastructure failure are difficult to quantify and include in the vulnerability analysis. However, recording such concerns within the XLRM Matrix helped engage planners and stakeholders and can be a resource for future analysis.

5.1.2 Non-climate uncertainties

As part of both pilot studies, non-climate uncertainties (e.g. water demand growth, unplanned infrastructure limits, and regulatory or legal issues) were included in the development of the experimental designs. While the focus of these pilots was to explore the effects of climate change on the utilities, other typical long-term planning concerns could not be ignored. As observed with very high levels of demand in the DEP pilot, non-climate drivers can overshadow climate-related hydrologic changes. In other instances, the non-climate uncertainties together with climate-related drivers resulted in vulnerabilities that were not exhibited by either condition individually. It is difficult to predict which drivers will contribute to vulnerabilities, underscoring the importance of exploring a wide range of uncertainties as part of the participatory scoping process.

5.1.3 Weather and climate threats

Utilities may be vulnerable to changes in weather and climate at multiple temporal scales, and there are three distinct weather scales of concern: average annual conditions, seasonal variations, and individual extreme events, such as storms, droughts, or heat waves. The interplay of changing weather patterns with the unique characteristics of a particular water utility may dictate how the utility will be impacted, if at all.

For example, climate change projections for the northeast U.S. generally exhibit warmer and wetter average conditions. However, the precipitation increases are not distributed evenly, as the models project less precipitation in summer and fall and more precipitation in winter and spring. The frequency of extreme storm events has been increasing, and this trend is projected to continue under many climate change projections. Increased annual precipitation was not considered a concern for DEP, and the analysis focused on drier summer and fall seasons that could lead to increased short-term drought. Future analyses should seek to incorporate extreme storm events.

5.1.4 Data gaps

Water utilities need quantitative datasets that identify changes to both frequency and magnitude of extremes under future climate change projections to fully evaluate potential vulnerabilities. The availability of downscaled GCM data has removed a major hurdle hindering many utilities from evaluating climate change vulnerabilities.[25] However, while climate change is an extremely active research area, significant data gaps exist with respect to both changing climate conditions and how those conditions could influence water resource systems in the future. For example, extreme weather is a major concern for water utilities, but the ability to quantify changes in extremes, particularly precipitation, is currently limited.

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[25] Downscaled GCM data is currently available from multiple organizations including the US Bureau of Reclamation, US Geological Survey, NOAA, National Center for Atmospheric Research, and the US Environmental Protection Agency.

There remains a strong need to further improve our understanding of these processes in order to better predict how changing climate will impact water quality. While modeling tools for observable physical or chemical processes (i.e. flow of surface water, transfer of gases, etc.) can provide results with relatively high confidence, there are significant gaps in available modeling tools for complex processes that are difficult to observe, such as turbidity mobilization, algal blooms, and biogeochemical cycling of nutrients and organic carbon. It is common practice to use surrogates or empirical simplifications where modeling gaps exist. However, changing weather and climate may significantly impact the processes that drive surface water quality, calling into question the accuracy of existing tools.

5.2 ADDRESSING CLIMATE AND OTHER UNCERTAINTIES

For both pilot studies (CSU and DEP), the partner utility had begun to develop projections of the future climate and had initiated efforts to evaluate the effects of these projections on their respective systems. The RDM methodology was of interest to our utility partners because it provided them a means to interpret the highly uncertain results without having to develop or assign probabilities to the climate and hydrologic projections. The RDM methodology also enabled CSU to evaluate paleo-derived projections alongside GCM-derived projections, despite the challenges they have had in developing climate change projections given the legacy of analyzing system performance based on historic hydrology (i.e. assumptions of stationarity).

RDM enabled both pilot studies to quantitatively evaluate the relative importance of other uncertain factors, such as future demand, as compared to climate uncertainty. The CSU pilot also was able to consider uncertainty about infrastructure-related system failure or constraints alongside demand and climate.

5.2.1 Vulnerability Assessment

The vulnerability assessments for each pilot study evaluated the results of the simulations of large ensembles of futures to determine which uncertain factors were driving poor system performance.

In the CSU pilot, demand was significantly less important to the success of its management system than was climate. The RDM vulnerability analysis also determined that the infrastructure risk factors identified were of lesser importance than climate. In the DEP pilot, demand had a very large influence and within the range evaluated, dominated climate uncertainty. It was only when the range of future demand was narrowed that climate uncertainty made a difference. However, this conclusion may be inconclusive because the uncertainty in future climate, particularly with regards to extreme event frequency and intensity, could not adequately be characterized at this time.

5.2.2 Risk Management and Informing Planning

The RDM Framework supports the development of risk management strategies first by identifying key vulnerabilities. This information then can inform the development of more robust strategies. In some cases, changing system operating procedures or investing in new infrastructure is shown to provide a hedge against the vulnerabilities identified. In the case of the DEP pilot, operational changes and supply augmentation measures were effective in reducing water quality vulnerabilities. The options evaluated, however, did not significantly reduce water supply vulnerabilities. This does not mean that RDM is not informative, but rather it highlights that other options may need to be considered if DEP is to further reduce its vulnerability.

Although not highlighted in the DEP pilot, robust strategies are often adaptive and should be designed to consist of some near-term actions, conditions to monitor over time, and deferred actions to be implemented only if conditions warrant. Recent RDM applications for the IEUA (Lempert and Groves 2010) and Reclamation's Colorado River Basin Study (Groves et al., 2013b) developed adaptive, robust strategies that implement additional investment only under conditions similar to those described by the key vulnerabilities. This enables the strategies to address challenges when needed, thus only incurring necessary costs, while avoiding costly intervention when not needed.

5.2.3 Applying Framework in Other Contexts

There appears to be growing interest among utilities in the United States and other water management agencies, such as the U.S. Bureau of Reclamation, to use new planning methods to address climate change in long-term water resources planning. This report shows that RDM offers a useful framework for application in different contexts.

Common across all applications of RDM is the participatory scoping exercise. In some cases it is fruitful to take the next step and use quantitative models to evaluate the performance of a utility's plan across futures reflecting the uncertainty identified. It is important to resist the temptation of over thinking the development of these futures. Because the vulnerability analysis focuses on defining thresholds of poor performance—the vulnerable conditions—it is less sensitive to the specific futures included than a probabilistic or traditional scenario process would be. This offers a tremendous advantage by enabling the technical analysis to proceed without arriving at consensus about which few scenarios to include or how to weight them.

The RDM process is iterative and necessarily participatory. This makes it well suited to support IWRM, but it also can require a significant investment in time and resources to implement successfully. Fortunately, the iterative nature enables utilities to apply it in a limited fashion at first and then incorporate more sophistication on subsequent iterations.

5.3 RECOMMENDATIONS FOR WATER UTILITIES PURSUING CLIMATE CHANGE ASSESSMENTS

While incorporating climate change uncertainty into long range planning is relatively new for most utilities, the increasing availability of data and tools will make climate change vulnerability analyses more accessible. The findings from this project offer practical guidance to the water industry on how to address climate change risk. Below is a summary of specific recommendations for utilities interested in pursuing climate change assessments.

- Define the scope of the analysis with the participation of stakeholders. Participatory scoping procedures, such as XLRM, can help itemize important uncertainties, available data and models, policy options, and performance metrics.
- Use climate projections from GCMs and other sources to stress test existing and proposed plans rather than to assign probabilities to projections and develop a probabilistic future forecast.

- Include non-climate related uncertainties to fully evaluate potential future vulnerabilities for a system. Projections can be handcrafted to bridge data gaps.
- Analyze the performance of the current management system and possible augmentations to understand which uncertain future conditions are most stressing to the system. These conditions define scenarios that are most relevant for planning.
- Incorporate climate change into regular utility long-term planning activities, such as for IWRPs or Capital Improvement Plans. Adapting to climate change will require adaptation and cannot be defined at a single point in time. As assessments become more commonplace, planning and engineering staff and utility managers will become more comfortable with conducting assessments and interpreting results.

APPENDIX A: COLORADO SPRINGS UTILITIES PILOT STUDY SUPPLEMENTAL MATERIAL

CLIMATE CHANGE PROJECTIONS FOR COLORADO SPRINGS UTILITIES

Problematically, global climate models (GCMs) produce climate data (precipitation and temperature in this case), while the Yield Model needs inflow data. Thus, we needed to reflect how these climate change sequences would manifest themselves in terms of the inflows into the Colorado Springs Utilities (CSU) raw water system, while recognizing CSU's dependence on the use of the observed inflows or the period 1950 to 2008. To do this, we first developed a simple hydrologic model using the Water Evaluation and Planning system (WEAP). The simple WEAP model of the Arkansas River at Salida and South Platte River was calibrated against observed flows for the period 1951 to 2000, using the climate data from http://gdo-dcp.ucllnl.org/. Figure A.1 is a screenshot of the model, which includes 7 catchment objects and demonstrates the time series of precipitation sequence for each.

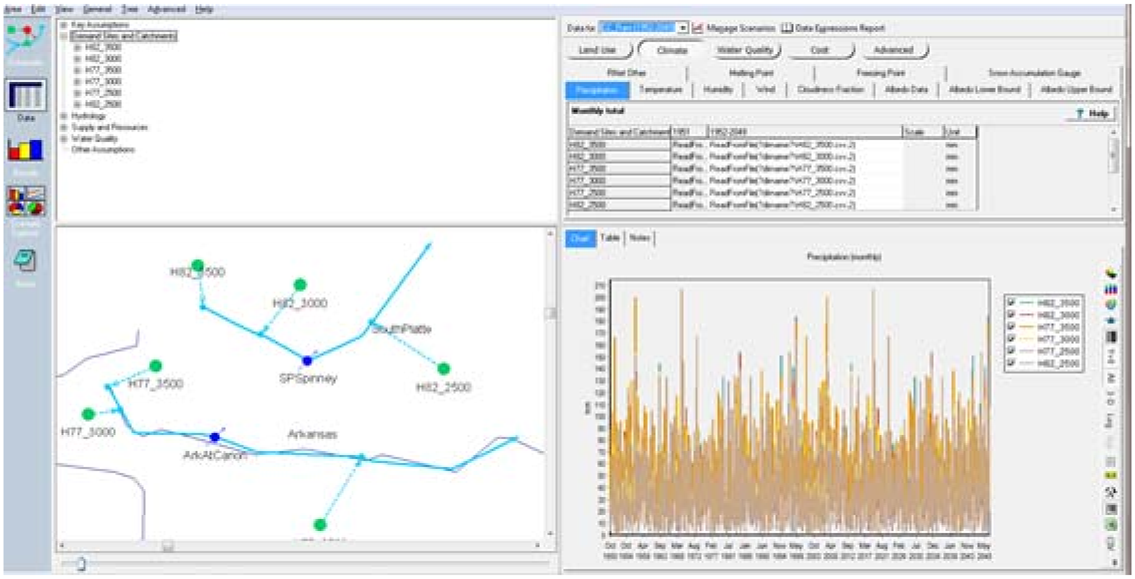


Figure A.1 Simple WEAP model of the Arkansas and Platte River Basins

Figure A.2 shows the annual simulated and observed flows (red and blue lines, respectively) for the period 1951 to 2000 for the Arkansas at Canon gage showing strong agreement between the observed and simulated flows.

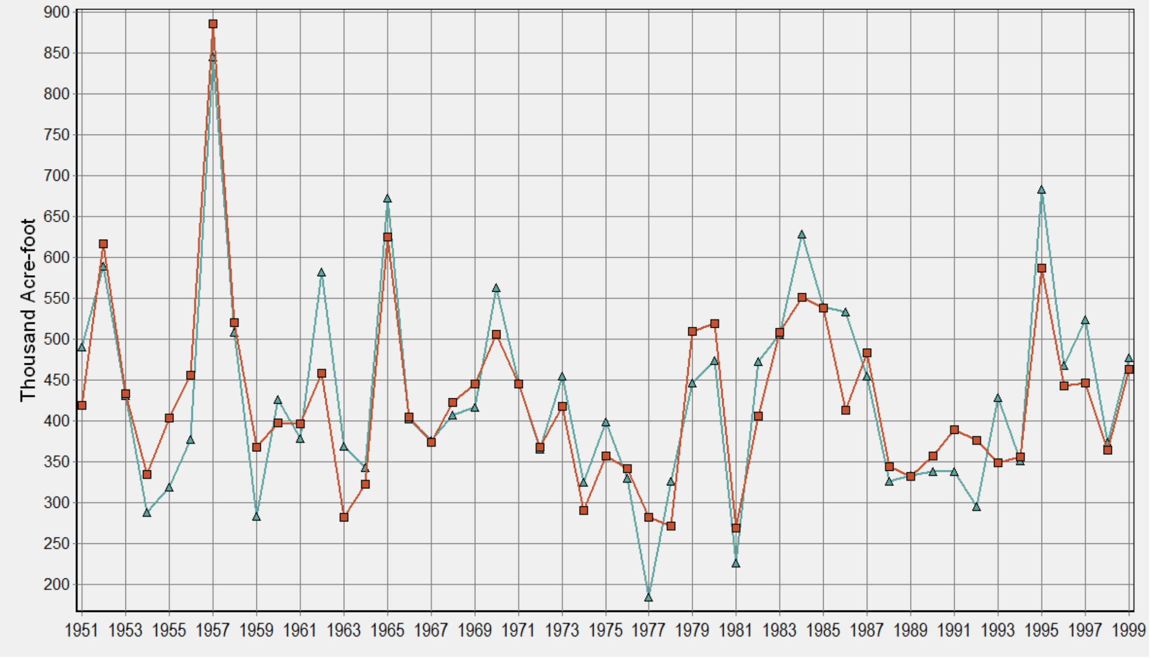


Figure A.2 Annual simulated and observed flows of the Arkansas and Platte River Basins

This calibrated WEAP model was then used to simulate flows for the contemporary period and future period for each of the 112 climate projections. Since the WEAP model is made up of individual catchment objects and each has a unique climate and resulting simulated flow time series, it was possible to map each Yield Model inflow node to a unique catchment object. This allowed us to characterize the spatial pattern of climate change as reflected in each of the GCM projections, as CSU's distant water supplies are derived from the high elevation Rocky Mountains, while the local water supply comes from a region that is at lower elevation and much drier. The procedure to develop Yield Model inflow nodes that reflect the GCM-derived climate change projections is shown below, with an example given for a single, natural inflow node referenced in the Yield Model database as In_33rdInt.

1. For each inflow node in the Yield Model, compute the average monthly values for the full period of record, 1950 to 2008. Figure A.3 shows the monthly mean inflow for the In_33rdInt node.

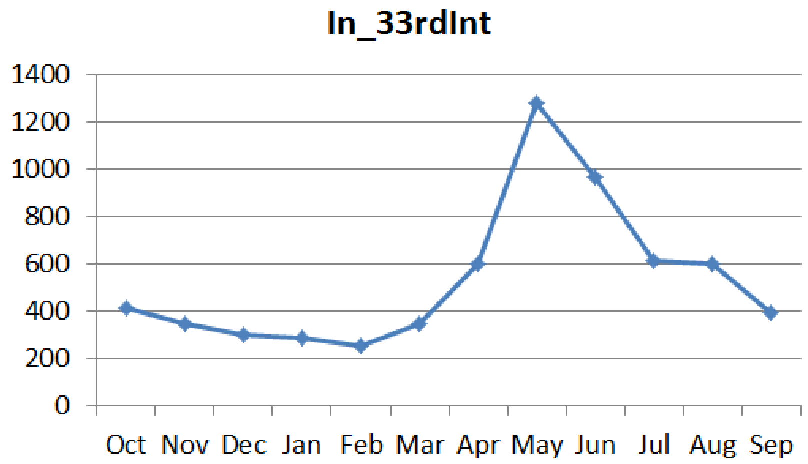


Figure A.3 Average monthly flows for 1950 to 2008

2. Run the calibrated WEAP hydrology model for all 112 climate change projections, resulting in a monthly time series of flows for each of the seven catchment objects. Figure A.4 shows the time series of monthly flows from a sample of four climate projections for node In_33rdInt.

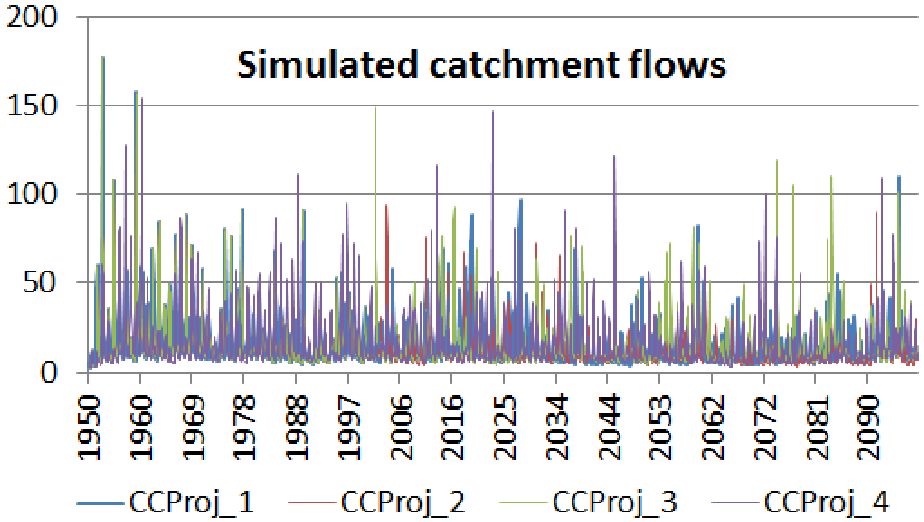


Figure A.4 Simulated monthly catchment flows for four climate projections

3. For each catchment object and climate change projection, compute the monthly mean flow for the period 1950 to 2008, corresponding to the time period of the historic inflow series in the Yield Model. Figure A.5 shows the simulated monthly mean flows for four climate projections.

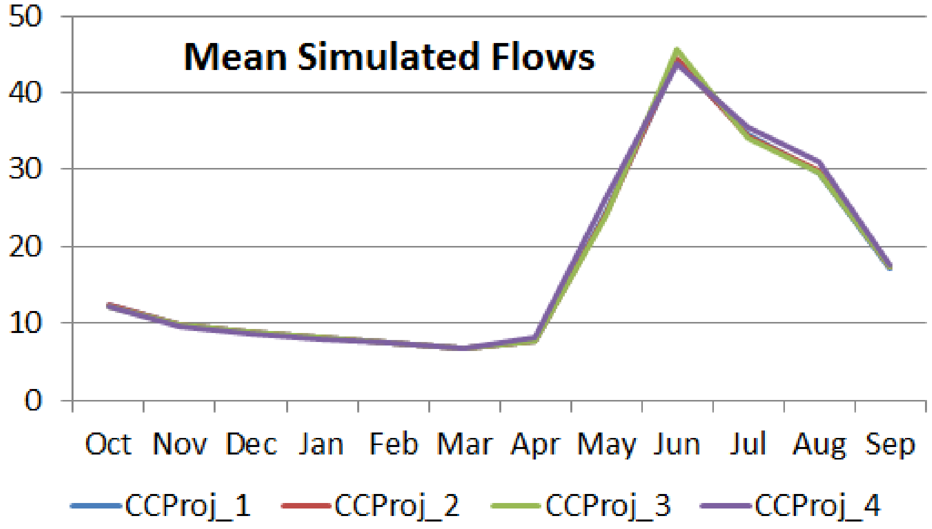


Figure A.5 Simulated mean monthly flows for four climate projections

4. Derive a flow anomaly as the ratio of each monthly value and the monthly mean for each of the climate change projections (Figure A.6).

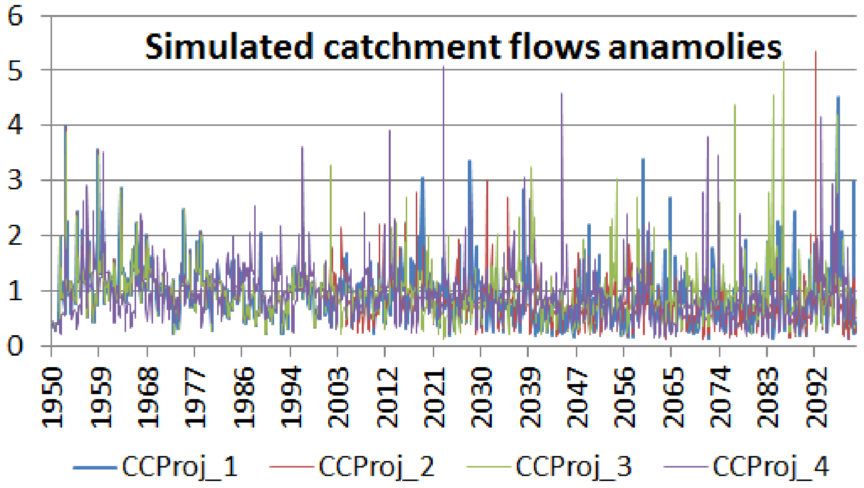


Figure A.6 Simulated catchment flow anomalies for four climate projections

5. Apply the anomaly field to the monthly mean of the Yield Model inflow node, resulting in a new monthly time series that can be used directly in the Yield Model (Figure A.7).

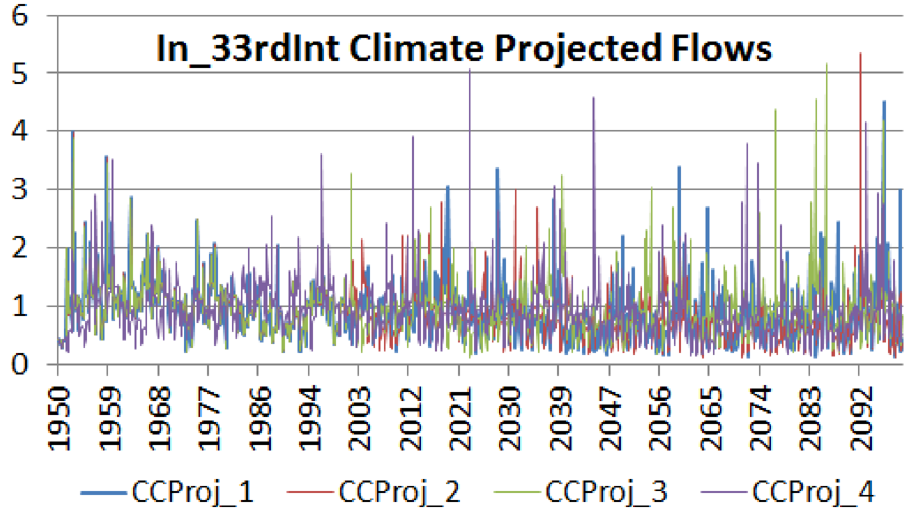


Figure A.7 Updated monthly projected flows for four climate projections

The Yield Model makes use of a 59-year time series of monthly flows for all nodes, and so we extracted the period 2015 to 2074 of monthly flow values for each of the inflow nodes for all 112 GCM-based climate projections. Finally, to define the exchange potential, linear regression relationships were developed that defined the exchange potential as a function of these climate-altered flow sequences.

PARTICIPATORY SCOPING FOR THE INTEGRATED WATER RESOURCES PLAN-XLRM

(Used with permission. These lists are preliminary and CSU may or may not use these for further analysis or may add additional items to the lists.)

SECTION 6

Preliminary XLRM Matrix

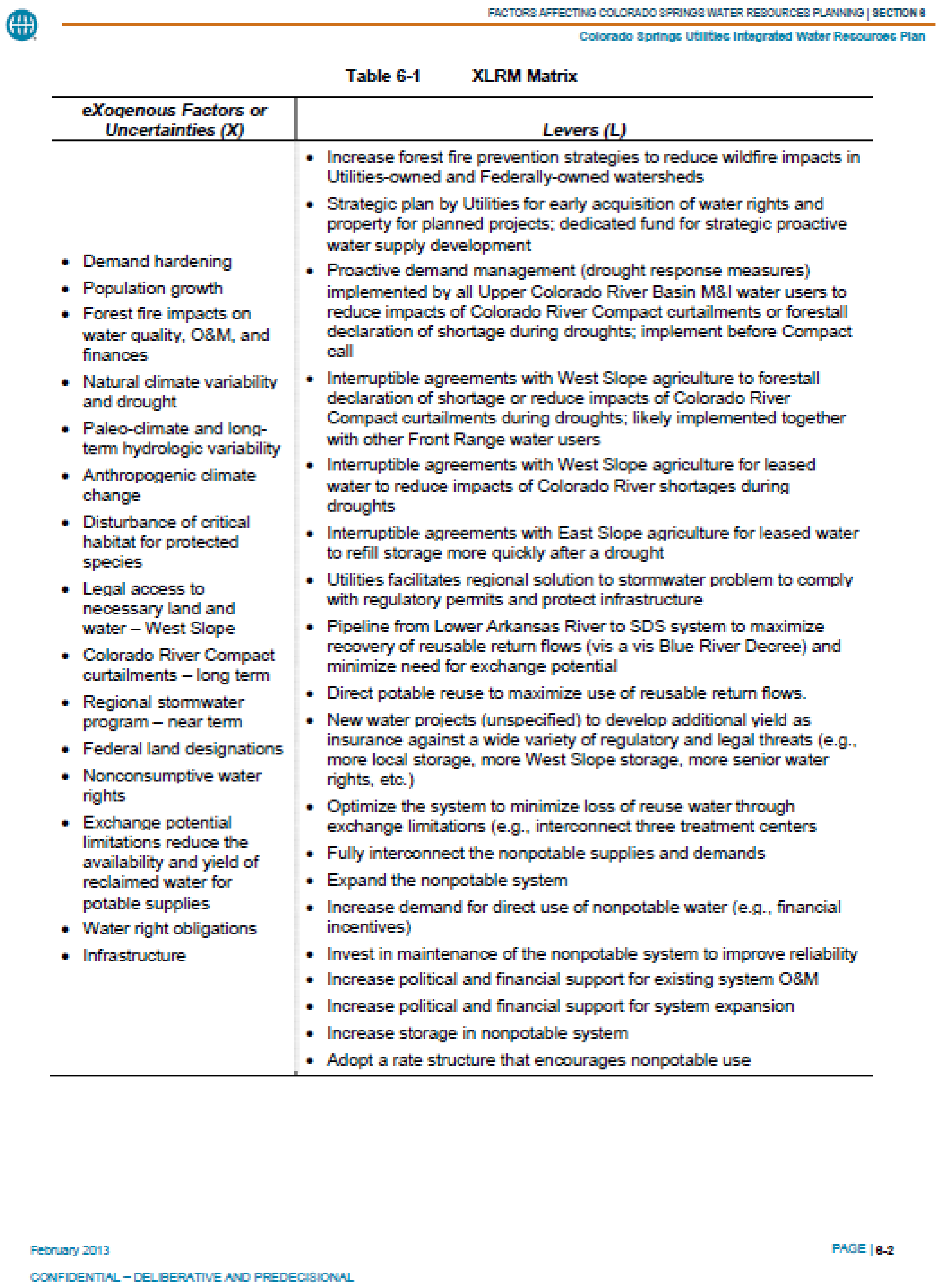
> "The difficulty lies not in the new ideas, but in escaping from the old ones." *John Maynard Keynes*

The composite XLRM matrix developed using the high priority issues, risks, and vulnerabilities identified by the Technical Team is shown in **Table 6-1**. The exogenous uncertainties Xs include the highest priority issues, risks, and vulnerabilities from **Table 4-1**. These Xs represent factors over which Utilities has little or no control. The levers (Ls) are projects, programs or policies that Utilities could adopt to mitigate the effect of the Xs. Some of the Xs cannot be addressed directly or indirectly by Utilities through projects or programs because they are matters beyond Utilities' influence alone, or because they are very general and not tied to a particular source of water or delivery system.

Table 6-1 is a preliminary XLRM matrix based on the information currently developed for the IWRP by the individual subject-matter work groups. Another iteration of the XLRM matrix will be prepared after initial modeling of Xs and Ls in Phase 1B of the IWRP.

The Ls listed in the XLRM matrix are the main ideas discussed to date by the IWRP work groups that address the highest priority issues, risks, and vulnerabilities. The discussion of Ls will be expanded in Phase 2 of the IWRP to include more specific projects, programs or policies influenced by public input that could be implemented to address the issues, risks, and vulnerabilities identified in this Planning Factors Report. The IWRP team will determine which Ls should be simulated using the MODSIM raw water system operations model in Phase 2.

The Ms listed in the XLRM matrix are general metrics developed by the IWRP work groups. Subsequent evaluation by the IWRP team refined definitions of some of the metrics, and expanded the list to include state variables that should be tracked in the modeling of risks and levers. For purposes of the IWRP, metrics are defined as measures that will be used to assess system performance and may be used in multi-objective optimization functions. M's must be quantifiable and capable of being computed for each scenario in the MODSIM model of the raw water collection system. System state variables are defined as model results that are important and will be tracked but not optimized.



FACTORS AFFECTING COLORADO SPRINGS WATER RESOURCES PLANNING | SECTION 6

Colorado Springs Utilities Integrated Water Resources Plan

Table 6-1 XLRM Matrix

eXogenous Factors or Uncertainties (X)	*Levers (L)*
• Demand hardening • Population growth • Forest fire impacts on water quality, O&M, and finances • Natural climate variability and drought • Paleo-climate and long-term hydrologic variability • Anthropogenic climate change • Disturbance of critical habitat for protected species • Legal access to necessary land and water – West Slope • Colorado River Compact curtailments – long term • Regional stormwater program – near term • Federal land designations • Nonconsumptive water rights • Exchange potential limitations reduce the availability and yield of reclaimed water for potable supplies • Water right obligations • Infrastructure	• Increase forest fire prevention strategies to reduce wildfire impacts in Utilities-owned and Federally-owned watersheds • Strategic plan by Utilities for early acquisition of water rights and property for planned projects; dedicated fund for strategic proactive water supply development • Proactive demand management (drought response measures) implemented by all Upper Colorado River Basin M&I water users to reduce impacts of Colorado River Compact curtailments or forestall declaration of shortage during droughts; implement before Compact call • Interruptible agreements with West Slope agriculture to forestall declaration of shortage or reduce impacts of Colorado River Compact curtailments during droughts; likely implemented together with other Front Range water users • Interruptible agreements with West Slope agriculture for leased water to reduce impacts of Colorado River shortages during droughts • Interruptible agreements with East Slope agriculture for leased water to refill storage more quickly after a drought • Utilities facilitates regional solution to stormwater problem to comply with regulatory permits and protect infrastructure • Pipeline from Lower Arkansas River to SDS system to maximize recovery of reusable return flows (vis a vis Blue River Decree) and minimize need for exchange potential • Direct potable reuse to maximize use of reusable return flows. • New water projects (unspecified) to develop additional yield as insurance against a wide variety of regulatory and legal threats (e.g., more local storage, more West Slope storage, more senior water rights, etc.) • Optimize the system to minimize loss of reuse water through exchange limitations (e.g., interconnect three treatment centers • Fully interconnect the nonpotable supplies and demands • Expand the nonpotable system • Increase demand for direct use of nonpotable water (e.g., financial incentives) • Invest in maintenance of the nonpotable system to improve reliability • Increase political and financial support for existing system O&M • Increase political and financial support for system expansion • Increase storage in nonpotable system • Adopt a rate structure that encourages nonpotable use

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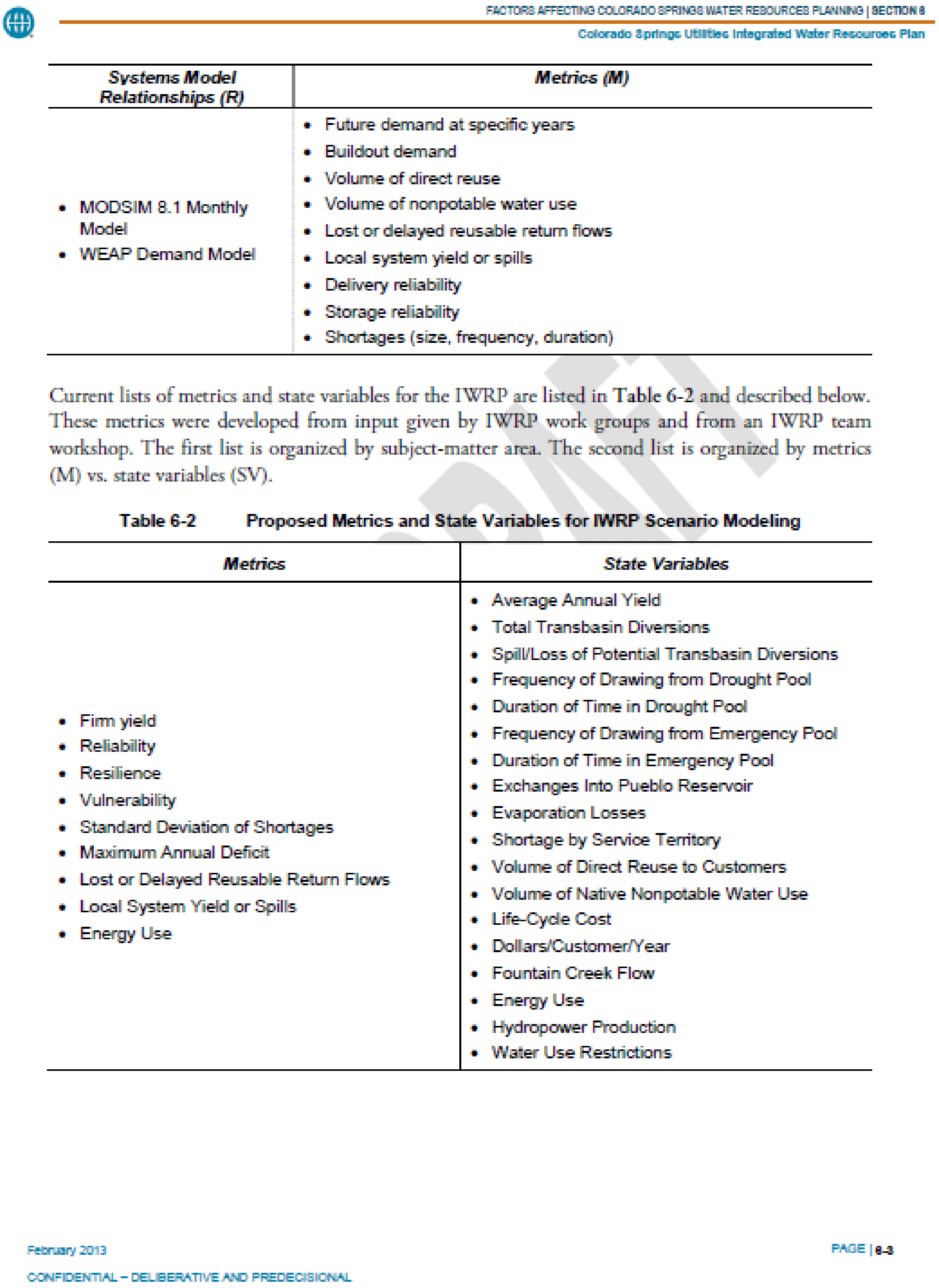
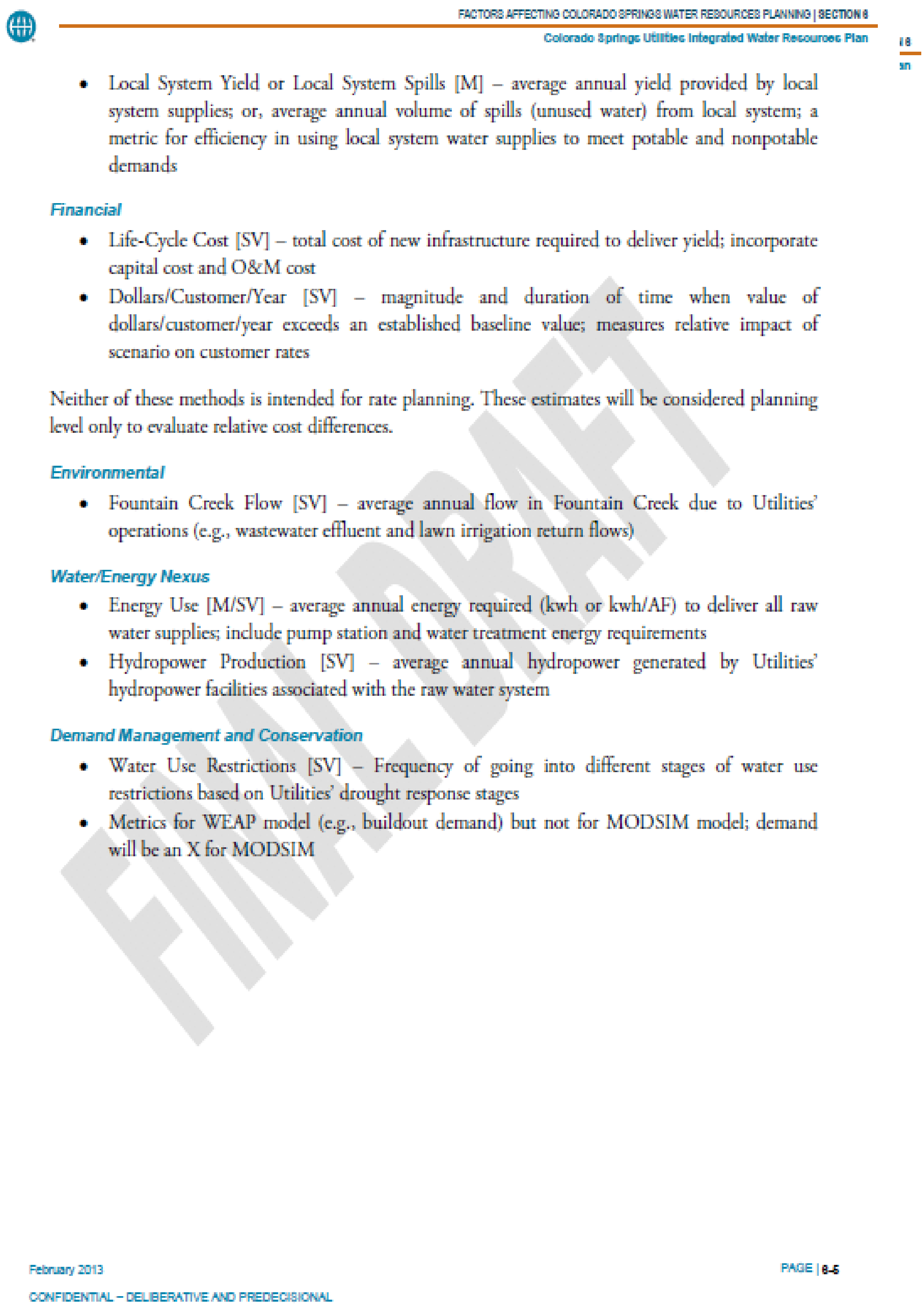


Systems Model Relationships (R)	***Metrics (M)***
• MODSIM 8.1 Monthly Model • WEAP Demand Model	• Future demand at specific years • Buildout demand • Volume of direct reuse • Volume of nonpotable water use • Lost or delayed reusable return flows • Local system yield or spills • Delivery reliability • Storage reliability • Shortages (size, frequency, duration)

Current lists of metrics and state variables for the IWRP are listed in Table 6-2 and described below. These metrics were developed from input given by IWRP work groups and from an IWRP team workshop. The first list is organized by subject-matter area. The second list is organized by metrics (M) vs. state variables (SV).

Table 6-2 Proposed Metrics and State Variables for IWRP Scenario Modeling

Metrics	***State Variables***
• Firm yield • Reliability • Resilience • Vulnerability • Standard Deviation of Shortages • Maximum Annual Deficit • Lost or Delayed Reusable Return Flows • Local System Yield or Spills • Energy Use	• Average Annual Yield • Total Transbasin Diversions • Spill/Loss of Potential Transbasin Diversions • Frequency of Drawing from Drought Pool • Duration of Time in Drought Pool • Frequency of Drawing from Emergency Pool • Duration of Time in Emergency Pool • Exchanges Into Pueblo Reservoir • Evaporation Losses • Shortage by Service Territory • Volume of Direct Reuse to Customers • Volume of Native Nonpotable Water Use • Life-Cycle Cost • Dollars/Customer/Year • Fountain Creek Flow • Energy Use • Hydropower Production • Water Use Restrictions



- Local System Yield or Local System Spills [M] – average annual yield provided by local system supplies; or, average annual volume of spills (unused water) from local system; a metric for efficiency in using local system water supplies to meet potable and nonpotable demands

Financial

- Life-Cycle Cost [SV] – total cost of new infrastructure required to deliver yield; incorporate capital cost and O&M cost
- Dollars/Customer/Year [SV] – magnitude and duration of time when value of dollars/customer/year exceeds an established baseline value; measures relative impact of scenario on customer rates

Neither of these methods is intended for rate planning. These estimates will be considered planning level only to evaluate relative cost differences.

Environmental

- Fountain Creek Flow [SV] – average annual flow in Fountain Creek due to Utilities' operations (e.g., wastewater effluent and lawn irrigation return flows)

Water/Energy Nexus

- Energy Use [M/SV] – average annual energy required (kwh or kwh/AF) to deliver all raw water supplies; include pump station and water treatment energy requirements
- Hydropower Production [SV] – average annual hydropower generated by Utilities' hydropower facilities associated with the raw water system

Demand Management and Conservation

- Water Use Restrictions [SV] – Frequency of going into different stages of water use restrictions based on Utilities' drought response stages
- Metrics for WEAP model (e.g., buildout demand) but not for MODSIM model; demand will be an X for MODSIM

APPENDIX B: NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION PILOT STUDY SUPPLEMENTAL MATERIAL

This appendix includes additional information supporting the New York City (NYC) Department of Environmental Protection (DEP) Pilot Study.

DEP OPERATIONS SUPPORT TOOL

In order to maximize the potential benefits of dynamic reservoir operations, DEP has deployed an Operations Support Tool (OST) to assist operators with daily decision-making.[26] Figure B.1 shows a schematic of OST. The modeling portion of the tool, shown in the lower left of the figure, consists of a systems model developed in OASIS, a generalized computer program for modeling the operation of water resources systems (HydroLogics, Inc. 2009). OASIS represents the system using nodes (reservoirs, junctions) and arcs (aqueducts, streams), and uses linear programming optimization to simulate water routing decisions (e.g., reservoir releases or diversions) in the system, subject to both human operating rules and physical constraints. The OASIS model of the DEP's reservoir system simulates daily operations throughout the entire system and the entire Delaware River Basin.

The OASIS model includes data that represent physical constraints on the flow and storage of water (e.g., spillway rating curves, maximum capacities of aqueducts and release works, elevations of structures, reservoir storage-elevation curves). Inflows throughout the system are based on a 76-year historical dataset for the watersheds. Inflow to reservoirs only represents the local inflow to that reservoir and does not include flows from upstream reservoirs, which are determined during model simulations. In addition to historical hydrology, inflows can also be represented by statistical hydrology or climate change hydrology.

Demands in the OASIS model include both NYC and outside community demands and are modeled as an average annual daily demand with multipliers based on either a recurring monthly pattern or a monthly regression model based on average maximum monthly temperatures.

The OST is also linked to a number of two-dimensional CE-QUAL-W2 (W2) water quality models, a dynamic, laterally averaged, two-dimensional (longitudinal-vertical), hydrothermal/transport model developed by the Army Corps of Engineers (Cole & Wells 2006).[27] In addition to the underlying fluid motion and mass transport framework, the Catskill W2 models include a three particle size class turbidity submodel that simulates the fate and transport of turbidity in the reservoirs, and accounts for both settling and resuspension processes.

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[26] Despite the fact that the final OST had not been fully deployed during this study, most functional components of the tool were currently in use by DEP.

[27] The CE-QUAL-W2 models significantly increase the run time of the OST. Therefore, simpler, flow-based triggers for turbidity were used to model reservoir processes for turbidity concentrations in the data presented in this study. A subset of runs was conducted with the CE-QUAL-W2 models to verify the consistency of the results using the flow-based triggers.

In addition to functioning as the system model of the NYC water supply system, the OST is linked with the various sources of data collected by DEP and a number of forecast tools, all of which work in concert during model simulations.

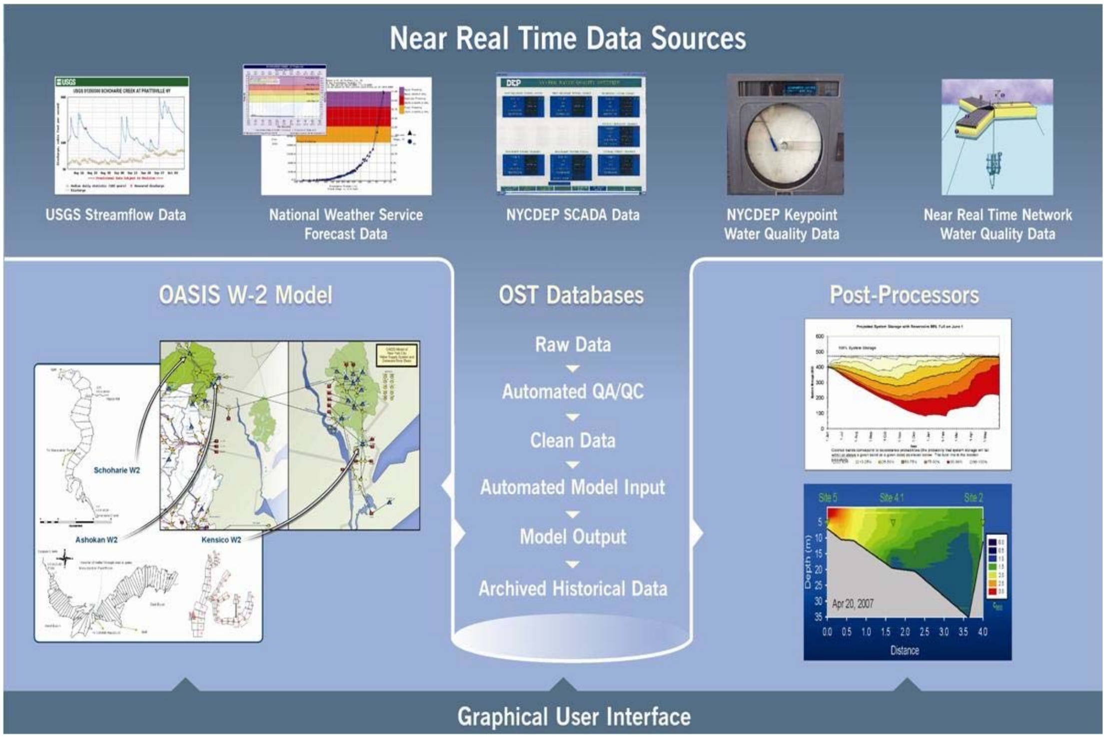

Figure B.1 Schematic of NYC's Operations Support Tool

Reservoir operations decisions are supported by a variety of system data, shown at the top of Figure B.1:

- United States Geological Survey (USGS) Streamflow Data - The USGS maintains a network of continuously telemetrically monitored gaging stations to measure surface elevations and associated flow rates for many streams in the NYC watershed and the Delaware Basin. USGS stream flow data are compiled, archived, and made available to the public through an existing web interface and acquired by OST using standard data extraction techniques.
- National Weather Service Forecast data - In addition to historical and near-real time data, the OST utilizes a statistical hydrologic forecast from the National Weather Service, which is based on the fact that streamflows often exhibit serial correlation from month to month (i.e. continuation of the current hydrologic trend). This "memory" is commonly attributed to month-to-month persistence in baseflow and/or soil moisture. According to Hirsch (1981), this serial correlation allows for the generation of monthly streamflow forecast ensembles based on flows from the preceding month and the application of random noise. Generally, this statistical method allows for forecasts with tighter distributions (less variance and uncertainty) when compared to the historical analog method. This means that the forecasts reflect more forecast skill.
- DEP SCADA Data - DEP operates and maintains automated reservoir and transmission system supervisory control and data acquisition (SCADA) systems to support the moni-

toring and control functions. Monitoring and control responsibility is currently divided between two SCADA systems that address the West of Hudson and East of Hudson systems independently. The two SCADA systems provide real-time monitoring functionality for a number of remote facilities and sensors and archive associated data.

- DEP Keypoint Water Quality Data - DEP monitors a broad range of water quality parameters (turbidity, nutrients, dissolved solids, etc.) at critical locations within the water supply system through its Keypoint Monitoring Program. Some data are grab-sampled while others are monitored and transmitted continuously.
- Near Real Time Network Water Quality Data - DEP operates in-reservoir sampling buoys at selected reservoirs to support water quality modeling and DEP operational efforts. The buoys measure turbidity, temperature, conductivity and dissolved oxygen at one-meter intervals from the water surface to near the bottom. Additional automated sampling instruments measure temperature, conductivity, and turbidity at major reservoir inflow points.

DECISION STRUCTURING

The research team conducted an XLRM workshop with DEP staff, and this section summarizes the resulting outcomes related to the XLRM process and work plan development conducted at the workshop.

Exogenous Factors (X)

During the workshop the research team and DEP staff reviewed the major issues facing DEP, developed a list of key uncertainties, and grouped them into six major categories: climate forcings, demand drivers, watershed and land use, policy and regulations, financials, and technical. It was noted that it would be unlikely for each uncertainty to be included in the analysis; the team made every effort to include as many of the uncertainties as possible if sufficient data and modeling tools were available. For selected uncertainties, values were calculated that described the range of projections in the future.

Climate Forcings

Based on the results of a preliminary analysis of climate-related impacts of the 145 downscaled global climate model (GCM) projections developed by DEP, it was determined that it was not necessary to analyze all of the climate change projections. The NYC water supply is vulnerable to extreme hydrology: extreme inflows (often in the 99th percentile of recorded rainfall events) that mobilize turbidity and cause flood impacts, and long periods (multiple years) of below average inflows that reduce stream flows and result in drought restrictions. Therefore, a mix of climate change projections with drier and wetter than historical average conditions were selected for analysis. Because the objective of this project is not to predict changes for the NYC water supply, but to understand the potential impacts and adaptation options, selecting the more extreme projections bounds the range of potential changes based on available GCM data.

Demand Drivers

It was recognized that demands change significantly over time and that demands would need to be estimated beyond the existing planning horizon.

DEP's current estimate of residential water use is 78 gallons per capita per day (GPCD) with approximately 380 million gallons per day (mgd) of non-residential and unaccounted for water (Siskind and Keniff 2010). Future demands may be very different from the present because of changes in domestic use characteristics, economic growth, emergence/decline of commercial or industrial water users, or other uncertain factors.

For this study, future demand was divided into two uncertain factors: per capita usage and population. Per capita usage in the NYC service area has been dropping over the last 30 years, but is not expected to continue dropping in the future. A range of per capita use rates of 65 to 90 GPCD (approximately +/- 15% of the current rate) was used to represent the potential maximum and minimum values over the future time horizon. The NYC Department of City Planning estimates an annual population growth rate of 0.5% through 2030 (NYCDCP 2009). In the absence of projections of population growth beyond 2030, two annual population growth rates (0.25% and 0.5% per year) were used to calculate populations at 2055 and 2090.

Per capita use rates were multiplied by projected population with non-residential and unaccounted for water added to the total. In addition to in-city demands, NYC supplies water to a number of communities outside of the city limits. A general approximation of 10% of total system demands was assumed for calculating upstate demands. This results in a range of future demand of 1,085 to 1,638 mgd. Three points were selected in this range representative of (1) lower-than-projected demand (1,120 mgd) consistent with current demands, (2) NYC's demand projections through 2030 (1,250 mgd), and (3) higher-than-projected demands (1,450 mgd).

Usage in the DEP service area varies seasonally and the existing modeling framework uses a monthly repeating pattern of multipliers based on historical data to estimate seasonal demand variation. However, temperatures are expected to change under climate change and rising temperature is strongly correlated with higher demands. Thus, a regression equation was developed that relates monthly average demand to monthly maximum average temperatures in order to capture the influence on seasonal demand variations.

Watershed Land Use

As an unfiltered watershed, DEP exercises strict control of new sources of pollution through its watershed regulations. The one potential exception would be potential impacts to the watershed from future natural gas development, which is generally outside the jurisdiction of DEP regulations. Subsequent to the XRLM workshop, New York State Department of Environmental Conservation issued a ban on the use of high volume hydraulic fracturing in unfiltered watersheds in the state. With this decision it was decided that it was not necessary to develop projections of alternate land use projections at this time.

Policy and Regulations

Within the Catskill Subsystem, releases from Schoharie Reservoir are heavily regulated to control flow, temperature, and turbidity: no changes are anticipated for these rules. Historically, the Ashokan Reservoirs had few restrictions on releases. As DEP has improved the Ashokan Release Channel, it has begun negotiating rules with downstream stakeholders. Currently these rules are still under negotiation, so the currently modeled rules were left in place. The Delaware Subsystem has more developed rules for reservoir operation, and there are a number of stakeholder groups who are advocating for specific changes to current reservoir rules.

NYC's Delaware System provides approximately half of the City's annual supply and is also consistently the highest quality supply, but it is also the most heavily regulated of NYC's three systems. The two primary requests of DEP from downstream stakeholders are to (1) increase downstream releases during periods of low flow, and (2) reduce peak flows during high flow events for flood control. Both conditions have the potential to negatively impact DEP's water supply objectives. Increased releases during dry periods reduce stored water available for NYC withdrawals, which if a drought were to occur could lead to more severe water restrictions. Reservoirs naturally attenuate peak inflows by slowing the movement of the peak downstream and spreading it over a longer timeframe. Despite natural attenuation of peak flows by NYC's Delaware Reservoir, it has not typically been a management objective of the reservoirs. In order to provide further attenuation of peak flows during high flow events, it is necessary to maintain available storage capacity (i.e., storage void) in the reservoirs in anticipation of large inflows. Unfortunately, if a void is maintained in a reservoir, and large inflows do not materialize, there could be a storage deficit that results in drought conditions or use restrictions for NYC.

Since the implementation of the OST's advanced forecast and management capabilities in recent years, DEP has been more able to apply non-water supply objectives to its management of the Delaware Reservoirs. A bundle of revisions to the current non-water supply objectives for the Delaware Reservoirs was implemented in the model to evaluate the impacts on overall performance under climate change conditions for a more aggressive policy of downstream releases and flood control. Table B.1 summarizes the differences between the current and alternate management policies. The overall effect of these changes is that a larger void is maintained during periods of typically high flows, downstream releases are held at a higher level during drier summer months, and during drought conditions NYC must release more water to meet the downstream flow target.

Table B.1
Differences between baseline and alternative Delaware release policies

Baseline policies (current agreements)	Alternative policies (more downstream releases and flood control)
• Reserve 10% of storage for peak flows PCN reservoirs from September to March	• Reserve 20% of storage for peak flows PCN reservoirs from September to March
• Downstream releases per tables based on forecasted inflows	• Downstream releases per maximum Flexible Flow Monitoring Plan tables regardless of forecasted inflows
• Downstream flow target at Montague is reduced during droughts per the Delaware River Basin Commission	• Montague target constant at 1,750 cubic feet per second regardless of drought

PCN = Pepacton, Cannonsville, Neversink

Financial

Review of available cost data with DEP staff revealed that data are not sufficient to perform a full-scale cost evaluation as part of the vulnerability analysis. The major reason these data are not available is that the facilities that will result in the highest operational cost to DEP (e.g. Croton Water Treatment Plant, Catskill-Delaware ultraviolet facility, and the pump station capacity upgrades) were not yet online at the time of this analysis. Therefore, the team recorded flow values from the model runs for these facilities in order to develop relative comparisons independent of actual cost data.

Technical

Technical uncertainties are used to account for the uncertainties in model parameters, which may substantially affect the performance of our policies. As described in section 4.1.4, DEP identified the relationship between precipitation, flow, and turbidity as a key technical uncertainty, as levels of turbidity affect how often DEP must apply alum. This, in turn, affects DEP's ability to maintain its Filtration Avoidance Determination (FAD).

Policy Options (L)

The team determined that for the Robust Decision Making (RDM) analysis, the baseline system should consist of the system as it exists in 2010 along with the current-near term improvements that will be in place by 2020 (Table B.2). Additionally, it was decided the analysis should include a set of runs with the current 2011 system and operating rules in order to provide some information on benefits of near term system improvements.

Table B.2
Current system and near term improvements

Current System
• 2010 System, without 2012-2020 improvements • Current operating rules
Near-term Improvements
• Croton Water Treatment Plant • CAT-DEL UV Facility • Croton Falls / Cross River Pump Station upgrades • Shaft 4 Connection • Schoharie Low-Level Outlet • Rondout-West Branch (RWB) leak repair • OST Implementation • Conservation (demand reduction program - passive) • Conservation (drought management plan - active) • Planned operating rules

During the workshop, the team also identified potential system alternatives that could be implemented as adaptation measures to address vulnerabilities revealed during baseline model runs as described in Chapter 4 of the main body of the report.

- Delaware River Basin rules could be adjusted to better meet the needs of the Delaware River stakeholders. NYC cannot do this unilaterally, but the analysis could be useful to support rule modification.
- Revised Balancing Operations – Revise rules for balancing subsystems (Croton, Delaware, and Catskill) in order to increase system resilience to hydrologic variations.

- Drought curves and available water use restrictions could be revisited to better manage supplies during periods of drought.
- Hudson River supply – DEP has an existing pump station that could be used to supply NYC with water as an alternative supply.
- Implementation of filtration of the West-of-Hudson supply would enable NYC to remove contaminants from source waters, which may lessen the impact of source water quality on available supplies.
- Restore in-city groundwater capacity – DEP is pursuing upgrades to its existing groundwater wells so that this water could be used during the RWB repair. Due to treatment costs, this is not anticipated to be a permanent supply, but it could be included as an adaptation alternative.
- Regional interconnections are being pursued by DEP as alternative supplies for use during the RWB repair. At this time DEP is not planning for these to be permanent, but they could be included as an adaptation alternative.
- Improvements in forecast skill could enable the city to more fully utilize the system to provide sufficient volumes of high quality water while meeting other constraints on the system.

Metrics (M)

During the XLRM workshop, the group agreed on key objectives and identified specific decision criteria under each objective. Table B.3 lists the decision criteria that are represented in the current modeling system. Table B.4 lists those decision criteria that are desirable but not currently available in the model. Through subsequent discussions on threshold level for each performance measure, it was determined that the performance for each metric would be set based on the current demand for the planned near term system.

DEP and project partners originally identified four broad categories of metrics that are relevant for judging the performance of NYC's water system: water reliability, water quality, environmental performance (e.g. adequate downstream releases), and economic impacts both to DEP and the region as a whole. Our pilot analysis focuses on two of these, water reliability and water quality, because these are DEP's principal goals and are modeled in DEP's existing modeling framework.[28]

Water reliability was quantified using the NYC drought condition trigger, which is an indicator of hydrologic stress in either the Delaware or Catskill subsystems and adjusts modeled demand levels to indicate voluntary and mandatory use restrictions during drought conditions for the DEP service area. The drought condition can have values of "normal," "watch," "warning," and "emergency." While no explicit threshold for acceptable frequency of drought conditions

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[28] Rules for compliance with current downstream release regulations are coded into the model as constraints, such that the model meets these releases under all circumstances. Thus a severe drought in the model could result in a shortfall of water for NYC. By contrast, during severe droughts, releases from the Delaware System are negotiated based upon current conditions as per the DRBC Flexible Flow Management Plan agreement. These subjective conditions cannot be adequately modeled in the OST. Additionally, economic impacts were not included because sufficient data on quantitative economic impacts from water supply restrictions or water quality excursions were not available.

currently exists, the study team determined that it would be useful to distinguish future conditions in which the system experiences worse drought than it has in the past. Therefore, the threshold for acceptable reliability was set at the percent of drought warning and emergency days under baseline conditions and historic climate—2%. [29]

We measure water quality as the percent of days in which alum must be applied – an undesirable condition and also an indicator of potential threat to NYC's FAD. While DEP's goal is zero alum usage, it was decided an absolute threshold may be impracticable for a long term simulation; therefore a threshold of 1% was selected as a suitably low value that would have a low probability of affecting DEP's FAD.

Table B.3
Decision criteria currently available in the OST

Objective	Decision Criteria	Desired Outcome
Reliability	Drought days	Minimize
	Shortfall	Minimize
	Storage	Optimize
Drinking water quality	Turbidity/alum addition	Minimize
Environmental	Unmet minimum flow requirements	Minimize
	Spill mitigation	Minimize

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[29] Drought watch was not included in the metric for reliability because DEP's drought plan does not require any restrictions on water consumption. By contrast drought warning and emergency requires voluntary or mandatory water use restrictions, and authorizes DEP to set an emergency rate plan to provide enhanced incentive for use restrictions.

Table B.4
Decision criteria not currently available in the OST

Objective	Decision Criteria	Decision Criteria
Drinking water quality	Nutrients/chlorophyll	Minimize
	Disinfection byproducts	Minimize
	Taste and odor	Minimize
	Microbiological	Minimize
Environmental	Flows that enhance ecology	Maximize
	Unmet release water quality requirements	Minimize
	Spill mitigation	Minimize
	Lower Delaware salinity	Minimize
	Recreational releases	Maximize
	CO_2/GHG emissions	Minimize
Economic	Operating cost	Minimize
	Capital cost (present-value and annual)	Minimize
	Revenue (hydropower, forestry, other)	Maximize
	Economic impact of drought restrictions	Minimize
	Rates	Minimize

Water Reliability

Water reliability is measured by the percent of drought "warning" or "emergency" days that occur in a simulation run. The overall drought condition (referred to as the NYC super system (NYCSS) condition) is determined according to the worst condition of either the Delaware or Catskill subsystems, as shown in Table B.5. The Croton subsystem does not currently factor into the drought determination. These classifications, in turn, are defined by separate storage curves for the Catskill and Delaware subsystems for normal, drought watch, drought warning, and drought emergency conditions, shown in Figure B.2 and Figure B.3.

Table B.5
NYCSS condition based on individual subsystem conditions

		Delaware Drought State			
		Normal	**Watch**	**Warning**	**Emergency**
Catskill Drought State	**Normal**	Normal	Watch	Warning	Emergency
	Watch	Watch	Watch	Warning	Emergency
	Warning	Warning	Warning	Warning	Emergency
	Emergency	Emergency	Emergency	Emergency	Emergency

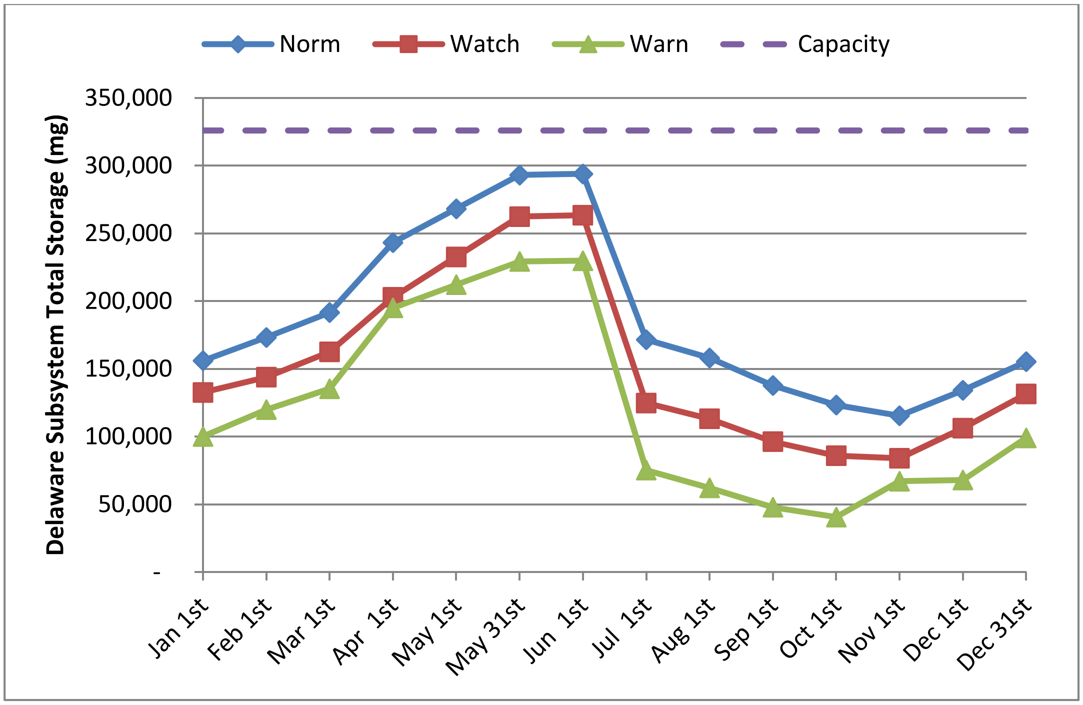


Figure B.2 Delaware subsystem drought trigger curves based on total system storage

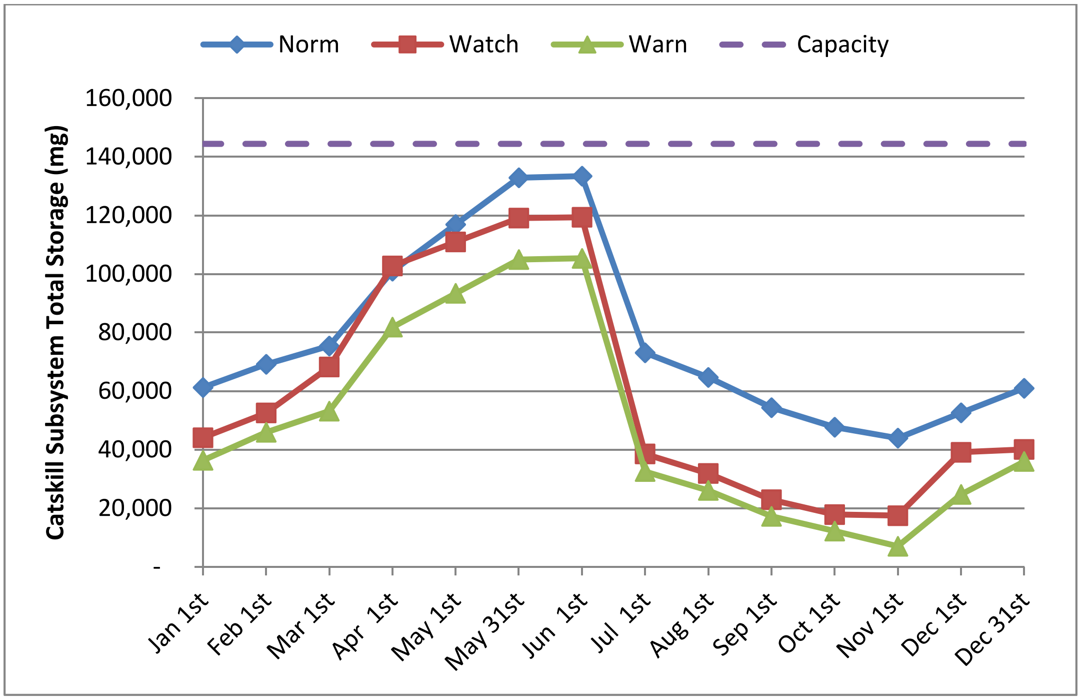


Figure B.3 Catskill subsystem drought trigger curves based on total system storage

Water Quality

Maintaining the FAD for the Catskill and Delaware watersheds, which is accomplished by maintaining high water quality, is of utmost importance. NYC must reapply for its FAD periodically, and if water quality declines, the City's FAD status could be threatened, requiring NYC to construct a filtration plant. Typically, DEP is able to meet drinking water quality regulations with disinfection alone (NYC utilizes a combination of chlorination and ultraviolet disinfection). Unfortunately, silt and clay deposits in the Catskill watershed are mobilized during heavy rainfall events, leading to turbidity excursions in the system, overwhelming the natural settling processes in upstate reservoirs. During these events DEP must apply alum and sometimes sodium hydroxide at its terminal reservoir, Kensico, so as not to exceed the maximum contaminant level for turbidity. The U.S. Environmental Protection Agency has stated in NYC's FAD that it cannot rely exclusively on alum addition to control turbidity. While there is no numeric threshold for alum application stated in the FAD, DEP has conducted an extensive Catskill Turbidity Control Program and is implementing numerous infrastructure and operational improvements in order to minimize alum usage.

Models (R)

This study relied on downscaled GCM data developed by DEP based on the delta change factor methodology (Anandhi et al. 2011). Climate-adjusted streamflows were modeled using the downscaled GCM data and DEP's rainfall-runoff modeling tool. Streamflows were then routed through DEP's existing systems modeling framework, the OST, to calculate the water reliability and water quality performance for each water management strategy under unique sets of assumptions about climate, demand, and other factors (Figure B.4).

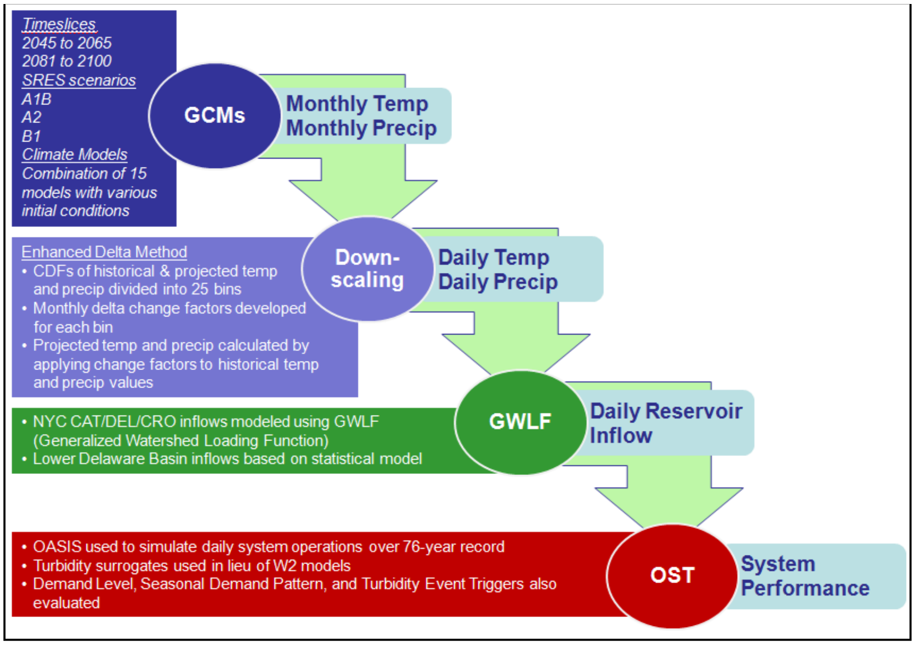


Figure B.4 Modeling structure for the NYC pilot

The team reviewed the existing model framework and potential additional model tools that could be used for the vulnerability assessment. It was decided that, given the timeframe of the research project, it would be best to use the existing framework with targeted updates for the climate change analysis.

APPENDIX C: CASE STUDIES OF UTILITY VULNERABILITY ASSESSMENTS

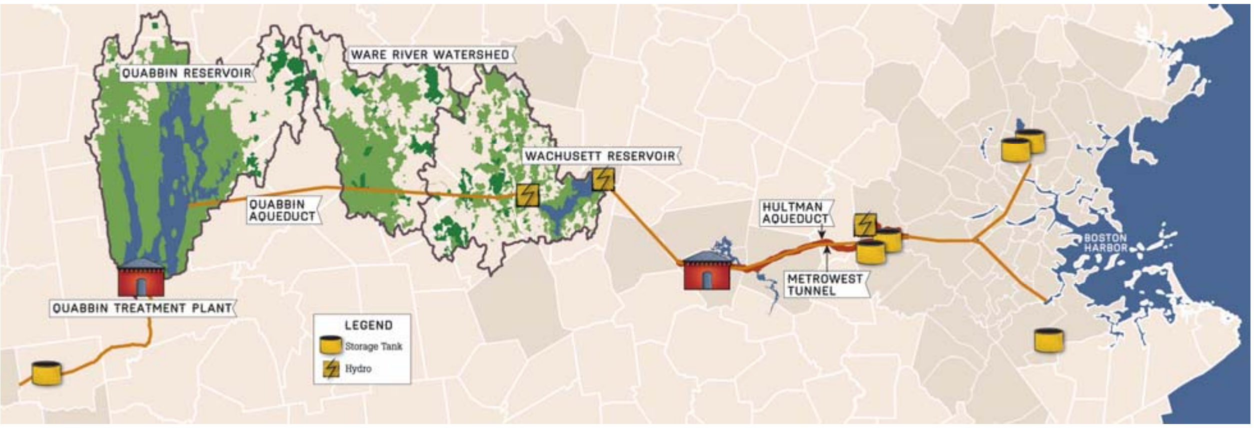
A series of case studies were developed and compiled to complement the main Pilot Studies envisioned for this research effort. The cases were designed to help (a) characterize climate risks that have been identified by participating utilities; (b) identify the specific methods used for assessing those risks; and (c) determine which features of a climate risk assessment and management framework are most useful to support utility planning. Utilities included are those that have had prior active collaboration with one or more members of the research team on matters related to climate change risk or agreed to contribute to the case study component of this project. Most have also been shown throughout the literature to be leaders among water utilities addressing climate change. Information included within each case is derived from publicly available documents, project team experience, interviews with key informants within each utility, or a final project document.

With respect to climate risk identification, assessment, and management, each of these utilities tailored their analytical approach and tools to meet their specific objectives. Although institutions like the U.S. Environmental Protection Agency (EPA) have developed an array of readily available tools, the utilities integrated climate change risks into their existing tools and analytical processes. The tools used to identify climate risk ultimately depend on the size and complexity of utilities. For example, when asked about existing tools like the EPA's CREAT (Climate Resilience Evaluation and Awareness tools), part of its Climate Ready Water Utilities (CRWU) initiative, utility staff interviewed acknowledged that they were useful for smaller utilities initiating thinking about climate change or ones that have not yet thought about climate change. However, utilities like the Massachusetts Water Resources Authority (MWRA) and New York City Department of Environmental Protection (DEP), given their advanced ongoing modeling efforts, found it more useful to look internally to develop a tool that meets their needs. This observation reflects the general sense that climate change is a distinct challenge, but its management, as much as possible, needs to be accommodated within existing processes and tools designed to regularly deal with multiple challenges.

METRO-BOSTON: MASSACHUSETTS WATER RESOURCES AUTHORITY

The MWRA provides wholesale water and wastewater services to over 2.5 million customers in 61 communities in and around Boston (Figure C.1). On average, MWRA delivers an average 215 million gallons per day (mgd) to its water customers, with a peak demand of up to 350 mgd. Its source reservoirs, the Quabbin and Wachusett can reliably supply 300 mgd of water, as the "Safe Yield" (a measure for supply adequacy). MWRA also collects and treats an average of 350 mgd of wastewater, with a peak capacity of 1.2 billion gallons (Yates and Miller 2011; MWRA 2013a).

A Culture of Preparedness for High-Impact Low-Probability Events: In the mid-1980s, facing a potential supply-demand imbalance, the MWRA introduced a serious, successful program to reduce demand through retrofits, changing state codes, improving meters, and upgrading and repairing aging infrastructure. Ever since, system withdrawals have remained below the Safe Yield threshold (Yates and Miller 2011). Climate change was never explicitly dealt with as a separate problem; it has been part of the institution's "normal responsible planning," something considered alongside an array of future risks the utility may face. "Well-run" utilities, "take a long-view to do a risk assessment on all the major factors that affect them" (Estes-Smargiassi and Nvule 2012). A well-cited example of MWRA's culture of 'forward-thinking' is the Deer Island Waste Water Treatment Plant, built in the late 1980s, and whose design included two feet of assurance accounting for the uncertainties of sea-level rise. This engineering decision was not something mandated from on high, but rather someone further down the chain of command embedded climate risks into the planning process. By institutionalizing addressing uncertainty, MWRA is able to be responsible in the face of political uncertainty—"not everyone has the same amount of comfort with it [climate change], if it's front and center you could run up against obstacles" (Estes-Smargiassi and Nvule 2012).



Source: MWRA 2013b

Figure C.1 Map of MWRA service area

Ensuring supplies under vulnerable conditions: Climate change is already a part of MWRA's Master Planning Process, and will be treated as an "extra dimension" when assessing infrastructure investment (Estes-Smargiassi 2011). The utility has identified certain components of the system where it thinks that climate change may have an impact; it has the analytical capabilities to reasonably answer whether these consequences of climate change will come to pass. Adaptation is under consideration, not as a stand-alone investment, but as something to be considered within the context of the schedule for the ongoing rehabilitation of the system; e.g., making facilities less susceptible to floods, or ensuring they will not be severely damaged by storms. Another component of the MWRA's approach to climate uncertainty is to take advantage of events: "every time there's a discontinuity in planning or thinking, a new uncertainty it offers an opportunity to rethink assumptions and solve problems from a new angle" (Estes-Smargiassi and Nvule 2012). As part of Water Research Foundation's (WRF's) research effort "*Climate Change in Water Utility Planning: Decision Analytic Approaches*", MWRA was able to explore how climate change might affect its Safe Yield estimates using both K-NN[30] and CMPI3[31] climate

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[30] The K-NN algorithm is used to develop individual sequences of weather variables for key weather station locations; the algorithm uses the outputs from the Bayesian method to condition the K-NN resampling scheme, which yielded an ensemble of daily sequences used to force the MWRA's planning model (Yates and Miller 2011).

[31] The World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (CMIP3) is a multi-model data that is a publicly available archive of statistically downscaled climate projects. This is actually the same

projections to estimate a future "expected value" of safe yield. MWRA found that due to large capacity for over-year storage in its system, MWRA is situated to enjoy a modest increase in its safe yield given projections of a wetter climate in the Northeastern United States—higher levels of precipitation than had been estimated using historical climate data (Yates and Miller 2011).

SOUTHEAST FLORIDA: PALM BEACH COUNTY WATER UTILITIES DEPARTMENT

Palm Beach County Water Utilities Department (PBCWUD) provides drinking water to approximately 500,000 residents in the central and south-central unincorporated areas of Palm Beach County and the western communities. The water available to PBCWUD is regulated by the South Florida Water Management District (SFWMD), the lead agency on planning and permitting of water withdrawals (Tobon and Galliano 2012) which manages regional supplies for 7.7 plus million people in Southern Florida.

Through a WRF study (O'Neil and Yates 2011), PBCWUD developed a dynamic decision support system (D2S2) that incorporates future uncertainty related to water supply management in the context of climate change. The D2S2 uses the Water Evaluation and Planning system (WEAP), a combination of dynamic simulation/scenario testing, and decision analysis. The decision analysis was further used to incorporate three bottom-line criteria. The D2S2 approach is composed of iterative and adaptive steps that address uncertainty through scenario analysis. D2S2 outputs are geographic information system–based and have dynamic links to spreadsheets and other models (Means et al. 2010).

A Climate and Development Supply Challenge: PBCWUD has a 20-year permit for water withdrawal from 2003-2023, based on the SFWMD's regional model of available water, including alternative uses in conjunction with population and demand projections. SFWMD's population is projected to increase to over ten million by 2025 and possibly 12–15 million by 2050. Existing infrastructure, like the Central and Southern Florida Flood Control Project, now 60 years old, is insufficient to meet the environmental and water needs of the current population, let alone the anticipated growth (Obeysekera et al. 2010). Groundwater wells draw from a system of inland surface aquifers; supply diversification plans include deepening those wells, developing Aquifer Storage and Recovery (ASR) wells and using reclaimed water for irrigation augmentation (Tobon and Galliano 2012) and a model validated through a series of collaborative stakeholder meetings (Yates and Miller 2011).

Climate informed decision-support tools for long term planning: To manage its long-term water supply, PBCWUD uses a WEAP software model developed several years ago, initially without the integration of climate change data. In 2008, PBCWUD was introduced to Dr. David Yates who helped PBCWUD incorporate climate risks that may affect the utility (Tobon and Galliano 2012). As part of WRF's research effort "Climate Change in Water Utility Planning: Decision Analytic Approaches," PBCWUD was one of several utilities that developed a structured analytic approach to incorporating climate change into long-term water utility planning—a similar approach to the one outlined in the main body of this report. PBCWUD's resulting D2S2

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climate data used in the Palm Beach County Study (Yates and Miller 2011) referenced in the subsequent case description.

links scenario-based planning through WEAP and Multi-Criteria Decision Analysis (MCDA) to yield a model validated through a series of collaborative stakeholder meetings (Yates and Miller 2011).

A Regional Climate Strategy: Given its low topography, droughts, wet and dry extremes, and the increasing amount of storm activity, Florida realizes it will be among the first states to be severely affected by climate change (Tobon and Galliano 2012). The leadership is conscious of the potential effects of climate change on the utility. This support from its leadership helps PBCWUD continue its work as a primary partner in the Southeast Florida Regional Climate Change Initiative in collaboration with Broward, Miami-Dade, and Monroe Counties. This multi-county initiative emerged in parallel to ongoing efforts at the county level. It was driven by elected officials, and especially a commissioner in Broward County, concerned with environmental issues and in recognition of the vulnerability of low-lying Miami-Dade County. Following a series of Southeast Florida Climate Leadership Summits, participants drew up the Southeast Florida Regional Climate Compact (SFRCC 2010) and later a Regional Climate Action Plan (SFRCC 2012). The Regional Compact brought many issues to the surface. By convening utility leadership at management conferences where climate change is discussed with neighboring counties, the counties are able to collaborate, share experiences and resources, and as part of the Compact, all counties have agreed to review the effects of climate change on their individual and shared infrastructure. The climate summits have been arguably one of the most beneficial engagements for those working on climate change at the county, utility level (Tobon and Galliano 2012). PBCWUD continues its proactive approach to addressing climate change through its partnership with a National Oceanic and Atmospheric Administration Climate and Societal Interactions-Water funded University of Florida Water Institute study entitled Public Water Supply Utilities Climate Impacts Working Group (UFWI 2013).

More recently, PBCWUD, as part of the Southeast Florida Climate Change Compact team, participated in the Institute of Sustainable Communities Climate Change Academy in Philadelphia. This team was one of a dozen addressing climate change issues from all sectors of the country and illustrating the variety of issues, from water and food supply to risk mitigation as the consequences of climate change are manifested in the years ahead. The South Florida team identified action items that will be pursued through the Compact and among the individual compact members. These action items include: Work with the Climate Ready Utilities program at EPA Headquarters to arrange a webinar for the Southeast Florida Utility Council, encourage the South Florida Water Management District to undertake more detailed modeling and analysis of the regional drainage system with sea level rise scenarios and establish a regionally consistent and updated set of elevation standards using a common sea level datum to govern future development and re-development standards. This team will remain together as sub-group of the Compact to be helpful in whatever way they can as they agenda unfolds, particularly with respect to those items we have identified above as priorities.

NEW YORK CITY DEP: PREVIOUS CLIMATE EFFORTS

Top-down support for climate action:[32] Former DEP Commissioner Chris Ward established a DEP Climate Change Task Force in 2004. By working with the NYC water board, funds were made available to hire consultants and begin designing a DEP climate response plan (Cohn and Beckhardt 2011). Under his successor, Emily Lloyd, the DEP task force began to work across DEP bureaus and with Columbia University to produce *Responding to Climate Change: Draft Guidelines for DEP* in 2006 and later, the 2008 *Climate Change Program Assessment and Action Plan* (Licata 2005; DEP 2008). Mayoral level requests to the DEP to respond to climate change came in 2007-2008, after these initial initiatives were already underway (Cohn and Beckhardt 2011). Climate change is now at the core of DEP's strategic and capital planning. Adaptation options for the water system include retrofitting existing infrastructure and building risk-based infrastructure to provide water services under changing weather patterns, e.g. increased temperature; changes in rainfall, snow pack, storm intensity; and sea level rise (Lloyd 2008).

Climate Risks: The DEP Bureau of Water Supply (BWS) manages New York City's upstate water supply system. Its priority climate concerns are altered storm intensity and timing, altered precipitation regimes, and the resultant flooding and turbidity events. The region currently experiences intermittent drought and flooding; perturbations to the system due to climate remain unknown. These concerns are aligned with meeting the EPA's filtration avoidance criteria (EPA 2010), on which the modeling group is responsible for updating the EPA. The BWS characterizes climate risks as one among an array of risks to the supply system: it is accounted for in the 10-year capital plan for the 2020 strategy as well as the 2030 Mayor's Sustainability Plan (Cohn and Beckhardt 2011). The BWS has an in-house modeling group, led by Section Chief Donald Pierson, whose staff works with post-doctoral researchers as well as consulting firms to develop climate scenarios and subsequent risks to the system. These scenarios are often based on historical events, e.g. extreme rainfall and turbidity events, combined with efforts to downscale global climate models (GCMs) to the New York watershed level.

Planning Under Uncertainty: Scenario planning enables the incorporation and combination of climate and non-climate risks. The Mayor's Office of Long Term Planning and Sustainability is trying to standardize the DEP's response to climate change, and is increasingly involved on the policy end: developing city-wide recommendations on codes, design standards etc. and conducting a city-wide vulnerability analysis to look at the costs of climate change effects. The Office released climate change projections for NYC that the DEP's scenarios use in 2008. The DEP BWS similarly employs scenarios through their decision-support OST, which integrates the water systems model (OASIS) with the water quality model (CA-QUAL-W2) and more recently climate information and extreme event scenarios. DEP has been able to leverage participation in projects like WRF Project 4262 and WRF Project 4306 to model the potential impacts of climate change and evaluate pathways to adaptation (see Chapter 4 and Appendix B).

Managing Climate Risks: DEP's efforts to ensure the high quality and reliability of the water supply system align with the major goals of PlaNYC 2030, a map towards a "greater, greener" sustainable New York by 2030 that was the result of work by more than 25 City agencies. Integral to PlaNYC, released in 2007, is a major goal that specifically addresses climate

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[32] An interview with staff at DEP, conducted in December 2011, informs this case study.

change: “increase the resilience of our communities, natural systems, and infrastructure to climate risk” (CoNY 2012). Shortly after PlaNYC 2030 was released, Mayor Michael Bloomberg formed the NYC Panel on Climate Change and launched the NYC Climate Change Adaptation Task Force to conduct a “Climate Risk Information” study (Rosenzweig et al. 2009). Bloomberg, quoted in a *New York Observer* article that year, explained that, *“Planning for climate change today is less expensive than rebuilding an entire network after a catastrophe...We cannot wait until after our infrastructure has been compromised to begin to plan for the effects of climate change now”* (Cohen 2009). An updated PlaNYC, released in April 2011, devoted an entire chapter to climate change, outlining 132 initiatives with 400-plus specific milestones for December 2013.

Recent efforts have focused on estimating climate impacts, but the next phase will move towards recommendations for planning and adaptation. The process of going from identifying impacts to planning for adaptation has been somewhat ad-hoc, and oriented around developing a portfolio of options rather than selecting and implementing priority actions. The 2008 DEP Action Plan identified adaptive steps that are included in that portfolio of options, but Cohn and Beckhardt (2011) underscored the fact that, “very little of what we do is solely for climate change”. The 2011-2014 Strategy for the Bureau is to *maintain robust, secure, and cost-effective water supply infrastructure and improve operational efficiency with new technology.* Addressing climate change is just one part of meeting the operations’ goals under that strategy; the management strategies will be implemented are those that are most robust and cost-effective.

CENTRAL NEW YORK: ONONDAGA COUNTY WATER AUTHORITY

Onondaga County Water Authority (OCWA) serves over 340,000 people in communities and villages across suburban Onondaga County (Syracuse), and parts of Madison, Oneida, and Oswego counties including major industrial consumers like Anheuser Busch. OCWA provides an average of 40 mgd supplied from Otisco Lake, Lake Ontario, and Skaneateles Lake. Since 2008, Onondaga County has been thinking and planning around concerns for sustainability, including adopting the State of New York’s *Climate Smart Community Pledg*e in 2009, which encourages emissions reductions and acknowledges the potential effects climate change will have on city infrastructure, local livelihoods, and ecological recreational sites. The County’s Climate Action Plan (ONGOV 2012) is similarly focused on reducing greenhouse gas (GHG) emissions across various county authorities, including OCWA, as the Water Board (MWB) and Water Environment Protection, which use electricity for pumping and processing purposes and represents nearly half of the County’s emissions related to electricity use (ONGOV 2012).

OCWA has begun to think about climate change in relation to observed or experienced perturbations to the system. It has existing concerns about natural hazards like flooding (riverine, flash, coastal, and urban flooding), severe storms (windstorms, thunderstorms, hail, lightning and tornados), and severe winter storms (heavy snow, blizzards, ice storms) that may be impacted by climate change (ONGOV 2010). In terms of responses, OWCA has implemented activities through the Hazard Mitigation Plan, like a watershed monitoring program. OWCA is always looking for ways to make its system more robust with respect to climate change through investments in critical infrastructure and other capital improvements. For now, climate considerations are driven by OWCA’s past experience with flooding events and changes in storm and precipitation intensity and frequency, but OWCA has not yet employed climate scenarios to inform system management (Miller 2013). OWCA is aware of the climate risks it faces; like many other utilities it treats climate change as one among an array of management challenges to the system.

COLORADO'S FRONT RANGE: METROPOLITAN WATER PROVIDERS

Colorado's Front Range refers to the populated region of Colorado east of the Front Range Mountains. Water for this region is sourced from several major river basins likely to be affected by climate change (Figure C.2). The Joint Front Range Vulnerability Study, prepared by Woodbury et al. (2012), is a WRF-tailored collaboration amongst the Colorado Water Conservation Board, the Western Water Assessment, the principal investigators, and six water utilities (Denver Water, CSU, Boulder Department of Public Works, City of Aurora Utilities, Fort Collins Utilities, and Northern Colorado Water Conservancy District). Rather than pursuing independent studies, these organizations collaborated to support and implement a common assessment methodology, and to develop a coordinated set of evaluation tools. The primary objective was to assess the sensitivity of streamflow from three watersheds to climate changes and to integrate projected climate changes into future streamflow sequences. A secondary objective was to have key Basin actors and utilities collaborate in the hope that collaboration and relationships developed through the project would lead to further regional collaboration on climate change planning.

Source: Searls 2010

Figure C.2 View of Boulder, CO and the Front Range mountains

The motivation behind this research undertaking was to examine future regional water availability for the Front Range water providers. In contrast to the traditional planning approach that relies on historical streamflow data for future forecasts, Woodbury et al. (2012) uses variability in the observed record to simulate the effect of projected climate change, examining the following series of decisions in three large-scale basins by:

- Selecting specific climate projections representative of the range of outputs from several climate models (112 GCMs from which 10 scenarios were selected);
- Identifying a spatial and temporal climate change "signal" (a specified change in temperature and precipitation between a reference period and a selected future period) from each model;

- Applying that climate change signal to the historical inputs for two hydrologic models for the basins noted previously;
- Simulating the hydrologic response from each hydrologic model to produce time series of climate-adjusted natural runoff; and
- Comparing the simulation of climate-adjusted natural runoff with an unadjusted baseline simulation of runoff to identify potential impacts of climate change.

What the research consortium found was that given climate models' uncertainties, there may be value in simulating system operations using several climate projections to reveal potential vulnerabilities specific to the hydrologic response to each projection. For those scenarios that were selected, utilities were able to represent spatial and temporal climate vulnerability perturbations to their systems. The Joint Front Range Vulnerability Study yielded "output time series" that represent possible climate futures that are compatible with and can be incorporated into utilities' current tools and can be used to compare against simulations using historical climate series that do not account for future climate change. The project focused on assessing climate impacts and assessing system vulnerabilities, but did not go into assessing risk management strategies.

SOUTHERN CALIFORNIA: INLAND EMPIRE UTILITIES AGENCY[33]

Researchers from the RAND Corporation, as part of a multiyear research project sponsored by the National Science Foundation, used Robust Decision Making (RDM) methods to help Southern California's Inland Empire Utilities Agency (IEUA) consider and respond to the effects of climate change on its long-range urban water-management plan (UWMP).

To accommodate rapid population growth in the coming decades, IEUA's 2005 Regional UWMP aims to increase its local supplies through an expanded groundwater-replenishment program and a significant increase in the use of recycled urban wastewater. IEUA's plan envisions increasing groundwater use by 75 percent and reusing about 70,000 acre-feet of recycled water (a more than six-fold increase) by 2025. As of 2005, IEUA received slightly more than half its supply from its local groundwater basin, a third from imports, and only about 1 percent from recycling. While the agency is confident that its plans would perform well under historical climate conditions, it had not yet considered its potential vulnerabilities from future climate change.

RAND researchers helped IEUA identify these vulnerabilities and assess options for reducing them. In particular, they helped the agency consider which actions it should take now and which it could defer until later.

To address these questions with the RDM approach, the research team first customized WEAP for the IEUA region. Developed by the Stockholm Environment Institute, WEAP is a water-balance simulation tool that can be used to evaluate the performance of an agency's water-management plans under a wide range of planning assumptions. For instance, for IEUA, the team considered plausible weather conditions and other planning assumptions, such as the timing for achieving resource-development milestones (e.g., extent of a wastewater-recycling or groundwater-replenishment program), groundwater hydrology (such as rates of percolation), wa-

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[33] This project summary was published by RAND and is available on the web here: http://www.rand.org/pubs/research_briefs/RB9315.html.

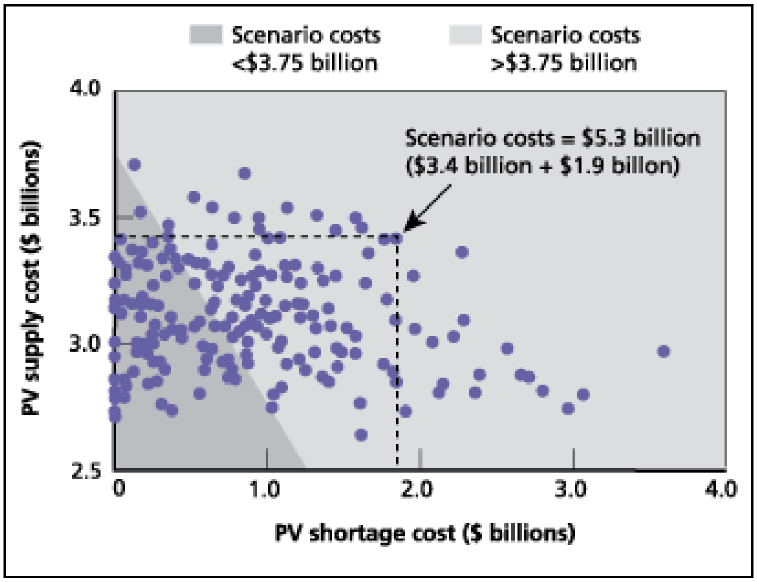
ter intensity of future urban development, the effects of climate change on imported water supplies, and the future costs of specific supplies and water-use efficiency programs.

The team worked with the National Center for Atmospheric Research (NCAR) to develop weather data for use in the WEAP model that reflect state-of-the-art climate projections for the IEUA region. NCAR colleagues first created probabilistic regional projections for the U.S. Southwest by combining the climate projections from 21 atmosphere-ocean GCMs, which suggested that the region's average summer temperature is virtually certain to rise by 2030, increasing by between 0.1 and 2 degrees C, and that winter precipitation could rise by roughly 10 percent but is more likely to fall by up to 20 percent. NCAR colleagues next used sophisticated statistical techniques to develop hundreds of time sequences of future monthly weather parameters for the IEUA region consistent with this range of future temperature and precipitation trends. These data enabled the RAND researchers to consider many uncertain possibilities about climate-change effects over the region.

As expected, these climate projections and the WEAP simulations confirm that IEUA's plan performs well if the region's climate remains unchanged or grows wetter but that it can suffer significant shortages if the drier-climate projections come to pass.

To better understand IEUA's vulnerabilities and response options, the RAND team next used the WEAP model to evaluate hundreds of scenarios that explore assumptions about future climate change, resource-development milestones, groundwater hydrology, urban development, program costs, and future import costs. It used statistical methods to ensure that the scenarios efficiently sampled the plausible combinations of these assumptions. It then evaluated the scenarios using a variety of measures, including the cost of supplying water to the agency's end users under different combinations of response options, plus the costs of incurring any shortages through the simulated time horizon (2040). Shortage costs were estimated as the likely cost of purchasing additional imported water during drought years, about 2.5 times as high as current import costs.

Figure C.3 shows the present-value costs of 200 scenarios that IEUA faces if it follows its current plan for the next 35 years (UWMP forever). (For this analysis, we evaluated only scenarios in which precipitation declines.) Each dot indicates the cost of supplying water in a scenario and the cost of any shortages; total costs are the combination of both costs for the scenario, as shown by the example marked by the dotted line. The dots in the darker shaded area show total 35-year costs under $3.75 billion, a sum that is within 20 percent of the cost expected under UWMP forever if all the agency's planning assumptions remain valid. Scenarios in the lighter shaded area would impose costs on IEUA above this threshold, an amount considered unacceptably high.



Source: Groves et al. 2008d

Figure C.3 How UWMP forever plays out across 200 scenarios

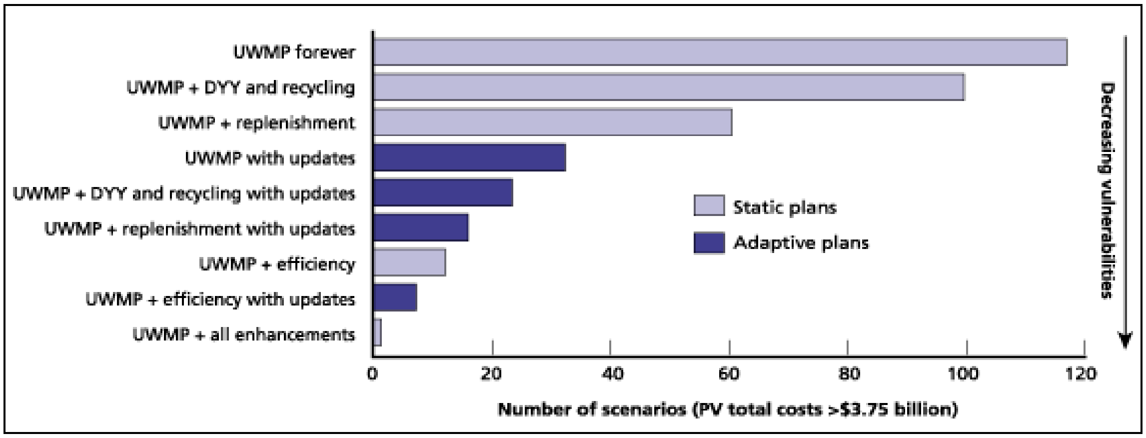
What combinations of uncertain factors are most important in generating these high-cost scenarios? Statistical "scenario-discovery" analysis of the 200 cases shown in Figure C.3 indicates that three future conditions must hold simultaneously for UWMP forever to be likely to lead to large costs for IEUA: (1) large precipitation declines, (2) large climate-change effects on imports, and (3) small or large reductions in natural percolation into the Chino ground-water basin.

How can IEUA mitigate these vulnerabilities? In particular, what actions should it take now, and which can it defer until later? IEUA identified several options for enhancing UWMP forever, including expanding its dry-year yield (DYY) program with Metropolitan Water District of Southern California, meeting recycling goals sooner, gaining approval to increase groundwater replenishment with more recycled water, capturing more storm water to replenish groundwater, and meeting increased water-efficiency goals.

The RAND team used the WEAP model to evaluate four "static" modifications to UWMP forever that each augment the plan with some combination of these actions now and make no further modifications to the plan through 2040. It also evaluated four "adaptive" strategies that implement the plan and some additional actions now, monitor IEUA's supply reserves (the difference between potentially available supply and demand), and then take additional actions (specifically, implementing more efficiency and capturing more storm water for groundwater replenishment) in the future if the average five-year supply reserve level drops below a specified threshold.

Figure C.4 shows the number of scenarios in which each of the nine plans would impose costs greater than $3.75 billion on IEUA. Consistent with Figure C.3, UWMP forever generates this undesirable outcome in nearly 120 of the 200 cases in which precipitation declines. If IEUA were to implement all the considered enhancements now—expanded DYY program, increased replenishment with storm water, faster implementation of the recycling program, and increased urban water-use efficiency (the UWMP + all enhancements plan in Figure C.4)—it eliminates almost all the vulnerability, as shown in the figure. However, just allowing UWMP forever to update—that is, add actions in response to observed declines in the five-year average surplus—

reduces the number of vulnerable scenarios from about 120 to 30 (the UWMP with updates plan in Figure C.4). A mixture of current actions and updates reduces the number of vulnerable scenarios even further.



Source: Groves et al. 2008d

Figure C.4 Options analysis for IEUA

Figure C.4 suggests that IEUA has a range of options for reducing its future vulnerabilities, depending on the degree to which it wishes to mitigate the risk. Each of these options improves IEUA's ability to accommodate climate change and other planning uncertainties in different ways. Expanding the DYY program, for example, reduces the extent and frequency of shortages during temporary drought periods, but it does not help under conditions in which precipitation systematically declines. Replenishing groundwater by allowing more recycled water and capturing storm water increases supplies under most climate conditions. In general, earlier implementation of these improvements reduces the region's vulnerability to the more adverse changes in future climatic conditions.

IEUA estimates that many local resource development options (including increasing efficiency) will be cheaper in the future than acquiring imported supplies; thus, implementing local resource options not only reduces the severity and costs of shortages, but also reduces costs of meeting the region's water needs. As a result, the agency is in a fortuitous position; taking more aggressive near-term actions not only reduces climate vulnerability but also lowers its near-term financial costs and vulnerability to other supply disruptions. While Figure C.4 suggests that the most aggressive near-term options will most reduce future vulnerabilities, IEUA managers may find that such aggressive early action imposes less quantifiable burdens, such as excessive staff time and political capital within the community. The information summarized in Figure C.4 helps IEUA balance these opportunities and costs.

IEUA has already begun to use the results described here to better understand and counter its future climate risks. In particular, it has used these results to highlight the benefits of the actions laid out in its current plan to stakeholders and partner agencies and to articulate the reasons for implementing the more aggressive actions evaluated in this project.

Like those at IEUA, water managers across the United States and beyond face a new, rapidly changing, difficult-to-predict environment. Traditional planning assumptions, such as assuming future climate to be similar to that of the past, will likely prove inadequate. RAND's approach provides a powerful set of tools that can help water agencies identify, evaluate, and communicate their climate-change and other vulnerabilities and the best means for reducing them.

NORTHERN CALIFORNIA: EL DORADO IRRIGATION DISTRICT[34]

This study, funded by a California Energy Commission grant, demonstrates a relatively simple application of RDM for the El Dorado Irrigation District (EID)—a local water agency in the foothills of California's Sierra Nevada Mountains. The analysis is deliberately designed to be straightforward so that it can be replicated by other local water agencies. It illustrates how agencies can use climate data that are readily available and develop simple assumptions to explore uncertainty that is often ignored in long-term planning exercises—in this case, future demand and the availability of a critical new supply. Lastly, it illustrates an RDM analysis through a series of planning questions that will resonate with water agencies and can be adapted for other applications. While this analysis uses a water management simulation model to quantitatively assess outcomes in about 50 different future scenarios, many of the RDM concepts could be used to inform less quantitative assessments.

EID faces many of the same challenges facing other water utilities in the Western United States—increasing population, limited new local supply opportunities, and potential reductions in and altered availability of supplies due to climate change. EID has several opportunities for addressing these challenges. Its recently developed Master Plan (EID 2013) identifies a number of different strategies including developing additional programs that increase the efficiency of water use, acquiring new water supplies through arrangements with other agencies (e.g., the Sacramento Municipal Utility District), and constructing new reservoir facilities.

This study uses RDM to analyze the potential vulnerabilities of EID's current water management plan to future climate, demographic growth, and availability of external new supplies. This study uses a water-planning model developed in the WEAP modeling environment. The model evaluates water management conditions using climate drivers (i.e., temperature and precipitation), rather than historical stream flows, and is thus ideally suited for evaluating the effects of climate change on the management system. The model was calibrated to project future supply and demand levels that are consistent with the assumptions used by EID for their recently completed master planning process. This study, however, explores a broader set of scenarios to encompass additional uncertainties and focuses on different performance metrics and management strategies from the Master Plan.

This study addresses several key long-term planning questions using the RDM iterative methodology.

How Reliable Is EID's Current Plan Under a Wide Range of Plausible Assumptions About the Future?

We simulated EID's current plan under historical climate conditions and with access to new supplies from the Upper American River Project (UARP) in 2020. We found that under

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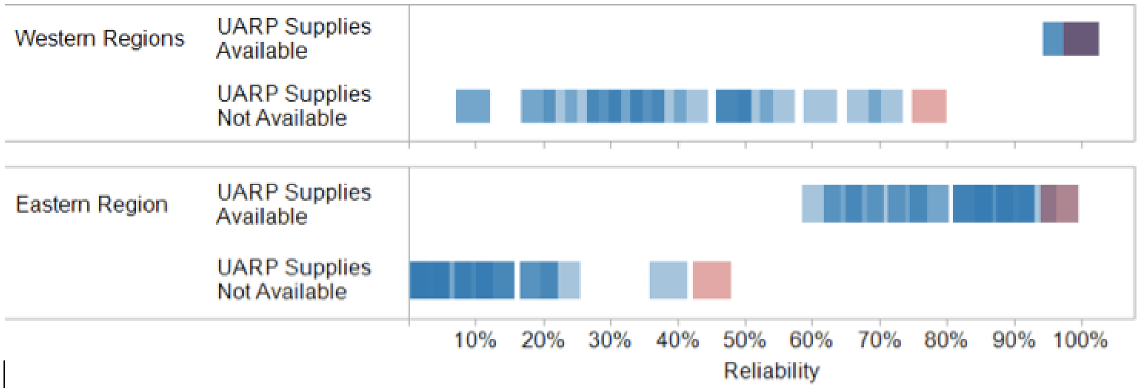
[34] This study is documented in Groves et al. (2013a) and is available on the RAND Corporation website (http://www.rand.org/pubs/research_reports/RR491.html). This description is a reproduction of its Executive Summary.

these baseline-planning assumptions, EID's current plan is 100-percent reliable in EID's Western Regions (i.e., El Dorado Hills and Western Region) and 94-percent reliable in the EID's Eastern Region. The Eastern Region is less reliable as it does not have access to many of the supplies available in the west. Reliability in this study is defined as the percentage of years in which demand is largely met. The thresholds for a year to be considered reliable are 85 percent of demand for the Western Regions and 90 percent for the Eastern Region.

We next explored how well EID's current plan would perform under different but plausible assumptions about future climate, demand growth rates, and the availability of UARP supplies. We found that reliability for both regions would be substantially degraded.

Figure C.5 shows the reliability for the Western Regions and Eastern Region for each future, separated by the UARP supply assumption. Each square represents reliability results for one of the 52 simulation results. Results for the baseline growth scenario are shown in light red. Overlapping results appear darker in the figure. Without UARP supplies available (bottom rows for each region), reliability in both regions varies significantly across the climate and demand scenarios. If UARP supplies are not available, the most stressing scenario reduces reliability in the Western Regions to about 10 percent, and to 0 percent for the Eastern Region. The most favorable climate and demand assumptions, however, lead reliability to exceed 75 percent and 45 percent for the Western Regions and Eastern Region, respectively, for the given thresholds. The reliability of supply in the Eastern Region with UARP supplies is also sensitive to climate and growth assumptions—reliability ranges between about 65 percent and 95 percent.



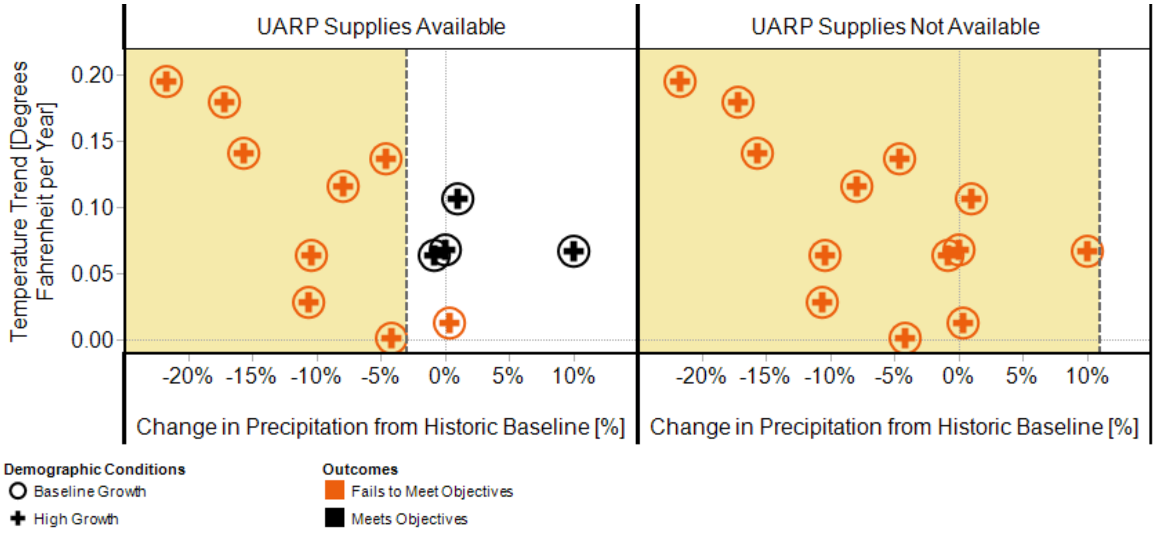
Note: Each square represents reliability results for one of the 52 futures evaluated. Results for the baseline assumptions (historical climate, baseline growth) are indicated in light red.
Source: Groves et al. 2013a

Figure C.5 Reliability for each future disaggregated by region and UARP availability

Under What Conditions Is EID's Current Plan Most Vulnerable?

In order to focus the analysis on outcomes that would not meet EID broad planning goals, we defined a vulnerability threshold of 90 percent—reliability outcomes less than this threshold for either region indicate a vulnerability. Through iteration, we identify two sets of conditions—one for the Western Regions and one for the Eastern Region—that lead to a high number of vulnerable cases and relatively few non-vulnerable cases. For the Western Regions, 26 of the 52 futures evaluated are vulnerable, and they all correspond to futures in which there is no new UARP supply. These conditions are called "UARP Supplies Not Available" and describe all the vulnerable outcomes (100-percent coverage) and none of the non-vulnerable outcomes (100-percent density).

The vulnerable conditions are more nuanced for the Eastern Region and include all futures in which UARP supplies are not available. For those futures in which UARP supplies are available, however, the vulnerable conditions include futures in which precipitation declines by more than 3 percent over the historical average of 1,070 millimeters/year. The assumptions about future growth in the region do not distinguish between scenarios that are vulnerable and those that are not. We call these conditions "UARP Supplies Not Available or Drying Climate." They describe 96 percent of the vulnerable outcomes and include no non-vulnerable outcomes. Figure C.6 shows the vulnerable conditions graphically in terms of the change in precipitation and temperature trends (horizontal and vertical axes), with and without UARP supply (left and right graphs), and demographic growth rates (symbols). Results colored red are those that are vulnerable. The shaded region corresponds to the definition of the vulnerable conditions.



Source: Groves et al. 2013a

Figure C.6 Vulnerable conditions for the Eastern Region

In summary, the vulnerability analysis determined that the Western Regions are primarily vulnerable to the availability of supplies from UARP, regardless of climate and growth rates. For the East, vulnerable outcomes occur even with UARP supply available; these outcomes are associated with conditions that are only slightly drier than those in the historical record. These results suggest that climate uncertainty is more critical to determining the success of EID's plans than the assumptions about demographic growth.

How Can EID's Vulnerabilities Be Reduced Through Additional Management Options?

Following the iterative RDM steps, we reevaluated EID's system under the 52 scenarios three more times—once for each of three strategies. We found that increasing efficiency reduces vulnerabilities in the Western Regions when UARP supplies are not available and significantly reduces vulnerabilities in the Eastern Region when UARP supplies are available (Figure C.7). Constructing a new reservoir (Alder Reservoir) does not reduce the vulnerabilities in the Western Regions, but in the Eastern Region it does reduce vulnerabilities from 69 percent to 46 percent of futures when UARP supplies are available. Increasing efficiency and constructing the Alder Reservoir provide reductions in vulnerability for both the Western Regions when UARP supplies are not available and for the Eastern Region when UARP supplies are available. Note that while increasing efficiency and constructing the Alder Reservoir benefit the Eastern Region when UARP supplies are not available, the Eastern Region is still vulnerable in 100 percent of the scenarios evaluated. This indicates that none of the additional strategies evaluated in this study improve reliability enough in the Eastern Region under futures in which the UARP supplies are not available.

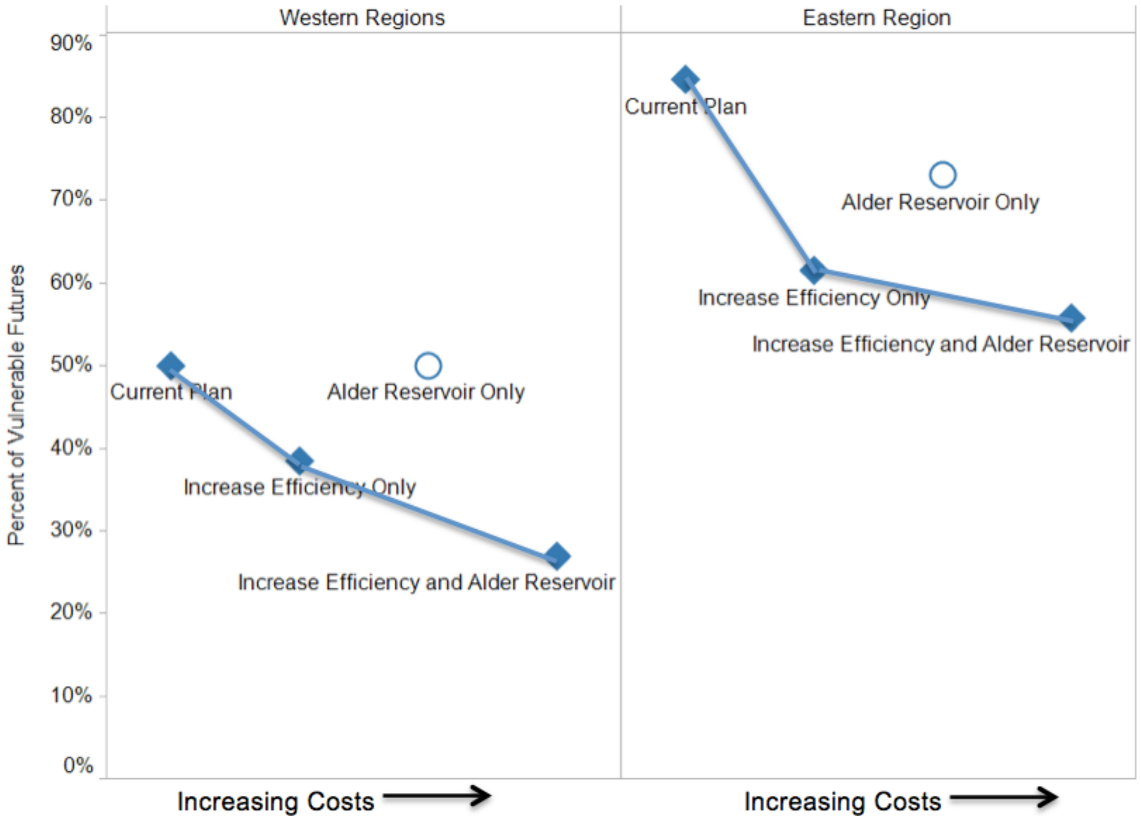
Source: Groves et al. 2013a

Figure C.7 Percentage of vulnerable scenarios by region, UARP scenario, and strategy

What Are the Key Tradeoffs and How Can They Inform Decisions?

Decision makers never have perfect foresight; they have to consider the full range of possible conditions that they may face and the tradeoffs among strategies. In this case, the tradeoffs are simplified to be vulnerabilities in the Western and Eastern Regions versus cost of implementing additional options. Figure C.8 plots each strategy by the percentage of futures that are vulnerable (vertical axis) and the ranked cost (horizontal axis). The Construct Alder Reservoir Only strategy entails more effort and costs and reduces vulnerability less than the Increase Efficiency Only strategy; hence it is a dominated strategy. The other strategies form a tradeoff curve between effort and percentage of futures that are vulnerable, with the current plan requiring the least effort but leading to the greatest percentage of futures vulnerable in both regions.

In the final step of the RDM analysis, we combine the empirically derived information about vulnerabilities and the conditions that lead to them with subjective information about how likely are the conditions to which the system is vulnerable. Together this information provides guidance on how much to invest to reduce vulnerabilities.



Source: Groves et al. 2013a

Figure C.8 Tradeoffs between ranked costs and percentage of vulnerable futures

Conclusions

This study illustrates how RDM can be used in water agency planning to consider climate and other deep uncertainties. In this case, the study considers uncertainty about future climate and hydrologic conditions, urban growth rates, and success in developing a new, large water supply. The approach can be easily expanded to consider many more uncertainties of concern. While the results are largely demonstrative, they confirm the importance of the UARP supplies that EID is seeking for supply augmentation. This new supply alone, however, will not ensure robustness to climate change in the Eastern Region. Increasing efficiency could be an important hedge.

U.S. BUREAU OF RECLAMATION'S COLORADO RIVER BASIN STUDY[35]

Introduction

The Colorado River is the single most important source of water in the southwestern United States, providing water and power for nearly 40 million people. In recent decades, federal managers and Colorado River water users have grown increasingly concerned about the future reliability of the River's water supply. Demand for water in the Lower Basin already exceeds the 7.5 million acre-feet volume allocated in 1922 through the Colorado River Compact (the Compact)—the legal document that determines the allocation of water to the Upper Basin (Colorado, Utah, Wyoming, and New Mexico) and the Lower Basin (California, Arizona, and Nevada). Demand continues to grow in the Upper Basin states.

Water from the Colorado River was initially allocated based on two decades of unusually high river flow, meaning that the river was likely significantly over-allocated when the Compact was signed. In addition, an extended drought from 2000 to 2007 has reduced total water storage in Colorado Basin reservoirs from nearly full to 55 percent of capacity; the system remains just over half full as of this writing. The combination of increasing demand and lower-than-expected streamflow has steadily eroded system resilience.

Moreover, a growing body of literature suggests the Colorado River system is now—or soon will be—operating in a new hydrologic regime for which past data and experience are not an adequate guide for future river conditions. Climate simulations applied in the Basin Study are generally consistent in indicating that the entire basin will track global trends and become warmer, but climate simulations of regional precipitation changes in the Upper Colorado Basin—where most Colorado River source water falls as snow or rain—generate very different forecasts. Some models project precipitation *declines* of up to 15 percent over the next 50 years in the Upper Basin, while others forecast an *increase* in precipitation of up to 11 percent over that time. Despite this uncertainty, Basin shortages are projected to increase, the question remains how much and when.

Motivated by these challenges and in response to directives in the United States SECURE Water Act of 2009 (U.S. Congress 2009), the Bureau of Reclamation (Reclamation) and water management agencies representing the seven Basin States initiated the *Colorado River Basin Water Supply and Demand Study* (Basin Study) in January 2010 to evaluate the resiliency of the Colorado River system over the next 50 years (2012–2060) and compare different options for ensuring successful management of the River's resources.

However, in conducting this evaluation, Reclamation and the water agencies must deal not with a future that is uncertain but well understood; instead, they must plan for a future that is *deeply uncertain* and one that cannot be described statistically because of a lack of knowledge

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[35] This case study description is derived from the Executive Summary of a RAND report describing a portion of Reclamation's Colorado River Basin Study (USBR 2012, Groves et al. 2013b). The Basin Study is available from Reclamation's website (http://www.usbr.gov/lc/region/programs/crbstudy.html). The complete RAND report and interactive research brief are available on the RAND website (http://www.rand.org/pubs/research_reports/RR242.html and http://www.rand.org/jie/projects/colorado-river-basin/interactive-brief.html).

about how changes will unfold. Under these conditions, developing an optimal management strategy designed to perform well for a single deterministic or probabilistic forecast of future conditions is not very useful; rather, planners need a *robust* and *adaptive* strategy—robust in that it performs well over a wide range of possible futures and adaptive in that it can adjust over time in response to evolving future conditions.

Given these circumstances, RAND was asked to join the Basin Study Team in January 2012 to help develop an analytic approach to identify key vulnerabilities in managing the Colorado River basin over the coming decades and to evaluate different options that could reduce these vulnerabilities. Building off the earlier Basin Study efforts, RAND applied an approach called RDM—a systematic, objective approach for developing management strategies that are more robust to uncertainty about the future. In particular, RAND researchers:

- Identified future vulnerable conditions that could lead to imbalances that could cause the Basin to be unable to meet its water delivery objectives;
- Developed a computer-based tool to define "portfolios" of management options reflecting different strategies for reducing Basin imbalances;
- Helped evaluate these portfolios across a range of simulated future scenarios to determine how much they could improve Basin outcomes; and
- Analyzed the results from the system simulations to identify key tradeoffs among the portfolios.

This case study summarizes RAND's contribution to the Basin Study (released in December 2012). In contrast to the study itself—which covers the entire Basin Study and is comprised of seven primary documents, dozens of appendices, and thousands of pages of results—this case study is intended to concisely summarize RAND's evaluation of long-term water delivery reliability for the Colorado River Basin across the range of future uncertainties and with proposed new options in place. This case study focuses more than the Basin Study on the analysis of vulnerabilities and how this information can inform the development of a robust management strategy for the Colorado River Basin. RAND worked closely with the Basin Study Team and state partners to complete this analysis. This case study presents only a small subset of the study results to tell the story of emerging water supply vulnerability and possible actions to reduce vulnerability. For example, although the Basin Study developed a wide range of performance metrics, we considered only broad, high-level performance metrics—each representing delivery reliability for the Upper and Lower Basin.

Developing Robust Management Strategies for the Colorado River Basin

RDM uses a framework called XLRM to summarize scenarios developed to reflect future uncertainty (X), the options and strategies (L) evaluated that would comprise a robust management strategy, the model used to simulate future conditions (R), and the performance metrics (M) used to evaluate system robustness. Figure C.9 shows the XLRM framework for this effort; a much larger set of performance metrics were used in the full Basin Study, but here we focus on two of the key ones to simplify the discussion of RDM's contribution.

Uncertainties (X)	Decisions, Options, or Levers (L)
• Demand for Colorado River water • Future streamflow or water supply climate drivers • Reservoir operations post-2026	• Current management • Four portfolios comprised of individual options • Demand reduction • Supply augmentation
Relationships or Models (R)	**Performance Metrics (M)**
• Colorado River Simulation System	• Upper basin reliability – Lee Ferry deficit • Lower basin reliability – Lake Mead elevation • Cost of option implementation

Figure C.9 Summary of uncertainties, policy levers, relationships, and metrics

During the first year of the study (and before RAND was involved), the Basin Study Team developed a set of supply, demand, and reservoir operations scenarios designed to capture the uncertainties planners face. Each scenario describes one plausible way that each of these three factors could evolve over the study's 50-year time horizon (2012–2060).

The Basin Study Team developed four ***supply scenarios*** based on different sources of future streamflow estimates. Each scenario is comprised of many different 2012–2060 time series of streamflows—known as *future traces* or *traces*. The first scenario is based on the *recent historical record*. Each trace within the Historical scenario is a repeat of the historical record (from 1906 to 2007) with a different starting year. The second and third scenarios are based on streamflow estimates derived from *paleoclimatological proxies*, such as tree ring data. Each trace is consistent with a subset of years from the paleoclimatological record. The fourth scenario is derived from the projections of *future climate conditions* from 16 GCMs and three global carbon emissions projections. Each trace is derived from downscaled results from a single GCM projection and emissions scenario.

The Basin Study Team also developed six ***demand scenarios*** that span a range of plausible future demands, not considering additional programs and incentives for water conservation: (1) current projected growth; (2) slow growth with an emphasis on economic efficiency; (3) rapid growth due to economic resurgence (4) rapid growth with current preferences toward human and environmental values; (5) enhanced environment due to expanded environmental awareness; and (6) enhanced environment due to stewardship with growing economy. As input to the vulnerability analysis, RAND calculated the average demand in the last two decades of each trace (2041-2060). The post-2040 demand ranges from 13.8 maf (slow growth) to 15.6 maf (rapid growth).

Lastly, two ***reservoir operations scenarios*** were created, reflecting different assumptions about how the system would be operated beyond 2026, when the 2007 Interim Guidelines are scheduled to expire. In one, the guidelines for Lower Basin shortage allocation and reservoir management are extended; in the other, they instead revert to the "No Action" Alternative as stipulated in the 2007 Interim Guidelines Environmental Impact Statement. Continuation of the Interim Guidelines means the continuation of mandatory, agreed-upon Lower Basin shortages to help maintain storage in Lake Mead if the lake elevation drops below 1,075 feet above mean sea level.

When evaluating the performance of the Colorado River Basin system, the four supply scenarios, six demand scenarios, and two reservoir operations scenarios were combined and totaled 23,508 individual traces.

The Basin Study evaluated the baseline reliability of the Colorado River system by simulating current operating rules and procedures—what is referred to as the *Current Management* baseline. It also evaluated a wide array of different supply-augmentation and demand-reduction options that could improve system performance and reduce vulnerabilities. Such options were organized into eight categories: (1) agricultural conservation; (2) desalinization; (3) energy water use and efficiency; (4) import water into basin; (5) local supply; (6) municipal and industrial (M&I) conservation; (7) reuse; and (8) watershed management. Starting with 150 different options, the Basin Study team ultimately evaluated a smaller set of these options—about 80—according to cost, yield, availability, and 16 other criteria, including technical feasibility, permitting risk, legal risk, policy risk, and energy intensity.

The RAND team developed a "Portfolio Development Tool" that was used by the Basin Study Team and stakeholders to develop four prioritized portfolios of supply-augmentation and demand-reduction options (drawn from the 80 evaluated ones): Portfolio A (Inclusive), Portfolio B (Reliability Focus), Portfolio C (Environmental Performance Focus), and Portfolio D (Common Options) (Table C.1).

Table C.1
Descriptions of four portfolios

Portfolio Name	**Portfolio Description**
A (Inclusive)	Includes all options included in the other portfolios
B (Reliability Focus)	Emphasizes options with high technical feasibility and high long-term reliability; excludes options with high permitting, legal, or policy risks
C (Environmental Performance Focus)	Excludes options with relatively high energy intensity; includes options that result in increased instream flows; excludes options that have low feasibility or high permitting risk
D (Common Options)	Includes only those options common to Portfolio B (Reliability Focus) and Portfolio C (Environmental Performance Focus)

Note: The portfolio names in brackets were developed for this report only. The Basin Study used only the lettered names (USBR 2012).

To evaluate how each portfolio of options would perform across the wide range of futures, the Basin Study Team defined *dynamic portfolios*, which include rules within the simulation model used in this study to implement options only when conditions indicate a need for them. The RAND and Study Team developed a set of "signposts" for six different water delivery metrics, including the two discussed in this report—Lee Ferry Deficit and Lake Mead Pool Elevation. Signposts specify a set of observable system conditions and thresholds that indicate that vulnerabilities are developing. During a simulation, the model monitors the signpost conditions; if any thresholds are crossed, then it implements options from the top of the portfolio option list. In this way, the dynamic portfolios seek to more realistically mimic how options would be implemented over time in response to system needs.

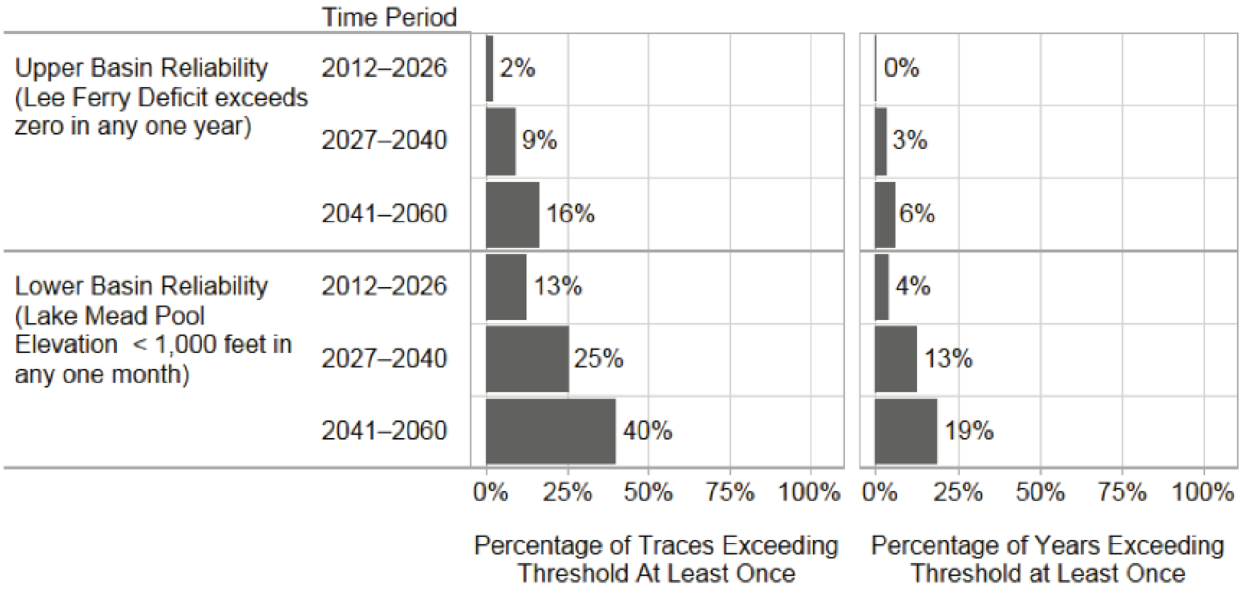
The Basin Study used the Colorado River Simulation System (CRSS), Reclamation's long-term planning model, to simulate the Colorado River system. CRSS estimated the future performance of the system with respect to a large set of different types of performance metrics—***water deliveries*** (9 metrics), ***electric power resources*** (2 metrics in 3 locations), ***water quality*** (1 metric in 20 locations), ***flood control*** (3 metrics in 10 locations), ***recreational resources*** (2 metrics in 13 locations), and ***ecological resources*** (5 metrics in 34 locations).

While the full Basin Study used all the performance metrics, this report focuses on two key water delivery metrics—Lee Ferry deficit and Lake Mead pool elevation. These were the metrics used in the Basin Study to compare the performance of options and strategies, as they broadly summarize the reliability of the Upper and Lower Basins, respectively. If there is a Lee Ferry deficit, then there could be delivery reductions in the Upper Basin to augment flows to the Lower Basin. The health of the Lower Basin system and deliveries to the Lower Basin states are similarly closely tied to the Lake Mead pool elevation.

Future Vulnerabilities to Colorado Basin Water Deliveries

Using the RDM approach and inputs described above, RAND and the Study Team first evaluated the vulnerabilities of the Colorado River system. They addressed two key questions: (1) under which futures does the basin not meet water delivery objectives, and (2) what future external conditions lead to vulnerabilities? Again, here the focus is on the two key water delivery performance metrics.

Figure C.10 summarizes *Upper Basin Reliability* (Lee Ferry Deficits) and *Lower Basin Reliability* (Lake Mead Elevations) across all 23,508 traces representing future uncertainty in two ways: (1) the percentage of traces in which management objectives are not met at least once during the time period (left side), and (2) the percentage of all years in the simulation in which outcomes did not meet objectives (right side). For *Upper Basin Reliability*, the percent of traces in which at least one Lee Ferry Deficit occurs increases from 2 percent (from 2012 through 2026) to 16 percent (from 2041 through 2060), with Lee Ferry deficits occurring in 6 percent of the years (3 years) in the last period (top half of the figure). Similarly, for *Lower Basin Reliability*, Lake Mead elevations fall below the 1,000-foot elevation threshold more frequently across traces and years in later periods.



RAND *RR242-S.1*

Source: Groves et al. 2013b

Figure C.10 Summary of long-term water delivery outcomes that do not meet objectives

While the above analysis tells us how vulnerable the Current Management approach is over time, it does not tell us what external conditions lead to those projected vulnerabilities. Using RDM vulnerability analysis techniques and statistical summaries of streamflow at Lee Ferry, they looked for a set of future conditions that best captures the vulnerable traces. We find that the Upper Basin is susceptible to a Lee Ferry deficit when two future conditions are met: long-term average streamflow declines beyond what has been observed in the recent historical record (below 13.8 maf per year) and there is an eight-year period of consecutive drought years where the average flow dips below 11.2 maf per year. Traces that meet both of these conditions—called *Declining Supply* vulnerable conditions—lead to a Lee Ferry Deficit 87 percent of the time.

Using the same approach, they find that Lake Mead pool elevation is vulnerable to conditions in which supplies are simply below the long-term historical average. Specifically, when long-term average streamflow at Lees Ferry falls below 15 maf, and an eight-year drought with average flows below 13 maf occurs. They call these conditions *Low Historical Supply* vulnerable conditions, and they describe 86 percent of all traces that lead to unacceptable results. They also defined vulnerable conditions for both the Upper Basin and Lower Basin delivery reliability using climate inputs to describe supply in the Historical and Future Climate supply scenarios.

Reducing vulnerabilities through new management options

RAND and the Study Team evaluated the four portfolios of supply-augmentation and demand-reduction options —Portfolio A (Inclusive), Portfolio B (Reliability Focus), Portfolio C (Environmental Performance Focus), and Portfolio D (Common Options)—across all the scenarios described above. They next reviewed how each performed under the vulnerable conditions—*Declining Supplies* and *Low Historical Supplies*. They found that implementation of the portfolios reduces the number of years in which the system fails to meet Basin goals across many, but not all, scenarios.

For the Upper Basin reliability metric—Lee Ferry deficits—implementation of the portfolios reduces the percent of years and traces in which deficits occur. Portfolio C (Environmental Performance Focus) is more effective than Portfolio B (Reliability Focus) in reducing vulnerabilities. For the Lower Basin Reliability metric—Lake Mead elevations—implementing the portfolios significantly reduces the number of years in which the Basin goals are not met. Even in the most stressing *Declining Supply* vulnerable conditions, the percent of years is reduced from 50 percent to around 25 percent. These reductions in yearly vulnerability, however, do not lead to significantly fewer traces in which Lake Mead elevation drops below 1,000 feet in at least one year. The results also show that Portfolio B (Reliability Focus) is somewhat more effective at reducing Lower Basin vulnerability than Portfolio C (Environmental Performance Focus).

The implementation of portfolios increases the robustness of the system and shrinks the set of conditions in which the system would not meet its goals. The Basin becomes less vulnerable to lower flow sequences and drying periods. In terms of climate conditions, with a portfolio in place, the Basin performs well over warmer and drier climate conditions.

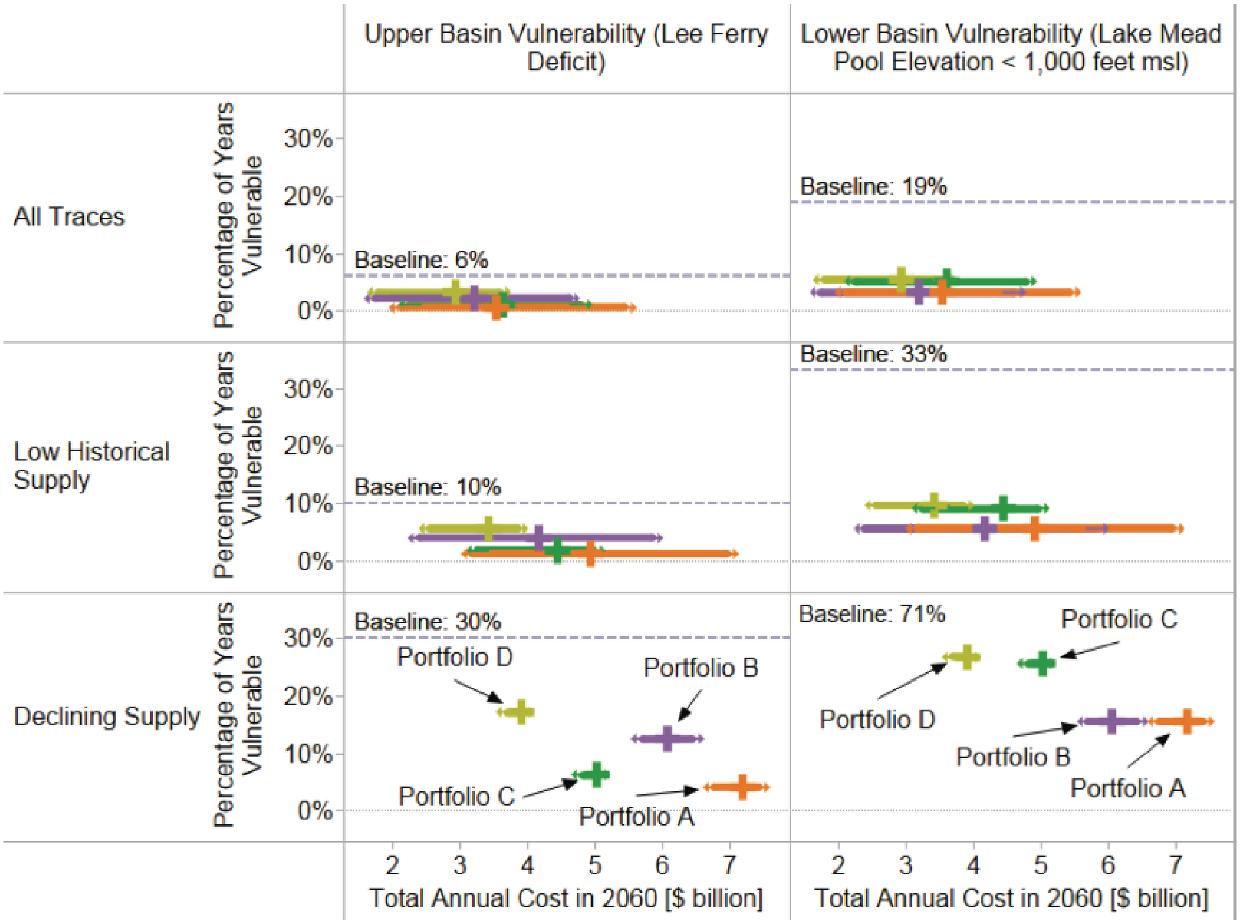
How effective the portfolios are in reducing vulnerabilities is not the only criterion for assessing them. Implementation costs, which increase over time as options are implemented in response to the signposts, are another assessment criterion. There is a wide range in costs across the traces. For Portfolio A (Inclusive), for example, the costs range from just under $2 billion/year to over $7 billion/year in 2060. This wide range of costs indicates that the dynamic portfolios as designed for the study help restrain unnecessary investment in futures when conditions do not warrant it.

One of the advantages of the RDM approach is that it allows us to combine the cost and vulnerability results together to draw out the distinctions and tradeoffs among the four portfolios. C-10 shows total annual implementation costs in 2060 for the four portfolios (the horizontal axis) and percent of years vulnerable from 2041-2060 (the vertical axis) for all traces and for the two vulnerable conditions. We are looking for portfolios that have the lowest costs (furthest to the left in all the graphs) and that reduce vulnerabilities the most (the lowest on all the graphs). The portfolios are distinguished by color here, with the labeling shown in the bottom band in Figure C.11.

As shown in Figure C.11, we find little difference among portfolios when looking across *all traces* evaluated. That is, the range in vulnerability reduction and costs overlap significantly for all the portfolios (the top band in Figure C.11). This is not surprising because there are many traces evaluated in which there is only a modest need for improvement. All four of the portfolios can address those needs using options with similar costs.

However, when we focus on traces corresponding to the two vulnerable conditions, we see some differences across the portfolios. First, in the *Lower Historical Supply* conditions (the middle band in Figure C.11) we see that the portfolio with the most options (Portfolio A) reduces the number of years in which the Upper Basin and Lower Basin goals are not met the most. The ranges in costs (horizontal spread) across the traces increase significantly, but there is again significant overlap among the portfolios.

When we only include traces in the *Declining Supply* vulnerable conditions (the bottom band in Figure C.11), the tradeoffs become clear. For the Upper Basin (left panel of Figure C.11 Portfolio C (Environmental Performance Focus) is not only more effective than Portfolio B (Reliability Focus) and Portfolio D (Common Options), but it costs significantly less than Portfolio B (Reliability Focus). Only Portfolio A (Inclusive) reduces vulnerability more, but it does so at significantly higher cost. Portfolio C (Environmental Performance Focus) dominates because it includes an Upper Basin water bank, which is used to maintain flow to the Lower Basin at Lee Ferry and excludes other more expensive new supply options (discussed more in Chapter 6).



RAND *RR242-S.2*

Source: Groves et al. 2013b

Figure C.11 Tradeoffs between portfolio costs and vulnerabilities (2041–2060) across portfolios for the upper and lower basins

However, performance with respect to the Lower Basin objectives in the *Declining Supply* vulnerable conditions (the bottom band in Figure C.11, right panel) shows that Portfolio B (Reliability Focus) improves reliability as well or better than the other portfolios in all three sets of conditions. Portfolio B (Reliability Focus) includes more options that directly benefit the Lower Basin, including Pacific Ocean desalination projects. Given this more focused investment, Portfolio B (Reliability Focus) dominates Portfolio A (Inclusive) by being just as effective but less costly.

Implementing a Robust, Adaptive Strategy for the Colorado River Basin

The CRSS simulations of portfolios reveal sequences in which options are implemented. Options that are implemented across many future traces soon after they become available can provide the foundation of an initial robust strategy. We focus this analysis on the two vulnerable conditions (i.e. *Declining Supplies* and *Low Historical Supplies*) identified by this study, because these represent conditions when options are generally needed to alleviate system imbalances.

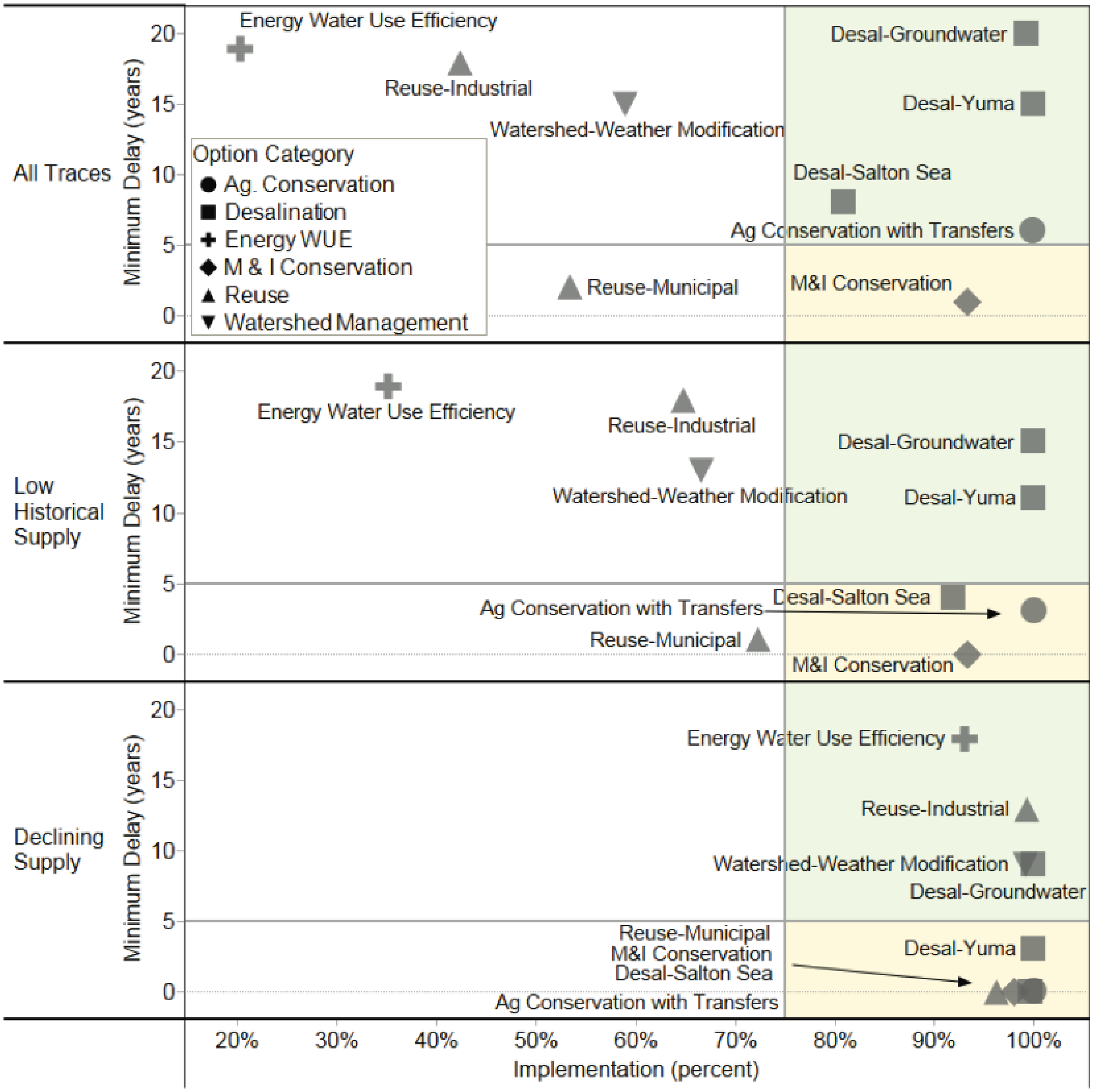
For each portfolio, we identified those options that are almost always needed regardless of differing assumptions about future conditions. Because Portfolio D (Common Options) includes only options selected for both of the two stakeholder-derived portfolios (Portfolios B and C), options always or frequently implemented in this portfolio as soon as they are available can be considered both near-term and high priority.

Figure C.12 summarizes how frequently options from Portfolio D (Common Options) are implemented by 2060 (horizontal axis) and the delay in their implementation (vertical axis), expressed as the median delay across all traces relative to the time they become available. The results are presented for three sets of traces—all traces (top panel), those traces in the *Low Historical Supply* vulnerable conditions (middle panel), and those traces in the *Declining Supply* vulnerable conditions (bottom panel).

Results in the lower-right corner of the all traces panel (bounded by 5 years or less and 75 percent implemented or more) are near-term, high-priority options. In this case, *M&I Conservation* is shown to be required in over 90 percent of all traces examined in the study with a minimum delay of only one year. *Ag Conservation with Transfers* is implemented in almost 100 percent of traces, but with a delay of 6 years. Three desalination options—*Desal-Salton Sea, Desal-Yuma,* and, *Desal-Groundwater*—are all high priority but are needed only after delays of 8 years or more.

For future conditions consistent with the two key vulnerable conditions—*Low Historical Supply* and *Declining Supply*—more options are needed, and with less delay. The middle panel of Figure C.12 shows that for the *Low Historical Supply* vulnerable conditions, the urgency of implementation of *Ag Conservation with Transfers* and *Desal-Salton* Sea increases, making them both near-term, high priority options. The *Reuse-Municipal* option is also required in over 70 percent of traces. The bottom panel shows that for *Declining Supply* vulnerable conditions, all options in Portfolio D (Common Options) are needed by 2060 in nearly all traces.

Figure C.12 shows that most of the options in the Portfolio D (Common Options) are needed in only some future traces and in many cases are implemented only after a delay. However, the conditions corresponding to the *Low Historical* vulnerable conditions have been experienced in the recent past and those corresponding to the *Declining Supply* are predicted by many global climate model simulations. As the Basin Study highlights, the Basin does not need to commit to all possibly needed options now, but it might use the available lead-time to prepare to invest in new options if conditions suggest they are warranted. The implementation of some options with longer lead times will need to be initiated soon so that they would be available if needed under particular future traces. Exploring plans during this time for design and permitting of selected options would provide decision makers with a hedge against potential delays in implementation if the options are needed in response to changing conditions.



NOTE: Ag = agricultural; Desal = desalination; WUE = water use efficiency.

RAND *RR242-S.3*

Source: Groves et al. 2013b

Figure C.12 Percent of traces in which options are implemented and associated implementation delay for Portfolio D (Common Options)

Reclamation and other agencies are already collecting critical information (e.g., streamflow, climate conditions, status of the reservoirs) that can be used to inform assessments of which options should be implemented in the future. Building this information into systematic and recurring system assessments would enable managers and users of the Basin to better understand how conditions are evolving and plan for additional management options accordingly.

The vulnerability analysis specifically showed that the Upper Basin is vulnerable to climate conditions that are consistent with many of the simulated conditions emerging from a variety of global climate models. Over the next few years, it may be easier to discern whether the future climate is going continue to deviate from the historical record, drawing from new climate models or higher resolution regional climate projections. If the results from improved models are consistent with the more pessimistic current projections, the Basin is increasingly likely to face vulnerable conditions for the Lee Ferry deficit and Lake Mead levels. Many of the options identified as necessary under these conditions would need to be considered for implementation.

The analysis has shown that as vulnerable conditions develop in the Basin, increasingly expensive adaptation options will be required. The analysis highlighted which options would be needed and when. However, for many of these options, preparation for implementation would need to begin well before the time of their implementation. For this mid- to longer-term implementation period of a robust, adaptive strategy, Reclamation and the Basin States could identify the key long lead-time options that may be needed and begin to take near-term planning and design steps to ensure their availability.

It may also be beneficial to consider additional management and governance-based approaches for addressing future imbalances. Many of these options, such as some types of water transfers, could be consistent with the current Law of the River, but could not be easily modeled by CRSS within the time available to complete the study. As suggested by the Basin Study, evaluating these additional options in the coming months could further improve the ability for the portfolios to address supply and demand imbalances. Revisiting the options included in the portfolio is fully consistent with the RDM analysis framework used in the Basin Study. Comparing and contrasting the performance and other attributes of additional approaches alongside the adaptive options evaluated for the Basin Study would support the successful implementation of a robust, adaptive strategy.

GLOSSARY OF SELECT TERMS

Term	**Definition**
future	uncertain future conditions that arise in response to specified projections (e.g. supply, demand, and reservoir operations scenarios)
model run	a single simulation of a water management model over time
option	a specific investment or program that modifies the management of a water system
performance metric	a quantitative variable that indicates the functioning of the water management system
projection	a single timeseries of climate or other factor, such as demand, that is used to simulate the time evolution of the water management system
scenario	set of uncertain factor ranges that lead to conditions in which a management strategies fails to meet utility goals (see vulnerable conditions)
strategy	a specific set of options implemented over time to improve the performance of the water system
vulnerable conditions	set of uncertain factor ranges that lead to conditions in which a management strategies fails to meet utility goals (see scenario)
vulnerable future / vulnerability	a future which leads to outcomes not consistent with the basin's management goals
uncertainty or uncertain factor	a distinct component or descriptor of the water management system that is uncertain

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ABBREVIATIONS

ASR	Aquifer Storage and Recovery
BCSD	Bias Correction Spatial Disaggregation
BWS	[DEP's] Bureau of Water Supply
CAT/DEL	Catskill and Delaware Systems
CART	Classification and Regression Tree
CMPI3	Coupled Model Intercomparison Project Phase 3
CREAT	[EPA's] Climate Resilience Evaluation and Awareness tools
CRWU	[EPA's] Climate Ready Water Utilities
CRSS	Colorado River Simulation System
CSU	Colorado Springs Utilities
D2S2	dynamic decision support system
DEP	New York City Department of Environmental Protection
DYY	dry-year yield
EID	El Dorado Irrigation District
EPA	United States Environmental Protection Agency
FAD	Filtration Avoidance Determination
FFMP	Flexible Flow Management Plan
GCM	global climate model
GPCD	gallons per capita per day
GHG	greenhouse gas
IEUA	Inland Empire Utilities Agency
IPCC	International Panel on Climate Change
IWRM	Integrated Water Resource Management
IWRP	Integrated Water Resource Plan
MCDA	Multi Criteria Decision Analysis
mgd	million gallons per day
MWH	MWH Global, Inc.
MWRA	Massachusetts Water Resources Authority
NAS	National Academy of Sciences
NCAR	National Center for Atmospheric Research
OCWA	Onondaga County Water Authority
ONGOV	Government of Onondonga County, New York
OST	Operations Support Tool

PBCWUD	Palm Beach County Water Utilities Department
PCN	Pepacton, Cannonsville, Neversink
PRIM	Patient Rule Induction Method
RDM	Robust Decision Making
RWB	Rondout-West Branch
SCADA	supervisory control and data acquisition
SDS	Southern Delivery System
SFRCC	Southeast Florida Regional Climate Compact
SFWMD	South Florida Water Management District
UARP	Upper American River Project
UFWI	University of Florida Water Institute
USGS	United States Geological Survey
UWMP	[IEUA's] urban water-management plan
WEAP	Water Evaluation and Planning system
WRF	Water Research Foundation
XLRM	Refers to the "XLRM Matrix" of uncertain factors (Xs), the management decisions or levers that comprise alternative strategies (Ls), the performance metrics or measures (Ms), and the relationships or models (Rs)