Developing a Robust Water Strategy for Monterrey, Mexico

Diversification and Adaptation for Coping with Climate, Economic, and Technological Uncertainties

Edmundo Molina-Perez, David G. Groves, Steven W. Popper, Aldo I. Ramirez, Rodrigo Crespo-Elizondo
Preface

Planners in growing metropolitan regions in Latin America and across the developing world face many challenges in developing water-resources management strategies that will support current and future needs. Traditional approaches that look to divert water from large rivers are increasingly risky, as competing needs for those supplies reach or exceed sustainable levels and hydrological changes lead to reduced or modified runoff patterns and amounts. This study applies methods for decisionmaking under deep uncertainty—specifically, the RAND Corporation’s Robust Decision Making methods—to structure an analysis of water-management vulnerabilities and the development of a robust, adaptive strategy for Monterrey, Mexico. It was performed via a novel partnership between RAND and Tecnológico de Monterrey, funded by Fondo de Agua Metropolitano de Monterrey (FAMM). This work informed the final long-term water-management strategy described in the 2018 Monterrey Water Plan (FAMM, undated). This report will be of interest to water-resources managers and stakeholders in Monterrey, Mexico, and any other region grappling with developing water-management strategies that account for climate change.

About RAND Social and Economic Well-Being

RAND Social and Economic Well-Being is a division of the RAND Corporation that seeks to actively improve the health and social and economic well-being of populations and communities throughout the world. This research was conducted in the Community Health and Environmental Policy Program within RAND Social and Economic Well-Being. The program focuses on such topics as infrastructure, science and technology, community design, community health promotion, migration and population dynamics, transportation, energy, and climate and the environment, as well as other policy concerns that are influenced by the natural and built environment, technology, and community organizations and institutions that affect well-being. For more information, email chep@rand.org.
About Tecnológico de Monterrey

Tecnológico de Monterrey is the largest private university in Mexico with 31 campuses in 25 cities. It is a private, nonprofit, independent institution with no political and religious affiliations. In 2018 and 2019, the Quacquarelli Symonds World University Rankings recognized Tecnológico de Monterrey as the best private university in Mexico. Its work is supported by civil associations made up of numerous outstanding leaders from all over Mexico who are committed to quality in higher education. Research programs include strategic partnerships with the Massachusetts Institute of Technology, the Femsa Biotechnology Center, the Water Center for Latin America and the Caribbean (financed by the Inter-American Development Bank and the Femsa Foundation), the Motorola Research and Development Center on Home & Networks Mobility, the Center for Advanced Design at the Guadalajara Campus, and the School of Government and Public Transformation Energy Knowledge Networks funded by Conacyt. Questions or comments about Tecnológico de Monterrey’s participation in this study should be sent to Edmundo Molina-Perez (edmundo.molina@tec.mx).
## Contents

Preface .......................................................... iii
Figures .......................................................... vii
Tables ........................................................... ix
Summary ........................................................ xi
Acknowledgments ............................................. xvii
Abbreviations .................................................. xix

### CHAPTER ONE

**Water Planning in Monterrey: Future Uncertainties and Political Gridlock** ........................................... 1

1.1. Introduction ............................................... 1
1.2. Challenges and Opportunities for Monterrey’s Water System .................................................. 3
1.3. Questioning an Ambitious Pipeline Project for Monterrey .................................................. 4
1.4. A New Approach for Water-Resources Planning in Monterrey ........................................... 5

### CHAPTER TWO

**Developing a Robust, Adaptive Water-Management Strategy** .................................................. 7

2.1. Using Robust Decision Making for Long-Term Water Infrastructure Planning in Monterrey ........................................................ 7
2.2. Framing the Decision Analysis Through Stakeholder Engagement ........................................... 9
2.3. Uncertain Future Drivers of Water-Management Conditions ............................................... 13
2.4. Options and Strategies .......................................... 19
2.5. Performance Measures .......................................... 25
2.6. Simulating the Performance of Monterrey’s Water-Management System ..................................... 25
2.7. Characterizing the Uncertain Future ........................................................ 27
2.8. Analyses to Stress Test and Improve the Robustness of Monterrey’s Water-Management System ........................................................ 29

### CHAPTER THREE

**Future Vulnerability of Monterrey’s Water Supply** ........................................................ 31

3.1. Performance of the Current System ........................................................ 31
3.2. Vulnerabilities of Current System ........................................................ 33
# Figures

1.1. Location of Monterrey, Mexico, and Major Water Infrastructure ................. 2  
1.2. Historical Growth in Water Demand in Monterrey, 1980–2015 .................. 3  
2.1. RDM Conducted as an Integrated Process of Deliberation with Analysis ...... 9  
2.2. Historical and Future Water-Demand Projections ............................... 14  
2.3. Range of Hydrological Projections by Basin .................................... 17  
2.4. Per-Unit Water Costs for Two Desalination Technologies .................. 19  
2.5. Existing Tariff Schedule and Proposed Simplification ....................... 24  
2.6. Integrated Assessment Model to Estimate System Performance and Define Optimal Adaptation Pathways ........................................ 26  
2.7. Analytical Steps Used in the Study .................................................. 29  
3.2. Simulated Water Demand-and-Supply Conditions for 2016–2050 for a High Water-Demand Growth and Drier Future ......................... 33  
3.3. Current System Reliability Across Futures for Three Implementation Periods ......................................................................................... 34  
4.1. Elements of a Robust, Adaptive Strategy ........................................ 37  
4.2. Portfolio Alternatives Regret Analysis .............................................. 50  
4.3. Example Identifying Longer-Term Portfolios Using Scenario Discovery .... 52  
4.4. Example Decision Tree Based on Scenario Discovery .......................... 53  
4.5. Adaptive Plan for Low-Regret, Near-Term Portfolios (P2) .................. 54  
4.6. Adaptive Plan for Low-Regret, Near-Term Portfolios (P6) ................... 57  
4.7. Scatter Diagram of the Vulnerability Conditions of the Adaptive Plan for P2 in Each of the Analysis Periods Considered ....................... 59  
4.8. Monterrey Adaptive Water Plan Based on P2 Under an Alternative Tariff Schedule ................................................................. 60  
B.1. RiverWare Schematic of Monterrey’s Water System ............................ 78
# Tables

2.1. List of Stakeholders .............................................................................................................................................. 11
2.2. Scope of RDM Analysis ........................................................................................................................................... 12
2.3. Supply Sources for Monterrey ............................................................................................................................. 15
2.4. Economic and Technical Characteristics of the Infrastructure Options ............................................................ 22
2.5. Monterrey’s Water-Tariff Segments and Shares of Consumption ................................................................. 23
2.6. Experimental Designs to Reflect Plausible Futures .............................................................................................. 27
4.1. Optimal Portfolios for Various Water Demands for the Historical Climate Projection ................................................. 39
4.2. Optimal Portfolios for Various Water Demands for a Dry Climate Projection (~10%) ................................................. 41
4.3. Probability of Option Inclusion in Optimal Investment Portfolios Across Futures Ensemble, by Time and Change in Water Demand and Flow ................................................................................................. 42
4.4. Percentage of Futures in Which an Option Is Included as Part of an Optimal Future in the First Period ..................... 45
4.5. Correlations of Options Included in Optimal Portfolios in the Near-Term ........................................................... 46
4.6. Low-Regret, Near-Term Portfolios ......................................................................................................................... 49
4.7. Mean Cost of P2 Based Adaptive Plan under Two Tariff Schedules ......................................................................... 61
B.1. Consumption Clustering in Water-Demand Model .................................................................................................... 76
Monterrey is the economic capital of northern Mexico and plays an important role in the economic industrial cluster across Mexico’s border with the United States. But the economic success of Monterrey has also led to increased environmental and social challenges, including water security and future equity. In response to these challenges, the water-policy community of Monterrey decided to develop the first long-term water plan for the region in 2016—the Monterrey Water Plan (MWP). To support this effort, the Fondo de Agua Metropolitano de Monterrey (FAMM) sponsored Tecnológico de Monterrey and the RAND Corporation to perform an analysis of the current water management system and how it would perform across a wide range of plausible futures and then suggest an adaptive and robust management strategy using RAND’s Robust Decision Making (RDM) methods. This is the first comprehensive long-term water plan for the region. The study began in April 2016 and was carried out in two phases. The first phase focused on the pertinence of the proposed Pánuco aqueduct. It subjected the design for this project to a wide set of plausible future climate and water-supply simulations. The results showed that there were more cost-effective expansion alternatives available in the near term and that the aqueduct would be inappropriate unless Monterrey experiences very high-demand growth and extremely adverse local climate conditions in the long term.

The second phase of our research project—described in this report—built upon the tools initiated during the first phase to create a full analytical framework to support water-infrastructure master planning for Monterrey. The objective is to allow examination of alternative portfolios of near-term infrastructure projects for their robustness to uncertainty. Analysts may then map an adaptive approach to future expansions in later periods according to criteria that may be outlined in advance.

The project mandate was to support FAMM’s design for an entirely new robust, adaptive water-management strategy that will meet the water needs of the region despite the great uncertainty over future demand and water availability. Such a strategy would need to demonstrate careful stewardship of public resources and be transparent to a heterogeneous group of stakeholders, including consumers, environmentalists, and local business and political leaders. Therefore, the two phases of this study were carried out in close collaboration with Monterrey’s water-planning community. Tecnológico
de Monterrey convened three workshops in 2016 and 2017 to elicit from key stakeholders what the key aspects of the analysis should be. The first set of workshops, during the first phase of the project, focused on discussing at length all available options for expanding water supply to the city. The second set addressed the key uncertainties, options, performance measures, and available data and modeling tools for developing the water plan. In the third set of workshops, we reviewed interim results with stakeholders to collect feedback and also gathered suggestions for expanding the scope of research. A final engagement was to brief FAMM’s technical committee on key findings, fundamental trade-offs, and the performance of the candidates for the robust adaptive plan. This feedback is reflected in the analysis presented in this report and in the MWP.

We built an integrated assessment model (IAM) to simulate future water management—system performance with and without various augmentation strategies. The IAM integrates several models within an optimization framework to determine optimal water-management adaptation strategies—sequences of policy or investment options implemented over time. An econometric demand model yields demand projections. Hydrological projections are generated using a Markov autoregressive hydrological model (MARHM). These projections—combined with other assumptions about groundwater yield, desalination costs, and the list of available options—are the inputs to a dynamic optimization engine that estimates for individual scenarios the optimal investment sequence that meets Monterrey’s water planners’ reliability objective while minimizing investment costs. The resulting database is a rich set of cases showing how different assumptions about uncertain future conditions trigger the implementation of different project combinations. These data are then used to identify near-term trade-offs and develop long-term adaptive strategies.

An initial survey of future vulnerabilities showed that the current capacities of Monterrey’s water system are not sufficient to guarantee current delivery reliability levels over the near, medium, or long terms. These results show that relatively small increases in water demand will certainly reduce the reliability of the system below the current levels. This confirms the intuition and previous analyses by local stakeholders of the need to expand supply capacities. This does not mean the city faces an imminent water crisis if it fails to expand the system. The finding reveals that, in the absence of any augmentation or efficiency enhancement, the reliability of Monterrey’s water system will erode in response to increases in water demand, especially if adverse climate conditions (e.g., runoff decline, higher losses because of evapotranspiration) affect current sources. If these stressors materialized, they would likely lead to more-frequent pressure losses or temporary cuts to water supply. Both could have long-term consequences for Monterrey’s attractiveness as a place for investment or residence.

The decision to expand Monterrey’s water-supply infrastructure must balance the trade-off between two metrics: water-supply reliability (the probability of satisfying demand at any given time) and cost (i.e., investment plus operational costs). If
water-system investment is too heavy, then reliability will likely be high; however, some investments may likely lie idle, thus becoming an unnecessarily expensive burden. Of course, investing too little may mean frequent availability shortfalls. In this respect, the goal of this study is not to dictate a solution, but instead to provide decisionmakers with better strategic insight into both their near-term options and how to modify its adaptation strategies for the medium and long terms.

To respond to these challenges, we use the RDM framework to develop a robust, adaptive strategy that includes a set of low-regret, near-term options that represent good foundational investments for future adaptation. Accompanying the portfolio of near-term options is a set of medium- and long-term signpost conditions and associated medium- and long-term contingent options.

Using the IAM to estimate the optimal strategy for each future included in the scenario ensemble, we first identify a Pareto frontier—the strategies that represent the best trade-offs between cost and reliability. Our results show that near-term portfolio options fall into three groups. The first, with low cost-regret levels but high reliability regret, are portfolios that rely on small-scale and low-cost projects. The second group, with high reliability but high cost regret, includes portfolio alternatives combining two medium-scale projects—La Libertad Dam and WW Injection Well—with several of the small-scale projects. The third group of portfolios display medium levels of regret in both cost and reliability. These portfolios either combine a set of small-scale projects with La Libertad Dam (the efficiency and groundwater options) or rely only on the Cuchillo II Dam.

We then run the IAM as a scenario generator across the entire experimental design for each of the portfolio alternatives identified as lying on the Pareto frontier. This generates a new database that describes the optimal expansion of the system, now into the medium and long terms as well, for each of the futures considered in the experimental design. In the final analytical phase, this database is analyzed using classification algorithms for scenario discovery such that a specific adaptive strategy may be identified for each of the near-term options along the Pareto frontier.

This analytical framework highlights the medium- and long-term implications of investment decisions made in the near term. First, the potential vulnerability to different uncertainties (i.e., stressors) in the medium and long terms will change depending on the decision made in the near term. If the first period portfolio (2016–2026) relies significantly on groundwater resources, then groundwater availability will be critical for triggering contingent actions. If the first period portfolio relies primarily on surface water, then hydrological changes in the medium and long terms at the serving basins will be more relevant than groundwater conditions.

Second, although all adaptive plans stipulate contingent actions for meeting system reliability objectives, each strategy’s capacity for tolerating different combinations of water demand and availability of groundwater and surface water before triggering a full-scale system expansion varies greatly. Therefore, different adaptive
strategies display varying capacity to accommodate demand growth before launching a full expansion of the system. This fundamental performance difference shows that the medium- and long-term resilience of the system (i.e., its capacity to assimilate stressors) is greatly determined by near-term actions.

Finally, the implementation costs estimated at each decision node for the adaptive plans defining the Pareto frontier reveal the economic opportunity afforded (i.e., potential investment savings) by effective water-demand management. For instance, the difference in expansion costs between the scenarios under which water demand is lower than 14.6 cubic meters per second ($m^3/s$) and the scenarios under which water demand is higher than 19.1 $m^3/s$ is US $4 billion. This reinforces the message that significant savings may be achieved if water demand is managed to prevent rapid growth.

Using these findings, we designed an adaptive plan for expanding Monterrey’s water infrastructure that significantly reduces the vulnerabilities that could arise from the current system. The plan consists of two elements:

- A set of selected near-term infrastructure projects (through 2026) that moderate exposure to both excess cost and insufficient reliability and so appear robust to plausible ranges of uncertainty
- An adaptive strategy for future additional projects in the medium (2027–2038) and longer (2039–2050) terms that build on the near-term infrastructure expansion.

These two elements represent a coherent framing for planning Monterrey’s water system through 2050. This approach proposes a set of projects to be developed in the near term for which water planners will not regret their implementation. These projects are likely to meet the reliability objectives under the majority of circumstances and will avoid excessive infrastructure spending. For the medium and long terms, our plan establishes optimal adaptation strategies for responding to different future water-demand conditions, as well as combinations of groundwater and surface-water availability.

This adaptive strategy’s performance significantly reduces system vulnerability across all decision periods and proposes a strategy of expansion and improvement of the current system that is cost-effective.

For completeness, we also evaluated the potential influence of regulatory changes that modify the current charges for water delivery. This new tariff schedule would protect the lower-income deciles in the population while encouraging more-efficient water use in the upper-income deciles. The result is an average 3-percent water-demand reduction across all scenarios considered. This minor reduction in demand permits the adoption of a different adaptation strategy—one that is as robust as the one previously selected. However, it reduces the costs of expanding the water infrastructure in the long term for a subset of the futures considered. Specifically, with the alternative tariff
schedule, the mean cost of expanding the system is reduced by US $703 million under the low water-demand scenarios, US $419 million under the low- to medium-demand scenarios, and US $1.075 billion under the medium-demand scenarios. However, if water demand follows a trajectory of rapid growth and high levels, the effect of water tariffs is negligible, as the same costly investments are required under the old and new tariff strategies.
Acknowledgments

This report was the result of an active and productive collaboration with many partners whose collective contributions, support, and feedback proved invaluable. We thank and acknowledge Eugenio Clariond Reyes-Retana and Alfonso Garza-Garza, presidents of Fondo de Agua Metropolitano de Monterrey (FAMM), who commissioned this study, oversaw the overall effort, and were active and engaged partners throughout. We would also like to thank the governor of the State of Nuevo León, Mexico, Jaime Rodríguez Calderón, for his trust in this research effort, Manuel Vital and Martín Mendoza from Nuevo León’s Secretaría de Desarrollo Sustentable, and Consejo Nuevo León. For the development of this study, we worked closely with Servicios de Agua y Drenaje de Monterrey I.P.D. (Monterrey Water and Sewage Services). We extend our particular thanks to Gerardo Garza, Enrique Torres, Florentino Ayala, Octavio Salinas, Cristal Lagarda, Ramón Morga, Daniel Salas, and Francisco Cantú-Ramos. We are grateful to the vast network of experts that interacted with us during the development of this study. Prominent members of this group include Ismael Aguilar and Rodolfo Montelongo (Tecnológico de Monterrey), Oscar Gutiérrez, Amalio Cardona, and Alberto Pérez (Comisión Nacional del Agua [CONAGUA]), Mariano Montero, Carlos Hurtado and David Moreno (Fundación FEMSA), Victor Hugo Guerra (Universidad Autónoma de Nuevo León), and Eduardo Mestre and Álvaro Aldama. We would also like to express our special appreciation to the entire team of researchers who collaborated in the development of the Plan Hídrico de Nuevo León: Sergio Ramirez (FAMM); Francisco Navarro (independent consultant); and Alejandra Herrera, Ricardo Sandoval, Daniel Gómez, Eliana Torres, and Carlos Lugo (Tecnológico de Monterrey). We are grateful to Alejandro Poiré Romero, dean of the School of Social Sciences and Government at Tecnológico de Monterrey, for supporting this research effort. Finally, we gratefully acknowledge and thank the peer reviewers for this document, Michelle Miro (RAND Corporation) and Luis Bojorquez-Tapia (Universidad Nacional Autónoma de México). Comments from both reviewers were very insightful and helped us improve the analysis described in these pages. Any faults or errors remaining in these pages are attributable to the authors alone.
**Abbreviations**

ARDL  
autoregressive distributed lag

cms  
cubic meters per second

CONAGUA  
Comisión Nacional del Agua [National Water Commission]

CPU  
computer processing unit

DMDU  
decisionmaking under deep uncertainty

FAMM  
Fondo de Agua Metropolitano de Monterrey [Monterrey Metropolitan Water Fund]

GW  
groundwater

IAM  
integrated assessment model

m³/s  
cubic meter per second

mm  
millimeter

NGO  
nongovernmental organization

MARHM  
Markov autoregressive hydrological model

MWP  
Monterrey Water Plan

P[number]  
portfolio [number]

Q[number]  
quantile [number]

SADM  
Servicios de Agua y Drenaje de Monterrey I.P.D. [Monterrey Water and Sewage Services]

RDM  
Robust Decision Making
CHAPTER ONE

Water Planning in Monterrey: Future Uncertainties and Political Gridlock

1.1. Introduction

Monterrey, located in Mexico’s northern state of Nuevo León, is the country’s third-largest metropolitan area (Figure 1.1). It is the economic capital of northern Mexico and plays an important role in the economic industrial cluster across Mexico’s border with the United States (Balán, Browning, and Jelin, 2014; Hernández, 2008). But the economic success of Monterrey has also led to increased environmental and social challenges, including water security and future equity (Sisto et al., 2016). These issues need to be addressed strategically to ensure that the city continues to be an attractive region for new investment, human capital development, and social welfare (Castro, 2004).

Water security has come to the forefront in public discussions of regional challenges (Bennett, 1995; Sisto et al., 2016). Monterrey’s current system relies on a mixture of surface reservoirs and groundwater supplies. Seventy percent of current supply comes from the reservoirs at La Boca, El Cuchillo Reservoir, and Cerro Prieto. The groundwater component—which comes from various groundwater systems, including the Monterrey Metropolitan Area, Mina, Buenos Aires, and Santiago well fields (Figure 1.1)—supplies the other 30 percent. In recent years, the government of the state of Nuevo León has been exploring the possibility of expanding the water infrastructure of the city to support both population and industrial growth. However, the task has not been easy. Different stakeholder groups have put forward a wide range of grey and green infrastructure project proposals, making it difficult to decide which projects have the highest merit in terms of reliability of performance, cost, and environmental sustainability.

Local water politics have played an important role in defining Monterrey’s water policy over the years (Bennett, 1995). There is also increasingly wide recognition that

---

1 Grey infrastructure refers to the human-engineered infrastructure for managing water resources. Examples include reservoirs, aqueducts, groundwater wells, and wastewater treatment plants. Green infrastructure uses vegetation, soils, and other elements and practices to manage water resources in an urban environment. Examples include wet ponds, wetlands, and urban filtering practices.
the city also needs to address the planning and policy challenges posed by deep uncertainty. While future water infrastructure in the city clearly should be developed in consideration of potential demand growth, it is not possible to anticipate with precision how greatly that demand will grow in the coming decades. And, of course, it has become clear that it is no longer possible to predict the potential effects of climate change on the basins from which the city’s water supply is drawn (López-García, Manzano, and Ramírez, 2017).

In response to such challenges, the Fondo de Agua Metropolitano de Monterrey (FAMM) commissioned staff from Tecnológico de Monterrey, in partnership with the RAND Corporation, to conduct an analysis of the long-term trends and vulnerabilities in water management in Monterrey and to help design a long-term robust water

---

2 Deep uncertainty is characterized by an inability to determine or agree upon (1) what values important variables may take in the future, (2) what model of causality best represents the relationship between policy actions or other inputs and resulting outcomes, or (3) how to weigh priorities to determine whether outcomes should be considered to be good or bad (Lempert, Popper, and Bankes, 2003).
strategy. This study uses the Robust Decision Making (RDM) method to organize the analysis. The mandate of the research effort documented in this report was to advise the local water community on the merits of alternative water infrastructure investments proposed by previous administrations and to outline alternatives to ensure that the city’s water infrastructure will be able to respond to potential demand across a wide range of plausible, but sharply differing, alternative futures.

1.2. Challenges and Opportunities for Monterrey’s Water System

Figure 1.2 shows the historical growth in water demand for Monterrey. Clearly, the city is on an accelerated trajectory of demand growth. From 1980 to 1990, water demand grew by 13 percent, while, in the ensuing two decades, growth amounted to 20 percent from 1990 to 2000 and fully 25 percent from 2000 to 2010.

Projections of continued growth suggest that the population in Monterrey could increase from 4.2 million people in 2015 to 6.25 million people in 2030. Assuming constant per capita water use of 200 liters per person per day, this would imply that water demand could grow by an additional 6 cubic meters per second (m³/s)—from 10.5 m³/s to 16.5 m³/s. While there is considerable uncertainty about future demand growth, any such increase poses serious challenges for the city, as it needs to look for alternatives to expand the city’s sources of water supply.

Figure 1.2
Historical Growth in Water Demand in Monterrey, 1980–2015

NOTES: Time series of historical water demand in Monterrey. The vertical axis denotes mean yearly water demand in m³/s. The horizontal axis denotes the historical record considered.
Rainfall is scant in the urban areas of Monterrey. Mean annual precipitation is approximately 600 millimeters (mm) and highly variable: 44 percent of monthly precipitation observations are less than one-half of the historical mean, while 14 percent are triple the mean. Furthermore, there is not much surface-water storage to buffer this variability. High temperatures in the region cause high evaporation from surface reservoirs. Evaporation from El Cuchillo Reservoir alone results in annual losses ranging from 100 to 250 million cubic meters (Mora et al., 2017; Sisto et al., 2016). To supplement surface supplies held in three main reservoirs (La Boca Dam, Cerro Prieto Dam, and El Cuchillo Reservoir), Monterrey derives about 30 percent of its supplies from groundwater originating from several well-fields—a group of wells, proximate to each other, drawing on an aquifer—located within urban areas (i.e., Monterrey Metropolitan Area Groundwater Field, Mina Groundwater Field, Buenos Aires Groundwater Field, and Santiago Groundwater Field).

There are a range of options for expanding water supply, including increasing use of the region’s groundwater resources, building new surface-water reservoirs, importing surface-water supplies from other watersheds, desalinating seawater, and increasing water-use efficiency. The reliability of these new supplies, as well as existing supplies, are difficult to ascertain because of the complicated hydrological conditions of the region and uncertainty about future climate conditions.

1.3. Questioning an Ambitious Pipeline Project for Monterrey

In 2014, the government of the state of Nuevo León put forward a plan for expanding Monterrey’s water infrastructure. The plan called for a large (US $3 billion) water-transfer project that would import 5 m$^3$/s (about 40 percent of Monterrey’s annual demand) of water from the Pánuco River in the state of Veracruz, 500 kilometers south of Monterrey. While this river is expected to have excess capacity to supply water to other regions in the near term, there is no guarantee that Monterrey’s water allocation will be available during all years in the future, as other states in the Bajío region also maintain a legal claim to this water. The cost of this single project was also a concern, as it would require high commitments of public funds. Additionally, environmentalist groups were deeply troubled about the possibility of expanding Monterrey’s water supply by importing water from such a distant ecosystem. As a result, the prospect of the project was met with strong opposition by different actors within the local water-planning community. In response, proponents of the project emphasized the urgent

---

3 We use the term “MWP [Monterrey Water Plan] community” in reference to the set of institutions and stakeholders with whom we interacted throughout this study. This includes federal and state agencies, government officials, various environment-focused nongovernmental organizations (NGOs), the state’s public utility company, academic institutions, representatives of the local business community, and private companies. This network of collaborators is described in more detail in Chapter Two, section 2.2.
need to expand Monterrey’s water supply and the economies of scale and proven technology of the proposed aqueduct. This polarized atmosphere was accompanied by growing dissatisfaction with the state government. That government was voted out of office in 2015 and replaced by the first elected nonparty-affiliated state authority in the country, which rescinded the pipeline project and commissioned this study that is the focus of this report (Arteaga, 2015).

This political gridlock was conducive to various institutional changes in water policy in the state of Nuevo León. In 2016, the water-policy community of Monterrey decided to develop the first long-term water plan for the region. This water plan also occasioned new collaborative ties among the federal government, state authorities, the local water-utility company, and various stakeholders interested in the development of Monterrey’s water system, including local NGOs and universities. This planning process also fostered a new institutional body, FAMM, which has coordinated the activities relating to the development of the MWP. The analysis in this report provides the analytic basis for the proposed strategy included in the water plan (FAMM, undated).

1.4. A New Approach for Water-Resources Planning in Monterrey

Our study was conducted in two phases. The first phase of the analysis was focused on assessing the pertinence of the proposed aqueduct by considering a vast set of climate- and water-demand scenarios. The results of the first phase showed that there were more cost-effective expansion alternatives that could be implemented in the near term and that the aqueduct was only appropriate if in the long term Monterrey will face very high demand growth and extremely adverse local climate conditions. The second phase of our research project—described in this report—focused on refining the analytical tools developed during the short time allowed in the first phase, with a special emphasis on providing the analytic and methodological foundations for the design of a master infrastructure strategy for Monterrey’s Water Plan.

Monterrey needs a robust, adaptive water-management strategy to ensure that the water needs of the region are met even as these needs remain deeply uncertain. This strategy must also use limited public resources wisely for investing in infrastructure and be transparent to a heterogeneous group of stakeholders, including consumers, environmentalists, and local business and political leaders.

This report describes an analysis of water resources trends and vulnerabilities in Monterrey and the subsequent development of a robust infrastructure plan. The context of any particular water agency’s infrastructural and operational planning offers specific challenges that need to be considered from an analytical perspective. While, in some cases, water agencies have already defined an initial implementation sequence for their project alternatives, in the case of Monterrey, water planners had at their disposal only a list of alternatives that could be included in the MWP.
Thus, we developed a computational experimentation approach that not only evaluates system performance across a wide range of long-term futures but also informs water planners about the merits of different near-term options. To conduct this study, we built an integrated assessment model (IAM) to evaluate the performance of the water-management system across a large set of plausible futures and then developed and compared portfolios of different water-management options. The resulting database is extremely rich, containing detailed information about how different combinations of uncertainty conditions trigger the implementation of different project combinations, thus producing valuable data for identifying near-term trade-offs and developing long-term adaptive strategies.

This report is the first comprehensive look at Monterrey’s potential water needs through the mid–21st century and is noteworthy in that it applies best-practice methods for decisionmaking under deep uncertainty (DMDU) to consider future water needs and supplies. It not only provides a showcase of these methods but also yields important conclusions about how Monterrey can ensure that it will meet the future water needs of the region even with significant future uncertainty.

In Chapter Two, we describe the overarching methodology used to perform this analysis. We describe the stakeholder interactions, which defined the major elements of the analysis, including the key uncertainties, performance measures, and options. We then summarize the models used to evaluate Monterrey’s water system in a manner consistent with stakeholder concerns. In Chapter Three, we report on the vulnerability analysis that evaluates how the current water plan would perform across a wide range of futures and then identified the drivers of poor performance. Chapter Four describes in detail different options to improve the long-term performance of the water system and the robust, adaptive plan that was identified and incorporated into Monterrey’s latest water plan. Chapter Five summarizes the study’s main findings and policy recommendations. Several appendixes provide details on the models and technical analysis.
CHAPTER TWO

Developing a Robust, Adaptive Water-Management Strategy

2.1. Using Robust Decision Making for Long-Term Water Infrastructure Planning in Monterrey

Major infrastructure project planning requires confronting the problem of uncertainty. Developers of major water-supply development projects must anticipate future demand, estimate the costs of construction, and allow for changes in water cycles because of unevenness of precipitation levels across decades, among other considerations. Traditionally, planners have relied on projections for these and similar variables and then built in safety factors to account for possible variation within historical ranges (Lempert and Groves, 2010).

Today, planners face the reality that—in the presence of greater doubt stemming from demographic, economic, technological, hydrological, and, most prominently, climate uncertainty—many traditional rules of thumb may not hold true in the future (Lempert, 2015; Popper, Lempert, and Bankes, 2005). The conventional approach to forecasting and then implementing plans based on such forecasts no longer appears to constitute best practice nor does it provide due diligence for either the planning itself or the oversight that government needs to provide. Deep uncertainty is a term applied to circumstances for which we find it hard to determine (or agree on) which probabilities to assign to important trends, what models linking actions to results we should rely on, and even how, among competing interests, we should characterize possible outcomes as either meeting or falling short of our goals (Lempert, Popper, and Bankes, 2003; Walker, Lempert, and Kwakkel, 2013). Under conditions of deep uncertainty, what constitutes due diligence for analysts wishing to determine what options are available, and how to assess and select among them?

Today, this problem extends beyond water-supply planning into most long-term and large-scale public investment projects. Quantitative analytical methods, which include probabilistic risk analyses, work well when uncertainties may be characterized by statements regarding probabilities with which most observers would agree (Kalra et al., 2014; Lempert and Kalra, 2011; Lempert, Popper, and Bankes, 2003). However, traditional methods prove brittle in the face of deep uncertainties. Disagree-
ments about future predictions can lead to gridlock among stakeholders. Worse, decisions tailored to one set of assumptions about a deeply uncertain future may well prove inadequate or even harmful if another future comes to pass.

Complications arising from deep uncertainty appear to be undermining previous consensus in many policy areas on what constitutes best practice for policy analysis. In response, the past quarter century has seen the emergence of methods designed specifically to assist DMDU (Marchau et al., 2019; DMDU Society, undated). In the analysis of Monterrey’s water-planning problem, we employed RDM, one of the first and most widely applied of these methods (Lempert et al., 2006; Lempert, Popper, and Bankes, 2003).

RDM first identifies vulnerabilities of current policies or strategies and then iteratively discovers and evaluates alternatives that are robust—that is, that satisfy decision-makers’ objectives in many plausible futures rather than being optimal for any single best estimate of the future (Lempert et al., 2013). RDM rests on a simple concept: Rather than use models and data to generate a reliable forecast to assess policies under a single set of assumptions, the method runs models over hundreds or thousands of different sets of assumptions to describe how plans perform in many plausible conditions. Unlike, for example, Monte Carlo analysis, which attaches probabilities to assumptions to estimate expected outcomes, RDM uses model evaluations to stress test strategies.

With RDM, the same models and data that were inadequate to the task of prediction may be harnessed to create an ensemble of systematically varied cases over which we can reason about the implications of potentially changing relationships and increased uncertainty on policy decisions. Rather than predict definitive outcomes, RDM allows us to address systematically the question, “What assumptions would we need to believe were true for us to reject option ‘A’ and instead recommend option ‘B’?” This represents not a new approach to modeling but rather a reframing of how best to use models to inform policy decisions under deep uncertainty.

Rather than devote often-scarce analytical resources to determining which set of assumptions are the most accurate predictors of the future (an always-contentious and often fruitless enterprise), RDM analysis instead focuses on finding robust courses of action that may be adopted through consensus. By embracing many plausible sets of assumptions or futures, RDM can help reduce overconfidence and the deleterious effects of surprise, can systematically include imprecise or incomplete information in the analysis, and can help decisionmakers and stakeholders who have differing expectations about the future nonetheless reach agreement on action. In essence, RDM helps plan for the future without first predicting it.

RDM uses an iterative process of futures exploration, vulnerability analysis, and adaptive strategy development and comparison, as described in Figure 2.1 and Appendix A. RDM begins with a decision-framing step in which the key uncertainties, decision options, performance measures, and models are defined. This information is generally gathered through significant interaction with stakeholders and regional experts.
Next, the analysis uses one or more models of the system of interest to evaluate how current policies would perform across a wide range of plausible futures. This largely quantitative step provides the needed information to perform a vulnerability analysis. It may (and often does) lead to successive rounds of model-based simulation as new potential strategies or future conditions are explored. At some point, the analysis is sufficiently refined to permit assessment of trade-offs among a small number of potential candidate courses of action for the policy decision makers to consider.

We will explain the RDM process in application to the water-planning problem for Monterrey in the next section. RDM and similar methodologies have already been applied to water-resources management worldwide (Groves et al., 2015; Groves et al., 2013; Groves et al., 2008), water-quality planning (Fischbach et al., 2015); coastal and urban flood-risk management (Fischbach et al., 2017), terrorism risk insurance (Dixon et al., 2007), and energy planning (Popper et al., 2009), to name a few examples.

2.2. Framing the Decision Analysis Through Stakeholder Engagement

This study performs a systematic evaluation of water-management vulnerabilities and adaptations using the RDM methodology. As the first step, we held three workshops at Tecnológico de Monterrey during the second and third quarters of 2016 to discuss
with a set of highly heterogeneous stakeholders what the key aspects of the analysis should be. In addition to these workshops, individual meetings with parties interested in the study and water policy in Nuevo León were held to expand the scope and increase the usefulness of the analysis. The list of institutions with which we interacted throughout the study is listed in Table 2.1. This list includes state and federal agencies, private companies, NGOs, academic institutions, and the public water-utility company in Nuevo León. The workshops and engagements held with these parties followed an open-dialogue approach that had three objectives: (1) Describe the mandate and scope of the study; (2) communicate relevant findings; and, most important, (3) engage in a constructive discussion with participants regarding how to improve the study and make it more relevant for Monterrey. This list is a first step toward developing a broader network of actors that can be engaged in Monterrey’s water-policy discussions, and the intention of FAMM is to continue expanding this network in the future.

The first set of workshops were focused on discussing at length all available options for expanding water supply in the city. The second set of workshops was organized to discuss the key uncertainties, options, performance measures, and available data and modeling tools for developing the water plan. In a third set of workshops, we presented interim results on this RDM study to stakeholders with the objective of receiving feedback and of expanding the scope of this research effort. We concluded our engagement with stakeholders by briefing FAMM’s technical committee on key findings of the study, including the fundamental trade-offs and the performance of the robust adaptive plans described in this document. The feedback and results of this final engagement were reflected in the analysis presented in this report and in the MWP.

These interactions with Monterrey’s diverse water-planning community were important for designing a framework that could assist in evidence-based policy deliberations for the MWP. Therefore, the list of projects considered in the study, as well as the uncertainties and performance metrics used in the analysis, reflect the multiple priorities and interests reported by these actors in the workshops. For instance, the information we gathered on the cost of the MWP and its potential effect on reliability captures the diverging points of view among stakeholders with respect to how best to expand water infrastructure in the city. On one side of the spectrum of preferences, some of the stakeholders were more interested in ensuring the reliability of the system because water is a critical resource for the city’s economic and social development. On the opposite side of the spectrum, there were stakeholders who were more concerned about the potential fiscal burden of the MWP on the city. Project proposals were another channel used by stakeholders to put forward their preferences, and, as a result, the set of projects considered in the study became very diverse, including traditional supply expansion projects but also unconventional options, such as wastewater injection, network efficiency, desalination, and regulatory changes.
The framework that resulted from the interactive workshops is summarized in Table 2.2. It is structured, as is typically the case during the framing stage of an RDM analysis, using the XLRM framework (X = uncertainties, L = options and strategies, R = model relationships, M = performance measures). In this framework, the category uncertainties (X) represents exogenous factors over which the decisionmakers do
not have influence or control. In the context of Monterrey’s water plan, SADM and FAMM do not have control over how large water demand will grow in the future; water demand is partly the result of other factors, such as population and economic growth. Greater industrial activity and new business development may well attract more people and businesses into the city. Yet the reality is that no one can predict Monterrey’s economic future. As a result, the water utility cannot, nor should it, develop an infrastructure plan considering a fixed view of the future. Section 2.3 describes the uncertainties in more detail.

The category options and strategies (L for policy levers) describes the alternatives that water planners in the city have at their disposal for expanding the capacity of Monterrey’s water system. These options were derived from workshop discussions with Monterrey’s water experts. We then estimated for each option the specific construction and operational costs that would be incurred were these projects to be developed. At an aggregate level, these options could be placed into two groups: (1) infrastructure options that expand the current system’s supply capacity by exploit-
ing new water resources and (2) demand-management measures that make more efficient use of existing water resources. Section 2.4 describes the different options that we evaluated to ensure good performance over a wide range of futures. The category performance measures \( (M) \) describes the quantitative measures that we used to evaluate and compare the merits of different system configurations. In this study, we compared water-supply reliability in the system (i.e., the probability that the system will be able to satisfy water demand at any given time) with total investment costs (i.e., construction and operational costs), presenting a critical trade-off that can be described through these measures. If water planners in Monterrey invest too heavily on water infrastructure, then system reliability will likely be high, but parts of the resulting system may lie idle, thus becoming unnecessarily expensive. In contrast, if water managers invest too little, then the system will frequently be unable to meet water demand, increasing its vulnerabilities. In this respect, our study focuses on identifying the trade-offs in this decision context. The goal is not to dictate a solution but instead to provide decisionmakers with much better strategic insight into their near-term options and how to modify their adaptation strategies for the medium and long terms. See Section 2.5 for more elaborations on the performance measures.

Lastly, the category model relationships \( (R) \) describes the causal links, represented by computer models, used for evaluating the performance of these options across the exogenous uncertainty factors identified. It is through these computational tools that we assess the effect \( (M) \) that different courses of action \( (L) \) have on system outcomes across different alternative future states of the world \( (X) \). The objective of developing and using these models is to be able to describe formally and unambiguously the causality in the system. Section 2.7 describes the modeling framework used in this study.

### 2.3. Uncertain Future Drivers of Water-Management Conditions

We explored future uncertainty based on four aspects of water management relevant to Monterrey: water demand, surface-water availability, groundwater availability, and desalination costs.

#### 2.3.1. Water Demand

Future water demand in Monterrey is deeply uncertain because demographic, socioeconomic, and technological conditions that determine water demand can change rapidly and abruptly in response to other phenomena, such as local and foreign macroeconomic trends, technological progress of different platforms, and migration patterns. If the economic growth of Monterrey continues, both residential and industrial water demand would be expected to rise unless these new needs were completely offset by increased water-use efficiency. The economic growth of Mexico’s north is highly dependent on the economic outlook and ties with the North America region.
(e.g., North American Free Trade Agreement renegotiation). However, the current political environment in the region makes it difficult to anticipate whether such economic ties will continue in the coming years, thus creating a wide range of possibilities regarding the economic future of Monterrey. In addition, current urban policy and sprawl patterns in Monterrey make it difficult to anticipate whether the city will become denser in the future or if current urban sprawl patterns will continue during the next decades (Hernández, 2008). The pattern of growth would affect water demand because urban sprawl tends to use more water per capita than high-density growth. Finally, migration in and out of the city is also deeply uncertain. Future population growth in the city will depend on the economic performance and job opportunities in the city and in neighboring U.S. cities but will also depend on the future economic performance of other rapidly growing cities in Mexico (e.g., the Bajío region).

Figure 2.2 shows the historical water demand from 1981 to 2016 and a set of plausible future demand projections through 2050. The future projections are derived from a detailed exploratory analysis of plausible future water demand using an econometric water-demand model, described in Appendix B. The projections are labeled according
to the quantile within the full range of demands explored. For example, quantile Q50 describes the median result in the whole set of water-demand futures considered.

The panel on the left shows the steady increase in water demand over the last 35 years. In the past, as water demand increased, water planners expanded the water supplies and supporting infrastructure. As a result, for the most part of its history, Monterrey’s water system has had high reliability (i.e., probability of satisfying demand at any given time), which is currently estimated at 97 percent. The right panel shows that demand is expected to continue to rise in all but a small share of the plausible futures developed. As such, the system will require additional expansion of capacities or the acceptance of declines in system reliability.

2.3.2. **Surface-Water Availability**

Monterrey derives its surface-water supplies from three main surface-water reservoirs (La Boca, Cerro Prieto, and El Cuchillo Reservoir) and from four independent groundwater fields (Monterrey Metropolitan Area, Mina, Buenos Aires, and Santiago). Table 2.3 indicates sustainable flow at the 97-percent reliability level for each of Monterrey’s supply sources.\(^1\) The current system is 97-percent reliable, so we use this as the standard for desired performance in our study.

Future river inflows into Monterrey are deeply uncertain because they depend on global climatology that is changing in ways difficult to predict as concentrations of greenhouse gases increase (Deser et al., 2012). Climate change is deeply uncertain because it is difficult to anticipate at the local level whether its effects will be the cause of drier or wetter conditions (Tebaldi et al., 2005). There is also significant uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>Sustainable Supply (m(^3)/s) at 97-Percent Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monterrey Metropolitan Area Groundwater Field</td>
<td>0.88</td>
</tr>
<tr>
<td>Mina Groundwater Field</td>
<td>0.43</td>
</tr>
<tr>
<td>Buenos Aires Groundwater Field</td>
<td>1.80</td>
</tr>
<tr>
<td>Santiago Groundwater Field</td>
<td>0.81</td>
</tr>
<tr>
<td>La Boca Reservoir</td>
<td>0.73</td>
</tr>
<tr>
<td>Cerro Prieto Reservoir</td>
<td>3.63</td>
</tr>
<tr>
<td>El Cuchillo Reservoir</td>
<td>4.78</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13.06</strong></td>
</tr>
</tbody>
</table>

1 The sustainable flow is the amount of water that each source can deliver on a constant basis at the indicated probability. Higher probabilities are associated with lower constant flows that can be delivered, lower probabilities are associated with higher flows that can be delivered.
in how any hydrology changes would affect the system as the hydrological dynamics of the water basins and rivers upon which the city’s supply depends are not completely understood or represented in available models.

As described next, we simulate the performance of the water-management system using different assumptions about future hydrological conditions. To represent the potential uncertainty in future hydrology, we developed 54 different hydrological projections that reflect different variations in streamflow across six sub-basins (discrete bins with variations from −20 to +20 percent change) and, for completeness, different timing of historical variability, which essentially cycles (i.e., through permutations without repetition) the 1992 to 2004 historical dry period through the future simulation period. This range is informed by an ensemble of downscaled global climate models, which suggest that plausible variations in regional temperature and precipitation patterns could lead to a wider range of drier and wetter conditions than in the recent historical conditions. There is no guarantee that hydrological conditions would be wetter or dryer in the future. Regardless, this range allows us to perform a sensitivity analysis around the historical conditions that will inform an improved adaptive plan. Appendix C provides more detail on the methods and approach used for creating this ensemble of hydrological scenarios.

Figure 2.3 highlights the broad range of future hydrological conditions considered in the study. Each panel describes mean runoff per year for different basins. The thick blue line indicates the recent historical record but transposed into the future as one sequence that replicates historical conditions. The gray lines denote the alternative hydrological projections.

2.3.3. Groundwater Availability
Monterrey currently derives 30 percent of its supply from groundwater. Furthermore, several future water-management options under consideration rely on groundwater resources. However, little is known of the geological composition, storage capacities, or hydrological dynamics of the aquifers from which different groundwater alternatives will be developed (Mora et al., 2017; Taylor et al., 2012), and this is of particular concern to stakeholders. Some of the aquifers present challenging geological compositions (i.e., limestones, shales, and karstic stones) and locations that could potentially produce less water than anticipated, as the risk of fracture is higher. At the same time, based on the city’s previous experience exploiting some of the local aquifers, several of the local experts believe that the amount of water that could be sustainably extracted from the local groundwater reservoirs may prove to be higher than anticipated. In response to this, water planners are currently designing a strategy for the systematic collection of evidence that could guide the design and implementation of the different proposed groundwater projects. The results from this study will not be available until 2020.

As such, the uncertainty associated with the potential availability of groundwater resources in the city is an important dimension to consider in this analysis. There is
Figure 2.3
Range of Hydrological Projections by Basin

Notes: Range of future hydrological conditions considered in the study. Each panel describes mean runoff per year (in m³/s) for different basins. The blue line indicates the recent historical record but transposed into the future as one sequence that replicates historical conditions. The gray lines denote the alternative hydrological projections developed for this study.
a lack of information about how the sustainable groundwater yield could vary from the current estimate. We therefore consider a wide range of yields, between 70 and 130 percent of the current estimate. This range covers the estimated recommendations made by local groundwater experts regarding the uncertainty associated with the potential sustainable supply yields of the project proposals considered in the study. Although there is uncertainty regarding the potential yields of groundwater resources in the region, it is very unlikely that this variability exceeds the range proposed in this study, as suggested by recent groundwater modeling efforts conducted in Mexico (Hernández et al., 2011).

2.3.4. Desalination Costs

Given its proximity to the Gulf of Mexico, desalination of seawater is an option for expanding Monterrey’s water supply. Desalination is generally more expensive than conventional surface or groundwater supplies owing to high energy costs, but there are circumstances in which the cost and reliability attributes can be favorable as part of a portfolio of water-management options. Furthermore, as costs decline with growing technological efficiency, desalination projects become increasingly favorable. Thus, trends in desalination cost have immense strategic importance for developing the MWP. If desalination technologies continue to improve while implementation costs decline, then it may be better for water planners in Monterrey to wait and analyze the suitability of implementing the desalination project later in the future. In contrast, if cost and efficiency of this technology were not to improve much further, this would drastically change the opportunity cost of implementing this alternative. Thus, it is fundamental for water planners in Monterrey to analyze the potential implications that technological improvements in desalination technologies may have on the configuration of the city’s water plan.

Desalination technologies have improved markedly over the past 30 years primarily because of improvements in membrane module performance and reduction in energy consumption (Reddy and Ghaffour, 2007). These technological improvements have led to cost reductions (Figure 2.4).

This marked improvement in desalination technologies may continue to grow. Yet it is difficult to anticipate how much further this technology could continue to move down the cost curve, given that this will depend in part on the speed of its diffusion and implementation in various water systems. Projections of future desalination costs suggest likely reductions but significant uncertainty—in particular because of uncertain energy costs. For example, Voutchkov (2017) suggests that incremental improvements to desalination membranes; innovative thermal, membrane, or hybrid desalination technologies; and equipment improvements could bring down the cost of desalination by 20 percent over the next five years and 60 percent over the next 20 years. According to this projection, within 20 years, the cost of desalinated water could move from the range of 0.8–1.2 U.S. dollars/m³ in 2017 to 0.3–0.5 U.S. dollars/m³. At
these lower costs, desalination would be less expensive than some other water-supply options, such as the proposed large-scale aqueduct.

We sample uniformly across a range of desalination costs to most efficiently identify any critical cost thresholds for this study. The most optimistic cost-reduction scenarios in our ensemble assume that the desalination project currently under consideration will be 30 percent less expensive by 2027, while the most-pessimistic scenarios assume that this project will in fact be more expensive (i.e., up to 5 percent more expensive) in the future.

2.4. Options and Strategies

Water planners in Monterrey have at their disposal an array of options that could be implemented to expand the city’s water infrastructure. Over the course of this study, we interacted closely with local stakeholders to define and characterize a comprehensive list of such options for inclusion in the MWP. Through various technical workshops, we discussed at length each one of the options currently being considered and carefully scrutinized whether they should be considered in the study. As a first step, we included in deliberations all alternatives proposed by the stakeholders without establishing a selection criteria to be as inclusive of stakeholders’ concerns as possible. Subsequently, we selected a subset of alternatives for which we could establish a reliable estimation
of their costs, design, and potential effect on water supply. As a second step, after carrying out a first iteration of RDM analysis (i.e., phase one of the study), we removed from the set of alternatives those options that were considered politically unfeasible by stakeholders. This included the International Reservoir Falcon, which supplies water to the United States and Mexico. In the end, 15 options were identified as legally and financially viable for inclusion in the analysis. These options include a wide diversity of approaches and scales, as described below. Section 2.4.1 describes in greater detail the characteristics of these alternatives.

While many options were discussed in these workshops, we only included in this study those for which there was sufficient technical detail (i.e., project location, technology to be used, design capacity, required complementary infrastructure) to support a reliable estimation of implementation and operational costs and that were held to be feasible by local stakeholders. For example, increasing Monterrey’s forest cover was repeatedly mentioned in our interaction workshops as an alternative for expanding water-supply capacity (i.e., through improved filtration to groundwater reservoirs). However, there was insufficient information and tools that we could use to estimate the potential costs of this alternative and its effect on groundwater supplies.

It is not possible to evaluate the suitability of these projects by considering solely their design capacity and total investment costs. In this decision context, the evaluation of options is far more complex because these options interact non-linearly within the water system. Some of the options would complement one another (e.g., an injection well and new groundwater wells), while others depend on interdependent water sources (e.g., Cuchillo II Dam, La Libertad Dam, and Tunnel San Francisco II) or are affected differently by current operational rules in the system (e.g., Cuchillo II Dam, groundwater wells). In addition, the uncertainties described in the previous section affect each of these options in different degrees and forms. As a result, from a systemic point of view, it is preferable to analyze the suitability of these options by evaluating their performance within different investment portfolios.

---

2 Operational changes to this reservoir were considered to be unfeasible because these would require modifying current water treaties between the United States and Mexico. Given the fact that Mexico is currently running a deficit on water delivery on this treaty and the prevailing political environment with respect to the economic and political relations between and United States and Mexico, stakeholders considered this to be a politically unfeasible alternative.

3 Nonlinear behavior exists under three circumstances. First, because of hydrological variability, a reservoir or a groundwater well does not always supply water according to its design capacity. If water availability is high, then it can do so; if water availability is persistently low, water supply will be less than the design capacity. Second, because of storage capacity, the behavior of this type of project is subject to important delays, as a lack of runoff in a given period is only perceived after certain period of time. Third, the volume of water available for extraction depends on the number of projects using a specific water resource. If more than one project extracts water from the same source and hydrological conditions are not favorable (i.e., less available water for extraction), it is possible that one or both projects are unable to supply water at their design capacities.
For this study, we evaluate options as elements of different investment portfolios implemented in one of three different periods: near term (2016–2026), medium term (2027–2038), and long term (2039–2050). Portfolios chosen in successive periods thus represent adaptive strategies. We do not evaluate all possible portfolios, as the 15 options could be combined, over the three decision periods considered, in millions of different ways. Instead, we use an optimization engine to iteratively identify the most-effective portfolio of options of a specified set of future conditions (see Chapter Four). Tariffs are also considered as an alternative approach to influencing demand, and thus they are evaluated on top of the adaptive portfolios. Section 2.4.2 describes in more detail how tariffs are considered in the study.

### 2.4.1. Traditional Water-Management Options

Table 2.4 lists the complete set of infrastructure options considered, excluding tariffs. Each option is described in terms of its total investment cost—including both construction and operational costs (only over the initial 15 years of its operation); its design capacity; and its feasibility across environmental, financial, legal, social, and technical dimensions—scored qualitatively, through documental analysis and consultation with experts, using a three-point scale (1 = low feasibility, 2 = medium feasibility and 3 = high feasibility). The specific supplied flow of each option depends on how these interact with the water-management system and exogenous forces (e.g., hydrological conditions). As described next, the supplied flows are estimated for each future using the water-management model. The projects are ordered by total investment costs.

This set of options includes groundwater projects (i.e., the Ballesteros–Buenos Aires, Monterrey Country, El Pajonal, and Obispado Groundwater Wells), shallow wells in the river’s hyporheic zone\(^4\) (i.e., the Conchos, La Union, and Pilon Chapotal Rivers), new or expanded surface-water reservoirs (i.e., Cuchillo II Dam, La Libertad, and Vicente Guerrero), new diversion projects (i.e., Tunnel San Francisco II and Panuco Aqueduct), a treated wastewater injection well project,\(^5\) increased efficiency in distribution networks, and a desalination plant. This is a diverse set of options that vary greatly by their water-supply capacities, associated water sources, and sensitivity to changing climate conditions.

---

\(^4\) For ease of reading, in the rest of the document, we refer to shallow wells in the river’s hyporheic zone simply as **shallow wells**.

\(^5\) Treated wastewater is injected into aquifers and wells to be used as needed as part of groundwater banking. For this alternative, injected water follows CONAGUA regulations and standards, which require injected water to be treated at potable levels.
<table>
<thead>
<tr>
<th>Project Name</th>
<th>Total Investment (in Millions US $)</th>
<th>Construction Cost (in Millions US $)</th>
<th>Operational Cost (in Millions US $)</th>
<th>Capacity (m³/s)</th>
<th>Environmental Feasibility</th>
<th>Financial Feasibility</th>
<th>Legal Feasibility</th>
<th>Social Feasibility</th>
<th>Technical Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monterrey Country Groundwater Well</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0.1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Obispado Groundwater Well</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>0.1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Shallow Wells: Pilon Chapotal River</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>0.3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>El Pajonal Groundwater Wells System</td>
<td>14</td>
<td>12</td>
<td>2</td>
<td>0.3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Shallow Wells: Conchos River</td>
<td>17</td>
<td>12</td>
<td>5</td>
<td>0.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Tunnel San Francisco II</td>
<td>19</td>
<td>18</td>
<td>1</td>
<td>0.32</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Ballesteros–Buenos Aires Groundwater Well</td>
<td>41</td>
<td>37</td>
<td>4</td>
<td>0.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Shallow Wells: La Union</td>
<td>51</td>
<td>43</td>
<td>8</td>
<td>0.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Efficiency</td>
<td>100</td>
<td>90</td>
<td>10</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>WW Injection Well Project</td>
<td>148</td>
<td>100</td>
<td>48</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>La Libertad Dam</td>
<td>184</td>
<td>160</td>
<td>24</td>
<td>1.5</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Cuchillo II Dam</td>
<td>460</td>
<td>352</td>
<td>107</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Vicente Guerrero Dam</td>
<td>796</td>
<td>619</td>
<td>177</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Panuco Aqueduct</td>
<td>1,354</td>
<td>1,113</td>
<td>241</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Desalination plant in Matamoros</td>
<td>1,406</td>
<td>1,055</td>
<td>351</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

NOTES: Complete set of infrastructure options considered, excluding tariffs. Each option is described in terms of its total investment cost, including both construction and operational costs, its design capacity, and its feasibility across environmental, financial, legal, social, and technical dimensions, scored qualitatively using a three-point scale (1 = low feasibility, 2 = medium feasibility and 3 = high feasibility).
2.4.2. Alternative Water Tariffs

In addition to these infrastructure options, we were also asked by stakeholders to include in the analysis new water tariffs as a measure for managing water-demand growth in Monterrey’s metropolitan area.

The introduction of new water tariffs as a tool of water policy is frequently controversial (Grafton, Chu, and Kompas, 2015; Marzano et al., 2018; Sahin, Bertone, and Beal, 2017). From a traditional policy analysis perspective, it is difficult to quantify the potential positive and negative effects that new water tariffs may have on the system as it would be necessary to consider how consumer welfare is affected by the introduction of new tariffs. In addition, economic considerations alone are unlikely to be sufficient to evaluate the cost and effectiveness of the introduction of new water tariffs to the satisfaction of all stakeholders.

Thus, in this analysis, water tariffs are treated as an additional alternative (i.e., regulatory policy change) that can increase water-consumption efficiency. We estimated the potential effect of changes in water tariffs by evaluating their effect when combined with a portfolio of the infrastructure options described earlier. Using this approach, we do not make a normative assessment regarding whether new tariffs should be implemented. Rather, we quantify how this regulatory change affects how we would view adaptation options in the medium and long terms and whether it increases the resilience of Monterrey’s water system.

The current tariff schedule in Monterrey and its metropolitan area consists of 13 categories segmented by at least seven different types of users. Table 2.5 describes in an aggregated form this tariff segmentation, along with the current consumption share for each.

Three segments represent the sources of greatest demand: domestic users in single-family homes, public-sector users, and commercial and industrial users. These account for a full 89 percent of water demand in recent years. As a result, the alternative water-tariff schedule developed for this project focuses on these water-consumption blocks.

We developed a tariff optimization tool for exploring an alternative tariff schedule. This tool first estimates the price-demand elasticity for potable water across different categories.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Share of Total 2015 Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-family residential</td>
<td>66.1%</td>
</tr>
<tr>
<td>Multifamily residential</td>
<td>3.1%</td>
</tr>
<tr>
<td>Commerce and industry</td>
<td>11.5%</td>
</tr>
<tr>
<td>Public sector</td>
<td>19.3%</td>
</tr>
</tbody>
</table>

NOTE: Water-consumption shares in Monterrey for different water-tariff segmentation groups.
Different consumption groups in the current tariff structure. It then finds modifications to the current tariff schedule with the objective of reducing water consumption. The optimization process is constructed around two constraints: The consumer groups specified to have the greatest socioeconomic vulnerability (i.e., low-income households) may not be subjected to water-tariff increases, and the revenues of the water-utility company cannot be permitted to fall below the current level. More information regarding the tariff optimization tool used for this part of the analysis can be found in Crespo (2017b).

Figure 2.5 compares the proposed water-tariff schedule from the optimization tool (i.e., blue line) to the existing water-tariff schedule (i.e., orange line) in Monterrey for the single-family residential groups. The new tariff schedule reduces the number of tariff segments from approximately 100 (13 segments with at least seven different user types) to ten, protects the lowest-income households by keeping their water tariffs at the same level as today, and, for the rest of consumers, proposes an average price increase of 27 percent, increasing revenues of the water-utility company by 41 percent.6

6 Although derived from an optimization tool, there is, of course, no suggestion that such a new tariff schedule would be politically or socially acceptable. The analysis conveyed in this section is intended to illustrate how one could explore how a potential change in tariff structures interacts with the other infrastructure investments.
2.5. Performance Measures

We worked with the local stakeholders and Monterrey’s water planners to define two key performance measures—performance and cost. Performance is evaluated with respect to the reliability of Monterrey’s water system. These two measures are used to identify the conditions under which a water-system configuration (i.e. infrastructure and regulations) does not meet the management objectives and to compare the performance of alternative strategies in the near, medium, and long terms. In this study, we define reliability as the probability of monthly supply meeting monthly demand. This approximates the probability that the average consumer will see water coming out of the tap when they turn the faucet on.

The cost-performance measure is estimated only for the infrastructure-based adaptation options and not for the potential tariff schedule, which is a regulatory change. The cost is calculated by adding the upfront, or capital, cost of an option to the first 15 years of annual operational costs brought to net present value using a 5-percent discount rate. These two cost components are brought to present value because stakeholders in Monterrey are interested in securing funds for both building new water infrastructure and supporting its optimal performance. Thus, any funding strategy would provide the local water-utility company a window of time for implementing the necessary management and regulatory changes to accommodate the new water-supply infrastructure.

2.6. Simulating the Performance of Monterrey’s Water-Management System

To estimate how the Monterrey water-management system would perform in the future with and without an augmented water-management strategy, we developed an IAM, which integrates several models within an optimization framework to define optimal water-management adaptation strategies—sequences of options that are implemented

---

7 Formally, \[ \text{Reliability} = \frac{\sum_{t=1}^{n} \max\left(\min\left(D_t - S_t, 0\right), 0\right)}{\alpha} \], where \(D_t\) and \(S_t\) represent water demand at water supply at time \(t\); \(n\) indicates the number of periods considered in the reliability estimation, and \(\alpha\) is the interperiod reliability tolerance (i.e., in this study, it is set to 95 percent).

8 This 5-percent discount rate is conservative, as it is set higher than the 3.3-percent discount rate recommended by Mexico’s Ministry of the Treasury and the World Bank using the rate of time preference method (Coppola, Fernholz, and Glenday, 2014).

9 The estimated operational cost for each project is estimated as a function only of its supply capacity for a fixed operational period of 15 years. An alternative approach would be to consider the actual water volumes being supplied by each infrastructure option. But these may vary across different demand, climate, and groundwater conditions and would entail more-complex present-value calculations according to its period of implementation. Thus, the former approach is more conservative in nature, as it results in higher-estimated operational costs compared with the latter.
over time. An econometric autoregressive distributed lag (ARDL) demand model is used to define the demand projections in a way that accounts for variation across time and geography. Similarly, a Markov autoregressive hydrological model (MARHM) is used to generate the hydrological projections of surface-water flows in a way that their stochastic behavior is calibrated using the available historical data. These projections, combined with additional assumptions about groundwater yield and desalination costs and the list of available options, are then inputted into a dynamic-optimization engine that seeks to define the optimal investment sequence that meets Monterrey’s water planners’ reliability objective while minimizing investment costs. Figure 2.6 describes this architecture. Appendix B provides additional detail on these models, and Appendix C provides additional detail on the methods used for developing the scenario projections for each module in the IAM.

This IAM-scenario generator estimates the optimal investment path for the three decision periods considered in this study (i.e., near term = 2016–2026, medium term = 2027–2038, and long term = 2039–2050) for each specific combination of future demand, hydrological conditions (i.e., surface-water flows), groundwater-availability assumptions, and desalination costs over time. In each future instance (i.e., combination of conditions), the IAM derives the project portfolio that would be optimal for conditions occurring during the first period; then, based on this decision, it estimates

---

**Figure 2.6**

Integrated Assessment Model to Estimate System Performance and Define Optimal Adaptation Pathways

the optimal expansion of Monterrey’s water infrastructure for the second decision period and, subsequently, for the third decision period.

2.7. Characterizing the Uncertain Future

This study evaluates how Monterrey’s current water-management system would perform across a wide range of plausible futures. We then identify additional options that, as part of an adaptive strategy, would improve the robustness of the water-management system.

Table 2.6 describes the experimental designs used in the study. We first define a test-bed set of plausible futures for the current water-management system that reflect the uncertainties described in section 2.3 (Table 2.3). This “experimental design” is constructed by first combining each of the 12 water-demand projections with the 54 hydrological projections for a “full factorial” design of 648 futures. Next, for each of these 648 futures, random values of groundwater assumptions are combined (ranging between 70 and 130 percent of the current estimate) to yield a 648-element design that varies demand, hydrology, and groundwater assumptions (see Appendix C). This design is used to evaluate the vulnerabilities of the current water-management system, as described in Chapter Three.

For the second experimental design, the 648 demand and hydrological futures are combined with random values of groundwater assumptions and desalination costs to yield a 648-element design that varies demand, hydrology, groundwater assumptions, and desalination costs. This design is similar to the first, except that it combines

<table>
<thead>
<tr>
<th>Table 2.6</th>
<th>Experimental Designs to Reflect Plausible Futures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>Surface-Water Flows</td>
</tr>
<tr>
<td>Experimental design 1</td>
<td>12 projections</td>
</tr>
<tr>
<td></td>
<td>648 full factorial sample</td>
</tr>
<tr>
<td>Experimental design 2</td>
<td>12 projections</td>
</tr>
<tr>
<td></td>
<td>648 full factorial sample</td>
</tr>
<tr>
<td>Experimental design 3</td>
<td>12 projections</td>
</tr>
<tr>
<td></td>
<td>648 full factorial sample</td>
</tr>
</tbody>
</table>

NOTES: Set of experimental designs used in the study. Demand, surface-water flows, groundwater, and desalination-cost scenarios used are indicated for each design. Total number of elements and the tariff schedule under analysis are also indicated.
the original full factorial design of water demand and hydrological uncertainty with a matching Latin Hypercube sample across groundwater-availability and desalination-cost uncertainties. This second design is used when developing adaptation strategies, as described in Chapter Four.

The last experimental design explores the effect of changing the current tariff schedule to one that incentivizes water conservation. The new tariff schedule would have an effect on water consumption and is simulated by the ARDL water-demand model. This experimental design is the same as the second design, but with demands that reflect the proposed tariff schedule. The analysis of new tariffs is described in Chapter Four.

These experimental designs allow for the evaluation and direct comparison of different future ensembles. The first experimental design allows for the identification of vulnerabilities in the context that was initially considered more relevant by the group stakeholders (i.e., demand, surface water, and groundwater). The second experimental design expands the analysis to jointly consider groundwater variability and the potential reduction of desalination costs to enable the consideration of new options and strategies. The third experimental design allows for the direct comparison of experimental design 1 and experimental design 2 under two alternative policy levers sets: one that considers only infrastructure investments and another that expands this original set of policy alternatives including regulatory changes (i.e., water tariffs). The cross-sectional comparison of the robust strategies resulting from these three experimental designs is illustrative for comparing costs across different robust strategies and how thresholds for specific medium- and long-term investments may be affected by changing assumptions and by an expanded set of policy options.

Evaluating these experimental designs required significant computational effort. One iteration of the RiverWare model developed for this study requires on average 10 seconds to be completed on a single computer processing unit (CPU) core. One full run of the IAM (i.e., dynamic optimization algorithm in combination with RiverWare model) requires on average 2,500 simulation runs to estimate the optimal dynamic expansion of the system. Thus, completing the second phase of our analytical approach—defining optimal strategy for each future—required approximately 4.9 million simulation runs (i.e., 2,500 x 3 x 648). This analytical task could not have been completed using only one CPU, as completing one sequence of the analysis would take close to four years. As a result, for this study, we developed a computational architecture that as much as possible runs the different processes of this workflow in parallel. The computer cluster used for this study comprises several virtual computers using in total 320 CPU cores. This made it possible to complete a full iteration of the

---

10 A Latin Hypercube experimental design will yield a set number of data points by sampling all regions of the multidimensional uncertainty space equally. This contrasts with either a Monte Carlo design, which would sample this space randomly up to the specified number, or one that would weight the sampling by presuming a probability distribution.
Developing a Robust, Adaptive Water-Management Strategy

2.8. Analyses to Stress Test and Improve the Robustness of Monterrey’s Water-Management System

Following the RDM methodology, this study performs an iterative analysis that first identifies vulnerabilities of Monterrey’s water system, then identifies new strategies that would perform better under future conditions, and then lastly defines an adaptive, robust strategy (Figure 2.7).

In the vulnerability analysis stage (described in Chapter Three), the IAM evaluates the current management system across a set of futures reflecting uncertainty. The results of these simulations are examined to identify the main drivers of vulnerability. In the optimal strategies stage (described in Chapter Four), the IAM calculates the optimal portfolio of options across the three periods for each uncertain future. Then in the robust, adaptive strategy stage, the results from the optimal strategy runs inform the definition of the three components of a robust strategy: low-regret, near-term portfolios, signposts to trigger new options, and contingent options. Consistent with the iterative nature of an RDM analysis, the resultant robust, adaptive strategy is lastly tested against an alternative tariff structure. The details of this process are also defined in Chapter Four.

Figure 2.7
Analytical Steps Used in the Study

| Vulnerability analysis | • Evaluate current management system across plausible futures.  
|                       | • Describe drivers of low reliability. |
| Optimal strategies    | • Develop optimal investment pathways for each plausible future. |
| Robust, adaptive strategy | • Select low-regret, near-term portfolio of options.  
|                       | • Identify signposts and options contingent on future conditions.  
|                       | • Define robust, adaptive strategy.  
|                       | • Test robust, adaptive strategy against a revised tariff structure. |

NOTE: Each block lists the analytical steps completed under each phase of the study.
CHAPTER THREE

Future Vulnerability of Monterrey’s Water Supply

To answer the important question of how best to prepare Monterrey’s water system for the uncertain future, we first must understand what challenges might lie ahead. Even though local stakeholders share a sense of urgency in the need to prepare for expanding water needs, the specific vulnerability of the existing system has not been quantified previously.

In this first analytical phase, the IAM is used to evaluate the performance of the current water-management system across hundreds of plausible futures. Below, we first illustrate how demand, supply, and unmet demand evolve over time under two sample futures. Then we use a reliability metric to summarize unmet demand over time across the full set of futures. Those cases with reliability below a specified threshold are shown as vulnerable.

3.1. Performance of the Current System

We used the IAM described in Chapter Two to perform the evaluation of current system performance across widely differing futures. Each run of the model traces out how demand would change over time and how different supplies could be allocated to meet those demands, given the constraints on water availability and the current infrastructure. The performance of the system is characterized by its reliability—percentage of months in which supply meets at least 95-percent demand. The system is considered vulnerable for a specific period (i.e., near term, medium term, or long term) if this percentage is below 97 percent and nonvulnerable otherwise.

As an example, Figure 3.1 shows projected total water demand for Monterrey over time (line) and sources of supply (colored stacked bars) for a future in which demand growth is projected to grow slower than current trends (e.g., fifth percentile) and hydrological conditions are more favorable than historical conditions (e.g., 20-percent wetter conditions than historical mean conditions). In this case, the system is, for the most part, capable of meeting demand conditions in the first and last periods. However, in the later years of the second period and the early years of the third period, demand
can no longer be met with current available water resources and capacities, leading to noticeable unmet demand levels. Specifically, the model projects the following:

- Demand remains at 12.34 m$^3$/s through 2038 and then grows slightly to 14.2 m$^3$/s by 2050.
- Demand is completely met in 82 percent of the months in total. The reliability of the first period (2016–2026) is 84 percent, that of the second period (2027–2038) is 75 percent, and the reliability of the third period (2039–2050) is 83 percent.

Figure 3.2 shows another example in which demand is projected to be more rapid (e.g., 90th quantile) and hydrological conditions are 20-percent drier than in the past. For this case, the model projects far less-favorable outcomes:

- Demand is completely met in only 2 percent of the months. The reliability of the first period (2016–2026) is 11.8 percent; for the second and third periods, it is 0 percent.
3.2. Vulnerabilities of Current System

For all simulations, we define a vulnerable case as one that fails to meet the current reliability levels in Monterrey—97 percent. Based on this definition, the two previous examples are vulnerable, as they fail to meet this performance threshold in all three simulation periods.

To more fully characterize the vulnerability of the system, we estimate the reliability level of Monterrey’s current water system for each plausible future for the first experimental design described in Chapter Two. Recall that this design is built around uncertainties in demand, hydrology, and groundwater availability. Figure 3.3 shows, for each period, average annual reliability during the years of that period for each future. Each mark in the scatter plot represents an individual combination of demand (horizontal axis), hydrological conditions (vertical axis), and groundwater conditions (higher groundwater availability on left and lower groundwater availability at right). Note that the figure shows the actual projected demand for each period and the average surface-water inflows into the system as an aggregate measure of the hydrological conditions. Groundwater availability results are binned into two groups—below historical groundwater availability and equal to or greater than historical groundwater availability. Each mark also denotes whether the current system is vulnerable under that specific future (signified by the “x”) or not, based on the 97-percent reliability threshold. The color legend further describes the estimated level of reliability—colors...
closer to the red margin indicate low reliability levels, and colors closer to the light-green margin denote reliability levels nearer to the system’s reliability objective.

The results of this initial assessment of vulnerabilities are clear: The current capacities of Monterrey’s water system are not sufficient to sustain current reliability levels in the near, medium, or long terms. Relatively small increases in water demand will certainly reduce the reliability of the system below the current 97-percent level even if, in most cases, the decrease or increase in water availability from current sources is relatively minor.

Figure 3.3
Current System Reliability Across Futures for Three Implementation Periods

NOTES: Each mark in the scatter diagram represents an individual combination of demand (horizontal axis), hydrological conditions (vertical axis), and groundwater availability (panels). The color legend describes the estimated level of reliability. The “x” indicates results in which reliability is below 97 percent. cms = cubic meters per second.
These results confirm the intuition and previous analyses of local stakeholders of the need to expand the supply capacities of the current system. This initial assessment does not imply that the city faces an imminent water crisis if it fails to expand the system. Rather, it shows that if nothing is done to expand the capacities of the system or to make it more efficient, future increases in water demand may erode the reliability of Monterrey’s water system. This may be exacerbated further if adverse climate conditions affect current sources. If the current system is not expanded, these stressors are likely to materialize into more-frequent pressure losses and temporary cuts to water supply, which will ultimately affect the attractiveness of the city for investment or habitation.
4.1. Introduction to the Analytical Framework

The previous chapter described an analysis confirming that, across a range of plausible futures, the reliability of Monterrey’s water system would degrade below the historical level of 97-percent reliability. In fact, in cases of higher water demand and/or drier conditions, reliability could decline well below that level. In this chapter, we describe how Monterrey could augment its current water-management system by adding options in an adaptive way that would be robust in the sense of performing well regardless of future conditions. A robust, adaptive strategy includes a set of low-regret, near-term options that Monterrey can implement knowing that they represent good foundational investments for future adaptation. Accompanying the portfolio of near-term options is a set of medium- and long-term signpost conditions and associated medium- and long-term contingent options (Figure 4.1).

We are not attempting to forecast future outcomes but rather to understand the relative performance of different courses of action under various future conditions. Therefore, we would like to measure the “regret” attached to each alternative if we

Figure 4.1
Elements of a Robust, Adaptive Strategy

NOTES: Each block describes a component of the robust, adaptive strategy across time. Arrows indicate the sequencing of these elements, as well as data inputs into each component.
chose that course of action rather than the one that would have been optimal under each set of future conditions.\textsuperscript{1} We first use the IAM to identify an optimal strategy for each future included in the second experimental design (see section 2.7). Next, we use this standard to identify a small set of portfolios of near-term options that exhibit low regret in the measures that concern us. These portfolios include different combinations of options that are selected to be implemented during the first period. We then compare the cost and reliability characteristics of these near-term portfolios and use a decision-tree classification system to identify for each near-term portfolio those future conditions that should be monitored to inform future adaptations. These adaptations will take the form of possible additional options to implement under the different conditions. The results of these analyses then enable Monterrey to make a choice of low-regret, near-term options and a strategy for future adaptation. Finally, we show that the adaptive master plan derived during the course of this project is, indeed, robust to a wide range of uncertain, future conditions.

4.2. Optimal Portfolio of Options for Each Future

In Chapter Two, we described 15 options that would improve the performance of Monterrey’s water-management system. These options can be combined in various ways. A portfolio consists of a specific combination of projects selected for implementation over three periods. For instance, one portfolio alternative for the near term (2016–2026) might combine small groundwater projects (e.g., the El Pajonal and Obispado Groundwater Wells) with one surface project, such as the La Libertad Dam, and then implement larger-scale projects, such as the Cuchillo II and the Vicente Guerrero Dams, for the medium and long terms (2027–2050). In contrast, another portfolio could include only large-scale projects, for example, the Cuchillo II Dam in the near term and the Vicente Guerrero Dam, the Panuco Aqueduct, or the desalination plant for the medium and long terms.

We first use the IAM to identify those options that would meet or exceed the historical reliability target (97 percent) at the least cost. Table 4.1 shows the optimal portfolios corresponding to each of the demand projections for historical supply, current groundwater availability, and no change in desalination-cost assumptions.

This example shows that all optimal expansion portfolios estimated using our computational approach meet or exceed the reliability threshold set for our analysis. At the same time, this example also shows that the cost of meeting this threshold increases as higher water-demand scenarios are faced—from US $154 million under the water-

\textsuperscript{1} By definition, those courses of action that perform best under a specific set of future conditions have zero regret. We still may not care for the outcomes if that future is particularly stressful, but the zero-regret choice is the best we can do. We could measure regret in terms of each one of the measures we use to assess outcomes.
### Table 4.1
Optimal Portfolios for Various Water Demands for the Historical Climate Projection

<table>
<thead>
<tr>
<th>Total Cost</th>
<th>Q5</th>
<th>Q10</th>
<th>Q20</th>
<th>Q30</th>
<th>Q40</th>
<th>Q50</th>
<th>Q60</th>
<th>Q70</th>
<th>Q80</th>
<th>Q90</th>
<th>Q95</th>
</tr>
</thead>
<tbody>
<tr>
<td>$154 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$399 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$806 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$899 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1,694 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1,588 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1,969 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2,123 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2,281 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3,609 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4,379 M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>97%</td>
<td>98%</td>
<td>98%</td>
<td>98%</td>
<td>97%</td>
<td>98%</td>
<td>97%</td>
<td>97%</td>
<td>97%</td>
<td>97%</td>
<td>97%</td>
</tr>
<tr>
<td>Monterrey Country Groundwater Well</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obispado Groundwater Well</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Wells: Pilon Chapotal River</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Pajonal Groundwater Wells System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Wells: Conchos River</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunnel San Francisco II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ballesteros--Buenos Aires Groundwater Well</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Wells: La Union</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW Injection Well Project</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>La Libertad Dam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuchillo II Dam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vicente Guerrero Dam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panuco Aqueduct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desalination plant in Matamoros</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTES:** Rows depict available projects for inclusion. The header rows indicate the total cost and average reliability for each portfolio and demand-scenario combination. Colors indicate the period in which a project is implemented: dark blue = near term, light blue = medium term, and light gray = long term. The Historical Synthetic Climate Scenario represents a scenario calibrated to replicate historical conditions but transposed into the future as one scenario.
demand scenario Q5 (i.e., lowest projected water demand) to US $4.380 billion for the highest water-demand scenario considered (i.e., Q95).

The composition of these portfolios differs greatly across the demand scenarios. For the lower-demand projections (Q5–Q40), high reliability can be met by a combination of groundwater projects with network efficiency. In general, options are implemented in earlier periods for the higher-demand projections. If demand is higher than Q40, however, these options are not enough, and reliability can only be achieved through a combination of various dam projects, desalination, and the Panuco Aqueduct—the larger and more-expensive options.

As another example, Table 4.2 shows the same results but for a drier climate (−10-percent precipitation). In this case, one sees that more options are required earlier than under historical climate conditions. If demand is at the very high end of the scale, then all options are required by the second implementation period. Note also that, in the most-stressing conditions, the reliability objective cannot be achieved, even with all projects implemented.

Table 4.3 summarizes the percentage of times that an option is implemented in the optimal portfolio across the full set of futures, disaggregated by the implementation periods, three groupings of demand, and two groupings of climate conditions. It is important to note that no estimation of probability for any set of conditions enters into this analysis, but rather that these percentages are indicative of the probability that any given project is included in the optimal portfolio across the different combinations of groupings.

There are several main conclusions that can be drawn from this figure. In the first period, there are some projects that are never or rarely implemented (e.g., Vicente Guerrero Dam, Panuco Aqueduct). These options can be safely taken off the table for near-term implementation. There are also other projects that are always or almost always implemented (e.g., Conchos River Shallow Wells and Monterrey Country Groundwater Well). These options are likely good near-term options for a robust strategy. There are then several options for which implementation percentage varies significantly across the demand and supply categories (e.g., Cuchillo II Dam) or for which the implementation percentage is not low and not high (e.g., La Union Shallow Wells). The value of implementing these options in the near term is unclear, as we are not able to predict the future.

We can also see implementation percentages increasing in later periods, but there is still significant ambiguity about which options should be implemented even by the last period. In summary, the optimal expansion of Monterrey’s water system is not an invariant proposition but rather a dynamic one that changes significantly from one set of future conditions to another.
Table 4.2
Optimal Portfolios for Various Water Demands for a Dry Climate Projection (–10%)

<table>
<thead>
<tr>
<th>Total Cost</th>
<th>Q5</th>
<th>Q10</th>
<th>Q20</th>
<th>Q30</th>
<th>Q40</th>
<th>Q50</th>
<th>Q60</th>
<th>Q70</th>
<th>Q80</th>
<th>Q90</th>
<th>Q95</th>
</tr>
</thead>
<tbody>
<tr>
<td>$154 M</td>
<td>$387 M</td>
<td>$806 M</td>
<td>$1,047 M</td>
<td>$1,383 M</td>
<td>$1,900 M</td>
<td>$2,584 M</td>
<td>$2,265 M</td>
<td>$4,583 M</td>
<td>$4,583 M</td>
<td>$4,602 M</td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>97%</td>
<td>97%</td>
<td>97%</td>
<td>97%</td>
<td>97%</td>
<td>99%</td>
<td>97%</td>
<td>98%</td>
<td>97%</td>
<td>95%</td>
<td></td>
</tr>
</tbody>
</table>

- Monterrey Country Groundwater Well
- Obispado Groundwater Well
- Shallow Wells: Pilon Chapotal River
- El Pajonal Groundwater Wells System
- Shallow Wells: Conchos River
- Tunnel San Francisco II
- Ballesteros–Buenos Aires Groundwater Well
- Shallow Wells: La Union
- Efficiency
- WW Injection Well Project
- La Libertad Dam
- Cuchillo II Dam
- Vicente Guerrero Dam
- Panuco Aqueduct
- Desalination plant in Matamoros

NOTES: Colors indicate the period in which a project is implemented: dark blue = near term, light blue = medium term, and light gray = long term.
<table>
<thead>
<tr>
<th>Water-Demand Growth Levels</th>
<th>2016–2026</th>
<th>2027–2038</th>
<th>2039–2050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td><strong>Monterrey Country</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater Well</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>100%</td>
<td>72%</td>
<td>96%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>100%</td>
<td>80%</td>
<td>95%</td>
</tr>
<tr>
<td><strong>Obispado Groundwater Well</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>30%</td>
<td>26%</td>
<td>28%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>46%</td>
<td>33%</td>
<td>29%</td>
</tr>
<tr>
<td><strong>Shallow Wells: Pilon Chapotal River</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>95%</td>
<td>62%</td>
<td>86%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>89%</td>
<td>74%</td>
<td>80%</td>
</tr>
<tr>
<td><strong>El Pajonal Groundwater Wells System</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>58%</td>
<td>58%</td>
<td>52%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>62%</td>
<td>61%</td>
<td>52%</td>
</tr>
<tr>
<td><strong>Shallow Wells: Conchos River</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>84%</td>
<td>63%</td>
<td>82%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>87%</td>
<td>74%</td>
<td>78%</td>
</tr>
<tr>
<td><strong>Tunnel San Francisco II</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>36%</td>
<td>40%</td>
<td>34%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>34%</td>
<td>43%</td>
<td>29%</td>
</tr>
<tr>
<td><strong>Ballesteros–Buenos Aires Groundwater Well</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>41%</td>
<td>53%</td>
<td>41%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>37%</td>
<td>68%</td>
<td>32%</td>
</tr>
<tr>
<td><strong>Shallow Wells: La Union</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>13%</td>
<td>23%</td>
<td>16%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>13%</td>
<td>39%</td>
<td>12%</td>
</tr>
</tbody>
</table>
Table 4.3—Continued

<table>
<thead>
<tr>
<th></th>
<th>2016–2026</th>
<th>2027–2038</th>
<th>2039–2050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>30%</td>
<td>53%</td>
<td>58%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>35%</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>WW Injection Well Project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>0%</td>
<td>14%</td>
<td>23%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>2%</td>
<td>12%</td>
<td>35%</td>
</tr>
<tr>
<td>La Libertad Dam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>10%</td>
<td>42%</td>
<td>21%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>8%</td>
<td>52%</td>
<td>24%</td>
</tr>
<tr>
<td>Cuchillo II Dam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>0%</td>
<td>37%</td>
<td>91%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>0%</td>
<td>25%</td>
<td>79%</td>
</tr>
<tr>
<td>Vicente Guerrero Dam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>0%</td>
<td>0%</td>
<td>4%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>0%</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>Panuco Aqueduct</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>0%</td>
<td>0%</td>
<td>4%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>0%</td>
<td>0%</td>
<td>18%</td>
</tr>
<tr>
<td>Desalination plant in Matamoros</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wetter conditions</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Drier conditions</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

NOTES: Colors and text indicate the probability of individual projects (primary row montage) falling in optimal strategy. Cells denote combinations of period (primary column montage), water demand (secondary column montage), and climate conditions (secondary row montage).
4.3. Defining Near-Term, Low-Regret Portfolios of Options

These results suggest that water planners could consider many different combinations of options in the near term for improving reliability. The results shown in Table 4.2 provide only partial guidance for which options would be low regret in the first period. While one approach might be just to include the options that appear most often in the near term (left panel of Table 4.2), this would potentially mix and match options included in some portfolios but not others. Therefore, we also look at the correlation of options implemented in the near term. Specifically, we take the following three steps:

1. Remove options that are included in fewer than 10 percent of the near-term portfolios.
2. Estimate the correlation matrix and identify all pairs that are at least 20 percent correlated.
3. Identify the total number of unique combinations by which these options with both high probability of implementation and medium-to-high correlation may be arranged into groups.

Table 4.4 lists the share of futures in which each option is included in the near term. These probability estimates show that the highest-ranked projects in the first decision period are primarily small-scale projects consisting mainly of groundwater options and network-efficiency improvements. Medium-scale projects, including Cuchillo II Dam, and La Libertad Dam, and WW Injection Well, are ranked second in terms of their relevance for the first decision period. Finally, the large-scale projects are rarely included in the optimal portfolio for this first period. Three options, including the Panuco Aqueduct, are included in fewer than 10 percent of all optimal near-term portfolios. These are shaded in gray in Table 4.1 and are excluded in subsequent development of near-term portfolios.

Table 4.5 shows the level of correlation across all projects included in at least 10 percent of the near-term optimal portfolios. It shows clearly that some of the projects are more likely to be implemented together than others. For example, whenever the Cuchillo II Dam is included in the optimal policy response in the first decision period, none of the other projects are implemented. In contrast, such medium-sized projects as La Libertad Dam are highly correlated with small-scale projects such as improved network efficiency and several of the small groundwater projects. These medium-sized projects, however, are not strongly correlated among themselves—meaning that usually only one of these is included in the optimal portfolio. Finally, for the third aggregation step, we filter from this table the correlations that are less than 20 percent and

---

2 The choices of the 10- and 20-percent cutoffs were made by the research contrasting the potential for aggregation of other cutoff options as described later in this chapter.
This analytical procedure yields nine different low-regret portfolios that could be implemented during the first decision period (Table 4.6).

There are important differences among these near-term portfolios, as they are tailored toward different futures. For instance, the portfolios relying solely on small-scale projects (e.g., P7 and P8) are better foundations for futures in which new supply needs are low, as they limit unnecessary total investment costs. Yet it is possible that these portfolios would lead to lower overall reliability in other futures that require more investment to meet Monterrey’s reliability objective. In contrast, the portfolio relying on the Cuchillo II Dam (P6) and the implementation of various small- and medium-scale projects (i.e., P2 and P4) are more expensive. Therefore, these are likely to meet the reliability objective in a greater range of future conditions but, in some cases, at a higher cost than would be necessary.
### Table 4.5
Correlations of Options Included in Optimal Portfolios in the Near-Term

<table>
<thead>
<tr>
<th>Monterrey Country Groundwater Well</th>
<th>Shallow Wells: Pilon Chapotal River</th>
<th>Shallow Wells: Conchos River</th>
<th>El Pajonal Groundwater Wells System</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monterrey Country Groundwater Well</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Wells: Pilon Chapotal River</td>
<td>73%</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Wells: Conchos River</td>
<td>70%</td>
<td>58%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>El Pajonal Groundwater Wells System</td>
<td>44%</td>
<td>53%</td>
<td>49%</td>
<td>100%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>32%</td>
<td>33%</td>
<td>34%</td>
<td>29%</td>
</tr>
<tr>
<td>Ballesteros–Buenos Aires Groundwater Well</td>
<td>36%</td>
<td>44%</td>
<td>51%</td>
<td>43%</td>
</tr>
<tr>
<td>Cuchillo II Dam</td>
<td>−9%</td>
<td>−19%</td>
<td>−17%</td>
<td>−19%</td>
</tr>
<tr>
<td>Tunnel San Francisco II</td>
<td>29%</td>
<td>35%</td>
<td>41%</td>
<td>34%</td>
</tr>
</tbody>
</table>
## Table 4.5—Continued

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Obispado Groundwater Well</td>
<td>27%</td>
<td>25%</td>
<td>21%</td>
<td>8%</td>
<td>17%</td>
<td>16%</td>
<td>-10%</td>
<td>6%</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>La Libertad Dam</td>
<td>22%</td>
<td>27%</td>
<td>29%</td>
<td>24%</td>
<td>28%</td>
<td>29%</td>
<td>-21%</td>
<td>21%</td>
<td>9%</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>La Union Shallow Wells</td>
<td>19%</td>
<td>25%</td>
<td>29%</td>
<td>18%</td>
<td>23%</td>
<td>48%</td>
<td>-20%</td>
<td>15%</td>
<td>10%</td>
<td>16%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>WW Injection Well Project</td>
<td>8%</td>
<td>5%</td>
<td>3%</td>
<td>3%</td>
<td>39%</td>
<td>3%</td>
<td>17%</td>
<td>7%</td>
<td>3%</td>
<td>8%</td>
<td>4%</td>
<td>100%</td>
</tr>
</tbody>
</table>

**NOTES:** Each cell denotes the correlation of inclusion across all pairs of projects included in at least 10 percent of near-term portfolios. Columns indicate individual low-regret portfolios, and rows indicate the individual projects. Cell shading indicates which projects are included in each of the nine portfolios.
All portfolios for the first period exclude the large-scale projects—Vicente Guerrero Dam, the Panuco Aqueduct, and the desalination plant. Recall that Table 4.1 suggests that these are better suited for the medium- and long-term expansion of the system. Instead, these low-regret, near-term portfolios also show that small groundwater projects and the efficiency-improvement project are more suited for implementation in the near term. In fact, these projects work primarily as complements to such medium-sized projects as the La Libertad Dam and the WW Injection Well.

To sufficiently weigh which near-term portfolio to choose, we quantify the performance and cost trade-offs among portfolios, comparing their performance against the optimal choice in the first period. Thus, the projects found to be part of the optimal portfolio in the second and third period are not used for estimating these near-term trade-offs.\(^3\) Specifically, we use a robustness measure—regret. Formally, regret is defined as the difference between the performance of a strategy in a specific future, given a value function, and the best performing strategy for that same future. Formally:

\[
\text{Regret}(j, f) = \max_j \left[ V(j', f) - V(j, f) \right],
\]

where

- \(j\) refers to one of the policy portfolios under consideration
- \(f\) denotes a particular future (i.e. combination of uncertainties)
- \(V()\) denotes the function use to evaluate the performance of alternatives strategies.

In addition, in an RDM analysis, regret is estimated across the cross product \(\mathcal{R} = \mathcal{S} \times \mathcal{F}\), such that total regret (i.e., \(\mathcal{R}\)) is estimated for all alternatives (i.e., \(\mathcal{S}\)) across the full ensemble of plausible futures (\(\mathcal{F}\)).

In this study, we measure regret in terms of reliability and total investment costs. Since our computational approach first estimates the optimal system-management portfolio for each individual future, then, in a given future, regret is simply the difference between the performance of a proposed portfolio alternative and the performance of the one that would have been the optimal strategy if we somehow had complete foreknowledge of the circumstances defining that future. This, in turn, allows us to identify a Pareto frontier in the first decision period—in this case, the set of points that define the trade-off surface along which any improvement on cost regret would entail more reliability regret and vice versa.

Figure 4.2 shows the distribution of cost and reliability regret across all the futures for the nine portfolios. The lightest gray color point for P9 shows that, in the

---

\(^3\) This does not imply that optimal projects implemented in the second and third periods for each future are not relevant for the projects selected in the first period. As described in Appendix B, the dynamic optimization model is forward looking and, as a result, the optimal decision made in the first period is influenced by what can be achieved in the second and third periods.
10 percent more-adverse futures (i.e., 90th percentile), reliability and cost regret are on average 64 percent and US $271 million, respectively.

Viewing the results in this way, one can see that three groups of portfolios have similar regret profiles. The first group includes alternatives that display low cost-regret levels but high reliability regret (P7, P8, and P9). These are portfolios that rely on small-scale and low-cost projects; if selected as an option for the first decision period, decisionmakers would run little risk of overinvesting in Monterrey’s water infrastructure. Yet, under many plausible futures, the system would fail to meet reliability objectives. There is also a portfolio that exhibits low regret reliability but high cost regret (P4). This portfolio combines two medium-scale projects—La Libertad Dam and WW Injection Well—with several of the small-scale projects. If implemented, this alternative would meet reliability objectives across a wide range of plausible conditions.
but could also prove more expensive in futures for which such an expansion of the system is not necessary. The third group of portfolio alternatives display medium levels of both cost and reliability regret. Interestingly, this group comprises project portfolios that combine La Libertad Dam, efficiency, and groundwater options (i.e., P1, P2, P3, and P5) but also a project portfolio that relies only on the Cuchillo II Dam (P6). Thus, these groups describe fundamentally different approaches to executing near-term investments. The former set embodies a strategy of water-source diversification, while the latter opts for one large-scale surface project in the near term.

The results presented in Figure 4.2 show that this classification of portfolio alternatives is largely stable with no cross-overs, regardless of the part of the distribution considered. This implies that, if decisionmakers have preferences about reliability and cost regret, it is possible to identify a near-term portfolio from this analysis. Our interaction with water planners in Monterrey indeed did suggest that they showed more interest in the portfolios resulting in medium reliability and cost regret. While maintaining current reliability levels was very important for water planners, they also expressed concerns about failing to invest wisely in the development of water infrastructure in Monterrey. As such, near-term P1, P2, and P3 were of interest to them. Ini-
tially, stakeholders were only interested in portfolios 1 and 3 because of their balanced reliability and cost regret. However, as these portfolios are very similar in structure to P2 (in fact, P1 and P3 are subsets of P2) they also expressed interest in this particular option. For completeness, we paid special attention to these portfolios and contrasted them with competing options with similar cost and reliability regret levels, such as P6.

Each of the near-term alternatives identified in the prior analysis has direct implications for how Monterrey’s water infrastructure could and should be developed in the future. Assuming, for instance, that no project other than the 15 considered in this study will be available in the future, then developing the comparatively costly but low reliability regret portfolio alternative (P4) in the first decision period would mean fewer project alternatives left for implementation in the second and third decision periods and, as a result, fewer options for adaptation. In contrast, if Monterrey’s water planners decide to implement one of the low cost-regret alternatives, there might be greater supply vulnerability in the near term, but, at the same time, there would be more adaption options available in the second and third decision periods. In summary, all infrastructure decisions are path dependent. This adds another layer of complexity to developing a water master plan in a context shrouded by uncertainties.

4.4. Defining Complete Robust, Adaptive Strategies

This section describes the method used to identify robust medium- and long-term options for each near-term portfolio and future. The near-term portfolio plus decision rules for implementing medium- and long-term options constitute a robust, adaptive strategy. As a first step, we stress test each of the nine low-regret, near-term alternatives across the full range of futures and estimate the optimal response in terms of medium- and long-term option implementation. The resulting database thus describes, for each near-term portfolio, alternatives for how that system should be expanded optimally in the medium and long terms in response to changes in water demand, hydrological conditions, desalination costs, and groundwater availability.

We then use scenario-discovery techniques to identify the future conditions that would lead to the implementation of different additional options (Bryant and Lempert, 2010). RDM studies regularly use scenario discovery to define the uncertain conditions that lead a static strategy to fail (Groves et al., 2014; Lempert et al., 2006). As the IAM used in this study defines optimal strategies for each future, this study builds on the conventional approach and evaluates the uncertainties that lead not to vulnerabilities but to distinct additional investments. This information can then guide the specification of a robust, adaptive strategy. Figure 4.3 shows how this approach works in the context of this study. In this simple example, the analysis suggests that if in some future the value of uncertain factor A is below the horizontal dotted line, then portfolio Z would most often represent the best adaptation. If some future’s value of uncertain
variable A is above the horizontal line, then the value for uncertain factor B listed in a specific future state of the world would determine whether portfolio X or portfolio Y is likely to be the best choice.

In this study, we implemented scenario discovery using the C5.0 decision-tree classification algorithm (Quinlan, 1993) with the public R interface developed by Hornik et al (2007). The C5.0 is a recursive algorithm that uses such splits to build a model in the form of a tree structure. The model comprises a series of logical decisions with decision nodes that denote a decision to be made on an uncertain factor. For choosing the best split, the algorithm computes two statistics: (1) entropy, which measures how homogenous class values are (i.e., purity of the end-node in the decision tree) and (2) information gain, which is the difference in entropy between the data segment before the split and the partitions resulting from the split. The algorithm carries out this process until each class is perfectly classified or the algorithm runs out of features to split on. Both pre-pruning and post-pruning process are carried to improve the decision tree parsimony and accuracy (Lantz, 2015).

This algorithm is useful in this context because, in this second phase of the analysis, patterns in the identified optimal portfolios begin to emerge as some futures share the same optimal portfolio. Thus, the application of this algorithm results in what amounts to a flow chart describing the combination of uncertainty conditions that lead to one optimal portfolio over another. We then can compare these flow charts and

![Figure 4.3](image-url)

**Figure 4.3**

*Example Identifying Longer-Term Portfolios Using Scenario Discovery*

SOURCE: Modified from Lantz, 2013.

NOTES: Horizontal and vertical axes denote value ranges of uncertain factors. The shapes indicate different portfolios of options that are found to be optimal across the uncertainty space. Dash lines denote splits in the ranges of uncertainty that describe the conditions under which a particular project portfolio is optimal.
4.5. Selecting a Robust, Adaptive Strategy for Monterrey

The analysis and tools described in the previous section were used by Monterrey water planners to select a robust, adaptive strategy from the nine developed through this analysis. To support the required deliberations over these alternatives, we developed a custom-made planning support tool using the Tableau business analytic software.\(^4\) This tool shows the uncertainties used to define the plausible futures, presents key results for a subset of individual IAM simulations, summarizes reliability for the current system, lists and describes the main attributes of the different options, presents the near-term portfolio analysis, presents the decision trees for each near-term portfolio, and summarizes the reliability for the selected robust adaptive strategy.

Monterrey water planners and stakeholders were first presented with information about the current vulnerabilities of the water-management system (see Chapter Three). Next, they reviewed the analytically derived near-term portfolios (P1–P9) and the cost- and reliability-regret results (Figure 4.2). From this, they indicated that portfolios P1, P2, and P3 were of most interest. Next, we developed and showed the decision tree representing a robust, adaptive plan based on P2 (as P1 and P3 are both subsets of P2).

---

\(^4\) Information on accessing the tool is provided in a supplemental tool (see Groves and Molina-Perez, 2019).
Figure 4.5
Adaptive Plan for Low-Regret, Near-Term Portfolios (P2)

Demand (cms) <= 14.6

Demand (cms) > 14.6 and demand (cms) <= 15.76

Demand (cms) > 15.76 and demand (cms) <= 18.61

Demand (cms) > 18.61

Ballesteros–Buenos Aires GW Well
Obispado GW Well
El Pajonal GW system
Shallow Wells: La Union
Shallow Wells: Rio Conchos
Shallow Wells: Pilon Chapotal
Tunnel San Francisco II
Monterrey Country GW Well
La Libertad Dam

Efficiency
Cost (million US $) = 439
Reliability (%) = 91

GW availability (%) > 15

GW availability (%) <= 15

GW availability (%) > –6.0

GW availability (%) <= –6.0

Panuco aqueduct
Vicente Guerrero dam
Desalination plant
Cuchillo II dam
Conjunctive use
WW Injection Well Project

Cost (million US $) = 4,163
Reliability (%) = 100

Cost (million US $) = 2,758
Reliability (%) = 100

Cost (million US $) = 460
Reliability (%) = 97

Cost (million US $) = 148
Reliability (%) = 100

Cost (million US $) = 1,406
Reliability (%) = 100

Cost (million US $) = 1,406
Reliability (%) = 100

Cost (million US $) = 1,406
Reliability (%) = 100

No action
Cost (million US $) = 0
Reliability (%) = 100

Desalination plant
Cost (million US $) = 1,406
Reliability (%) = 100

No action
Cost (million US $) = 0
Reliability (%) = 100

Desalination plant
Cost (million US $) = 1,406
Reliability (%) = 100

No action
Cost (million US $) = 0
Reliability (%) = 100

Desalination plant
Cost (million US $) = 1,406
Reliability (%) = 100

No action
Cost (million US $) = 0
Reliability (%) = 100

Desalination plant
Cost (million US $) = 1,406
Reliability (%) = 100

No action
Cost (million US $) = 0
Reliability (%) = 100
(Figure 4.5). This type of diagram describes the sequence of decisions to be implemented based on different combinations of actual values that are attained by prior uncertainties. The segments indicated in the lower section with dashed lines describe the three analyzed decision periods. The end of each branch presents those projects implemented by the relevant branch; the combination of conditions that lead to these decisions can be inferred by following the ramifications of each of the lines in the adaptive plan and the uncertainty thresholds indicated in the ramifications. Finally, investment costs and reliability statistics are provided for each decision node.

For the P2-based adaptive plan, the current system is augmented using a combination of broadly diversified alternatives while keeping costs for this expansion at a comparatively low level (i.e., US $439 million). This confirms the importance of first developing a diverse set of small-scale projects, including new surface-water sources, groundwater sources, and increased efficiency in the network.

In the following periods, the expansion of the system would be designed to respond to different trends. If Monterrey’s water demand grows excessively in the next 12 years (i.e., above 19.6 m³/s), then the adaptive plan stipulates that it would be necessary to fully expand Monterrey’s water infrastructure for 2027–2038 at a cost US $4.163 billion. In contrast, if demand growth in the 2027–2038 period proves minimal (i.e., below 14.6 m³/s), then there would be no need to further expand Monterrey’s water infrastructure. On the one hand, under this trajectory in the adaptive plan for the period 2039–2050, the expansion of the city’s water infrastructure would only require a further US $1.406 billion and would only be necessary if demand grows beyond 15 m³/s.

On the other hand, if the demand for water in the city grows at a medium-low (above 14.6 m³/s and below 15.76 m³/s), medium (above 15.76 m³/s and below 18.61 m³/s), or medium-high (above 18.61 m³/s and below 19.6 m³/s) level, the expansion of the city’s water infrastructure will depend mainly on the prevailing groundwater availability conditions. If demand grows at a medium-low level and groundwater availability is drastically reduced (i.e., groundwater availability more than 6 percent below the historical trend), then the expansion of the system would require implementing the US $1.406 billion desalination plant investment. If groundwater resources do not severely decline, then the investments implemented in the first decision period would suffice for meeting the reliability objectives in the second period. This desalination investment would also be appropriate if demand grows at a medium level or if demand grows at a medium-high level and groundwater availability turns out to be considerably higher than originally estimated (i.e., groundwater availability more than 15 percent above the historical trend). Finally, if water demand grows at a medium-high level and groundwater availability is not considerably higher than originally estimated, then it would be necessary to implement a very large expansion effort to continue meeting the reliability objectives set out by water planners, which would amount to an investment of US $4.163 billion.
In this adaptive strategy, the desalination alternative plays an important role because it is an expansion option that is insensitive to potential hydrological changes. Additionally, it is possible that once the desalination project is implemented, the expansion of the system in the long term turns out to be trivial. In most of the branches of the adaptive strategy, the costs of long-term expansion are in the range of US $100 million to $500 million, except in the case in which demand grows above 21 m$^3$/s, which would then require an investment of US $2.758 billion.

This adaptive plan also highlights the hierarchy that exists among the uncertainty dimensions under consideration and the inherent relation between the first-period investment decision and the medium- and long-term triggers of the adaptive plan. First, it shows that, once P2 is implemented in the first decision period, then the most important factor determining the evolution of the MWP in the medium and long terms is water-demand growth. Second, because portfolio P2 relies on various groundwater projects, the second uncertainty dimension of importance is groundwater availability, such that depending on which groundwater availability scenario materializes, then more or less investment is required to meet the reliability objective.

We also contrasted the key features of the P2 strategy against the plan based on P6 (Figure 4.6). The hierarchy of uncertainties is not the same across all adaptive strategies that are derived from the near-term portfolios in the Pareto frontier. For instance, the adaptive strategy presented in Figure 4.6 highlights this feature for the near-term portfolio P6, which considers only the implementation of the medium-size surface project Cuchillo II Dam. In this case, the corresponding adaptive plan shows that if the Cuchillo II Dam is built in the first period, then, once more, water demand is a key factor for triggering different adaptation options. However, in this case, the second most-relevant dimension is the availability of water at the current water-supply sources, this being best represented by the time interval that a drought affects these sources. If the duration during which these basins remain below historical mean conditions is sufficiently large, then more projects are needed for meeting Monterrey’s water planners’ reliability objective, and, as indicated in this adaptive plan, this critical threshold changes for different water-demand levels.

The thresholds at which contingent actions are triggered are also another important feature of these two adaptive plans. In general, the adaptive strategy based on P6 triggers contingent actions at lower demand levels than the adaptive strategy based on P2. For example, the adaptive strategy based on P2 triggers additional projects in the second period when demand is higher than 14.6 m$^3$/s and when significantly adverse groundwater conditions materialize. In contrast, in the strategy based on P6, additional actions are triggered when demand is higher than 11.65 m$^3$/s and when adverse surface-water conditions also appear. Similarly, for the adaptive plan based on P2, the implementation of the entire set of projects is first triggered when demand is higher than 18.61 m$^3$/s and groundwater availability is not substantially higher than the baseline estimates, while for the strategy based on P6, the full set of projects is triggered.
Figure 4.6  
Adaptive Plan for Low-Regret, Near-Term Portfolios (P6)

NOTES: This diagram describes the sequence of decisions to be implemented based on different combinations of uncertainties. Dashed lines with arrows in the lower section show year ranges representing the three analyzed decision periods. Nodes indicate projects implemented by the relevant branch; the combination of conditions that lead to these decisions is indicated by ramifications of each of the lines in the adaptive plan and the uncertainty thresholds indicated in the ramifications. Investment costs and reliability statistics are provided for each node.
when demand exceeds 14.6 m$^3$/s and significantly adverse water-availability conditions are realized at the current source basins.

The analytical framework used in this study highlights the medium- and long-term implications of investment decisions made in the near term. First, the importance of different uncertainties (i.e., stressors) in the medium and long terms will change depending on the decisions made in the near term. If the first-period portfolio relies significantly on groundwater resources, then groundwater availability will be critical for triggering contingent actions. If the first-period portfolio relies primarily on surface water, then hydrological changes in the medium and long terms at the serving basins will be more relevant than groundwater availability.

Second, although all adaptive plans stipulate contingent actions that contribute to meeting the reliability objective of the system, the capacity that each strategy has for assimilating different combinations of water demand and groundwater and surface-water availability before triggering a full-scale expansion of the system varies greatly. Depending on the decision made in the first period, some adaptive strategies may accommodate higher demand growth levels before launching a full expansion of the system (i.e., P2), while other strategies trigger such expansion at a much lower demand growth level (i.e., P6). This is a fundamental performance difference that shows that the medium- and long-term resilience of the system (i.e., its capacity to assimilate stressors) is greatly determined by near-term actions. In this case, this evidence suggests that P2 is a more resilient adaptive strategy than P6.

Finally, the implementation costs estimated at each decision node in both adaptive plans reveal the huge economic opportunity that exists in managing water-demand growth. For instance, in the case of the adaptive strategy based on P2 (Figure 4.5), the difference in expansion costs between the scenarios under which water demand is lower than 14.6 m$^3$/s and the scenarios under which water demand is higher than 19.1 m$^3$/s is US $4,000 million. This underscores the message that significant savings may be achieved if water demand is managed to prevent rapid growth.

### 4.6. Evaluation of the Robustness of the Adaptive Plan

The previous section outlines a long-term development plan for Monterrey’s water system that not only relies on a combination of robust, near-term options for the next 12 years but also defines the conditions that would warrant the implementation of additional options for the medium and long terms. This approach helps to ensure reliability without unnecessary costs by triggering new investments only when predetermined signposts indicate they are needed.

To test and establish robustness of this strategy, we again use the IAM to simulate the portfolio’s performance across all futures. Figure 4.7 shows the performance of the P2 adaptive strategy across all the plausible futures in the same form as Figure 3.3.
The results suggest that, for the adaptive plan, the vulnerability of Monterrey’s water system is significantly reduced across all decision periods and that the adaptive water plan markedly reduces the levels of vulnerability of the city’s water system in the near and long term and proposes a strategy of expansion and improvement of the current system that is cost-effective.

We next evaluated the performance of the adaptive strategy with the proposed new tariff schedule in place. As expected, the new tariff schedule encourages a more-efficient use of water and reduces demand, although only by about 3 percent on aver-
Figure 4.8
Monterrey Adaptive Water Plan Based on P2 Under an Alternative Tariff Schedule

NOTES: This diagram describes the sequence of decisions to be implemented based on different combinations of uncertainties. Dashed lines with arrows in the lower section show year ranges representing the three analyzed decision periods. Nodes indicate those projects implemented by the relevant branch; the combination of conditions that lead to these decisions is indicated by ramifications of each of the lines in the adaptive plan and the uncertainty thresholds indicated in the ramifications. Investment costs and reliability statistics are provided for each node.
age across the futures (from 17 m$^3$/s to 16.5 m$^3$/s). This minor reduction in demand, however, leads to lower costs for the adaptive plan for a subset of the water-demand scenarios considered, as seen in Figure 4.8. These differences are more evident in the long term. For example, if demand is low, medium-low, or medium, the number of projects required for meeting the reliability objective is lower than in the case with the current tariff schedule.

Water demand is the preponderant factor determining adaptation strategies in the medium and long terms. Therefore, as new water tariffs incentivize more-efficient use of water resources and reduce water-demand growth, this regulatory change results in an adaptation strategy that is equally robust as the pathways previously discussed but also reduces the costs of expanding the water infrastructure in the long term for a subset of the futures considered. Specifically, with the alternative tariff schedule, the mean costs of expanding the system is reduced by US $703 million under the low water-demand scenarios, US $419 million under the medium-low demand scenarios, and US $1.075 billion under the medium-demand scenarios.

Interestingly, we show that this is only true for the low, medium-low, and medium water-demand conditions. If water demand follows a trajectory of high demand and rapid growth, the effect of water tariffs is negligible, as the same costly investments are

Table 4.7
Mean Cost of P2 Based Adaptive Plan under Two Tariff Schedules

<table>
<thead>
<tr>
<th>Demand Conditions</th>
<th>Mean Expansion Cost [in Millions US $]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Schedule</td>
</tr>
<tr>
<td>Low</td>
<td>1,142</td>
</tr>
<tr>
<td>Medium-low</td>
<td>1,845</td>
</tr>
<tr>
<td>Medium</td>
<td>3,298</td>
</tr>
<tr>
<td>Medium-high</td>
<td>3,456</td>
</tr>
<tr>
<td>High</td>
<td>4,602</td>
</tr>
</tbody>
</table>

NOTES: Mean portfolio costs are estimated by averaging portfolio costs across the ramifications of each of the water-demand branches in the adaptive strategies presented in Figures 4.5 (current tariff schedule) and 4.8 (alternative tariff schedule).

required under the old and new tariff strategies. Table 4.7 compares the mean cost of the P2 strategy under the two tariff schedules.
CHAPTER FIVE
Conclusions and Policy Recommendations

This research was undertaken with the explicit intent to support current water planning in the Monterrey region. It was conducted in close collaboration with local water planners and experts. Specifically, the analytical tools developed for this study were used to support a series of participatory workshops with SADM’s water managers, CONAGUA officials, water experts from local universities, leaders from the local business community, and FAMM’s technical committee. This interaction was fundamental for us, since it allowed us to explore different analytical approaches and enrich the scope of the study.

In the next section, we describe how the technical analysis presented in this report can inform the policy agenda for Monterrey’s water system. Then, we discuss relevant factors that need to be considered in subsequent studies. Finally, we analyze what lessons our work in Monterrey could provide to other water-planning initiatives in Latin America.

5.1. An Adaptive Master Plan: Robust Options and Critical Signposts

We estimated reliability levels of Monterrey’s current water system across a diverse set of uncertainties regarding future water demand, hydrological conditions, desalination costs, and groundwater availability. The results of this initial assessment of vulnerabilities showed that the current capacity of Monterrey’s water system is not sufficient to guarantee current reliability levels in the near, medium, or long term. Increased water demand would reduce the reliability of the system below current levels (i.e., 97 percent); the same is true for plausible shortfalls in water availability across current source basins and groundwater sources. If nothing is done to expand the capacities of the system or to make it more efficient, the reliability of Monterrey’s water system is likely to be progressively eroded in the coming years.

Prior to this study, the predominant policy view was to expand current capacities by importing water from another basin. However, our analysis shows that it is preferable to follow an adaptive investment strategy. In the near term, we show that it is best to expand the capacities of the current system by implementing a combination
of broadly diversified alternatives while keeping costs for this expansion at a comparatively low level (i.e., US $439 million). Then, for the medium and long terms, different contingent investments have been identified. This adaptive approach consists of two main elements:

- in the near term (2016–2026): a diversified set of small-scale of projects, including new groundwater sources, a new surface source (i.e., La Libertad Dam), and greater efficiency in the distribution network.
- in the medium and long terms (2027–2050): alternative expansion strategies that are tailored to respond to different combinations of changes in water demand, groundwater availability, and surface-water conditions at source basins.

The set of projects to be implemented in the near term are demonstrably themselves a robust expansion alternative because they balance reliability and cost regret. This implies that the proposed near-term portfolio will help the city meet its reliability objectives across a wide range of possible future conditions. At the same time, the total implementation cost of this near-term portfolio is much lower than the original estimated cost of importing water from basins located in other states. This also makes it a strategy that does not overspend on Monterrey’s water-infrastructure expansion.

The proposed near-term portfolio diversifies hydrological risk by making use of different local water sources—both groundwater and surface water. At the same time, it shows that investing in the network’s efficiency is also an important element for robustness of the system.

For the medium- and long-term evolution of Monterrey’s water system, we find that vulnerabilities are best addressed from an adaptive planning perspective. Our work was able to identify an underlying hierarchy among the uncertainty dimensions under consideration. We find that that the most important determinant for the future scope and cost of Monterrey’s water-infrastructure expansion is water demand. Water demand on a high-growth path (i.e., above 18.61 m$^3$/s for 2027–2038) will require Monterrey to implement a very large expansion of the system, with an estimated cost of US $4.163 billion. In contrast, if demand growth remains below this critical threshold, then the capacities of the system may be expanded more gradually in response to groundwater and surface-water availability trends.

In particular, the desalination project is found to be an important element in the adaptive strategy because it is an expansion option that is insensitive to potential changes in groundwater and surface-water availability. Similarly, the Cuchillo II Dam and the WW Injection Well projects are found to be suitable alternatives for expansion of the system under various scenarios.

Finally, our analysis shows that new water tariffs also play an important role in this adaptive strategy, particularly if water demand is on a path of low, medium-low, or medium growth. In these cases, new water tariffs that effectively incentivize greater
consumption efficiency result in a less-expensive master plan in the medium and long terms. However, for the subset of scenarios in which water demand is medium-high or high, water tariffs have no effect on the scale of the expansion required to meet such a scenario.

5.2. A Research Agenda for Future Water Planning in Monterrey

The adaptive plan described in the previous paragraphs is in itself a clear policy recommendation. However, during the development of this study, other areas that are critical for the successful implementation of the plan have been identified. First, Monterrey needs to continue developing adequate planning tools (e.g., simulations models, data visualization tools, open data sources) to support future updates of the master plan and also support the evaluation of progress being made across the different areas of concern. In this respect, Monterrey’s water planners need to expand on and fine tune the tools used in this study. This will help the city consolidate relevant information needed for evidence-based policy discussions in future planning exercises. Water planning is a complex exercise that is subject to path dependency, uncertainties, and multiple layers of analysis such that it is unthinkable to attempt to address water challenges in the city systematically without adequate computational tools. To better analyze other project proposals, such as increasing forest cover, permeable pavements, and urban densification, it would be necessary to develop new tools and integrate these aspects into the IAM developed and used in this study.

Second, to successfully implement the robust, adaptive plan proposed in this study, water planners must continue improving their understanding of local groundwater and surface sources. During the execution of this study, we found that there was limited consolidated evidence that could be used to understand the behavior of both groundwater and surface sources. This is a serious limitation that the water community needs to address in the near term. For instance, local groundwater resources are a critical component of the adaptive strategy proposed in this study, yet to manage groundwater sources sustainably—and to justify the realization of these projects to the satisfaction of all stakeholders—water planners would require a deeper understanding of the hydrological dynamics and characteristics of these sources. The same is true for surface sources. While our analysis considers a wide range of potential hydrological scenarios, it is still necessary to understand in more detail the paleo-hydrological history of these basins and study more formally the potential effects climate change may inflict on these sources.

Third, we show that, without rigorous systematic analysis of project alternatives, it is not possible to know which combination of alternatives is better suited for meeting future water challenges in Monterrey, nor is it possible to identify latent risks implicit within different project proposals. Systematic analysis of alternatives is always neces-
sary in this context because projects complement or substitute for one another as determined both by their inherent technical characteristics and the hydrological dynamics of surface and groundwater sources. If these interactions are not assessed carefully across a wide set of feasible future conditions, project-evaluation exercises could yield biased results. In the future, new project and regulatory proposals should be evaluated in terms of their potential effect on the adaptive master plan for Monterrey.

Finally, the tools and project alternatives developed during this study stemmed from intersectoral collaboration across federal and state agencies, NGOs, local universities, and international experts. This type of collaboration should continue to be incentivized in the future, as it would help Monterrey continue exploring innovative proposals and more-critical dimensions for strengthening its water plan. For instance, in future expansions of the study, in addition to considering the implementation costs of the plan and its effect on the system’s reliability, other criteria—such as water-distribution inequality and environmental impacts of project alternatives—can be explicitly considered as performance metrics.

5.3. Lessons for Water Planning in Latin America

The water-planning challenges of Monterrey are similar to challenges faced by other rapidly developing cities in Latin America. Such cities are currently looking for new alternatives for expanding water resources. Yet such searches also confront the same uncertainties over the environmental and financial sustainability of water systems that confound traditional planning approaches.

Water-demand growth in these cities is difficult to anticipate with precision owing to their rapid development trajectories. Previous experience in such cities as Mexico City and São Paolo shows that water demand can grow exponentially in a very short time. This presents a monumental challenge for local water-planning communities. Traditionally, such demand growth has been addressed through water imports, new surface storage, advanced wastewater treatment, and the use of groundwater resources (Castro, 2004; Tortajada, 2006; Tortajada and Castelan, 2003; Vorosmarty et al., 2000). This has indeed expanded the supply capacities of these cities, but, at the same time, it has created enormous fiscal and environmental pressures that are hard to escape from.

Rapidly developing cities in the region should be wary of following the same water policies as its major capitals because the planning context is completely different today. For example, the regulatory environment and competition over existing resources has become more restrictive. Additionally, from an environmental and fiscal perspective, water-demand growth management is becoming a more-important element in water policy. There also many more options available today for meeting water needs. For instance, desalination, wastewater treatment, and network-efficiency tech-
Technologies are much more affordable than they were ten years ago, such that a growing number of cities are weighing the feasibility of implementing these nonconventional alternatives. Finally, the uncertainty associated with the influence that climate change can have on the hydrological dynamics of their water resources will grow in relevance in water-planning processes.

In this respect, the study described in these pages adds to recent RDM analyses in the region (Kalra et al., 2015), which consider a wide range of unknowns, including water demand, climate change, and technological or implementation uncertainties. These analyses have shown that both water-demand management and supply expansions are necessary for the resilience of water systems in emerging economies. These studies also show that the systematic evaluation of project portfolios highlights key complementarities across alternatives, which can be conducive to the development of more cost-effective and robust expansion strategies.
RDM uses a number of techniques to conduct analyses when deep uncertainty is present. While of interest to methodologists, from a policymaker’s perspective, the most important aspect of RDM is that it seeks to create an integrated system for “deliberation with analysis.” That is, for policymakers to be best positioned to address a complex problem, the processes of analysis and policy deliberation should be not sequential steps but concurrent processes; not isolated from one another but recursively integrated (National Research Council, 2009). The following paragraphs describe in more detail the phases of an RDM study as indicated in Figure 2.1.

**Step 1: Decision Structuring**

The figure shows a recursive process that may go through several iterations. However, it labels “Decision Framing” as a first step because this establishes the structure for all that follows. The RDM study team works with stakeholders and decisionmakers to structure an analysis of alternative strategies or plans. Generally, this consists of first establishing the goals of the plan and specific performance measures to characterize alternative outcomes relative to the goals. An RDM analysis will always begin at the end to inform both the modeling and the experimental design for the study. The actual decisions to be informed are also placed within the analytical framework so that outputs feed directly into the context of the policy deliberation and require no translation.

It is usually convenient to structure the results of the problem framing as a four-quadrant matrix, the so-called XLRM matrix, setting the identified elements of the analysis into four main categories: external uncertainties (X), policy levers (L), causal relationships (R), and the measures (M) used to characterize outcomes (Lempert, Popper, and Bankes, 2003). The levers are thought of as discrete actions by policymakers. The idea is that the formulation of policy or a course of action requires selecting from among these fundamental choices to construct different alternative strategies. The importance of identifying and including the decisionmakers within the analytical framework itself becomes clear when considering that, for some groups of decision-
makers, what they regard as choices for action (Ls) would be viewed by other groups as factors outside of their immediate control (Xs) and vice versa.1

The R factors represent causal statements about how inputs lead to different outcomes. In addition to parametric uncertainty about the future values of important system factors (X), we may also have structural uncertainty about the underlying model of the system we are assessing. There may be opposing views difficult to refute with the information available and so this too can become a matter for RDM analysis. Finally, we need to be able to assess different outcomes that we may observe with different assumptions about the future or by testing alternative strategies. Frequently, we are dealing with a multi-attribute problem for which there is no single sufficient criterion for assessing how good an outcome is relative to our stated goals. Instead, we often have different or even competing objectives (e.g., economic growth and environmental protection). The M factors are lists of measures that we will apply to the many outcomes the RDM analysis will yield so that we can see how each may serve our goals. When we assess the implications of many sets of alternative assumptions, we are no longer in the world of optimization. Instead, we are trying to see how we can hedge among our different objectives to find courses of action that are robust to uncertainty and will lead to as the most-satisfactory outcomes that we can manage. This is achieved by generally setting a minimum or maximum value to each of our M factors: how small or how large can this factor become before we deem the outcome to be insufficient to meet our basic criteria for “goodness.” This is an application of the “satisficing” principle described by Nobel laureate Herbert Simon (1991). The XLRM framing for the future of Monterrey’s water supply is discussed in Section 2.3

As shown in Figure 2.1, later stages of the RDM analysis may raise new questions, yield new insights, or reveal systematic patterns that were previously unobserved. This may then lead to a revision of the problem framing and the constituent factors of the XLRM problem framing.

Step 2: Evaluate Strategies Across Futures

RDM analysis may be thought of as conducting a compound computational experiment (Bankes, 1993). It uses models for simulation but does so many times and then reasons over the entire ensuing ensemble of cases, not just a small handful. These cases are generated through an experimental design conducted both according to a prior plan for generating cases as well as by drawing from the learning and inferences received from earlier iterations to inform later runs. In the terminology of RDM, one “case” would be generated by modeling the performance (M) recorded from employing

---

1 For central bankers, setting specific interest rates is one of their main policy levers. For everyone else, future interest rates are a principal uncertainty (X) factor.
a particular strategy (combination of L factors) within a future defined by a specific set of X factor assumptions as influenced by a particular set of relationships (R). We estimate that this RDM study generated approximately 4.9 million cases relevant for comprehending choices for Monterrey’s water infrastructure across many futures. This is described in more detail in section 2.7 of this report.

Cases may be generated to model a wide range of proposed candidate strategies across many different plausible futures. The results may then be stored in a single database for analysis in subsequent steps. Such a database may also be housed in a widely available format, such as Tableau, and made available for others to also derive direct inferences from observing the behavior of the full ensemble of cases.

**Step 3: Vulnerability Analysis**

Among other things, we could now look at the resulting database of cases and divide them into those cases in which we achieve the minimal criteria to satisfy all of our objectives and those for which one or more of the minimal criteria were not met. We can then look at, for example, the cases in which a particular candidate strategy failed to cross the threshold criteria for “goodness” and ask what factors caused that course of action to fail in each instance, what the causes of stress were, and what is systematic across these cases of failure. At this point, advanced data-mining techniques (as described in greater detail in later sections) may be employed to search across the many dimensions of uncertainty, each defined by the breadth of alternative assumptions about the future value of particular factors (such as future interest rates, precipitation levels, or rates of demographic change). These algorithms construct alternative lower-dimensional explanations by drawing “boxes” around the highest-density cluster of failed cases. These “dimensional collapses”—taking a multidimensional problem and finding those few factors that explain most of the cases of failure or success—allow us to then review candidate strategies to see how they might be modified sufficiently to be less vulnerable to the uncertainties revealed.

This process provides a very valuable capability. In most scenario analyses, considerable effort is spent ex ante in building a representative set of analytically meaningful future states of the world. While valuable as a consciousness-raising exercise, this process has several shortcomings as a tool for analysis. Briefly, this usually limits consideration to only three to four scenarios selected on the basis of two to three main drivers or trends that will have been identified based on qualitative reasoning. Not infrequently, this means that supposedly widely differing scenarios are actually clustered rather tightly within the full dimensionality of the uncertainties present in the system. It also leaves the possibility that the factors making the most difference in outcomes and policy choice will not have been correctly identified.
The vulnerability-analysis step in RDM, however, determines analytically those scenarios that make a difference in discriminating among the choices before us. The “boxes” proposed by the data-mining algorithms in effect provide precise descriptions of stressful future scenarios that are meaningful for the decisionmaking process. We now know based on systematic analysis what scenarios we need to be concerned with given the specifics of the decision we are seeking to inform. Depending on the number of cases generated, this step may be done either through case-by-case inspection or through an automated means of identifying the most significant vulnerabilities. The outcome of the scenario discovery step is generally several scenarios that will be used to identify and stress candidate strategies relative to each other. Chapters Three and Four demonstrate this feature of RDM analysis and show how it is possible to use novel analytical approaches for this phase of the analysis.

**Step 4: Trade-Off Analysis**

The next step of the RDM process is conducted interactively with partners and stakeholders. The purpose is to illuminate the performance across the key planning goals of the various candidate strategies. No strategy is likely to be optimal across all performance measures. More likely, the choice of strategy will involve making trade-offs against one or more goals relative to the other strategies. But by this point, the alternative choices will have been modified in light of successive iterations of case generation and vulnerability assessment. Whereas before there may have been dozens of major uncertainties, it will now be the case that only a few remain as potential stressors of the remaining, highly modified candidate strategies.

This is not to say that outcomes will not vary considerably based on what values these myriad unknown factors actually display in the future. The outcomes will vary. But with RDM, we are no longer trying to predict the future. Rather, the goal of the analysis is to identify robust, adaptive strategies that are most likely to perform well across a range of scenarios and thus inform the preferences and processes that decision-makers can follow. This means that an uncertainty that may change actual outcomes greatly is no longer a factor in the decisionmaking process if the alternative values for this factor do not change our ranking of preferences among the strategies we are considering. In this sense, the vulnerability assessments and successive improvements of strategies against particular failure modes stemming from some of the dimensions of uncertainty allow us to no longer consider those dimensions and instead focus on the remaining few that would still change our preference among the choices that remain. These few key uncertainties are the dimensions we consider when performing the trade-off analysis. Chapter Four describes the approach used in this study to identify trade-offs among alternative adaptive strategies.
Step 5: New Options and Strategies

In response to analysis in steps 2–4, additional options and futures and strategies may be defined. For example, the initial case-generation and vulnerability analysis in steps 2 and 3 may reveal futures of particular interest to the choice of strategy, which are then explored in greater detail through new futures. As another example, identifying the vulnerabilities of several initial strategies and comparing their performance in steps 3 and 4 may suggest new, better-hedged strategies for evaluation.

Central to the application of RDM is the coordinated exploration of the future by analysts, decisionmakers, and stakeholders. The decision-framing step sets the stage by providing an opportunity for all interested parties to convey concerns about different plausible future conditions and outcomes of interest, as well as possible solutions. After computer models simulate policy outcomes, the exploration of results generated in step 2 and vulnerability analyses in step 3 can be highly participatory, supported through interactive visualization tools. Lastly, the iterative nature of the process emphasizes the purpose of analysis that is designed to support deliberations, rather than prediction and the subsequent prescriptive ranking of decision options (National Research Council, 2009).
APPENDIX B

Integrated Assessment Model

Water-Demand Model

The model developed for this study estimates water demand in Monterrey as a function of various factors, water tariffs, sociodemographic characteristics, and climatic and regional conditions, and it is calibrated using a comprehensive data set describing water consumptions at the household level.

In particular, this water-demand model uses dynamic econometric modeling based on an ARDL model. The autoregressive property comes from the model’s inclusion of lagged values of water demand. It is a distributed model because it includes multiple lags of the key independent variables, water prices in particular.

The dynamic nature of the ARDL models makes them especially suitable for modeling water demand in that this allows for the identification of near- and long-term effects of lagged variables on water demand (Crespo, 2017a). This is particularly important because the effects of many such factors and variables are not reflected instantaneously on water demand; rather, these become more influential after the passage of time, which makes it a suitable way of creating exploratory long-term water demand scenarios.

The ARDL model used in this study was estimated from panel data obtained by time series and cross-sectional data. Cross-sectional data represent information regarding many consumers in a given period of time. Time series data, on the other hand, are collected from a single consumer over time. In this study, as a result of our collaboration with SADM, the panel data used for estimating the model compose the full set of SADM’s consumer-demand records from January 2012 to December 2015.1

These records were also segmented by consumption level by single-family residential, multifamily residential, commercial-industrial, and public use using statistical clustering (Table B.1). This technique is based on identifying groups of consumers that

---

1 This large water-demand database was aggregated geographically via records from the following municipalities in Monterrey: Apodaca, General Escobedo, Guadalupe, Juárez, Monterrey, San Nicolás de los Garza, San Pedro Garza García, and Santa Catarina. The following municipalities in the greater metropolitan area were also included: Cadereyta Jiménez, Ciénega de Flores, García, General Zuazua, Pesquería, Salinas Victoria, Santiago, El Carmen, Abasolo, Hidalgo, and Mina.
are homogeneous within the group but heterogeneous with respect to the other groups. Crespo (2017a) describes the identified consumption groups across the different geographic regions.

For each of the groups identified, one ARDL model was estimated, with the nine geographic zones as cross sections. Thus, the water-demand model is the collection of 12 ARDL submodels. Finally, the independent variables considered in the water-demand model include water tariffs, mean rainfall and temperature levels in the metropolitan area, population size, population density, economic activity, and consumers’ income. More-technical details of the water-demand model can be found in Crespo (2017a).

### Hydrological Model

We developed a simulation model for constructing an ensemble of future hydrological scenarios at Monterrey’s different surface-water sources. The model is calibrated using more than 34 years of historical information. The hydrological scenarios are developed using statistical techniques that estimate potential runoff implications of drier or wetter conditions at the different water sources.

<table>
<thead>
<tr>
<th>Group</th>
<th>Consumer Type</th>
<th>Consumption Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Residential: single family</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>Residential: single family</td>
<td>Medium-low</td>
</tr>
<tr>
<td>3</td>
<td>Residential: single family</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>Residential: single family</td>
<td>Medium-high</td>
</tr>
<tr>
<td>5</td>
<td>Residential: single family</td>
<td>High</td>
</tr>
<tr>
<td>6</td>
<td>Residential: multifamily</td>
<td>Low</td>
</tr>
<tr>
<td>7</td>
<td>Residential: multifamily</td>
<td>Medium</td>
</tr>
<tr>
<td>8</td>
<td>Residential: multifamily</td>
<td>High</td>
</tr>
<tr>
<td>9</td>
<td>Commercial-industrial</td>
<td>Low</td>
</tr>
<tr>
<td>10</td>
<td>Commercial-industrial</td>
<td>Medium</td>
</tr>
<tr>
<td>11</td>
<td>Commercial-industrial</td>
<td>High</td>
</tr>
<tr>
<td>12</td>
<td>Public</td>
<td>Single user</td>
</tr>
</tbody>
</table>

NOTES: Water-consumption groups are indicated for the 12 consumer types considered in the water-demand model.
Using this stochastic, auto-regressive model (MARHM), we developed synthetic scenarios of monthly precipitation using climatological station data relevant to the different water-supply sources. The contributing basins for each one of the proposed project alternatives were delimited through the Thiessen polygons spatial weighting method and the available isohyetal information.

MARHM is the first tool created to understand the hydrological dynamics of these basins (i.e., La Boca, Cerro Prieto, El Cuchillo Reservoir, La Libertad, Marte R. Gomez, and San Juan River). Although this model is estimated using data from available weather stations in the region covering several decades of accumulated data, it is evident that there is an important difference between the available data and the time lengths associated with the long-term dynamics of these basins. Other methodological approaches and tools may be implemented to understand in more detail the paleontological dynamics of these basins, but these are not currently available for Monterrey.

The fitted MARHM produces synthetic series corresponding to mean rainfall conditions at each one of the water-supply basins of the project alternatives. Using Monte-Carlo analysis in combination with the MARHM, we generated a sample of 1,000 different precipitation sequences. The resulting synthetic ensemble of hydrological sequences was then classified into different variation bins of mean precipitation with respect to historical conditions. These bins display a range from –20-percent to +20-percent precipitation with respect to the historical record, which summarizes in categorical form the range of variation of the different probability distributions of the water sources considered in the study. In this way, nine climatological scenarios for all potential supply sources were obtained: four of precipitation excess, four of precipitation deficit, and one corresponding to historical conditions.

Using the weather stations’ information for each one of the contribution basins, we estimated runoff coefficients on a monthly basis. For this, we estimated different statistical models that associated the month-to-month correspondence between precipitation and runoff, controlling by the climatological variables registered at each of weather stations. In the end, the model that provided a better fit includes one- and two-month delays between rain events and observed hydrographs. By using these calibrated runoff coefficients, the runoff associated with the nine climatological scenarios is simulated. More technical details of the MARHM used in this study may be found in Ramírez et al. (2018a, 2018b).

**RiverWare Model**

A model of the hydrological system was developed in RiverWare, a commercially available water-modeling platform. This RiverWare model describes the characteristics of the rivers and reservoirs basins of Monterrey’s water system. It also supports modeling and describes the technical characteristics of each infrastructure and water-supply
Developing a Robust Water Strategy for Monterrey, Mexico

enhancing alternative considered in this study. RiverWare uses physical-balance equations and discrete equations to describe the interrelation between river basins, water infrastructure, and current operational rules at monthly time resolution. Figure B.1 illustrates the structure of the RiverWare model developed for this study.

This model considers current operational rules of Monterrey’s water system, including water transfers to other basins and commitments to other water uses. The current system relies primarily on five surface reservoirs: Las Blancas, Marte R. Gomez, La Boca, Cerro Prieto, and El Cuchillo Reservoir and on the four basins of the Pablillo, San Juan, Pesquería and Alamo Rivers. The city also depends on a series of groundwater wells and water-treatment plants, but the importance of these two components has varied over time. Currently, industrial users depend heavily on water treatment to meet their needs, and, as new surface reservoirs have been built, the city has reduced its usage of groundwater resources (Sisto et al., 2016).

**Figure B.1**
RiverWare Schematic of Monterrey’s Water System

NOTES: Lines connect surface sources (blue river icon) and groundwater sources (blue well icon) with surface reservoirs (purple triangles) and demand notes (water faucet).
We built this RiverWare model with the objective of estimating Monterrey’s water-system reliability as a function of water-demand and -supply infrastructure. Formally, we define reliability of the system as:

\[
\text{Reliability} = \frac{\sum_{t=1}^{n} \max\left[\min\left(\frac{\alpha D_t - S_t}{S_t}, 1\right), 0\right]}{n},
\]

where

- \(D_t\) and \(S_t\) represent water demand at water supply at time \(t\)
- \(n\) indicates the number of periods considered in the reliability estimation
- \(\alpha\) is the interperiod reliability tolerance (in this study, it is set to 95 percent).

Thus, this reliability estimation is an indication of the probability that the system can satisfy demand in any given period. Evidently, the more infrastructure is built, the higher the probability that the system will be able to satisfy different demand levels. However, this also leads to higher infrastructure costs. More technical details of Monterrey’s RiverWare Model can be found in Ramírez et al. (2018c).

**Dynamic Optimization Engine**

We developed also a dynamic optimization model that estimates the best investment path for a specific combination of future circumstances. This optimization routine is forward looking as it identifies the best performing path forward (i.e., assuming perfect foresight of future conditions) as a function of preceding decisions.

To evaluate which investment path would satisfy Monterrey’s objectives for a specified future, this dynamic optimization routine works alongside the RiverWare model described earlier. For this analysis, we consider three different decision periods: near term (2016–2026), medium term (2027–2038), and long term (2039–2050). For each decision period, our optimization routine solves the following problem:

\[
\min \{\bar{x}_p\} \sum_{i=1}^{\tau_p} I_i x_i \forall x_i \in \bar{x}_p,
\]

so that

\[
\sum_{j=1}^{p} \text{Reliability}(S_j[\bar{x}_p, \bar{x}_{p-1}, \bar{x}_{p-2}, SW_t, GW_t], D_j) \geq \hat{R},
\]

where

- \(I_i\) are decision variables
- \(x_i\) are decision variables
- \(\tau_p\) is the length of the decision period
- \(p\) is the number of decision periods
- \(\text{Reliability}\) is the reliability function
- \(\hat{R}\) is the target reliability.
where

$T_p$ is the set of infrastructure options available at each decision period $p$

$x^*_i$ is a binary index denoting if infrastructure option $i$ is used ($i = 1$) or not ($i = 0$)

$X^*_p$ is the set of infrastructure options implemented at decision period $j$ in the set of $p$ periods

$I_i$ denotes total development cost (i.e., construction and operational costs) of infrastructure option $i$

The RiverWare model estimates, for each future and infrastructure portfolio, the reliability of the system that will be achieved, such that this can be evaluated in the restriction clause of the optimization problem. Thus, reliability of the system is determined by two components: supply $S_t$ and demand $D_t$. The former is in turn determined by the infrastructure decisions in the current period and the previous periods, as well as surface-water $SW_t$ and groundwater $GW_t$ conditions associated to current water sources or, if required, associated with new infrastructure options. This optimization model is forward looking and assumes perfect foresight of future demand ($D_t$) conditions. Finally, $\hat{R}$ is a policy variable that is set to 97 percent, a value consistent with Monterrey’s water managers’ planning policies. This denotes the system’s reliability threshold to be met by infrastructure expansion decisions. The solution to this optimization problem is then a sequence of infrastructure expansion decisions ($\{x_{p1}, x_{p2}, x_{p3}\}$) that meet the reliability threshold $\hat{R}$ in all periods at a minimum cost.

The stated optimization problem is rather complex both with respect to its mathematical structure and its computational architecture. To solve this nonlinear optimization problem, we used the genetic optimization algorithms developed by Mebane and Sekhon (2011). In addition, we also developed a series of computational protocols that make the RiverWare model interact with the optimization routine in a network of multiple-core computers.

The integration of all the tools described in the previous paragraphs is an extremely useful computational laboratory to be used in the context of a RDM analysis. On the one hand, the water-demand and hydrological models allow the exploration of diverse potential demand and supply conditions in the context of Monterrey’s water plan and the historical record, and the exploration of plausible potential deviations from that record. On the other hand, the combination of the RiverWare and optimization models allows for the possibility of estimating the optimal expansion of Monterrey’s water system for specific demand and supply conditions.
For this study, we created 20,000 different water-demand trajectories using Monte Carlo sampling over uncertain input values for the econometric model described in the report. This sample size was prescribed to explore fully the different value ranges associated with the diverse set of sociodemographic dimensions considered in the econometric model. This ensemble of water-demand scenarios describes different trajectories of future water demand as a function of population, economic, urban densification, and climate dynamics (Crespo, 2017a). In addition, to explore more efficiently the variations portrayed in this ensemble of potential future conditions, we aggregated these 20,000 individual trajectories into 12 representative water-demand scenarios. For this, each period (in this case, a monthly level of resolution) was summarized statistically across different quantiles, then each representative quantile was connected across periods to create individual aggregated scenarios.

To develop a set of future hydrological conditions, we used Monte Carlo sampling over the MARHM to generate 1,000 hydrological sequences across all considered surface-water sources. Similar to the treatment of water-demand futures, to explore the potential implications of alternative hydrological conditions more efficiently, we aggregated the original scenario ensemble into different groups, in this case represented by variation in runoff with respect to historical conditions. In the development of this ensemble of hydrology scenarios, we also introduced variations to the historical record that would allow for a richer exploration of potential climate variability in Monterrey; this expanded ensemble of hydrological scenarios displays more-diverse conditions for when the driest and wettest conditions may occur.

In particular, we selected nine different bins with variations of –20, –15, –10, –5, 0 (historical conditions), +5, +10, +15, and +20 percent to represent a range of wetter and drier conditions in the different potential water sources. For each of these bins, the corresponding subset of hydrological scenarios was aggregated into one single scenario describing the mean variation of the group. Additionally, we split these aggregated hydrological-change scenarios into three periods matching the dynamic optimization decisions (near term [2016–2026], medium term [2027–2038], and long term [2039–2050]) and also added further permutations to the time series across periods to expand the aggregated set from nine scenarios to 54 different hydrological scenarios.
(i.e., nine variations bins times six—the full number of possible order permutations of three periods). This responds to the fact that the historical data available show that, from 1980 to 2015, the driest period was 1992–2004. As the MARHM recast historical conditions, the original set of hydrological scenarios displayed a similar pattern of behavior in the corresponding scenario interval (medium term [2027–2038]). However, from an exploratory analytical perspective, it is important to consider alternative scenarios in which the driest conditions occur within different time intervals.
Arteaga, José Roberto, “Monterrey VI: mentiras y verdades de una lucha por el agua,” Forbes México, April 23, 2015. As of April 15, 2019: https://www.forbes.com.mx/monterrey-vi-mentiras-y-verdades-de-una-lucha-por-el-agua/

Balán, Jorge, Harley L. Browning, and Elizabeth Jelin, Men in a Developing Society: Geographic and Social Mobility in Monterrey, Mexico, Vol. 30, Latin American Monographs, Austin, Tex.: Institute of Latin American Studies by the University of Texas Press, 1973.


Crespo, R. N., Francisco, “Construcción de una herramienta de optimización tarifaria para el agua potable en la ciudad de Monterrey y su área metropolitana,” Monterrey, Mexico: Fondo de Agua Metropolitano de Monterrey, 2017b.


DMDU Society, website, undated. As of April 18, 2019: http://www.deepuncertainty.org/
FAMM—See Fondo de Agua Metropolitano de Monterrey.


Groves, David G., Evan Bloom, Jordan R. Fischbach, and Debra Knopman, Adapting to a Changing Colorado River: Making Future Water Deliveries More Reliable Through Robust Management Strategies, paper presented at the American Geophysical Union, fall meeting abstracts, December 2013.


Mexico’s third-largest metropolitan area, Monterrey, faces future water security challenges as the region grows. Fondo de Agua Metropolitano de Monterrey commissioned staff from Tecnológico de Monterrey in partnership with the RAND Corporation to conduct an analysis of the long-term trends and vulnerabilities in water management in Monterrey and to help design a long-term robust water strategy. The study documented in this report uses RAND’s Robust Decision Making (RDM) framework to organize the analysis and was carried out in close collaboration with Monterrey’s water planning community. The results of the study show that the current capacity of Monterrey’s water system is not sufficient to sustain current reliability levels in the near term or beyond. Increases in water demand will soon reduce the reliability of the system below current levels (i.e., 97 percent), and potential declines in water availability across current source basins and groundwater sources would further erode reliability. In their analysis, the researchers defined a robust, adaptive water management strategy that includes near-term investments to expand the capacities of the system and make it more efficient while monitoring future water demand and climate conditions to inform expansions in the coming years. This plan is consistent with the intuition and previous analysis of local stakeholders regarding the need to expand the supply capacities of the current system while being mindful of the significant uncertainties about the future. Finally, the analysis shows that this adaptive strategy significantly reduces the latent vulnerabilities present in the current system.