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TECHNICAL REPORT



Presenting Uncertainty About Climate Change to Water-Resource Managers

A Summary of Workshops with the
Inland Empire Utilities Agency

David G. Groves, Debra Knopman, Robert J. Lempert,
Sandra H. Berry, Lynne Wainfan

Sponsored by the National Science Foundation



Environment, Energy, and Economic Development

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Preface

Water-resource managers are accustomed to planning and operating water facilities under conditions of uncertainty about future hydrology, weather forecasts, available water supply, and projected water demand. Weather is naturally variable on all time scales, and persistent periods of drought and wetter weather are common. In the past decade or so, another dimension of uncertainty has been added as scientists have been documenting evidence of longer-term global climate change that is likely to persist for more than a century. Whatever its causes, global climate change—a trend beyond the usual variability seen in the weather—is occurring now, albeit with uncertain local consequences. Water-resource managers will need to determine how to cope with it along with other natural and anthropogenic changes as they revise their planning in the coming years.

This report documents a series of three workshops conducted by RAND with the Inland Empire Utilities Agency (IEUA) in southern California in fall 2006. About 40 individuals from IEUA and cooperating agencies and organizations participated in one or more of the workshops. The purpose of the workshops was to explore how different descriptions of uncertainty about the effects of climate change and other key factors on IEUA's projected supply and demand might influence water managers' perceptions of risk and preferences for new infrastructure investments, changes in operational policies, and adoption of regulatory measures. To support the workshops, we developed a water-management model (WMM) with the assistance of IEUA staff members and other collaborators. This model continues to be refined and developed as a part of this on-going project. The intended audience for this report are water managers, state and local officials, and water-resource analysts who are seeking insights into how global climate change may call into question well-established planning assumptions and influence future plans.

This study represents one part of a larger project, "Improving Decisions in a Complex and Changing World," a larger multiyear effort funded by the National Science Foundation under the climate-change decisionmaking under uncertainty (DMUU) component of the agency's Human and Social Dynamics (HSD) priority area. The RAND DMUU project aims to conduct basic research to improve computer-based tools that support decisionmaking under conditions of deep uncertainty; examine the best means of representing uncertain scientific information to individuals and groups so they can act on it more effectively; and strengthen the scientific foundations of robust decisionmaking (RDM), a new approach to decision support under deep uncertainty.

The RAND Environment, Energy, and Economic Development Program

This research was conducted under the auspices of the Environment, Energy, and Economic Development Program (EEED) within RAND Infrastructure, Safety, and Environment (ISE). The mission of ISE is to improve the development, operation, use, and protection of society's essential physical assets and natural resources and to enhance the related social assets of safety and security of individuals in transit and in their workplaces and communities. The EEED research portfolio addresses environmental quality and regulation, energy resources and systems, water resources and systems, climate, natural hazards and disasters, and economic development—both domestically and internationally. EEED research is conducted for government, foundations, and the private sector.

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Contents

Preface	iii
Figures	vii
Tables	ix
Summary	xi
Acknowledgments	xvii
Abbreviations	xix
CHAPTER ONE	
Introduction	1
Purpose of the Study	1
Overview of Study Approach	2
Organization of This Report	3
CHAPTER TWO	
Alternative Treatments of Uncertainty	5
Characterization of Uncertainty for Long-Term Planning	6
Workshop Design Patterned on Laboratory Experiments	7
CHAPTER THREE	
Modeling Climate-Change Effects on the Inland Empire Utilities Agency	9
Hydrologic Features of IEUA's Service Area	9
IEUA's Sources of Supply	10
Water Management in IEUA	11
IEUA's Long-Term Water-Management Plans	12
Potential Effects of Climate Change on IEUA Water Management	13
Water-Management Model Overview	14
WEAP Model Representation	14
Major WEAP Model Elements	16
Catchments	17
Rivers	18
Groundwater Basins	19
Irrigation Demand	19
Indoor Demand	21
Supplies	21
Chino Basin Conjunctive Use	22
Dry-Year Yield Program	23

Unused Supply	23
Allocation of Supply to Meet Demand.....	24
Monthly Weather Projections	24
Performance Metrics.....	28
IEUA’s Existing and Potential Management Actions.....	29
Model Calibration and Sensitivity to Planning-Document Assumptions.....	31
Uncertainty About Future Management Conditions.....	37

CHAPTER FOUR

Performance of Inland Empire Utilities Agency Plans Under Future Conditions	39
Traditional Scenarios	39
Probability-Weighted Scenarios	44
Policy-Relevant Scenarios	47

CHAPTER FIVE

Evaluating Uncertainty Frameworks in Workshops	55
Study Design	55
Overview of Workshop Participation.....	56
Measuring the Effect of Decision Tools on Decisionmaking: Review of the Literature.....	58
System Analysis	58
Management Risk Taking	58
Results	59
Perceptions of Climate Change	59
Preferences for Presentations of Uncertainty	63
Managing Risk.....	65
Value of Modeling	67
Observations.....	70

CHAPTER SIX

Final Observations and Discussion	73
WEAP Modeling Environment.....	73
The Effect of Climate Change on IEUA Water Management.....	73
Views of Performance Under Different Types of Scenario Analysis	74
Workshop Results.....	75
Attitudes About Climate Change.....	75
Comparison Among Presentations of Uncertainties.....	75
Attitudes About Responsibility for Long-Term Planning.....	75
Attitudes About Modeling.....	75
Preferences for Strategies.....	75

References	77
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Figures

3.1.	Boundary Map of the IEUA Service Area	10
3.2.	Sources of Urban Supply for the IEUA Service Area, 2005	11
3.3.	Changes in Key Supplies Over Time Under the Pre-2000 Plan and the 2005 UWMP	13
3.4.	Schematic of Modeling Framework	14
3.5.	RAND-IEUA WEAP Model Schematic	15
3.6.	Simple Schematic of WEAP Soil-Moisture Model	20
3.7.	Annual Historical Precipitation and Temperature Near Ontario, California	25
3.8.	Cumulative Distribution Functions of Change in Summer Temperature from 2000 to 2010, 2020, 2030, and 2060	27
3.9.	Cumulative Distribution Functions of Change in Winter Precipitation from 2000 to 2010, 2020, 2030, and 2060	27
3.10.	Representative Time Series of Precipitation for Dry and Wet Climate-Change Deciles	28
3.11.	WMM-Projected Demand Under Historical Weather Conditions and the 2005 UWMP and IEUA RUWMP Demand Forecast	31
3.12.	WMM-Projected Chino Basin Storage Under Historical Weather Conditions and the 2005 UWMP	32
3.13.	WMM-Projected Available Imports Under Historical Weather Conditions and the 2005 UWMP and the Average-Year Metropolitan Imports Specified in the IEUA RUWMP	32
3.14.	Supply and Demand for the 2005 UWMP, Assuming a Repeat of 1980–2003 Weather	33
3.15.	Supply and Demand for the Pre-2000 Plan, Assuming a Repeat of 1980–2003 Weather	35
3.16.	Shortage Exceedance Plot for the Pre-2000 Plan, Assuming a Repeat of 1980–2003 Weather	35
3.17.	Shortage Exceedance Plot for Variants on the 2005 UWMP Under Historical Climate	36
3.18.	Workshop-Participant Assessments of the Achieved Level of Recycled-Water Use and Annual Chino Basin Replenishment in 2025	36
3.19.	Annual Recycling Use and GW Replenishment Under Three Levels of Goal Achievement	38
4.1.	Delivered Supply, Surplus, and Shortages for the Slightly Warmer, Meet Goals Scenario Under the 2005 UWMP	41
4.2.	Delivered Supply, Surplus, and Shortages for the Slightly Warmer, Miss Goals Scenario Under the 2005 UWMP	42

4.3.	Delivered Supply, Surplus, and Shortages for the Hotter and Drier, Meet Goals Scenario Under the 2005 UWMP.....	42
4.4.	Delivered Supply, Surplus, and Shortages for the Hotter and Drier, Miss Goals Scenario Under the 2005 UWMP.....	43
4.5.	Relative Weights Applied to Numbered Weather Sequences for Winter Precipitation and Summer Temperature	45
4.6.	Shortage Exceedance Plots for the Four Water-Management Plans Based on 810 Probabilistically Weighted Simulations	47
4.7.	Four Responses of Imports to Climate-Change Decile	48
4.8.	Frequency Histogram of Average Surplus for Plan A.....	49
4.9.	Parameter Ranges Specifying the Dry, Flashy, Low-Recycling Scenario	51
4.10.	Frequency Histogram of Average Surplus for Plan A Under All Modeled Conditions and Those Consistent with the Dry, Flashy, Low-Recycling Scenario	51
4.11.	Parameter Ranges Specifying the Wet, Effective-Recycling Scenario.....	52
4.12.	Representation of Optimal Plan Choices Under Different Subjective Assessments of the Likelihoods of Future Conditions Being Consistent with the Dry, Flashy, Low-Recycling Scenario, Assuming a Desired Surplus of 20 taf.....	54
5.1.	Responses to Statement “Climate change is a very slow process that occurs over thousands of years.”.....	60
5.2.	Responses to Statement: “Substantial climate changes over a period of 5–10 years are very possible.”	61
5.3.	Responses to Statement: “We are likely to have plenty of notice that climate change is happening.”	61
5.4.	Responses to Statement: “Climate change may be upon us before we know it is happening.”.....	62
5.5.	Participants’ Perceptions of Responsibility for the Future	62
5.6.	Participants’ Responses to Statement: “There are things we can and should do despite an incomplete understanding about the effects of climate change.”	64
5.7.	Comparison of Approaches to Presenting Scenarios After Workshop 3: Responses to the Statement: “Provides results that can be used in planning.”	64
5.8.	Participants’ Responses to Usefulness of Quantitative Modeling.....	68

Tables

3.1.	Catchments in the RAND-IEUA Water-Management Model.....	17
3.2.	Land-Use Projections for the Lower and Mid-Basin Under Base-Case Assumptions.....	18
3.3.	Land-Use and Irrigation Parameters Used for Major Catchments.....	20
3.4.	Projected Rates of Chino Basin Replenishment by Water Source.....	23
3.5.	Demand Priorities in the Water-Management Model.....	24
3.6.	Management Actions Represented in the Water-Management Model.....	30
3.7.	Model Parameters Defining Specific Management Plans Considered in Analysis.....	30
3.8.	Management Conditions Used to Demonstrate Performance of the Water- Management Model and Illustrate Importance of Management Actions.....	34
3.9.	Management Strategies Used to Demonstrate Performance of the Water- Management Model and Illustrate Importance of Management Actions.....	34
4.1.	Parameters Associated with Two Climate Sequences.....	40
4.2.	Parameters Associated with the Two Levels of IEUA RUWMP Goal Achievement.....	40
4.3.	Scenarios Used for Traditional Scenario Analysis.....	40
4.4.	Management Strategies Evaluated in Traditional Scenario Analysis.....	41
4.5.	Years with Shortages for Four Management Plans Under Four Scenarios.....	43
4.6.	Average Surplus for Four Management Plans Under Four Scenarios.....	44
4.7.	Relative Probability of Missing, Meeting, or Exceeding the IEUA RUWMP Recycling and Replenishment Goals.....	46
4.8.	Performance of Four Management Plans Under Probability-Weighted Scenarios.....	46
4.9.	Uncertain Parameters and Value Ranges Used to Generate Ensemble of Simulations for Policy-Relevant Scenario Analysis.....	49
4.10.	Average Surplus for Four Management Plans Under the Three Policy-Relevant Scenarios.....	52
5.1.	Overall Presentation Structure for the RAND-IEUA Workshops.....	56
5.2.	Summary of Workshop Attendees Who Provided Data.....	57
5.3.	Scales for Measuring Management Risk Taking.....	65
5.4.	Scales for Measuring Preferences for Risk-Reducing Measures.....	67

Summary

Water-resource managers have long strived to meet their goals of system reliability and environmental protection in the face of many uncertainties, including demographic and economic forecasts, intrinsic weather variability, and short-term climate change induced by El Niño and other naturally occurring cycles. Now water managers also face a new uncertainty—the potential for longer-term and more persistent climate change, which, in coming years, may significantly affect the availability of supply and patterns of water demand. Information about the future effects of climate change is deeply uncertain and likely to remain so for the foreseeable future. Thus, the scientific community is debating how to most usefully characterize this important yet uncertain information for decisionmakers.

RAND is conducting a large, multiyear study under a grant from the National Science Foundation (NSF) on climate-change decisionmaking under uncertainty (see ISE, 2007). As part of this project, we are working with water agencies in California to help them better understand how climate change might affect their systems and what actions, if any, they need to take to address this challenge. As a key component of this effort, RAND has conducted three workshops in cooperation with the Inland Empire Utilities Agency (IEUA), whose service area overlies southern California’s Chino groundwater (GW) basin. In this report, we document our methods and observations to preserve an archive of the workshop process and provide a basis for refining our approach for future applications.

Purpose and Scope of IEUA Workshops

The IEUA region has already begun implementing many of the water-management strategies described in IEUA’s *2005 Regional Urban Water Management Plan* (RUWMP) (IEUA, 2005). This plan includes a description of some of the analysis that California’s Department of Water Resources (DWR) and Metropolitan Water District of Southern California (Metropolitan) conducted related to the effect of global climate change on imported water supplies available to IEUA. However, this information did not provide IEUA with a systematic assessment of the potential effects of future climate change on its service area and the actions that the region’s cities and agencies might take to address these changes.

The purpose of the RAND-IEUA workshops was three-fold:

- Develop and exercise a new planning model for IEUA that enables consideration of the effects of large uncertainties on future system performance.

- Provide IEUA with state-of-the-art estimates of future climate change for its service area.
- Measure and assess decisionmakers' preferences among three different representations of key uncertainties and these uncertainties' effect on water-resource system performance.

Working in close consultation with IEUA staff and other water agencies, the project team developed a computer simulation model to estimate the performance of the IEUA RUWMP and potential modifications over a wide variety of scenarios that include different future climates as well as different levels of achievement of critical recycling and replenishment goals in the IEUA RUWMP. Over the course of three workshops (September 28, October 20, and November 3, 2006), the project team helped officials, technical staff, other water managers and planners, and other participants from the IEUA region to consider the significance of potential climate change relative to a few other key uncertainties and how planners might respond by reducing the vulnerability of supply disruptions under some scenarios. The RAND project team presented three different characterizations of uncertainty and administered surveys to workshop participants before, during, and after each of the workshops to record their views about the effectiveness and implications of the different presentations.

The first workshop characterized what is known about future climate change and then demonstrated differences in the performance of the IEUA RUWMP and variants (IEUA, 2005), based on assumptions that the current climate would continue into the future. In this first workshop, the RAND team presented climate and other uncertainties using a traditional scenario approach in which planners examined a small set of future conditions without assigning any likelihood or probability to their occurrence. In the second workshop, we presented state-of-the-art, probabilistic scenarios of climate change and then used these distributions to estimate the expected performance of the IEUA RUWMP and variants. Finally, in the third workshop, we presented a new approach, RDM, to develop policy-relevant scenarios, which were analytically derived from an extensive examination of many future conditions. We intended these scenarios to help IEUA consider ways in which it might augment its plans to reduce its vulnerability to potentially stressful future conditions.

Different Analyses of IEUA System Performance

The water-modeling analysis developed for this project not only offered the material for evaluating different presentations of uncertainty; it also provided useful information to IEUA and other regional water managers.

The traditional scenario analysis demonstrated that current plans would perform well if future climate were benign, that is, wetter than historic conditions, even with incomplete implementation of IEUA's recycling and replenishment goals. If the future climate were adverse, that is, drier and warmer than historic conditions, IEUA would need to meet its recycling and replenishment goals, as well as invest in more efficiency, and possibly allow more recycled-GW replenishment to ensure sufficient supply to meet demand. These traditional scenarios can provide a simple description of a range of future conditions relevant to IEUA. But such scenario analyses can also fall short of decisionmakers' needs because the choice of scenarios can appear arbitrary and the approach provides no systematic means to compare alternative policy choices.

The probability-weighted scenarios suggest that, if one believed the best-available probabilistic information about both future climate and the IEUA region's ability to meet the agency's recycling and replenishment goals, the IEUA RUWMP can ensure that the chance of a shortage over the next 25 years will not exceed 7 percent. Probabilistic scenarios can provide a concise ranking of the desirability of alternative IEUA plans but can lead to errors of omission in planning by downplaying the potential importance of possible futures that deviate from likeliest conditions. Further, effective use of probabilistic scenarios may require a wide range of stakeholders to agree on the validity of the distributions used in the analysis.

The policy-relevant scenarios identified two sets of conditions potentially most threatening to the success of the IEUA region's water-management plans—a Dry, Flashy, Low-Recycling scenario and a Wet, Effective-Recycling scenario. Under the Dry, Flashy, Low-Recycling scenario, the current plans fail to prevent frequent and significant shortages. Under the Wet, Effective-Recycling scenario, IEUA's current plan generates significantly more available water supply than the agency needs to meet demand. Such excess supply may indicate inappropriate overinvestment.¹ Additional efficiency and GW-management strategies improve performance under the Dry, Flashy, Low-Recycling scenario but may also generate excess surpluses if this adverse scenario does not come to pass. The analysis suggested that, if managers from the IEUA region believe that future conditions are more than 25 percent likely to be consistent with the Dry, Flashy, Low-Recycling scenario, investments in greater efficiency and more use of recycled water for GW replenishment than what is specified by the IEUA RUWMP would be prudent.

Policy-relevant scenarios are designed to provide concise descriptions of a plan's potential vulnerabilities and help suggest modified or new strategies that can reduce those vulnerabilities. However, generating such scenarios can prove a nontrivial exercise and may prove more complicated to explain to decisionmakers and stakeholders than the more familiar scenario and probabilistic scenario approaches. In addition, creating policy-relevant scenarios requires several explicit and potential subjective judgments on the part of decisionmakers and analysts (e.g., what level of adverse performance qualifies as a vulnerability?) that may influence the results.

As one of their key purposes, the workshops aimed to examine the extent to which IEUA decisionmakers would find useful each of these three different approaches to characterizing uncertainty.

Workshop Results

Before, during, and after each workshop, the RAND team administered surveys to measure how the presentations and discussions of the different characterizations of uncertainty influenced participants' views.

Attitudes About Climate Change

Participants whose opinions were measured after the third workshop were less likely to see climate change as a slow process and to feel that they would have warning and likelier to feel that

¹ There are likely to be other benefits from excess supply not explicitly examined in this study. This study used oversupply as a proxy for investment costs that will be handled more explicitly in later phases of the analysis.

climate change could be upon them before they were aware of it than were participants whose opinions were measured before the first workshop. This shift in opinion appears consistent with the climate science presented during the sessions.

Comparison Among Presentations of Uncertainties

Participants reported the traditional scenario approach the easiest to understand and to explain to decisionmakers. They found that it conveyed information in the most objective way but, compared to the other approaches, provided less of the information needed for planning in general and specifically to evaluate the plans of the IEUA region. The policy-relevant scenario approach, derived from RDM, was rated as providing the most valuable information for planning, comparing climate-related risks, and making choices among plans but least objective and least easy to understand and explain.

Attitudes About Responsibility for Long-Term Planning

Not surprisingly, participants reported feeling significantly more responsible for the immediate future (five to 10 years) than they did for the long-term future (50 to 250 years). Interestingly, this relationship did not change from survey to survey until after the third workshop, at which point participants rated themselves as slightly less responsible for the long-term future than did participants in the first workshop. In part, this small shift, if it was indeed due to anything other than noise in the data, may have been influenced by the focus in the workshops on a relatively short, 30-year time interval. Alternatively, the workshop results suggested that the IEUA region could become significantly more robust against a wide range of future climate-change scenarios by successfully achieving the agency's challenging near-term goal for an almost three-fold increase in its use of recycled water. Given a not-unreasonable expectation that the biggest risks to public acceptance of a new recycling program would come in its early years, an appropriate response to the information presented in the workshop might be to increase one's focus on the near term.

Attitudes About Modeling

Participants came to the workshop with a belief that quantitative modeling was useful and an eagerness to see what we could present. Exposure to the workshops did not shake this positive belief. We found some support for the hypothesis that modeling (including the approaches to scenario generation shown in these workshops) tended to make managers less confident about their management ability in the face of uncertainty, more willing to take risks, use models, and make adaptive changes; less willing to rely on their instincts; and less inclined to see situations as unique. Thus, these measures provide weak support for the proposition that the use of modeling can improve the management of risk and uncertainty.

Preferences for Actions the IEUA Region Might Take

When asked to rate a series of actions that the IEUA region might take, participants gave the highest marks to actions that the region's agency already has under way and that are key to their existing plans. Next in priority were measures related to new construction, increasing GW recharge, construction of new transmission lines for recycled water, construction of new GW-desalting plants, enacting tighter appliance standards, and improving the permeability of the basin to increase GW recharge. Taking more intrusive measures was viewed with less enthusiasm, and measures, such as increasing water rates to reduce demand, introducing recy-

pled water into the water supply, and slowing new development through zoning changes, were lowest priority. Ratings changed only slightly over the course of the workshops, and the rank ordering remained more or less the same.

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Abbreviations

af	acre-feet
AOGCM	atmosphere-ocean general-circulation model
CARS™	Computer Assisted Reasoning system®
CDF	cumulative distribution function
CDHS	California Department of Health Services
CII	commercial, industrial, and institutional
CU	conjunctive use
DMUU	decisionmaking under uncertainty
DWR	Department of Water Resources
DYY	dry-year yield
EEED	Environment, Energy, and Economic Development Program
ET	evapotranspiration
GW	groundwater
HSD	Human and Social Dynamics
IEUA	Inland Empire Utilities Agency
IPCC	Intergovernmental Panel on Climate Change
ISE	RAND Infrastructure, Safety, and Environment
JDM	judgment and decisionmaking
K_c	crop coefficient
LP	linear programming
maf	million acre-feet
MC	management condition
Metropolitan	Metropolitan Water District of Southern California

MF	multifamily
NCAR	National Center for Atmospheric Research
NSF	National Science Foundation
PAWN	Policy Analysis for Water Management in the Netherlands
PDF	probability density function
POLANO	Policy Analysis of the Oosterschelde
PRIM	patient rule induction method
RDM	robust decisionmaking
RUWMP	<i>2005 Regional Water Management Plan</i>
SANCAP	San Diego Clean Air Project
SAWPA	Santa Ana Watershed Project Authority
SF	single family
SRES	special report on emission scenarios
SWP	State Water Project
taf	thousand acre-feet
UWMP	urban water-management plan
WEAP	Water Evaluation and Planning
WMM	water-management model
W _x	workshop x, where x = a workshop number

Introduction

Purpose of the Study

This report documents the first stage of RAND-led field studies examining how different presentations of the uncertain effects of climate change affect water managers' perceptions of their risks and their preferences among actions they could take to possibly reduce those risks. We hypothesized that the characterization of uncertainties regarding causes, effects, and causal links among climate change, local water-resource impacts, and the effectiveness of water managers' actions to address these impacts has an influence on these managers' opinions about climate change and their preferences for management tools, operations, and infrastructure investments. Understanding whether and how characterizations of uncertainty affect water managers may have important implications for the design of decision-support tools and the provision of climate information services. If such tools and services do not reflect any important influences of uncertainty characterizations on changes in water managers' beliefs and actions, water managers may underutilize or misinterpret important information, fail to take appropriate actions, or have difficulty in reaching a consensus on planning priorities, any of which could lead to higher costs, increased vulnerability to supply disruptions, and less operational flexibility to recover from such disruptions.

Water-resource managers have long focused on providing reliable and cost-effective supplies in the face of many uncertainties, including demographic and economic forecasts and intrinsic weather and climate variability. Water managers typically rely on well-established planning methods and hydrologic estimation tools that assume that future climate will replicate the same statistical properties of precipitation and temperature as has been experienced in the past. This is known as the *stationarity* assumption in hydrologic analysis.

Until recently, few local and regional water-management agencies accounted for longer-term changes in climate. With the release of the most recent report of the Intergovernmental Panel on Climate Change (IPCC-I, 2007) and an increasing body of observations suggesting what appear to be significant, recent changes in the earth's climate, long-accepted conventions of prediction-based water-resource planning may no longer be appropriate. Of course, water-resource management is just one area of human endeavor vulnerable to uncertainties about climate change; response to uncertainty about climate change and its effects pervades many resource-oriented policy decisions. This study aimed to begin a systematic exploration of hypotheses about how different characterizations of uncertainty may affect decisionmakers' opinions and choices.

Overview of Study Approach

We conducted three workshops with the Inland Empire Utilities Agency (IEUA), whose service area generally overlies the Chino Basin. IEUA is a municipal water district formed in 1950, serves more than 800,000 people in eight cities, and is a member agency of the Metropolitan Water District of Southern California (Metropolitan). To gain a better insight into how to test hypotheses about the influence of different uncertainty characterizations on decisionmaking, RAND sought to partner with a water agency that recognized that climate change could affect the performance of its water-management activities in the future. Guided by earlier work examining urban water-management plans (UWMPs) in southern California (Wilkinson and Groves, 2006), the RAND team approached IEUA and asked it to host and participate in the workshops. The agencies and cities within the IEUA service area had already begun to implement measures contained in IEUA's new *2005 Regional Urban Water Management Plan* (RUWMP) (IEUA, 2005), and IEUA had become interested in systematic consideration of the potential effects of future climate change, a factor not explicitly considered in their earlier planning.

IEUA provided a setting for a gathering of staff and elected officials from IEUA and other water agencies and cities and, more importantly, provided a well-conceived water-management plan and a highly collegial staff with whom we could build our experiments and customize our modeling and testing tools to their conditions. With the assistance of IEUA staff members and others, we developed a water-management model (WMM) to evaluate the performance of the region's water management plans. This model continues to be refined and developed as a part of this on-going project. To model climate change in the Chino Basin, we worked with the National Center for Atmospheric Research (NCAR) to obtain state-of-the-art, regional climate forecasts for the IEUA service area. We used this information to create three presentations of the implications of climate change for IEUA's current long-range water plan (IEUA, 2005) and assessments of its current plan compared to various alternative plans. We conducted written surveys before, during, and after these presentations to measure how the presentations affected participants' understanding of the potential impacts of climate change on their system and their preferences among the various policy options they might pursue.

In this real-world setting, controlled experimental conditions were infeasible as the attendance of workshop participants shifted over the three sessions and their numbers were insufficient to produce statistically significant findings. Nonetheless, we were able to gain some useful insights about how varying characterizations of uncertainty influence perceptions of threat and vulnerability and how such studies could be better structured in the future.

These workshops were part of a larger research effort on climate-change decisionmaking under uncertainty (DMUU) in which new methods for representing uncertainty are being developed and their efficacy tested in both the laboratory and the field. In addition to more traditional methods of representing uncertainty in complex analyses, such as hand-crafted scenarios and probability-based forecasting, we tested a newer approach, called robust decisionmaking (RDM), which uses computational methods to identify scenarios likeliest to break assumptions embedded in a long-term resource-management plan. We patterned the experimental design of our workshops on judgment and decisionmaking (JDM) laboratory experiments that we have been conducting that examine how different decision aids affect subjects' choices for action under conditions of imprecise probabilities.

Organization of This Report

Chapter Two of this report describes the three characterizations of uncertainty that we used in the workshops. Chapter Three describes the model that we used to assess IEUA's current water-management plan and alternatives, and Chapter Four presents the modeling results for the three characterizations of uncertainty. Chapter Five describes how we evaluated participant views in our workshops. Last, Chapter Six presents some final observations and concluding thoughts. The appendixes (Groves et al., 2008a, 2008b) provide the workshop presentations and summary data from the workshop surveys.

Alternative Treatments of Uncertainty

Water-resource managers deal with uncertainty as a regular part of their business. They cope with variable weather, changing demand, volatility in energy costs, and infrastructure failures. But the uncertainties associated with climate change are different for several reasons. The very notion of global climate change happening in our lifetimes is novel. Until recently, it was not widely understood that climate change was actually under way, weakening any motivation of water managers to grapple seriously with the challenge. But even if climate change is virtually certain to be under way, the specific effects for any given region remain deeply uncertain. As we show in Chapter Three, it is not clear whether southern California will be wetter or drier in the decades ahead. Managers are used to dealing with known or well-characterized uncertainties, such as normal weather variability. But climate change presents a different challenge, because forecasts of regional effects remain novel and likely impossible to validate on any time scale that would prove useful for anticipatory planning. In addition, planners often expect that addressing climate change may be expensive and that the benefits will accrue far in the future, which may encourage skepticism about any projections of severe future effects that, if believed, could suggest the necessity of near-term actions.

Our main hypothesis is that improved methods for treating and presenting uncertainty in water planning will enable water managers to more effectively address the threat of climate change and other uncertain but influential factors. Traditionally, water managers have addressed uncertainty using a combination of historical data, quantitative point forecasts of future supply and demand, and ad hoc yet time-tested heuristics. For instance, water managers will plan against the worst drought in their region in the past several decades. They will combine their point supply and demand forecasts with their experience regarding the accuracy of such forecasts and how one adjusts to errors in those forecasts. In recent years, water managers have also begun to represent some variable and uncertain factors in their planning analyses using probabilities, leading to probabilistic forecasts of future supply, demand, and reliability. A natural extension of this approach is to integrate probabilistic, near-term climate forecasts that have become increasingly available.

However, these current approaches for addressing uncertainty may prove inadequate to the challenge posed by climate change. As water managers can no longer rely on past weather data to provide a good representation of future weather patterns, it becomes critical to replace historical weather characterizations with those that reflect possible changes in weather due to climate change. But the relevant, long-term, probabilistic climate forecasts are themselves uncertain. They encompass a very wide range of outcomes (from wetter to drier), do not resolve regional and local weather conditions critical to a water system, and may prove impossible to validate on any time scale useful for water planning. Probabilistic water-management fore-

casts based on such uncertain information may be justifiably viewed with some degree of skepticism.

Characterization of Uncertainty for Long-Term Planning

This report presents a decision analysis of potential IEUA-region water-planning responses to climate change using three different formulations of uncertainty: traditional scenarios; long-term, probabilistic forecasts; and policy-relevant scenarios derived from an RDM analysis. These three alternatives sample a range of the most promising approaches to long-term planning found in the literature (Lempert, Popper, and Bankes, 2003). We aim to determine which, if any, of these characterizations makes a significant difference in IEUA's ability to come to grips with the climate-change challenge.

A scenario is a self-consistent description of plausible future conditions. Traditional scenarios are developed in a qualitative process that identifies two or three key driving forces believed to be most important to defining a diverse range of future conditions and then builds a handful of scenarios around combinations of these forces (Schwartz, 1996). Such scenarios are often used to help decisionmakers understand and respond to an uncertain future. In particular, advocates see the development of scenarios as a useful means for enabling individuals and groups to consider and engage with potential futures they might otherwise reject as unpleasant or unlikely. Critics argue that scenarios often provide only limited utility to decisionmakers, because the choice of a particular set of scenarios is often arbitrary and because there is no established way to use those scenarios to assess alternative decisions (see Parson et al., 2007, for an excellent review of the strengths and weaknesses of traditional scenario analysis). In their standard usage, scenarios cannot by themselves inform decisionmakers about which uncertain factors drive variations in performance. In this analysis, we follow the standard scenario-axis approach for choosing four scenarios potentially relevant to IEUA's plans. We refer to these four scenarios as *traditional scenarios*.

Probabilities provide the foundation for the traditional approach to quantitative risk assessment. Some argue that decisionmakers, faced with an uncertain future climate, will require probabilistic forecasts of these future conditions to make sound choices (Giles, 2002; Reilly et al., 2001; Schneider, 2001; Webster et al., 2003). Others argue that, when probabilistic forecasts are themselves sufficiently uncertain and unvalidated (as is currently the case with long-term climate forecasts), they may be distrusted by decisionmakers, conceal information that decisionmakers may find useful, and generate controversy among stakeholders who hold differing expectations about the future (Allen, Raper, and Mitchell, 2001; Grübler and Nakicenovic, 2001; Lempert, Nakicenovic, et al., 2004; Rosenhead, 1989; Wack, 1985). In this analysis, we use elicitation and state-of-the-art, probabilistic climate forecasts created by combining the results of 21 major climate models to provide probabilistic estimates of the future performance of alternative IEUA plans.

Policy-relevant scenarios derive from a key step in RDM analysis, a form of quantitative decision analysis that seeks to identify strategies that perform reasonably well compared to the alternatives over a wide range of futures (Lempert, Popper, and Bankes, 2003). RDM identifies policy-relevant scenarios by running a computer simulation model many times to estimate the performance of a strategy over many combinations of uncertain model input parameters, then uses statistical algorithms to characterize, as simply as possible, the values of those few model

inputs most important in explaining cases in which the strategy performs poorly (Groves and Lempert, 2007). The region in the space of model inputs circumscribed by the values of these few parameters becomes a scenario, with the inputs themselves as the scenario's key driving forces. In this analysis, we use this quantitative scenario-finding process to identify a small number of scenarios that represent potential vulnerabilities of IEUA current plans.

As described in Chapter Five, we conducted workshops in which we assessed how decisionmakers responded to and used these three different characterizations of uncertainty.

Workshop Design Patterned on Laboratory Experiments

We patterned our workshops after JDM psychology experiments conducted to examine how alternative decision aids, based on different representations of uncertainty, affect individuals' choices. The abstract gamble addressed in the JDM experiments is not intended to reflect decisions that water managers face, and the quasiexperimental design of the workshops was chosen to accommodate real-world conditions. But we found it useful to base our workshop experimental design on that of the experiments, in which we measured the response to different types of decision aids from subjects facing a common set of choices influenced by imprecise probabilities.

Our collaborator, David Budescu, conducted these experiments in his laboratory with students at the University of Illinois (Budescu et al., 2006). Budescu presents each subject with an urn and 100 red and white balls of unknown proportion. The subjects are asked to play a game with three decision options in which a successful choice can earn up to \$20 or \$30. One option gives the subject the potential for the largest payout, but the payout depends strongly on the probability of avoiding drawing red balls from the urn. If unknowingly faced with an urn with a large number of red balls, the subject can earn nothing. The second option is guaranteed to earn a smaller amount, independent of the probability of drawing a red ball. The third option allows the subject to pay a small amount to retain the possibility of a larger payout, while insulating themselves against the consequences of drawing too many red balls. The subjects are divided into three groups, each of which is given a different type of decision aid. The control group gets no decision aid; the second group gets a summary aid, that is, an expected-value calculator that ranks the decision options contingent on the subject's best estimate of the probability of drawing a red ball. The third group gets a display aid that shows the performance of the options over the entire range of plausible probabilities. The summary aid roughly corresponds to the probabilistic forecast framing used in the workshops, and the display aid roughly corresponds to the policy-relevant scenario framing.

We found that individuals without decision aids gravitated strongly toward the precautionary option, that is, the option least dependent on the unknown probability of drawing a red ball. Both decision aids helped subjects take a more nuanced view of risk and produced slightly different preferences among the decision options. The expected-value calculator encouraged subjects to choose the option with the best expected value, while the display aid encouraged subjects to choose the option that performed best over the full range of probabilities. These results are consistent with results in the psychological literature that suggest that people exhibit an ambiguity aversion in which they tend to avoid choices in which the outcomes are ambiguous.

The design of our workshops roughly parallels that of these experiments. As described in Chapter Five, we presented the workshop participants with a common decision problem but alternative characterizations of uncertainty. Of course, the workshops with IEUA add a number of factors not present in the experiment, including group interactions, decisionmakers very familiar with and possessing strong opinions about the functioning of their water systems, and shifting groups. We hoped that, by measuring the IEUA decisionmakers' responses to different characterizations of the uncertainty, we would be able to learn how the way uncertainty is represented and linked to the analysis of options affects the way in which decisionmakers understand their options and the options they choose.

Modeling Climate-Change Effects on the Inland Empire Utilities Agency

The IEUA region will face significant water-management challenges in the future. Its current population of 800,000 is expected to grow to approximately 1.2 million by 2025. As the population grows and the economy evolves, demands on water supply and wastewater treatment will likely increase, raising new challenges to match demand with new supplies and means for disposal. Landowners and cities will continue to place heavy demands on the region's groundwater (GW) resources, requiring continuous, diligent management of both supply and quality. As a net importer of water from Metropolitan,¹ IEUA may face difficulties in meeting reliability objectives as other demands in the state compete for those same supplies. While IEUA already has reduced its vulnerability to cutbacks and interruptions of imported supply through conjunctive-use (CU) management and supply diversification, it could face supply shortfalls under prolonged drought conditions. Reliability concerns could be exacerbated under possible climate change.

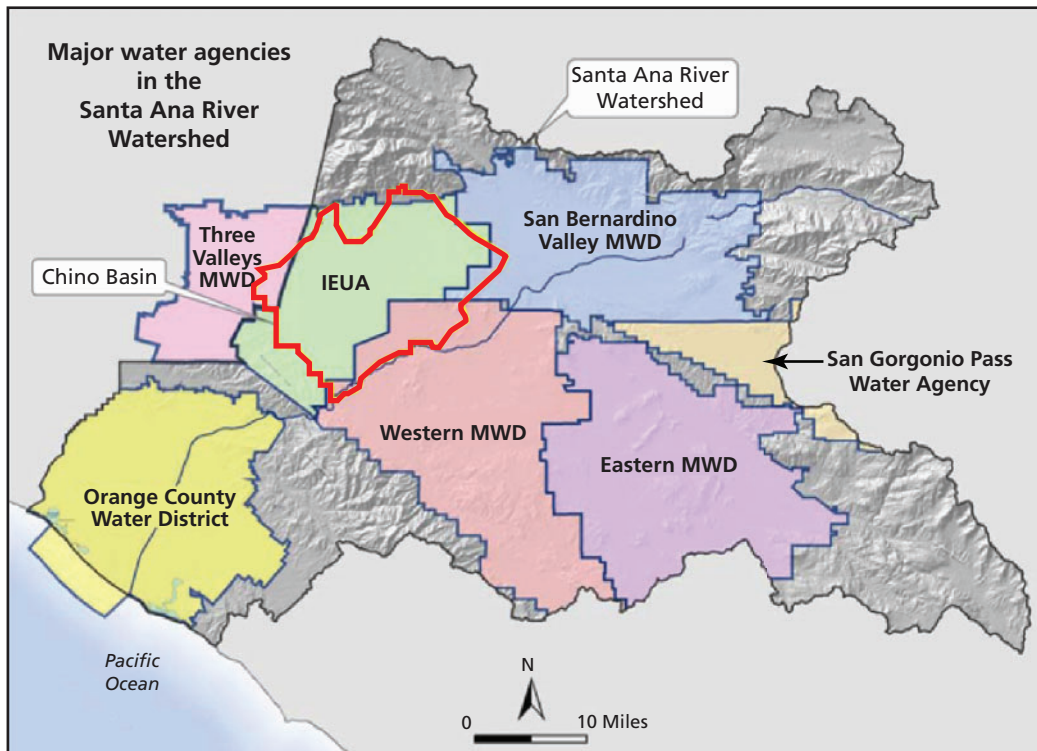
We developed a quantitative model of the IEUA system to examine relationships among supply and demand, changing climate and hydrologic conditions, and effects of various management actions and policies on supply, demand, and reliability. This system model is critical to our ability to understand how different characterizations of uncertainty—whether arising from ordinary hydrologic variability, supply- or demand-side implementation of management measures, or climate change—may influence long-term water-management decisions. We designed the model to accurately represent the water system's response to changes in supply, demand, and management measures. This chapter describes the key hydrologic features of the IEUA area, major components of supply and demand, the modeling framework used to represent these relationships, and representations of weather projections with and without future climate change.

Hydrologic Features of IEUA's Service Area

IEUA's service area covers 242 square miles and almost entirely overlays the Chino GW basin within the Santa Ana River Watershed region of southern California (Figure 3.1). IEUA is a wholesale water and wastewater provider serving the communities of Chino, Chino Hills, Fontana, Montclair, Ontario, Rancho Cucamonga, Upland, and San Antonio. The IEUA

¹ IEUA currently receives about 60,000 acre-feet annually for firm municipal supplies and additional supply for GW storage or CU deliveries. *Conjunctive use* refers to water-supply systems that draw on two or more types of sources, most commonly surface water and GW. CU management provides water suppliers with more flexibility to manage surface-water shortfalls by banking water in the subsurface or otherwise drawing on GW supplies to supplement surface deliveries.

Figure 3.1
Boundary Map of the IEUA Service Area



SOURCE: IEUA (2005).

NOTE: MWD = metropolitan water district.

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service area is in the midst of rapid urban growth and transformation from an agricultural region dominated by dairy farms to industrial and planned residential developments.

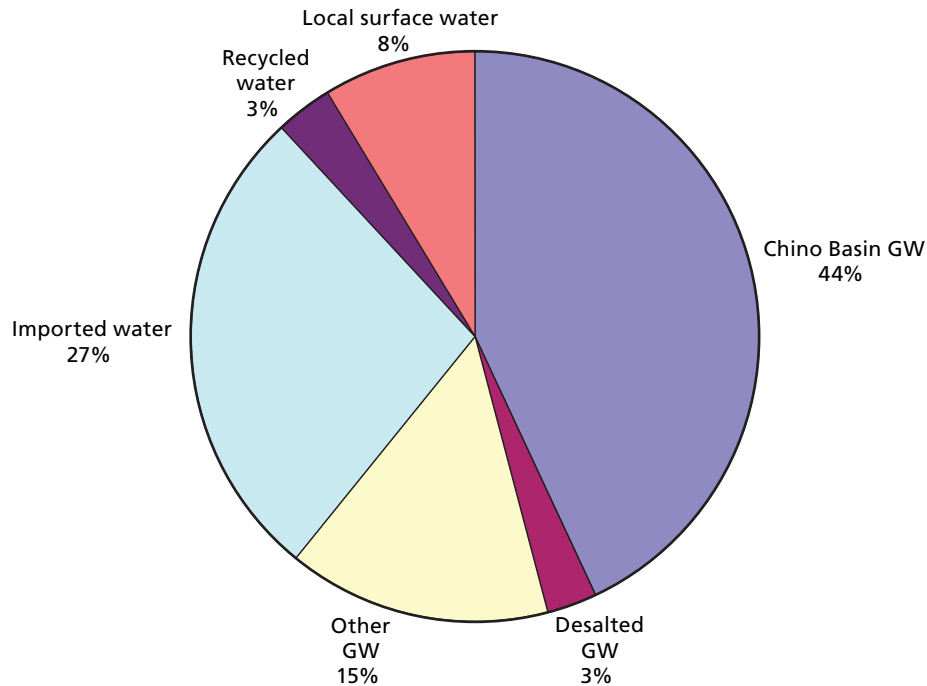
The Chino Basin is semiarid and receives, on average, 20 inches of precipitation per year, the bulk of which occurs between the months of November and March. Summers are hot and dry (around 85°F) with high evapotranspiration (ET). During the winter, temperatures are mild (around 59°F), and most of the season's precipitation derives from a few storms.

The region's two main natural hydrologic features are the Santa Ana River and its tributaries and the Chino GW basin, encompassing 235 square miles. The Chino Basin currently contains about 5 million acre-feet (maf) of GW and has an unused storage capacity of about 1 maf.

IEUA's Sources of Supply

The IEUA region obtains water from a diverse set of sources. Supply is diverted from local streams and rivers, pumped from the Chino Basin aquifer and other aquifers outside the service area, imported into the region from northern California via the State Water Project (SWP) (delivered by Metropolitan), and obtained from recycled municipal wastewater (Figure 3.2). This supply mixture provides flexibility in meeting the water needs within the service area. During years of low local precipitation, imports and GW supplies compensate for higher

Figure 3.2
Sources of Urban Supply for the IEUA Service Area, 2005



SOURCE: IEUA (2005, Table 3-8).
 RAND TR505-3.2

demands for irrigation and lower available local supplies. During wet years, imported and local sources are used to replenish the GW basin. As described below, the use of Chino Basin GW is regulated by the Chino Basin Watermaster to ensure long-term sustainability.

Water Management in IEUA

The water-management activities required to provide sustainable water services to end users in the IEUA service area are diverse and involve numerous water agencies. The key activities can be categorized in the following way:

- acquiring and transporting outside supplies to the service area
- collecting local surface supplies for direct use and for artificial recharge of the Chino Basin
- pumping local GW resources
- treating and distributing water to retail customers
- treating wastewater and producing recycled water supplies for direct, nonpotable use in the IEUA service area and GW replenishment²
- monitoring and controlling the salinity via the Chino desalters and replenishing the Chino GW basin

² Surplus recycled water flows into the Santa Ana River for reuse and replenishment purposes downriver in Orange County.

- funding, coordinating, and implementing water-use efficiency programs.

Metropolitan imports SWP supplies to IEUA. IEUA delivers these imported supplies to the region's retailers (typically city-run utilities); collects, treats, and disposes of wastewater; delivers recycled supplies back to end users; and provides renewable energy and compost services. Local, city-run utilities collect local surface supplies and deliver these and imported supplies to end users. The Chino Basin Watermaster, set up in response to a 1978 court order (*Chino Basin Municipal Water District v. City of Chino et al.*, San Bernardino Sup. Ct., 1978), manages GW pumping and replenishment programs throughout the Chino Basin. The Santa Ana Watershed Project Authority (SAWPA) coordinates regional planning and manages projects (notably the Santa Ana Regional Interceptor) throughout the larger Santa Ana Watershed.

IEUA's Long-Term Water-Management Plans

California law requires agencies that supply water to more than 3,000 customers to develop water-management plans every five years (California Water Code Part 2.6). The management plans must describe how the water agency intends to meet its customers' water needs during normal years and during two types of drought: a single-year drought and a three-year drought. The IEUA RUWMP (IEUA, 2005) outlines how the activity areas contribute to meeting current and future demand in the service area.

The IEUA RUWMP characterizes a comprehensive strategy being undertaken by IEUA and its member agencies and cities within its service area for ensuring that future supplies are sufficient to meet future demands. This plan implicitly assumes that climatic conditions in the future will be similar to those in the past. The IEUA RUWMP lays out three main strategies for achieving this objective:

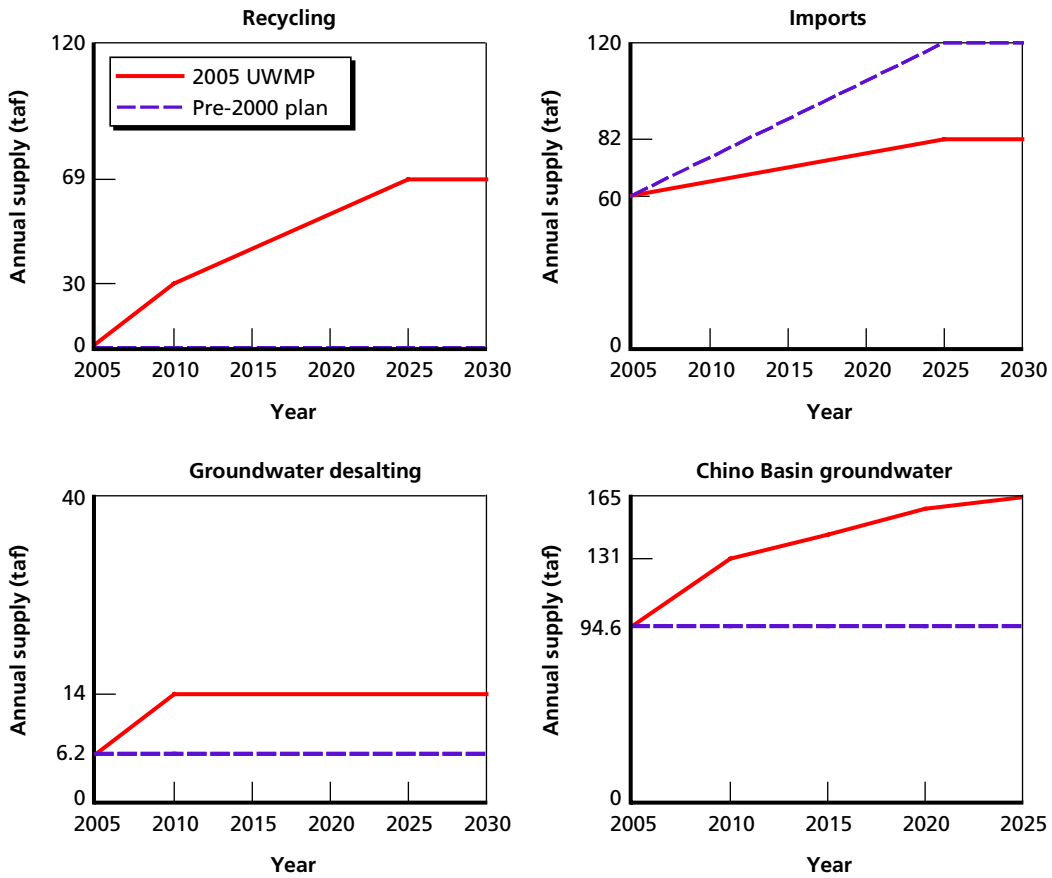
- Increase the long-term yield of Chino Basin GW production through CU and hydrologic control.
- Expand the treatment and distribution of wastewater for reuse by urban users.
- Develop regional agreements with other agencies to increase the flexibility in water management, such as the 2003 dry-year-yield program agreement with Metropolitan.

Increasing water-use efficiency and conservation are actively being implemented through cooperative efforts with Metropolitan, retail agencies, the Chino Basin Watermaster, and the Chino Basin Water Conservation District, although the goals articulated in the IEUA RUWMP are arguably modest.

This study evaluated the performance of different management plans, with each plan being comprised of individual water-management actions. This study focused on (1) a notional plan representing what current management would look like if the IEUA RUWMP were not implemented (pre-2000 plan), (2) the actions described in the RUWMP (hereafter, the 2005 UWMP), and (3) the 2005 UWMP with select enhancements.

Figure 3.3 compares the pre-2000 plan to the 2005 UWMP for select actions. Note that the 2005 UWMP calls for significantly lower expansions in Metropolitan imports but greatly expanded recycling and increased GW desalting and use.

Figure 3.3
Changes in Key Supplies Over Time Under the Pre-2000 Plan and the 2005 UWMP



NOTE: These figures do not include plans finalized after this study to increase the Chino desalters to 40,000 acre-feet (af). taf = thousand acre-feet.

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Potential Effects of Climate Change on IEUA Water Management

Climate change could affect water management in the IEUA service area in a number of ways. First, climate warming would likely increase the water needs of vegetation (natural, landscaping, and agricultural) through increased ET. With no change in precipitation, this warming could lead to (1) drying of soils and effects on natural vegetation in nonirrigated regions, (2) increasing irrigation demands for landscaping and agriculture, and (3) reductions in natural flows due to increased evaporation of lakes, rivers, and streams and greater absorption by soils.³

Precipitation changes add another dimension to the effects of climate change. The average amount of precipitation may decrease or increase, the intensity of precipitation events will likely become more intense, and the variability of precipitation could change and possibly increase (IPCC-I, 2007). These changes in precipitation could affect timing of winter snow

³ In some cases, warming and drying of the landscape could hinder percolation of precipitation and lead to increased runoff during precipitation events.

runoff, the variability of local surface supplies, the long-term replenishment of the GW basins, and the intensity of flooding events (Dracup et al., 2005; Zhu, Jenkins, and Lund, 2006).

Finally, climate-change impacts outside the region could also affect IEUA's operations. Of particular importance to IEUA, changes in rain and snowfall patterns in the Sacramento River watershed in northern California are likely to reduce the reliability of SWP supplies. Although a formal assessment of these effects on SWP supplies has not yet been completed, initial assessments suggest that climate change would reduce the reliability of this supply and reduce average yields (Vicuña, 2005).

Although there are not yet any legal requirements that water agencies do so, many agencies throughout California are beginning to consider how climate change may affect their operations and ability to achieve their management objectives.

Water-Management Model Overview

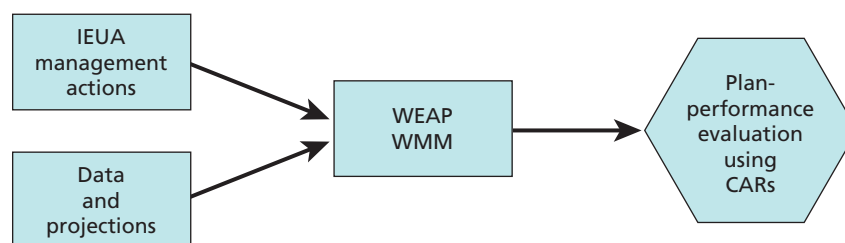
The RAND-IEUA WMM was developed using the Water Evaluation and Planning (WEAP) modeling platform, available from the Stockholm Environment Institute (undated). WEAP is a generic modeling environment for simulating the water-mass balance for a user-constructed, link-and-node representation of a water-management system (Yates, Purkey, Sieber, Huber-Lee, and Galbraith, 2005; Yates, Sieber, et al., 2005). It has been applied to numerous watersheds and districts throughout the world, including the Sacramento Valley in California. Huber-Lee et al. (2006) provided additional background on WEAP and present three case-study applications.

Output from the WEAP model was then coupled with Computer Assisted Reasoning system[®] (CARs[™]), available from Evolving Logic. CARs facilitates the generation and evaluation of large ensembles of simulations that represent a broad range of uncertainty about the future and the potential performance of alternative management strategies. Figure 3.4 shows a schematic of the modeling framework.

WEAP Model Representation

The project team created a unique representation of the IEUA water-management system in WEAP that simulates water supply and demand and a stylized representation of the major water flows of the system on a monthly time scale from 2005 to 2030. The RAND-IEUA

Figure 3.4
Schematic of Modeling Framework



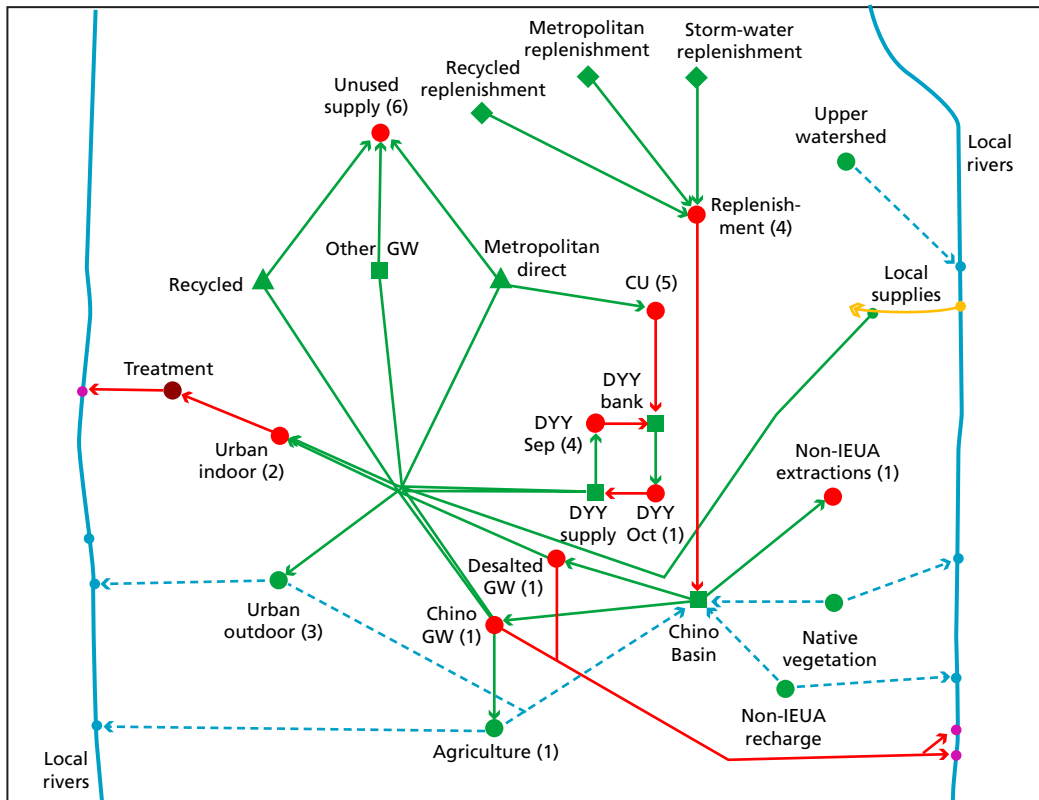
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WMM represents the system using a set of nodes corresponding to discrete water-management elements, such as catchments, indoor-demand sectors, supplies, and GW basins. These elements are linked together by rivers, conveyance facilities, and other pathways (such as percolation flows). Time series of monthly weather parameters are used to drive the system’s hydrology, using a two-bucket soil-moisture model. The model specification was based on the IEUA RUWMP (IEUA, 2005), the *Optimum Basin Management Program* (Wildermuth Environmental, 1999), and other documents provided by IEUA, such as Husing (2006). The model continues to be refined and developed as a part of this ongoing project. Figure 3.5 shows the basic model schematic.

The WMM reflects hydrologic flows in aggregate, distinguishing among individual flows only when necessary to represent the region’s large-scale water balance. For example, two local rivers represent all surface flows across the service area. One river represents all local surface flows; the other assimilates irrigation runoff and wastewater-treatment discharges. The WMM does not presently address water quality, so this simplification is inconsequential.

The RAND-IEUA WMM simulates water demand for urban and agricultural uses, imported supplies, local supplies that respond to scenario-specific weather and hydrologic conditions, and inflows and outflows of water to and from the Chino GW basin. We refer to each run of the model using a given set of parameters as a *simulation*. Each simulation represents

Figure 3.5
RAND-IEUA WEAP Model Schematic



NOTE: DYY = dry-year yield.
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trends in housing, employment, and land-use decisions, monthly climate sequences, and specified investments in efficiency and infrastructure projects and changes in GW management.

Hydrologic conditions are specified in the model via 25-year monthly sequences of four weather variables: temperature, precipitation, wind speed, and humidity. In this study, we considered three types of sequences:

- *climatological*: These sequences are generated by averaging monthly historical weather data from 1980 to 2003. For example, temperature data for all of the months of January between 1980 and 2003 are summed and then divided by the number of years of data (in this case, 24) to yield an average temperature for January. The process is repeated for each month for each of the four weather variables. These weather-data sequences are thus the same for each year of the simulation.
- *historical*: These sequences specify that each of the four weather parameters each month and year between 2005 and 2030 correspond to the same historical data for each month and year between 1980 to 2003.⁴ For example, the 12 months of temperature data observed in 1980 are used to represent the 12 months of temperature data in the simulations for the year 2005, 1981 monthly data is represented in 2006, and so on. In contrast to the climatological sequences, in which the same year's monthly data are repeated for every year, the historical sequence captures a 25-year historical record of monthly weather records and replicates those 25-year records in the simulation of future conditions.
- *synthetic future sequences*: An ensemble of synthetic weather sequences was developed to reflect plausible future weather under various climate-change conditions. These sequences are created using a statistical procedure to construct new sequences by selectively sampling from the historical sequence in a way that preserves the long-term inter- and intra-annual variability but reflects, on average, a specified trend in temperature and precipitation. This methodology, called *K-nn*, is described below.

The climatological sequences were used primarily to calibrate the long-term average behavior of the WMM. The historical sequences were used to evaluate how the water-management system will perform under alternative management strategies, assuming that the future climate is identical statistically to that of the past.⁵ For purposes of this study, they provided a base case against which to compare synthetic sequences of plausible climate-change trends, then were used to consider the effects of those trends on water-management strategies within the IEUA service area. The synthetic future sequences were used to develop plausible water-management simulations reflecting different levels of overall climate effects (in terms of regional temperature and precipitation trends). In this study, we looked at 90 weather sequences reflecting a wide range of possible climate-change effects.

Major WEAP Model Elements

WEAP provides a variety of different modeling objects to construct a specific water-management system. Catchment nodes represent areas that interact with externally specified weather

⁴ Data from 1980 and 1981 are assigned to 2029 and 2030, respectively.

⁵ This assumption of climate stationarity is commonly used in water management.

sequences to derive irrigation demands, surface runoff, and GW percolation. River and diversion objects track flows of water that are influenced by model-specified conditions (such as background flow), inflows from other objects, and outflows to other objects. GW nodes represent storages of water that receive flows from catchments and rivers and provide flows back to adjacent rivers. Reservoir nodes represent storages of water that receive and give up water flow from rivers and transmission links. Demand nodes represent end-user, non-hydrologic-based demands (such as indoor water use or fixed, outdoor water use). Other supply nodes represent exogenously specified inflows of water to the water system. Finally, wastewater-treatment plant objects receive outflows from urban-demand nodes, estimate treatment processes (such as cost, loss, and water-quality changes), and return flow to other demand nodes (representing reuse) or other rivers.

The RAND-IEUA WMM uses these elements to simulate the IEUA long-run water-management system. In some cases, we have used WEAP modeling objects in an unconventional way to achieve the desired operational properties, as described below.

Catchments

The WMM simulates water flows for catchment regions derived from prescribed monthly precipitation data. A *catchment* is a bounded hydrologic unit for which inflows, outflows, and storage can be counted. The WMM considers five catchments within the Chino Basin, representing the agricultural, native vegetation, upper watershed, urban landscape, and non-IEUA areas (Table 3.1). For each catchment, sequences of monthly temperature, precipitation, humidity, and wind speed are assigned from three specific locations: an upland, mid-basin, and lower-basin location. For each catchment, net precipitation flows to local rivers (as surface or subsurface flows) or to the Chino GW basin (deep percolation).

The catchment area in 2005 was derived from data obtained from Wildermuth Environmental, Inc. (Wildermuth, 2006) and evolves over time to represent conversion of land to different uses. We model this using the following set of rules:

Table 3.1
Catchments in the RAND-IEUA Water-Management Model

Catchment	Land Type (in 2005)	Area (acres)	Weather Data Location	Outflows
Agriculture	Irrigated (67%), nonirrigated (33%)	28,500	Lower basin (33°58' N, 117°37'W)	Local rivers, Chino Basin
Native vegetation	Forest (5%), shrubs (95%)	19,300	Mid-basin (34° 5'N, 117°37'W)	Local rivers, Chino Basin
Non-IEUA recharge	Shrubs	9,500	Mid-basin (34° 5'N, 117°37'W)	Local rivers, Chino Basin
Upper watershed	Forest	57,000	Upland (34°12'N, 117°37'W)	Local rivers
Urban outdoor	Impervious (79%), irrigated landscaping (21%)	86,900	Mid-basin (34° 5'N, 117°37'W)	Local rivers, Chino Basin

- Agricultural land area (irrigated and nonirrigated) decreases in proportion to the estimated agricultural water-use decline reported by the IEUA RUWMP.⁶
- Natural vegetation declines according the following schedule: 15 percent decline from 2005 to 2020, 60 percent decline by 2025, and a 70 percent decline by 2030.⁷ Agricultural land area and natural vegetation losses lead to equivalent gains in urban areas.

Table 3.2 shows the changes in land-use area resulting from these rules. We refer to this set of projections as *base-case assumptions*, because we later examine the system's performance when some of these assumptions are varied.

Rivers

Local surface hydrology is represented in stylistic terms within the WMM: The actual representation is a matter of modeling convenience and simplicity rather than a precise rendering of actual hydrology. Two rivers are included. The natural flow of the first local river ("Local rivers" in Figure 3.4) depends on the region's climate—its flow is derived solely from runoff from upper-basin catchment precipitation. Under all but the highest flow years, the entire river's flow is diverted to the local supply diversion. The area of the upper-basin catchment is adjusted so that, under historical monthly temperature and precipitation levels, the flow

Table 3.2
Land-Use Projections for the Lower and Mid-Basin Under Base-Case Assumptions (in acres)

Use	2005	2010	2015	2020	2025	2030
Agriculture	28.5	20.9	14.2	6.6	6.6	6.6
Irrigated	19.1	14.0	9.6	4.5	4.5	4.5
Nonirrigated	9.3	6.9	4.7	2.2	2.2	2.2
Natural vegetation	19.3	18.4	17.4	16.4	7.7	5.8
Forest	1.0	0.9	0.9	0.8	0.4	0.3
Shrub	18.4	17.4	16.5	15.6	7.3	5.5
Urban	86.9	95.5	103.1	111.7	120.3	122.3
Impervious (SF, MF, CII) ^a	68.4	75.1	81.1	87.8	94.7	96.2
SF landscape	9.0	9.9	10.7	11.6	12.5	12.7
MF landscape	0.8	0.9	0.9	1.0	1.1	1.1
CII landscape	8.8	9.6	10.4	11.3	12.2	12.4
Non-IEUA	9.7	9.7	9.7	9.7	9.7	9.7
Total	144.4	144.4	144.4	144.4	144.4	144.4

^a SF = single family. MF = multifamily. CII = commercial, industrial, and institutional.

⁶ The IEUA RUWMP projected agricultural water use to decline from 30 taf in 2005 to 7 taf by 2020 and remain constant from then until 2025.

⁷ Changes in natural vegetation are specified to accommodate projected growth in urban land areas and declines in agricultural land area.

of the local river provides the amount of flow needed for the derived local supplies to match the interannual variability of historical local supply as reported in the IEUA RUWMP. A second river exists simply as an outflow for treated sewage and urban and outdoor runoff.

Groundwater Basins

The WMM explicitly represents the Chino GW basin using a single GW node. The total available storage of this resource is 6 maf, with an initial storage of 5 maf. The basin receives infiltration from the urban outdoor, agriculture, native vegetation, and non-IEUA catchments. Additional inflow comes from the replenishment node, which represents all deliberate replenishment activities within the basin. There are three paths for water to leave the Chino Basin: (1) pumping for desalting, (2) pumping for direct use by entities outside the IEUA service area (non-IEUA extractions), and (3) IEUA direct-use pumping (Chino GW node). The model calculates the rate of IEUA direct-use pumping to reflect some allowable drawdown of the basin during years in which infiltration and replenishment are low. In general, during wet periods, more GW is allowed to be withdrawn for IEUA uses. During extended dry periods, GW use is limited, to ensure that drawdown of the aquifer is constrained. The details of this replenishment are discussed in the “Chino Basin Conjunctive Use” section later in this chapter.

We model GW imported from other regions using an other-supply node.

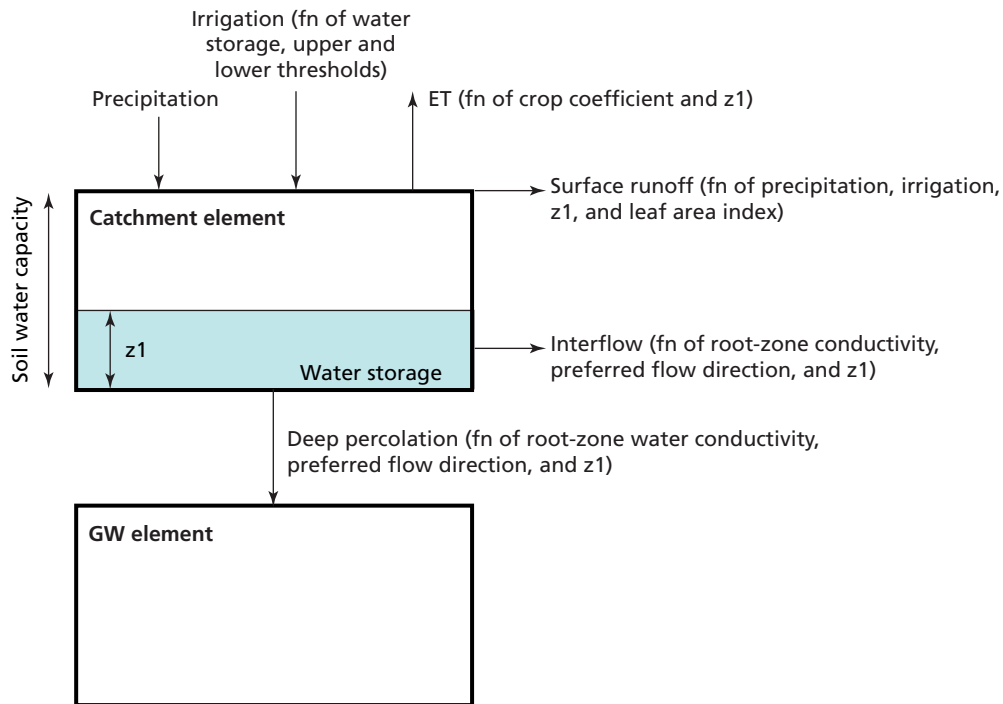
Irrigation Demand

Demand for irrigation water is controlled by the parameters defining the catchments according to a soil-moisture model that estimates the irrigation requirements and the return flow for any precipitation and applied irrigation water (e.g., ET, surface runoff, subsurface runoff, deep percolation). For each irrigated land and vegetation type, the following parameters are specified:

- *irrigated land area*: Irrigation demand is linearly proportional to irrigated land area.
- *crop coefficient (K)*: The crop coefficient prescribes the amount of irrigation water required for a particular crop relative to a reference crop; values range from 0 to 1.
- *soil water capacity*: This variable represents the effective water-holding capacity of the upper soil layer (millimeters).
- *leaf area index*: This parameter ranges from 0.1 to 10 and sets the surface runoff response, or the proportion of precipitation and irrigation that the plant and soil do not absorb and that becomes runoff. A lower number specifies that more precipitation and irrigation runs off and flows out of the system via adjacent streams.
- *root-zone conductivity*: This is the rate at which water moves through the upper soil layer (millimeters per month).
- *preferred flow direction*: This parameter indicates the relative proportion of water that flows horizontally to rivers and streams and vertically to GW basins (ranges between 0 and 1).
- *lower and upper irrigation thresholds*: These parameters control when irrigation water is demanded to keep soil sufficiently moist (saturation percent).
- *zI*: Initial relative water storage of the root zone.

Figure 3.6 shows a simple schematic of the water flows in WEAP’s soil-moisture model. Of particular importance for tuning the WEAP model to the IEUA region is the preferred flow direction and leaf area index parameters, which together dictate what portion of

Figure 3.6
Simple Schematic of WEAP Soil-Moisture Model



SOURCE: Adapted from WEAP documentation.

NOTE: fn = function.

RAND TR505-3.6

Table 3.3
Land-Use and Irrigation Parameters Used for Major Catchments

Parameter	Agriculture		Urban Outdoor		Native	
	Irrigated	Nonirrigated	Pervious	Impervious	Forest	Shrub
K_c	0.248–0.279 ^a	0.9	0.8	0.0	0.4	0.4
Soil water capacity (mm)	480	540	500	500	1,200	600
Leaf area index	10	6	5	5	16	6
Root-zone conductivity (mm/month)	153		150		360	
Preferred flow direction	0 (purely vertical)		0.5		0 (purely vertical)	
Lower and upper irrigation thresholds (%)	39, 42.5	N/A	35, 53	N/A	N/A	N/A
Initial z_1 (%)	50		50		16	

^a Varies by season.

precipitation and irrigation percolates into the connected GW basin (in this case, the Chino Basin GW node).

Parameter values specific to agricultural and urban irrigated land areas were developed with the assistance of Mohammad Rayej (of California's Department of Water Resources, or DWR) to produce ET rates and irrigation-demand rates appropriate for the region (Table 3.3). For the agricultural and outdoor catchments, alfalfa and turf were, respectively, specified to be the prevailing crop.

Indoor Demand

A single, urban, indoor-demand node accounts for all urban demand within the IEUA service area. This node disaggregates into the following categories, which evolve independently through each model simulation: SF (current and new buildings), MF (current and new buildings), and CII.

SF- and MF-household demand is calculated by multiplying projections of the number of SF and MF houses by an annual water-use rate. Housing projections are based on data specific to the IEUA service area provided by Metropolitan for an earlier study (Wilkinson and Groves, 2006). These housing projects, combined with IEUA-reported demand projections, are used to calculate IEUA projected per-household water use. The WMM then allows the projected water-use rate to vary, reflecting uncertainty about future per-household and policy-induced water-use efficiency.

Commercial and industrial water demand is estimated similarly to household demand, except that projections of commercial and industrial employees are used as the water-using entity. Finally, institutional demand is projected using the overall population as the water-using entity. More detailed discussion of this basic methodology can be found in Wilkinson and Groves (2006) and Groves (2006).

The WMM assumes that 10 percent of water supplied for indoor use is consumed and that 90 percent is returned to a wastewater-treatment node. A portion of the treated wastewater is supplied to the recycled supply node, and the remainder is routed to a local river.

Supplies

The recycled node represents treated wastewater that is redistributed to urban indoor and outdoor uses.⁸ The amount of recycled water supplied is specified according to each particular water-management scenario. The water-management scenario specifies the projected, planned amount of supply to be made available and the percentage of the planned recycling goal actually achieved. For example, the IEUA RUWMP calls for recycled water supply to increase by 7.5 taf in 2005 to 69 taf by 2025. A scenario in which only 80 percent of the IEUA 2025 goal was achieved would deliver 55.2 taf in 2025. The recycled node uses a reservoir representation in WEAP (known as a *reservoir WEAP object*) to specify a single, annual amount of available supply to meet end-use and Chino Basin GW-replenishment demands throughout the year. Any remaining water left in the reservoir at the end of the year is delivered, for accounting purposes, to the unused supply node. (See the "Unused Supply" section later in this chapter for further explanation and the rationale for treating it as a demand node.)

⁸ The WMM assumes that the agricultural sector receives all supply from GW, when, in fact, some portion of recycled supply is used by agriculture. Because demand for recycled water is an externally defined parameter (and one that could include changes in the agriculture sector), this simplification is not material.

The other-GW node represents the imported-GW source of supply to IEUA users. The IEUA RUWMP projects this supply to remain constant over time (around 34 taf). This supply is available for use by the urban-indoor and urban-outdoor nodes.

The Metropolitan-direct node represents imports from the SWP system as delivered by Metropolitan. The water-management strategy specifies the anticipated annual available supply. For example, the IEUA RUWMP projects a supply of 60.2 taf in 2005 to increase to 82.5 taf by 2025. The actual, delivered supply in any simulation is affected by the previous October-March precipitation totals for the IEUA region (dry years lead to reductions in Metropolitan imports as specified in the IEUA RUWMP),⁹ the extent of the climate-change signal (as defined by the climate decile, explained below), and an uncertain model parameter that specifies how much the Metropolitan supplies are reduced under climate change. The default sensitivity of Metropolitan supplies to climate change ranges between a 10 percent and 50 percent reduction by 2030 (depending on the severity of the climate-change signal).

Local supplies, primarily surface runoff from the San Gabriel Mountains, are a relatively small portion (about 5 percent) of the total IEUA supply. This supply responds to the weather pattern specified for the upper watershed. The model is tuned such that, on average, 18.7 taf of local supply is available. During dry years, this amount decreases approximately proportionally to the percentage decrease in precipitation during those years.

The desalted-GW node represents the annual quantity of Chino GW that is desalted to maintain hydrologic balance within the GW basin. This water supply is treated drinking water and is available for urban indoor and outdoor uses.

The Chino GW node represents IEUA use of nondesalted Chino GW. Chino GW meets agricultural demand completely. Any remaining available supply is used to meet urban indoor and outdoor demands.

Chino Basin Conjunctive Use

The WMM models Chino Basin CU through the interactions of the Chino Basin GW node, a replenishment-demand node that is satisfied by three replenishment supplies (recycled, Metropolitan imports, and storm water), catchments that provide natural recharge (agriculture, urban outdoor, native, and non-IEUA), and demand nodes that represent extractions (desalting, Chino GW, and non-IEUA extractions).

Metropolitan replenishment and storm-water replenishment are treated as exogenous supplies. Metropolitan replenishment responds to the weather sequence and severity of climate-change effects in the same way as Metropolitan direct supplies do, although they are treated as two separate sources. Metropolitan replenishment supplies tend to be abundant during years with above-normal hydrology and to be reduced significantly in years with below-normal hydrology (Metropolitan, 1999). Storm water does not respond to weather variability or climate trends in the version of the WMM used for this analysis. Recycled replenishment supplies originate from the recycled-supply node and are constrained by the projected availability of replenishment capacity and mix of recycled, Metropolitan imports, and storm water. Note that the California Department of Health Services (CDHS) and Santa Ana Regional Water Quality Control Board permits with the Chino Basin Watermaster and IEUA regulate

⁹ This scheme assumes a perfect correlation between precipitation in the IEUA service area and that in the source area of the SWP (northern California). An improved representation would relax this assumption.

the allowable fraction of replenishment water derived from recycled water (currently about 33 percent). Table 3.4 provides the nominal average rates of replenishment by source.

Dry-Year Yield Program

The WMM includes the DYY program that IEUA has with Metropolitan to bank the excess of imported supply in the Chino GW basin during wet years and draw on this bank during dry years. In reality, this program is administered through the in-lieu CU. During wet years, more imports and less GW are used by participating water agencies, with the net effect of increasing the storage of GW. During dry years, less imports and more GW are used, drawing down the storage of GW. The program tracks the puts and calls on the program to ensure that additional extractions during dry years do not exceed the deferred pumping during wet years.

In the WMM, the program is modeled as direct CU. The DYY replenishment–demand node receives surplus Metropolitan supply up to the inflow capacity of the program (nominally 5 taf) during years with no imported-supply constraints. This supply is stored in the DYY GW node, which begins with a storage of 250 taf. Each January, a specific amount of banked GW (nominally 30 taf) is available to the urban demand nodes.¹⁰ When all other available supplies are consumed, remaining demand is satisfied using this annual DYY amount. Any unused DYY water is returned to the DYY bank GW node at the end of the year.

Unused Supply

We added another demand node called *Unused Supply*. Any unused recycled, Metropolitan, or imported GW is delivered, for accounting purposes, to the unused-supply node. In actuality, unneeded Metropolitan supply would be made available to other Metropolitan contractors or not imported to Southern California, unneeded recycled supply would be discharged into the Santa Ana River along with other treated, nonreused wastewater, and unneeded GW imports would remain in their source regions.¹¹

Table 3.4
Projected Rates of Chino Basin Replenishment by Water Source

Replenishment Supply	Projected Replenishment Rates (taf)	
	2005	2030
Recycled	1	35
Metropolitan imports	45.3	60.1
Storm water	12	12

¹⁰ In actuality, the DYY program can yield 33 taf a year, of which 29 taf is available to IEUA.

¹¹ Note that the WMM does not account for the water balance of external GW sources. In the unlikely event that a simulation projects enough local supply so that Metropolitan imports, recycled supply, and GW imports are unneeded to meet demand, the WMM would not make that unused imported GW available in future years.

Allocation of Supply to Meet Demand

The WEAP model uses a linear-programming (LP) algorithm to allocate supplies to demands based on a system of demand priorities and supply preferences. For this application, the LP algorithm allocates supply on a monthly basis. The LP algorithm allocates supply to the demand sites sequentially according to priority. In months in which supply is limited, the algorithm assigns supplies such that each demand node of a given priority receives the same share of its total demand. More details of the algorithm can be found in Yates, Purkey, Sieber, Huber-Lee, and Galbraith (2005) and Yates, Sieber, et al. (2005). This scheme is quite flexible and is used to simulate the general allocation patterns for IEUA.

As shown in Table 3.5, agricultural users are the highest-priority end users in the system because they hold excess GW rights that they make available to urban users. Next-priority users are the urban-indoor and urban-outdoor users. The next priorities are for GW CU: recycled, Metropolitan replenishment, and storm water for Chino Basin replenishment and Metropolitan direct supply for the DYY program. Finally, the unused-supply node has the lowest priority. The numbers assigned to each use are the ordinal preferences specified in the WMM. A lower number indicates a higher priority.

Supply preferences specify which supplies are used to meet demands first. Every supply connected to a demand node is assigned a priority. The agriculture node receives supply only from the Chino GW. The indoor- and outdoor-demand nodes specify highest preference for low-cost, local supplies (e.g., local supply, Chino GW, and desalted GW), next-highest preferences for other GW and recycled supply, and the lowest preference for expensive imports (e.g., Metropolitan imports) and supply available only during droughts (e.g., DYY supply). Finally, the Chino Basin replenishment–demand node supply preferences are ordered by quality: storm water, Metropolitan imports, and recycled supply.

Monthly Weather Projections

For this analysis, we worked with researchers at NCAR to develop an ensemble of weather sequences that reflect a range of possible climate change over the IEUA service area as predicted by the major coupled atmospheric-ocean general-circulation models (AOGCMs). This methodology requires two key sources of information: (1) historical daily or monthly weather

Table 3.5
Demand Priorities in the Water-Management Model

Priority	Demand
1	Agriculture
2	Urban indoor
3	Urban outdoor
4	Chino Basin replenishment
5	DYY replenishment
6	Unused supply

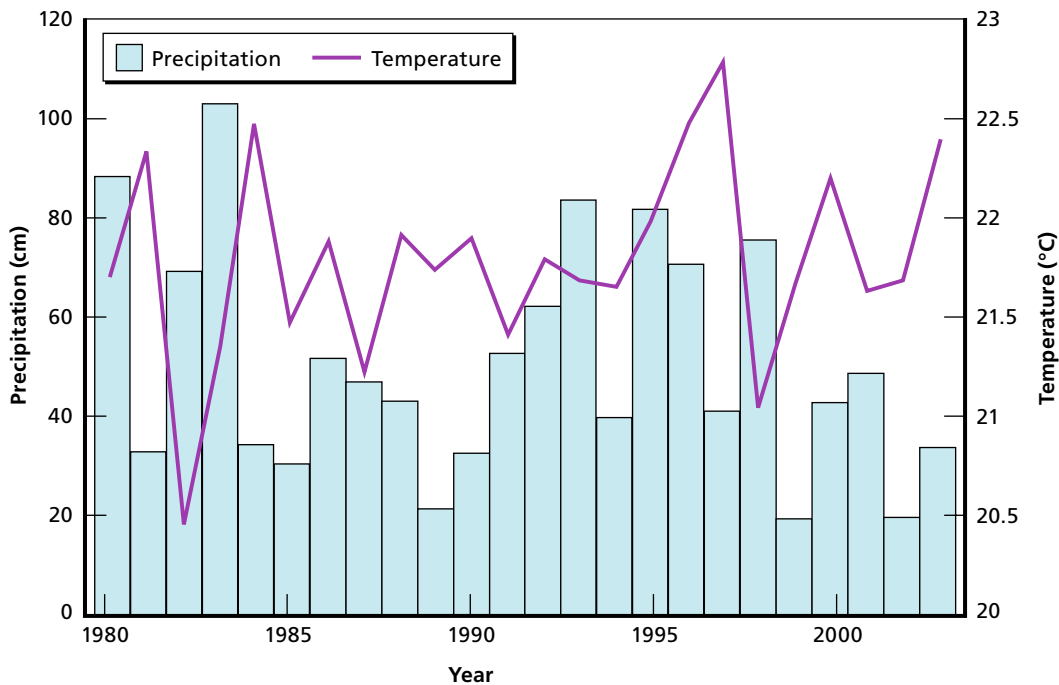
data for specific locations within the model domain and (2) probabilistic projections of 30-year trends in temperature and precipitation from an ensemble of global circulation models.

Climatological and historical weather sequences were developed using historical daily observations of temperature, precipitation, and dew-point temperature from 1980 to 2003 and monthly climatological wind-speed data for the region. Data were obtained for three locations representative of the agricultural region, urban region, and upper watershed from the Daymet U.S. data center (NTSG, undated). We supplemented this information with monthly climatological wind-speed data for the region.

Figure 3.7 shows the annual total precipitation and average temperature data from 1980 to 2003 for the urban catchment of IEUA. Note that the interannual variability in precipitation is extremely large—ranging from around 20 cm during two recent dry years to more than 100 cm in 1983. Average annual temperature differs by only a couple of degrees Celsius during the past 25 years.

Claudia Tebaldi of NCAR next provided us with probabilistic temperature and precipitation forecasts for the region of southern California that covered the IEUA service area, based on 21 AOGCMs. Tebaldi’s methodology (Tebaldi et al., 2004) uses a fully Bayesian approach to combine the predictions of the individual AOGCM forecasts into a single probabilistic forecast using the criteria of bias and convergence (e.g., the reliability ensemble average criteria from Giorgi and Mearns, 2002). In brief, a posterior distribution of the climate signal is developed using historical data and the AOGCMs’ projections. An initially noninformative prior distribution (i.e., one that is flat over a wide range of possible values for the future temperature or precipitation change) is updated numerically using Bayes’ theorem to account for the

Figure 3.7
Annual Historical Precipitation and Temperature Near Ontario, California



SOURCE: Based on data from NTSG (undated).
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observed record and the new observations of the future conditions as estimated by individual AOGCMs. The AOGCMs that perform well in recreating recent climate (low bias) and that show convergence (contribute to the consensus in the future trajectories) are weighted more heavily in the updating procedure. The method chooses to treat the latter criterion less stringently, in consideration of the possible lack of independence among AOGCMs (Tebaldi et al., 2004). Our study used a version of the methodology that develops distributions of temperature change and precipitation change independently. Soon-to-be-finalized advances in the methodology will produce joint probability distributions.

Tebaldi ultimately provided us with nine deciles of temperature and precipitation change for each of the four seasons from 2000 to 2030, as derived from the A1B emission scenario as defined by the Intergovernmental Panel on Climate Change (IPCC) special report on emission scenarios (SRES) (IPCC-III, 2000).¹² Figures 3.8 and 3.9 show the cumulative distribution function (CDF) for summer temperature (June, July, and August) and winter precipitation (December, January, February) change from 2000 for 2010, 2020, 2030, and 2060 for the A1B SRES emission scenario. The change in temperature by 2030, for example, ranges from slightly less than no change to 2.4 degrees Celsius.

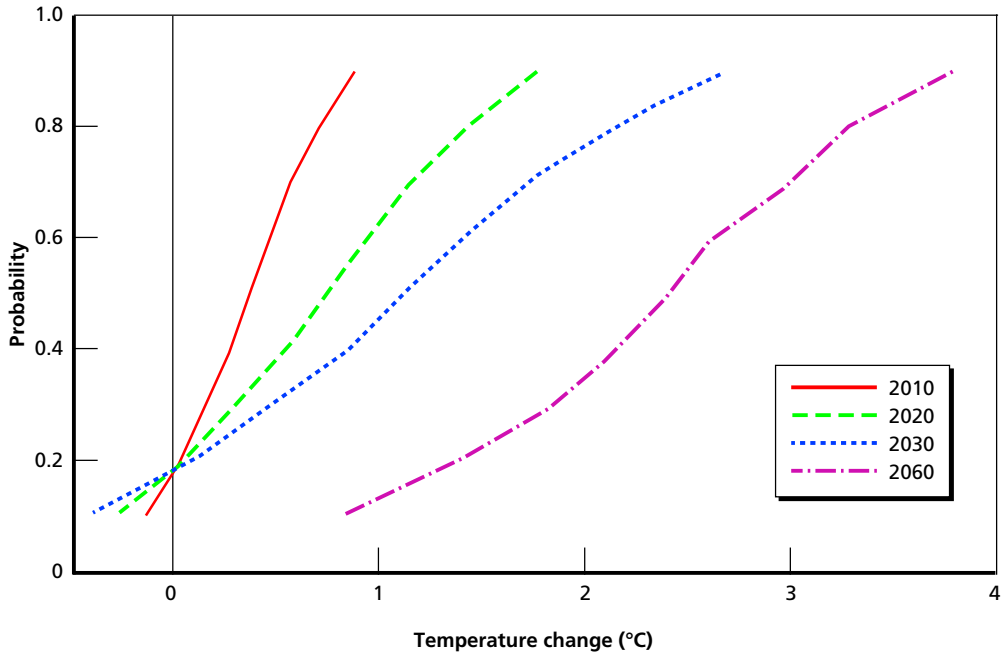
We next provided David Yates of NCAR with the historical data for the specific locations within the IEUA service area where we sought to develop the weather projections. Yates applied a climate downscaling procedure, called *K-nn* (Yates, Gangopadhyay, et al., 2003), to project regional-scale climate changes on the local weather patterns as characterized by the historical data. The *K-nn* procedure resamples historical, daily weather data so that the resulting sequences retain the basic statistical character of the historical data but include a specified exogenous trend. For this analysis, the *K-nn* method was used to create 10 realizations for each of the nine deciles of precipitation and temperature change, producing a total of 90 time series. Figure 3.10 shows two precipitation time series corresponding to the first and ninth decile.

The Bayesian climate ensemble method does not provide information about the covariance of temperature and precipitation trends, so we assumed that the driest (wettest) precipitation decile corresponds to the warmest (coolest) temperature decile.¹³ The *K-nn* resampling method does not guarantee that sequences with the appropriate precipitation trend will correspond to the desired temperature trend. We therefore adjusted the monthly temperature trends (using a growing linear additive factor) to meet the 2030 appropriate trend specified by the CDF.

¹² “The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies” (IPCC-III, 2000, box TS-1). The choice of emission scenario has little substantial effect on the temperature and precipitation projects before 2030, because all the SRES emission scenarios suggest similar atmospheric concentrations of greenhouse gases over the next few decades.

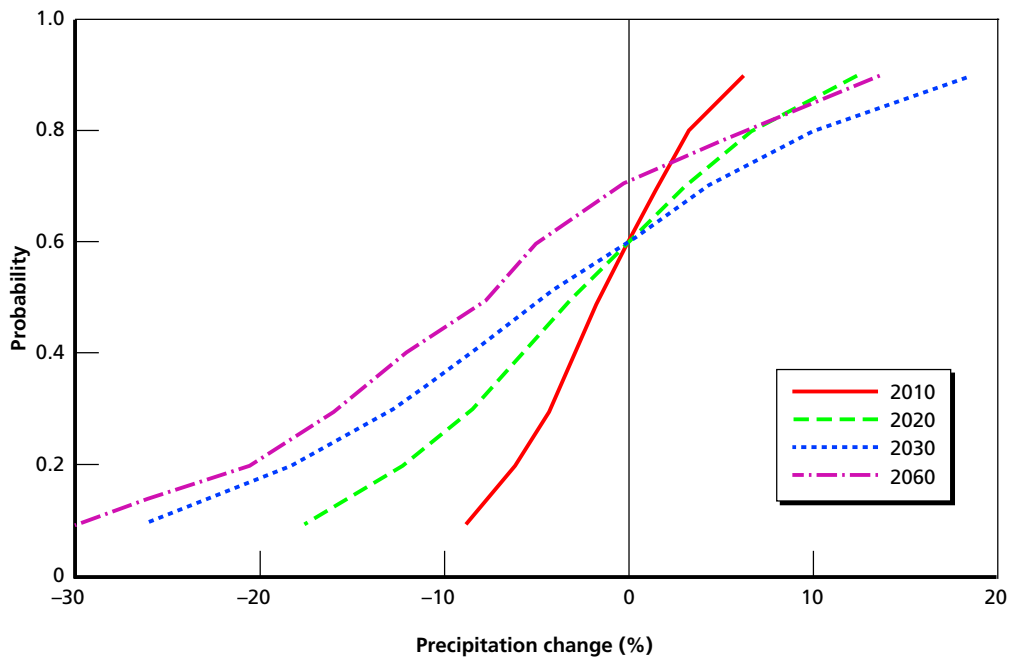
¹³ A simple regression of historical annual temperature on precipitation suggests a statistically insignificant negative relationship. Looking forward, the evidence is mixed. Most models suggest that strong warming will deepen persistent drought in the subtropical region—IEUA is at the northern edge of this boundary. This effect suggests a strong negative relationship between temperature and pressure. However, if El Niño conditions are disproportionately strengthened, the region could experience more warm and tropical storms, which would be consistent with a positive relationship. Our assumption relating drying trends to strong warming trends is a conservative one, in that it will lead to the most inclusive set of plausible climate scenarios as a basis of testing the water-management plans of the IEUA region.

Figure 3.8
Cumulative Distribution Functions of Change in Summer Temperature (degrees C) from 2000 to 2010, 2020, 2030, and 2060



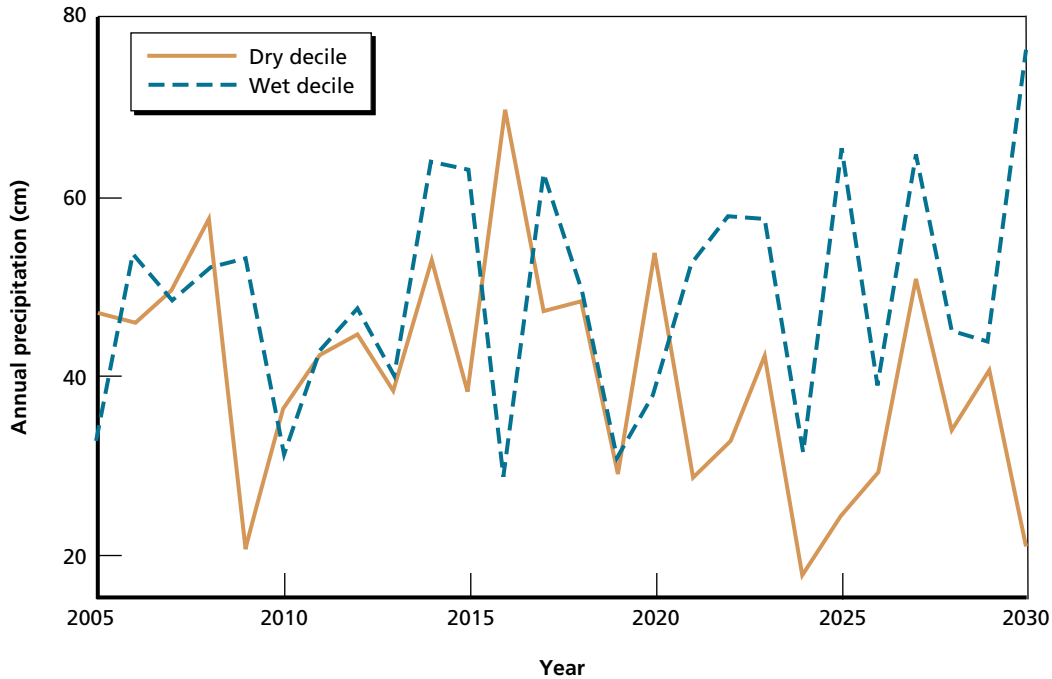
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Figure 3.9
Cumulative Distribution Functions of Change in Winter Precipitation (%) from 2000 to 2010, 2020, 2030, and 2060



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Figure 3.10
Representative Time Series of Precipitation for Dry and Wet Climate-Change Deciles



RAND TR505-3.10

Performance Metrics

The WMM provides a rich set of output measures, including time series of water flows among the supplies and demands, water stocks (such as the Chino GW basin), and tabulations of water demand, water supplied, and shortages corresponding to each simulation.¹⁴ The scenario analysis presented in the workshops focused on the annual water demand and supply balance and presented two key metrics: the annual supply surplus (difference between available supply and demand) and the frequency of shortages. For each of these metrics, we made determinations on what thresholds would distinguish good performance from varying degrees of underperformance.

For each WMM simulation, we report the frequency of shortages. To aid in interpretation of management strategies across different scenarios, we label simulations in which shortages occur less than one out of every 10 years (10 percent) as those with good performance.

We also reported the average annual surplus for each simulation. Interpretation of this outcome metric is less straightforward than is interpretation of the frequency of shortages. First, planning for some amount of surplus is prudent, because planning assumptions can be wrong and water-management conditions can change unexpectedly. For example, Metropolitan, in its 2005 RUWMP, sought to identify projects that would lead to a 10 percent buffer

¹⁴ In a follow-up application, we developed cost estimates for each supply option in the IEUA service area and reported annual costs and the net present value of costs for each simulation.

between supply and demand to coarsely accommodate for unanticipated changes in future conditions (MWD, 2005). On the other hand, developing more water supplies or implementing more programs than turns out to be necessary may be undesirable if those resources used to develop the unneeded supply or program could have been put to better use.

For the IEUA service area, we used the IEUA RUWMP as a guide for the desired amount of planning surplus—about 50 taf by 2025. As we are evaluating individual simulations and not expected or average conditions, a smaller planning surplus is more appropriate. We therefore define a plan as having good performance when its average surplus ranges between 20 and 40 taf. Below 20 taf, the margin may be insufficient to accommodate other variability not explicitly represented in the model; above 40 taf, it is likely to be unnecessarily large. Note that this approach assumes that the benefits of surplus supplies are less than the cost of developing (or making them available). As this may not be the case in actuality, in continuing analysis, we improve our set of performance measures by including estimates of supply-delivery costs in the IEUA region in our model, which will allow us to evaluate scenario performance by the monetary cost of supply development and provision.

IEUA's Existing and Potential Management Actions

Over the past decade or so, the management agencies within the IEUA service area have expanded its menu of management options to include more actions related to recycling, GW CU, and conservation. For modeling purposes, the RAND-IEUA WMM considers a wide range of water-management actions. A portfolio of such actions coordinated in a water-management plan constitutes a *water-management strategy*.

As a first step, the WMM implements static management strategies relating only to demand management, new supply, and GW operations. Static strategies are specified at the start of the simulation and do not change in response to evolving conditions. In follow-on work, we consider adaptive strategies that evolve over time in response to new information.¹⁵ The management actions available in the WMM are listed in Table 3.6 and are categorized by actions that moderate demand, expand supply, and modify the management of the Chino GW basin.

The analysis presented in the workshops considered five combinations of management actions, or plans: The pre-2000 plan, the 2005 UWMP, the 2005 UWMP with increased efficiency, the 2005 UWMP with increased recycled replenishment, and the 2005 UWMP with increased efficiency and increased recycled Chino Basin GW replenishment. The parameters in the WMM used to specify these management plans are described in Table 3.7.

¹⁵ In follow-on work, the WMM is modified to include an adaptive component to the water-management strategy. When specified, an adaptive strategy evaluates the performance of the strategy at five-year intervals beginning in 2015 by comparing the average supply surplus for the previous five years to the anticipated supply surplus (as specified in the IEUA RUWMP) for that period. If the modeled surplus is sufficiently lower than the expected surplus, then additional water-use efficiency and storm-water capture actions are implemented for the remainder of the simulation.

Table 3.6
Management Actions Represented in the Water-Management Model

Category	Management Objective	Representation in WMM
Demand	Reduce indoor water-use intensity	Increase in indoor water-use efficiency
	Reduce outdoor water-use intensity	Change in irrigation-water requirements for landscaping
Supply	Increase use of recycled water	Increase demand for recycled water
	Increase available supply during droughts via DYY program	Increase annual inflow, storage, and allowable outflow for DYY model element
Chino Basin GW management	Increase Chino Basin GW replenishment	Increase replenishment demand
	Desalt low-quality GW for supply and hydrologic control	Increase desalting extractions
	Maximize use of available local supply for replenishment	Increase allowable recycled replenishment

Table 3.7
Model Parameters Defining Specific Management Plans Considered in Analysis

Parameter	Pre-2000 Plan	2005 UWMP	2005 UWMP + Increased Efficiency	2005 UWMP + Recycled Replenishment
Efficiency2015 (%)	6	10	15	
Efficiency2030 (%)	6	10	20	
OutdoorEfficiency2015 (%)	0	0	5	
OutdoorEfficiency2030 (%)	0	0	10	
Recycling2010 (taf)	6	39		
Recycling2025 (taf)	6	69		
Replenishment2010 (taf)	91.6	91.6		
Replenishment2020 (taf)	94.9	94.9		
Replenishment2025 (taf)	107.1	107.1		
Desalted2010 (taf)	6.25	14.2		
Desalted2025 (taf)	6.25	14.2		
DYYield2010 (taf)	0	30 ^a		
DYYield2020 (taf)	0	30 ^a		
Recycled Replenishment				120% 2005 UWMP

^a The DYY program is currently sized to yield 33 taf/year. Only 29 taf of this yield is allocated to IEUA—the remaining is made available to other Metropolitan contractors. We used 30 taf in this analysis.

Model Calibration and Sensitivity to Planning-Document Assumptions

The WMM was developed to evaluate the performance of the IEUA region plans under different assumptions—not model the validity of the underlying assumptions. Therefore, the model was constructed so that the current planning assumptions, as described in the IEUA RUWMP, would yield the expected demand, supply, and average surplus.

Model calibration consisted of four main tasks:

1. tuning WEAP parameters so that modeled demand under historical climate and projected land-use and demographic assumptions match the demand forecast reported in the IEUA RUWMP (Figure 3.11)
2. tuning the Chino Basin catchment parameters so that percolation of historical precipitation and planned GW replenishment leads to the total basin inflow required to balance extractions according to the Chino Basin Peace I agreement, as described in the IEUA RUWMP. Figure 3.12 shows the simulated Chino Basin GW storage under historical climate conditions and 2005 UWMP model assumptions.
3. tuning Metropolitan import parameters so that periods of dry years trigger expected shortfalls in import deliveries. Figure 3.13 compares the WMM projections under historical climate and 2005 UWMP assumptions to the delivery schedule under normal years from the IEUA RUWMP. Years in which the model projects low deliveries correspond to low-precipitation years and subsequent Metropolitan delivery reductions as specified in the IEUA RUWMP.

Figure 3.11
WMM-Projected Demand Under Historical Weather Conditions and the 2005 UWMP (bars)
and IEUA RUWMP Demand Forecast (line)

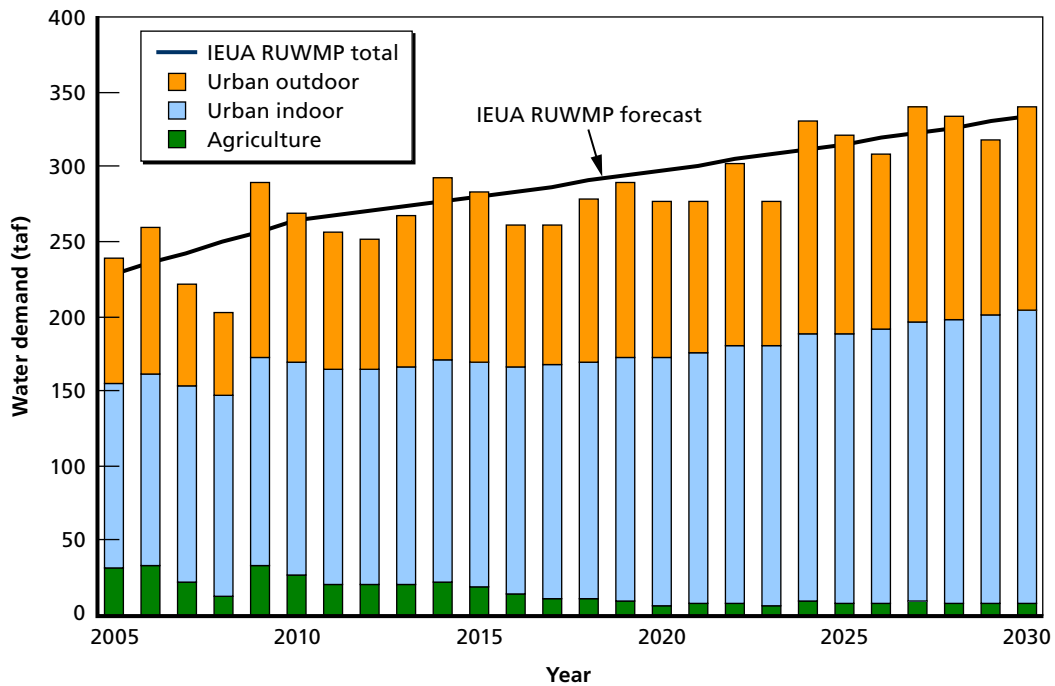
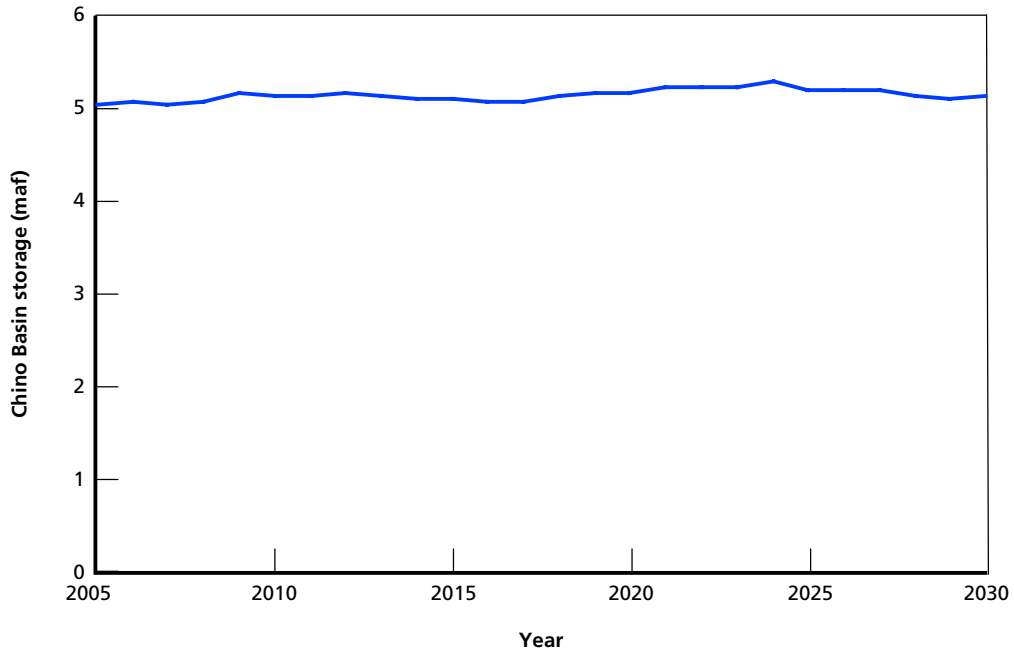
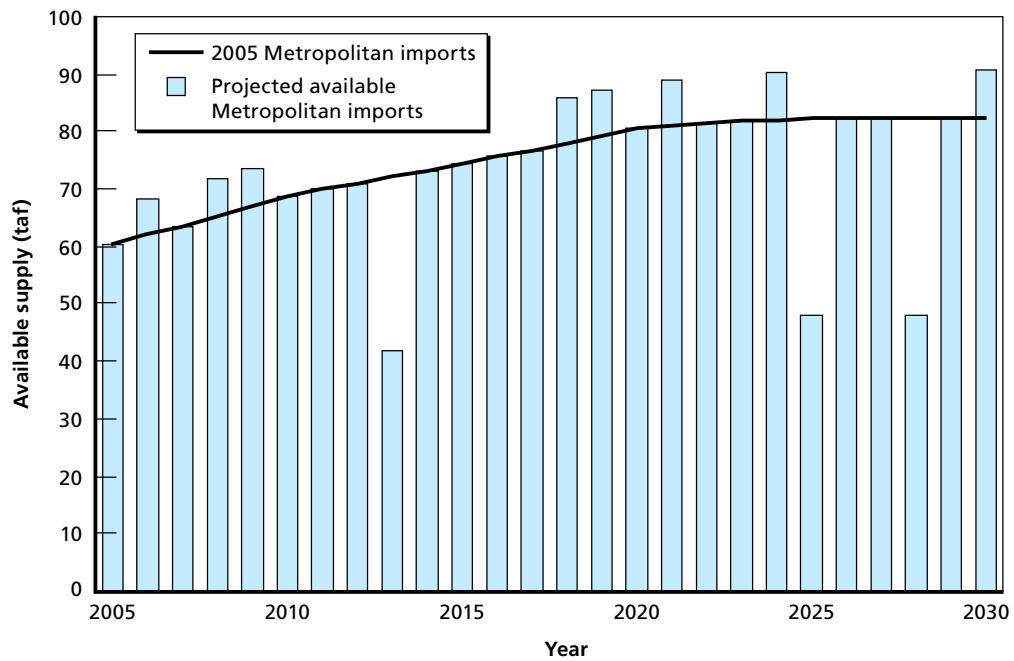


Figure 3.12
WMM-Projected Chino Basin Storage Under Historical Weather Conditions and the 2005 UWMP



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Figure 3.13
WMM-Projected Available Imports Under Historical Weather Conditions and the 2005 UWMP (bars) and the Average-Year Metropolitan Imports Specified in the IEUA RUWMP



RAND TR505-3.13

4. tuning the upper catchment and local river flow so that local supplies vary with precipitation within the historical range described in the IEUA RUWMP (not shown).

To demonstrate that the calibration to the IEUA RUWMP was successful, we present projections of supply, demand, and surplus using historical weather patterns and the 2005 UWMP assumptions (Figure 3.14). As projected by the IEUA RUWMP, the region’s development of new supplies exceeds increases in demand, leading to increasing supply surpluses.

To evaluate the sensitivity of the model to different management actions in meeting future demand, we evaluated the model assuming different levels of implementation for recycling, Chino Basin GW replenishment, and imports. Table 3.8 lists the management conditions, and Table 3.9 the strategies, evaluated for this portion of the analysis.

Management condition (MC) 1 assumes that the future demand evolves as projected in the 2005 UWMP and that supply evolves according to the assumptions embedded in the specific plan under evaluation. For example, MC1 under the 2005 UWMP (A) reproduces the basic assumptions and analysis provided in the IEUA RUWMP. MC1 under the pre-2000 plan (P) projects outcomes under recently forecasted demand but under the management strategies in place around 2000.

MC2 through MC4, respectively, consider the performance of the various plans but with recycling, replenishment, and imports levels remaining constant at current levels (and thus not evolving as specified in the various plan). MC5 considers the effect of all these supplies remaining constant.

Figure 3.14
Supply and Demand (by sector) for the 2005 UWMP, Assuming a Repeat of 1980–2003
Weather

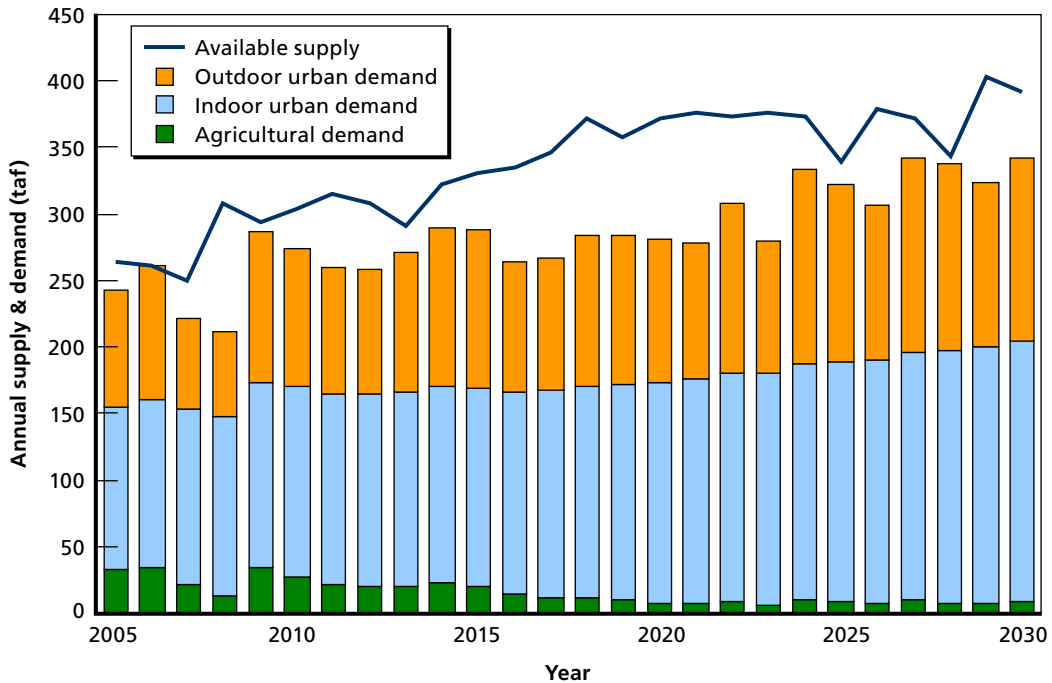


Table 3.8
Management Conditions Used to Demonstrate Performance of the Water-Management Model and Illustrate Importance of Management Actions

Abbreviation	Condition
MC1	Historical climate: base assumptions
MC2	Historical climate: current recycling
MC3	Historical climate: current replenishment
MC4	Historical climate: current imports
MC5	Historical climate: current recycling, replenishment, and imports

Table 3.9
Management Strategies Used to Demonstrate Performance of the Water-Management Model and Illustrate Importance of Management Actions

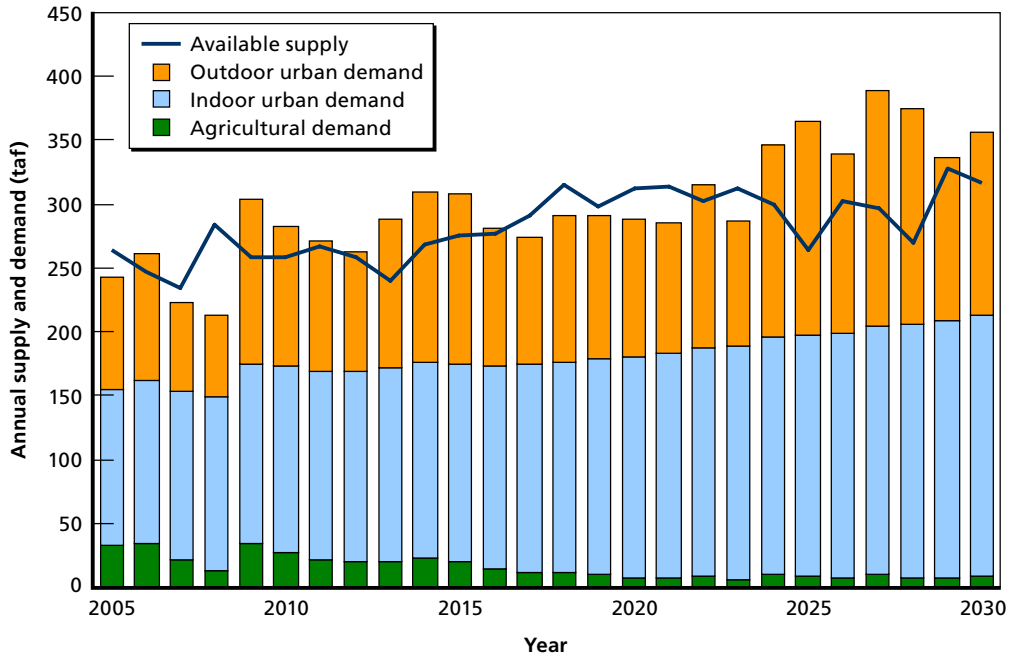
Abbreviation	Strategy
P	Pre-2000 plan
A	2005 UWMP

Under MC1, the pre-2000 plan growth in water demand outpaces the development of new supplies. Figure 3.15 shows the annual water demand by the agricultural sector, for indoor urban water use, and outdoor water use (bars), and total available supply (line) over the simulation period. Even in the early periods, years with high demand exceed supply. Figure 3.16 shows shortage exceedance plots, which display the fraction of years (in this case, out of 25 years) in which shortages of various levels occur.¹⁶ Shortages also occur with increasing frequency over time. Shortages of more than 40 taf occur in about 30 percent of the years simulated. The 2005 UWMP, in contrast, performs well under historical climate conditions if all its goals are met (Figure 3.17). The region's development of new supplies exceeds increases in demand, leading to increasing supply surpluses. There are no shortages, so the exceedance plot is a horizontal line along the x axis (not shown).

We next evaluated the performance of the 2005 UWMP if some of its ambitious goals are not met. Figure 3.18 shows that, if either the recycling or replenishment goals are not achieved, shortages during dry years are possible. For example, staying at the current recycling level would lead to a shortage of more than 30 taf 4 percent of the time (one out of 25 years), a shortage of about 20 taf 8 percent of the time (two out of 25 years), and about 5 taf 12 percent of the time (three out of 25 years). Staying at current levels for replenishment, recycling, and imports leads to large and frequent shortages. Staying at current levels of imports alone does not lead to significant shortages, because the projected increase in use of imports is modest compared to increases in recycling and replenishment.

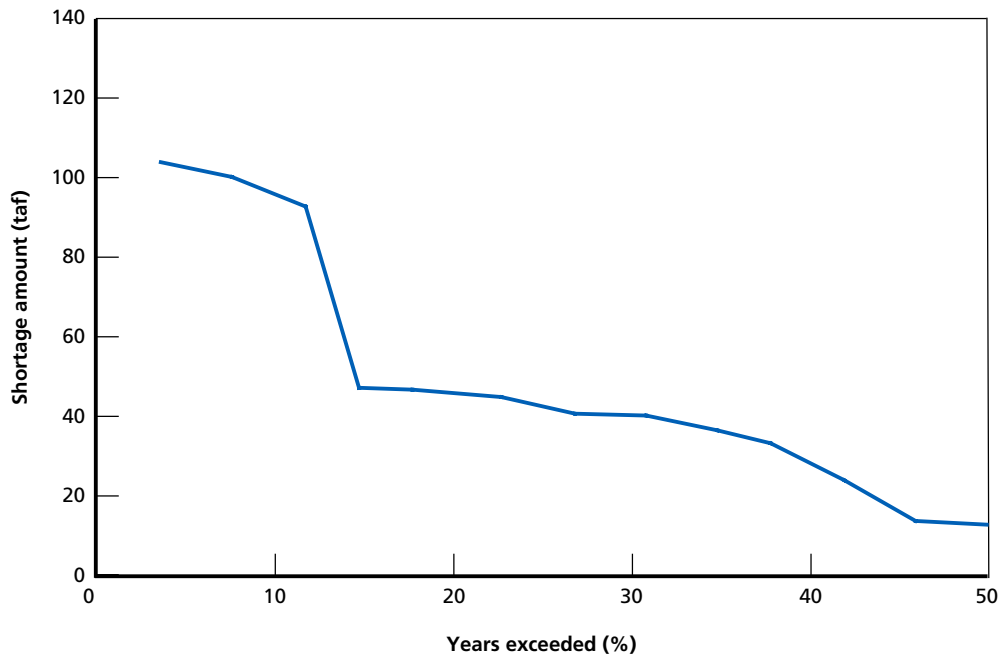
¹⁶ Note that an exceedance curve that is closer to the origin indicates fewer and less severe shortages than one farther away. A result with a horizontal line passing through the origin indicates that no shortages are projected.

Figure 3.15
Supply and Demand (by sector) for the Pre-2000 Plan, Assuming a Repeat of 1980–2003
Weather (MC1-P)



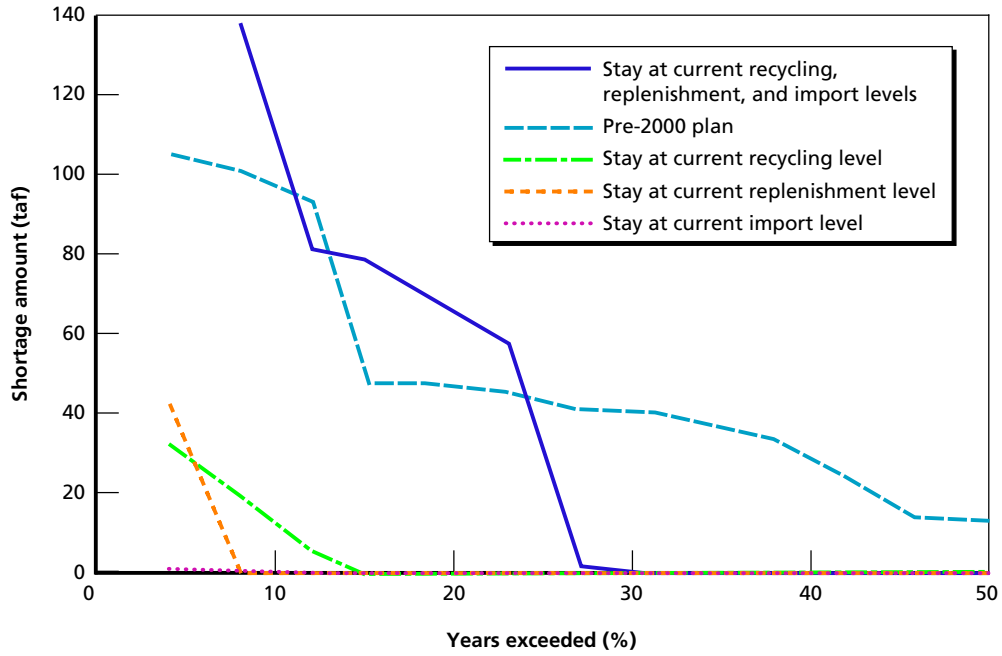
RAND TR505-3.15

Figure 3.16
Shortage Exceedance Plot for the Pre-2000 Plan, Assuming a Repeat of 1980–2003
Weather (MC1-P)



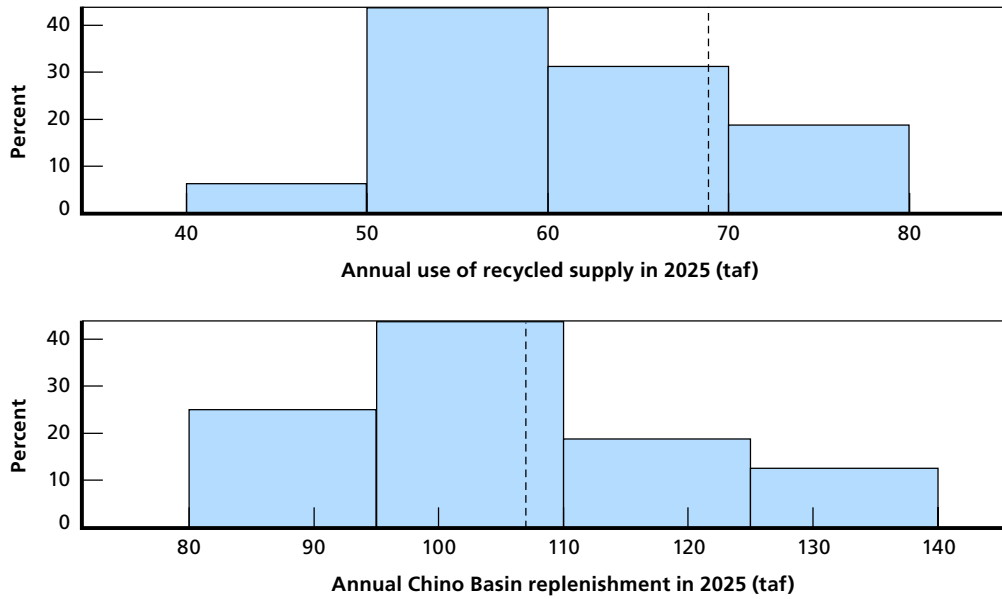
RAND TR505-3.16

Figure 3.17
Shortage Exceedance Plot for Variants on the 2005 UWMP (and Pre-2000 Plan) Under Historical Climate (MC2-A, MC3-A, MC4-A, MC5-A, MC1-P)



RAND TR505-3.17

Figure 3.18
Workshop-Participant Assessments of the Achieved Level of Recycled-Water Use and Annual Chino Basin Replenishment in 2025



NOTE: The recycled-supply goal and Chino Basin replenishment goal in the 2005 UWMP are 69 and 107 taf, respectively.

RAND TR505-3.18

Uncertainty About Future Management Conditions

The WMM is designed to reflect uncertainty about multiple aspects of future water management in the IEUA service area. For this analysis, we considered two sets of uncertainties to construct the three different types of characterizations described in Chapter Two: a smaller set for the creation of standard scenarios and probabilistic forecasts and a larger set (inclusive of the first) for the generation of the large ensemble of cases used for the policy-relevant scenarios.

For the scenario analysis, we chose two seemingly important uncertainties to vary when constructing scenarios: (1) the strength of the climate-change signal embedded in the monthly weather sequences and (2) IEUA's ability to meet its recycling and replenishment goals. The WMM addresses uncertainty about the pattern of wet and dry years and climate-induced temperature and precipitation trends through the application of different sequences of monthly weather. The first uncertainty is thus implemented by selecting weather sequences that exhibit trends in temperature and precipitation consistent with the tails of the probabilistic climate forecast generated for this study. The tails reflect values of temperature and precipitation that are different from the mean and have a lower probability of occurrence (see Figures 3.8 and 3.9).

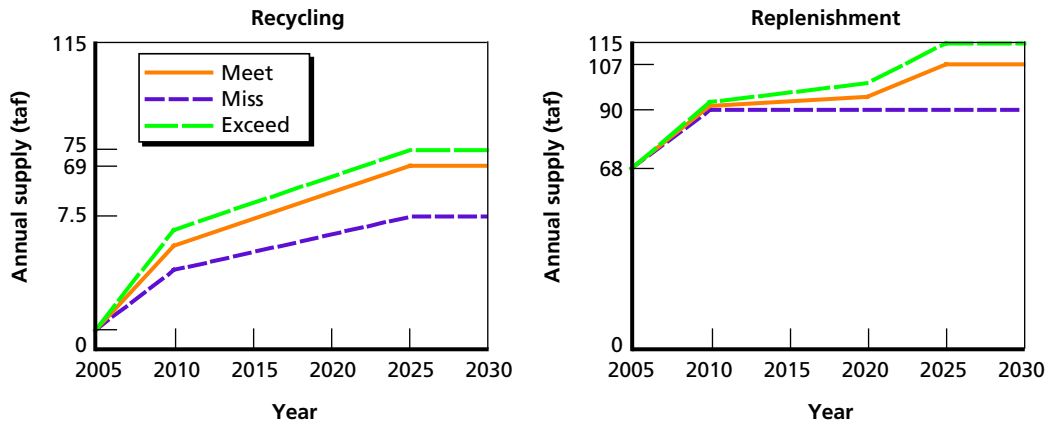
The second uncertainty is specified by constraining recycled-water supply and Chino Basin recharge demand. In the first workshop, we anonymously surveyed the participants about their estimates of what the annual recycling and GW replenishment rates would be by 2030. Figure 3.18 shows histograms of the participants' responses for annual use of recycled supply in 2025 and annual Chino Basin replenishment in 2025. Note that the recycled-supply goal in the IEUA RUWMP is 69 taf, and, thus, most participants believed the goal would not be met. The Chino Basin replenishment goal in 2025 is 107 taf, and a slight majority of the participants believed that this goal would be met or exceeded. We used these data as a basis for establishing three time sequences of recycling use and replenishment corresponding to missing, meeting, and exceeding the IEUA goals (Figure 3.19).

For the probabilistic forecast, we again considered the strength of the climate signal and levels of recycling- and replenishment-goal achievement. The climate sequences, however, are drawn from the entire range of the distribution (90 sequences across the nine climate deciles), not just the tails.

For the policy-relevant scenario analysis that considers a large ensemble of many runs of the simulation model, we considered a broader set of factors that could be considered uncertain: the specific hydrologic time series, urban water demand, supply reliability, and effectiveness of management strategies. To account for uncertainty about future urban water demand, we varied the following parameters:

- *demographic growth change*: a percentage change to the baseline growth rates of population, employment, and number of households
- *naturally occurring conservation*: change in the exogenous urban water-use intensity trends for new residential structures
- *outdoor water demand*: water-use intensity for outdoor urban irrigation as represented approximately by the leaf area index parameter.

Figure 3.19
Annual Recycling Use and GW Replenishment Under Three Levels of Goal Achievement



RAND TR505-3.19

To consider uncertainty in some key water supplies, we varied the following parameters:

- *average decline in imports due to climate change*: two parameters define the response in average imports under each climate-change effect decile—the first specifies the response under decile 9 (warm and wet), and the second specifies the response under decile 1. The responses for the other deciles are interpolated.
- *change in percolation in the urban areas*: as proxied by parameters that adjust the growth of impermeable surfaces in the urban areas of the Chino Basin.

Finally, as with the scenarios, the WMM reflects the ability of IEUA member agencies to achieve their recycling and Chino Basin replenishment goals.

Performance of Inland Empire Utilities Agency Plans Under Future Conditions

We used the RAND-IEUA WMM to evaluate how various water-management strategies in the IEUA region would perform under alternative future conditions. Consistent with the three presentations of uncertainty discussed in Chapter Two, three analyses were performed:

- *standard scenarios*. We evaluated four scenarios reflecting different assumptions about future climate and the level of success in meeting key management objectives.
- *probability-weighted scenarios*. A large set of future conditions was developed on the basis of information pertaining to their likelihood as reported in the scientific literature and surveys administered during the workshops. Single probability-weighted results were then computed for each management strategy.
- *policy-relevant scenarios*. To identify policy-relevant scenarios, we first generated a large number of simulations representing the performance of various management plans in many alternative plausible future conditions. We then used data-mining and statistical techniques in a process we call *scenario discovery* to search across the ensemble for those future conditions that lead to poor performance. These conditions are then characterized as *policy-relevant* scenarios, identified as such because of their presumptive importance in differentiating among alternative policy or management responses. We finally discuss ways of considering the performance trade-offs of various management plans across these scenarios.

Traditional Scenarios

Traditional scenarios are created using the scenario-axis technique pioneered by Schwartz (1996). Traditional scenarios are typically constructed by considering the combinations of contrasting values of two or three key uncertain factors. The art of scenario construction lies in identifying the key uncertain factors and ensuring a compelling and plausible pathway (typically described in a narrative) for such an outcome to occur. The likelihood of such scenarios occurring is typically not considered in the analysis.

Consistent with the scenario-axis technique, we examined two critical uncertainties about the performance of IEUA's water management: (1) the effect of climate change on hydrology in the IEUA region and source region of imports and (2) IEUA's ability to meet its management goals. For each uncertainty, we specified two levels, producing four discrete scenarios.

To define the uncertainty in future climate, we selected two climate time series with temperature and precipitation trends at opposing ends of the continuum suggested by ensembles of

AOGCMs. We defined two climate sequences: Slightly Warmer and Hotter and Drier (Table 4.1). To define the uncertainty about IEUA's ability to meet its goals, we chose two levels of achievement for direct use of recycled water by urban users and the annual Chino Basin artificial replenishment rate, drawn from surveys administered to the workshop participants in the first workshop (Table 4.2). We constructed four scenarios by combining each climate sequence with each level of management achievement.

We evaluated the performance of four different management strategies in the four scenarios—the 2005 UWMP and three variations that included additional management actions. The additional management actions were identified from user surveys administered during the first workshop. For one action, we adjusted the 2005 UWMP to increase efficiency improvement to 15 percent in 2015 and 20 percent in 2020. For the other, we increased the allowable amount of recycled water for Chino Basin replenishment by 20 percent (over the amount projected by the IEUA RUWMP). This action affects only years in which imported supply for replenishment is limited. With a higher allowable recycled content in replenishment, this leads to greater replenishment during years in which imports are low. Table 4.3 lists the scenarios and Table 4.4 the strategies evaluated for the traditional scenario analysis.

Figures 4.1 through 4.4 show the mix of supply delivered to meet demand (shaded areas), any available surplus (white area), and any unmet demand (black area) under the 2005 UWMP for the four scenarios. Under the Slightly Warmer scenarios, even when goals are missed by the amounts specified in Table 4.2 (S2), there are no projected shortages. Under the Hotter and

Table 4.1
Parameters Associated with Two Climate Sequences

Change (2005–2030)	Slightly Warmer	Hotter and Drier
Temperature (degrees C)	+0.7	+1.6
Precipitation (%)	+3	–10

Table 4.2
Parameters Associated with the Two Levels of IEUA RUWMP Goal Achievement

Parameter	Meet Goals (taf)		Miss Goals (taf)	
	2010	2025	2010	2025
Direct use of recycled water	39	69	30	50
Chino Basin replenishment	90	107	90	90

Table 4.3
Scenarios Used for Traditional Scenario Analysis

Abbreviation	Scenario
S1	Slightly Warmer, Meet Goals
S2	Slightly Warmer, Miss Goals
S3	Hotter and Drier, Meet Goals
S4	Hotter and Drier, Miss Goals

Table 4.4
Management Strategies Evaluated in Traditional Scenario Analysis

Abbreviation	Management Strategy
A	2005 UWMP
B	2005 UWMP + efficiency
C	2005 UWMP + replenishment
D	2005 UWMP + efficiency and replenishment

Drier scenarios, however, shortages are projected, particularly when the recycling and replenishment goals are not met (S4).

Table 4.5 provides a comparison of performance of the four strategies under the four scenarios as measured by percentage of years in which shortages exist between 2005 and 2030. In this and following stoplight charts, shading is used to signify relative desirability of the outcomes. Consistent with Figure 4.1 and Figure 4.2, no shortages are projected for plan A (2005 UWMP) under the two Slightly Warmer scenarios (S1 and S2). As plans B through D either reduce demand or increase supply (via increased Chino Basin GW replenishment), no shortages are projected for them under scenarios S1 and S2. Under the Hotter and Drier, Meet Goals scenario (S3), plans A and C lead to shortages in 19 percent and 12 percent of the years, respectively, whereas plans B and D are largely shortage free. Finally, under the Hotter and Drier, Miss Goals scenario, all plans lead to shortages, although plan D leads to the lowest frequency of shortages (15 percent). Using this metric, plan D is the best or equally as good as all other plans under all scenarios.

Figure 4.1
Delivered Supply, Surplus, and Shortages for the Slightly Warmer, Meet Goals Scenario Under the 2005 UWMP (S1-A)

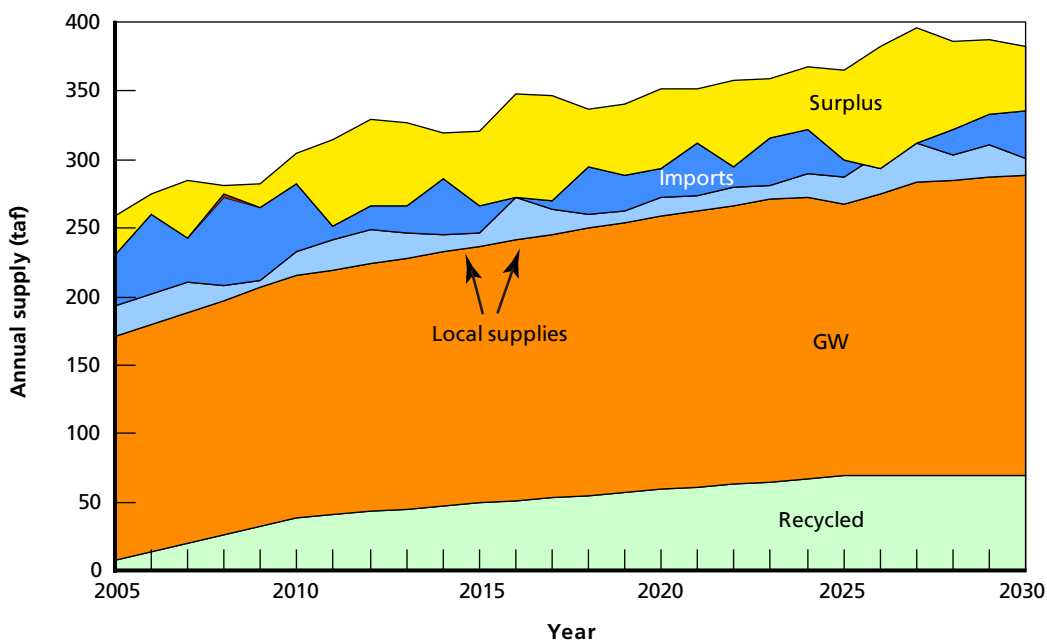
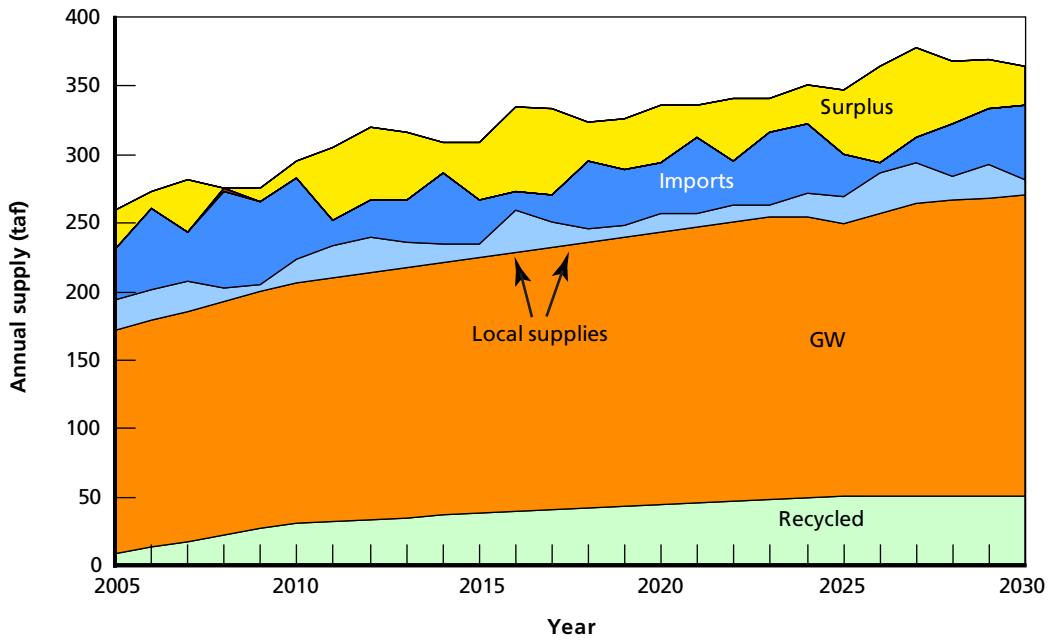
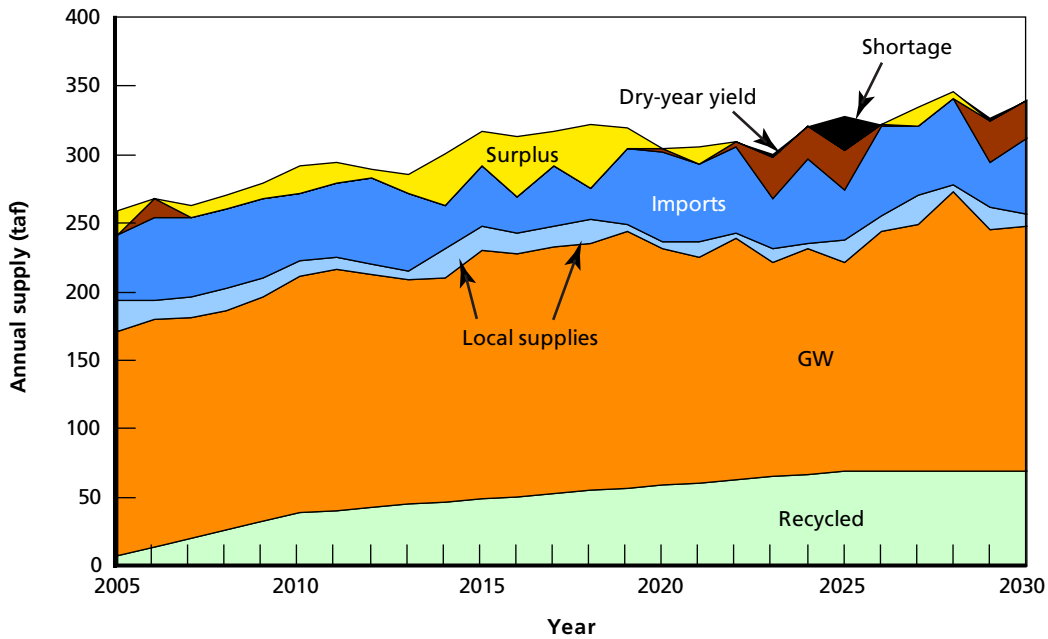


Figure 4.2
Delivered Supply, Surplus, and Shortages for the Slightly Warmer, Miss Goals Scenario Under the 2005 UWMP (S2-A)



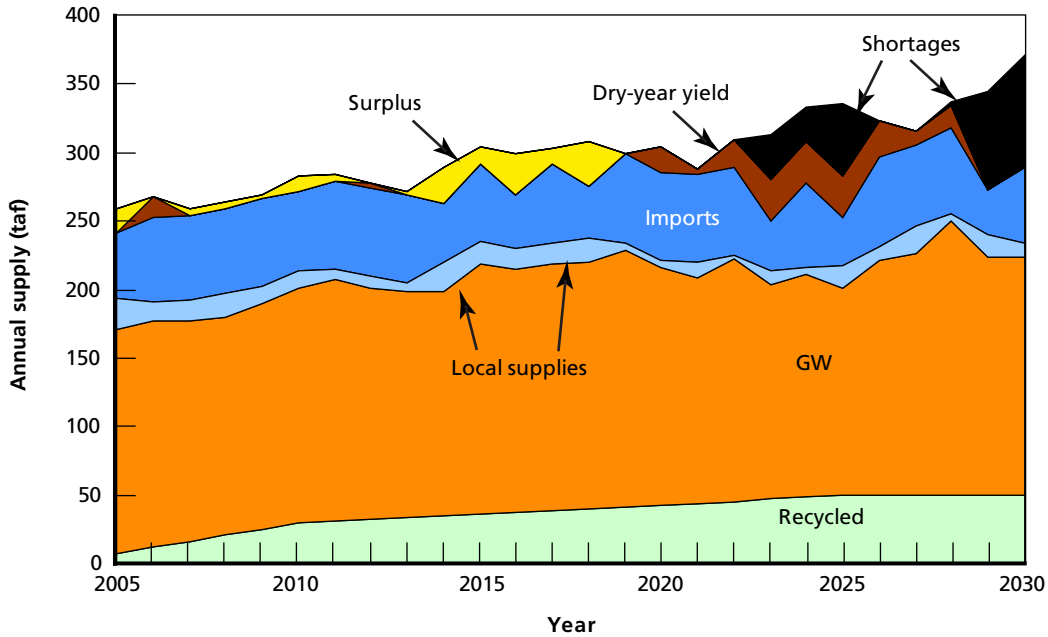
RAND TR505-4.2

Figure 4.3
Delivered Supply, Surplus, and Shortages for the Hotter and Drier, Meet Goals Scenario Under the 2005 UWMP (S3-A)



RAND TR505-4.3

Figure 4.4
Delivered Supply, Surplus, and Shortages for the Hotter and Drier, Miss Goals Scenario Under the 2005 UWMP (S4-A)



RAND TR505-4.4

Table 4.5
Years with Shortages for Four Management Plans Under Four Scenarios

Management Strategy	Scenario (%)			
	S1: Slightly Warmer, Meet Goals	S2: Slightly Warmer, Miss Goals	S3: Hotter and Drier, Meet Goals	S4: Hotter and Drier, Miss Goals
Plan A (2005 UWMP)	0	0	19	42
Plan B (+ efficiency)	0	0	4	27
Plan C (+ recycled replenishment)	0	0	12	42
Plan D (+ efficiency and replenishment)	0	0	0	15

NOTE: Cells with shortages less than 10 percent are not shaded, between 10 percent and 20 percent are shaded lightly, and greater than 20 percent are shaded darkly.

Table 4.6 shows the performance of the four plans under the four scenarios as measured by the average surplus between 2005 and 2030. Using this metric, we see that plans B, C, and D lead to large surpluses (greater than 40 taf) under the Slightly Warmer, Meet Goals scenario.¹ Using this metric, plan D is the best under S3 and S4, is about equal to all the plans under S2, but would produce substantially more water than is needed under S1.

¹ In this analysis, we suggest that outcomes with large surpluses may be considered undesirable, as they indicate unnecessary investment in capacity expansion. In follow-on analysis, we evaluated each scenario by the cost of supplying water to

Table 4.6
Average Surplus (2005–2030) for Four Management Plans Under Four Scenarios

Management Strategy	Scenario (taf)			
	S1: Slightly Warmer, Meet Goals	S2: Slightly Warmer, Miss Goals	S3: Hotter and Drier, Meet Goals	S4: Hotter and Drier, Miss Goals
Plan A (2005 UWMP)	39	26	11	8
Plan B (+ efficiency)	51	35	17	9
Plan C (+ recycled replenishment)	43	27	14	8
Plan D (+ efficiency and replenishment)	52	36	19	11

NOTE: Cells with surpluses between 20 and 40 taf are not shaded, between 10 and 20 taf and between 40 and 60 taf are shaded lightly, and less than 10 taf and greater than 60 taf are shaded darkly.

Probability-Weighted Scenarios

Our second approach to evaluating the performance of water-management actions under uncertainty was to generate a large ensemble of plausible scenarios and weight them by best-available probabilities.² As in the scenario approach, we considered uncertainty about the effect of climate change on Chino Basin weather and the ability of IEUA agencies to meet their recycling and Chino Basin replenishment goals.

We considered 90 weather sequences, 10 for each decile of the CDF developed by NCAR. We weighted each of the climate sequences according to the associated probability density functions (PDFs) for temperature and precipitation. Figure 4.5 shows these weights for winter precipitation and summer temperature. The numbers indicate the decile number—a lower decile signifies a warmer and drier sequence. As an example, a simulation based on a weather sequence selected from the second precipitation and temperature decile would be weighted about twice as much as sequences selected from the first decile (relative weights of 0.1 versus 0.05). Simulations based on deciles 4 or 5 would be weighted about five times as heavily as ones based on deciles 1 and 9.

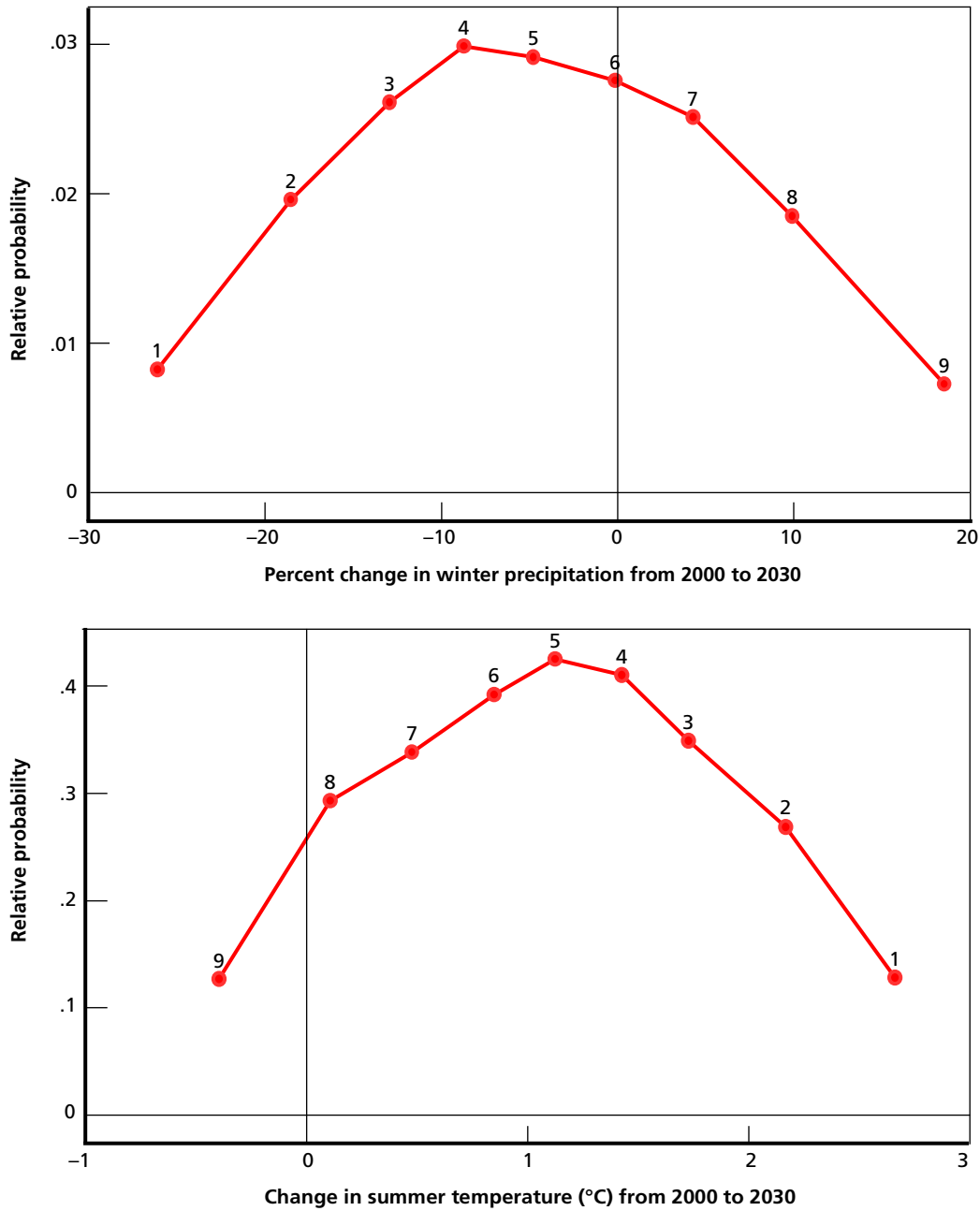
We then evaluated each of the 90 weather sequences nine different times—one for each possible combination of missing, meeting, and achieving the recycling and replenishment goals. Table 4.7 shows the relative weights that we calculated for each based on the survey information collected in the first workshop (as summarized in Figure 3.17 in Chapter Three).

Our analysis then weighted these 810 simulation results according to the joint probability of their occurring. The weights were calculated by multiplying the individual weights for the temperature and precipitation sequences and the level of achievement for recycling and replenishment, then dividing by the sum of the weights for all possible combinations. We evaluated each of the four water-management plans against the 810 probability-weighted scenarios.

the region's customers. Under this metric, surpluses may be desired if having them enables the region to reduce the use of relatively expensive imported supplies.

² Weighting a large set of simulations, each evaluated using a different value for uncertain parameters is one approach to computing a *probabilistic forecast*.

Figure 4.5
Relative Weights Applied to Numbered Weather Sequences for Winter Precipitation (top)
and Summer Temperature (bottom)



RAND TR505-4.5

Table 4.8 summarizes the results of the WMM for the 810 probability-weighted scenarios.³ The first column reports the probability of any shortage occurring, and the second column reports the probability-weighted average surplus for each of the 810 simulations. The

³ Due to time limitations between the first two workshops, we initially developed the probabilistic estimation based on only three levels of goals achievement (assuming that IEUA would miss, meet, or exceed the recycling and replenishment

Table 4.7
Relative Probability of Missing, Meeting, or Exceeding the IEUA RUWMP Recycling and Replenishment Goals

Goal Achievement	Relative Probability (%)	
	Recycling	Chino Basin Replenishment
Miss	56	50
Meet	31	31
Exceed	13	19

Table 4.8
Performance of Four Management Plans Under Probability-Weighted Scenarios

Management Strategy	Outcome Metric	
	Probability of Shortage (%)	Average Surplus (2006–2030) (taf)
Plan A (2005 UWMP)	7.0	29
Plan B (+ efficiency)	3.8	38
Plan C (+ recycled replenishment)	5.5	31
Plan D (+ efficiency and replenishment)	3.2	40

first metric indicates the percentage of years in which a shortage is experienced and is similar to reliability metrics routinely used for water planning. The second metric quantifies the average balance between supplies and demand. Greater probability of shortages often corresponds with smaller (or negative) average surpluses. According to the performance thresholds established for the standard scenario results, all four plans perform sufficiently well. One logical interpretation of this presentation of results is that each of the four plans is projected to perform well: They all have low probabilities of shortage and lead to probability-weighted average surpluses of between 20 and 40 taf. Because these results are weighted by the probabilities used to weight the scenarios, however, they could mask important outcomes that are worthy of better understanding, despite their projected low-probability of occurring.

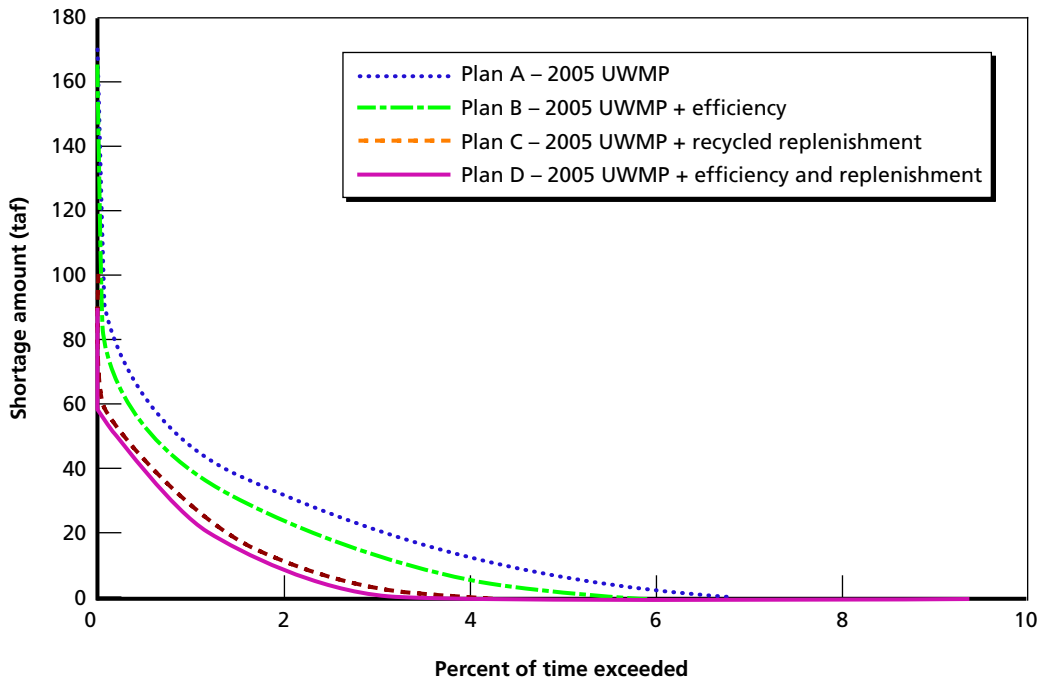
Shortage exceedance plots of these results provide more information about the range of possible outcomes. Figure 4.6 shows that, although shortages are projected to occur in only 7 percent of the years under plan A (also shown in Table 4.8), the shortages could be quite large if they were to occur. For example, according to the probabilities used in this assessment, there is a 1 percent chance of a 50-taf shortage, and the largest evaluated shortage is about 170 taf (this result occurs in one single year out of one of the 810 simulations—a 0.005 percent chance).

This calculation concurs with Table 4.8 and shows fewer shortages for the other plans over plan A. Plan B, for example, which includes additional efficiency, shows significant reductions in the magnitude of shortages. The 1 percent shortage level for plan B is only about 30 taf.

Although these results provide additional information over the simple ranking and summary information presented in Table 4.8, proper interpretation is important. For example, this

goals). We have reevaluated this estimate using all nine possible combinations of goal achievement. As a result, Table 4.8 and Figure 4.6 are different from those shown in workshop 2.

Figure 4.6
Shortage Exceedance Plots for the Four Water-Management Plans Based on 810
Probabilistically Weighted Simulations



RAND TR505-4.6

analysis assumes that the performance of the IEUA water-management system in any given year is independent of all other years. In fact, many of the shortages occur in multiple years of the same simulations. So, the IEUA region is likelier to face either no years with shortages at all or many years with shortages. A natural question, then is, which future conditions would lead to numerous shortages?

Policy-Relevant Scenarios

The last methodology used to assess the effect of uncertainty of IEUA water management was RDM. Using RDM, we evaluated the WMM over a wide range of plausible future conditions and identified a few key scenarios that were most relevant to the choice among plans. An important distinction between RDM and the probabilistic method just described is that the analysis of the results did not require a detailed assessment of the probabilities of various future conditions at the onset of the analysis. This may be an attractive feature when addressing uncertainties that are not well understood (for example, the effect of climate change on regional weather patterns).

Our RDM analysis began by generating a large ensemble of WMM simulations. Because we were not constrained by availability of probabilistic information, we could choose a larger set of uncertain parameters to evaluate. Similar to the probabilistic assessment, we evaluated 90 weather sequences reflecting the NCAR-estimated climate trends over the IEUA region.

We also evaluated the nine combinations of achievement levels of recycling and replenishment goals used for the probabilistic assessment.

We also considered three important concerns that IEUA had about future management conditions: (1) level of natural improvement in household water-use efficiency due to new more water-efficient development, (2) reduction in the permeability of the Chino Basin due to continued urbanization and increases in the intensity of precipitation events, and (3) the effect that climate change would have on imports from the SWP (Davis, 2006).

To evaluate the first, we varied the rate of water use for new households between 80 percent and 95 percent of what existing households use. To evaluate the second, we adjusted the projected increase in impermeable surfaces in the Chino Basin by up to 20 percent. Finally, for the last, we varied how much Metropolitan deliveries would be reduced under the different deciles of climate change. We considered the four plausible response relationships of Metropolitan imports to climate-change decile shown in Figure 4.7. We used a Latin hypercube (Saltelli, Chan, and Scott, 2000) quasiuniform sample over the six key uncertain parameters to generate a 900-element ensemble of simulations. These ranges were established based on conversations with IEUA staff and author judgment.

Table 4.9 summarizes the WMM parameters and ranges or values used in the experimental design.

Figure 4.7
Four Responses of Imports to Climate-Change Decile

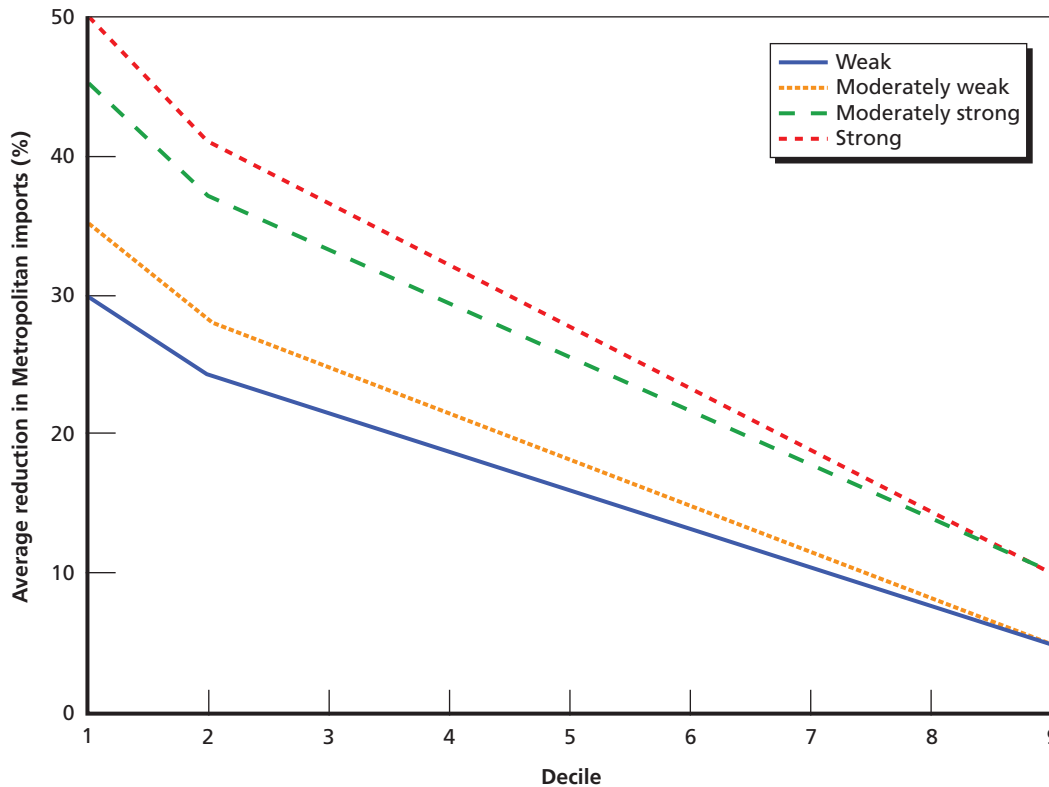
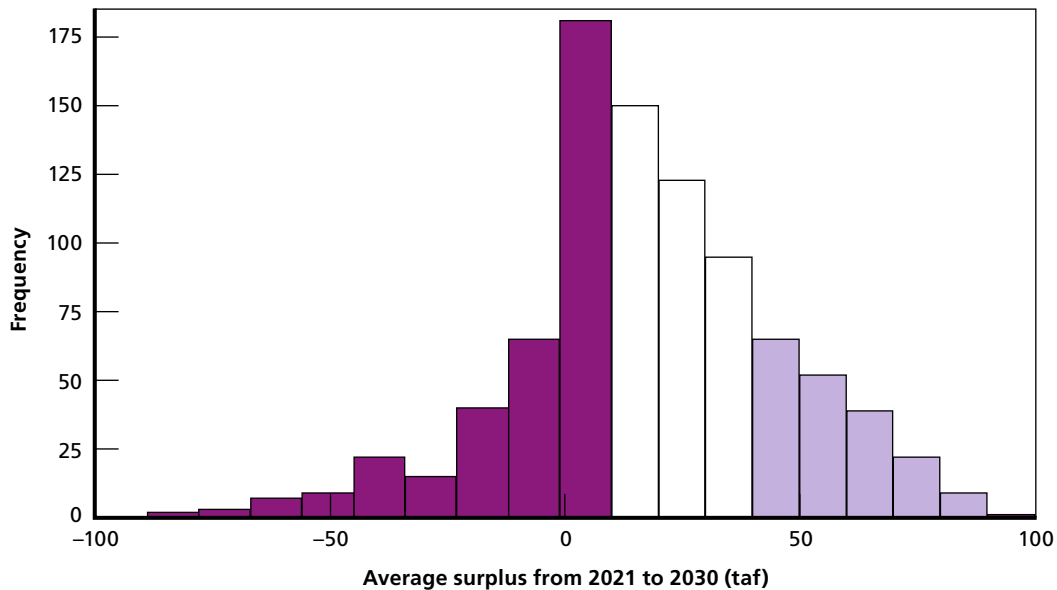


Table 4.9
Uncertain Parameters and Value Ranges Used to Generate Ensemble of Simulations for Policy-Relevant Scenario Analysis

Uncertain Parameter	Description	Values or Range Used
Future weather sequence	Sample from set of 90 discrete weather sequences	1 . . . 90
Recycling demand	Achievement of recycling goals	Miss, meet, exceed (see Figure 3.18 in Chapter Three)
Replenishment demand	Achievement of replenishment goals	Miss, meet, exceed (see Figure 3.18 in Chapter Three)
Naturally occurring conservation for new houses	Trend in water use for new households (over 25-year simulation)	-5% . . . -20%
Change in percentage of urban areas that is impervious	Decrease in percolation of precipitation in Chino Basin	0% . . . -20%
Reduction in Metropolitan imports by climate-change decile	Effect of climate change on imports	Weak; moderately weak, moderately strong; strong (see Figure 4.7)

A key objective of RDM analysis is to evaluate a broad range of possible outcomes and improve our understanding of the conditions that lead to unfavorable outcomes. Using the average surplus from 2021 to 2030 as the metric of performance, Figure 4.8 shows a frequency histogram of the performance of plan A (2005 UWMP) for the entire simulation ensemble.

Figure 4.8
Frequency Histogram of Average Surplus (from 2021 to 2030) for Plan A (the 2005 UWMP)



NOTE: The bars are shaded according to performance—dark bars represent cases in which average surplus is low (less than 10 taf), light bars indicate simulations in which average surplus is high (greater than 40 taf), and white bars indicate simulations with a more desired range (between 10 and 40 taf).

The histogram is colored to highlight those simulations in which the average surplus is too low (dark bars = 344 simulations), too high (light bars = 188 simulations), or just right (white bars = 368). As noted above, this designation assumes that any benefits that derive from having surplus water supply (such as declining high-priced imports, selling it to others, or devoting more to environmental purposes) are less desirable than forgoing the costs of developing or securing the local resources that lead to overabundance in supply. In ongoing analysis, we are accounting for some of these benefits to better evaluate a desirable level of supply development.

Following the scenario-discovery procedure outlined in Groves and Lempert (2007) and Lempert, Groves, et al. (2006), we use a cluster-finding algorithm called the patient rule induction method (PRIM) (Friedman and Fisher, 1999) to find and characterize clusters in the database of simulations that represent management conditions in which the 2005 UWMP performs poorly. PRIM is a data-mining algorithm designed to generate a set of low-dimensional boxes in high-dimensional data containing regions in which the value of a particular function is large (or small) compared to its value outside these boxes. PRIM seems particularly useful for suggesting scenarios because it aims to optimize both the classification accuracy of the boxes (the percentage of large or small function values they contain) and the interpretability of the boxes (the simplicity of the rules needed to define them).⁴

The PRIM algorithm suggests two clusters of simulations that have low performance. The first cluster, which captures 203 of 344 low-surplus simulations, is characterized by conditions in which the recycling goals are not exceeded, weather sequences are consistent with the drier deciles (1–4), and percolation to the Chino Basin decreases (as proxied by increases between 2.5 percent and 20 percent in impermeable surfaces in the urban areas) (Figure 4.9). We suggest that these ranges of input values characterize an important scenario because plan A (2005 UWMP) consistently performs poorly under these conditions, as seen in Figure 4.10. We call it the *Dry, Flashy, Low-Recycling scenario*, as it reflects conditions in which climate change reduces annual precipitation in the region, infiltration to the Chino Basin is low (due in part to more flashy storms), and recycling levels are lower than anticipated.

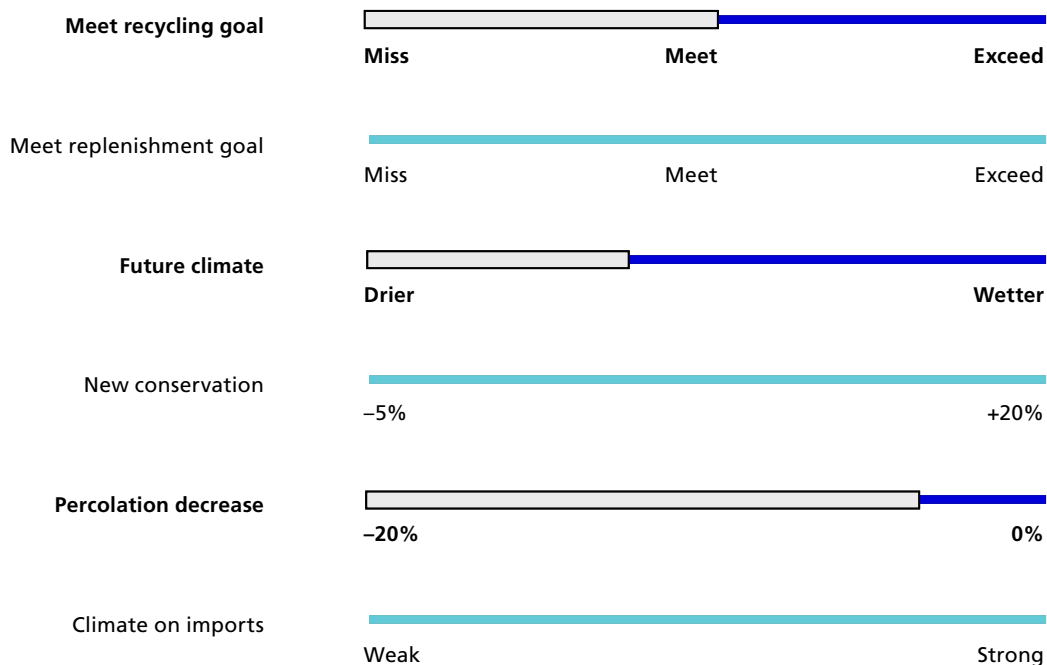
The PRIM algorithm also identifies another cluster of input-parameter values that lead to poor performance under plan A. This second cluster is defined as cases in which the recycling goals are exceeded and weather sequences are consistent with the higher deciles (8 or 9) (Figure 4.11). We call this scenario the *Wet, Effective-Recycling scenario*, and it captures 131 of the 188 high-surplus cases. This scenario leads the 2005 UWMP to consistently produce excess supplies, despite the achievement of replenishment goals, the levels of new conservation, percolation decreases, or the strength of climate change on imports.

We now have identified two important scenarios that characterize 63 percent of all the bad outcomes.⁵ All other simulations that are not members of these two scenarios can be considered a member of a third scenario, which we call *Favorable Conditions*. We then evaluated

⁴ We implement PRIM using publicly available software that inputs a data set (which can be the output of a model run over many combinations of input values) and a criterion for cases of interest. The algorithm outputs descriptions of several alternative low-dimensional regions, or boxes, that contain a high density of and span a high proportion of the interesting cases.

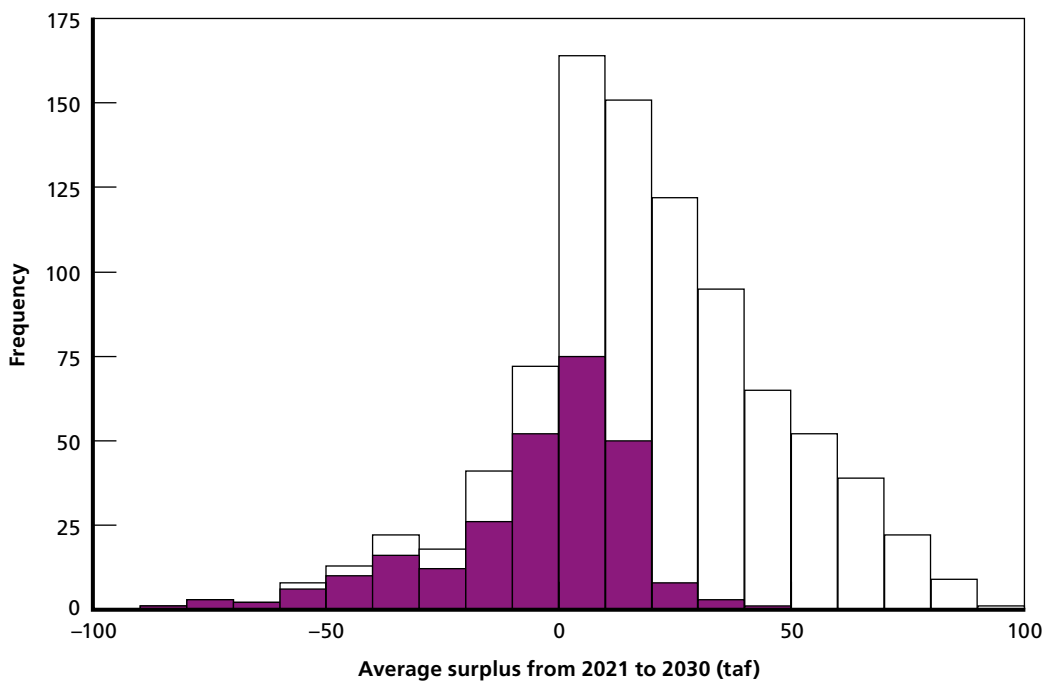
⁵ The identification of these scenarios depends on the selection of uncertain factors and the ranges of parameter values used in the experimental design. If the range used for one or more of the model parameters is unjustifiably large (or small), the scenario identified could either include parameters that are not, in fact, critical or miss other parameters that are. The strengths and weaknesses of PRIM-generated scenarios are discussed in more detail in Lempert, Bryant, and Bankes (submitted).

Figure 4.9
Parameter Ranges Specifying the Dry, Flashy, Low-Recycling Scenario



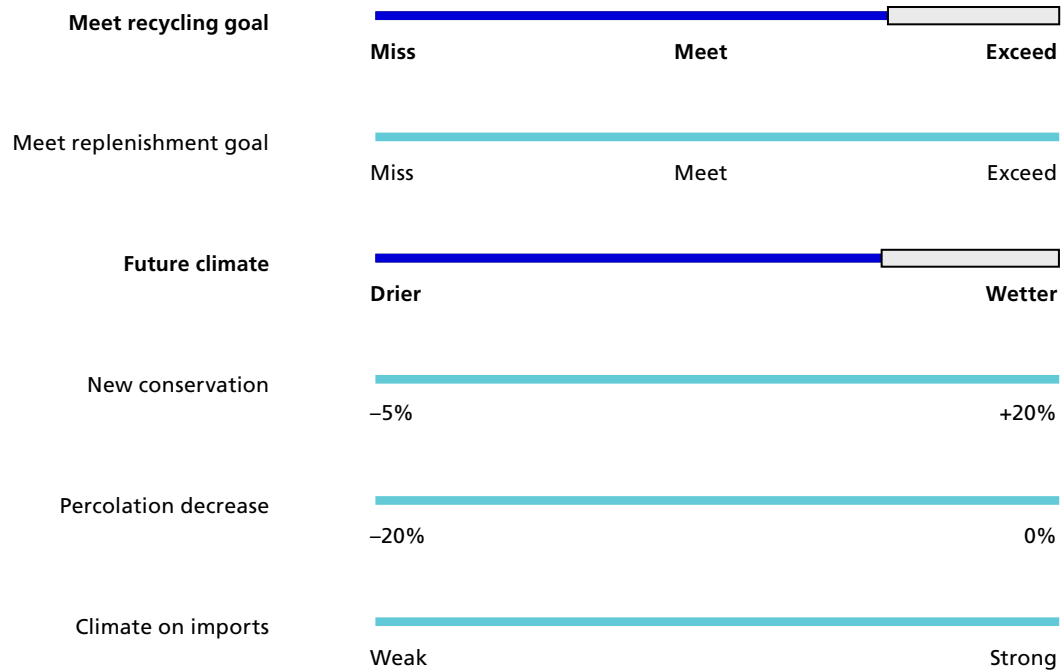
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Figure 4.10
Frequency Histogram of Average Surplus (from 2021 to 2030) for Plan A (the 2005 UWMP) Under All Modeled Conditions (white bars) and Those Consistent with the Dry, Flashy, Low-Recycling Scenario (dark bars)



RANDTR505-4.10

Figure 4.11
Parameter Ranges Specifying the Wet, Effective-Recycling Scenario



RAND TR505-4.11

the performance of all four plans under these three scenarios in terms of the average surplus from 2021 to 2030 (Table 4.10). Plan A, as expected, performs well under the Favorable-Conditions scenario (average surplus of 27 taf) and poorly for the other two (−0.3 taf for the Dry, Flashy, Low-Recycling scenario and 53 taf for the Wet, Effective-Recycling scenario). Plan C performs similarly to Plan A. Plans B and D (which include more aggressive efficiency) show significant improvements under the Dry, Flashy, Low-Recycling scenario but exacerbate poor performance under the Wet, Effective-Recycling scenario—the added efficiency leads to even greater surpluses.

Table 4.10
Average Surplus (2021–2030) for Four Management Plans Under the Three Policy-Relevant Scenarios

Management Strategy	Scenario (taf)		
	Favorable Conditions	Dry, Flashy, Low-Recycling	Wet, Effective-Recycling
Plan A (2005 UWMP)	27	−0.3	53
Plan B (+ efficiency)	42	16	68
Plan C (+ recycled replenishment)	29	5	55
Plan D (+ efficiency and replenishment)	46	20	72

NOTE: Cells with surpluses between 20 and 40 taf are not shaded, between 10 and 20 taf and between 40 and 60 taf are shaded lightly, and less than 10 taf and greater than 60 taf are shaded darkly.

These results suggest that no single plan evaluated is robust—that is, none of them performs adequately well across all three scenarios. This result is similar to that gleaned from the traditional scenarios but with two important differences.

First, the scenario-discovery process provides measures of merit for the quality of the scenarios. Because the three scenarios were developed in response to the performance of a specific plan (the 2005 UWMP, in this case), we can describe how well the scenarios characterize the risk of poor performance. In this case, we know that the two scenarios account for 334 of the 532 poor outcomes. Note that traditional scenario analysis provided no such information about the quality of the scenarios generated. The higher the proportion of bad cases covered by the scenarios, the more confident one can be that the critical risks to the management plans are characterized. The better the risks are clarified, the more useful the scenarios are for informing the trade-offs of various policies.

Second, the scenario-discovery process provides more precise information about the key driving forces that define the scenarios. As shown in Tables 4.1 and 4.2, points that combine values for four parameters define the two traditional scenarios. The policy-relevant scenarios, as shown in Figures 4.8 and 4.10, consider many more parameters and provide detailed information about which are more and less relevant to the performance of the plan. Note, for instance, that the standard scenarios do not differentiate between the importance of the recycling and replenishment goals—the policy-relevant scenarios suggest that the former are more critical to the success of the plan. The standard scenarios consider only future climate and IEUA's success in meeting its goals. The policy-relevant scenarios also suggest that decreases in Chino Basin percolation are an important determinant of future shortages. This more specific information about key driving forces may be important in helping planners from the IEUA region to understand their vulnerabilities and craft responses.

These policy-relevant scenarios suggest two alternative analytic paths. One could use the information about the plans' vulnerabilities to improve the plans. For example, efficiency appears to improve the performance of plan A under the Dry, Flashy, Low-Recycling scenario but leads to oversupply when conditions are otherwise. An improved strategy may increase efficiency but reduce investments in recycling and other supply-enhancing projects if climate-change effects appear to be more benign (more on the wet end of the range of effects—higher decile). In ongoing work, we evaluate adaptive policies that may be more robust to the critical uncertainties.⁶

An alternative is to consider just the four original plans but choose among them using the information provided by the RDM analysis. To demonstrate this simplistically, we consider only the trade-off among policies under the Favorable-Conditions scenario and the Dry, Flashy, Low-Recycling scenario. Looking at Table 4.10, it is clear that, if one were 100 percent certain that the Favorable-Conditions scenario were likely to come to pass, then plans A or C would perform the best. Alternatively, if one were 100 percent certain that the future would resemble the conditions characterized by the Dry, Flashy, Low-Recycling scenario, plan D would be the most prudent.

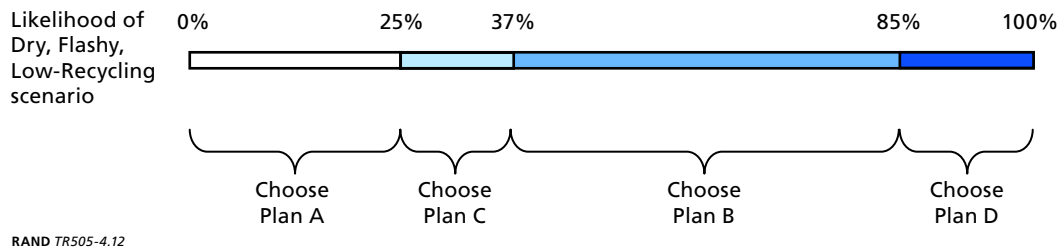
Using the data from the RDM simulations, we calculated the likelihood of the Dry, Flashy, Low-Recycling scenario that would lead a risk-neutral decisionmaker to prefer the

⁶ Such adaptive policies monitor the average surplus and trigger additional water-management actions (such as increased water-use efficiency or storm-water capture for GW replenishment) if the running average surplus drops below a threshold level. We expect that allowing for such adaptivity will enhance the robustness of IEUA plans.

other plans over plan A, assuming a goal of achieving an average surplus of 20 taf (with a preference toward not exceeding it). Figure 4.12 shows that, if the likelihood of the Dry, Flashy, Low-Recycling scenario is less than 25 percent, plan A is the best plan. If the likelihood is between 25 percent and 37 percent, plan C is the plan that would lead to 20 taf or greater surpluses without exceeding it more than necessary. Plan B would be best if the likelihood were between 37 percent and 85 percent. Finally, plan D would be best if the likelihood of the Dry, Flashy, Low-Recycling scenario were to exceed 85 percent.

This information may be quite useful to IEUA. It could now consider more carefully how likely it thinks the scenarios are. For example, it could accept the probabilistic climate-change information provided by NCAR, use the subjective assessments of the achievement levels for recycling and replenishment, and seek additional information to calculate what the probability is of the Dry, Flashy, Low-Recycling scenario. As an example of this, we used the NCAR information, the subjective assessments of recycling and replenishment, and assumed uniform distributions for percolation decrease parameter to estimate the probability of the Dry, Flashy, Low-Recycling scenario. A rough estimate suggests that it is 30 percent likely—to the right of the tipping point between choosing plan A and plan C shown in Figure 4.12.⁷

Figure 4.12
Representation of Optimal Plan Choices Under Different Subjective Assessments of the Likelihoods of Future Conditions Being Consistent with the Dry, Flashy, Low-Recycling Scenario, Assuming a Desired Surplus of 20 taf



⁷ The probability of a Dry, Flashy, Low-Recycling scenario (30.3 percent) is calculated as the joint probability of being in the driest and hottest four deciles (41 percent, Figure 4.5), the IEUA region not exceeding its recycling goals (87 percent, Table 4.6), and the Chino Basin percolation rates decreasing by more than 3 percent (85 percent, assuming a uniform prior rate between 0 percent and 20 percent).

Evaluating Uncertainty Frameworks in Workshops

In the previous chapter, we described our approach to modeling supply and demand relationships within the IEUA service area between the present and 2030 under varying assumptions about future climate and management success in meeting goals for GW replenishment and enhanced water efficiency. We used three approaches to representing climate and management uncertainties: a few traditional scenarios without probabilities, long-term probabilistic forecasts, and policy-relevant scenarios.

In this chapter, we examine how decisionmakers and stakeholders associated with IEUA assessed the value of the three approaches to accounting for uncertainty in future conditions and outcomes. Through a series of three workshops at IEUA headquarters in Chino, California, we presented information about uncertainties and system performance to water managers and planners, local officials, and others. The presentation is included in Appendix A (Groves et al., 2008a).

We were interested in understanding participants' views about the credibility of the methods, ease in interpreting results, effects of the methods on their confidence in the current management plan, and perceptions of vulnerability of the system to the prospect of persistent supply shortfalls. We used a paper-based survey approach to record responses from workshop participants before, during, and after each of the three workshops held between September and November 2006.

This chapter is organized as follows. We first provide an overview of our field test of our three approaches to representing uncertainty in a decision-support modeling framework. Next, we examine the literature on measuring effects of decision tools on decisionmaking, then present the measurement approach adopted for this study. Finally, we present results of the workshop surveys and discuss possible interpretations and limitations of the findings.

Study Design

We characterize our study design as a quasiexperimental field test of the relative merits of providing information about IEUA's future system performance using three characterizations of uncertainty. For simplicity, we refer to these approaches as *decision aids*, because each provides decisionmakers with a means of relating the effect of large uncertainties about the future on projected future performance of the water system. We call the design *quasiexperimental* because it represents a compromise we chose to make between carrying out a design that allows a clear causal inference (i.e., internal validity) of our test methods and our interest in fully engaging with workshop participants to address their real-time concerns about planning under

uncertainty (i.e., external validity). We approached this study from an exploratory design and modeling perspective; our intention was to learn from the workshop experience, then refine our methods of evaluation in subsequent work.

To maximize internal validity in a design, we would normally seek to randomly assign workshop participants to one of the three experimental treatments, which means, in this case, one of the decision aids used to represent uncertainties in IEUA's system performance in the future. In contrast, to maximize external validity, we would prefer to work directly with actual water managers, who would use decision aids to make water plans and policy. Our design represents a trade-off between the two, necessitated by practical considerations. It was not possible to randomize groups of actual water managers and gain their agreement to participate. Moreover, splitting up groups of managers who normally work together would have disrupted the relationships through which decisions are made.

Instead, we developed a quasiexperimental design that presented decision aids during three workshop sessions in a sequence of decreasing order of familiarity and increasing order of complexity, shown in Table 5.1. We started with the few traditional scenarios without probabilities and continued to the most complex and unfamiliar, the policy-relevant scenarios derived from examining many scenarios without probabilities (an analytical predicate to the application of a robust decision criterion). By following this progression of decision aids in a series of workshops, we were, in a sense, using participants in the prior workshop as a form of a control group for the next workshop. This allowed us to work with actual water managers and other interested parties in a way that was efficient and logical to them, while still observing the incremental effects of each treatment in relation to the prior treatment. However, this design implied that, for most of the participants, the effects of the workshops were cumulative. Each new presentation was necessarily affected by the previous presentations. Our compromise approach also enables us to continue to observe the influence of the decision aids after the workshops on IEUA's and stakeholders' decisionmaking through subsequent monitoring of key reports from the IEUA and observations of their meetings and deliberations.

Overview of Workshop Participation

Working with the staff of IEUA, the RAND team conducted a series of three workshops that took place on September 28, October 20, and November 3, 2006. In total, 40 people attended at least one of these workshops and filled out at least one questionnaire: 31 attended workshop 1 (W1), 23 attended W2, and 18 attended W3. Among the attendees in W3 were four students. We excluded their responses from our analysis. Seven people attended all three workshops.

Table 5.1
Overall Presentation Structure for the RAND-IEUA Workshops

Workshop	Traditional Scenarios Without Probabilities	Long-Term Probabilistic Forecasts	Policy-Relevant Scenarios (Derived from RDM)
1	Presented	—	—
2	Reviewed	Presented	—
3	Reviewed	Reviewed	Presented

The RAND team and IEUA extended invitations in the summer to senior managers and board members in IEUA and other water agencies in IEUA's service area. In addition, some elected officials were invited, along with technical consultants and representatives from southern California water agencies and state-level water planners. We were interested in how attendees characterized their job titles and roles in their respective institutions. Most attendees classified themselves as managers or directors (55 percent). The remainder classified themselves as planners (13 percent), public officials or consumer representatives (10 percent), or other (23 percent). Most attendees were professionally involved in water management. Twenty-three percent said that they spent all their time on planning water resources in southern California, and 21 percent spent most of their time in water management. Table 5.2 indicates the distribution of participants by self-described job titles over the three workshops.

Of the rest, almost half (49 percent) said that they spent from a little of their time to half time on water-management issues, and only 8 percent spent almost no time on water management. Since the workshop was based on IEUA's water planning, we asked how familiar they were with the existing water-management plans; the levels of familiarity varied. Thirteen percent were involved in developing them, and 5 percent had used them extensively. Eighteen percent had read one or both of the plans, and 25 percent said that they were familiar with the basics of the plans. Twenty-eight percent had little or no familiarity with the existing IEUA water plans.

Of the seven who attended all three workshops, four were managers, two were planners, and one was an other. Three spent more than half time on water management, three spent less than half time, and one spent almost no time on water-management issues. While one was involved in developing the IEUA plan, the rest were only somewhat or not at all familiar with the plan. Many of the participants in the first workshop who classified themselves as managers did not return for the second workshop. While the first workshop was held directly after another meeting that they attended at the IEUA headquarters, the other meetings were not and may have been more difficult to fit into their schedules. Naturally, some participants found the workshops more to their liking than others, and this self-selection for continued participation may have affected our results, though we cannot determine in what direction.

Qualitative results (responses to open-ended questions) indicated that participants came to the workshops seeking information about the future and the challenges they faced. Many saw this in general terms, for example, "an idea of the potential range of changes IEUA could face" and "a better understanding of water issues in the Chino Basin." Others were more specific: "(1) [a]n evaluation of how resilient our water plans are and (2) [w]hat factors and steps we should consider to further prepare for climate change." Another was looking for "[a]n

Table 5.2
Summary of Workshop Attendees Who Provided Data (Excluding Students)

Role	W1	W2	W3
Manager or director	18	10	6
Planner	3	5	4
Public official	4	1	0
Other or missing	6	7	4
Total	31	23	14

understanding of planning tools and processes that can and should be included in regional integrated water resource plans [and an] understanding of the potential risk and impact on water resources in [southern California].” Nearly all the responses to the question about what participants hoped to gain from the workshops were in this vein. This was clearly a sophisticated and enlightened group from the outset, looking for new information.

Measuring the Effect of Decision Tools on Decisionmaking: Review of the Literature

In designing the outcome measures for this experiment, we looked at several kinds of literature to suggest possible frameworks for measurement. These included literature on the use of system analysis in policymaking and literature on decisionmaking in relation to risks by managers. We drew on both these literatures in preparing the IEUA workshops. In addition, as described in Chapter Two, the experimental design of the workshops draws from our laboratory JDM psychology experiments on how alternative decision aids affect individuals’ choices when faced with deeply uncertain conditions.

System Analysis

Beginning in the early 1960s, methodologically powerful system-analysis methods came into wider use in policymaking. The single best example in the water-resource field is embodied in the Harvard water project (Maass et al., 1962). This work pioneered the use of system analysis, simulation modeling, and multiobjective decisionmaking methods as a way to structure the evaluation of complex public decisions. Many other types of applications of similar methods in different fields followed, but there was relatively less intellectual development in the field of evaluation of effectiveness of these kinds of methods on actual decisions and decisionmakers.

Goeller (1988) suggested that the effectiveness of system analysis could be judged by three criteria: analytic success, utilization success, and outcome success. Analytic success includes technical validity, or the use of sound methods, and persuasive validity, which includes cogent and clear presentation, credibility, timeliness, pertinence, and usefulness of the analytic results for decisionmakers. Utilization success is concerned with whether and how the analysis results were used and by whom. Possible uses include problem formation, generation of alternatives, estimation of consequences, and rejection of alternatives. Outcome success is concerned with what happens to the problem situation as a consequence of the use of analytic results.

We viewed the use of modeling in water planning in IEUA as similar to the kinds of system planning that was carried out in the projects that Goeller (1988) reviewed two decades ago. These included the San Diego Clean Air Project (SANCAP) and two projects carried out for the government of the Netherlands, the Policy Analysis of the Oosterschelde (POLANO) and the Policy Analysis for Water Management in the Netherlands (PAWN). For this reason, we chose to adopt some of Goeller’s suggestions about metrics for evaluation of such analyses in our workshops’ survey instruments.

Management Risk Taking

Kahneman and Lovallo (1993) discussed a cognitive perspective on management decisions in organizations. Their concern was with management of for-profit businesses. Water management is somewhat different but shares some similarities. They described managers as seeing risk

as a challenge that can be overcome by skills. Managers see themselves as prudent and determined agents, in control of people and events. They tend toward an optimistic denial of uncontrollable uncertainty that allows them to see themselves as prudent risk-takers, not gamblers.

March and Shapira (1987) discussed biases to which managers are subject. These include underweighting the value of probable gains in relation to sure ones, risk aversion when subject to frequent review, aversion to loss, and reluctance to take on responsibility for a small increase in the probability of a disaster. They described managers as tending to narrow framing, the tendency to see each problem as unique, rather than as part of a class of problems. They described managers as tending to prefer the inside view rather than the outside view. The inside view allows the manager to consider the case at hand, to plan, and to focus on scenarios of future success. The outside view is focused on the statistics of a class of cases similar in relevant respects to the current one and taking a comparative approach. The inside view is intuitive and natural, attempting to come to grips with uniqueness of the problems and capabilities of people. The statistical view is often seen as inappropriate for a particular case, a poor comparison, and they point out that facing facts can be demoralizing.

We saw the use of our third treatment (policy-relevant scenarios) and the decision criterion of robustness in particular as a form of outside view and considered the possibility that use of this RDM approach would reduce optimistic bias, reduce the tendency to see problems as unique, and increase willingness to accept the possibility of losses and take reasonable risks.

Results

Our primary goal in conducting analyses was to measure change in participants' attitudes in relation to the different workshop presentations of uncertainty, summarized in Table 5.1. With a sample size of between 15 and 30 for each workshop, we could not find comparative differences that reached statistical significance except for a few comparisons (as would be expected by chance). Therefore, in reporting results, we are presenting trends that are not statistically significant. Nevertheless, some of the trends are interpretable and can be viewed as suggestive rather than as evidentiary.

In this section, we present results in four categories of measurement:

- climate change: perceptions of the problem and expectations about its effects
- uncertainty: preferences for presentations of uncertainty (a few traditional scenarios without probabilities, a single probabilistic forecast, policy-relevant scenarios)
- risk reduction: willingness of managers and planners to take risks and their preferences for specific measures to reduce risk of persistent supply disruptions
- modeling: relevance, accessibility, and utilization potential of quantitative models for planning and decisionmaking

Perceptions of Climate Change

We asked participants about their perceptions of climate change at the beginning of the first workshop to establish a baseline, and then again at several points during the workshops. The survey question read, "Climate change is something that is being discussed a lot in the scientific literature and in the general press and we'd like to have your opinions about it. Please rate how much you agree or disagree with the following statements [about] climate change."

Each statement was rated on a five-point scale from 1 (agree strongly) to 5 (disagree strongly). Results in figures 5.1–5.4 are shown in pairs: before W1 and after W3. The horizontal lines show the mean response, and the length of the vertical lines corresponds to one standard deviation above and below the mean response.

In the baseline evaluation shown in figures 5.1–5.4, participants agreed somewhat that short-term climate changes were possible and agreed less that climate change would be slow. However, they felt that they would have warning of climate change. By the end of the third workshop, they were less likely to see climate change as a slow process and to feel that they would have warning and likelier to feel that climate change could be upon them before they were aware of it. None of these differences was statistically significant in relation to the size of the samples we observed. We did, however, describe the potential for abrupt climate change in the review of climate science in the first workshop. In addition, this tendency of participants to see climate change as a faster process could be consistent with a hypothesis that planners are more willing to acknowledge risks that they feel they can effectively address. Having demonstrated in the workshops that IEUA could go a long way toward addressing future climate effects by implementing its current plan, IEUA decisionmakers and stakeholders might have been more willing to accept those climate effects as a serious possibility.

At baseline, we also asked participants about their sense of responsibility for planning water supplies in the future, focusing on periods from five to 250 years in the future, as shown in Figure 5.5. For each period, we asked whether they felt completely responsible to not at all responsible, on a 1–5 scale. Clearly, participants felt significantly more responsible for the immediate future than they did for the distant future, and this relationship did not change

Figure 5.1
Responses to Statement “Climate change is a very slow process that occurs over thousands of years.”

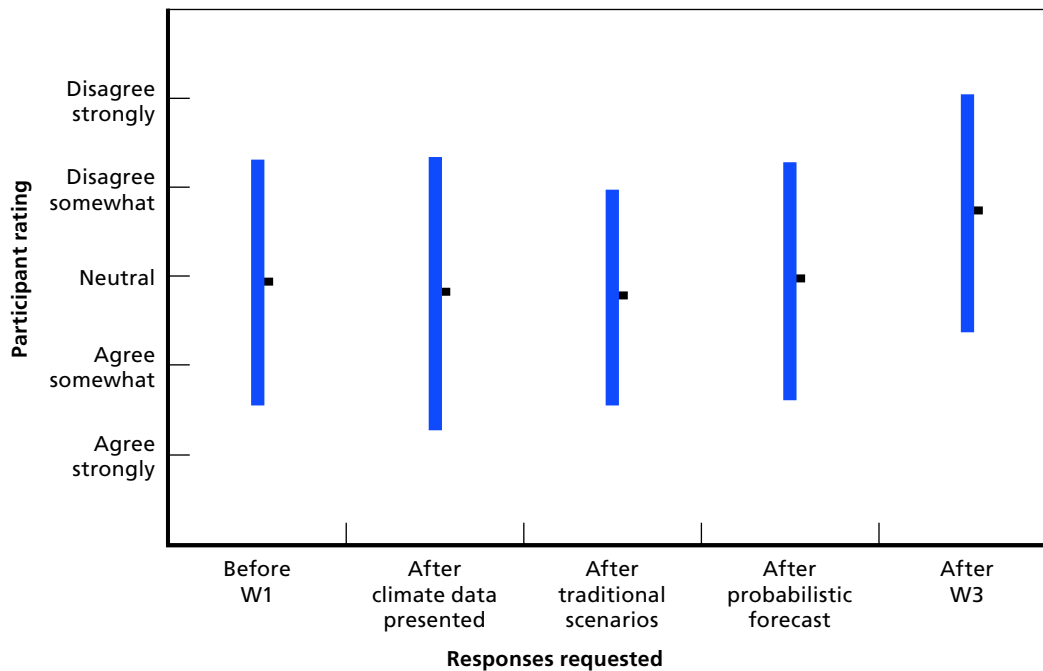
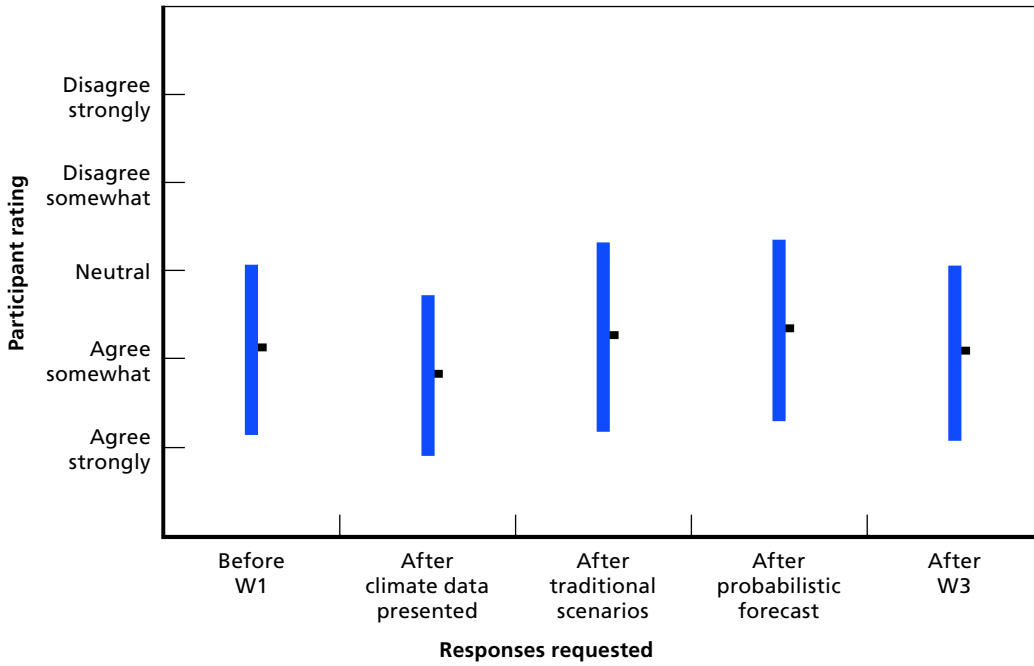
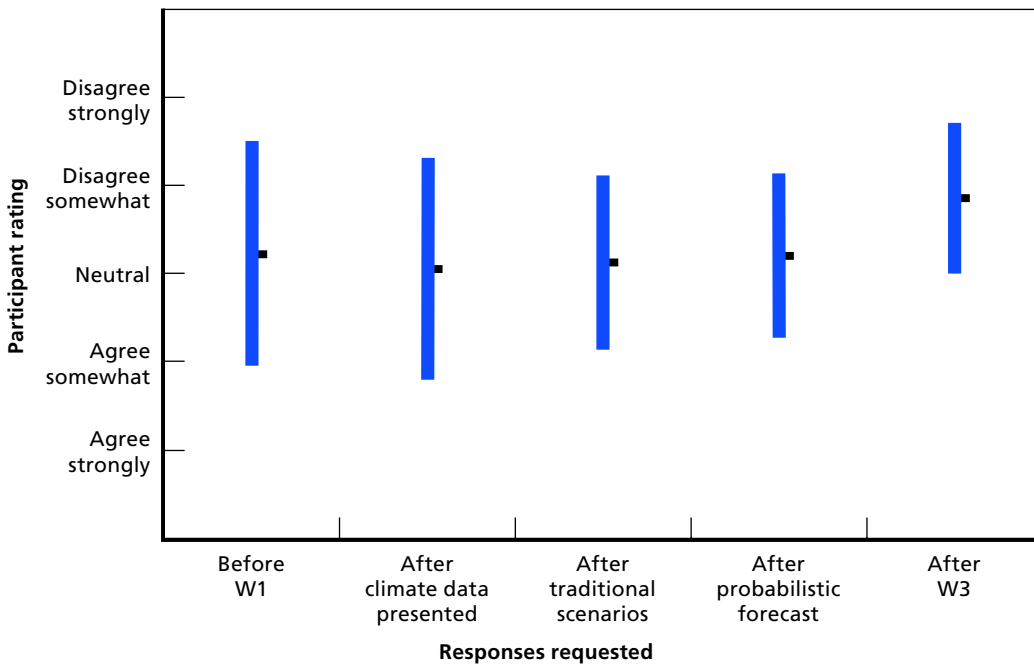


Figure 5.2
Responses to Statement: “Substantial climate changes over a period of 5–10 years are very possible.”



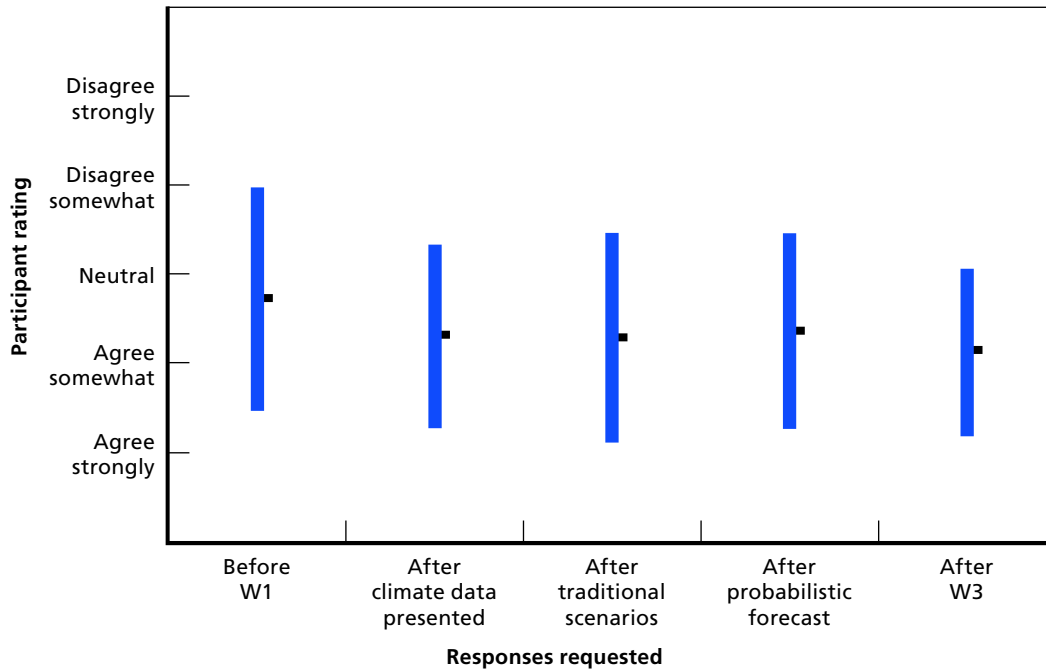
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Figure 5.3
Responses to Statement: “We are likely to have plenty of notice that climate change is happening.”



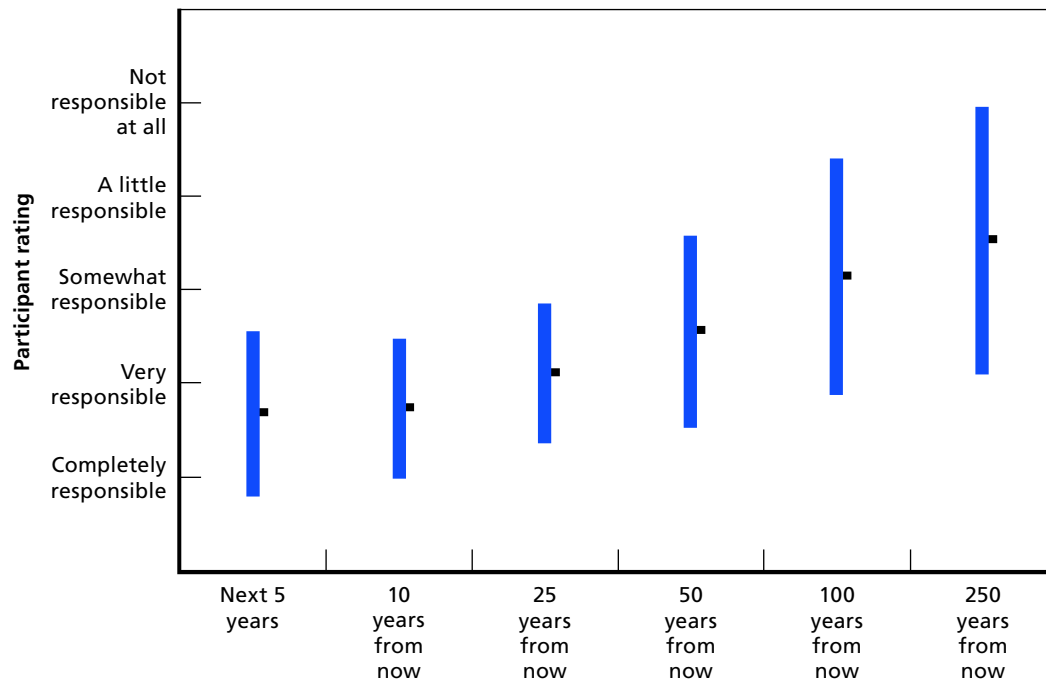
RAND TR505-5.3

Figure 5.4
Responses to Statement: “Climate change may be upon us before we know it is happening.”



RAND TR505-5.4

Figure 5.5
Participants' Perceptions of Responsibility for the Future



RAND TR505-5.5

from baseline to after the third workshop. Overall, participants in the last workshop rated themselves as slightly less responsible overall than did participants in the first workshop, although the difference is very small. In part, this may have been influenced by the focus in the workshops on a relatively short interval, to 2030. In fact, one of the participants noted in the comments, “What about 50–100 year climate models? Decisions can be made now to respond to greater climate change in the distant future more effectively than later. Is 2030 a reasonable time frame to look at?” Alternatively, the workshop results suggested that the IEUA region could become significantly more robust against a wide range of future climate-change scenarios by successfully achieving the agency’s challenging near-term goal for an almost three-fold increase in its use of recycled water. Given a not-unreasonable expectation that the biggest risks to public acceptance of a new recycling program would come in its early years, an appropriate response to the information presented in the workshop might be to increase one’s focus on the near term.

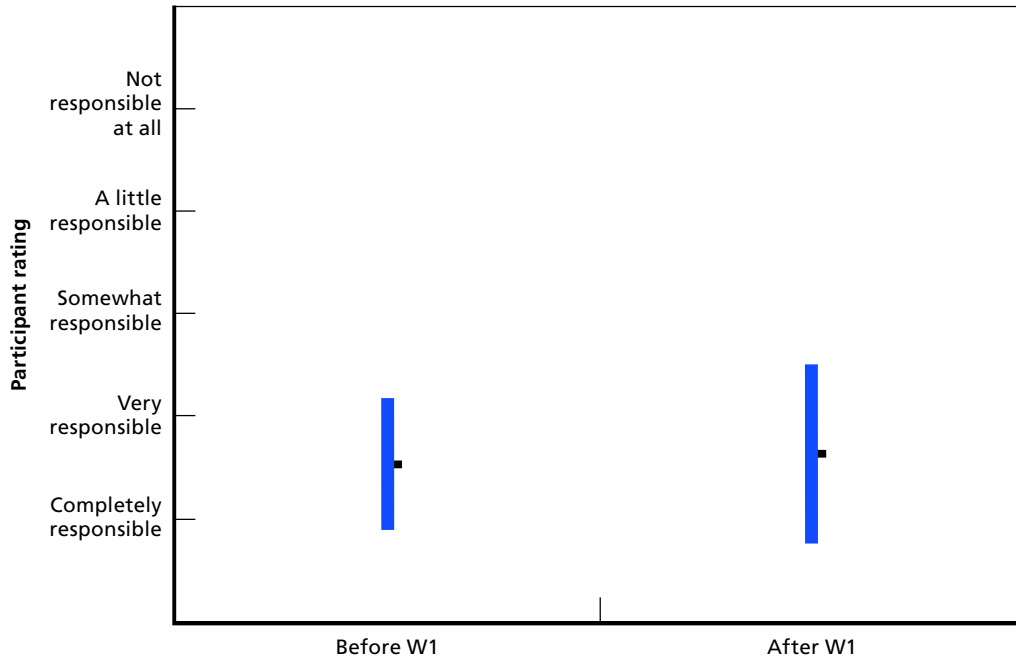
In addition to asking for a general sense of responsibility for water supplies in the future, we also asked how they thought climate change might affect water management in southern California. We provided a series of five statements with which they could agree or disagree. While, again, differences are small, the trend is that scores at the first workshop indicate less belief that planning for climate change is feasible than do scores after results are presented. Participants were likelier to disagree with statements indicating that it was not possible to plan water supplies to respond to climate change after the workshops and likelier to agree that it is possible to plan and that there are things that should be done. Generally, the largest changes occurred between baseline and the measures after W1, during which we presented an assessment of the current IEUA plan and how it would fare under some assumptions about climate change. Figure 5.6, for example, shows a slight increase in the mean belief that there are things we can and should do despite an incomplete understanding of climate change. This would have bolstered the view that the plan was robust and made participants more confident about it.

Preferences for Presentations of Uncertainty

At the end of W2 and W3, we asked participants in these workshops to specifically rate each of the approaches for characterizing uncertainty about potential effects of climate change on IEUA’s plans and potential alternatives. For this item, we asked participants to use a four-point scale, so the values 1 and 2 indicate agreement and 3 and 4 indicate disagreement (Figure 5.7).

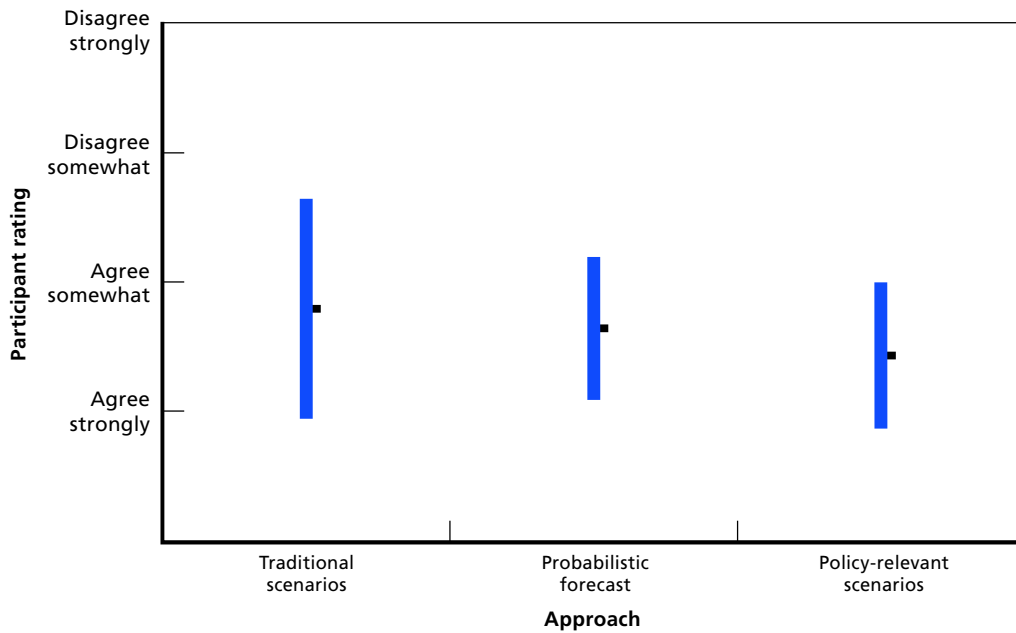
In both groups, the participants found the traditional scenario approach the easiest to understand and to explain to decisionmakers, and they found that it conveyed information in the most objective way. However, they felt that it did not convey as much information for planning purposes in general or to specifically evaluate the IEUA plans. W3, during which the concept of policy-relevant scenarios was presented for the first time, allowed a full comparison across all the three approaches. The same relationship was observed in terms of ease of understanding and explaining of the traditional scenarios approach, but, as the complexity of the presentation increased, the more participants thought they were receiving useful information for planning and for making choices. The policy-relevant scenario approach was rated as most difficult to understand and explain but as providing the most valuable information for planning, comparing climate-related risks, and for making choices among plans.

Figure 5.6
Participants' Responses to Statement: "There are things we can and should do despite an incomplete understanding about the effects of climate change."



RAND TR505-5.6

Figure 5.7
Comparison of Approaches to Presenting Scenarios After Workshop 3: Responses to the Statement: "Provides results that can be used in planning."



NOTE: Values of 1 or 2 indicate agreement.

RAND TR505-5.7

Managing Risk

When water managers and planners concern themselves with uncertainty in future supply and demand projections and the external conditions in which they operate, they are managing risk: the product of the probabilities of threat and vulnerability of major, sustained shortages and the consequences of those threats coming to pass, given the vulnerability of the plans. In the context of the three IEUA workshops, we sought to understand participants' attitudes toward managing and ultimately reducing risks.

Management Risk Taking. We developed new measures to operationalize the constructs that were suggested by the management literature referenced earlier in this chapter. These measures were collected twice, during W1 (baseline) and at the end of W3. The items were measured on a 1–5 scale, where 1 indicated strong agreement and 5 indicated strong disagreement. Items A (“Uncertainty is inevitable, but a well-managed organization can deal with it effectively”) and F (“Even good management can’t guarantee against bad outcomes in uncertain situations”) measure the belief of managers that they can handle risk. The items queried are summarized in Table 5.3.

Participants tended to agree that organizations are generally able to handle risk and to be slightly less certain of that after the workshops, in line with expectations. Items B (“Making

Table 5.3
Scales for Measuring Management Risk Taking

Measure	Statements About Management Risk Taking
Belief that he or she can handle risk	<p>A. Uncertainty is inevitable, but a well-managed organization can deal with it effectively.</p> <p>F. Even good management can’t guarantee against bad outcomes in uncertain situations.</p>
Willingness to take risks	<p>B. Making the wrong call in an uncertain situation can be a career ender.</p> <p>H. “Win a few, lose a few” is a good philosophy to have when making decisions in uncertain situations.</p> <p>L. When the result could be a disaster, even small increments in risk are unacceptable.</p>
Willingness to rely on models in making decisions	<p>C. I would advocate changing strategy based on the results of a good quantitative model.</p> <p>K. Modeling is a useful exercise, but in the end managers have to go with their instincts.</p> <p>I. Promoting a high-cost strategy on the basis of a quantitative model is difficult to defend.</p>
Perceived uniqueness or similarity of situations that managers encounter	<p>D. When considering uncertain situations, each one is unique and has to be considered on its own merits.</p> <p>J. Looking at the outcomes from similar situations in the past is a good guide to the future.</p>
Willingness to make adaptive changes as situations develop	<p>E. Picking a strategy and sticking with it is the right approach in uncertain situations.</p> <p>G. In uncertain situations it’s important to continually review results and change course if things are not going well.</p>

the wrong call in an uncertain situation can be a career ender”), H (“‘Win a few, lose a few’ is a good philosophy to have when making decisions in uncertain situations”), and L (“When the result could be a disaster, even small increments in risk are unacceptable”) measure the willingness to take risks. In items B and L, participants agreed only slightly that taking risks would be difficult, and, in item H, they tended to disagree with the “win a few, lose a few” philosophy. They were slightly less risk averse after W3, in line with expectations.

Items C (“I would advocate changing strategy based on the results of a good quantitative model”), K (“Modeling is a useful exercise, but in the end managers have to go with their instincts”) and I (“Promoting a high-cost strategy on the basis of a quantitative model is difficult to defend”) measured willingness to rely on models in making decisions. While item C shows less willingness to rely on models after the workshops than before, items K and I show more willingness to rely on models after the workshops, and item K indicates that participants were significantly less likely to prefer managerial instinct over modeling. Items D (“When considering uncertain situations, each one is unique and has to be considered on its own merits”) and J (“Looking at the outcomes from similar situations in the past is a good guide to the future”) measure perceived uniqueness or similarity of situations that managers encounter. Participants tended less to see their situations as unique after the workshops. Items E (“Picking a strategy and sticking with it is the right approach in uncertain situations”) and G (“In uncertain situations it’s important to continually review results and change course if things are not going well”) measured willingness to make adaptive changes as situations develop. Participants tended to see that as more valuable after the workshops than they had before.

This provides general support for the view that modeling (including the different approaches to uncertainty presented in these workshops) tended to make managers less confident about their management ability in the face of uncertainty, more willing to take risks, less willing to rely on their instincts and more willing to use models, less inclined to see situations as unique, and more willing to make adaptive changes. Thus, these measures provide some support for the desirability of seeking improvements in management of risk and uncertainty through the use of modeling.

Preferences for Risk-Reducing Measures. We asked participants at various points about their views of the importance of actions or policy measures that might lead to more reliable water supplies provided by IEUA. Responses from W1 and W3 are summarized in Table 5.4. Participants were asked to evaluate each action as a must-do, high priority, moderate priority, low priority, or not worth doing, and we calculated mean scores for each action. (Due to an oversight, the initial list of items was incomplete and was changed after the first workshop.) Mean scores for some of the actions, for example, promoting water conservation through public education and promoting California-friendly landscaping, received mean scores equivalent to a rating of high priority as did efforts to increase use of storm water. Carrying out these actions along with increasing basin retention and beneficial use of storm water are key to the existing IEUA plans, and each was rated as a must-do.

Next in priority were measures related to banking excess wet-year supplies and new construction, including requiring dual plumbing and use for recycled water in new developments. These received mean ratings equivalent to scores of must-do to high priority. Also rated as high priority were increasing GW recharge, construction of new transmission lines for recycled water, construction of new GW-desalting plants, enacting tighter appliance standards, and improving the basin’s permeability to increase GW recharge.

Table 5.4
Scales for Measuring Preferences for Risk-Reducing Measures

Priority	Risk-Reducing Measures
Must-do	Promote water conservation through public education
	Promote and subsidize California-friendly designs for housing and landscaping
	Increase basin retention and beneficial use of storm water
Must-do to high	Bank excess wet-year supplies in GW basins
	Require dual plumbing for recycled use in new developments
	Require use of recycled supply in new developments
High	Increasing GW recharge using injection wells or other means
	Construct new transmission lines for recycled water
	Construct new GW-desalting plants
	Improve permeability to increase GW recharge
	Enact tighter appliance standards
Moderate	Require white- and gray-water piping in new developments
	Make zoning changes to reduce landscaping demands
Moderate to low	Increase water rates to reduce demand
	Make plans to increase imports of water
	Introduce recycled water directly into the water supply
	Slow new development through zoning changes
Not worth doing	

Taking more intrusive measures was viewed with less enthusiasm and was rated as closest to moderate priority. These include requiring white- and gray-water piping in new developments and implementing zoning changes to reduce landscaping demands. Rated as moderate to low priority were measures such as increasing water rates to reduce demand, introducing recycled water into the water supply, and slowing new development through zoning changes.

Ratings changed only slightly over the course of the workshops, and the rank ordering remained more or less the same. There was a slight tendency to lose enthusiasm for many of the changes at the end of W1 and in W2 but to regain it after W3. However, it is important to remember that only about half the participants remained the same after the first workshop.

Value of Modeling

We developed a series of items to measure the usefulness of quantitative models in general, their accessibility, and their utilization potential.

Value of Quantitative Modeling. We asked participants to rate how valuable or harmful quantitative models were in their own work for making decisions in terms of 13 applications:

- considering the range of factors that could be important
- considering what levels of factors are critical in causing outcomes

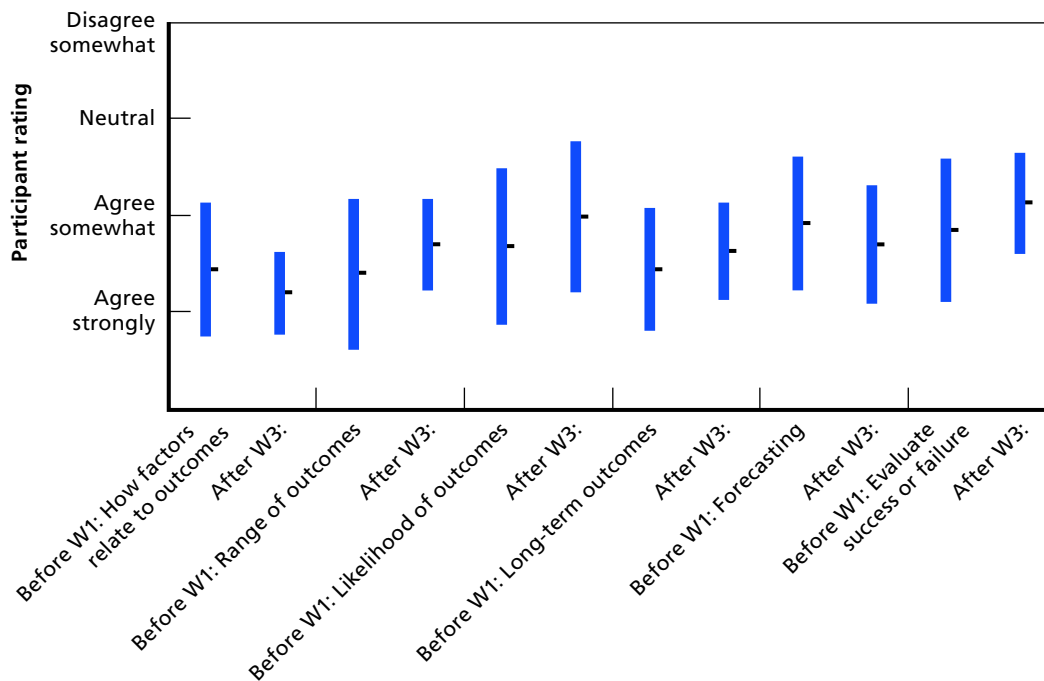
- considering how factors relate to each other in causing outcomes
- considering the range of outcomes that could occur
- considering how likely each outcome is
- considering how beneficial or harmful each outcome is
- considering short-term outcomes
- considering long-term outcomes
- forecasting the future in uncertain situations
- helping to evaluate the likely success or failure of strategies in uncertain situations
- identifying optimum plans
- considering worst-case scenarios
- identifying robust plans
- considering the range of factors that could be important.

Each was rated on a five-point scale: 1 = very valuable, 2 = somewhat valuable, 3 = neither valuable nor harmful, 4 = somewhat harmful, and 5 = very harmful.

In Figure 5.8, differences in responses before and after the workshops are shown graphically for six of the 13 applications. The horizontal lines show the mean response, and the length of the vertical lines corresponds to one standard deviation above and below the mean response. Results are shown in pairs: before W1 and after W3.

As can be readily seen in Figure 5.8, participants, on average, indicated that they found models very to somewhat valuable both before and after the workshops. The postworkshop participants rated quantitative models as slightly less valuable in most respects. While these results appear to be suggestive of an effect of the workshops on participants, no statistical

Figure 5.8
Participants' Responses to Usefulness of Quantitative Modeling



significance could be detected with such a small sample size. In addition, the individuals attending varied among the workshops.

Accessibility and Utilization. We also developed three multi-item scales that were intended to measure the accessibility and utilization value of the models for both planning and decision-making. First, we used a two-item scale to measure how well the model results were presented and, presumably, understood:

- The results from the model were presented in a way that was easy to understand.
- The presentation about the model results was confusing (reverse scored).

Second, we used an eight-item scale to capture the utilization potential of the model results for planning purposes:

- The model results give me new information about the performance of water plans.
- The model results don't tell me anything I didn't know before (reverse scored).
- The results will help develop a broader sense of the range of problems we could be facing.
- These results will help in evaluating the likely consequences of possible actions we could take.
- These results don't change my expectations about the future (reverse scored).
- These results give me information that I would use in planning.
- I can think about the future in terms of a broader range of possibilities based on these results.
- These results will help us to come up with a wider range of possible alternatives.

Finally, we used a five-item scale intended to capture the utilization potential of the model results for decisionmaking purposes, including reaching agreements:

- Decisionmakers will not be helped by these model results (reverse scored).
- These results can help us to reach agreement on what alternatives to pursue further.
- These results will be helpful to the actual decisionmakers.
- These results can help us to reach agreement on what alternatives should be rejected.
- These results will help to persuade others when we are advocating for options we think are the best ones.

Scales were computed to be consistent with the original 1 to 5 scoring of individual items from positive to negative, where 1 = strongly agree, 3 = neither agree nor disagree, and 5 = strongly disagree and 6 = don't know or not sure (omitted from analysis). Based on these scales, the uncertainty treatments were indistinguishable in terms of understandability, planning potential, and decisionmaking potential. The differences in absolute terms were small and, again, do not have statistical significance because of small sample sizes. Nonetheless, we observed the following: The probabilistic scenario was rated as less understandable than the four traditional scenarios and the policy-relevant scenarios. The traditional scenario approach was rated as most understandable. The traditional scenario and probabilistic approaches were rated as slightly less useful for planning and decisionmaking, and the traditional scenario approach was rated as more useful than the probabilistic approach. Since we did not present

the full range of results for the policy-relevant scenarios, we did not ask these rating questions after W3.

Observations

The workshops seemed to bring about only slight changes in views on climate change. The baseline participants agreed somewhat that short-term climate changes were possible and agreed less that climate change would be slow. At the end of the third workshop, participants were less likely to see climate change as a slow process and to feel that they would have warning and likelier to feel that climate change could be upon them before they were aware of it. None of these differences was statistically significant.

Responses to the different approaches to presenting scenarios were fairly consistent. When rating specific aspects of the models, such as their accessibility and potential usefulness for planning and decisionmaking, the traditional scenario approach was perceived to be most easily understood and explained, but the probabilistic forecasts were seen as most useful for making decisions. In direct ratings of the models, the participants found the traditional scenario approach the easiest to understand and to explain to decisionmakers, and they found that it conveyed information in the most objective way. However, they felt that it did not convey as much information for planning purposes in general or to specifically evaluate the IEUA plans. The participants rated the policy-relevant scenarios, one key step in the RDM method, as providing the most valuable information for planning, comparing climate-related risks, and making choices among plans but also as most difficult to understand and explain and as the least objective. The source of this last judgment is not clear. Perhaps the workshop participants were responding to the fact that the generation of policy-relevant scenarios requires several explicit judgments on the part of decisionmakers and analysts (e.g., what level of adverse performance qualifies as a vulnerability) that may affect the results. If so, the workshop participants must have reached a reasonably sophisticated understanding of the approach from our presentations, even if they judged that they could not easily explain it to others. Alternatively, the participants, who also ranked the traditional scenarios as most objective ahead of the probability-weighted scenarios, may merely have decided that the more complex and less transparent methods provided more scope for analysts' subjectivity, even if they did not know its exact source.

Participants did not make major changes in their views on specific actions to manage water in IEUA. Ratings changed only slightly over the course of the workshops, and the rank ordering remained more or less the same. There was a slight tendency to lose enthusiasm for many of the changes at the end of W1 and in W2 but to regain it after W3. However, it is important to remember that only about half the participants remained the same after the first workshop.

Participants came to the workshop with a belief that quantitative modeling was useful and an eagerness to see what we could present. This positive belief was not shaken by exposure to the workshops. We found some support for the hypothesis that modeling (including all the different models shown in these workshops) tended to make managers less confident about their management ability in the face of uncertainty, more willing to take risks, less willing to rely on their instincts and more willing to use models, less inclined to see situations as unique, and more willing to make adaptive changes. Thus, these measures provide weak support for improvements in management of risk and uncertainty through the use of modeling.

We asked for comments at the end of the workshops as well and received some frank assessments. Some commented on the accessibility of the material we presented: “I think a better job could have been done to convey outcomes of the probabilistic approach. One might get the sense that you were intentionally making the results difficult to understand.” Others commented on the analytic success: “It seems these models are good as thinking and discussion tools, but it is hard to ever capture the variability, variables and variation of the world they try to capture.” Another commented, “The climate change scenarios were clearly presented. However, I feel that they presented a static demand that does not respond to wet/dry years (or at least such was not explained). While the demand might take into account population projections and technology changes, could extra conservation efforts in times of drought help to mitigate shortage?”

Several made direct comparisons among the approaches to presenting scenarios. One commented, “Provided a new way of evaluating water management plans. I’m not sure about benefit of RDM relative to probabilistic or multiple scenarios approach. It depends on how well the scenarios are in capturing uncertain variables. Rather than look at alternative plans based on strategy A vs. strategy B, you should look at a mix of strategies for each plan and vary the level of investment. Today’s results indicated that recycling was more important than other strategies, but this was because its goal for further implementation was larger than the others. It was interesting that RDM enables you to test out the important factors. It is interesting that one factor, future climate, you have little control over as a water manager.” Another said, “Last workshop was best. Info on robust planning gets at questions commonly being considered. . . . Having plan to fund scenarios will be helpful to Chino Basin. Come back and work with us on a generation of scenarios.” Finally, another participant got straight to the heart of the comparative analysis: “I liked the lunch from 1st workshop better than this 2nd workshop.”

Final Observations and Discussion

In this chapter, we summarize our observations about the WEAP modeling environment and climate downscaling method, model results on IEUA's system performance under various approaches to scenarios, and key findings from the surveys we carried out before and during the workshops. While none of the results from the workshop surveys is statistically significant, we report on the trends we observed.

WEAP Modeling Environment

We view this first RAND application of the WEAP modeling system as largely successful in terms of our ability to represent a first-order approximation of the supply and demand dynamics in the IEUA system. The tool is flexible and can accommodate a wide range of actions and policy measures. With further refinements in close consultation with the technical staff of IEUA, the WEAP model could provide planners with a valuable analytic and visual means of demonstrating the implications of various planning options to a wide range of stakeholders with varying levels of technical sophistication.

With support from the staff of NCAR, we were able to bring state-of-the-art estimates of climate effects on the IEUA service area through a method of downscaling results from the leading global climate models. However, this method is still under development and will undergo further refinement and improvement over time.

The Effect of Climate Change on IEUA Water Management

The water-modeling analysis developed for this project provided not only the material for evaluating different presentations of uncertainty but also useful information to IEUA-region water managers.

The traditional scenario analysis demonstrated that the IEUA RUWMP would perform well if climate conditions were wetter than current, even with incomplete implementation of the recycling and replenishment goals. If the future climate were drier and warmer, IEUA would need to meet its recycling and replenishment goals, invest in more efficiency, and possibly allow more recycled-GW replenishment to ensure sufficient supply to meet demand.

The probability-weighted scenarios suggested that, if one believed the underlying probabilistic information about future climate and the IEUA region's ability to meet its recycling and replenishment goals, the current IEUA RUWMP would be sufficient to ensure only a 7 percent

chance of a shortage. We discussed in the workshop, however, that such a projection could vary significantly if assumptions about the underlying probability were different.

Finally, the policy-relevant scenarios identified two critical scenarios that are the most threatening to the success of IEUA's water-management plan—a Dry, Flashy, Low-Recycling scenario and a Wet, Effective-Recycling scenario. Under these conditions, the IEUA RUWMP is unlikely to perform well. Additional efficiency and GW-management strategies improve performance under the Dry, Flashy, Low-Recycling scenario but also lead to greater surpluses. The analysis suggested that, if managers think that future conditions are more than 25 percent likely to be consistent with the Dry, Flashy, Low-Recycling scenario, a policy with greater efficiency or more use of recycled water for replenishment would be prudent.

Views of Performance Under Different Types of Scenario Analysis

Looking across the results of traditional scenario analysis, we observe that one plan appears to be most favorable in some of the scenarios, but, under other scenarios, other plans appear better. Managers can use this information in a variety of ways. They could consider how likely the traditional scenarios are and discount those scenarios that are deemed less likely than the others. Choosing a plan based on this method, however, has a critical pitfall: There is no guarantee that the chosen four scenarios represent all the scenarios that are relevant to the comparison of the various plans. In other words, it is possible that another plausible scenario could have been initially constructed (based perhaps on another uncertain parameter) that would have suggested a different plan. Relying on traditional scenarios for planning purposes can lead water planners to errors of omission by failing to consider a sufficient range of conditions to which their plans may be subjected, thereby leaving their systems vulnerable to future uncertainties.

Probabilistic scenarios can similarly lead to errors of omission in planning by downplaying the importance of possible futures that deviate from likeliest conditions. Further, probabilistic scenarios, by definition, assume confidence in assigning probabilities to highly uncertain physical and economic phenomena. They present an attractive and relatively straightforward means of presenting uncertain outcomes, but they many not necessarily lead to acceptable management of risk.

Policy-relevant scenarios can also be simple and straightforward descriptions of possible future conditions, but they have the potential of providing a better test of a plan's vulnerabilities and therefore leading to modified or new strategies to reduce vulnerabilities or consequences of threatening conditions. At the same time, generating policy-relevant scenarios is a nontrivial exercise and more complicated to explain to decisionmakers and stakeholders than are the more traditional and probabilistic scenario approaches, as we documented in our workshops. This suggests a strong need to continue to work on presentational methods that simplify the explanations of how policy-relevant scenarios are generated. It remains a testable hypothesis that decisionmakers will arrive at more nuanced views and understanding of adaptive strategies and system vulnerabilities with a more refined scenario-generating tool.

Workshop Results

Attitudes About Climate Change

Participants whose opinions were measured after the third workshop were less likely to see climate change as a slow process and to feel that they would have warning and likelier to feel that climate change could be upon them before they were aware of it than participants whose opinions were measured before the first workshop.

Comparison Among Presentations of Uncertainties

Participants found the single-scenario approach the easiest to understand and to explain to decisionmakers, and they found that it conveyed information in the most objective way. However, they felt that it did not convey as much information for planning purposes in general or to specifically evaluate the IEUA plans. RDM was rated as most difficult to understand and explain but as providing the most valuable information for planning, comparing climate-related risks, and making choices among plans but least objective and easy to understand and explain.

Attitudes About Responsibility for Long-Term Planning

Participants felt significantly more responsible for the immediate future than they did for the distant future, and this relationship did not change from baseline to after the third workshop. Overall, participants in the last workshop rated themselves a slightly less responsible overall than participants in the first workshop, although the difference is very small. In part, this may have been influenced by the focus in the workshops on a relatively short interval.

Attitudes About Modeling

Participants came to the workshop with a belief that quantitative modeling was useful and an eagerness to see what we could present. This positive belief was not shaken by exposure to the workshops. We found some support for the hypothesis that modeling (including the different approaches to scenario generation shown in these workshops) tended to make managers less confident about their management ability in the face of uncertainty, more willing to take risks, less willing to rely on their instincts and more willing to use models, less inclined to see situations as unique, and more willing to make adaptive changes. Thus, these measures provide weak support for improvements in management of risk and uncertainty through the use of modeling.

Preferences for Strategies

Actions that are under way and key to the existing IEUA plans, including expanding the region's recycling program, increasing the sustainable yield of the GW basin, and increasing water-use efficiency, all were rated as must-do. Next in priority were measures related to new construction, increasing GW recharge, construction of new transmission lines for recycled water, construction of new GW-desalting plants, enacting tighter appliance standards, and improving the permeability of the basin to increase GW recharge. Taking measures that may affect customers in the short run was viewed with less enthusiasm. Examples include increasing water rates to reduce demand, introducing recycled water into the potable water supply, and slowing new development through zoning changes. Ratings changed only slightly over the course of the workshops, and the rank ordering remained more or less the same.

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