Integrated Water Management and Modeling at Multiple Spatial Scales

By

David Ezechiel Rosenberg

B.S.E. (Cornell University) 1998
M.S. (University of California, Davis) 2003
M.S. (University of California, Davis) 2003

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

____

____

____

Committee in Charge

2008

David Ezechiel Rosenberg
February, 2008
Civil and Environmental Engineering

Integrated Water Management and Modeling at Multiple Spatial Scales

Abstract

Water shortages from intermittent public supplies are a major and expanding global problem. Yet individual users, utility managers, and government officials can improve access or cope with shortages in numerous ways. New supplies, more efficient use of existing resources, long-term investments to expand infrastructure and reduce leakage, and short-term measures to flexibly transfer, ration, or curtail some uses, represent several different approaches, timings, and spatial scales for management. Integrated systems analysis identifies management actions that minimize costs or maximize benefits across a variety of water shortage conditions.

The systems analysis works as follows. First, identify a wide range of potential actions. Second, characterize each action by the financial costs, perceived costs, and effective water volume added or saved. Third, describe interdependencies when adopting multiple actions together. Fourth, list the shortage or water availability events and their likelihoods for which the system must adapt to deliver water. And fifth, use stochastic programming with recourse to identify the best mix of actions. Analytical error propagation, sensitivity analysis, Monte-Carlo simulations, robust and grey-number optimization explore implications of uncertainties on recommended actions.

Systems analysis is applied separately at three spatial scales in the Hashemite Kingdom of Jordan—for individual residential users, the water system serving 2.2 million residents in the capital Amman, and the entire kingdom comprising Amman and 11 other governorates. Jordan is a top-ten water-poor country and has a continuing annual population growth of 2% to 3%. Results can help inform current and future shortage coping strategies.

Foremost, model results identify a portfolio of actions to reduce shortage coping costs. However, results also establish a systematic approach to integrate source, quantity, reliability, quality, and conservation to estimate water demands; do so using disjoint empirical data sources; yield new insights to size, target, and market conservation actions to users; highlight limitations of a demand curve under block pricing; identify customer willingness-to-pay to improve access; show capital investments required to increase water availability; and show how to include water use efficiency at the regional scale. Together, the results identify complementary actions undertaken at multiple spatial scales in Jordan by individual users, utility managers, and government officials.

Acknowledgements

Primary financial support for this dissertation was provided through a U.S. National Science Foundation graduate research fellowship. Secondary financial and travel support were provided through two consulting contracts.

Foremost, I want to thank my advisor Jay, and committee members, Richard and Mimi for their open-ended support, encouragement, and feedback. Jay, too, for venturing to Jordan with me in Summer 2004 to jumpstart the project.

In Jordan, data collection and results discussions were only possible with the help, cooperation, and participation of Dr Samer Talozi, Dr. Hani Abu Qdais, Dr. Tarek Tawarneh, Dr. Hazem El-Nasser, Roger Griffin, Chris Decker, Osama El-Magrabi, numerous managers at LEMA and the Ministry of Water and Irrigation, various water tradesmen, 36 families I interviewed or surveyed, Anwar El-Halah, and Dawoud Said. *Shrukran gazielan* (thank you so much!).

And finally, thanks to my parents, Aron and Nikki, Shauna, Damian, the Domies, and Lia for your unending love, support, encouragement, and nurturing. Your providing this love—and especially at the end even after I turned in the draft to my committee—enabled me to see this dissertation through to completion. Thank you!

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1. Introduction

More than one billion people have limited or intermittent access to improved water supplies. Limited or intermittent service can mean long distances to water sources, frequent or regular service disruptions, uncertain and inadequate sanitation, high incidence of water-borne diseases and child mortality, or environmental degradation. Shortages resulting from intermittent service also promote water user's distrust in the utility service, force users to seek expensive and risky alternative provisions, or require the utility to adopt irregular and more expensive operations. Any of these can spur public relations disasters for a water utility, service provider, or regulating governmental institutions.

Causes of shortages or intermittent service include supply rationing to meet demands; polluted sources; non-existent, leaky, or poorly-functioning water storage, treatment, or distribution systems; belief that water is unfit to use or drink; contested water rights; or population growth exceeding the rate of new water resources and infrastructure development (Thompson et al. 2001). These causes span a commingled set of operational, engineering, planning, management, financial, social, political, and geographic factors.

Yet, water utilities can take numerous actions to improve water availability or cope with shortages. They can develop new water supplies or more efficiently use existing sources. Improving water use efficiency (often called *water conservation* or *demand management*) can include fixing leaks, reducing customer's billed water use, altering the timing of water demands to better fit supply availability, or converting un-accounted-for or non-revenue water to revenue-generating sales. These sales can fund additional supply enhancement or conservation actions.

Many parties are involved in urban water supplies, from household users, to local water utilities, to regional or national governments. Different parties can undertake supply enhancement and water conservation actions at different spatial scales (Table 1.1). For example, a regional or national authority can negotiate water rights agreements and inter-basin transfers with neighboring countries, reallocate supplies among water use sectors, institute water-efficient plumbing codes or import restrictions on water appliances such as toilets, showerheads, faucets, and laundry machines, fund research to develop more efficient water appliances, among others. A water utility or city water provider can develop new local surface or groundwater sources, desalinate nearby brackish waters or seawater, seed clouds to enhance runoff, promote the financial and water savings that customers realize when they install water efficient appliances, provide monetary incentives to encourage customers to install efficient appliances, or ration water availability. Individual water users and customers also make many operational and management decisions. Users select their water sources, appliances, expenditures, and use levels. They decide numerous daily end-uses and invest capital to improve water quality and use efficiency. They connect to the public pipe network, drill private wells, catch rainwater, reuse grey-water, purchase from vendors, borrow from neighbors, treat water at home, expand onsite storage capacity, install water efficient appliances, alter landscape or irrigation technology, fix leaks, or modify water use behaviors during critical periods, including the timing, duration, and frequency to wash dishes, cars, shower, bath, or irrigate.

In addition to differing spatial scales, actions also differ in their life span or period for which they are effective. Long-term actions such as building desalination plants, restructuring the distribution system to reduce physical leakage, or installing water efficient appliances require a one-time (and generally large) capital investment and establish infrastructure for supply or conservation. These actions must be taken well in advance of any actual supply provision or use reduction. Alternatively, short-term actions can be implemented when needed. Actions such as intra-district transfers, sector reallocations, or reducing shower or landscape irrigation time can flexibly respond to crisis or events as they occur and do not require advance planning.

Actions also typically differ in their operational costs, effectiveness or water volume purveyed or saved, water quality affected, or the perceived time, hassle, or other costs or benefits related to adoption. These characteristics typically differ among geographic regions and even among individual customers or water users in the same region.

This dissertation will identify the optimal mix of actions to cost-effectively respond to water shortages and improve water availability. The key research questions include what actions to adopt and at what spatial scales? Should management focus to develop new supplies, reduce demands, or both? Should actions include long-term capital investments or short-term measures that respond to specific crisis or shortage events as they occur? Also, how do interactions among actions such as demand hardening or supply softening affect recommendations? Importantly, what linkages, synergies, or conflicts exist among actions implemented at different spatial scales? And, how are decisions affected by uncertainties related to action characteristics and system performance?

This chapter reviews the management and modeling approach used to answer these questions. Section 2 reviews integrated water resources management (IWRM) including use of stochastic optimization with recourse to identify an optimal mix of actions. Section 3 describes the analytic, systemic, reactive, and proactive techniques used to address uncertainties. Section 4 outlines three applications of the approach in the Hashemite Kingdom of Jordan at three spatial scales—for individual customers, a utility, and the nation. It also explains why Jordan was chosen as a case example. Section 5 gives the timeline of data collection. And section 6 reviews the organization of dissertation chapters.

The combined effort does not merely identify optimal management actions to reduce costs to cope with shortages. It also establishes a systematic approach to integrate source, quantity, reliability, quality, and conservation to estimate water demands; does so using empirical data sources; yields new insights to size, target, and market water conservation actions to users; highlights important limitations of a demand curve under block pricing; identifies customer willingness-to-pay to improve access; shows the capital investments required to increase water availability; describes how to integrate water use efficiency in a regional context; and also shows complementary actions potentially undertaken by individual water users, the Amman water utility, and the Jordanian government. Each result highlights important additional considerations to successfully plan and operate a water system to avoid shortages.

1.2. Integrated Water Resources Management (IWRM)

Considerable integrated water resources management (IWRM) work has focused on redressing causes of scarce water resources (Jaber and Mohsen 2001; Joench-Clausen and Fugl 2001; Scott et al. 2003; Thomas and Durham 2003; Wilchfort and Lund 1997; Wolf and Murakami 1995). The basic approach is:

1. Identify a wide range of potential actions,
2. Characterize each action in terms of effectiveness, financial and perceived costs,
3. Describe interactions among management actions,
4. Identify events and likelihoods for which the system must deliver water, and
5. Suggest a set of actions that minimize service costs or maximize benefits across all expected events.

Both centralized decision makers (government officials, water utility managers) and individual water users apply the management approach (White et al. 1972).

IWRM differs from traditional project evaluation such as cost-benefit analysis in two ways. First, IWRM involves stakeholders throughout the planning process—even at the beginning to identify and characterize potential actions. Second, actions are not mutually exclusive. A mix of actions may more effectively meet service objectives than a single or “magic bullet” option. Selecting, combining, and timing actions while considering interactions and uncertainties are key aspects of planning decisions.

1.2.1. Stochastic optimization with recourse

Managers often use the systems analysis technique of stochastic optimization with recourse to identify a cost-effective mix of actions. Stochastic means something is not yet known (i.e., annual rainfall for next year), but has a pattern (i.e., averages 40 cm per year). Recourse permits corrective actions after more information is known (i.e., rainfall was 25 cm last year, so now we must…). The technique works as follows.

Decisions are divided into two types. Long-term (first- or primary-stage) decisions are made before the stochastic state is revealed. After the state is known, short-term (secondary- or recourse-stage) decisions are then implemented to respond to the remaining shortfall. Short-term decisions apply only to the particular state. Figure 1.1 shows the decision tree structure.

For shortage management, stochastic states are shortage or water availability events with each event described by a shortage or availability level (water volume) and probability (occurrence likelihood). Together, long-term actions plus sets of short-term actions for each event constitute the decision portfolio—mix of actions—to respond to shortages.

At the household and city scales, the optimal portfolio minimizes capital costs to implement long-term actions plus expected operational costs to implement short-term actions in each event. Expected operational costs are event-specific costs and are weighted by each event's probability. The optimal portfolio must meet the shortages for each event and respect upper limits for each long-term action, upper limits for each short-term action that are potentially increased or decreased based on interactions with other actions, and limits on use of storage, conveyance, treatment, reuse, and other infrastructure that apply to subsets of actions.

At the regional scale, the optimal portfolio maximizes expected net benefits. These expected net benefits are expected benefits and costs from short-term allocations and operations weighted by the event probability minus long-term capital costs. The regional portfolio also must obey constraints on mass balance, infrastructure use, social and political policies. Many commercial and public domain programs (including Excel) can solve stochastic programs to identify the optimal portfolio.

Several recent shortage management applications demonstrate the method. Lund considered 4 long- and 6 short-term conservation actions for a hypothetical household. Wilchfort and Lund (1997) examined 6 long- and 5 short-term actions for California's East Bay Municipal Utility District. And Garcia-Alcubilla and Lund (2006) included just 3 long- and 3 short-term conservation actions for a typical residential user in California. Elsewhere, stochastic optimization with recourse has seen extensive use to plan production, locate facilities, expand capacity, invest in energy, design chemical processes, manage water or the environment, and in agriculture, telecommunications, and finance (for reviews, see Sahinidis 2004; Sen and Higle 1999).

1.2.2. Model extensions for intermittent water systems

Users accessing intermittent public water supplies adopt a wide range of alternative supply enhancement and conservation actions to cope with shortages (White et al. 1972). To accommodate this variety, this research extends the prior shortage management work (Garcia-Alcubilla and Lund 2006; Lund 1995; Wilchfort and Lund 1997) in several important ways.

First, the work considers many more potential management actions—some 39, 23, and 20 potential management actions each at the household, utility, and regional scales.

Second, more potential actions means expanded interactions among potential actions. Adopting an action can either reduce or enhance the effectiveness of adopting one or more other actions. For example at the household scale, a user installing a toilet dual-flush mechanism would not install a low-flush toilet. A user purchasing a water-efficient automatic laundry machine would not also purchase a water-efficient semi-automatic machine. Also, a toilet displacement bag saves less water per flush after a household installs a low-flush toilet (and similarly for the water saved by decreasing shower or irrigation time after installing a low-flow showerhead or water-efficient landscape). Prior shortage management work has yet to include the first interaction, mutual exclusively, which can strongly constrain decisions. The second interaction type is often termed "demand hardening" to describe the relation between long- and short-term actions. Namely, that "as more [long-term] conservation measures are permanently placed, the effectiveness of short-term conservation measures decreases and their relative costs increase" (Lund 1995; Wilchfort and Lund 1997). Wilchfort and Lund (1997) considered 6 demand hardening interactions at the utility scale but required 6 additional constraints. Such enumeration becomes unwieldy for an expanded set of actions with many interactions. This work simplifies the notation by introducing matrices that summarize all interactions between short- and long-term actions. The matrices are referenced directly in specifying the upper limit for each short-term action.

Third, the work disaggregates water use into separate uses that accommodate different water qualities. At the household scale, drinking and cooking, indoor health and hygiene, and outdoor uses require different water qualities. At the utility and regional scales, freshwater differs from wastewater treated for reuse by agriculture. Disaggregating uses permits accounting for the costs and volumetric losses (evaporative, leakage, brine, etc) associated with actions that enhance water quality (e.g., home reverse osmosis units) or reuse wastewater (e.g., collect grey-water to irrigate landscaping).

A fourth extension recognizes restrictions infrastructures impose on multiple actions simultaneously. For example, at the household scale, rooftop and other household storage limit both the water volume a household can draw from the public network and rainwater it can collect during a shortage event. (Storage capacity is also a household decision, so this limitation also represents another interaction among actions). At the utility scale, treatment and conveyance capacities limit surface water use while wastewater-treatment capacity limits the ability for agricultural users to substitute treated-wastewater for freshwater.

And finally, we embed many of the above features in regional water management model that maximizes net benefits for a variety of water uses in multiple, connected locations.

1.2.3. Model inputs and outputs

In this work, model inputs are the costs, life spans, and effectiveness for each action. There are also shortage levels and probabilities for each event for which the system must adapt to deliver water. Additional inputs are particular to the spatial scale of application and include the interaction matrix, sub-sets of actions that can meet various infrastructure capacity requirements, or benefits from water use (see Chapters 4, 5, and 6 for details).

The primary model outputs are the recommended set of long-term actions, sets of short-term actions for each event, and expected costs (capital plus operational) associated with these actions. Secondary results include the reduced costs for actions (i.e., the cost reduction that makes implementing the action cost-effective) and shadow values associated with meeting shortage levels or respecting infrastructure capacities (i.e., the decrease in the expected annual costs were the requirement relaxed one unit).

Optimization software produce these outputs simultaneously as part of the solution. Secondary results help answer several economic and policy questions.

1.2.4. Major limitations

The limitations of stochastic optimization with recourse for shortage management are well described (Garcia-Alcubilla and Lund 2006; Lund 1995; Wilchfort and Lund 1997). Principal limitations and suggested workarounds are:

1. *Expected value decisions*. The objective function weights short-term action costs by the event probability to give an expected-value, risk-neutral decision criteria. However, households, utility managers, and government officials are generally risk-adverse. Risk aversion can be accommodated in two ways: i) revise upward probabilities for extreme shortage events (above their hydrologic likelihood), or ii) modify the objective function to minimize cost deviations (see chapter 5).

2. *Drought triggers*. Stochastic programming is a planning tool to respond to recurrent and long duration shortages. However, for systems that face short, infrequent shortages of a few days or weeks duration, trigger rules may play a more critical role to optimize responses. Yet, once an event is triggered, a simplified optimization program that only considers recourses (i.e., existing long-term actions are given) can still help identify the optimal response.

3. *Event independence*. The approach assumes shortage events occur independent of one another, ignoring effects of event timing or sequence. This assumption neglects actions such as groundwater banking or seasonal storage that permit temporal water transfers among events (i.e., from wet to dry periods).

4. *Cost minimization rather than benefit maximization*. Shortage management minimizes costs subject to meeting specified shortage levels. It sidesteps the economic question of *how much* water to allocate to maximize social benefits? Or, to what extent should operators ration (restrict) supplies to cope with shortages? Yet benefits (such as the utility water users derive from increased availability) are elusive to specify. Specification is further complicated when users value different levels of reliability, face complex price structures for municipal water, and have already adopted alternative strategies to cope with existing rationing. However, maximizing benefits reduces to minimizing costs when benefits are constant or linear with respect to the volume of water use. The work switches to maximize benefits in the regional scale application (Chapter 6).

1.3. Handling Uncertainties and Variability

Stochastic optimization as introduced above assumes all model inputs are described by singular, point values. Yet action costs, effectiveness, life spans, shortage event levels and probabilities are rarely known precisely. Nor are their values necessarily homogenous across the population of water users or geographic areas. Including uncertainties and variability more realistically shows how the optimal action mix changes with changing conditions. Including uncertainties also identifies both expected averages and distributions for various results. The distributions also guide several new insights to size, target, and market conservation actions to water users (Chapter 3 and 4).

Table 1.2 briefly describes the techniques used herein to handle uncertainties and lists chapter(s) where each technique is further described and applied. Propagating uncertainties analytically to derive the distribution of conservation action effectiveness (Chapter 3) is a new technique. Systematic specification and sensitivity analysis are the standard techniques to formulate a stochastic program with recourse and identify value ranges for model inputs where actions stay optimal. Monte-Carlo simulations and parametric analysis are *reactive*: they follow an initial base case model run with numerous, successive runs to represent different conditions. In contrast, *proactive* approaches such as robust or grey-number optimization integrate all numerical uncertainties into a unified formulation requiring just one (or two) runs (Sahinidis 2004; Sen and Higle 1999).

Most of these techniques to handle uncertainties have seen extensive prior applications—several even for shortage management. Here, the numerous techniques are applied to compare results among methods for a real example. In reviewing stochastic optimization with uncertainty, Sahinidis (2004, p. 979) finds a "need for systematic comparison between the different modeling philosophies." Also, review of grey-number optimization finds treatment limited to model formulation and solution for hypothetical examples.

1.4. Application in Jordan

The dissertation applies the integrated management and modeling method at three separate spatial scales in Jordan. These scales are for

- Individual residential water users in the capital city, Amman,
- The Amman water utility serving approximately 2.2 million people, and
- The region / nation comprising Amman and 11 other districts.

The three applications show that the same method can be applied at different spatial scales with little modification. Integrated modeling is typically applied for a limited set of potential actions at trans-boundary, national, or utility scales (Fisher et al. 2002; Haddad and Lindner 2001; Letcher et al. 2004; Maganga et al. 2002; Wolf and Murakami 1995) and for continuous supply systems (Wilchfort and Lund 1997). Less attention has been directed to supply enhancement or conservation actions available to water users [see Garcia-Alcubilla and Lund (2006) for a demand management example]. In Jordan, virtually all IWRM work has focused only on action identification and characterization (Abu Qdais and Batayneh 2002; Alkhaddar et al. 2005; Al-Salihi and Himmo 2003; Al-Weshah 1992; Jaber and Mohsen 2001; Scott et al. 2003; Taha and Magiera 2003). Virtually no prior work has considered a comprehensive set of actions for intermittent systems or identified potential synergies or conflicts among actions taken at different spatial scales.

Jordan is an interesting and relevant example for several reasons:

1. *Chronic shortages.* Jordan is one of the 10 most water-poor countries. Annual consumption of 1 billion cubic meters (BCM) per year far surpasses annual renewable freshwater surface and groundwater supplies of 850 million cubic meters (MCM) per year (groundwater overdraft covers the deficit). With 5.4 million persons (2004) and water use split nearly 69%, 27%, and 4%, respectively, among agricultural, urban, and industrial uses (Abu Qdais and Batayneh 2002; Alkhaddar et al. 2005), water availability averages approximately 167 m^3 per capita per year, but water use is only 22 to 36 m^3 per capita per year (60 – 100 liters per capita per day) (Al-Salihi and Himmo 2003; Hussein 2002; Scott et al. 2003). Low per-capita water use is enforced through a strict regime of availability rationing, with water commonly distributed through the municipal network for 12 to 60 hours per week (Abu-Shams and Rabadi 2003).

2. *Expanding shortages.* Jordan's population is also growing at 2% to 3% per year. New water supplies are expensive, distant, or difficult to bring online. Therefore, chronic shortages will likely worsen.

3. *Prior in-country experience*. I served as a U.S. Peace Corps volunteer in Jordan from 1998 to 2000. During my service I saw and lived with water shortages; developed a strong network of friends and colleagues; worked on wetlands, water, and environmental education and conservation; and acquired the cultural and language abilities to work with Jordanians in Arabic.

4. *Desire to do more*. It seemed quite natural to return and focus dissertation research in Jordan. Integrated modeling can both (i) answer academic questions to satisfy requirements for a dissertation, while (ii) provide some relevant, practical advice to friends, former colleagues, and others who live with weekly shortages, manage the system, or develop Jordan's water policies.

1.5. Research Timeline

The fieldwork, modeling, and analysis was made between September, 2003 and April, 2007 (Table 1.3), and included three separate trips to Jordan. The work was supported by a combination of funding sources, including a $2,000 U.C. Davis Jastro-Shields research grant, two consulting contracts, and a graduate research fellowship awarded by the National Science Foundation.

The first trip in Fall, 2003 involved networking and assessing research needs with more than 50 water-resources professionals working for academic institutions, non-governmental organizations, private consultants, and public institutions in the five countries riparian to the Jordan River. During meetings I asked each professional to identify the important water management issues in the basin that NSF-supported dissertation research could help address. Four topics surfaced which were:

- When and how to use fossil groundwater in regional optimization models (including overdraft above safe yields),
- How to optimize reallocation of water for environmental purposes,
- Can multi-objective economic optimization help support internet-based negotiations over water disputes, and
- How to integrate new supplies and conservation to improve system performance?

I was most attracted to internet-based negotiation support system (NSS). But limited funding, few contacts in Lebanon and Syria, and an unfavorable regional climate (the ongoing second *intifada* and the recent U.S. invasion of Iraq) prevented meaningfully addressing NSS. Most everyone mentioned integrated management, and the relevant data was available for Jordan.

In Winter, 2004, I used a consulting contract to develop a water demand management training course to be offered in Jordan in August. As part of this work, I developed a preliminary list of water management actions potentially applied at different spatial scales and made a second trip to Jordan to attend a demand management conference in June. I stayed in Jordan through the summer and informally interviewed 56 water vendors and tradesmen, surveyed 36 households, and collected billing records for the households from the Ministry of Water and Irrigation (MWI) and Suez Lyonnaise des Eaux/Arabtech Jardaneh and Montgomery Watson (LEMA)—the management contract operator for the Amman water system. This empirical data helped identify and describe potential household water management actions, costs, water quantities, and household perceptions regarding potential actions (see Chapter 2 for details).

From January to October, 2005, the limited empirical data plus extensive—but disjointed—data from prior studies (see Chapter 2 for a review) were used to demonstrate an analytical approach to estimate the distribution of water conservation effectiveness. I also programmed the stochastic model for water users and generated preliminary results.

In November 2005 during a third and final trip to Jordan, I shared model recommendations with the households I interviewed in Summer 2004 (results not included here). I also presented and discussed aggregate results with water managers, decision makers, and other interested parties. These discussions yielded valuable feedback, and better and updated empirical data for water users. I also met with 20+ persons working for MWI, LEMA, and in private practice to learn more about actions potentially taken at the utility scale to cope with shortages (see Chapter 5).

For the rest of 2006, I made more model runs at the water user scale, programmed the utility-scale stochastic model, shared results by email with contacts in Jordan, and recast a regional-scale water allocation system optimization model (Fisher et al. 2005) in stochastic form using regional hydrology (El-Naser et al. 1998; Taha and Magiera 2003). In Winter and Spring, 2007, I showed how households installing water efficient appliances shift the water demand curve, made the final regional model runs, and wrote up the regional and overall conclusions.

1.6. Dissertation Structure

The dissertation is organized in three sections that correspond to the three spatial scales of application. Work in later sections (utility, nation) builds upon results from earlier sections (individual users, the utility). A final chapter summarizes results and identifies links, synergies, and conflicts among actions taken at different scales.

Each chapter is written as a standalone unit and includes problem identification, theoretical development, and practical application in Jordan. With this framework, some content and information repeats among chapters.

Section I: Shortage management and modeling for individual water users. Chapter 2 reviews the challenges and opportunities for residential water users in Jordan facing intermittent supplies. Chapter 3 presents a new analytical approach to derive the distribution of water saved among a community of users who install a single water efficient appliance. Monte-Carlo simulations verify the analytical derivations and results yield several new insights to size and target conservation actions to customers. Chapter 4 presents the integrated stochastic program for water users. It links Monte-Carlo simulations to estimate both the average aggregate and distributions of billed water use and conservation action effectiveness among residential customers. It also presents several parametric analyses to estimate economic water demands and customer willingness-to-pay to avoid shortage.

Section II: Shortage management and modeling for a water utility. A single Chapter 5 presents the stochastic program for a utility plus two alternative formulations to proactively and systematically include uncertainties for all model inputs. It uses household-scale results to characterize several utility-scale conservation actions. Parametric analyses show capacity expansions over time to accommodate growing population and capital investments to increase water availability to customers.

Section III: Management and modeling for the region / nation. A single Chapter 6 extends a deterministic, non-linear, single-year Water Allocation System model (Fisher et al. 2005) to include water use efficiency, stochastic water availability, and long-term infrastructure expansions and conservation programs.

Chapter 7 concludes. It summarizes suggestions to manage shortages at each spatial scale, identifies important synergies and conflicts among actions implemented at different scales, lists the dissertation's key contributions, and further required work.

1.7. Literature Cited

Abu Qdais, H. A., and Batayneh, F. (2002). "The Role of Desalination in Bridging the Water Gap in Jordan." *Desalination*, 150(2), 99-106.

Abu-Shams, I., and Rabadi, A. (2003). "The strategy of restructuring and rehabilitating the greater Amman water network." *Water Resources Development*, 19(2), 173-183.

Alkhaddar, R. M., Sheehy, W. J. S., and Al-Ansari, N. (2005). "Jordan's Water Resources: Supply and Future Demand." *Water International*, 30(3), 294-303.

Al-Salihi, A. H., and Himmo, S. K. (2003). "Control and Management Study of Jordan's Water Resources." *Water International*, 28(1), 1-10.

Al-Weshah, R. A.-M. (1992). "Jordan's Water Resources: Technical Perspective." *Water International*, 17(3), 124-132.

El-Naser, H., Nuseibeh, M. F., Assaf, K. K., Kessler, S., Ben-Zvi, M., Landers, M. N., Clarke, J. S., and Wipperfurth, C. J. (1998). "Overview of Middle East Water Resources." U.S. Geological Survey, Executive Action Team (EXACT) of Multilateral Working Group on Water Resources, Washington, D.C. http://exact-me.org/overview/index.htm.

Fisher, F. M., Arlosoroff, S., Eckstein, Z., Haddadin, M. J., Hamati, S. G., Huber-Lee, A., Jarrar, A. M., Jayyousi, A. F., Shamir, U., and Wesseling, H. (2002). "Optimal water management and conflict resolution: The Middle East Water Project." *Water Resources Research*, 38(11), 25-1:17.

Fisher, F. M., Huber-Lee, A., Amir, I., Arlosoroff, S., Eckstein, Z., Haddadin, M. J., Hamati, S. G., Jarrar, A. M., Jayyousi, A. F., Shamir, U., and Wesseling, H. (2005). *Liquid Assets: An economic approach for water management and conflict resolution in the Middle East and beyond*, Resources for the Future, Washington, D.C.

Garcia-Alcubilla, R., and Lund, J. R. (2006). "Derived willingness-to-pay for household water use with price and probabilistic supply." *Journal of Water Resources Planning and Management-Asce*, 132(6).

Haddad, M., and Lindner, K. (2001). "Sustainable water demand management versus developing new and additional water in the Middle East: a critical review." *Water Policy*, 3(2), 143-163.

Huang, G. H., Baetz, B. W., and Patry, G. G. (1995). "Grey Integer Programming - an Application to Waste Management Planning under Uncertainty." *European Journal of Operational Research*, 83(3), 594-620.

Huang, G. H., and Loucks, D. P. (2000). "An inexact two-stage stochastic programming model for water resources management under uncertainty." *Civil Engineering and Environmental Systems*, 17(2), 95-118.

Hussein, I. A. J. (2002). "Water Planning in Jordan: Future Scenarios." *Water International*, 27(4), 468-475.

Ishibuchi, H., and Tanaka, H. (1990). "Multiobjective Programming in Optimization of the Interval Objective Function." *European Journal of Operational Research*, 48(2), 219-225.

Jaber, J. O., and Mohsen, M. S. (2001). "Evaluation of non-conventional water resources supply in Jordan." *Desalination*, 136(1-3 SU), 83-92.

Joench-Clausen, T., and Fugl, J. (2001). "Firming up the Conceptual Basis of Integrated Water Resources Management." *International Journal of Water Resources Development*, 17(4), 501-510.

Law, A. M., and Ketton, W. D. (1991). "Chaper 8. Generating Random Variates." Simulation Modeling and Analysis, McGraw-Hill, New York.

Letcher, R. A., Jakeman, A. J., and Croke, B. F. W. (2004). "Model development for integrated assessment of water allocation options." *Water Resources Research*, 40(5).

Li, Y. P., Huang, G. H., and Nie, S. L. (2006). "An interval-parameter multi-stage stochastic programming model for water resources management under uncertainty." *Advances in Water Resources*, 29(5), 776-789.

Lund, J. R. (1995). "Derived estimation of willingness to pay to avoid probabilistic shortage." *Water Resources Research*, 31(5), 1367-1372.

Maganga, F. P., Butterworth, J. A., and Moriarty, P. (2002). "Domestic water supply, competition for water resources and IWRM in Tanzania: a review and discussion paper." *Physics and Chemistry of the Earth, Parts A/B/C*, 27(11-22), 919-926.

Mulvey, J. M., Vanderbei, R. J., and Zenios, S. A. (1995). "Robust optimization of large-scale systems." *Operations Research*, 43(2), 264-281.

Sahinidis, N. V. (2004). "Optimization under uncertainty: state-of-the-art and opportunities." *Computers & Chemical Engineering*, 28(6-7), 971-983.

Scott, C. A., El-Haser, H., Hagan, R. E., and Hijazi, A. (2003). "Facing Water Scarcity in Jordan: Reuse, Demand Reduction, Energy, and Transboundary Approaches to Assure Future Water Supplies." *Water International*, 28(2), 209-216.

Sen, S., and Higle, J. L. (1999). "An introductory tutorial on stochastic linear programming models." *Interfaces*, 29(2), 33-61.

Taha, S., and Magiera, P. (2003). "National Water Master Plan: Water Resources in Jordan." Ministry of Water and Irrigation, Amman, Jordan. http://www.mwi.gov.jo/nwmp/NWMP/index.htm.

Thomas, J. S., and Durham, B. (2003). "Integrated Water Resource Management: looking at the whole picture." *Desalination*, 156(1-3), 21-28.

Thompson, J., Porras, I. T., Tumwine, J. K., Mujwahuzi, M. R., Katui-Katua, M., Johnstone, N., and Wood, L. (2001). "Drawers of Water II: Summary." International Institute for Environment and Development, London. http://www.iied.org/sarl/dow/pdf/summary.pdf.

White, G. F., Bradley, D. J., and White, A. U. (1972). *Drawers of Water*, The University of Chicago Press, Chicago, IL.

Wilchfort, O., and Lund, J. R. (1997). "Shortage management modeling for urban water supply systems." *Journal of Water Resources Planning and Management*, 123(4), 250-258.

Wolf, A. T., and Murakami, M. (1995). "Techno-political decision making for water resources development: the Jordan River watershed." *Water Resources Development*, 11(2), 147-161.

Table 1.1. Potential water management actions

Scale	New Supplies	Conservation
Regional	• Negotiate water rights • Inter-basin transfers • Secure aid to develop infrastructure	• Import food, reallocate among water sectors • Restrict imports on inefficient water appliances • Establish water efficient plumbing codes • Fund research to develop water efficient appliances • Give tax credits to persons who install water-efficient appliances
Utility or District	• Expand wastewater recycling and reuse • Develop new surface and groundwater resources • Seed clouds to enhance runoff • Expand system storage, conveyance, and treatment capacities • Desalinate seawater or brackish waters • Negotiate and exercise options to buy water during droughts or shortages • Purchase water on the spot market	• Detection and repair distribution system leaks • Optimize system flows • Reduce system operating pressure • Ration service • Restrict certain water uses (outdoor) • Reduce un-accounted for or illegal water use • Re-price water • Subsidize customers to install water-efficient appliances • Customer education and awareness programs
Water User or Customer	• Develop alternative, local sources (rainwater catchment, groundwater, springs) • Increase draw from distribution network • Collect and reuse grey-water • Purchase from water venders • Borrow or steal from others • Boil or treat water to drink	• Install water-efficient appliances • Landscape or grow low-water consuming plants or crops • Detect and repair leaks • Modify or reduce water-use behaviors

Table 1.2. Techniques to handle uncertainties

	Technique	Description	Classification	Reference(s)	Chapters Used
1.	Propagate analytically	Specify functional relation between output and uncertain inputs. Develop distributions for uncertain inputs. Calculate lognormal mean and variance if all uncertain inputs are independent and multiplied together.	New technique		2,3
2.	Systematic specification	Specify shortage levels and probabilities for each shortage event.	Stochastic optimization	(Sahinidis 2004; Sen and Higle 1999)	4,5,6
3.	Sensitivity analysis	Examine reduced costs and shadow value optimization outputs.	Stochastic optimization	(Lund 1995; Wilchfort and Lund 1997)	4,5,6
4.	Monte-Carlo simulation	Numerically sample model input values from their known distributions.	Reactive	(Garcia-Alcubilla and Lund 2006; Law and Ketton 1991)	2,3,4,5
5.	Parametric analysis	Systematically change value of one model input but hold all others constant at base case values.	Reactive	(Garcia-Alcubilla and Lund 2006)	4,5
6.	Robust optimization	Reformulate objective function to minimize action or cost deviations across data scenarios.	Proactive	(Mulvey et al. 1995; Sahinidis 2004)	5
7.	Grey-number optimization	Specify fixed range of values for each model input. Decompose optimization program into two sub-models whose solutions identify the stable, feasible ranges for the objective function and decision variables	Proactive	(Huang et al. 1995; Huang and Loucks 2000; Ishibuchi and Tanaka 1990; Li et al. 2006)	5

Table 1.3. Timeline of research

Time	Location	Funding source[a]	Activities	Output(s)
2003				
Sep–Nov	Jordan, Israel, Pal., Syria, Leb.	JS	Network and assess research needs with 50+ professionals	4 potential research topics
2004				
Feb–May	Davis, CA	CC	Develop demand management course materials	Preliminary list of actions
Jun–Aug	Jordan	CC	Interview + survey households and tradesmen	Empirical data for water users
2005				
Jan–Apr	Davis + Berkeley, CA	NSF	Derive analytical approach to estimate distribution of water conservation effectiveness	Chapter 3
Apr–May	Davis + Berkeley, CA	NSF	Apply approach to other water user actions	Chapter 2
June	Davis, CA	NSF	Take qualification exam	Presentation; Start introduction
Aug–Oct	Davis + Pioneer, CA	NSF + CC	Program stochastic model for water users; Modify regional optimization model	Preliminary Chapter 4 results; Learn model for regional scale
Nov–Dec	Jordan	NSF	Share preliminary household results	Presentations; Feedback; Better data for water users
2006				
Jan	Jordan	NSF	Interview 20+ water managers	Empirical data for utility actions
Feb–Apr	Davis, CA	NSF	Additional model runs for water users	Chapter 4
Jun–Oct	Davis, CA	NSF	Program stochastic model for utility; Share utility-scale results; Write introduction	Chapter 5; Feedback; Chapter 1
2007				
Jan-May	Davis, CA	NSF	Program regional scale model; Draw conclusions from work at 3 spatial scales	Chapter 6; Chapter 7

Note: a. JS = Jastro-Shields grant; CC = consulting contract; NSF = National Science Foundation graduate research fellowship

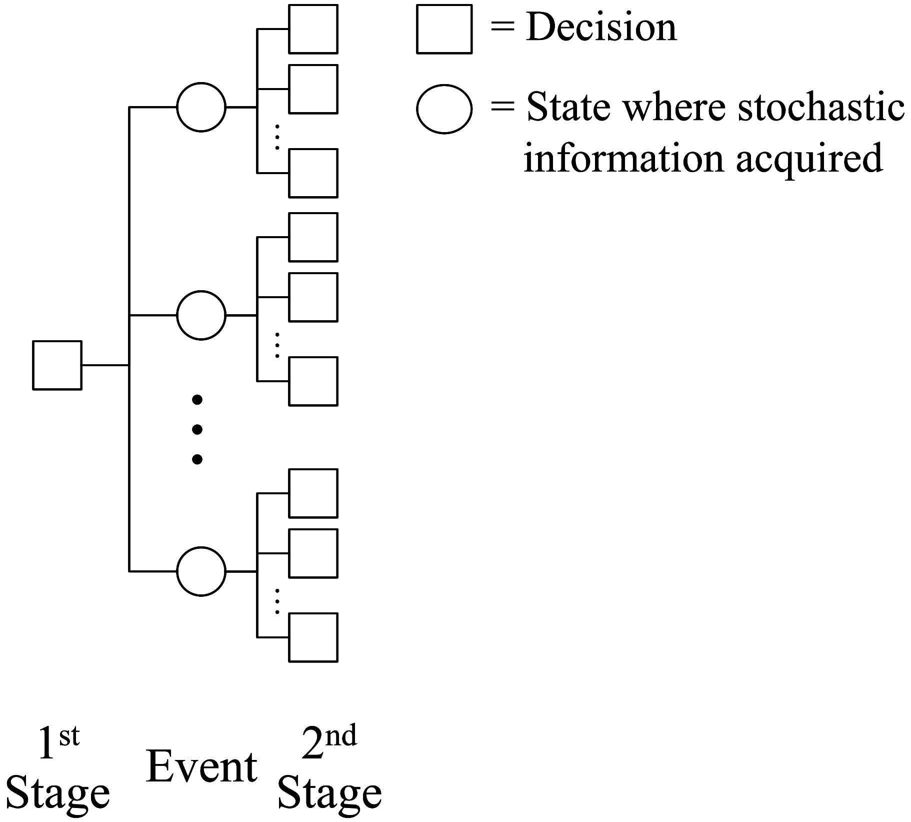


Figure 1.1. Decision tree structure for stochastic program with recourse.

Part I

Management and Modeling for Individual Water Users

Chapter 2

Intermittent Water Supplies: Challenges and Opportunities for Residential Water Users in Jordan

Abstract – Intermittent access to improved urban water supplies is a large and expanding global problem. This paper describes 16 supply enhancement and 23 demand management actions available to urban residential water users in Jordan. Actions are characterized by implementation, financial costs, and water quantities and qualities acquired or conserved. This effort systematically identifies potential options to cope with intermittent supplies prior to detailed study and shows that water users have significant capacity to regulate system performance. We suggest several methods to evaluate identified options and highlight the need to include local water management decisions in integrated water resources management (IWRM) and planning at broader utility and regional scales.

2.1. Introduction

More than one billion people have limited or intermittent access to improved water supplies characterized by long distances to sources, frequent and regular service disruption, and increased costs. Intermittent service is often linked to high incidence of water-borne diseases, uncertain and inadequate sanitation services, and environmental degradation. Intermittent service has many causes, including supply rationing to meet demands; polluted sources; non-existent, leaky, or poorly-functioning water storage, treatment, or distribution systems; or population growth or urbanization exceeding the rate of new water resources and infrastructure development (Thompson et al. 2001).

Considerable integrated water resources management (IWRM) work (Joench-Clausen and Fugl 2001; Thomas and Durham 2003) has focused on redressing causes of scarce water resources with efforts typically focused at transboundary, national, water basin, and water utility scales (Dziegielewski et al. 1992; Fisher et al. 2002; Haddad and Lindner 2001; Jaber and Mohsen 2001; Letcher et al. 2004; Maganga et al. 2002; Scott et al. 2003; Wilchfort and Lund 1997; Wolf and Murakami 1995). The starting point is to identify a wide variety of actions that increase supplies, improve qualities, decrease demand, or alter demand timing to improve system performance. Then characterize actions by costs, benefits (financial, time, energy, and other currencies), and quantities and qualities of water provided or conserved. Finally, use integrated systems analysis to develop a mix of cost-effective and water-efficient actions that provide acceptable service levels and reliabilities given physical and institutional constraints. Here, we identify a broad range of potential options individual water users can adopt to cope with intermittent supplies.

Users select their own water sources, appliances, expenditures, and use levels. They invest capital to improve water quality and use efficiency and make decisions on numerous daily end-uses (Table 2.1). Potential water sources include the public pipe network, wells, rainwater, grey-water, private venders, or water borrowed from neighbors. Users also can treat water inside the house, expand household storage capacity, replace high water consuming appliances like toilets, faucets, showerheads, or laundry machines, alter landscaping, crops, or choice of irrigation technology, find and fix leaks, or modify water use behaviors, including timings, durations, and frequencies of dish washing, car washing, showering, bathing, floor washing or irrigation. Examples from Punjab province, Pakistan; Katmandu, Nepal; East Africa; and Dehli, India show households adopt diverse and complex strategies to cope with unreliable supplies (Altaf 1994; Pattanayak et al. 2005; White et al. 1972; Zérah 2000).

This chapter reviews the global scope and problems associated with intermittent water service and describes a range of water supply enhancement and demand management actions available to urban residential water users facing service disruptions in Jordan. Actions are characterized by implementation, financial cost, water volume gained or conserved, and affected water quality. Jordan is a relevant case as water is generally available through the distribution network for only 12 to 60 hours per week (Abu-Shams and Rabadi 2003) and most households desire to improve their supply access. Systematically identifying and characterizing potential water user actions is an important first step to understand water user decisions prior to more detailed modeling and analysis.

2.2. Global Scope of Intermittent Water Service

Approximately 82% of the world's people have access to improved water service with some 816 million persons acquiring access since the 1990 assessment (WHO and UNICEF 2000). In this context, "improved service" means a household connection, public standpipe, borehole, or protected spring, dug well, or rainwater catchments. However, the assessment did not consider the distance to the improved source nor the hours per day (or per week) that water is available. More detailed examination shows that many populations in the Americas, Africa, Middle East, and Asia have access to improved water sources for less than 12 hours per day (Table 2.2).

Table 2.2 is only a partial listing and excludes populous countries such as Brazil, Mexico, Russia, and rural areas of China and India for which data are not readily available. Table 2.2 also reports average water availabilities for cities and thus neglects inequities within a city between different neighborhoods, topographical zones, or apartments in buildings. The potential water quality, public safety, economic loss, public nuisance, and large number of persons affected make intermittent water supplies a major global problem.

2.3. Urban Residential Water Use and Service in Jordan

As seen in Table 2.2, Jordan has one of the least frequent water availabilities. Jordan faces a severe and expanding water scarcity crisis. Annual consumption of 1 BCM per year far surpasses annual renewable freshwater surface and groundwater supplies of 850 MCM/year (groundwater overdraft covers the deficit). Although water consumption is split nearly 69%, 27%, and 4% among agricultural, urban, and industrial uses, respectively (Abu Qdais and Batayneh 2002; Alkhaddar et al. 2005), most of Jordan's population of 5.4 million persons (2004) reside in cities such as Amman, Zarka, and Irbid where more than 92% of the population has access to piped water in their house. These demographics mean that although water availability averages approximately 167 m^3 per capita per year, water use is only 22 to 36 m^3 per capita per year (60 – 100 liters per capita per day) (Al-Salihi and Himmo 2003; Hussein 2002; Scott et al. 2003). This level is just at the WHO minimum water use requirements for health and hygiene and nearly 1/10th the rate of water use in countries such as the USA or Australia. Low per-capita water use is enforced through a strict regime of availability rationing, with water commonly distributed through the municipal network for 12 to 60 hours per week. Scarcities are projected to worsen with Jordan's population growing at 2 to 3% per year.

In response, the Jordanian government has launched ambitious programs to further develop water resources and better manage demands. Supply-side expansions include building the Unity, Mujib, and Wala Dams, expanding the Zai treatment plant capacity, and bringing the Zara-Ma'een desalination project online. Mega projects such as the Disi-Amman conveyer and Red-Dead Canal are being planned with hopes to move some or all of Amman towards continuous piped supply. These projects also recognize that shortages are due to limited capacity to convey water to the upland and populous areas of Amman, Zarka, and Irbid (Fisher et al. 2002).

Demand management is gaining attention through water-sector reforms and non-governmental organization (NGO) sponsored projects. The Ministry of Water and Irrigation has entered public-private partnerships and delegated responsibility for municipal water service in Aqaba and Amman to separate private companies. The French/Jordanian consortium Suez Lyonnaise des Eaux/Arabtech Jardaneh and Montgomery Watson (LEMA) holds a management contract to provide water service in Amman. The contract includes requirements to improve the distribution network and reduce illegal connections and non-revenue water losses.

The Jordanian government recently enacted laws specifying water-related plumbing and building practices for new construction (2003), co-sponsored an international conference on water demand management (2004), and set up a Demand Management unit within the Ministry of Water and Irrigation. Non-governmental projects and programs have focused on introducing water demand management concepts in schools, demonstrating grey-water collection and treatment, encouraging low-water consuming landscaping, rainwater collection, and promoting water saving devices (CSBE 2004a; CSBE 2004b; Faruqui and Al-Jayyousi 2002; WEPIA 2000a; WEPIA 2000b; Whalen and Al-Saudi 1998). An unresolved question is whether demand management can effectively reduce water consumption given that residential water consumption is, on average, extremely low.

Characterizing potential household management actions by implementation, costs, and effectiveness is an important step towards making these evaluations.

2.3.1. Municipal Water Service to Residential Customers

Municipal piped water is the primary water supply for most Jordanian households. In most areas, piped water is intermittently (but regularly) available for between 12 and 60 hours per week (Abu-Shams and Rabadi 2003). In Amman, LEMA has divided the network into approximately 250 distribution zones and rotates the days and times water is available in each zone.

Amman households pay a one-time fee of JD 230 (JD 1.00 = $US 1.41 in 2004, exchange rate stable since 1995) to connect to the distribution network through a lateral monitored by a water meter and a surcharge of 1 JD for each square meter of floor area in excess of 150 m^2. Water use is metered and billed at three-month intervals. The meter rate varies from JD 0.18 to 2.34 per m^3 according to a price schedule with four increasing blocks and a quadratic formula. (Outside Amman, households pay a one-time connection fee of JD 200, the same additional surcharge of 1 JD for each square meter in excess of 150 m^2, and slightly lower metered rates).

Illegal connections, unpaid bills, unread meters, and "rolled" meters (improperly rotated by up to 90 degrees to ease reading but consequently underreport usage by up to 50%) are common problems that complicate metering and billing accuracy, represent lost revenue, and distort price signals to consumers (Griffen 2004). In Amman, LEMA is working aggressively to redress each of these non-revenue water losses. Recently, LEMA has started continuous service to a select number of Amman distribution zones, but has yet to report impacts on either billed water use or non-revenue water loss. This change may increase non-revenue water since existing meters under record use at low flows.

Figure 2.1 shows a Jordanian household's typical water sources and uses. Because municipal water is intermittent and rationed, most households store this water in rooftop tank(s). Households may also store water in ground tank(s) or a cistern. The rooftop tank is the primary means of local, continuous, gravity-flow distribution to water fixtures in and around the house (often excluding drinking water). Household water pressure depends on the elevation difference between the roof tank and the point of use. Typically, heads range from 3 to 18 meters depending on the building height.

When roof and other storage tanks empty before water is next available through the municipal network, households are confronted with a water scarcity crisis. Scarcity crises also arise when municipal water service does not resume as expected. In these situations, households purchase water from secondary sources delivered to the house on demand. Alternatively, the household can drastically reduce water use. This chapter identifies and describes the many potential household actions to prepare for and cope with scarcity. Methods used to identify and learn about household water management actions are discussed first followed by descriptions of actions, including their implementation, financial costs, and affected water quantities and qualities.

2.4. Research and Data Collection Methods

56 informal interviews with tradesmen, 34 semi-structured surveys and written questionnaires with heads of households, municipal water service billing records for 21 households surveyed, and prior empirical surveys were used to identify potential household water management actions, costs, water quantities, and household perceptions regarding potential actions. The diversity and number of theses interviews and surveys was *not* intended to randomly sample Jordanian households. Rather, it served to create a wide-ranging inventory of household water management activities. Interviews, surveys, and questionnaires were conducted principally in Arabic in and outside Amman between June and October 2004.

2.4.1. Informal Interviews

Informal interviews with tradesmen included meetings with plumbers, construction contractors, irrigation engineers, landscape architects, water engineers, municipal water service managers and workers, water tanker truck drivers and customers, and retailers selling water appliances, plumbing fixtures, garden supplies, potable drinking water, and water storage tanks. Interviews occurred at their place of work and were used to solicit purchase or implementation costs, and associated water quantities for the service(s) or product(s) related to the interviewee's trade or profession. Interviewees also were asked to identify alternative water supply enhancement or demand management actions households might implement to improve access. Generally, at least three tradesmen (or organizations) were interviewed regarding each management action. Interviews lasted from 30 minutes to several hours.

2.4.2. Semi-structured Surveys with Heads-of-Households

16 heads of households were surveyed in-depth at their home or place or work for 1 to 3 hours about their household water use behaviors, practices, infrastructure, and perceptions regarding each potential management action. Surveys comprised closed and open-ended questions. Survey's conducted at the home also included a walking tour inside and outside the house to visually identify all water use appliances, infrastructure, and water uses. As part of the survey, participants were asked to identify their water meter or provide their latest water bill. With consent, the meter and customer identification numbers were used to obtain the history of billed water use (see below).

Cultural, timing, and budget reasons prevented randomly sampling from the population of heads-of-households in Amman. Instead, the first author asked each of his Jordanian acquaintances, friends, neighbors, and colleagues whether they would participate in a survey that asked them about their domestic water use and might recommend actions to reduce water management-related costs. Nearly all persons identified in the primary tier agreed to and were eventually surveyed. Following the questions, participants were asked to recommend additional people who would also be willing to participate. These references provided a culturally appropriate method to "snowball" the sample size and approach a second tier or participants (Blaikie 2000, p. 205-6). However, less than 50%

of referrals were successfully contacted and interviewed. Three of the 16 participants interviewed did not provide water meter or customer identification numbers.

2.4.3. Written Questionnaires

A written questionnaire in Arabic posed the same closed and open-ended questions asked in the semi-structured surveys. The second author and another professor distributed the questionnaire to their undergraduate and master's engineering students at the Jordan University of Science and Technology (JUST) in Irbid. Response rate for the written questionnaire was about 30% with 18 total responses. When necessary, follow-up questions or clarifications were asked via email in English to respondents who provided an email address.

2.4.4. Water Billing Records

Using water meter or customer identification numbers provided, the past history of water billing records for each household were obtained from the appropriate water service provider (LEMA for customers in Amman, Water Authority of Jordan (WAJ) for households outside of Amman). Both LEMA and WAJ read water meters and bill customers at 3-month intervals. Water billing records were used to crosscheck participants' oral and written responses.

2.4.5. Prior empirical surveys

Several recent household surveys have examined individual components of residential water use and conservation in Jordan (Table 2.3). Where appropriate, these survey results were used to estimate distributions of parameters influencing water conservation action effectiveness (see below).

2.5. Management Actions Available to Jordanian households

Summaries of 16 supply enhancement actions (Table 2.4) and 23 demand management actions (Table 2.5) available to Jordanian urban and residential water customers are presented. We classify actions as either long- or short-term. Long-term actions require a one-time (and generally large) capital investment and establish infrastructure for supply and demand management. These actions must be taken well in advance of any actual supply provision or demand reduction. Short-term actions can be implemented or purchased when needed. These actions provide great flexibility to cope with crisis or events as they occur. The summaries below for each management action highlight implementation, financial costs, effective volume of water gained or conserved, and the type of use or water quality affected.

Here we report financial costs as the average, highest, and lowest price quotes from interviews and surveys. We report the effective quantity as either a (i) firm number (i.e., storage tank volume), (ii) range based on physical upper and lower limits (i.e., total capacity to store water and draw water from storage), or (iii) the estimated 10th and 90th percentiles of the effectiveness distribution derived for Amman households (i.e., for most demand management actions)(see Chapter 3).

2.5.1. Supply Enhancement Actions

2.5.1.1. Long-term supply actions

Long-term actions establish the infrastructure of water supply.

Connect to network. A one-time fee is paid to the water service provider to run a lateral to the house, install a water meter, and set up an account. Network connections provide access to an intermittent water source with low unit cost. Households differ in their assessments of municipal water quality. Nearly all households use network water indoors for washing and hygiene and outdoors to irrigate landscaping or wash cars. In Amman, a small percentage of households use municipal water untreated for drinking or cooking. Outside of Amman, this percentage is larger.

Install storage tanks on roof. Households typically install water tanks on the roof to store water when it is available through the municipal network or purchased from a private tanker truck. Roof tanks serve as the primary point for distribution to water fixtures in and around the house. Roof tanks are either plastic or welded thin galvanized metal sheets. Tanks range from 1 to 2 m^3 and are purchased at metal-working shops throughout the Kingdom. Price depends on the material (metal sheet thickness ranging from 1.15 to 1.35 mm), workmanship quality, and shop owner's flexibility to negotiate. For an extra charge, shop owners can deliver the tank, raise it to the roof, and provide a stand to prevent water collecting on the roof during winter rains from corroding the tank. Households use water stored in a tank and municipal water for similar purposes.

Install storage tank at ground level. Homeowners frequently install additional water tanks on the ground to expand their capacity to store water when it is available through the municipal network. Ground tanks are identical to roof tanks in construction and cost. However, homeowners must also purchase a 1 to 2 hp pump to transfer water from ground tanks to the roof. Many plumbing or hardware stores sell pumps. Households use water stored in a ground tank and municipal water for similar purposes.

Install cistern. Homeowners can install cisterns or underground tanks larger than 13 m^3 to store rainwater or municipal water. In Jordan, cisterns are either pre-existing plaster-lined excavations in the underlying limestone [a technology at least 3000 years old (Wahlin 1995)] or concrete-lined excavations underneath the car-park or part of the foundation made when a house is constructed (Ahmed 2004; Whalen and Al-Saudi 1998). The Jordanian Water Code mandates each new residential building to have a water cistern of at least 6 m^3 (2003), but code enforcement can be lax. Retrieving water from a cistern also requires a pump. Cistern water can serve all household water uses. Some households maintain that rainwater is of superior quality to municipal water and use cistern water exclusively for drinking. Other households find rainwater quality inadequate and use cistern water exclusively outdoors to irrigate landscaping or wash cars.

Collect rainwater. Homeowners can collect rainwater by diverting rainwater from the roof into a ground tank or cistern. Most buildings are pre-fitted with downspouts to divert rainwater from the roof to a gutter, sewer, or street. Rainwater collection requires (a) cleaning the roof, (b) installing pipe from the downspout to the storage container, and (c) adding a first-flush valve to bypass organic matter, chemicals, and other matter built up through the dry season and entrained in runoff from the first winter storm. The annual volume of rainwater collected depends on winter season precipitation, roof surface area, number of families sharing the roof, water storage capacity, and sequence of rainfall and water consumption during the rainy season. Households use rainwater and water stored in cisterns for similar purposes.

Collect and reuse grey-water. Grey-water collection and reuse is expanding in Jordan (Bino et al. 2000; CSBE 2004a; Faruqui and Al-Jayyousi 2002). Homeowners can collect water from showers, faucets, and laundry machines and reuse the water outside to irrigate landscaping or grow food crops such as olive, fruit, or nut trees. Some households also reuse water indoors to flush toilets or wash floors.

Installation costs depend on plumbing retrofits and a household's perceived need for treatment. Estimates range from:

- 0 JD for no plumbing or treatment achieved by disconnecting sink drains and collecting water in buckets,
- 19 JD for simple basins that settle particulates or strainers that separate them (CSBE 2004a), or
- 150 JD and up for more elaborate two- or four-barrel closed anaerobic digesters that achieve secondary treatment standards (Bino et al. 2000).

If a dual piping system is installed at the time of home construction, plumbing construction costs increase by about 33% or 61 JD per bathroom since the additional (dual) grey-water pipes are easily laid with other potable and black-water pipes before cement floors are poured. (Retrofitting a house with dual piping requires excavating pre-existing cement floors and is much more expensive).

Reusing grey-water can help rural households without sewer services avoid most of the 200 – 400 JD cost to excavate upwards of 60 m^3 of ground for a septic tank.

Household surveys in Amman estimate that upwards of 50% of a households' water budget may constitute grey-water suitable for reuse. However, the volume collected will depend on the household size, flow rates of existing water appliances, and occupants' water use practices and behaviors.

Drill well. Homeowners can hire a contractor to drill a borehole, tap groundwater, and install a pump to lift the groundwater to the surface for use. Well installation costs include:

- Up to 60 JD per meter drilled
- A licensing fee of 1750 JD, and
- Monthly operational expenses for diesel fuel or electricity to run the pump.

Depths to ground water generally exceed 60 meters. Although groundwater basins in Jordan are generally overdrafted beyond their sustainable yield and WAJ no longer issues well permits to households or small farmers; there is still illegal well drilling and use. Well drilling is only available to homeowners who live in rural areas. Households put well water to all types of uses.

Install in-home water treatment. Homeowners can purchase off-the-shelf in-home water treatment units consisting of filters, reverse-osmosis membranes, and ultraviolet disinfection lights at many retail outlets in Amman. Units are foreign made, fit under the kitchen sink, and can produce up to 180 liters per day of treated water. Purchase price excludes additional annual operational and maintenance costs to replace filters, RO membranes, and UV lamps. Most units generate saline waste streams and require raw water inputs up to four times the volume of treated water generated. Water treated at home is an expensive but reliably high quality source. Households use this water exclusively for drinking and cooking.

2.5.1.2. Short-term supply options

Short-term supply actions have an immediate and therefore flexible effect on household water supply. Short-term actions can be implemented when needed or in response to particular events. The actions require no advance planning (unless conditioned on long-term infrastructure discussed above).

Take delivery through public network. The Amman water utility charges residential users with established connections for their metered water consumption quarterly according to an increasing schedule with four price blocks:

$$TC = \begin{cases} 3.47, & X \leq 20 \\ 4.47 + 0.18\,(X - 20), & 20 < X \leq 40 \\ 9.19 + 0.58\,(X - 40) + 0.0098\,(X - 40)^2, & 40 < X \leq 130 \\ 163.26 + 1.24\,(X - 130), & X > 130 \end{cases}$$

Where TC = total charge in Jordanian Dinars and X = cubic meters of water consumed per quarter. There is a flat charge for use up to 20 m^3 per quarter, fixed price for use between 20 and 40 m^3 per quarter, quadratic formula for use between 40 and 130 m^3 per quarter, and fixed price for use above 130 m^3 per quarter. Rates includes all water and sewage charges, meter reading and pumping fees. Generally, water serves most uses but is only available intermittently.

Buy water from water store. Since 1998, more than 180 retail outlets in Amman have registered with the Ministry of Health and are licensed to sell potable water (Fitzgerald, personal communication, 2004). Homeowners telephone a store to request home delivery. The water stores pay up to 2 JD per m^3 for raw (untreated) water from private tanker trucks or the municipal network. They treat the water with large-scale water softeners, filters, reverse-osmosis membranes and ultraviolet lights. They bottle treated water in 10 or 20-liter plastic jugs and deliver jugs upon request. Storeowners primarily manage water treatment for taste and to meet Ministry of Health standards for pH, total dissolved solids, and coliforms. Each store serves from a hundred to a thousand residential and institutional customers. Water store purchases are an expensive but trusted, high quality source. Households use this water exclusively for drinking or cooking.

Buy bottled water. Homeowners can readily buy mineral or spring water in 1.5- or 2-liter plastic bottles at all supermarkets and mini-markets throughout Jordan. Bottles are marketed under brands such as Furat, Ghadeer, and Nivea. Bottled water is an expensive but trusted, high quality source used for drinking or cooking.

Buy water from private vendor. Homeowners can contract with drivers of private water tanker trucks to deliver bulk water supplies to the house, for example, to fill rooftop tanks, ground tanks, or a cistern. Tanker truck capacities range from 6 to 20 m^3. Drivers often fill their tankers at licensed governmental wells twenty to thirty km outside the city for 5 JD, congregate at specific locations, and wait for customers. The congregation points represent a spot market for water sales where sale price fluctuates depending on the season, customer demand, and negotiation flexibility of the driver and buyer. Drivers generally require sales to be at least 3 or 4 m^3. This requirement forces families with small tanks to cooperate and coordinate their purchases. Tanker water is an expensive, readily-available source of variable water quality. Most households use this water indoors for washing and hygiene, or outdoors for irrigating and car washing.

LEMA also maintains a fleet of tanker trucks that draw water from Ain Ghazal (spring) in East Amman and deliver water to customers for 1.5 JD per m^3 the day following a telephone request. Minimum purchase quantity is 4 m^3. LEMA trucks service more than 30 requests per day in summer (150 to 200 m^3) and 10 to 15 requests per day in winter. These requests are a small fraction of the water tanker truck demand for Amman.

Borrow water from neighbors. Homeowners can borrow water from the rooftop tanks of neighbors or fill a bucket to temporarily cover essential indoor washing or hygiene uses like toilet flushing. Water is generally borrowed or lent without financial charge. All persons interviewed described lending water as obligation to families in need; no persons reported paying cash for water given to them by neighbors.

Draw water from well. Rural homeowners who have installed a well may draw water from that well. Operation costs are for diesel fuel to run the pump and depend on the depth to groundwater and quantity of water drawn. No further data is available since none of the urban, residential households surveyed reported having or using a well.

Treat water inside home for drinking. Homeowners can also boil water on propane kitchen stoves to treat water to drink. This water is routinely served as tea or coffee. Preparation costs depend on purchase price of propane fuel (2 – 3 JD per tank), time tank lasts (1 – 4 months), fraction of time the stove is used to heat water as apposed to other cooking tasks (0.4 to 0.6), and daily quantity of water consumed (5 – 15 liters per day).

Store water. Homeowners can store excess water in ground tanks or a cistern for use at a later time. There is a negligible cost to store water since water is delivered by gravity.

Quantity is limited by storage capacity and available sources. Quality depends on the water source (households tend not to consider storage as degrading quality).

Draw water from storage. Homeowners also pump water from storage up onto the roof for distribution and use during a crisis or when needed. The cost depends on the quantity of water drawn and elevation difference between the storage vessel and roof. Quantity is limited by water held in storage and quality depends on the original source (households tend not to consider storage as degrading quality and clean cisterns annually).

2.5.2. Demand Management Actions

Demand management actions can reduce the quantity or alter the timing of a household's water use. Water volumes conserved vary among households and depend on the product of many household geographic, demographic, technologic, and behavioral factors.

No published information exists describing the effectiveness of demand management actions in Jordan and we did not measure effectiveness empirically. Thus, we report estimated benchmark statistics from derived likely distributions of effectiveness among Amman households. The derivation steps are: a) Identify the various factors influencing conservation action effectiveness and specify the functional relation among parameters. b) Specify a probability distribution for each parameter. c) Propagate parameter uncertainties to generate a composite distribution of effectiveness, and d) Note statistics for the composite effectiveness distribution (see Chapter 3 for details).

We use statistical values reported in the empirical literature to develop probability distributions for most parameters. Where empirical data did not already exist, we developed parameter distributions using either (i) the lower limits and mean results from the 36 households surveyed or questioned, or (ii) engineering estimates of the physical upper and lower limits (uniform distribution). Generally, we propagated parameter uncertainties analytically to derive log-normal distributions of effectiveness. However, the effectiveness functions to install pressure reducing valves and reduce laundry wash frequency were complicated and therefore generated using Monte-Carlo simulation (interestingly, lognormal curves fit these Monte-Carlo simulated results).

Because many of these parameters are functionally multiplied together, effectiveness tends towards a lognormal distribution with significant skew towards a small number of households that can possibly achieve large savings by implementing the conservation action. Effectiveness ranges (Table 2.5, column 6) represent the estimated 10th and 90th percentiles of the effectiveness distribution among Amman households. Maximum coverage (column 7) estimates the percentage of households with effectiveness greater than zero and indicates the potential market penetration rate. Below, actions are described by implementation and affected water uses.

2.5.2.1. Long-term demand management actions

Long-term demand management actions must be taken well in advance of reductions seen in household water use. These actions generally represent infrastructure modifications.

Install water saving devices. Homeowners can replace high-volume showerhead, faucet, or western toilets with substitute fixtures or water saving devices (WSDs) that maintain the quality of service but reduce the volume of water employed per use. Examples include installing faucet aerators on showerheads, kitchen faucets, or bath baucets, retrofitting western toilet tanks with dual-flush or adjustable water level mechanisms, or replacing western toilet tanks larger than 7 liters with smaller tanks. Retrofit appliances and parts are readily purchased at many bathroom fixture or hardware stores in and around Amman. WSDs installed at Amman's largest institutional water users reduced water use by about 50% (Tawarneh, personal communication, 2004). However, actual water savings depend on the flow rate of the new device, flow rate of the existing device, and frequency and duration of use.

Install water-conserving laundry machine. Homeowners can purchase an efficient laundry machine to reduce laundry water use by up to 61% for semi-automatic (dual-basin) machines or 20% for automatic machines (IdRC 2004). A variety of efficient models are available for purchase in appliance stores in and around Amman. Currently, customers pay little attention to water efficiency and little information exists to differentiate water efficiency among models. Actual water savings depend on the reduction in water consumption (l water per kg clothes), weight of clothes washed, and rinse behaviors (for semi-automatic machine owners). Households washing laundry in buckets or semi-automatic machines may *increase* water consumption when switching to an efficient automatic machine.

Install low-water consuming landscape. Homeowners can apply principles of permaculture and xeriscaping to reduce outdoor landscape water use. Costs and actual water savings depend on household-specific factors such as garden area, existing landscaping, and homeowner's priorities for shading, cover, seating areas, ornamental and food production, lawn areas, materials, and changes in irrigation practices. For example, a homeowner could consult with a landscape architect for 1,000 to 1,500 JD to develop a low-water consuming landscape plan for a setback garden area less than 200 m^2. The homeowner could then purchase the required ground cover, seedlings, and trees from local nurseries for 300 to 1,500 JD (CSBE 2004). These estimates include 3-weeks of labor costs.

Install drip irrigation system. Homeowners can install plastic drip irrigation systems (including piping, micro-sprayers, emitters, and drippers) in lieu of outdoor irrigating with hoses and furrows. Drip irrigation system components are sold at many gardening and irrigation stores in and around Amman. Installation costs vary for each house according to landscaped area. Water savings depend on the landscaped area and watering times prior to and after installing the drip system.

Install spray nozzle on hoses. Homeowners can install spray nozzles on outdoor hoses to reduce wastage while watering. Nozzles are sold at many gardening stores. Savings depend on the hose diameter, household water pressure, and frequency of hose use.

Install carpet on floors. Homeowners can install floor carpeting to avoid regular indoor floor washing with water. Installation costs depend on floor area.

Install pressure-reducing valve. Homeowners can install a pressure-reducing valve (PRV) to reduce household water pressure to between 5 to 10 meters of head (0.5 to 1.0 bar). PRVs reduce leakage and consumption for indoor washing and hygiene such as showering, dish, hand, and face washing (uses that depend more on time length of use than flow rate). PRVs most effectively reduce water use in multi-floored buildings with four or more floors between the roof storage tanks and point of use.

2.5.2.2. Short-term demand management actions

Households can implement short-term actions to immediately reduce water use. Implementing some long-term actions may enhance or reduce the effectiveness of a short-term action. The effectiveness values in Table 2.5 neglect these interactions.

Install bottles or bags in toilet tanks. Homeowners can insert filled plastic bottles or bags into the tanks of western toilets to reduce water volume per toilet flush. Implementation costs are negligible as used plastic bottles are readily available. Alternatively, homeowners can lower the level of toilet flush mechanisms.

Find and fix leaks. Homeowners should regularly search for leaks and fix them as soon as they are detected. Homeowners can hire a plumber to make a house visit. Water savings will vary and depend on the household water pressure, leak size, and duration the leak persists before repair.

Reduce irrigation to landscape. Homeowners can decrease the time per week that landscaping is irrigated. Financial costs are negligible and may even free time to pursue other activities. However, repeated stress irrigation can undermine plant productivity, reduce the desired aesthetic values, or permanently damage or kill plants. Effectiveness depends on the hose diameter, household water pressure, irrigation length and frequency.

Modify water use behaviors. Homeowners and household members can also temporarily modify water-use behaviors to reduce indoor consumption for washing and hygiene or outdoor use for irrigating and car washing. Examples include closing faucets while shaving, brushing teeth, washing dishes or washing hands; partially opening faucets to constrict flow rates during use; reducing shower time by using water only during initial soak and final rinse; reducing shower frequency; reducing laundry wash frequency; sweeping rather than washing floors; washing cars with water from a bucket; or washing cars at a gas station. The financial costs of these behavior changes are difficult to estimate. However, in several instances, estimated water savings are significant.

2.6. Discussion

Households in Jordan can adopt a wide variety of water supply enhancement and demand management actions. The actions have varying time-scales for implementation, financial costs, water effectiveness, and affected qualities. Combining different short- and long-term actions gives households great flexibility to respond to many types of service disruptions. Combinations of actions also imply financial costs, perceived costs (such as inconvenience or non-conformity with social, political, or cultural norms), risk tolerance, and preference for different levels of service or access.

Action costs and effectiveness depend on many household-specific geographic, demographic, technologic, and behavioral factors. Such factors include building location; house type; gardening or livestock area; family size; household water pressure; lengths and frequencies of water appliance uses; their water use efficiencies; and efficiencies of potential WSDs. Households may also assess different lifetimes for long-term actions.

Some management actions are only available to households with specific classes of water uses. For example, only households with gardens can xeriscape, install drip irrigation, or spray nozzles on hoses to reduce outdoor demands. Likewise, only apartment building owners with ground-level access can install a cistern or ground tank. Other households may find a management action achieves little or no water savings because of preexisting infrastructure. Maximum coverage (Table 2.5, column 7) estimates the percentage of Amman households likely to save water with a conservation action.

Effectiveness estimates assume households adopt a conservation action individually. Yet adopting one conservation action (faucet retrofits for example) may reduce water saved by other behavior changes (reduced wash time or partially opened faucet). More detailed systems analysis can help resolve interactions among actions and identify combinations of management actions to cost-effectively respond to service disruption events (Lund 1995). A systems perspective can also integrate physical and institutional constraints affecting user decisions.

Interactions become important when evaluating potential actions with increasing network water availability. For example, continuous piped supply may render various storage, sources, or conservation actions obsolete or cost-ineffective. Still, other conservation actions may beneficially lower household water management costs. Further work should empirically verify that estimated water savings pan out, investigate household tradeoffs for costs and risk tolerance to different levels of service or access, market penetration rates for conservation actions, and aggregate effects of user choices on water use.

The aggregate effects will have important implications for IWRM at wider utility and national scales. Aggregate results can help shape public education and awareness campaigns (actions to feature and likely water savings), suggest rebate amounts or tax credits to motivate customers to adopt water conservation technologies, or highlight inefficient water use practices to change with technology development programs or plumbing code modifications. Water utilities or governments can also use aggregated results to selectively target the subset of users who can save the most water and money by adopting a specific action. These examples show that identifying and characterizing potential water user actions is a key first step to successful IWRM at wider utility and regional scales.

2.7. Conclusions

Intermittent water deliveries are a major and expanding global problem. In Jordan and other countries, water users can adopt a wide and complex range of supply enhancement and demand management actions to improve performance or better cope with local water service conditions. Actions have different financial costs, inconveniences, water volumes gained or conserved, and associated water qualities. These characteristics can vary significantly among individual users. Users need only implement some actions for short time periods to respond to particular service disruptions or shortages whereas other actions require significant long-term capital investment and prior planning. Identifying and characterizing available options is an important IWRM first step to be followed by water use efficiency evaluation (Dziegielewski et al. 1992) and detailed systems analysis (Garcia-Alcubilla and Lund 2006; Lund 1995).

Individual water users make most water management decisions. These analyses can help identify cost-effective, water efficient actions, clarify interactions among potential management actions, develop strategies for individual water users, and summarize the aggregate affects of decentralized water user decisions. Understanding the aggregate effects of water user decisions is key to successfully pursue IWRM at wider utility, regional, and national scales.

2.8. References

Abu Qdais, H. A., and Batayneh, F. (2002). "The Role of Desalination in Bridging the Water Gap in Jordan." *Desalination*, 150(2), 99-106.

Abu-Shams, I., and Rabadi, A. (2003). "The strategy of restructuring and rehabilitating the greater Amman water network." *Water Resources Development*, 19(2), 173-183.

Asian Development Bank (ADB). (1997). "Second Water Utilities Data Book – Asian and Pacific Region." Asian Development Bank, Manila, Philippines. http://www.adb.org/Documents/Books/Second_Water_Utilities/default.asp [Accessed on: January 18, 2005].

Ahmed, I. T. A. (2004). "Rainwater Harvesting in Amman." *International water demand management conference*, Dead Sea, Jordan, June 1, 2004.

Al-Ghamdi, A. S., and Gutub, S. A. (2002). "Estimation of leakage in the water distribution network of the Holy City of Makkah." *Journal of Water Supply Research and Technology-Aqua*, 51(6), 343-349.

Alkhaddar, R. M., Sheehy, W. J. S., and Al-Ansari, N. (2005). "Jordan's Water Resources: Supply and Future Demand." *Water International*, 30(3), 294-303.

Al-Salihi, A. H., and Himmo, S. K. (2003). "Control and Management Study of Jordan's Water Resources." *Water International*, 28(1), 1-10.

Altaf, M. A. (1994). "The Economics of Household Response to Inadequate Water-Supplies - Evidence from Pakistan." *Third World Planning Review*, 16(1), 41-53.

Bino, M., Al-Jayyousi, O., Sawan, J., Al-Beiruti, S., and Al-Makhamereh., S. (2000). "Evaluation of Permaculture and Greywater Reuse Project in Tafila, Jordan: Final Report." Inter-Islamic Network on Water Resources Development and Management (INWRDAM) for the International Development Research Centre (IDRC), Ottawa, Ontario, Canada. http://www.inwrdam.org/page/158.

Blaikie, N. (2000). *Designing Social Research: The Logic of Anticipation*, Policy Press, Cambridge, MA.

Center for Study of the Built Environment (CSBE). (2004a). "Greywater Reuse Project." Amman, Jordan. http://www.csbe.org/graywater/contents.htm [Accessed on: November 29, 2004].

Center for Study of the Built Environment (CSBE). (2004b). "Water Conserving Landscapes." Amman, Jordan. http://www.csbe.org/water_conserving_landscapes/index.html [Accessed on: November 29, 2004].

Department of Statistics (DOS). (1994). "General Census of Population and Housing." Amman, Jordan. http://www.dos.gov.jo/sdb/sdb_pop/sdb_pop_e/inde_o.htm [Accessed on: January 15, 2005].

Department of Statistics (DOS). (1999). "Urban Agriculture Survey." Amman, Jordan. http://www.dos.gov.jo/sdb/env/env_e/home.htm [Accessed on: June 26, 2004].

Dziegielewski, B., Opitz, E. M., Kiefer, J. C., and Baumann, D. D. (1992). "Evaluation of urban water conservation programs: a procedures manual." California Urban Water Agencies. http://www.cuwcc.com/uploads/tech_docs/EvaluationOfUrbanWaterCnsvPrgms.pdf.

Faruqui, N., and Al-Jayyousi, O. (2002). "Greywater reuse in urban agriculture for poverty alleviation - A case study in Jordan." *Water International*, 27(3), 387-394.

Fisher, F. M., Arlosoroff, S., Eckstein, Z., Haddadin, M. J., Hamati, S. G., Huber-Lee, A., Jarrar, A. M., Jayyousi, A. F., Shamir, U., and Wesseling, H. (2002). "Optimal water management and conflict resolution: The Middle East Water Project." *Water Resources Research*, 38(11), 25-1:17.

Garcia-Alcubilla, R., and Lund, J. R. (2006). "Derived willingness-to-pay for household water use with price and probabilistic supply." *Journal of Water Resources Planning and Management-Asce*.

Griffen, R. (2004). "Management of Water Losses Due to Commercial Reasons: A Study in Amman." *International Water Demand Management Conference*, Dead Sea, Jordan, June 2. http://www.wdm2004.org/new_web/technical_session/files/roger_griffin.pdf.

Haddad, M., and Lindner, K. (2001). "Sustainable water demand management versus developing new and additional water in the Middle East: a critical review." *Water Policy*, 3(2), 143-163.

Hussein, I. A. J. (2002). "Water Planning in Jordan: Future Scenarios." *Water International*, 27(4), 468-475.

Interdisciplinary Research Consultants (IdRC). (2004). "A Survey of Home Appliances and Toilets in the Jordanian Markets." Academy for Educational Development: Water Efficiency for Public Information and Action (WEPIA) Program, Amman, Jordan, 50 pp.

Iskandarani, M. (2002). "Economics of Household Water Security in Jordan." Development Economics and Policy, F. Heidhues and J. v. Braun, eds., Peter Lang, Frankfurt am Maim, 133.

International Water Demand Management Conference (IWDMC). (2004). Dead Sea, Jordan. http://www.wdm2004.org/.

Jaber, J. O., and Mohsen, M. S. (2001). "Evaluation of non-conventional water resources supply in Jordan." *Desalination*, 136(1-3 SU), 83-92.

Jordanian National Council for Buildings (JNCB). (2003). "Water Code for Buildings." Ministry of Public Works and Housing, Amman, Jordan, 99 pp., (In Arabic).

Joench-Clausen, T., and Fugl, J. (2001). "Firming up the Conceptual Basis of Integrated Water Resources Management." *International Journal of Water Resources Development*, 17(4), 501-510.

Kyessi, A. G. (2005). "Community-based urban water management in fringe neighbourhoods: the case of Dar es Salaam, Tanzania." *Habitat International*, 29(1), 1-25.

Letcher, R. A., Jakeman, A. J., and Croke, B. F. W. (2004). "Model development for integrated assessment of water allocation options." *Water Resources Research*, 40(5).

Lund, J. R. (1995). "Derived estimation of willingness to pay to avoid probabilistic shortage." *Water Resources Research*, 31(5), 1367-1372.

Maganga, F. P., Butterworth, J. A., and Moriarty, P. (2002). "Domestic water supply, competition for water resources and IWRM in Tanzania: a review and discussion paper." *Physics and Chemistry of the Earth, Parts A/B/C*, 27(11-22), 919-926.

McKenzie, D., and Ray, I. (2004). "Household water delivery options in urban and rural India." *Working Paper No. 224*, Stanford Center for International Development, Stanford, California. http://scid.stanford.edu/pdf/SCID224.pdf.

Pattanayak, S. K., Yang, J.-C., Whittington, D., and Kumar, K. C. B. (2005). "Coping with unreliable public water supplies: Averting expenditures by households in Kathmandu, Nepal." *Water Resources Research*, 41(W02012), 1-11.

Scott, C. A., El-Haser, H., Hagan, R. E., and Hijazi, A. (2003). "Facing Water Scarcity in Jordan: Reuse, Demand Reduction, Energy, and Transboundary Approaches to Assure Future Water Supplies." *Water International*, 28(2), 209-216.

Snobar, A. H. (2003). "Feasibility of Domestic Graywater Recycling," Senior Thesis, Jordan University of Science and Technology, Irbid.

Soares, L. C. R. (2001). "Regional Report on the Evaluation 2000 in the Region of the Americas: Water Supply and Sanitation, Current Status and Prospects." Pan American Health Organization. http://www.cepis.ops-oms.org/bvsaas/i/fulltext/infregio/infregio.pdf. [Accessed on: January 15, 2005].

Theodory, G. (2000). "The willingness and ability of residential and non-residential subscribers in Greater Amman to pay more for water." *PN-ACQ-616*, Development Alternative, Inc., and U.S. Agency for International Development, Bethesda, Maryland. http://dec.usaid.gov/index.cfm?p=search.getCitation&CFID=4686300&CFTOKEN=50535563&rec_no=116108.

Thomas, J. S., and Durham, B. (2003). "Integrated Water Resource Management: looking at the whole picture." *Desalination*, 156(1-3), 21-28.

Thompson, J., Porras, I. T., Tumwine, J. K., Mujwahuzi, M. R., Katui-Katua, M., Johnstone, N., and Wood, L. (2001). "Drawers of Water II: Summary." International Institute for Environment and Development, London. http://www.iied.org/sarl/dow/pdf/summary.pdf.

Tokajian, S., and Hashwa, F. (2003). "Water quality problems associated with intermittent water supply." *Water Science and Technology*, 47(3), 229-234.

Wahlin, L. (1995). "The Family Cistern: 3000 Years of Household Water Collection in Jordan." *Third Nordic Conference on Middle Eastern Studies*, Joensuu, Finland, 19-22 June 1995, 233-249.

Water Efficiency and Public Information for Action (WEPIA). (2000a). "Assessment of Water Saving Devices Sector in Jordan." Amman, Jordan, 39 pp.

Water Efficiency and Public Information for Action (WEPIA). (2000b). "Capacity building project in Fuhies." Amman, Jordan, 14 pp. http://pdf.dec.org/pdf_docs/PNADB639.pdf.

Water Efficiency and Public Information for Action (WEPIA). (2001). "Capacity building project in Amman, Irbid, and Aqaba." United States Agency for International Development, Amman, Jordan, 12 pp. http://pdf.dec.org/pdf_docs/PNADB469.pdf.

Whalen, M., and Al-Saudi, H. (1998). "Small Project Assistance Grant Proposal: Repairing Cisterns in Hisban, Jordan." U.S. Peace Corps-Jordan and United States Agency for International Development, Amman, Jordan.

White, G. F., Bradley, D. J., and White, A. U. (1972). *Drawers of Water*, The University of Chicago Press, Chicago, IL.

World Health Organization and United Nations Children's Fund (WHO, and UNICEF). (2000). "Global Water Supply and Sanitation Assessment 2000 Report." Joint Monitoring Programme for Water Supply and Sanitation, Geneva: WHO and New York: UNICEF. http://www.who.int/docstore/water_sanitation_health/Globassessment/GlobalTOC.htm [Accessed on: January 15, 2005].

Wilchfort, O., and Lund, J. R. (1997). "Shortage management modeling for urban water supply systems." *Journal of Water Resources Planning and Management*, 123(4), 250-258.

Wolf, A. T., and Murakami, M. (1995). "Techno-political decision making for water resources development: the Jordan River watershed." *Water Resources Development*, 11(2), 147-161.

Zérah, M.-H. (2000). "Household strategies for coping with unreliable water supplies: the case of Delhi." *Habitat International*, 24(3), 295-307.

Table 2.1. Potential water management actions for urban water users

Stage	Supply Enhancement	Conservation
Long-term Actions	• Develop new supplies – Establish network connection – Install rainwater collection system – Drill well • Install local storage – Rooftop tanks – Ground tanks – Cisterns (underground storage) • Improve quality • Install grey-water collection system • Install in-home drinking quality water treatment	• Install water efficient appliances – Showerheads – Kitchen or bath faucets – Low flush toilets or dual flush mechanisms – Auto- or semi-automatic laundry machines – Drip irrigation system – Spray nozzles on outdoor hoses • Reduce water use – Install low water-consuming landscape or crops – Pressure reducing valve – Install permanent carpets in rooms
Short-term Actions	• Access supplies – Take delivery through public network – Buy water from private vendor (tanker truck) – Buy drinking quality water from a store – Buy bottled water – Drink collected rainwater – Borrow water from a neighbor – Steal water – Draw water from well – Store or draw water from local storage • Improve quality – Treat water inside home for drinking – Boil water – Collect, treat and apply grey-water to landscaping	• Insert bottles or bags in toilet tank • Find and fix leaks • Modify water use behaviors – Stress irrigate landscape or crops – Use water only when necessary – Sweep floors rather than wash them – Turn off faucets while washing – Wash car with bucket – Partially open faucet – Reduce laundry-washing frequency – Reduce shower-taking frequency – Reduce shower length

Table 2.2. Availability of improved water services in select world cities and countries

City, Country	Year	Population (millions)	Pop. with Improved Service (%)	Availability	Source
Amman, Jordan	2003	2.2	92	12–60 hrs/wk	Abu-Shams and Rabadi (2003)
Bandung, Indonesia	1995	2.2	42	6 hrs/day	ADB (1997)
Calcutta, India	2004	4.4	66	9 hrs/day	McKenzie and Ray (2004)
Cebu, Philippines	1995	1.2	23	18 hrs/day	ADB (1997)
Chennai, India	1995	4.4	97	4 hrs/day	ADB (1997)
Cuba (entire country)	1998	11.1	93	12 hrs/day	Soares (2001)
Dar es Salam, Tanzania	2005	3.0	30	24–72 hrs/wk	Kyessi (2005)
Delhi, India	1997	10.8	86	4 hrs/day	ADB (1997)
Faisalabad, Pakistan	1996	1.8	60	7 hrs/day	ADB (1997)
Guatemala (entire country)	1998	9.0	80	6–12 hrs/day	Soares (2001)
Haiti (entire country)	1998	7.7	46	6 hrs/day	Soares (2001)
Honduras (entire country)	1998	6.0	81	6 hrs/day	Soares (2001)
Karachi, Pakistan	1996	11.5	70	1–4 hrs/day	ADB (1997)
Kathmandu, Nepal	1995	0.9	81	6 hrs/day	ADB (1997)
Manila, Philippines	1995	10.6	67	17 hrs/day	ADB (1997)
Mekkah, Saudi Arabia	2002	1.2	70	Intermittently	Al-Ghamdi and Gutub (2002)
Mumbai, India	1996	10.3	100	5 hrs/day	ADB (1997)
Naccache, Lebanon	2003	0.03	NA	48 hrs/week	Tokajian and Hashwa (2003)
Peru (entire country)	1998	24.8	75	14 hrs/day	Soares (2001)
Phnon Penh, Cambodia	1996	0.8	83	12 hrs/day	ADB (1997)
Saint Lucia (entire country)	1998	0.15	98	10–12 hrs/day	Soares (2001)
Thimphu, Phutan	1996	0.03	93	12 hrs/day	ADB (1997)
Yangon, Myanmar	1995	3.2	60	12 hrs/day	ADB (1997)

Table 2.3. Empirical studies on residential water use and conservation in Jordan

Location		Sample Size (Households)	Year	Study Method	Topic / Subject	Reference
1.	Kingdom	672,472	1994	Census	Households; house type, available household units; and buildings	DOS (1994)
2.	Ein Al-Baida, Tafilah	15	1998-2002	Follow-up household evaluation	Use and economic value of grey-water	Faruqui and Al-Jayyousi (2002)
3.	Greater Amman Municipality	1,800	1998	3-tiered household survey	Urban agricultural activities; garden areas	DOS (1999)
4.	Greater Amman Municipality	1,000	1999	Focus groups; household survey	Water storage; willingness-to-pay	Theodory (2000)
5.	Fuheis, Amman	344	2000	Household survey	Laundry and car washing activities; awareness of water saving devices	WEPIA (2001)
6.	Kingdom	200	2001	Stratified household survey	Borrowing and other water use behaviors	Iskandarani (2002)
7.	Greater Amman Municipality	30	2002	Household survey	Shower, faucet, and toilet use, grey-water reuse potential	Snobar (2003)
8.	Greater Amman Municipality	10 – 30 products	2004	Product surveys; import records	Water appliance water and energy use efficiency	IdRC (2004)
9.	Greater Amman Municipality	36	2004	Survey; questionnaire; billed water use	Household demographics, water infrastructure, water use behaviors	Current study

Table 2.4. Potential actions to enhance household water supplies in Jordan

Water Management Action	Price Quotes[a]				Water Volume (m^3)	Uses[b]	Est. lifespan	Additional notes	Sources
	Average (JD)	Highest (JD)	Lowest (JD)	Num.					
Long-term actions									
Connect to network	230.	--	--	1	--	D,I,O	10+ years	Plus 1 JD/m^2 floor area above 150 m^2	LEMA (2004); WAJ (2004)
Install roof or ground tanks	74.	95.	65.	5	2	D,I,O	5 years	Volume per tank. Add up to JD 20 to deliver	Interview retail store owneres
	46.	55.	38.		1		5 years		
Install cistern	690.	1,500.	440.	4	16 to 36	D,I,O	10 - 20 years	Volume per cistern[c].	Whalen and Al-Saudi (1998); Ahmad (2004); Household surveys
Collect rainwater	200.	300.	100.	2	11.5 - 65.2	D,I,O	5 - 10 years	Volume per year[d].	Ahmad (2004); JMD (2000)
Install grey-water collection and treatment system	57.	130.	0.0	4	0 - 15	O	10 - 20 years	Volume per quarter[c].	Bino (2000); CSBE (2004); Faruqui and Al-Jayyousi (2002); Interview plumber
Drill well	10,300.	13,800.	5,400.	1	--	D,I,O	10 - 20 years	Price to license well and drill to depths of 60 to 200 meters.	Hadidi, pers. comm., 2004; El-Halah, pers. comm., 2004
Install in-home water treatment	210.	330.	140.	4	0 to 0.7	D	3 years	Input volume per day. Excludes JD 54 - 180 per year upkeep cost.	Retail store interviews
Short-term actions									
Take delivery through municipal network									
Up to 20 m^3 per quarter	--	Infinity	0.17	I	1	D,I,O	3 months	Flat charge of JD 3.47.	LEMA (2004); WAJ (2004)
20 - 40 m^3 per quarter	0.18	--	--		1		3 months	Constant price of JD 0.18/m^3	LEMA (2004); WAJ (2004)
40 - 130 m^3 per quarter	--	0.57	2.34		1		3 months	Variable price from quadratic formula	LEMA (2004); WAJ (2004)
Above 130 m^3 per quarter	1.24	--	--		1		3 months	Constant price of JD 1.24/m^3	LEMA (2004); WAJ (2004)
Buy water from water store	46.	50.	40.	5	1	D	day - week	Price includes delivery to house	Retail store interviews
Buy bottled water	153.	233.	104.	4	1	D	day	Purchase price at store	Purchases at mini-markets
Buy water from tanker truck	2.40	4.30	1.50	5	1	I,O	week	Generally requires minimum 6 m^3 purchase	LEMA (2004); Driver interviews; observe customer purchases
Borrow from neighbor	--	--	--	4	< 0.25	I	day	Never pay for water	Iskandarani (2002); survey responses
Draw water from well	--	--	--	0	--	D,I,O	day	Not available to urban customers	Survey responses
Boil water in home to drink	3.42	0.44	11.80	4	1	D	day	Price estimated by fuel cost to heat 10 to 20 teapots per day	Engineering estimate
Store water	--	--	--	0	1 - 42	D,I,O	week	Volume per week[c] limited by storage. Negligible costs.	Engineering estimate
Draw water from storage	--	--	--	0	1 - 42	D,I,O	week	Volume per week[c] limited by storage. Excludes pump costs	Engineering estimate

Notes:

a. JD 1.00 = $US 1.41

b. Water use quality classifications: D=for drinking and cooking; I=indoor for washing and hygiene; O=outdoor for irrigating, livestock, and car washing

c. Water volume range represents absolute physical lower and upper limits (0 and 100th percentiles)

Table 2.5. Potential actions to reduce household water demands in Jordan

Water Management Action	Price Quotes[a]				Estimated savings[b]	Maximum coverage[c]	Uses[d]	Est. lifespan	Information source(s)
	Average	Highest	Lowest	Num.					
Long-term actions	**(JD)**	**(JD)**	**(JD)**		**(m^3 per year)**	**(Percent)**			
Retrofit showerheads	58.	150.	5.	3	0.0 - 107	82%	I	5 years	WEPIA (2000a); interview retail store owners
Retrofit kitchen faucets	3.0	3.5	2.0	3	2.1 - 93	93%	D,I	5 years	WEPIA (2000a); interview retail store owners
Retrofit bath faucets	3.0	3.5	2.0	3	0.0 - 19	90%	I	5 years	WEPIA (2000a); interview retail store owners
Install toilet dual-flush mechanisms	14.	25.	4.	4	0.0 - 118	70%	I	5 years	IdRC (2004); interview store owners
Retrofit toilets	83.	165.	28.	16	0.0 - 73.5	84%	I	10 years	IdRC(2004); Interview store owners
Install water efficient semi-automatic laundry machine	137.	290.	80.	4	0.0 - 30.3	84%	I	5 years	IdRC (2004); interview store owners
Install water efficient automatic laundry machine	552.	620.	370.	12	0.0 - 6.3	68%	I	5 years	IdRC (2004); interview store owners
Install low-water consuming landscape	2,100.	3,500.	300.	1	0.0 - 46.3	11%	O	10 years	CSBE (2004)
Install drip irrigiation system	18.	20.	15.	4	0.0 - 18.0	10%	O	5 years	Interveiw retail store owners and employees
Install spray nozzle on hoses	3.0	4.0	1.0	5	0.0 - 7.0	12%	O	2 years	Interveiw retail store owners and employees
Install carpet on floors	3,150.	6,000.	300.	2	4.0 - 42.5	100%	I	5 years	Interview store owners
Install pressure reducing valve	35.	40.	30.	1	0.0 - 20.7	14%	I,O	5 years	Interview with pipe engineers
Short-term actions	**(JD)**	**(JD)**	**(JD)**		**(m^3 per week)**	**(Percent)**			
Install bags or bottles in toilets	--	--	--	--	0.1 - 0.4	100%	I	1 - 6 months	
Find and fix leaks	5.	8.	2.	4		100%	I,O	day	Interview plumber & households
Reduce landscape irrigation	--	--	--		0.0 - 0.2	12%	O	week	
Turn off faucets while washing	--	--	--	--	0.0 - 0.4	75%	I	day	
Partially open faucet	--	--	--	--	0.0 - 0.4	88%	I	minutes	
Reduce shower length	--	--	--	--	0.0 - 19.8	77%	I	minutes	
Reduce shower-taking frequency	--	--	--	--	0.0 - 17.1	42%	I	week	
Reduce laundry-washing frequency	--	--	--	--	0.0 - 0.3	100%	I	week	
Sweep rather than wash floors	--	--	--	--	0.1 - 0.8	100%	I	day	
Wash car with buckets	2.5	5.0	0.0	2	0.0 - 15	74%	O	week	
Wash car at gas	1.5	2.0	1.0	3	0.0 - 14.5	74%	O	week	Household interviews

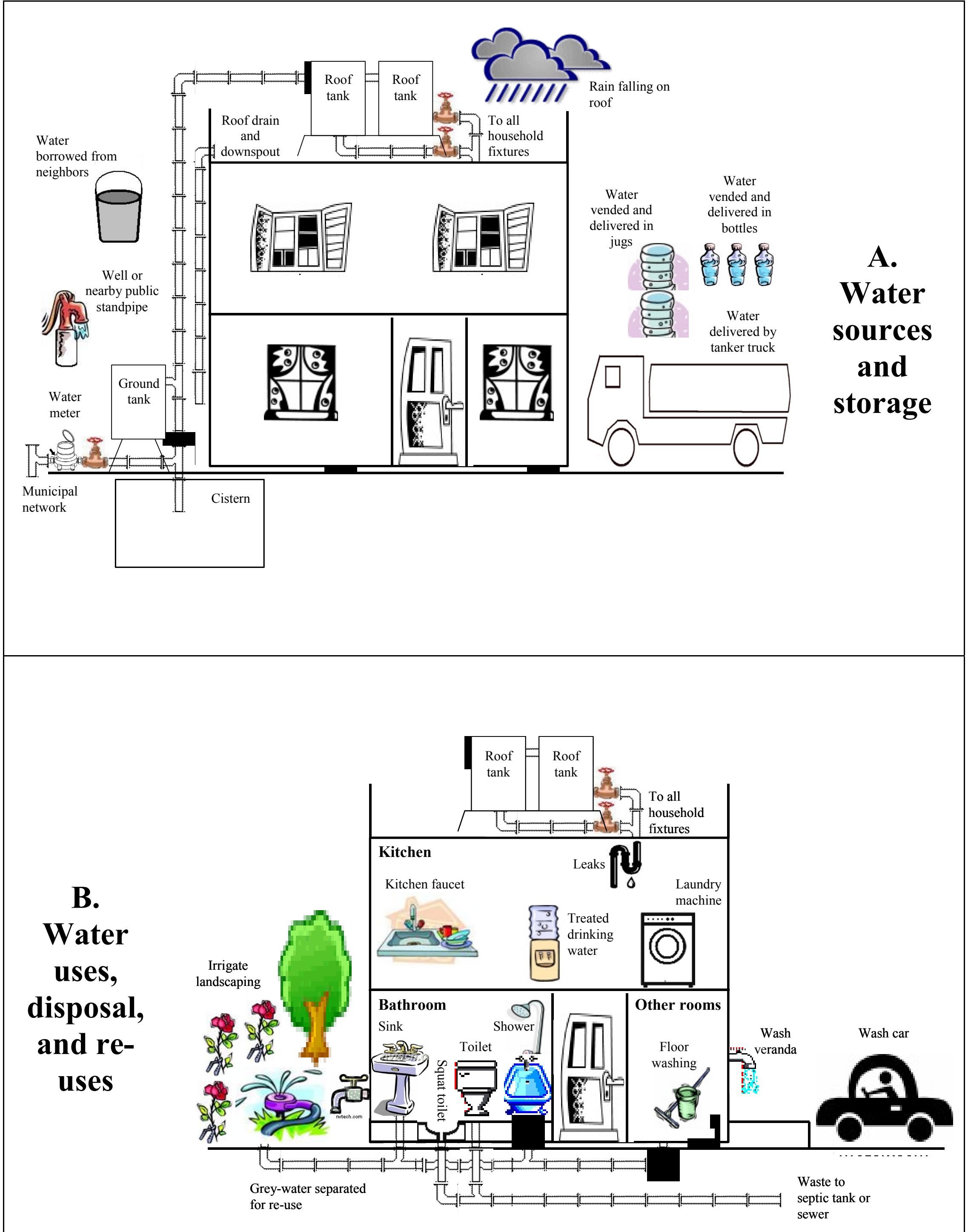
Notes:

a. JD 1.00 = $US 1.41

b. Range represents estimated 10th and 90th percentiles for population of Amman households based on varying household geographical, technological, and behavioral factors

c. Percent of households estimated to save water by adopting the action

d. Water use classes: D=drinking and cooking; I=indoor for washing and hygiene; O=outdoor for irrigating, livestock, and wash cars.



2.9.

Figure 2.1. Scheamtic of household water sources and uses in Jordan.

Chapter 3

Probabilistic Estimation of Water Conservation Effectiveness

Abstract – An analytical method is derived to describe the distribution of water quantity saved among customers within a water-use sector who adopt a water conservation action. Analytical results tend towards lognormal distributions with long tails, quantifying a smaller subset of customers that show potential to achieve large savings. Example effectiveness distributions are shown for seven long-term conservation actions potentially implemented by urban, domestic water users in Amman, Jordan. Monte-Carlo simulations verify the analytical derivations. The probabilistic outputs contrast with common methods that estimate conservation action effectiveness as a product of typical (average) characteristics for disaggregated customer groups. Implications to size water conservation programs to meet conservation objectives and target customers to adopt conservation actions are discussed.

3.1. Introduction

Water consumption and the effective quantity of water conserved by implementing conservation actions vary significantly among customers with important effects related to various geographic, demographic, technological, behavioral, and temporal factors (Mayer et al. 1999; Optiz and Dziegielewski 1998; Vickers 2001; Walski et al. 1985). Conventional approaches to estimate water conservation action effectiveness commonly disaggregate water use by sectors and estimate effectiveness within a sector as a simple product of single parameter values representing average customer characteristics (Optiz and Dziegielewski 1998; Vickers 2001; Walski et al. 1985). For example, Vickers (2001, p. 25) presents typical values of 15 liters (4 gallons) per flush for residential toilets manufactured before 1994, 6 liters (1.6 gallons) per flush for low-volume toilets manufactured after 1997, 5.1 flushes per person per day, 2.64 persons per residence, and 365 days per year to show that a U.S. residential customer installing a low-flow toilet should typically conserve $(15 - 6)(5.1)(2.64)(365)/(1000) = 44\ \text{m}^3\ \text{year}^{-1}$. The number of customers needed to meet a conservation objective is then found by dividing the water conservation objective by the typical savings per customer. Sector-wide effectiveness is also estimated by multiplying parameters for total unrestricted water use, fractional water use reduction, coverage (fraction of customers adopting the action), and interaction with other conservation actions (Optiz and Dziegielewski 1998; Walski et al. 1985).

Conventional estimation approaches work well for homogenous customer populations where customers within each water-use sector have nearly identical unrestricted water uses, similar reduction potentials, and both factors can be quantified as singular values. In such cases multiplying typical customer effectiveness by the number of customers in the water-use sector likely to adopt the action readily yields the sector-wide effectiveness. However, when a customer population is heterogeneous, shows multiple water use behaviors and reduction fractions, or the likely coverage is uncertain, effectiveness calculated solely from typical values can prove problematic for several reasons. First, parameter values are uncertain and differ for different customers. The uncertainties propagate and also make the resultant effectiveness uncertain. Second, customers facing (extreme) situations represented by one or more parameters taking values at the lower end of their feasible ranges should have little or no water savings. These customers may have insufficient financial or other incentives to adopt a conservation action. Third, data gathering, computing, and analysis efforts increase multiplicatively as the analyst further disaggregates the customer population to form homogenous sub-sectors (Walski et al. 1985). The analyst also must set separation points by trial and error. And fourth, effectiveness parameters are multiplied together so the uncertainties interact rather than cancel. Effectiveness will not necessarily be normally (i.e., evenly) distributed above and below the simple product of average parameter values. Thus, a single effectiveness value does not show how water savings may be distributed among the customers under study.

This chapter presents an alternative, probabilistic approach to describe the likely distribution of effectiveness among a sector of customers considering adopting a water conservation action. First, probabilistic information is developed to describe the range and likelihood of values possible for each parameter influencing effectiveness (Jaynes 2003; Tribus 1969). Second, the uncertainties are propagated analytically—and verified numerically with Monte Carlo simulations—to develop the distribution of effectiveness. Because parameters are multiplied together, effectiveness tends to a lognormal distribution (Aitchison and Brown 1957). And third, the continuous effectiveness distribution is used to select and size water conservation programs to meet conservation objectives. The approach is demonstrated for seven long-term conservation actions that are potentially implemented by urban, residential water users in Amman, Jordan. Probabilistic treatment achieves a continuous disaggregating of a customer population and suggests the minimum number of participants needed to meet a specific water conservation objective. The approach is useful to planners who understand the ranges of potential values for customer demographic, behavioral, and technological factors influencing effectiveness but who cannot measure effectiveness directly.

3.2. Probabilistic method

The probabilistic method to describe the likely distribution of effectiveness among customers considering adopting a water conservation action is summarized as follows:

1. Define how effectiveness is calculated from its component parameters,
2. Estimate a probability distribution (pdf) for each uncertain parameter,
3. Propagate uncertainties to calculate a composite probability distribution for conservation effectiveness,
4. Note statistics for the composite distribution, and
5. Use distribution properties to size conservation programs or estimate aggregate water savings.

These steps are further described as follows.

3.2.1. Functional form of conservation action effectiveness

Engineering estimates of the expected quantity of water conserved in a particular place over a specific period of time by implementing a conservation action are often calculated as a simple product of single parameter values (Optiz and Dziegielewski 1998; Vickers 2001; Walski et al. 1985). Although the effectiveness function is specific to each conservation action, the general form is

$$W = f_{conv} \cdot \prod_{j=1}^{m} \left(X_j\right)^{r_j} \prod_{k=m+1}^{n} \left(Z_k - Y_k\right)^{r_k} . \tag{3.1}$$

Here, W is the uncertain water conservation effectiveness or volume conserved per customer per unit time when a customer implements the conservation action; X_j, Z_k, and Y_k are uncertain parameters in units specific to the conservation action; r_j or r_k are fixed powers to which those parameters may be raised; f_{conv} is a unit conversion factor; m is the number of individual-termed uncertain parameters; and $n - m$ is the number of paired terms. (The capital letters X, Y, Z, and W reflect notation common to the probability literature where a capital letter, i.e. X, means the parameter is uncertain. The lower case counterpart, i.e., x, refers to a particular value that the uncertain parameter may take.)

The paired parameters Z_k, and Y_k have the same units and occur together as a difference term when effectiveness is a function of change in state. For example, the effectiveness of installing a water-conserving fixture depends in part on the difference between the flow rate of the existing fixture (i.e., Z [l min^{-1}]) and flow rate of the water-conserving fixture (i.e., Y [l min^{-1}]). Both flow rates are often uncertain; therefore, their difference is also uncertain and must be considered explicitly. (Dividing the difference between the average existing flow rate and average conserving flow rate by the average existing flow rate gives the sector-wide reduction parameter used by Walski et al. (1985)).

3.2.2. Estimate probability distributions for parameters

The second step is to estimate probability distributions for each uncertain parameter. Distributions will depend on the prior information known about the parameter. They can be specified from detailed, statistically sampled, empirical information concerning customer demographics, water appliances, water-related behaviors and consumption [for example, see Mayer (1999)]. Distributions can also be fit to empirical data. Or, absent detailed information, distributions may be estimated using the method of maximum entropy. This method minimizes information content (maximizes entropy) to suggest the most simple distribution shape that completely encapsulates the limited prior information known for the parameter (such as upper bound, lower bound, and/or average value) [see Jaynes (2003) or Tribus (1969, pp. 128-130) for details]. Rows 1 and 2 of Table 3.1 summarize the likely distribution forms or pdfs for different cases of prior known information. Cases are discussed further in the sections below. Methods to estimate distribution forms for difference terms common to water conservation actions are summarized in rows 1 and 2 of Table 3.2. These resultant distributions depend on the distributions of the component parameters and are also discussed below.

3.2.2.1. *Known lower and upper bounds*

When only the lower and upper bounds for a parameter are known, the principle of maximum entropy suggests that parameter values should be uniformly (rectangular) distributed. The parameter should have an equally likely (or constant) probability to take any value in the feasible range.

3.2.2.2. *Known lower bound and mean*

When only the lower bound and mean for a parameter are known, the principle of maximum entropy suggests that the lower bound value is most likely to occur. However, the occurrence probability should decay exponentially as the potential value the parameter may take increases. The initial value (λ_0) and rate of decay (λ_1) are calculated analytically from the prior known lower bound and mean.

3.2.2.3. *Known frequencies for discrete ranges of parameter values*

Results from empirical surveys are often summarized as frequencies for discrete ranges of parameter values (histograms). Frequencies can be used as-is, or fitted with a continuous functional form. In addition, any analytical probability density function may be approximated as a set of frequencies for discrete ranges of parameter values when the ranges chosen are sufficiently small.

3.2.2.4. *Difference of two parameters*

The difference of two uncertain parameters is also uncertain, and will be distributed according to the *convolution* of the uncertain parameters (Jaynes 2003, p. 677). For example, the uncertain difference U = Z – Y has the probability distribution,

$$h(u) \equiv \int_{-\infty}^{\infty} pdf_z(x) \cdot pdf_y(x-u) \cdot dx \quad . \tag{3.2}$$

Here, pdf_z and pdf_y are, respectively, the probability density functions of the component uncertain parameters *Z* and *Y*. For example, when *Z* is the uncertain flow rate of the existing fixture [l min^{-1}] and *Y* is the uncertain flow rate of the water conserving fixture [l min^{-1}], *h(u)* will represent the distribution of reduced flow (hereafter, the convoluted distribution). The convoluted distribution may exist for some or all of the negative range (u < 0) depending on the lower and upper bounds (if any) of *Z* and *Y*. The convolution distribution will depend on the distribution forms of the component parameters (see results in rows 1 and 2 of Table 3.2 for example distributions and differences common to water conservation actions). Convolution allows us to transform a term with two uncertain parameters into a term with one uncertain parameter and further generalize the functional form of conservation action effectiveness to

$$W = f_{conv} \cdot \prod_{j=1}^{n} \left(X_j\right)^{r_j} \quad . \tag{3.3}$$

3.2.3. Propagate uncertainties

With distributions specified or derived for each component parameter, the next step is to propagate uncertainties to determine the composite probability distribution of effectiveness among customers in the water use sector. Uncertainty can be propagated analytically or by Monte Carlo simulation.

3.2.3.1. Analytical propagation

The logarithm of the generalized effectiveness equation (3.4) gives

$$\log(W) = \log(f_{conv}) + \log(X_1) + \log(X_2) + \cdots + \log(X_n) \quad (3.5)$$

Sampling from the right hand side of (3.5) and applying the Central Limit Theorem yields a sum that will be normally distributed about a composite mean value, $\mu_{(n)}$. This observation applies irrespective of the distributions of the log-adjusted component parameters. Thus, the logarithm of the composite conservation effectiveness *W* is normally distributed, meaning that *W* is lognormal distributed with a probability density function of

$$pdf(w) = \partial\Lambda(\mu, \sigma^2) = \begin{cases} 0, & w \leq 0 \\ \dfrac{1}{x\sigma\sqrt{2\pi}} \exp\left[-0.5\left(\dfrac{\log w - \mu}{\sigma}\right)^2\right] dw, & w > 0 \end{cases} \quad (3.6)$$

Equivalently, we may write *W* is distributed as $\Lambda(\mu, \sigma^2)$. Here μ and σ^2 are, respectively, the mean and variance of the normal distribution describing the log-transformation of *W* (and are different than the mean and variance of *W*) (Aitchison and Brown 1957). To determine the composite mean and variance indicators, Aitchison and Brown (1957, p. 14), find that the product $\prod_{j=1}^{N} X_j$ is asymptotically distributed as $\Lambda(\mu_{(n)}, \sigma^2_{(n)})$ when:

- Each $\{X_j\}$ is an independent, positive variate, (3.7a)
- $\mu_{(n)} = \sum_{j=1}^{N} \mu_j \text{ and } \sigma^2_{(n)} = \sum_{j=1}^{N} \sigma^2_j$, and (3.7b)
- $\mu_j = E\{\log X_j\}$ and $\sigma^2_j = D^2\{\log X_j\}$. (3.7c)

Here, E{} and D^2{} denote, respectively, the expectation and variance operators.

For the more general function $f_{conv} \cdot \prod_{j=1}^{N} (X_j)^{r_j}$ that describes water conservation effectiveness, the multiplicative and additive properties of the natural logarithm can be used to recast (3.7b) as

$$\mu_{(n)} = \sum_{j=1}^{N} r_j \mu_j + \log f_{conv} \quad and \quad \sigma_{(n)}^2 = \sum_{j=1}^{N} r_j^2 \sigma_j^2 \tag{3.7d}$$

The log-weighted first and second moments of parameter X_j are calculated as

$$\begin{aligned} \mu_j &= E\{\log X_j\} = \int_a^\infty \log x \cdot pdf_j(x) \cdot dx \\ \sigma_j^2 &= D^2\{\log X_j\} = \int_a^\infty (\log x)^2 \cdot pdf_j(x) \cdot dx - \mu_j^2 \end{aligned} \tag{3.8a}$$

and can be evaluated analytically or numerically depending on the distribution form of parameter X_j (rows 4 through 7 of Table 3.1). For these cases, the lower limit of integration, *a*, is the lower bound of the parameter distribution.

The method also applies to convolution distributions (rows 4 and 5 of Table 3.2) with two modifications. These modifications avoid integrating over negative ranges for which the convolution distribution may exist but for which the logarithm operation is not defined,

$$\begin{aligned} \mu_j &= \int_c^\infty \ln x \cdot \frac{pdf(x)}{1-p_c} dx \\ \sigma_j{}^2 &= \int_c^\infty (\ln x)^2 \cdot \frac{pdf(x)}{1-p_c} dx - \mu_j{}^2 \end{aligned} \tag{3.8b}$$

First, the analyst must specify the cutoff value *c* – the lower limit of integration – as greater than zero ($c > 0$). This cutoff value represents the analyst's best estimate of the value below which customers will not implement the conservation action because the reduced flow (or consumption) will be either negligible or negative (i.e., increased flow or consumption). Second, the analyst must re-weight the convolution *pdf* by a divisor $1 - p_c$ so that the cumulative proportion of customers above the cutoff value who participate in the conservation action sum to unity

$$1 = \int_c^\infty \frac{pdf(x)}{1-p_c} \cdot dx . \tag{3.9a}$$

Rearranging (3.9a) and switching the integration limits show that p_c is just the proportion of customers below the cutoff value who do not implement the conservation action

$$p_c = cdf(c) = \int_{-\infty}^{c} pdf(x) \cdot dx . \tag{3.9b}$$

This fraction is also the *cumulative density function* (cdf) evaluated at *c*.

Because selecting a cutoff value amounts to censoring the portion of customers that do not implement the conservation action, the distribution of conservation action effectiveness must likewise reflect censoring [$\Lambda(\mu, \sigma^2)$ is insufficient]. A censored lognormal distribution, $\Delta(\delta,\mu,\sigma^2)$ can be defined (Aitchison and Brown 1957, p. 95) as:

$$pdf(z) = \partial\Delta\left(\delta, \mu, \sigma^2\right) = \begin{cases} 0, & z < 0 \\ \delta, & z = 0 \\ \delta + (1-\delta)\Lambda\left(z \mid \mu, \sigma^2\right)dz, & z > 0 \end{cases} \tag{3.10}$$

Where δ is the fraction of the population that tends towards zero (or negative) values. In specifying the censored pdf for a conservation action, substitute p_c from equation (8b) for δ. When $\delta = 0$, equation (3.10) simplifies to (3.6).

In summary, when all uncertain parameters are independent, have values greater than zero, and are multiplied together to determine conservation action effectiveness, equations (3.6), (3.7d), and (3.8a) together define the analytical probability density function, mean, and variance for the lognormal-distributed conservation action effectiveness. When one of the parameters can have negative values, the analyst must specify a cutoff value, and equations (3.10, (3.7d), (3.8b), and (3.9b) define the analytical lognormal distribution of effectiveness for customers implementing the action.

3.2.3.2. Monte Carlo propagation

Uncertainties also can be propagated with Monte Carlo simulation. The general method is: a) generate random variates from the distributions of the component parameters [see (Law and Ketton 1991) for details]. b) Combine instantiations of the random variates according to the effectiveness function. c) Repeat steps (a) and (b) for a large number of samples. And (d) Sort effectiveness samples from smallest to largest and report the fraction (frequency) of samples falling within discrete ranges of water conservation action effectiveness. Together, the frequencies will form a histogram. Divide each frequency by the width of the range from which values were aggregated to obtain the Monte Carlo simulated pdf of water conservation action effectiveness.

3.2.4. Statistics of the composite distribution

When the composite distribution is lognormal distributed, the mean and quantiles are:

$$\begin{aligned} Mean &= \overline{w} = (1-\delta)e^{\mu_{(n)}+0.5\cdot\sigma^2_{(n)}} \\ Quantile_q &= w_q = \begin{cases} 0 & q \le \delta \\ e^{\mu_{(n)}+z_{q'}\cdot\sigma^2_{(n)}} & q > \delta \end{cases} \end{aligned} \tag{3.11}$$

where $z_{q'}$ is the z-value associated with the normal distribution N(0,1) for the quantile q' = (q – δ)/(1 – δ) (Aitchison and Brown 1957, pp. 95-6). With no censoring (δ = 0), the mean, median, and mode are simply $e^{\mu_{(n)}+0.5\cdot\sigma^2_{(n)}}$, $e^{\mu_{(n)}}$, *and* $e^{\mu_{(n)}-\sigma^2_{(n)}}$, and are successively decreasing indicating significant positive skew.

For an effectiveness distribution generated by Monte Carlo simulation, the mean is best estimated by the average of the entire sample of effectiveness calculations. The quantile q can be approximated by the value of the (k*q)th sample in the list of simulated effectiveness sample results sorted from lowest to highest (*k* = number of simulations). The mode will correspond to the effectiveness range with the largest frequency.

3.2.5. Size conservation programs

The final step is to use the derived effectiveness distribution and its common properties to size a conservation program to meet an overall water conservation objective. Program sizing can be done by several methods. The first method, blanket application, as used by typical engineering approaches requires just

$$s_{blanket} = \frac{t}{\hat{w}}. \tag{3.12}$$

where $s_{blanket}$ is the estimated number of customers required to implement the conservation action, t is the program-wide conservation objective [m^3 per year], and $\hat{w}$ is the average savings per customer [m^3 per customer per year] generally calculated as a point estimate using (typical) average parameter values. The conservation objective t represents the desired annual water savings and can correspond to the projected shortfall between future water supplies and future water demand or some portion of that shortfall that the utility wants to meet by encouraging customers to adopt conservation actions. Blanket application assumes customers adopt with uniform effectiveness.

The second sizing method focuses on market segmentation and targeting customers that show potential to achieve large water savings. A targeted approach makes use of the probabilistic distribution of effectiveness.

The targeted customers should have large values for effectiveness w. The sizing task is to determine the threshold effectiveness level, w_t, so that water saved by the customer with the largest effectiveness plus the water saved by the customer with the next largest effectiveness, and so on down to the water saved by the customer with effectiveness at the threshold level sum to meet the conservation goal. This sum is the integral of the first moment distribution of W (i.e., the customer effectiveness level w weighted by its probability of occurrence) evaluated from the threshold w_t through infinity, or

$$t = s_{\text{sec}t} \int_{w=w_t}^{w=\infty} w \cdot \partial\Delta\left(w \mid \mu_{(n)}, \sigma_{(n)}^2, p_c\right). \tag{3.13}$$

Here, s_{sect} is the sector size (number of customers) potentially available to adopt the conservation measure and is required to scale customer effectiveness, w [m^3 per customer per year], to the absolute conservation objective, t [m^3 per year]. Equation (3.13) is solved for w_t using two identities. First, the integral of the first moment of $\Delta(w| \mu, \sigma^2, \delta)$ over the entire feasible range of W is, by definition, the mean effectiveness,

$$\overline{w} = \int_{w=0}^{w=w_t} w\cdot\partial\Delta\left(w \mid \mu_{(n)},\sigma^2_{(n)},p_c\right) + \int_{w=w_t}^{w=\infty} w\cdot\partial\Delta\left(w \mid \mu_{(n)},\sigma^2_{(n)},p_c\right). \tag{3.14a}$$

Second, the first moment of $\Lambda(w|\ \mu,\ \sigma^2)$ is lognormal distributed as $\Lambda(w|\ \mu+\ \sigma^2,\ \sigma^2)$ (Aitchison and Brown 1957, p. 12). This identity also applies to the censored distribution $\Delta(w|\ \mu,\ \sigma^2,\ \delta)$, so

$$\frac{1}{\overline{w}}\int_{w=0}^{w=w_t} w\cdot\partial\Delta\left(w \mid \mu_{(n)},\sigma^2_{(n)},p_c\right) = \int_{w=0}^{w=w_t}\partial\Delta\left(w \mid \mu_{(n)}+\sigma^2_{(n)},\sigma^2_{(n)},p_c\right). \tag{3.13b}$$

Rearranging and then substituting (13a) and (13b) into (12) gives

$$1-\frac{t}{s_{\sec t}\cdot\overline{w}} = \int_{0}^{w_t}\partial\Delta\left(w \mid \mu_{(n)}+\sigma^2_{(n)},\sigma^2_{(n)},p_c\right) = CDF_{\Delta\left(\mu_{(n)}+\sigma^2_{(n)},\sigma^2_{(n)},p_c\right)}\left(w_t\right). \tag{3.15}$$

Here, $CDF_{\Delta(\mu+\ \sigma 2,\ \sigma 2,\ pc)}$ is the cumulative density function of $\Delta(\mu+\ \sigma^2,\ \sigma^2,\ p_c)$. The left hand side of (3.15) is a fraction between 0 and 1 ($0 \le t \le s_{\sec t}\cdot\overline{w}$). Since *CDFs* monotonically increase, they are invertible. Thus,

$$w_t = CDF^{-1}_{\Delta\left(\mu_{(n)}+\sigma^2_{(n)},\sigma^2_{(n)}\right)}\left(1-\frac{t}{s_{\sec t}\overline{w}}\right),\ 0 \le t \le s_{\sec t}\overline{w}\,. \tag{3.16}$$

Finally, the targeted conservation program size is determined by multiplying the sector size by the fraction of the sector having effectiveness above the threshold w_t

$$s_{t\arg eting} = \left(1-CDF_{\Delta\left(\mu_{(n)},\sigma^2_{(n)},p_c\right)}\left(w_t\right)\right)\cdot s_{\sec t}\,. \tag{3.17}$$

Equation (3.18) may also be rearranged to express the fraction $t\,/\,s_{sect}$ as a function of w_t,

$$\frac{t}{s_{\sec t}} = \overline{w}\cdot\left(1-CDF_{\Delta\left(\mu_{(n)}+\sigma^2_{(n)},\sigma^2_{(n)},p_c\right)}\left(w_t\right)\right). \tag{3.19}$$

Varying the threshold w_t (or the fraction of the community represented by w_t) will identify the average conservation expected per customer. This formula determines the sizing curve for the conservation action and is demonstrated below.

3.3. Example Application

We now develop distributions of water savings for seven conservation actions available to urban, residential water users in Amman, Jordan. The actions include rainwater harvesting from roofs, installing spray nozzles on garden hoses (rather than using open hoses), installing carpets on floors (to replace floor washing with water), and retrofitting showerheads, bathroom faucets, kitchen faucets, or toilets with water saving devices.

These actions represent some of the many long- and short-term water supply enhancement and demand management actions that can help residential, urban customers cope with water shortages. Probabilistic analysis is readily applied to each action; here, we demonstrate the approach for seven long-term water conservation actions.

The Amman water utility serves about 1,940,000 residents through 306,000 residential connections and reported 52.4 million cubic meters (Mm^3) of residential billed water use in 2004. Customers face severe water shortages: water is typically available through the distribution network for only 12 – 60 hours per week. Jordan is starting to implement water demand management programs but there is scarce empirical documentation showing the effectiveness of water conservation actions. Thus, probabilistic statements describing potential effectiveness can help guide conservation program planning.

The seven functions for conservation effectiveness are:

$$W_{Rainfall\,Catch} = \frac{1}{1000}(A)(B)^{-1}(C), \tag{3.20a}$$

$$W_{Showerhead\,Retro} = \frac{52}{1000}(G-T)(D)(L)(M), \tag{3.20b}$$

$$W_{Bath\,Faucet\,Retro} = \frac{365}{1000}(H-U)(O)(D), \tag{3.20c}$$

$$W_{Kitchen\,Faucet\,Retro} = \frac{365}{1000}(H-U)(P), \tag{3.20d}$$

$$W_{Toilet\,Retro} = \frac{365}{1000}(I-V)(N)(D), \tag{3.20e}$$

$$W_{Spray\,Nozzle} = 0.429(J)^2(F)^{0.5}(X)(Q)(R)(E), \text{ and} \tag{3.20f}$$

$$W_{Carpet\,Install} = \frac{52 \cdot 3.785}{1000}(K)(S)(Y). \tag{3.20g}$$

The letters *A* through *V*, *X,* and *Y* represent the uncertain parameters influencing effectiveness and are further described in Table 3.3 (DOS 1999; DOS 2004; IdRC 2004; JMD 2000; Snobar 2003; WEPIA 2000).

The following details are also important. The 78-year record of rainfall at the Amman Airport (JMD 2000) was fitted with a Gamma distribution by estimating the shape and scale parameters from the mean and variance of the observed annual rainfalls. The water conserved by installing a spray nozzle on a garden hose was estimated by the reduction of flow through an open-ended hose. This flow is related to the square of the hose diameter, square root of the customer water pressure, and time for which the nozzle restricts wastage flow. In the example, the distribution of water pressure was assumed to correlate directly to the distribution of households sharing a building. In Amman, rooftop tanks are the primary regulator of residential water pressure; thus, pressure depends on head differential been roof and point of use. This difference is also the number of floors (or apartments, i.e. households) in the building. This conservation action is only available to the approximately 15.4% of households that garden outdoors (DOS 1999).

Limited information is available concerning several of the parameters, and in some cases, distributions were derived from engineering estimates of maximum upper and lower limits. These estimates rely on the author's experiences living and working in Jordan and were verified by others with significant experience in the Jordan residential water sector (Tawarneh, pers. comm., 2004; Abdul Al-Khalaq, pers. comm., 2004).

Some parameters may co-vary. For example, more single-family residences may be located in West Amman where elevation differences result in higher rainfall. With better data, we could segment Amman households into classes and subclasses (such as by geographic location and building type within a location) to eliminate covariance. Then, calculate effectiveness distributions for each subclass using parameter distributions specific to the subclass. While further disaggregating the population requires increased data gathering, computation, and analysis effort, the probabilistic approach can achieve continuous disaggregating (within the sub-classes) which is not possible with point estimate approaches. Based on the data readily available and for demonstration purposes, the population of Amman residential customers was not disaggregated.

Parameter uncertainties were propagated both analytically and with Monte Carlo simulation (10,000 simulations for each conservation action). In analytical derivations, numerical integrations of the log-weighted exponential decay functions were made with central differences and approximately 10,000 steps over the feasible parameter range. Figure 3.1 and Figure 3.2 compare the analytically derived distribution of effectiveness to the Monte Carlo simulation results for the first two conservation actions.

Both actions show a preponderance of the population with effectiveness close to the lower limit, but also a large tail stretching towards a small proportion of customers who show potential to realize large water savings by adopting the conservation actions. Both distributions have positive skew with mean > median > mode. This behavior is also seen in the effectiveness distributions derived for the other conservation actions (Figure 3.3).

A chart for sizing targeted conservation programs (Figure 3.4) was calculated using equation (3.19). The chart shows water conservation level as a function of the coverage or fraction of total customers who adopt the action. This fraction is explicitly ordered from left to right by customers with potentials to conserve the largest down to the smallest volumes of water. The sizing curves are fastest rising for small program sizes as customers with the most effectiveness adopt first. As coverage reaches 100%, the curves become flat and approach the mean value of the effectiveness distribution. This value defines an upper bound for the savings when all customers adopt.

The chart is used as follows: First, set the overall water conservation objective (in volume per year) and community size or number of customers that can potentially adopt the conservation action. Second, divide the conservation objective by the community size to figure the average water volume conserved per customer. Third, find this volume on the vertical axis. Fourth, use the sizing curve to find the corresponding targeted coverage. Finally, multiply the coverage by the community size to determine the number of customers required to meet the conservation objective (when customers with the largest potential to conserve are targeted to participate in the program).

The sizing chart can also help identify water efficient conservation actions. Actions with faster rising curves require smaller number of customers to meet a specified conservation objective. Thus, retrofitting showerheads or kitchen faucets are more effective than installing carpets or spray nozzles on garden hoses. For example, to meet a water conservation objective of 6.5 Mm^3 per year (12% of Amman's billed residential water use), the Amman water utility need only target 8% of its 306,000 residential customers to retrofit kitchen faucets (should the utility identify its customers with the potential to conserve 124.8 m^3 per year or more; 60% of customers are needed with a blanket approach). Alternatively, the utility need only target the largest 10%, 26%, and 49% of customers that show potential to conserve more than 106.8, 38.8, or 20.6 m^3 per year by, respectively, retrofitting showerheads, toilets, or collecting rainwater (Table 3.4). The utility will likely not meet the conservation object even if all customers (100%) retrofit bath faucets, install carpets or spray nozzles on outdoor hoses. The sizing chart also shows these infeasibilities: these actions never reach an average water conservation level of 21.2 m^3 per customer per year (6.5 Mm^3 per year / 306,000 customers).

Including average retrofit costs for each conservation action identifies the cost-effective actions (Table 3.4). Here, costs reflect estimates for customers to purchase water saving devices (author's estimates; IrDC, 2004) and exclude utility costs to implement a program. However, utility costs would likely be similar for each conservation action. In the Amman, Jordan example, retrofitting kitchen faucets appears as the most cost effective conservation action to meet the annual conservation objective.

3.4. Discussion

Although Table 3.4 shows that average conservation action effectiveness values calculated with typical point estimates and the proposed probabilistic approach are often similar, the implications for sizing conservation programs differ substantially. In the Amman, Jordan example to achieve annual water savings of 6.5 Mm^3 per year, targeted conservation programs to retrofit kitchen faucets, showerheads, and toilets sized using the probabilistic approach can be much smaller than blanket application programs sized using point estimates of average effectiveness. These targeted conservation programs can reduce implementation costs by factors of 2.5 to 8 over typical blanket application approaches. These differences are most pronounced when the annual water conservation objective is small compared to the maximum savings achievable when the entire community adopts the conservation action. Differences are less pronounced as the conservation objective approaches or exceeds the maximum savings.

An outstanding issue concerns how to expeditiously identify and target the customers with the most potential to conserve (where they are located and what characteristics distinguish them from low-effective customers). Three customer identification methods—use of surrogate indicators, customer surveys, and water audits—are introduced below and their relative advantages and disadvantages are discussed. These methods represent public awareness, education, and targeted marketing approaches typical for water conservation programs (Baumann et al. 1998; Vickers 2001). The single difference is using the probabilistic-determined threshold effectiveness level to determine which customers to contact and suggest to adopt the conservation action. Discussion also emphasizes that no one method to identify customers can efficiently and precisely demarcate all customers with high effectiveness from customers with low effectiveness. Rather, a combination of approaches is likely needed.

3.4.1. Surrogate indicators of effectiveness

Geographic information systems and databases offer the water utility or conservation program coordinator a wealth of customer-specific information related to conservation action effectiveness. Example data include water-billing records (indicating customer water consumption), land assessments (indicating building size and age, i.e., a further surrogate indicator of water appliance age and flow rates), satellite or digital orthographical photos (showing landscaped areas), or census records (indicating household size), among others. In fact, the coordinator may have used such data to estimate distributions for some component parameters. Linking and joining multiple data sources provides a powerful tool to identify the subset of customers with co-occurrence of multiple factors that suggest high conservation action effectiveness. If data sources are not linked, low indicator values can still flag customers with low effectiveness. This analysis can beneficially shrink the customer pool on which to focus more costly or labor-intensive identification approaches.

3.4.2. Customer surveys

A utility can also telephone or distribute written questionnaires to each customer to learn more about the customer's demographic makeup, water use behaviors, and other factors that influence water conservation action effectiveness. The utility can use responses to project the customer's likely effectiveness if they adopt and then follow up with customers that show effectiveness larger than the threshold effectiveness level. And while telephone surveys and written questionnaires are quick and relatively inexpensive to implement, customer response rates may be low. However, positive customer response can also indicate strong willingness to adopt the conservation action.

3.4.3. Water Audits

A utility can also dispatch staff to visit each customer, solicit the information that bears on the customer's water conservation effectiveness, and then instantaneously estimate the effectiveness. If the estimated effectiveness exceeds the threshold effectiveness level, staff can then immediately recommend or proceed with retrofits. Although water audits are costly in terms of time, staff, and materials, they still serve as beneficial screening tools. Identifying customers for which no follow-up action is taken can save the utility resources required to implement the conservation action and time required for follow-up visits to verify continued implementation and actual water savings.

Together, surrogate indicators, customer surveys, and water audits can help identify customers with potential to achieve large water savings. After adoption, these methods can also help verify that estimated effectiveness translates into actual effectiveness.

3.5. Conclusions

Water conservation program planners can probabilistically describe water conservation effectiveness by understanding the ranges of values for customer demographic, behavioral, and technological parameters influencing water savings. Probabilistic treatment achieves a continuous disaggregating of a customer population but avoids the time and costs of additional data gathering, computation, and analysis associated with common point estimates and blanket application that further disaggregate the population into smaller, homogenous sub-sectors. Because effectiveness is a product of uncertain parameter values, it tends towards a lognormal distribution with significant positive skew towards a small population of customers that show potential to achieve large savings by implementing a conservation action.

Effectiveness distributions are readily used to suggest cost efficient conservation actions, the minimum number of customers needed to meet specific water conservation objectives, or the threshold effectiveness levels on which to target customer adoption. Seven example distributions for urban, residential water users in Jordan show that a small subset of customers can achieve significant annual water savings by retrofitting showerheads or kitchen faucets. Also, that targeting consumers with the largest potential to conserve can significantly reduce the size and cost of programs to meet water conservation objectives compared to blanket application approaches. To realize these size and cost savings, planners must develop targeted marketing, public awareness, and education campaigns to first identify the customers with high conservation effectiveness and then persuade or encourage them to adopt. Follow-up work is also needed to verify that estimated effectiveness translates to actual effectiveness.

3.6. References

Aitchison, J., and Brown, J. A. C. (1957). *The Lognormal Distribution: with special reference to it uses in economics*, Cambridge University Press, London, U.K.

Baumann, D. D., Boland, J. J., and Hanemann, W. M. (1998). *Urban Water Demand Management and Planning*, McGraw-Hill, Inc., New York.

Department of Statistics (DOS). (1999). "Urban Agriculture Survey." Amman, Jordan. http://www.dos.gov.jo/sdb/env/env_e/home.htm [Accessed on: June 26, 2004].

Department of Statistics (DOS). (2004). "The Preliminary Results of The Population And Housing Census." Amman, Jordan. http://www.dos.gov.jo [Accessed on: January 2, 2006].

Interdisciplinary Research Consultants (IdRC). (2004). "A Survey of Home Appliances and Toilets in the Jordanian Markets." Academy for Educational Development: Water Efficiency for Public Information and Action (WEPIA) Program, Amman, Jordan, 50 pp.

Jaynes, E. T. (2003). *Probability Theory: the logic of science*, Cambridge University Press, Cambridge, United Kingdom.

Jordan Meteorological Department (JMD). (2000). "Rainfall." http://www.jmd.gov.jo/climate-rain.html [Accessed on: January 23, 2005].

Law, A. M., and Ketton, W. D. (1991). "Chaper 8. Generating Random Variates." Simulation Modeling and Analysis, McGraw-Hill, New York.

Mayer, P. W., DeOreo, W. B., Opitz, E. M., Kiefer, J. C., Davis, W. Y., Dziegielewski, B., and Nelson, J. O. (1999). "Residential End Uses of Water," American Water Works Association, Denver, Colorado. http://www.aquacraft.com/index.htm.

Optiz, E. M., and Dziegielewski, B. (1998). "Demand Management Planning Methods." Urban Water Demand Management and Planning, W. M. Hanemann, ed., McGraw-Hill, Inc., New York, 237-281.

Snobar, A. H. (2003). "Feasibility of Domestic Graywater Recycling," Senior Thesis, Jordan Unversity of Science and Technology, Irbid.

Tribus, M. (1969). *Rational Descriptions, Decisions and Designs*, Pergamon Press, New York.

Vickers, A. L. (2001). *The handbook of water conservation*, WaterPlow Press, Amherst, Massachusetts. www.waterplowpress.com.

Walski, T. M., Richards, W. G., McCall, D. J., Deb, A. K., and Morgan, J. M. (1985). "Calculating Effectiveness of Water Conservation Measures." *Journal of Environmental Engineering-Asce*, 111(2), 209-221.

Water Efficiency and Public Information for Action (WEPIA). (2000). "Capacity building project in Fuhies." Amman, Jordan, 14 pp.

Table 3.1. Parameter distributions and methods to calculate log-weighted moments for different types of known information

Parameter information known	Lower bound *a* Upper bound *b*	Lower bound *a* Mean *m*	Frequencies, f_i, for discrete ranges of parameter values
PDF est. method	Maximum entropy (rectangular distribution)	Maximum entropy (exponential decay distribution)	Empirical results (histogram)
PDF formula	$pdf(x)=\begin{cases}0, & x\le a\\ \dfrac{1}{b-a}, & x\le b\\ 0, & x\ge b\end{cases}$	$pdf(x)=\begin{cases}0, & x\le a\\ e^{\lambda_0+\lambda_1\cdot x}, & x\ge a\end{cases}$ $\lambda_1=\dfrac{1}{a-m}$, $\lambda_0=\ln(-\lambda_1)-\lambda_1\cdot a$	$P(x_i\le x\le x_{i+1})=f_i$
Log-weighted parameter moments	$\mu_j=\int\limits_{x=a}^{b}\ln x\cdot\dfrac{1}{b-a}dx$ $\sigma_j^{\ 2}=\int\limits_{x=a}^{b}(\ln x)^2\dfrac{1}{b-a}dx-\mu_j^{\ 2}$	$\mu_j=\int\limits_{x=a}^{\infty}\ln x\cdot e^{\lambda_0+\lambda_1\cdot x}dx$ $\sigma_j^{\ 2}=\int\limits_{x=a}^{\infty}(\ln x)^2\cdot e^{\lambda_0+\lambda_1\cdot x}dx-\mu_j^{\ 2}$	$\mu_j=\sum\limits_{i}\int\limits_{x=x_i}^{x_{i+1}}\ln x\cdot f_i\cdot dx$ $\sigma_j^{\ 2}=\sum\limits_{i}\int\limits_{x=x_i}^{x_{i+1}}(\ln x)^2\cdot f_i\cdot dx-\mu_j^{\ 2}$
Integration method	Analytic integration by parts	Numerical integration	Analytic integration by segments
Formula for 1^{st} moment	$\mu_j=\left[x(\ln x-1)\right]_{x=a}^{x=b}\cdot\dfrac{1}{b-a}$	$\mu_j\approx\sum\limits_{i=0}^{N}\left\{\ln x_i\cdot e^{\lambda_0+\lambda_1 x_i}\cdot(x_{i+1}-x_i)\right\}$	$\mu_j=\sum\limits_{i}\left\{\left[x(\ln x-1)\right]_{x=x_i}^{x=x_{i+1}}f_i\cdot(x_{i+1}-x_i)\right\}$
Formula for 2^{nd} moment	$\sigma_j^{\ 2}=\left[x\left((\ln x)^2-2\ln x+2\right)\right]_{x=a}^{x=b}\cdot\dfrac{1}{b-a}-\mu_j^{\ 2}$	$\sigma_j^{\ 2}\approx\sum\limits_{i=0}^{N}\left\{(\ln x_i)^2\cdot e^{\lambda_0+\lambda_1 x_i}\cdot(x_{i+1}-x_i)\right\}-\mu_j^{\ 2}$	$\sigma_j^{\ 2}=\sum\limits_{i}\left\{\begin{matrix}\left[x\left((\ln x)^2-2\ln x-2\right)\right]_{x=x_i}^{x=x_{i+1}}\\ \cdot f_i\cdot(x_{i+1}-x_i)\end{matrix}\right\}-\mu_j^{\ 2}$

Table 3.2. Probability distributions and methods to calculate log-weighted parameter moments for different types of parameter convolutions

Parameter information known	Uniform dist. with range [a_2, b_2] subtracted from uniform distribution with range [a_1, b_1].	Uniform dist. with range [a_2, b_2] subtracted from exponential decay distribution with lower bound a_1 and mean m_1.	Exponential decay distribution with lower bound a_2, mean m_2 subtracted from exp. decay dist. with lower bound a_1, mean m_1.
PDF est. method	Convolution to give trapezoid dist. with fixed lower bound d_1 and upper bound d_2.	Convolution to give quasi-triangle dist. with fixed lower bound and exponential decaying upper bound	Convolution to give exponential rising limb and exponential falling limb centered at a_1- a_2.
PDF formula	$pdf(x) = \begin{cases} 0, & x < d_1, \\ m \cdot (x - d_1), & x \le d_2 \\ 1/d_3, & x \le d_3 \\ -m \cdot (x - d_4), & x \le d_4 \\ 0, & x > d_4 \end{cases}$ $d_1 = a_1 - b_2$, $d_4 = d_2 + d_3$, $d_2 = d_1 + \min(b_1 - a_1, b_2 - a_2)$, $d_3 = d_1 + \max(b_1 - a_1, b_2 - a_2)$, and $m = 1/(d_2 d_3)$	$pdf(x) = a \cdot \begin{cases} 0, & x \le a_1 - b_2 \\ e^{\lambda_1 (x + b_2)} - e^{\lambda_1 a_1}, & x \le a_1 - a_2 \\ e^{\lambda_1 x}\left(e^{\lambda_1 b_2} - e^{\lambda_1 a_2}\right), & x \ge a_1 - a_2 \end{cases}$ Where $a = \dfrac{e^{\lambda_0}}{(b_2 - a_2) \cdot \lambda_1}$, $\lambda_1 = \dfrac{1}{a_1 - m_1}$, and $\lambda_0 = \ln(-\lambda_1) - \lambda_1 \cdot a_1$	$pdf(x) = \dfrac{-1}{\lambda_{1,1} + \lambda_{1,2}} e^{\lambda_0 + \lambda_1}$ where for x < a_1 - a_2 $\lambda_1 = -\lambda_{1,2}$ and $\lambda_0 = \lambda_{0,1} + \lambda_{0,2} + a_1 \cdot (\lambda_{1,1} + \lambda_{1,2})$ and for x > a_1 - a_2 $\lambda_1 = \lambda_{1,1}$ and $\lambda_0 = \lambda_{0,1} + \lambda_{0,2} + a_2 \cdot (\lambda_{1,1} + \lambda_{1,2})$
Log-weighted parameter moments	$\mu_j = \int_c^{d_4} \ln x \cdot \dfrac{pdf(x)}{1 - p_c} dx$ $\sigma_j^{\,2} = \int_c^{d_4} (\ln x)^2 \cdot \dfrac{pdf(x)}{1 - p_c} dx - \mu_j^{\,2}$ where $p_c = \int_{-\infty}^{c} pdf(x) \cdot dx$	$\mu_j = \int_{x=c}^{\infty} \ln x \cdot \dfrac{pdf(x)}{1 - p_c} dx$ $\sigma_j^{\,2} = \int_{x=c}^{\infty} (\ln x)^2 \cdot \dfrac{pdf(x)}{1 - p_c} dx - \mu_j^{\,2}$ where $p_c = \int_{-\infty}^{c} pdf(x) \cdot dx$	$\mu_j = \int_{x=c}^{\infty} \ln x \cdot \dfrac{pdf(x)}{1 - p_c} dx$ $\sigma_j^{\,2} = \int_{x=c}^{\infty} (\ln x)^2 \cdot \dfrac{pdf(x)}{1 - p_c} dx - \mu_j^{\,2}$ where $p_c = \int_{-\infty}^{c} pdf(x) \cdot dx$
Integration	Analytic integration by parts	Numerical integration	Numerical integration

Table 3.3. Description of parameters influencing water conservation effectiveness

Effectiveness parameter	Units	Low value	High value	Average	St. Dev	Distribution[1]	Reference (sample size)
Geographic							
A. Annual rainfall	mm/yr	110	550	270	94	FG	JMD, 2000 (78 years)
Demographic							
B. Households sharing building	#/building	1	--	2.7	--	ED	DOS, 2004 (383,000 households)
C. Roof area of building	m2	100	--	206	--	ED	DOS, 1999 (1,800 households)
D. Household size	persons	3	--	5.1	--	ED	DOS, 2004 (383,000 households)
E. Households that garden outdoors	unitless, 1 = yes	0	1	0.15	--	BI	DOS, 1999 (1,800 households)
Technologic - existing infrastructure							
F. House water pressure	bar	0.29	--	0.80	--	ED	Linearly correlated to parameter (b)
G. Shower flow rate - current device	l/min	6	20	--	--	UN	Engineering estimate (10 devices)
H. Faucet flow rate - current device	l/min	5.5	20	--	--	UN	Engineering estimate (10 devices)
I. Toilet tank volume - current device	l/flush	5.5	15	--	--	UN	IrDC, 2004 (31 devices)
J. Hose diameter	cm	1.3	3.8	--	--	UN	Engineering estimate, 0.5 to 1.5 inches
K. Bucket size	l	11.4	26.5	--	--	UN	Engineering estimate, 3 to 7 gallons
Behavoiral - existing water uses							
L. Length of shower - currernt	min	3	--	8.4	--	ED	Engineering estimate
M. Shower frequency	#/week	1	--	3.6	--	ED	Engineering estimate (28 persons)
N. Toilet flushes	#/person/day	1	--	4.03	--	ED	Snobar, 2003 (30 households)
O. Faucet use - bathroom	min/day/person	0.1	--	0.6	--	ED	Snobar, 2003 (30 households)
P. Faucet use - kitchen	min/day	1	--	14.36	--	ED	Snobar, 2004 (30 households)
Q. Irrigation frequency	#/week	0.22	--	1.45	--	ED	Engineering estimate (23 households)
R. Irrigation season	weeks/year	20	40	--	--	UN	Engineering estimate
S. Floor wash frequency	#/week	1	7	--	--	UN	Engineering estimate
Technologic - potentially adopted							
T. Shower flow rate - retrofit device	l/min	6	9	--	--	UN	Engineering estimate (10 devices)
U. Faucet flow rate - retrofit device	l/min	5.5	6.5	--	--	UN	Engineering estimate (10 devices)
V. Toilet flush rate - retrofit, full	l/flush	5.5	6.5	--	--	UN	IrDC, 2004 (16 devices)
Behavoiral - potential modifications							
X. Reduced irrigation time - nozzle	minutes/use	0.5	--	3	--	ED	Engineering estimate
Y. Bucket application to floor	buckets/wash	1	--	5	--	ED	Engineering estimate

[1] Distributions: BI=binary; FG=fitted gamma; ED=exponential decay; UN=uniform.

Table 3.4. Indicators of effectiveness for conservation actions

Effectiveness Indicator	Collect Rainwater^{b}	Retrofit Showerhead	Retofit Bath Faucets^{b}	Retrofit Kitchen Faucets	Retrofit Toilets	Spray Nozzle on Hoses^{b}	Install Floor Carpets^{b}
Average effectiveness				[m^3 per customer per year]			
Point estimate (typical)	20.4	43.8	8.0	35.4	31.7	7.7	19.7
Probabistic analytical estimate (proposed)	27.4	44.7	8.2	44.7	31.7	6.6	19.9
Required program size				[percentage of customers]^{a}			
Point estimate (blanket application)	104 %	48 %	265 %	60 %	67 %	275 %	108 %
Probabilistic analytical estimate (targeted application)	49 %	10 %	NA	8 %	26 %	NA	NA
Threshold effectiveness level from probabistic est.				[m^3 per customer per year]^{a}			
Target customers with effectiveness larger than	20.6	106.8	NA	124.8	38.8	NA	NA
Retrofit cost				[$US per customer]			
Average customer expenditure	$282	$82	$4	$4	$117	$4	$4,442
Required program expenditure				[$US Million]^{a}			
Blanket application (point estimate)	NA	$12.1	NA	$0.8	$24.0	NA	NA
Targeted application (probabilistic approach)	$42.7	$2.5	NA	$0.1	$9.3	NA	NA

Notes: a. Percentage based on potential customer population of 306,000 households and conservation objective of 6.5 Mm3/year

b. Percentage greater than 100% or NA means not possible to achieve conservation objective

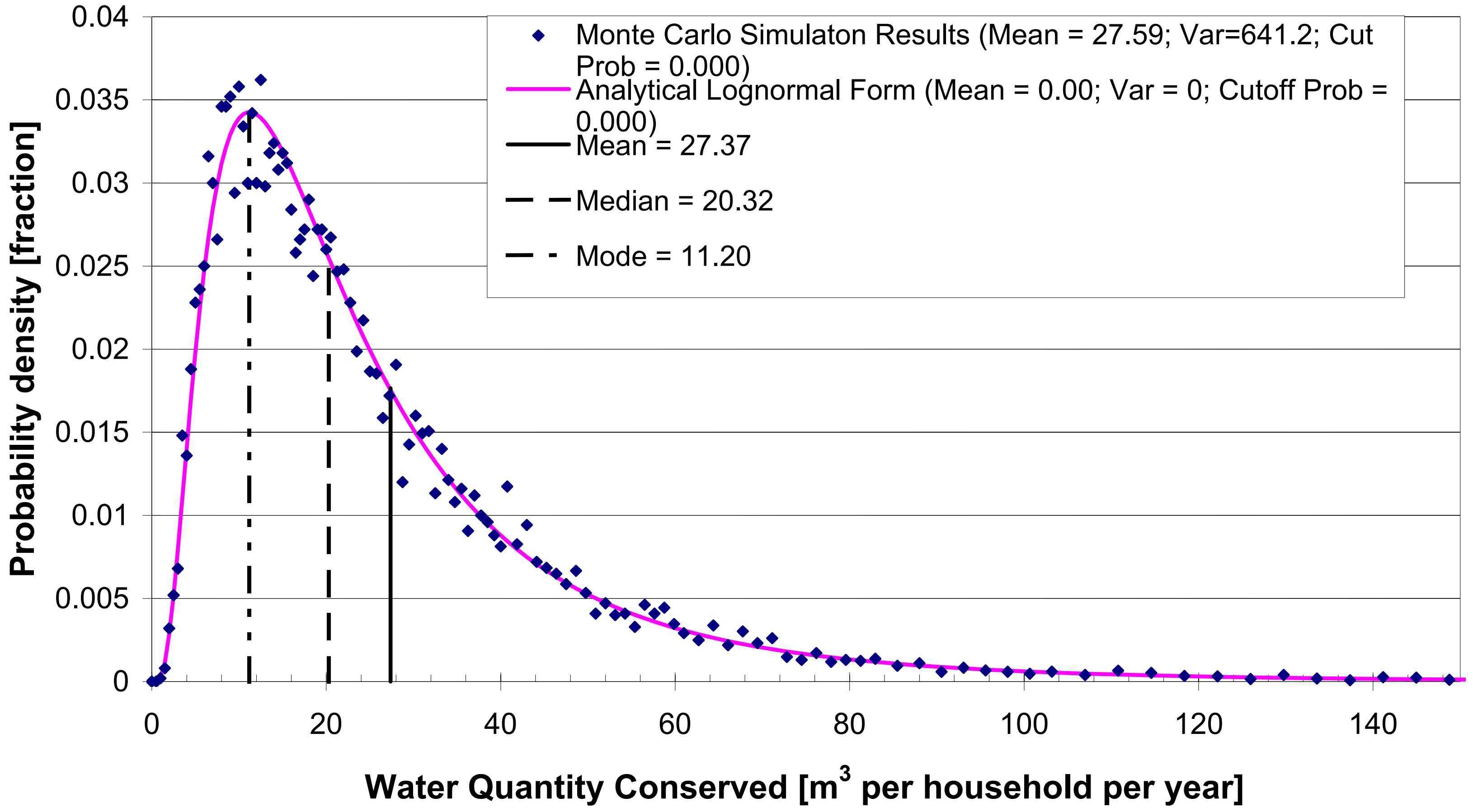


Figure 3.1. Distribution of rainfall catchment among households in Amman, Jordan.

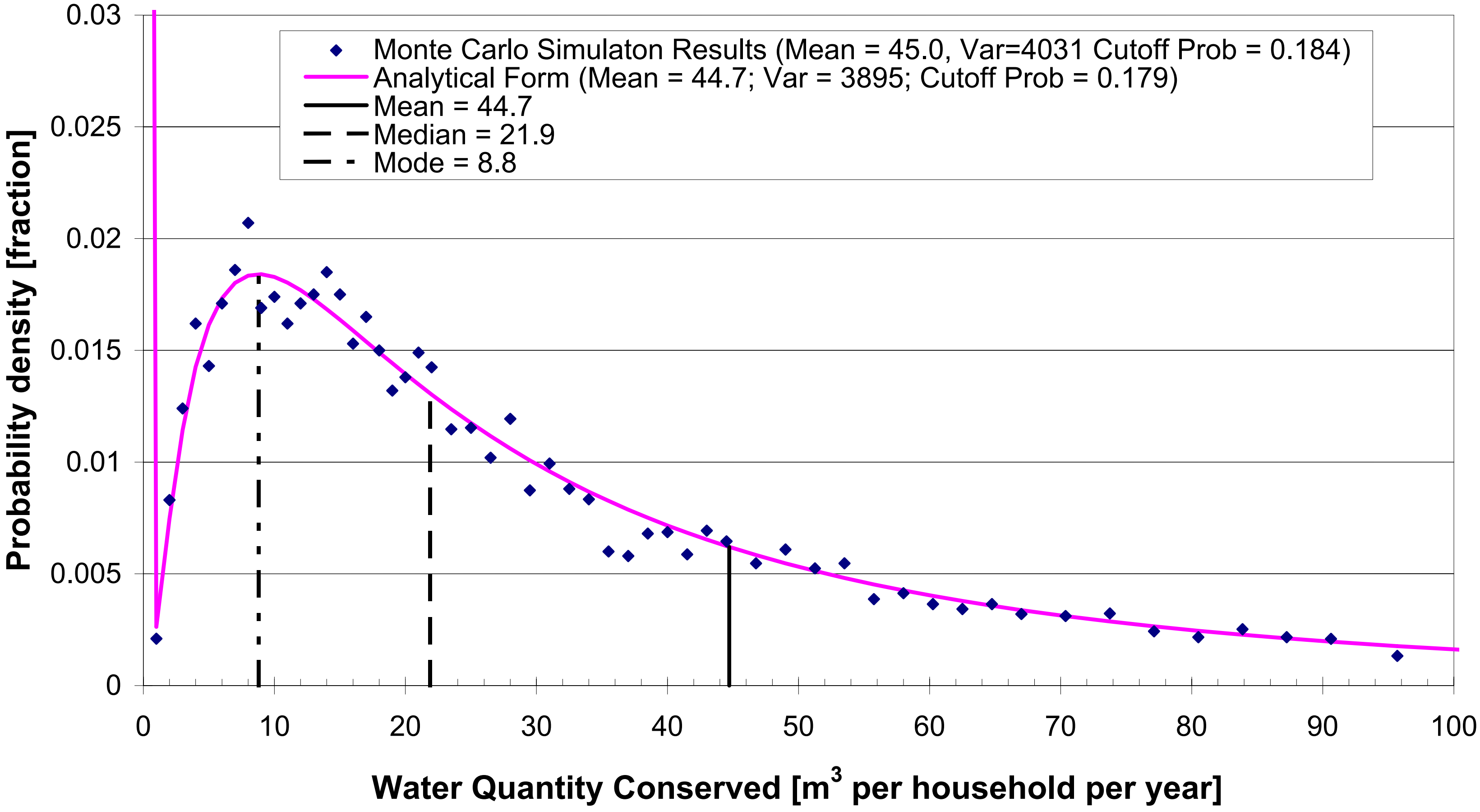


Figure 3.2. Distribution among households of water conserved by retrofitting showerheads.

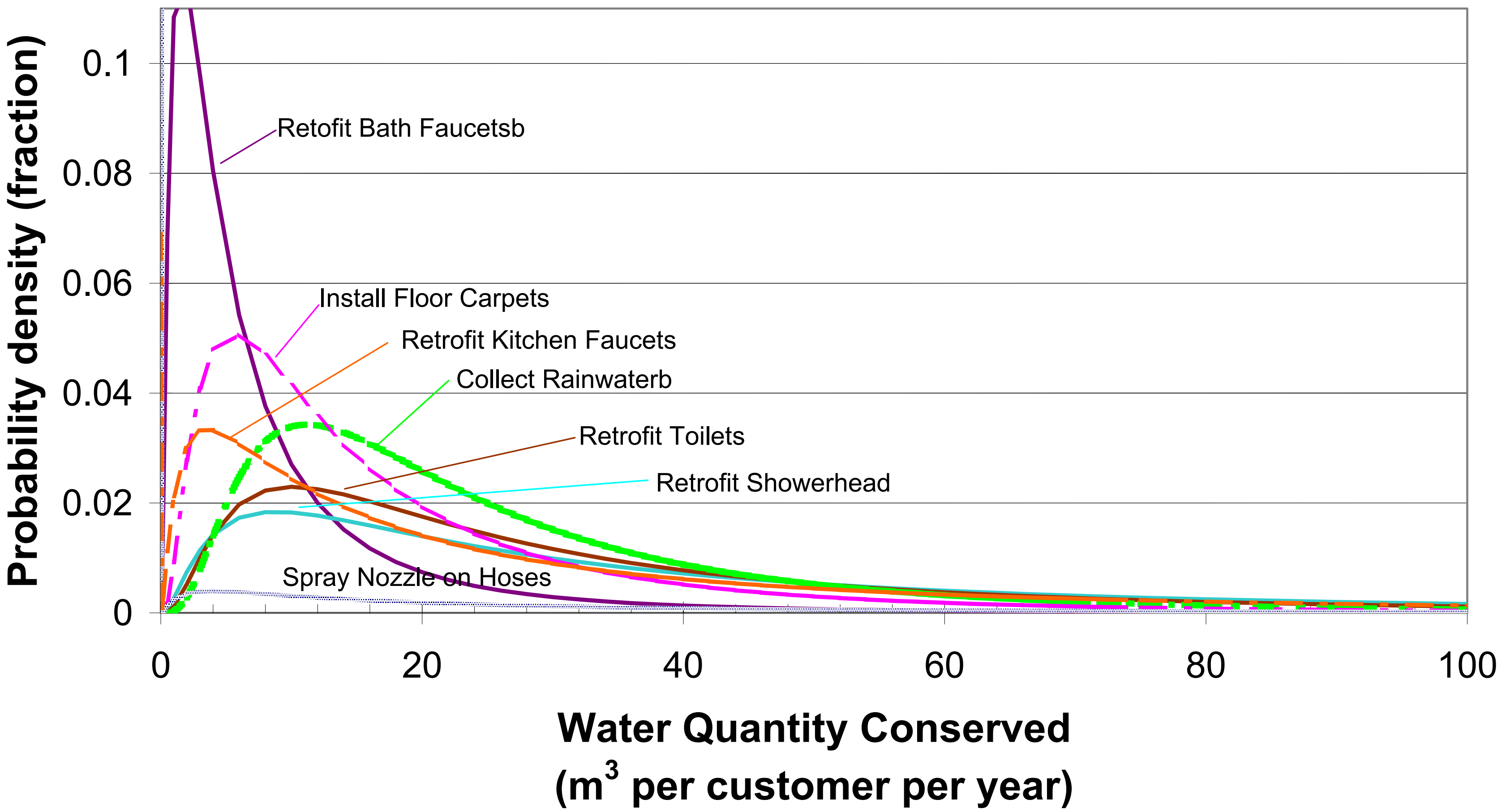


Figure 3.3. Analytically derived distributions of conservation action effectiveness.

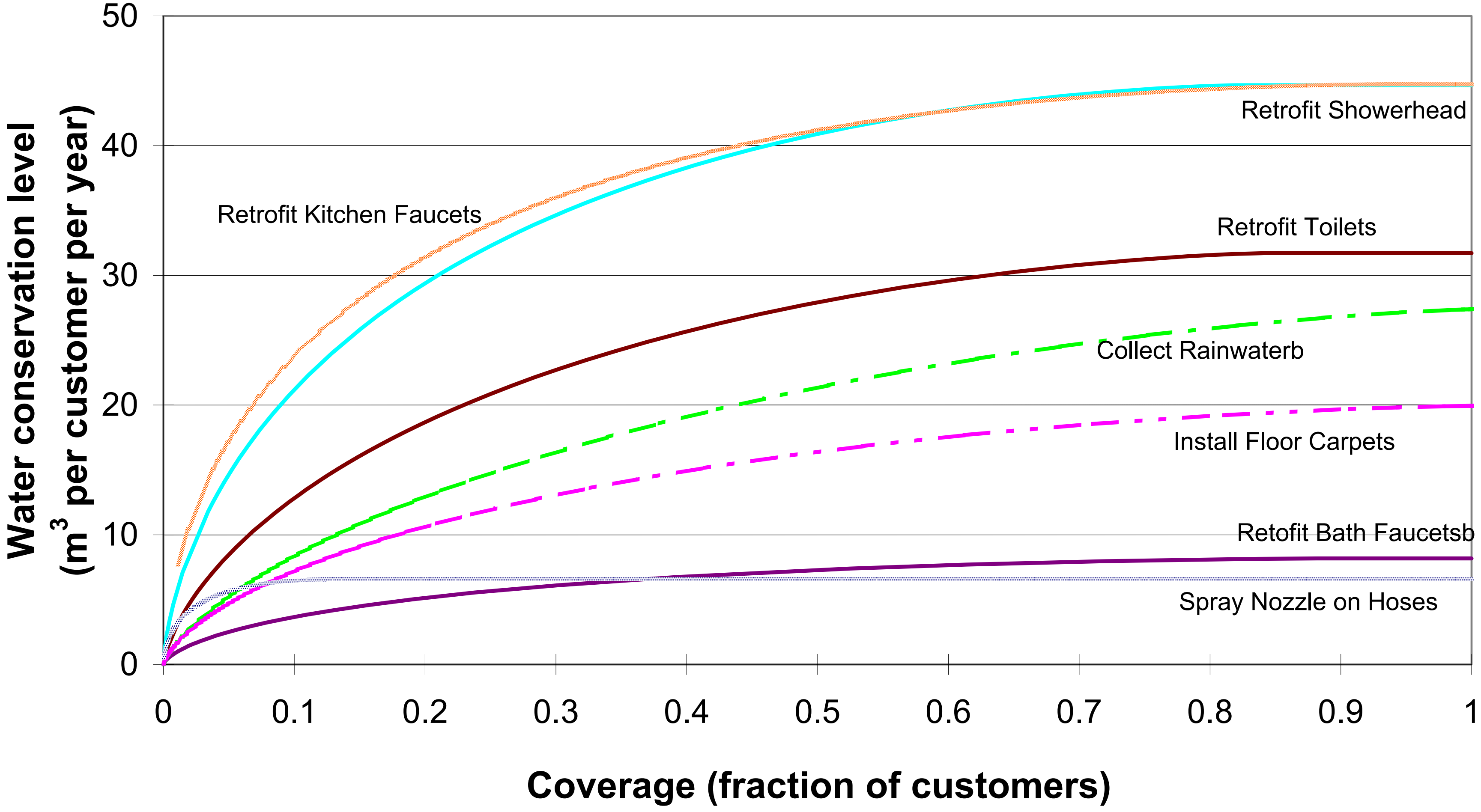


Figure 3.4. Chart for sizing targeted water conservation programs.

Chapter 4

Modeling Integrated Water-User Decisions in Intermittent Supply Systems

Abstract—We apply systems analysis to estimate household water use in an intermittent supply system considering numerous interdependent water user behaviors. Some 39 household actions include conservation, improving local storage or water quality, and accessing sources having variable costs, availabilities, reliabilities, and qualities. A stochastic optimization program with recourse decisions identifies the infrastructure investments and short-term coping actions a customer can adopt to cost-effectively respond to a probability distribution of piped water availability. Monte-Carlo simulations show effects for a population of customers. Model calibration reproduces the distribution of billed residential water use in Amman, Jordan. Parametric analyses suggest economic and demand responses to increased availability and alternative pricing. It also suggests potential market penetration for conservation actions, associated water savings, and subsidies to entice further adoption. We discuss new insights to size, target, and finance conservation programs and interpret a demand curve with block pricing.

4.1. Introduction

Water users make many behavioral, operational, and investment decisions that affect their water use. They invest capital to improve on-site storage capacity, water quality, and use efficiency. And they allocate water daily from different quality sources to numerous end uses. Yet water use models have given little systematic attention to sources, availabilities, reliabilities, qualities, conservation options, and local storage. These considerations are important in intermittent supply systems where households adopt many interdependent actions to cope with insufficient piped water [*White et al.*, 1972].

The literature on water use modeling and user behaviors has developed in two directions. First, regression models (for reviews, see [*Hanemann*, 1998; *Young*, 2005; *Garcia-Alcubilla and Lund*, 2006]) have used proxy indicators such as water price, household income, family size, house age, and weather to explain residential water use with continuous supplies. Studies draw on large panel data sets and natural experiments where one indicator (such as water price) naturally varies across the sample population. Effort is focused on understanding volumetric use and price elasticity of demand rather than the customer behaviors that drive responses. At times, *price*, *simultaneity*, and *model specification* problems arise when prices vary with water use as with block rate structures [*Hewitt and Hanemann*, 1995; *Young*, 2005, p. 252]. Regression studies—even for intermittent supply systems [*Mimi and Smith*, 2000]—have yet to consider alternative sources, water availability, conservation behaviors, local storage, or interdependencies.

A second class of choice, contingent valuation, and averting cost models use observed or revealed customer preferences to explain coping actions rather than quantify water use [*Madanat and Humplick*, 1993; *Theodory*, 2000; *Iskandarani*, 2002; *McKenzie and Ray*, 2004; *Pattanayak et al.*, 2005]. These approaches are applied in intermittent supply systems and consider many behaviors and conditions that regression methods have yet to include. Surveys use large cross-sectional samples and require detailed specification and respondent understanding of alternatives—particularly probabilistic information related to supply availability and reliability. They often assume mutually exclusive choices and, to our knowledge, have not yet included conservation options (although they can). Customer preference methods focus on estimating the economic value of behaviors such as customer willingness-to-pay (WTP) to improve service.

This chapter expands water use modeling for an intermittent supply system to consider numerous, interdependent water user behaviors. We present a systems analysis that integrates multiple sources having different costs, availabilities, reliabilities, and qualities; many conservation options; and actions that improve local storage or water quality (Table 2.1). We also embed uses that accommodate different water qualities (Table 4.1). Integration helps quantify demand responses for indoor and outdoor uses over different time horizons and how customers may respond to conservation incentives embedded in a tariff structure.

The systems analysis applies integrated approaches typically made at regional or utility scales [*Wolf and Murakami*, 1995; *Wilchfort and Lund*, 1997; *Jaber and Mohsen*, 2001; *Joench-Clausen and Fugl*, 2001; *Scott et al.*, 2003] to individual users. It works as follows:

1. Identify a wide range of potential long and short-term user actions (Table 2.1),
2. Characterize each action in terms of a financial cost, effective water quantity added or conserved, and water quality affected (see Chapter 2),
3. Describe interdependencies among actions (demand hardening, supply enhancement, and mutual exclusivity),
4. Characterize the events through which the user must manage water (source availabilities, uses, and likelihoods),
5. Identify the actions and associated use that minimize the user's costs across all events (stochastic optimization with recourse decisions), and
6. Repeat for a wide variety of user conditions (Monte-Carlo simulations).

We identify and characterize actions and events in the study area using prior empirical work, our own surveys and questionnaires (Chapter 2), and prior estimates of conservation action effectiveness (Chapter 3). Characterization involves developing probability distributions for some 126 parameters that are then sampled in Monte-Carlo simulations. We adjust one parameter to calibrate modeled piped water use to the distribution of billed use. And finally, we parametrically change select parameters to infer demand responses. Changes elicit customer willingness-to-pay to avoid intermittent service, price elasticity of demand, potential market penetration for conservation actions, associated water savings, and subsidies to entice more adoption. The latter inferences are preliminary and still require verification in the study area.

Herein, we demonstrate the systems analysis for residential water users and use in Amman, Jordan. Roughly 2.2 million people access the Amman network through 346,000 residential connections. Water is generally available for only 12 to 72 hours per week and many customers want to improve their access. LEMA, the urban water service management company, is following a detailed program of physical and commercial loss reduction while the Jordan Ministry of Water and Irrigation is working aggressively to develop new bulk supplies and implement water conservation programs. Systems analysis can help inform and target these efforts. The chapter is organized as follows. Section 4.2 reviews systems analysis for an individual water user. Section 4.3 extends existing stochastic optimization programs with recourse decisions for continuous supplies [*Lund*, 1995; *Wilchfort and Lund*, 1997; *Garcia-Alcubilla and Lund*, 2006] to intermittent supply conditions. Sections 4.4 and 4.5 describe Monte-Carlo simulations and model calibration. Sections 4.6 and 4.7 present results for parametric changes and discuss implications to estimate economic water demands and to size, target, and subsidize water conservation programs to residential water users. Section 4.8 concludes.

4.2. Systems analysis for water users

Integrated water resources management for utilities or regions [*Wolf and Murakami*, 1995; *Wilchfort and Lund*, 1997; *Jaber and Mohsen*, 2001; *Joench-Clausen and Fugl*, 2001; *Scott et al.*, 2003] is readily applied to individual water users with a few changes.

4.2.1. Identify actions

Water utilities or ministries combine long- and short-term actions to respond to a variety of conditions [*Lund*, 1995; *Wilchfort and Lund*, 1997]. Long-term actions represent irreversible capital investments while short-term actions constitute temporary operational or emergency measures that are reversible.

For water users, long-term actions can include developing new supplies, expanding local storage, or installing appliances that improve water quality or use-efficiency (Table 2.1). Short-term actions are frequent daily or weekly choices regarding water sources, qualities, and quantities to access, buy, treat, store, use, and reuse. Users can implement multiple long- and short-term actions. Preference towards a long-term action depends on the water user’s expectation of capital cost, lifespan, discount rate, and future water availability, reliability, and quality.

4.2.2. Characterize actions

Centralized decision-makers often explicitly estimate financial and perceived costs and effectiveness for potential projects. Water users do this too, however informally with estimates differing among users. For example, the number of occupants, flow rates of existing appliances, outdoor landscaping, length of occupancy, and water-use behaviors all influence water consumption, effectiveness (Chapter 3), financial, and perceived costs of potential actions. Users typically differ in their perceptions of life spans for long-term actions, discount rates, and risk aversion to service disruption.

4.2.3. Interdependencies among actions

Implementing some actions render other actions less or more effective. Interdependencies can take the form of "demand hardening" [*Lund*, 1995; *Wilchfort and Lund*, 1997], supply enhancement, or mutual exclusivity. For example installing a low-water consuming landscape, drip irrigation, or spray nozzles on hoses reduce water savings from stress irrigation. Similarly, installing a low-flow showerhead reduces the (i) water saved by taking shorter or less frequent showers and (ii) grey-water available for reuse outdoors. Alternatively, a customer must install roof downspouts and storage before collecting and using rainwater. A user can install a water-efficient semi-automatic *or* automatic laundry machine, not both. Interdependencies critically depend on the actions under consideration. In the Amman, Jordan example, we consider 42 interdependencies.

4.2.4. Characterize events for which the system must adapt

Water systems must adapt to events that decrease bulk supplies (during droughts or dry seasons) or increase use (peak load). Water system managers often characterize events by water availabilities (volumes) and likelihoods (probabilities). Managers seek to economically serve drinking-quality water to all users regardless of use.

Water users also face complex water-related events. In Jordan, intermittent piped service, service disruptions, uncertain alternative supplies, and variable costs shape water availability and likelihoods. Increased use (household guests) and different uses accommodating different water qualities (Table 4.1) often force users to seek alternative sources when availability is limited. Event characteristics typically differ among users.

4.2.5. Suggest mixes of actions

Identifying the potential actions, costs, effectiveness, interdependencies, uses, events, and event probabilities as discussed above allows a water user to frame their choice of water management actions in terms of service availability, reliability, quality, and cost. We now describe in greater detail the optimization model to represent choices.

4.3. Stochastic Optimization with Recourse Decisions

We formulate the water user's decision problem as a two-stage stochastic program. The program identifies and quantifies the mix of actions that minimize a water user's expected costs to meet all water quality uses across different water availability events. Events are described by water source availability (volume) and likelihood (probability).

Decision staging works by partitioning actions into two types. Long-term (first- or primary-stage) actions apply for all events. Then, additional short-term (secondary- or recourse-stage) actions are implemented in particular events to cover remaining uses not met by long-term actions. Together, long-term actions plus sets of short-term actions for each event constitute the mix of actions that respond to the probability distribution of water availability. And, as water availability or reliability decrease, water users adopt increasingly expensive short-term actions.

The program extends a prior two-stage linear program of water user with continuous supplies [*Garcia-Alcubilla and Lund*, 2006] to include:

- An expanded set of sources, storage, and water quality improvement actions,
- A variety of drinking, indoor, and outdoor water uses that accommodate different water qualities,
- Interdependencies among actions,
- Limited source availability and reliability, and
- Non-linear costs.

These extensions reflect actions, uses, conditions, and costs (Appendices I and II) typical for residential water users with intermittent supplies in Jordan. The model is readily adapted for other users (commercial, industrial, agricultural, etc.) and other locations.

4.3.1. Decision Variables

The decision variables are:

- $\underline{\mathbf{L}}$ = vector of implementation levels for long-term actions (binary or integer),
- $\underline{\mathbf{S}}$ = matrix of water volumes for short-term actions in each event (m^3 event^{-1}), and
- $\underline{\mathbf{X}}$ = matrix of supply volumes allocated to each water quality use in each event (m^3 event^{-1}).

In the notation below, *lt*, *st*, *e*, and *u* are, respectively, indices for long- and short-term actions, events, and water quality uses. L_{lt}, $S_{st,e}$, and $X_{u,e}$ are individual decision elements of $\underline{\mathbf{L}}$, $\underline{\mathbf{S}}$, and $\underline{\mathbf{X}}$.

4.3.2. Model Formulation

Risk-neutral water users minimize their annual expected long- and short-term water management costs, Z [\$ year^{-1}]. With $c_1(\underline{\mathbf{L}})$ = annualized costs to implement long-term actions [\$ year^{-1}], $c_{2,e}(\underline{\mathbf{S}})$ = event-specific costs to implement short-term actions [\$ event^{-1}], p_e = probability of event e [unitless, but $\sum_e p_e = 1$ and $0 \le p_e \le 1, \forall e$], and a = constant that relates the periods of short- and long-term actions [events year^{-1}], the objective can be expressed as:

$$\text{Minimize } Z = c_1(\underline{\mathbf{L}}) + a \cdot \sum_e p_e \cdot c_{2,e}(\underline{\mathbf{S}}). \tag{4.1}$$

Event probabilities (p_e) weight event-specific costs ($c_{2,e}$) associated with short-term actions [*Lund*, 1995; *Wilchfort and Lund*, 1997]. Piped water charges are a component of $c_{2,e}$. Long-term costs (c_1) include network connection fees and other capital expenses.

The objective function (4.1) is subject to several constraints.

- Water supplies, $s_{u,e}(\underline{\mathbf{S}},\underline{\mathbf{X}})$ [m^3 event^{-1}], must satisfy the initial estimate of water use, $d_{u,e}$ [m^3 event^{-1}] for each quality use *u* in each event *e*, reduced by water saved from conservation actions, $h_{u,e}(\underline{\mathbf{L}},\underline{\mathbf{S}})$ [m^3 event^{-1}],

  $$s_{u,e}(\underline{\mathbf{S}},\underline{\mathbf{X}}) \geq d_{u,e} - h_{u,e}(\underline{\mathbf{L}},\underline{\mathbf{S}}),\ \forall e \forall u\,. \tag{4.2}$$

  This specification disaggregates initial estimates into separate estimates for each water quality use *u* in each event *e*. Users meet estimates by acquiring and/or conserving water. The physical volume allocated, $s_{u,e}$, is the optimal water use. However, this use can (and often is) less than the initial estimate ($d_{u,e}$).

- Each long-term action L_{lt} has a fixed upper limit of implementation, u_{lt} [integer],

  $$L_{lt} \leq u_{lt},\ \forall lt\,. \tag{4.3}$$

- Each short-term action S_{st} has an availability or fixed upper limit of implementation, $u_{st,e}$ [m^3 event^{-1}], that can potentially decrease or increase, $g_{st,e}(\underline{\mathbf{L}},\underline{\mathbf{S}},\underline{\mathbf{X}})$ [m^3 event^{-1}], based on interdependencies with other actions,

  $$S_{st,e} \leq u_{st,e} + g_{st,e}(\underline{\mathbf{L}},\underline{\mathbf{S}},\underline{\mathbf{X}}),\ \forall e\ \forall st\,. \tag{4.4}$$

  Intermittently available sources have different upper limits ($u_{st,e}$) in different events *e*. The interdependency function, $g_{st,e}$, is an *n* x 1 vector, $n = \mathrm{rank}(\underline{\mathbf{L}}) + \mathrm{rank}(\underline{\mathbf{S}}) + \mathrm{rank}(\underline{\mathbf{X}})$, whose elements describe pair-wise interdependencies with the short-term action $S_{st,e}$. Negative elements represent demand hardening relations (reduce the upper limit), positive elements supply enhancement relations, and zero-values (the vast majority) reflect no relation. For mutually exclusive relations, $g_{st,e}$ is equal but opposite to $u_{st,e}$.

- In each event *e*, the user must direct all primary (rain and municipal water) and secondary (from vendors or neighbors) supplies (together, PSSs) to one or more water quality uses *u*, allowing high-quality water to meet lower-quality uses,

  $$\sum_u X_{u,e} \leq \sum_{st \in PSSs} S_{st,e},\ \forall e\,. \tag{4.5}$$

- Local storage capacity, $v_{stor}(\underline{\mathbf{L}})$ [m^3 event^{-1}], associated with long-term actions limits the total volume of primary supplies *(PSs)* in each event *e*. After exhausting primary supplies, the user must draw on secondary sources,

$$\sum_{st \in PSs} X_{st,e} \leq v_{stor}(\underline{\mathbf{L}}), \ \forall e. \tag{4.6}$$

- And, finally, all decision variables must be positive

$$L_{lt} \geq 0, \forall lt; \ S_{st,e} \geq 0, \forall st \forall e; \ X_{u,e} \geq 0, \forall u \forall e. \tag{4.7}$$

4.3.3. Model Discussion

In the Amman, Jordan example, equations (4.1) through (4.7) are setup as a mixed integer nonlinear program in the Generic Algebraic Modeling System (GAMS) [*Brooke et al.*, 1998] and solved with DICOPT [*Grossmann et al.*, 2002]. However, when the cost (c_1 and $c_{2,e}$), supply ($s_{u,e}$), conservation ($h_{u,e}$), and interdependency ($g_{st,e}$) functions are linear and separable by management action, the program is more easily solved as a mixed integer linear program.

4.4. Monte-Carlo Simulations

Action costs (c_1 and c_2), initial estimates of water use ($d_{u,e}$), conservation (h_u), water availabilities / upper limits on actions ($u_{st,e}$ and u_{lt}), event probabilities (p_e), and action interdependencies ($g_{st,e}$) vary among customers. We embed the optimization in Monte-Carlo simulations (MCS) of customers to represent customer heterogeneity, but maintain consistency in each input set. MCS takes three steps.

First, we develop an empirical basis of water user behaviors and conditions from 9 prior studies in Amman, Jordan [*DOS*, 1999; *JMD*, 2000; *Theodory*, 2000; *WEPIA*, 2001; *Iskandarani*, 2002; *Snobar*, 2003; *CSBE*, 2004; *DOS*, 2004; *IdRC*, 2004]. Absent other data, we make engineering estimates. Second, we use the empirical data to develop probability distributions for some 126 parameters (Table 4.2, Table 2.4 and Table 2.5) that influence a customer's water use, water availability or reliability, effectiveness of one or more conservation actions, or costs. A probability distribution characterizes each parameter with a range and likelihood of values the parameter can take. Third, we sample from each distribution, combine sampled values to estimate optimization model inputs, then optimize for the customer-specific inputs. We repeat step 3 for a large number of simulated customers then observe averages and distributions of the optimized results.

Empirical parameter distributions were sampled and combined in Excel and then fed to GAMS. Below, we describe calculations for optimization model inputs and how MCS allows detailed specification of end uses and correlated and conditional sampling. In these calculations, we define the event period as a week based on the weekly rationing schedule for piped water.

We calculate action costs (c_1 and $c_{2,e}$) by sampling from normal or uniform distributions of capital costs, life spans, and operational costs (Table 2.4 and Table 2.5). The price schedule for piped water use and some operational costs are fixed and constant among customers. We use the 2001–2005 price schedule. During this period, four increasing blocks had, respectively, fixed, variable, and quadratic charges for water use below 20, 40, and 130 m^3 per customer per quarter. Use above 130 m^3 reverted to a variable charge (for formulas, see Chapter 2).

We make initial estimates of water use as products and summations of the relevant sampled empirical parameter values. For example, the initial estimate of bathroom faucet water use, $d_{BathFaucet}$ [m^3 customer^{-1} week^{-1}], is

$$d_{BathFaucet} = \frac{7}{1000}(P_N)(P_Y)(P_G), \tag{4.8}$$

where P_N = the flow rate of the existing bathroom faucet [l min^{-1}], P_Y = wash time [min person^{-1} day^{-1}], and P_G = household size [persons]. (The capital letters P_N, P_Y, etc. reflect notation common to the probability literature where a capital letter, i.e. P_N, means the parameter is uncertain. Before sampling, use is also uncertain. Table 4.2 describes the parameters. Hereafter, P_N, refers to parameter N in the Appendices; similarly for other subscripts). Combining initial estimates for bath faucet, toilet, shower, kitchen faucet, floor washing and laundry uses gives the total indoor water use, $d_{indoor,e}$ [m^3 customer^{-1} week^{-1}]. Except for showering and outdoor irrigation (see below), we assume initial estimates are the same across all events.

We use previously reported effectiveness functions for seven long-term conservation actions (Chapter 3). For example, the water saved when retrofitting a bathroom faucet with a faucet aerator, $W_{FaucetRetroBath}$ [m^3 customer^{-1} year^{-1}] is

$$W_{FaucetRetroBath} = \frac{365}{1000}(P_N - P_{AN})(P_Y)(P_G), \tag{4.9}$$

where P_{AN} = faucet aerator flow rate [l min^{-1}], and $P_{N,}$, P_Y , and P_G as defined previously.

Similar parameter combinations shape initial estimates of other end uses and the effectiveness of related conservation actions with several modifications. (1) We disaggregate shower use and effectiveness of related conservation actions by summer and winter differences in shower behavior (P_U and P_V). (2) Toilet water use and effectiveness of toilet conservation actions key to toilet flush volume (P_O). Customers with squat (Arabic) toilets (1st category of P_O) have zero effectiveness for toilet conservation actions. (3) Laundry water use multiplies by a rinse factor (P_{AL}) when the household has a semi-automatic machine (category 2 of P_{AJ}). (4) The drinking water use estimate was a linear combination of household size (P_G) and a random effect (P_H). This relation was determined by regressing reported household drinking water consumption and purchases (Chapter 2) against household size. Household size explained 59% of variability. (5) Irrigation water use ceases during winter. (6) Piped water and tanker truck water availabilities were unconstrained. However, in the summer event with limited availability, households can only use 2 m^3 per week of piped water. Borrowing water was available only to the portion of households that find the practice acceptable (P_{AH}); borrowing extends availability up to 0.3 m^3 per event. (7) An occupancy parameter (P_I) serves as a global multiplier on the effectiveness of all conservation actions and all water uses except outdoor irrigation. The multiplier was zero, 0.5, and 1.0 when P_I was sampled, respectively, as *vacant*, *partial*, or *full* occupancy. Partial occupancy indicates that only some household members live at the house full time, or, that the household occupies the house part-time and other times the house is empty with little/no water use.

In the Amman example, we consider three events: weeks of summer use with (a) limited and (b) unlimited piped water availability, and (c) winter use with winter supplies. We calculate probabilities for these events from the sampled number of irrigation weeks in summer with limited availability (P_C), the sampled remaining irrigation season (P_B — P_C), and noting that all event probabilities must sum to one:

$$p_{\mathit{Summer\ Limited\ Availability}} = \frac{(P_C)}{a}, \qquad (4.10a)$$

$$p_{\mathit{Summer\ Unlimited\ Availability}} = \frac{(P_B)-(P_C)}{a}, \text{ and} \qquad (4.10b)$$

$$p_{\mathit{Winter}} = 1 - p_{\mathit{Summer\ Unlimited\ Availability}} - p_{\mathit{Summer\ Limited\ Availability}}. \qquad (4.10c)$$

Equations (4.8) through (4.10) and the paragraph of modifications show that MCS allows detailed and correlated customer-specific specification of optimization model inputs including water use. For example, several effectiveness and use functions are conditioned on existing water use appliances (toilets and laundry). Other parameters appear repeatedly in the water use and effectiveness functions and indicate these optimization input parameters are strongly correlated (P_N, P_Y, and P_G in (4.8) and (4.9) for faucet use and related conservation actions). Regression or customer preference models do not typically include these details or interdependencies.

4.5. Model Calibration

We calibrate the cumulative distribution of modeled piped water use to use billed to Amman residential customers in 2005 (Figure 4.1). Calibration included 500 Monte-Carlo simulated customers and set upper limits for all long-term conservation actions to zero ($u_{lt} = 0$ in (4.3)). This setting represents current conditions with limited adoption of long-term conservation actions (low sample values for technological parameters represent adoption). Calibration varied only the fractions of *vacant* and *partially* occupied households (P_G) by trial and error to maximize the Kolmogorov-Smirnov goodness of fit (K-S Test) between the billed and modeled water use distributions.

Occupancy was chosen as the calibration parameter since the number of residential connections (customers) differs from the census of total and vacant housing units [*DOS*, 2004; *WAJ*, 2006]. The difference is likely due to different sampling frames (i.e., some connections serve multiple housing units). Calibration found the percentages of *vacant* and *partially* occupied connections as 10% and 15%, respectively.

The K-S Test (D statistic = 0.019; $n_1 = 20$; $n_2 = 500$) indicates that the distributions of billed and modeled piped water use are similar at the 98% significance level (Figure 4.1). Both distributions skew heavily towards large fractions of customers that use less than 40 m^3 per customer per quarter and smaller fractions who use considerably greater volumes.

Billed and modeled uses average, respectively, 39.6 and 37.8 m^3 per customer per quarter, a difference of 4%.

4.6. Results for Parametric Changes

The calibration model run described above represents a base case with existing (limited) adoption of long-term conservation actions. Parametrically changing base case parameter value(s) can show how availability, pricing, and conservation campaigns may influence water use. These changes are used to infer economic effects such as willingness-to-pay (WTP) to avoid limited piped water availability, price elasticity of demand, and potential market penetration rates for conservation actions.

4.6.1. Municipal water availability

We increased piped water availability from 2 to 20 m^3 per week during the summer event with limited availability to derive the distribution of customer WTP to avoid network shortages (Figure 4.2). Customer WTP is the difference between the customer's total (optimized) water management costs when network water is limited and widely available. Some 50% of customers may pay to avoid rationing. Also, a K-S Test confirms a null hypothesis that the imputed WTP distribution is similar to an empirical WTP distribution reported by a contingent valuation survey of 1,000 Amman households [*Theodory*, 2000]. The K-S significance of fit is 98% (D statistic = 0.038; $n_1 = 7$; $n_2 = 500$).

4.6.2. Demand response to water pricing

Alternative water sources. Changing vended water (tanker truck purchase) costs were used to derive the demand curve and price elasticity for tanker water and cross-elasticity of piped water use (Figure 4.3). Average tanker price in summer was increased from $US 0.05 to 5.70 per m^3 in 7 discrete steps. Results show a switch-point from elastic to non-elastic response near an average price of $US 2.5 per m^3. This switch point is also the current average price for tanker water.

Municipal piped water. We simulated the cost schedules for piped water adopted in 1997, 2001 (base case), and 2006 to derive the demand curve for piped water (Table 4.3). We use historical schedules to avoid the political issue of price setting. Schedules had the same block spacing. The 2001 schedule increased all sewerage charges from 1997 by 12% while the 2006 schedule further increased flat charges in blocks 1 through 4 by $US 2.33, 3.74, 5.15, and 5.15 per customer per quarter.

A demand curve for piped water was derived by comparing average piped water use by customers under each schedule to the schedule's representative price. Here, the representative price was the average charge (total utility revenues from all simulated customers divided by the total piped water use). Results show a small decrease in average piped water use and inelastic price response in the expected range (Table 4.3, Column A).

4.6.3. Conservation campaign

Releasing constraints on upper limits for long-term conservation actions (Eq. 4.3) suggests that an education and awareness campaign to encourage cost-conscious decisions regarding household conservation actions may, on average, reduce municipal water consumption in Amman by about 33% (Table 4.4, Columns A and B). Simulating the three historic rate structures for this case shows a slightly more elastic price response and a significant shift inward (left) of the demand curve (Table 4.4, Column B). This analysis provides a way to differentiate short- and long-term demand curves (i.e., before and after adoption of long-term conservation actions). A conservation campaign would incidentally reduce tanker truck water use by more than 60%, decrease customer's overall water-related expenditures by 35%, and, alas, reduce utility revenues nearly 60% (due to the convex rate structure)!

Interestingly, a small fraction of customers with very significant water savings drive reductions in piped water use (Figure 4.4). For example, just 38% of the Monte-Carlo simulated customers retrofit showerheads. The adopting customers average water savings of 50 m^3 per customer per year with savings ranging from 5 to more than 100 m^3 per customer per year. Other actions such as installing drip irrigation or xeriscaping have low market penetration rates, but are extremely effective for customers who adopt. These distributions suggest that a targeted conservation campaign can achieve significant water savings with concentrated effort.

Examining the reduced costs for long-term conservation actions identifies drip irrigation, kitchen faucet aerators, and toilet dual flush mechanisms as actions the water utility might target with financial incentives (Figure 4.5). The reduced cost is the decrease in cost required for the customer to benefit overall to adopt the action. It is also the customer's willingness-to-accept, or, alternatively, the subsidy to entice adoption. The utility may find it cheaper to pay customers to adopt these conservation actions to reduce use rather than produce, treat, and deliver the equivalent water volume.

4.7. Discussion

A systems analysis estimates water use with intermittent supplies by considering interdependent effects of numerous water user behaviors. Behaviors include infrastructure investments and short-term coping strategies such as accessing multiple sources having different availabilities, reliabilities, and qualities, conservation options, local storage, and water quality improvements. The analysis embeds end uses requiring various water qualities and variable costs, including block rate structures. Model calibration reproduces both the mean and distribution of existing piped water use in Amman, Jordan. It simultaneously estimates use for a wide range of alternative supplies (vended water, rainwater, grey-water, etc.). Further parametric changes permit study of economic water demands, including willingness-to-pay for increased availability, price elasticity of demand, and cost, water savings, and potential penetration rates for conservation actions. We discuss each of these results plus limitations. We emphasize that the price and conservation results still require empirical verification.

4.7.1. Increased availability and willingness-to-pay

Increasing piped water availability is used to derive a distribution of customer willingness-to-pay (WTP) to avoid rationing. This distribution reproduces WTP reported by a prior contingent valuation study (Figure 4.2). An advantage of systems analysis is ability to *post-facto* specify and re-specify WTP intervals with greater resolution. The analyst simply increases the number of Monte-Carlo simulations and/or decreases the spacing used to tally MCS results. This ease contrasts with difficulties for surveyors posing contingent valuation questions to respondents. They must pose new, narrower questions again to respondents. Also, cost parameters (Table 2.4 and Table 2.5) excluded hassle, so customers may have greater WTP than suggested by the model or the prior survey.

4.7.2. Price elasticity of demand

Piped water use was estimated for several historic rates structures. Comparing use and the "representative price" for the rate structure permits estimating a price-elasticity of demand. However, there are numerous ways to *post-facto* calculate the "representative price". For example, averaging the average prices paid by each customer gives a slightly more elastic price response. Substituting marginal prices gives an infinitely elastic response (in the Amman example, fixed charges increase but the variable (marginal) charges do not). For conservation efforts, using lower prices associated with lower use achieved by conservation gives a more elastic price response. These different interpretations of price response are artifacts of:

1. Customer behavior (ability to substitute other sources and conservation actions),
2. The fixed and variable charges in the existing schedule, and
3. Method to calculate a "representative" price for the schedule.

Block spacing can also create an artifact (although not in the Amman example). A wider block captures more customers and pulls the representative price closer to prices faced by customers in that block. This artifact also manifests with customers who switch blocks.

These issues identify an important limitation of demand curves under block pricing. Reducing multiple degrees of freedom (block spaces, fixed, and variable charges) to a single representative price influences the interpretation of price response.

4.7.3. Conservation campaigns

Allowing users to adopt long-term conservation actions (when they find it cost-effective) predicts significant water savings despite low adoption rates. At most, 38% of customers retrofit showerheads, 33% install aerators on kitchen faucets, 18% catch rainwater, 4% retrofit semi-automatic laundry machines, 0.5% xeriscape, etc. These findings suggest water conservation campaigns should target customers who will realize large financial and water savings. Obviously, success requires identifying real customers with significant potential to save water and money, determining what action(s) they should adopt, motivating adoption, and verifying that estimated savings translate to actual savings. In

Chapter 3, we suggested using surrogate data indicators, customer surveys, and water audits to identify high potential customers and actions.

Numerically integrating the distributions of water savings shown in Figure 4.4 gives conservation program sizing curves (Figure 4.6). The curves suggest the minimal market penetration needed to meet a conservation objective (Chapter 3). Minimal market penetration is achieved by ordering customers (x-axis in Figure 6) left to right from the largest down to the smallest (zero) water savings. At first, sizing curves are steep, but then flatten to the average effectiveness achieved with full participation (this average exactly equals the product of (i) average water savings for implementing customers and (ii) the market penetration rate shown in Figure 4). Here, average effectiveness estimates by systems analysis are much lower than estimates for individual actions that ignore implementation costs and interdependencies (Chapter 3). For example, in Chapter 3 we reported average savings of 45 m^3 per customer per year to retrofit showerheads or kitchen faucets compared to current estimates of 19.4 and 11.6 m^3 per customer per year, respectively. The decrease occurs because systems analysis screens out customers with high effectiveness but insufficient financial incentive to adopt. Also, customers who adopt cost-effective conservation action(s) and then have no incentive to *further* conserve. Despite decreases, systems analysis still reproduces the more *general* finding: target conservation actions to customers who will save the most water *and money*.

Examining the reduced costs associated with conservation actions also shows the Amman water provider might find it cheaper to subsidize some customer conservation rather than provide the equivalent water volume. The utility could offer subsidies as a rebate or credit on the water bill to customers who verify installation. In Amman, verification will be critical and is potentially compromised by *wasta* (favors). To make subsidies more effective, governance should improve employee accountability, reward performance, enforce water conserving plumbing codes, restrict the import and manufacture of inefficient water appliances, label efficient appliances, and raise awareness about the financial savings associated with purchasing efficient appliances.

4.7.4. Further methodological limitations

First, the optimization assumes expected, financial cost-minimizing customer decisions with full information even though customers may include time, hassle, and social desirability values in their decisions. However, a cost-minimizing model is not necessarily mis-specified. Rather, cost-minimizing behavior is borne out empirically through model calibration so customers in Amman behave *as if* they minimize their costs. Hewitt and Hanemann [1995] deploy this *as if* argument to justify their Discrete / Continuous choice water use model. For the un-calibrated conservation campaign results, including convenience costs, hassle, and other factors may well reduce modeled adoption rates and water savings. Still, this reduction does not compromise the more *general* recommendation reached after examining the Monte-Carlo *distribution* of responses: target conservation actions to customers who will save the most water and money.

Second, initial estimates of water use set upper bounds for the optimal use (Eqs. 4.2 and 4.8). Customers can only choose from an exhaustive set of sources and conservation actions to set their use at or below the initial estimate. Yet customers may also benefit to expand their garden area or take longer or more frequent showers, etc. The upper bound means that availability runs should be strictly interpreted as willingness-to-pay *to avoid rationing*. Quite possibly, use could significantly increase should piped water become widely available.

Third, the two limitations above suggest further work to develop a utility-maximizing rather than cost-minimizing decision criterion. This change requires estimating the utility contributions of hassle, social desirability for each action, plus specifying variability among customers. Yet little empirical data exists to describe these contributions. Estimating contributions requires assembling a large dataset, specifying a regression model, and teasing apart diverse and potentially interdependent responses. These tasks require significant effort beyond the scope of the current study.

Fourth, significant unaccounted-for and non-revenue water loss in Amman means actual and billed use differ [*Griffen*, 2004]. Fortunately, systems analysis already includes losses from physical leakage, billing, and metering errors. Physical leakage reduces piped water availability and is represented by limited availability events in optimizations. Customers react to these conditions. Calibration captures metering and billing errors by attributing these losses to *partial* or *vacant* occupancy. Also, absent empirical data on illegal connections, we exclude thieving customers. With data on illegal connections, we could better specify the parameter distribution to borrow water (P_{AH}, a free source).

Finally, targeted conservation programs substantially reduce piped water use and erode utility revenue. In Amman, a convex (quadratic) price schedule means high use customers disproportionately contribute to utility revenues and have the most potential to save water and money. To reduce use and protect revenue, a utility may encourage customers with low use to conserve further. Such targeting raises social and equity issues. It illustrates that pricing, source availabilities, conservation options, and utility revenues interrelate and must be considered jointly to develop coherent water conservation programs. Minimally, utility revenue requirements suggest needs for further analysis at a wider scale. One should compare costs and water savings of targeted conservation programs with alternatives that increase bulk supplies or reduce physical losses.

4.8. Conclusions

This chapter extends water use modeling in an intermittent supply system to consider numerous, interdependent water user behaviors. Behaviors include water conservation, improving local storage and water quality, and accessing multiple sources having variable availabilities, reliabilities, qualities, and costs. An optimization program suggests the mix of actions a user should adopt to reduce expected water management costs given a probability distribution of piped water availability and action interdependencies such as demand hardening, supply enhancement, and mutual exclusivity. Monte-Carlo simulations show average citywide effects and distributions of customer responses, including piped water use. Parametrically changing model parameters allows inferring potential economic effects for several water availability, pricing, and conservation efforts. The primary results, findings, limitations, and recommendations for future work are:

1. The modeling approach reproduces both the existing average and distribution of piped water use for residential customers in Amman, Jordan.
2. Willingness-to-pay to avoid rationing closely matches reports from a contingent valuation method. However, significant untapped or unmet uses may exist for continuous supplies.
3. Price response is highly inelastic. However, the rate structure (block spaces, fixed and variable charges) complicates interpretation of price response.
4. In Amman, a conservation campaign may significantly reduce piped water use.
5. Campaigns should target select customers that show the most potential to save water and money.
6. In limited cases, the utility can subsidize customers to install water efficient appliances to realize further water savings. Successful implementation will require improving employee accountability.
7. Targeted conservation programs will reduce utility revenues. Balancing these impacts with the benefits of reducing water use requires further analysis at a wider utility scale.
8. Results for pricing and conservation efforts still require empirical verification. Including hassle, time, and other factors may reduce adoption rates.

Overall, systems analysis helps model and understand several complexities and impacts of water user behaviors.

4.9. Notation

a	number of events per year.
c_1	annual cost of long-term actions, \$/year.
$c_{2,e}$	cost of short term actions in event *e*, \$/event.
$d_{u,e}$	initial estimate of water quality use *u* in event *e*, m^3/event.
$g_{st,e}$	interaction function for short term action *st* in event *e*, m^3/event.
$h_{u,e}$	water savings for use *u* in event *e* from conservation actions, m^3/event.
L_{lt}	implementation level of long-term action *lt*, binary or integer.
p_e	probability of event *e*, fraction.
P_N	current faucet flow rate, l/min, (parameter *N* in the Appendices).
$S_{st,e}$	water volume implied by short-term action *st* in event *e*, m^3/event.
$s_{u,e}$	water supply enhancement function for use *u* in event *e*, m^3/event.
u_{lt}	upper limit of long-term action *lt*, integer.
$u_{st,e}$	upper limit or availability of short-term action *st* in event *e*, m^3/event.
v_{stor}	local water storage capacity, m^3.

W_{Faucet}	water savings (effectiveness) to retrofit faucets, m^3/year.
$X_{u,e}$	supply volume allocated to use *u* in event *e,* m^3/event.
Z	objective function value, \$/year.

4.10. References

Brooke, A., D. Kendrick, A. Meeraus, and R. Raman, GAMS, a user's guide, GAMS Development Corporation, Washington, D.C., 1998.

Center for Study of the Built Environment (CSBE), "Water Conserving Landscapes." Amman, Jordan. http://www.csbe.org/water_conserving_landscapes/index.html [Accessed on: November 29, 2004], 2004.

Department of Statistics (DOS), "Urban Agriculture Survey." Amman, Jordan. http://www.dos.gov.jo/sdb/env/env_e/home.htm [Accessed on: June 26, 2004], 1999.

Department of Statistics (DOS), "The Preliminary Results of The Population And Housing Census." Amman, Jordan. http://www.dos.gov.jo [Accessed on: January 2, 2006], 2004.

Garcia-Alcubilla, R., and J. R. Lund, Derived willingness-to-pay for household water use with price and probabilistic supply, *Journal of Water Resources Planning and Management-Asce*, *132*, 424-433, 2006.

Griffen, R., Management of Water Losses Due to Commercial Reasons: A Study in Amman, International Water Demand Management Conference: Dead Sea, Jordan, June 2, 2004.

Grossmann, I. E., J. Viswanathan, A. Vecchietti, R. Raman, and E. Kalvelagen, DICOPT: A Discrete Continuous Optimization Package, GAMS Development Corporation, Washington, D.C., 2002.

Hanemann, W. M., Determinants of urban water use, in *Urban Water Demand Management and Planning*, edited by W. M. Hanemann, pp. 31-76, McGraw-Hill, Inc., New York, 1998.

Hewitt, J. A., and W. M. Hanemann, A Discrete-Continuous Choice Approach to Residential Water Demand under Block Rate Pricing, *Land Economics*, *71*, 173-192, 1995.

Interdisciplinary Research Consultants (IdRC), "A Survey of Home Appliances and Toilets in the Jordanian Markets." Academy for Educational Development: Water Efficiency for Public Information and Action (WEPIA) Program, Amman, Jordan, 50 pp., 2004.

Iskandarani, M., editor, Economics of Household Water Security in Jordan, Peter Lang, Frankfurt am Maim, 2002.

Jaber, J. O., and M. S. Mohsen, Evaluation of non-conventional water resources supply in Jordan, *Desalination*, *136*, 83-92, 2001.

Jordan Meteorological Department (JMD), "Rainfall." http://www.jmd.gov.jo/climate-rain.html [Accessed on: January 23, 2005], 2000.

Joench-Clausen, T., and J. Fugl, Firming up the Conceptual Basis of Integrated Water Resources Management, *International Journal of Water Resources Development*, *17*, 501-510, 2001.

Lund, J. R., Derived estimation of willingness to pay to avoid probabilistic shortage, *Water Resources Research*, *31*, 1367-1372, 1995.

Madanat, S., and F. Humplick, A Model of Household Choice of Water-Supply Systems in Developing-Countries, *Water Resources Research*, *29*, 1353-1358, 1993.

McKenzie, D., and I. Ray, Household water delivery options in urban and rural India, Working Paper No. 224, Stanford Center for International Development, Stanford, California, 2004.

Mimi, Z., and M. Smith, Statistical domestic water demand model for the west bank, *Water International*, *25*, 464-468, 2000.

Pattanayak, S. K., J.-C. Yang, D. Whittington, and K. C. B. Kumar, Coping with unreliable public water supplies: Averting expenditures by households in Kathmandu, Nepal, *Water Resources Research*, *41*, 1-11, 2005.

Scott, C. A., H. El-Haser, R. E. Hagan, and A. Hijazi, Facing Water Scarcity in Jordan: Reuse, Demand Reduction, Energy, and Transboundary Approaches to Assure Future Water Supplies, *Water International*, *28*, 209-216, 2003.

Snobar, A. H., Feasibility of Domestic Graywater Recycling. Senior Thesis. Jordan University of Science and Technology, Irbid, 2003.

Theodory, G., The willingness and ability of residential and non-residential subscribers in Greater Amman to pay more for water, PN-ACQ-616, Development Alternative, Inc., and U.S. Agency for International Development, Bethesda, Maryland, 2000.

Water Authority of Jordan (WAJ), "Res2004.xls." O. Maghrabi, personal communication, Amman, Jordan, 2006.

Water Efficiency and Public Information for Action (WEPIA), "Capacity building project in Amman, Irbid, and Aqaba." United States Agency for International Development, Amman, Jordan, 12 pp. http://pdf.dec.org/pdf_docs/PNADB469.pdf, 2001.

White, G. F., D. J. Bradley, and A. U. White, Drawers of Water, The University of Chicago Press, Chicago, IL, 1972.

Wilchfort, O., and J. R. Lund, Shortage management modeling for urban water supply systems, *Journal of Water Resources Planning and Management*, *123*, 250-258, 1997.

Wolf, A. T., and M. Murakami, Techno-political decision making for water resources development: the Jordan River watershed, *Water Resources Development*, *11*, 147-161, 1995.

Young, R. A., Determining the Economic Value of Water: Concepts and Methods, Resources for the Future, Washington, D.C., 2005

Table 4.1. Water quality associated with end uses

Drinking Water (Highest Quality)	**Other Indoor Uses** (Moderate Quality)	**Outdoor Uses** (Lowest Quality)
• Drinking • Cooking • Washing food[a]	• Bathing[a] • Cleaning[a] • Flushing toilets • Washing laundry[a] • Leaks and waste	• Irrigate landscaping • Irrigate crops • Water livestock • Wash car

a. Indicates water is available for re-use outdoors

Table 4.2. Parameters influencing initial estimates of water use and conservation action effectiveness

Parameter	Units	Low value	High value	Average	St. Dev	Distribution[1]	Reference (sample size)
Geographic							
A. Annual rainfall	mm/yr	110.0	550.0	269.7	93.5	FG	JMD, 2000 (78 years)
B. Irrigation season	weeks/year	20.0	35.0	-	-	UN	Engineering estimate
C. Network shortages	weeks/year	0.5	-	3.0	-	ED	WEPIA, 2001 (344 households)
D. Rainfall events	#/year	1.0	6.0	-	-	UN	Engineering estimate
Demographic							
E. Roof area of building	m2	100.0	-	206.1	-	ED	DOS, 1999 (1,800 households)
F. Households sharing building	#/building	1.0	-	2.7	-	ED	DOS, 2004 (383,000 households)
G. Household size	persons	3.0	-	5.1	-	ED	DOS, 2004 (383,000 households)
H. Drinking water random effects	l/event	(43.4)	19.9	(0.0)	67.1	NM	Rosenberg et al, in press (c. 28 pers.)
I. Occupancy	fraction	-	1.0	-	-	HS (3)	Calibrated
Technologic							
J. Garden area	m2	-	300.0	111.3	103.2	FG	DOS, 1999 (1,800 households)
K. Number cars	# cars	-	-	1.3	0.5	FG	WEPIA, 2001 (344 households)
L. House water pressure	bar	0.3	-	0.6	-	ED	Engineering estimate; func. of (F.)
M. Shower flow rate - current device	l/min	6.0	20.0	-	-	UN	Tawarneh, 2004 (c. 10 devices)
N. Faucet flow rate - current device	l/min	5.5	20.0	-	-	UN	Tawarneh, 2004 (c. 10 devices)
O. Toilet tank volume - current device	l/flush	5.5	15.0	-	-	HS (6)	WEPIA, 2001 (344 households)
P. Laundry water use - current device	l/kg	-	-	-	-	NM	IdRC, 2004 (c. 20 devices); func. of (AJ.)
Q. Hose diameter	inches	0.5	1.5	-	-	UN	Engineering estimate
R. Bucket size	gal	3.0	7.0	-	-	UN	Engineering estimate
S. Water use - cons. auto laundry	l/kg	6.2	-	8.3	1.4	NM	IdRC, 2004 (c. 20 devices)
Behavioral							
T. Length of shower - currernt	min	1.5	-	8.5	-	ED	Tawarneh, 2004 (c. 10 devices)
U. Shower frequency - summer	#/week	1.0	-	3.6	-	ED	Rosenberg et al, in press (c. 28 pers.)
V. Shower frequency - winter	#/week	1.0	-	0.4	-	NM	Rosenberg et al, in press (c. 28 pers.)
W. Toilet flushes	#/person/day	2.0	-	4.0	-	ED	Snobar, 2003 (30 households)
X. Flushes requiring full flush	fraction of flushes	0.3	0.7	-	-	UN	Engineering estimate
Y. Faucet use	min/day/person	0.1	-	0.6	-	ED	Snobar, 2003 (30 households)
Z. Car wash time	minutes/use	5.0	15.0	-	-	UN	WEPIA, 2001 (344 households)
AA. Car washes	washes/week	-	-	1.6	1.0	FG	WEPIA, 2001 (344 households)
AB. Irrigation frequency	#/week	0.2	-	1.7	-	ED	WEPIA, 2001 (344 households)
AC. Floor wash frequency	#/week	1.0	7.0	-	-	UN	Engineering estimate
AD. Irrigation applications	hrs/week	0.2	-	1.7	-	ED	Rosenberg et al, in press (c. 28 pers.)
AE. Bucket application to car	# buckets/car	2.0	5.0	-	-	UN	Engineering estimate
AF. Bucket application to floor	buckets/wash	1.0	-	5.0	-	ED	Engineering estimate
AG. Kitchen faucet use	min/day	1.0	-	14.4	-	ED	Snobar, 2003 (30 households)
AH. Borrow	m3/event	0.1	0.3	-	-	UN	Iskandarani, 2001 (200 households)
AI. Car wash method	(1=auto, 2=bucket, 3=hose)	1.0	3.0	1.9	-	HS (3)	WEPIA, 2001 (344 households)
AJ. Laundry wash method	(1=hand, 2=semi, 3 =auto)	1.0	3.0	2.3	-	HS (3)	WEPIA, 2001 (344 households)
AK. Laundry weight	kg/person/week	0.6	-	3.9	-	UN	Rosenberg et al, in press (c. 28 pers.)
AL. Water use - laundry rinse	fraction (wash volume)	1.5	3.0	-	-	UN	Engineering estimate
Technologic - Modifications							
AM. Shower flow rate - retrofit device	l/min	6.0	9.0	-	-	UN	Tawarneh, 2004 (c. 10 devices)
AN. Faucet flow rate - retrofit device	l/min	5.5	6.5	-	-	UN	Tawarneh, 2004 (c. 10 devices)
AO. Toilet flush rate - retrofit, full	l/flush	5.5	6.5	-	-	UN	IdRC, 2004 (c. 20 devices)
AP. Toilet flush rate - retrofit, half	l/flush	2.0	3.0	-	-	UN	Engineering estimate
AQ. House water pressure - reduced	bar	0.5	1.0	-	-	UN	Engineering estimate
AR. Irrigation rate - drip	l/hr/mister	125.0	1,080.0	-	-	UN	Engineering estimate
AS. Drip mister density	# misters/50 m2	3.0	10.0	-	-	UN	Engineering estimate
AT. Water use - cons semi-auto laundry	l/kg	3.3	-	5.1	1.5	NM	IdRC, 2004 (c. 20 devices)
AU. Drinking water treatment efficiency	fraction	0.3	0.8	-	-	UN	Rosenberg et al, in press (c. 28 pers.)
AV. Toilet bottle size	l/bottle	0.5	1.5	-	-	UN	Engineering estimate
AW. Toilet bottles installed	#	1.0	2.0	-	-	UN	Engineering estimate
Behavior Modifications							
AX. Faucet flow rate - partially open	l/min	2.0	8.0	-	-	UN	Engineering estimate
AY. Shower length -- shortened	min	1.0	6.0	-	-	UN	Engineering estimate
AZ. Shower frequency - reduced	#/week	0.5	-	0.8	-	ED	Engineering estimate
BA. Faucet wash time saved	min/person/day	0.1	-	0.5	-	ED	Engineering estimate
BB. Laundry frequency - reduced	fraction (curr. laundry)	0.1	0.5	-	-	UN	Engineering estimate
BC. Reduced irrigation time - nozzle	minutes/use	0.5	-	3.0	-	ED	Engineering estimate
BD. Reduced irrigation time - stress irr.	minutes/use	1.0	-	10.0	-	ED	Engineering estimate

1. ED = exponential decay, FG = fitted gamma, HS (x) = histogram with *x* categories, NM = normal, UN = uniform, FV = fixed value (constant)

Table 4.3. Demand response simulating piped water use for different historical rate structures

Demand curve component		A. Short-term (before conservation)			B. Long-term (with conservation)		
		1997	2001	2006	1997	2001	2006
Piped water use	(m^3 per average household per year)	152.9	152.4	151.7	101.7	100.8	99.3
Representative price	($US per m^3)	0.80	0.86	0.95	0.80	0.86	0.95
Point elasticity	(at 2001 price and use)		-0.05			-0.14	

Notes:

a. Representative price = (Total utility revenues)/(Total billed water use)

b. Long- and short-term curves plot at same representative prices

Table 4.4. Average responses to conservation efforts

Indicator	**A. Short-term** (Base Case calibration, before conservation)	**B. Long-term** (after conservaton)
Piped water use (m^3/customer/year)	152.0	100.7
Tanker truck use (m^3/customer/year)	9.2	1.5
Rainwater collected (m^3/customer/year)	0.0	4.7
Grey-water reused (m^3/customer/year)	0.0	3.9
Expenditures ($US/customer/year)	232.1	149.3
Utility revenues ($US/customer/year)	101.8	41.2

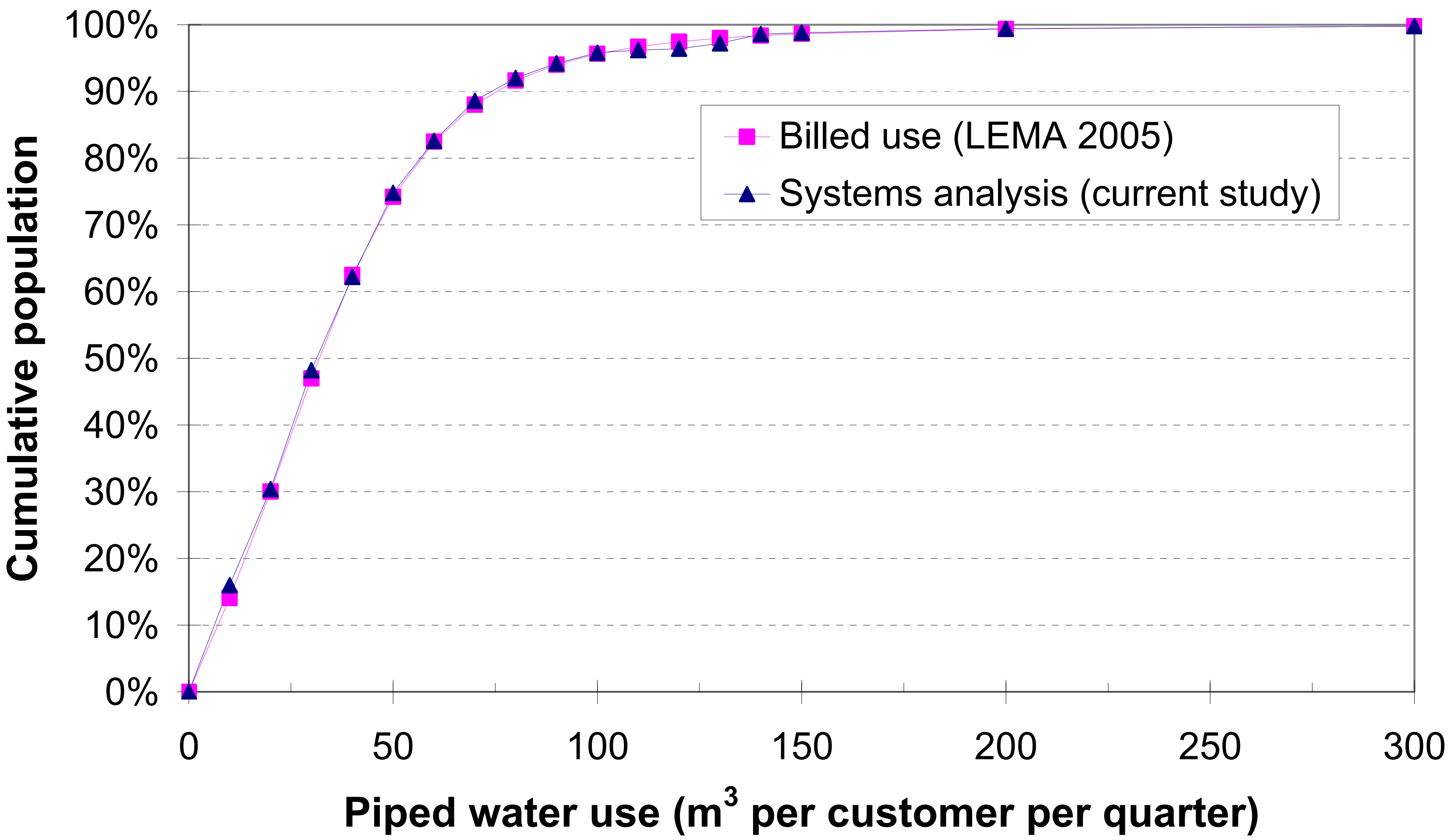


Figure 4.1. Model calibration against cumulative distribution of billed residential water use in 2005 for residential customers in Amman, Jordan

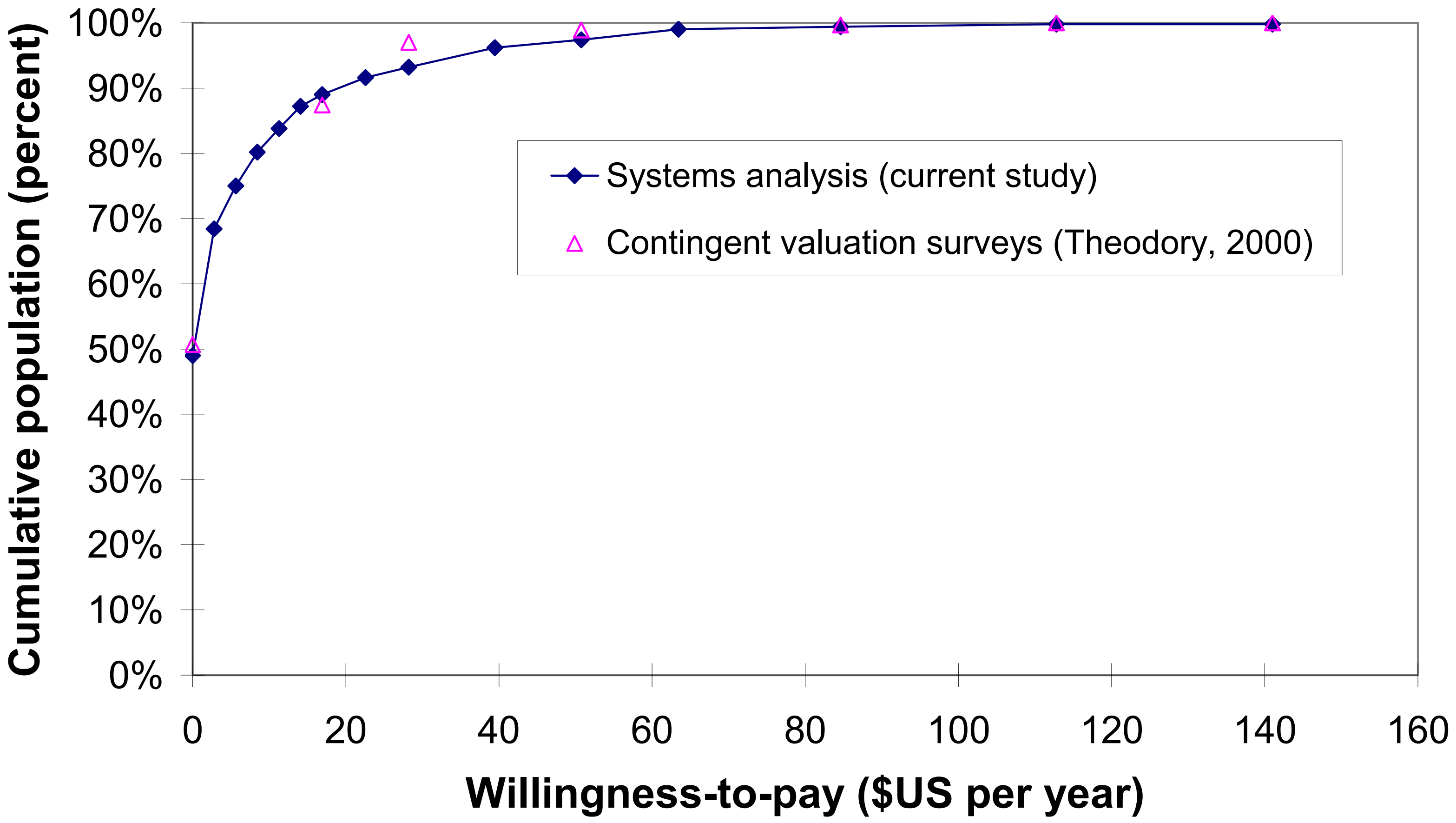


Figure 4.2. Cumulative distributions of willingness-to-pay to avoid shortage

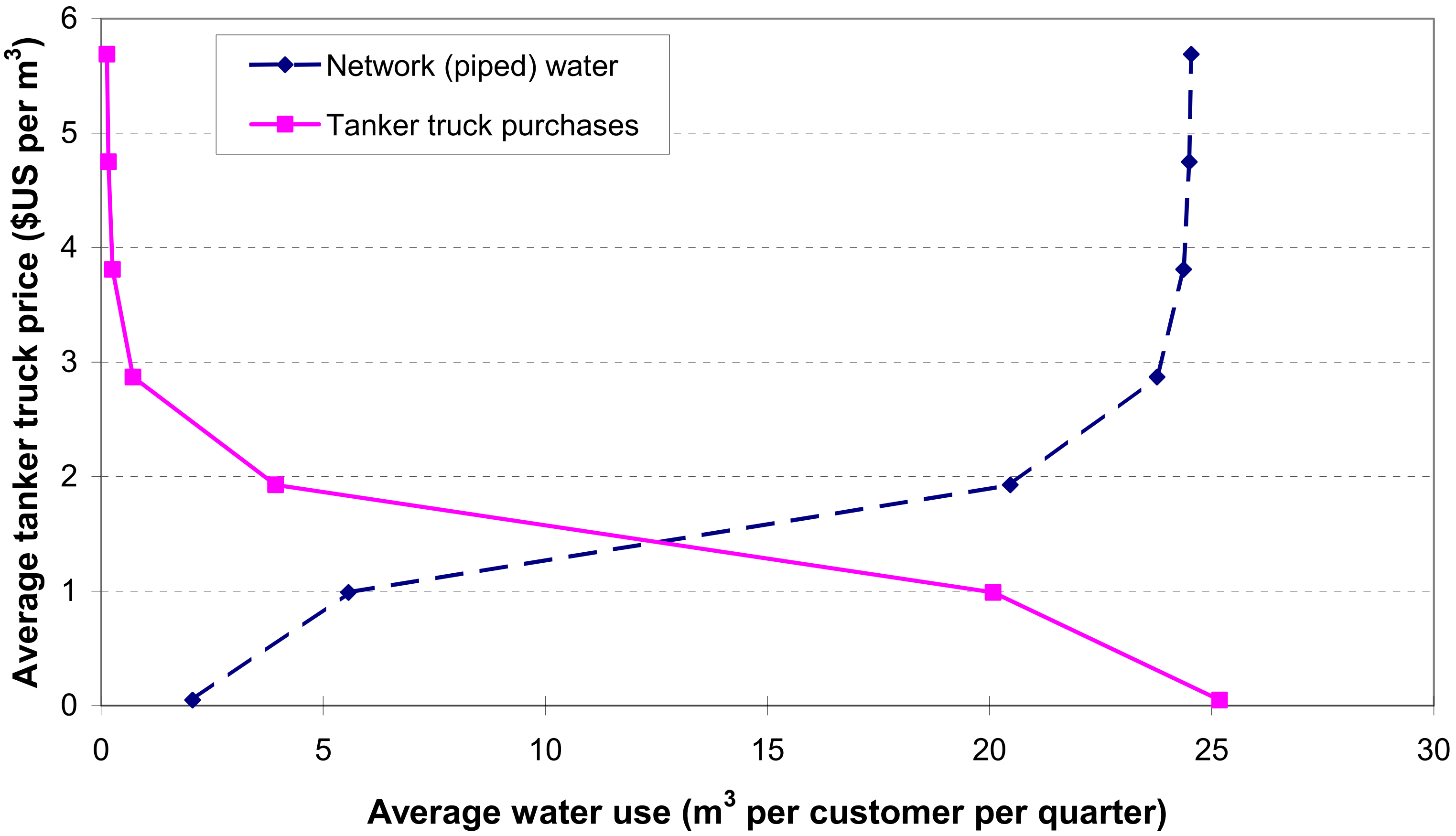


Figure 4.3. Elasticity and cross-elasticity of tanker truck water price.

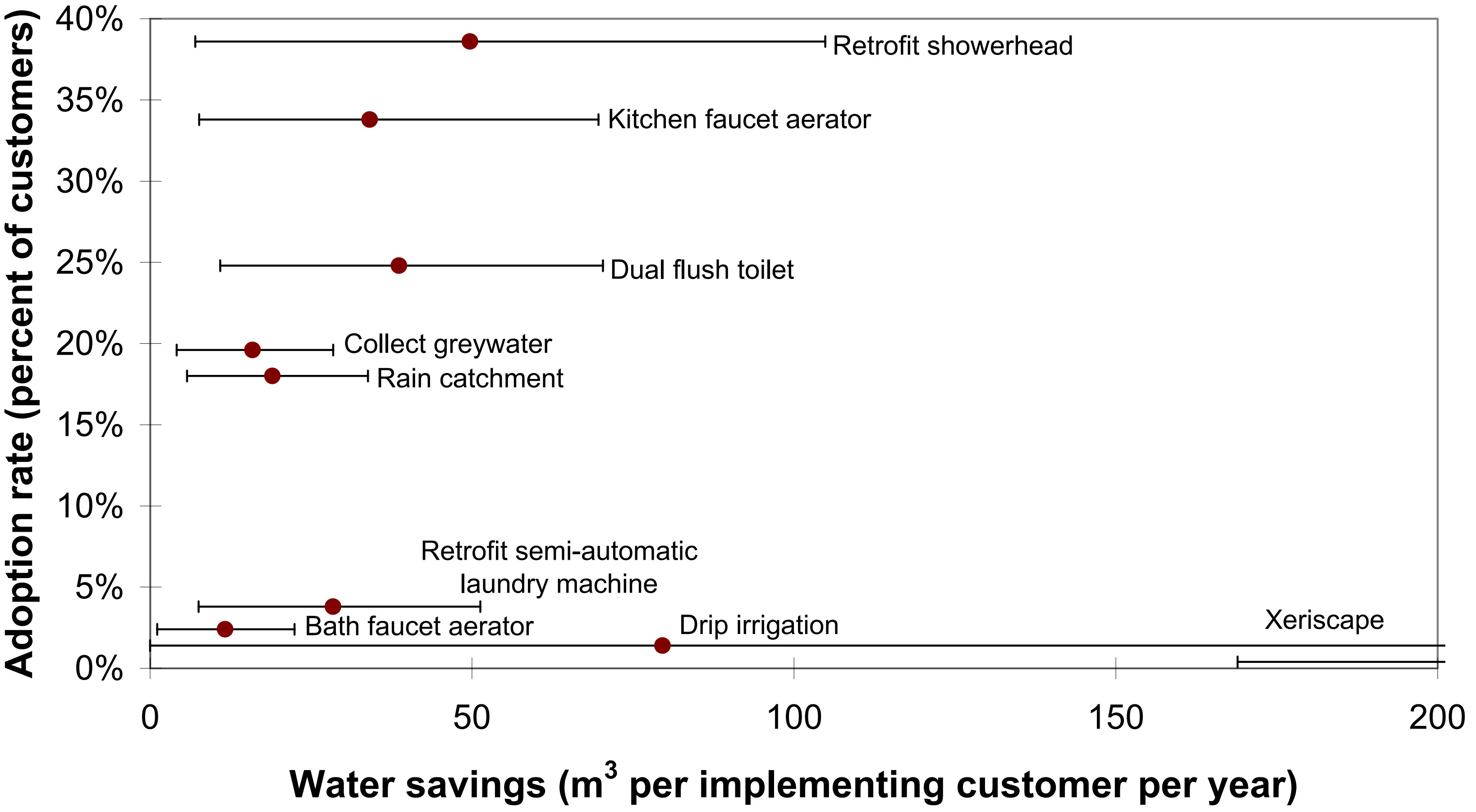


Figure 4.4. Estimated market penetration and water savings for conservation actions in Amman, Jordan. Circles show average and error bars show 10th and 90th percentiles of Monte-Carlo simulations.

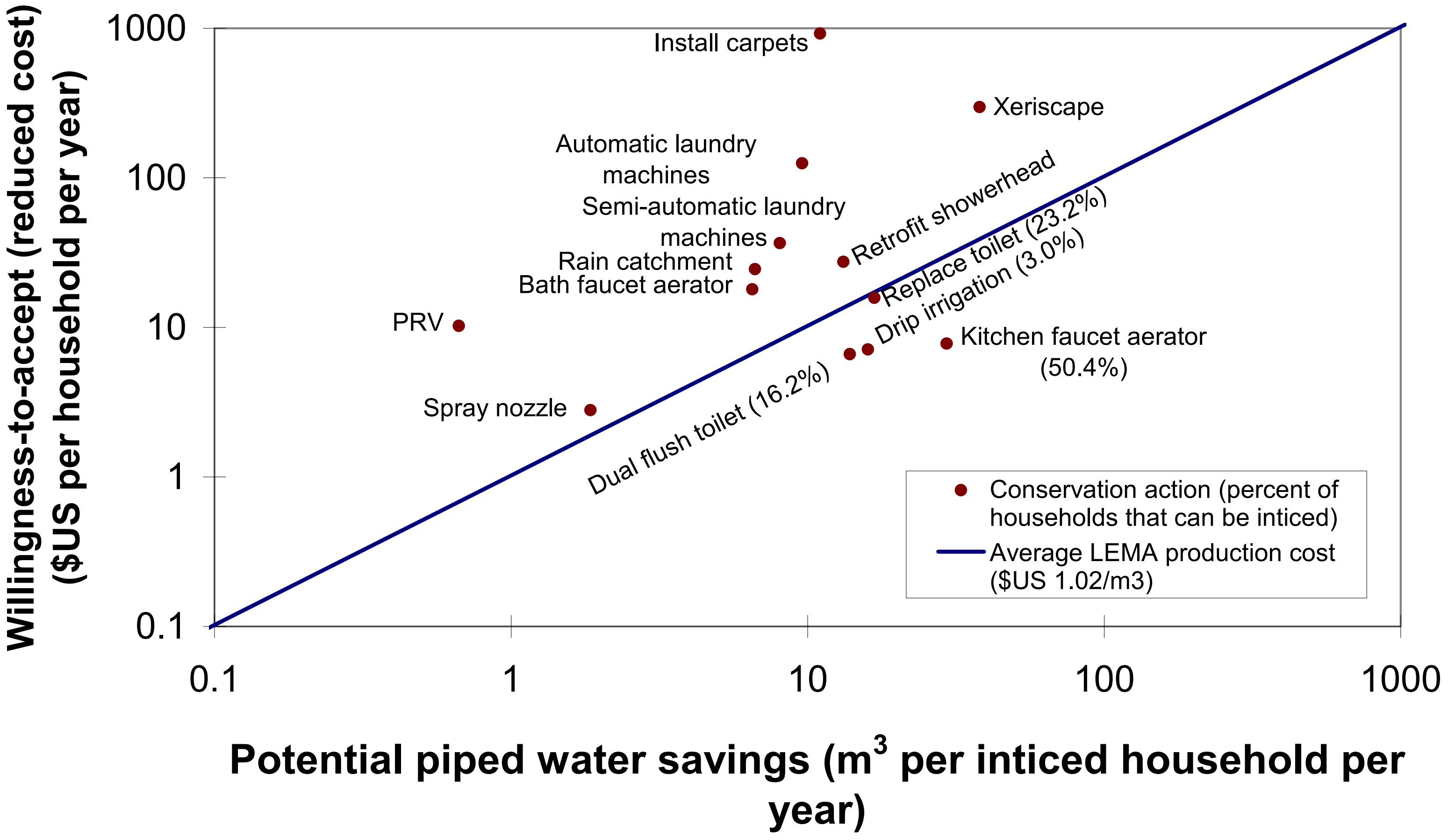


Figure 4.5. Average subsidies required to entice additional customers to install water efficient appliances. Actions below LEMA production cost curve also show fraction of households that are potentially enticed.

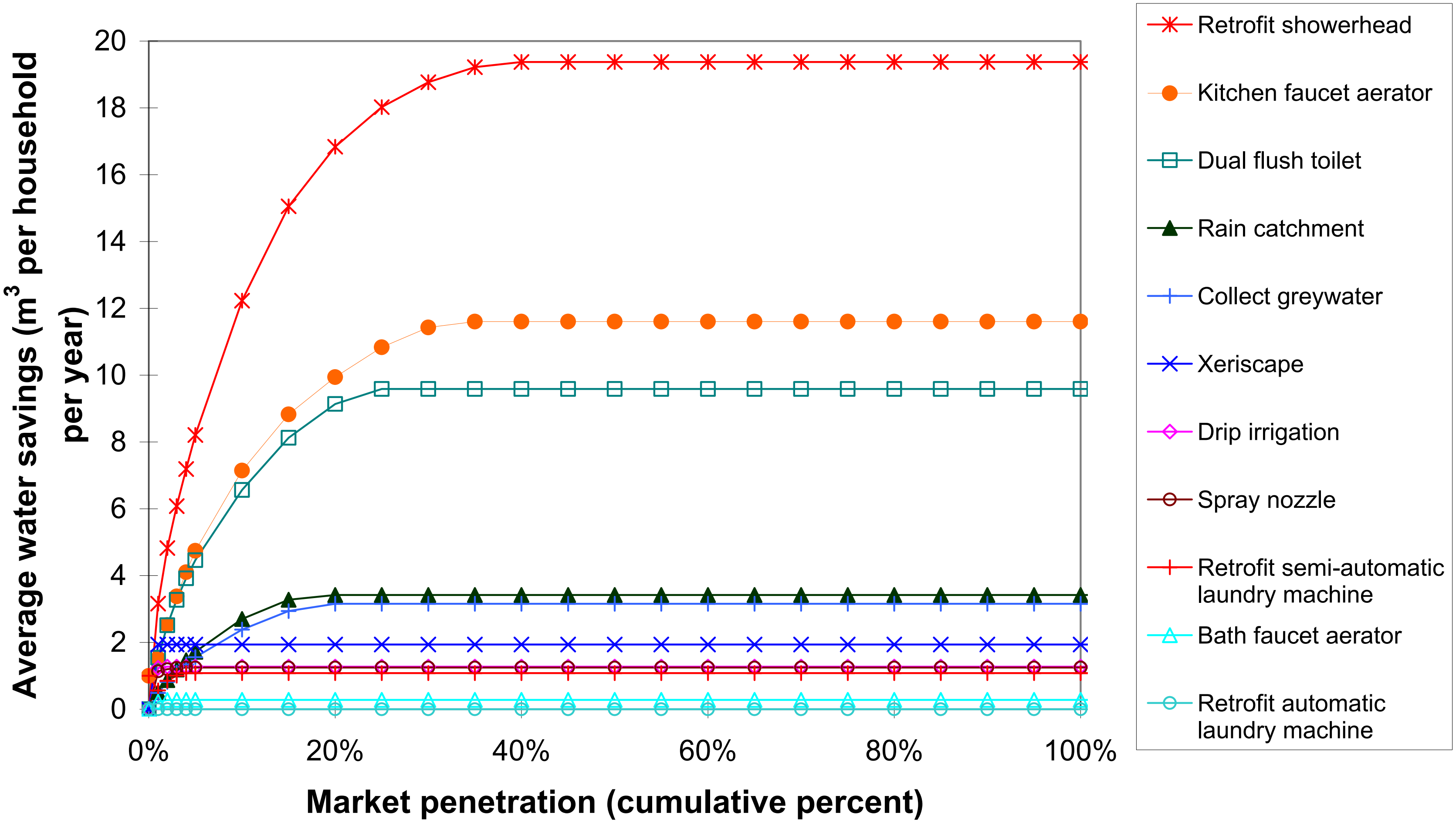


Figure 4.6. Sizing curves for water conservation programs. X-axis is ordered by customers from highest to lowest conservation action effectiveness.

Part II

Management and Modeling for a Water Utility

Chapter 5

Modeling Integrated Water Utility Decisions with Recourse and Uncertainties

Abstract – Stochastic mixed-integer optimization is used to identify a portfolio of long- and short-term supply and conservation actions for a municipal water system to cost-effectively accomodate a distribution of water shortages. Alternative robust, grey-number, and best/worst case formulations systematically explore implications of uncertainties in action costs, life spans, water volumes gained or saved, shortage levels, and shortage probabilities. A detailed example for Amman, Jordan considers 23 potential actions. Results show: (i) Remarkable consistency occurs across the different modeling approaches. (ii) Conserving water—reducing leakage and targeting select customers to install water efficient appliances—plays an important and growing role over time. (iii) A delayed need for mega supply projects like pumping the Disi aquifer. (iv) No role appears for seawater desalination (Red-Dead Canal) before 2040. (v) Desalinating brackish Zara-Ma'een water is the low-cost option to increase water availability to customers, but requires substantial capital investments. And (vi) two shortcomings arise for grey-number and best/worst case approaches.

5.1. Introduction

Uncertain surface water supplies, groundwater overdraft, rapid population growth, and sudden immigration make water shortages pressing or impending realities for Amman, Jordan and many other urban water utilities. Shortages are problematic because they often cause service disruptions that promote distrust in the utility service and force customers to seek expensive and risky alternative provisions. Disruptions also cost lost utility revenues, necessitate irregular and more expensive operations, increase the likelihood of water-borne disease outbreaks, or cause environmental degradation. Any disruption can spur public relations disasters. Planning to avoid and manage shortages is an active and expanding area of integrated water resources management (IWRM) (Jaber and Mohsen 2001; Joench-Clausen and Fugl 2001; Scott et al. 2003; Thomas and Durham 2003; Wilchfort and Lund 1997; Wolf and Murakami 1995).

Recent IWRM literature emphasizes planning that

1. Considers a wide range of potential long and short-term new supply and conservation actions,
2. Characterizes each action in terms of a financial cost, economic cost, and effective water quantity added or conserved,
3. Describes interactions among management actions,

4. Identifies events and likelihoods for which the system must deliver water, and
5. Suggests a set of actions that minimize costs to provide service through all expected events.

This approach extends traditional project evaluation such as cost-benefit analysis in two ways. First, IWRM involves stakeholders throughout the planning process—even at the beginning to identify and characterize potential actions. Second, actions are not mutually exclusive. Many actions together may more effectively meet service objectives rather than a single, best, or "magic bullet" option. For example, a utility can develop new water supplies, encourage or require customers to reduce their water use, reduce physical leakage from the distribution system, curtail accounting losses to increase revenues (Table 5.1), or combine some or all options. The utility also can initiate emergency actions (water transfers, water use restrictions, ration service, etc.) during the crisis, invest capital for new infrastructure or water use efficiency well in advance of expected shortages, or both. Selecting, combining, and timing actions while considering interactions and uncertainties are key aspects of planning decisions. Managing for multiple objectives such as costs, revenue generation, service provision, environmental regulations, social, and equity concerns should also factor into the planning.

Integrated planning to meet shortages is often done using stochastic optimization with recourse (staged programming). Recent applications include for a hypothetical household (Lund 1995), California's East Bay Municipal Utility District (Jenkins and Lund 2000; Wilchfort and Lund 1997), and residential users in California (Garcia-Alcubilla and Lund 2006). Elsewhere, stochastic optimization with recourse has seen extensive use in production planning, facilities location, capacity expansion, energy investment, environmental management, water management, agriculture, telecommunications, design of chemical processes, and finance (for reviews, see Sahinidis 2004; Sen and Higle 1999). The technique works as follows.

Decisions are partitioned into two types. Long-term (first- or primary-stage) decisions are taken before stochastic information is revealed. After the uncertain state is known, short-term (secondary- or recourse-stage) decisions are then implemented to cover the outstanding shortfall not met by long-term ones. Short-term decisions apply only to the particular state. Figure 5.1a shows the decision tree structure. For shortage management, stochastic states are shortage events with each shortage described by a shortage level (water volume) and likelihood (probability). Together, long-term actions plus sets of short-term actions for each event constitute the decision portfolio—mix of actions—to respond to the distribution of shortages.

Stochastic programs for shortage management have been exclusively formulated as deterministic-equivalent models that use singular, point values for all numerical inputs. Numerical uncertainties in model parameters (action costs, life spans, effective volume of water added or saved, etc.) are generally investigated *reactively* (after solution) using sensitivity analysis (Lund 1995), Monte-Carlo simulations (Garcia-Alcubilla and Lund 2006), or iterative simulation and optimization (Jenkins and Lund 2000). Reactive analysis requires numerous successive model runs. Yet, many *proactive* stochastic programming approaches exist to systematically include numerical uncertainties in a single, unified model formulation (Sahinidis 2004; Sen and Higle 1999). Robust optimization can minimize action or cost deviations across a variety of data scenarios (Mulvey et al. 1995). Probabilistic programming satisfies chance constraints with specified reliability. Flexible programs sometimes allow constraint violations. And possibilistic programs permit specifying model coefficients over fixed or uncertain (i.e., fuzzy) intervals. Fixed intervals are also called grey numbers (Ishibuchi and Tanaka 1990) with algorithms available to decompose stochastic grey-number formulations into two interacting deterministic-equivalent sub-models whose solutions can identify stable, feasible ranges for the objective function and decision variables (Huang et al. 1995; Huang and Loucks 2000; Li et al. 2006; Maqsood and Huang 2003). Additionally, the long-standing approach of best / worst-case analysis simply solves the deterministic-equivalent program twice for the combinations of parameter values that represent the most- and least- favorable conditions.

However, in reviewing stochastic optimization with uncertainty, Sahinidis (2004, p. 979) concludes with a “need for systematic comparison between the different modeling philosophies.” Also, our review of grey-number optimization finds a focus on model formulations and solution approaches for hypothetical examples.

Here, our three-fold objective is practical, methodological, and to extend prior household-scale shortage management work in Amman, Jordan (Chapter 2 through Chapter 4) to the utility scale. We 1) Identify cost effective ways for Amman water managers to bundle supply enhancement and conservation actions to cope with current and forecasted shortages, 2) Compare several existing approaches to incorporate uncertainties in the optimization, and 3) Show how targeting selected customers to install water efficient appliances and reduce their billed water use can fit with other utility actions potentially taken to acquire new supplies, reduce physical leakage, or curtail accounting losses. The chapter is organized as follows. Section 5.2 reviews deterministic-equivalent, robust, grey-number, and best/worst case model formulations. Section 5.3 describes the Amman, Jordan water system, potential actions, and shortages. Section 5.4 presents and discusses results. And section 5.5 concludes.

5.2. Model formulations

This section describes four approaches to incorporate uncertainties in a stochastic program with recourse. Each program identifies the water management actions that minimize a utility’s expected costs to provide water service over a range of probabilistic seasonal events, has two stages (long- and short-term decisions), and accommodates action interactions (demand hardening, supply softening) plus other physical limitations. These four approaches to incorporating uncertainties can then be compared.

The first approach is a deterministic-equivalent mixed integer program (single, point data inputs and decision outputs). It extends an existing deterministic-equivalent linear program (Wilchfort and Lund 1997) to include more management actions, integer decisions, interactions from additional conservation actions, and a constraint on reuse of treated wastewater. These extensions also address intermittent supply operations and probabilistic representations of the costs and water savings achieved when targeting select customers to install water efficient appliances (Chapter 4).

The remaining approaches attempt to systematically address uncertainties in the first model's inputs. A robust program (Mulvey et al. 1995) identifies a singular set of decision outputs over varying scenarios of data input. A grey-number program (Huang and Loucks 2000) shows feasible ranges for decision outputs using fixed lower and upper bounds on data inputs. Finally, a best / worst-case analysis solves the deterministic-equivalent program twice with parameter values that represent the most- and least-favorable conditions. Figure 5.1 shows decision trees for the first three approaches.

5.2.1. Deterministic-equivalent formulation

A deterministic equivalent of the stochastic program with recourse uses point estimates for all input parameters, including action costs, life spans, water volumes saved or gained, interaction functions, shortage event levels, and probabilities. It extends an existing formulation (Wilchfort and Lund 1997) to an intermittent supply system.

5.2.1.1. Decision Variables

Decision variables are levels of implementation for long- and short-term new supply and conservation actions. We denote L_i the implementation level of long-term action i (binary or integer) and $S_{j,s,e}$ the water supply volume added or conserved by short-term action j during season s and probabilistic shortage event e (m^3/season).

5.2.1.2. Model Formulation

A risk-neutral utility will operate for an expected value decision criteria and try to minimize the probability-weighted sum of long- and short-term water management costs subject to requirements to meet shortages during each shortage event, upper limits on long- and short-term actions, limits on water conveyed through the distribution system, and capacity for waste-water treatment and reuse. The deterministic-equivalent objective function minimizes expected annual costs, Z_1 [\$ year^{-1}],

$$\text{Minimize } Z_1 = \sum_{i=1}^{I} c_{1,i}\left(L_i\right) + \sum_{s=1}^{S}\sum_{e=1}^{E} p_e \sum_{j=1}^{J} c_{2,j,s}\left(S_{j,s,e}\right). \tag{5.1a}$$

Objective function costs include annualized costs, $c_{1,i}$ [\$ year^{-1}] for long-term actions (L_i) plus event costs, $c_{2,j,s}$ [\$ m^{-3} event^{-1}], for short-term actions ($S_{j,s,e}$) weighted by event probabilities, p_e [fraction].

Equation (5.1a) is subject to the following constraints:

- Water savings and increased supplies must meet or exceed the expected shortage level, $d_{s,e}$ [volume], for each season s of each event e,

$$\sum_{i=1}^{I} sf_{i,s,e} L_i + \sum_{j=1}^{J} \left(1 - al_j\right) \cdot S_{j,s,e} \geq d_{s,e},\ \forall s,e. \tag{5.1b}$$

Here, a savings factor, $sf_{i,s,e}$ [m^3 event^{-1}], describes water savings effectiveness for long-term conservation action *i* in season *s* and event *e.* The accounting loss indicator, al_j [fraction], takes the value of 1 when short-term action *j* contributes a financial accounting rather than actual water savings (such as retrofitting under-reporting meters or installing meters on illegal connections).

- Upper limits, $l_{max\ i}$ [integer], on long-term actions

$$L_i \leq l_{\max i},\ \forall i. \tag{5.1c}$$

- Upper limits, $s_{max\ j,s,e}$ [m^3 event^{-1}], on short-term actions given interactions, $g_{i,j}$ [fraction], with other long-term actions,

$$S_{j,s,e} \leq s_{\max j,s,e} + \sum_{i=1}^{I} g_{i,j} sf_{i,s,e} L_i,\ \forall j,s,e. \tag{5.1d}$$

A positive interaction ($g_{i,j} > 0$) increases the effectiveness of short-term action *j* when long-term action *i* is implemented (supply enhancement). Conversely for negative *g* (demand hardening). Use of some short-term actions requires first putting in place a long-term action. For example, delivering water with a utility-owned tanker truck requires purchasing the truck; operating new groundwater, surface water, and desalination facilities require building capacity. These interactions are represented by $g = +1$. Other short-term actions, such as detecting and repairing network leaks, restricting outdoor water use, or rationing become less effective when the utility restructures the distribution system or customers install water efficient appliances or landscaping. These interactions are represented by $g < 0$. Finally, *g* is zero for short-term actions such as buying agricultural water, enhancing precipitation, renting tanker trucks, or disconnecting illegal users that have a fixed upper limit and do not interact with long-term actions.

- Mass balance on system treatment and distribution capacity. The existing system capacity in season *s* and event *e*, $CAP_{s,e}$ [m^3 event^{-1}], plus expansions by new treatment plants or primary pipelines must exceed the water supplied from the subset *m* of short-term actions that feed water into the conveyance system,

$$\sum_{m=1}^{M} S_{m,s,e} \leq CAP_{s,e} + sf_{i,s,e} L_i,\ \forall s,e, \text{and } i\text{=expand capacity.} \tag{5.1e}$$

Here, we consider one expansion step, $sf_{expand\ capacity,s,e}$ [m^3 event^{-1}]. However, when economies of scale exist, expansion increments must be integer variables with additional constraints to enforce correct ordering of implementation increments with declining costs.

- Mass balance on reuse of treated wastewater. Reuse is also limited by return flows from supplied water, treatment efficiency, and conveyance losses. Here, a treated wastewater availability factor, t_s [fraction], applies to the subset k of short-term supply enhancement actions in season s generating wastewater,

$$S_{j,s,e} \le t_s \cdot \sum_{k=1}^{K} S_{k,s,e},\ \forall s,e, \text{and}\, j = \text{reuse treated wastewater, and} \qquad (5.1\text{f})$$

- Non-negativity of decison variables,

$$L_i \ge 0,\ \forall i;\quad S_{j,e,s} \ge 0,\ \forall j,s,e\,. \qquad (5.1\text{g,h})$$

5.2.1.3. Model Discussion and Solution

The event probabilities and expected shortage levels (p_e and $d_{s,e}$) constitute a set of stochastic conditions under which the system must operate. Their values are discrete shortage levels that range from small to more severe, characterize the probability distribution of shortages, and influence the extent to which long- and short-term actions are needed. Implementing a portfolio of fixed long- and event-specific short-term supply and conservation actions allows for flexibility. Long-term actions generate new supplies or water savings during all events; short-term actions are implemented only in the events as needed. And, as shortages become severe, more (higher-cost) short-term actions are implemented.

The program can be expressed and solved as a mixed-integer linear program when the cost functions (c_1 and c_2) can be expressed as unit costs (or are concave and made piecewise linear) and the other model inputs (p_e, $sf_{i,e,s}$, $d_{s,e}$, $l_{max\ i}$, $s_{max\ j,s,e}$, $g_{i,j}$, and t_s) are represented by point values.

5.2.2. Robust formulation

At times, model inputs (i.e., c_1, c_2, p_e, $sf_{i,s}$, $d_{s,e}$, $l_{max\ i}$, $s_{max\ j,s,e}$, $g_{i,j}$, and t_s) are not known definitively. Also, it is desirable to find a single good solution over a range of situations or input values. This type of goal programming seeks a robust solution that is nearly optimal for all scenarios of input data (Mulvey et al. 1995). Typically, robust optimization penalizes the objective function for small violations of constraint(s) in one or more data scenarios. The robust formulation can also minimize cost deviations across data scenarios. Here, we focus on expected costs, exclude a penalty, but instead set the upper limit for one management action sufficiently large so that it can be implemented (when needed) to satisfy all constraints. This "action of last resort" (Tier 2 rationing here) is the most expensive action and its cost is alternatively interpreted as a penalty.

The robust optimization program is formulated from the deterministic-equivalent model (5.1) as follows: First, specify scenario-specific model constraints [Eq. (5.1b) through (5.1h)] and short-term decisions ($S_{j,s,e,d}$) for each data scenario d (1, 2, …, D). And second, weight the expected annual cost for the data scenario by the scenario likelihood, pd_d [fraction]. Parameter values for each data scenario can be specified *a priori* by the modeler, or, if individual and joint probability distributions are known for them, sampled prior to optimization. The robust optimization program is:

5.2.2.1. Decision variables

Primary stage decisions [long-term actions, L_i (integer)] do not change, but secondary stage decisions [short-term actions, $S_{j,s,e,d}$ (m^3/season)] expand to consider the water volume in each season *s*, event *e*, and data scenario *d*.

5.2.2.2. Model formulation

The risk-neutral utility will minimize its expected long- and short-term water management costs over all seasons, events, and data scenarios. The robust objective function, Z_2 [\$ year^{-1}], is:

$$\text{Minimize } Z_2 = \sum_{d=1}^{D} pd_d \cdot \left[\sum_{i=1}^{I} c_{1,i,d}\left(L_i\right) + \sum_{s=1}^{S} \sum_{e=1}^{E} p_{e,d} \sum_{j=1}^{J} c_{2,j,s,d}\left(S_{j,s,e,d}\right) \right]. \qquad (5.2a)$$

Subject to:

$$\sum_{i=1}^{I} sf_{i,s,e,d} L_i + \sum_{j=1}^{J} \left(1 - al_j\right) \cdot S_{j,s,e,d} \geq d_{s,e,d}, \ \forall s,e,d, \qquad (5.2b)$$

$$L_i \leq l_{\max i,d}, \ \forall i,d, \qquad (5.2c)$$

$$S_{j,s,e,d} \leq s_{\max j,s,e,d} + \sum_{i=1}^{I} g_{i,j,d} sf_{i,s,e,d} L_i, \ \forall j,s,e,d, \qquad (5.2d)$$

$$\sum_{m=1}^{M} S_{m,s,e,d} \leq CAP_{s,e} + sf_{i,s,e,d} L_i, \ \forall s,e,d, \text{where } i = \text{expand capacity}, \qquad (5.2e)$$

$$S_{j,s,e,d} \leq t_{s,d} \cdot \sum_{k=1}^{K} S_{k,s,e,d}, \ \forall s,e,d, \text{where } j = \text{reuse treated wastewater, and} \qquad (5.2f)$$

$$L_i \geq 0, \ \forall i; \quad S_{j,e,s,d} \geq 0, \ \forall j,s,e,d. \qquad (5.2g,h)$$

Here, parameters $c_{1,d}$, $c_{2,j,s,d}$, $p_{e,d}$, $sf_{i,s,e,d}$, $d_{s,e,d}$, $l_{\max i,d}$, $s_{\max j,s,e,d}$, $g_{i,j,d}$, and $t_{s,d}$ have the same meaning as in model (5.1) but take different values for each scenario *d*. Similarly, constraints to meet each shortage level (5.2b), upper limits for long- and short-term actions [Eqs. (5.2) and(5.2d)], distribution system capacity (5.2e), reuse of treated wastewater (5.2f), and non-negativity for short-term actions (5.2h) expand to cover each scenario *d*.

5.2.2.3. Model discussion and solution

The robust model is similar to the deterministic-equivalent model except that it optimizes over a set of equally-weighted data scenarios. The modeler chooses the number of data scenarios, *D* (integer), to balance uncertainty enumeration and available computing resources. Larger *D* generates more short-term decision variables, constraints, and solution effort. However, each input for each data scenario is a point value; robust model (5.2) is solved as a mixed integer program.

The robust solution will consist of a single set of long-term actions, L_i (integer), and sets of short-term actions, $S_{j,e,s,d}$ (m^3/season), for each season, event, and data scenario. Often, it may help to summarize the numerous outputs by the number of data scenarios where a short-term-action is implemented, the average, or distribution of implementation levels or costs. Data presentation should depend on informational needs.

5.2.3. Grey-number formulation

The grey-number formulation incorporates numerical uncertainties when parameter values are expressed as intervals; its solution identifies feasible, stable ranges for the objective function and decision variables. These ranges are then used to select decision alternatives and contrast with point solution values identified by the deterministic-equivalent and robust approaches.

Grey numbers take values between fixed lower and upper bounds but with unknown distributions (i.e., $W^{\pm} \in \left[W^{-}, W^{+}\right]$ or $W^{-} \leq W^{\pm} \leq W^{+}$, also called interval numbers) and have well described mathematical properties and use in optimization (Huang et al. 1994; Huang et al. 1995; Ishibuchi and Tanaka 1990), including stochastic linear optimization programs with recourse (Huang and Loucks 2000; Maqsood and Huang 2003). We follow Haung and Loucks' (2000) solution algorithm.

5.2.3.1. Model formulation and solution algorithm

First, we substitute a grey number for each uncertain parameter ($c_1^{\pm}$, $c_{2,j,s}^{\pm}$, $sf_{i,s,e}^{\pm}$, $d_{s,e}^{\pm}$, $s_{max\,j,s,e}^{\pm}$, $g_{i,j}^{\pm}$, and $t_s^{\pm}$). These substitutions turn the objective function ($Z_3^{\pm}$) and all decision variables ($L_i^{\pm}$ and $S_{j,s,e}^{\pm}$) grey and yield a grey optimization model (5.3).

$$\text{Minimize } Z_3^{\pm} = \sum_{i=1}^{I} c_{1,i}^{\pm}\left(L_i^{\pm}\right) + \sum_{s=1}^{S}\sum_{e=1}^{E} p_e \sum_{j=1}^{J} c_{2,j,s}^{\pm}\left(S_{j,s,e}^{\pm}\right) \tag{5.3}$$

Subject to

$$\sum_{i=1}^{I} sf_{i,s,e}^{\pm} L_i^{\pm} + \sum_{j=1}^{J}\left(1 - al_j\right) \cdot S_{j,s,e}^{\pm} \geq d_{s,e}^{\pm}, \ \forall s,e. \tag{5.3b}$$

$$L_i^{\pm} \leq l_{\max i}, \ \forall i. \tag{5.3c}$$

$$S_{j,s,e}^{\pm} \leq s_{\max j,s,e}^{\pm} + \sum_{i=1}^{I} g_{i,j}^{\pm} sf_{i,s,e}^{\pm} L_i^{\pm}, \ \forall j,s,e. \tag{5.3d}$$

$$\sum_{m=1}^{M} S_{m,s,e}^{\pm} \leq CAP_{s,e} + sf_{i,s,e}^{\pm} L_i^{\pm}, \ \forall s,e, \text{ where } i = \text{expand capacity}, \tag{5.3e}$$

$$S^{\pm}_{j,s,e} \leq t^{\pm}_{s} \cdot \sum_{k=1}^{K} S^{\pm}_{k,s,e},\ \forall s,e,\ \text{where } j = \text{reuse treated wastewater, and} \quad (5.3f)$$

$$L^{\pm}_{i} \geq 0,\ \forall i;\quad S^{\pm}_{j,s,e} \geq 0,\ \forall j,s,e. \quad (5.3g,h)$$

Here, $Z_3^{\pm}$ ($/year) is the uncertain grey objective function with lower- and upper bounds, respectively, Z_3^- and Z_3^+; similarly for the other decision variables and parameters.

We solve grey optimization model (5.3) by decomposing it into two deterministic sub-models. The two sub-models correspond to the lower and upper bounds of the grey objective-function and interact. With cost-minimization, uncertain long-term decisions ($L_i^{\pm}$) are identified by first solving the lower-bound sub-model. Then, the determined long-term action levels (L_i^{*}) are used to solve the upper-bound sub-model for short-term action upper limits. Decomposition and solution requires three steps.

Step 1. Set up and solve the sub-model to identify the objective function lower bound, Z_3^-. Use parameter values that lower expenditures on and the need for long- and short-term actions ($L_i^{\pm}$ and $S_{j.s.e}^-$) [i.e., small capital and operational costs (c_1^- and c_2^-), large water savings when adopting long-term conservation actions (sf^+), small shortage levels (d^-), large upper limits for short-term actions (s_{max}^+), interactions that increase upper limits of short term actions (g^+), and large treated wastewater availability for reuse (t^+)]. The program solves for long-term decision levels ($L_i^{\pm}$) since these values influence the objective function positively or negatively depending on recourse (short-term) decisions. The lower-bound sub-model is:

$$\text{Minimize } Z_3^- = \sum_{i=1}^{I} c_{1,i}^-\left(L_i^{\pm}\right) + \sum_{s=1}^{S}\sum_{e=1}^{E} p_e \sum_{j=1}^{J} c_{2,j,s}^-\left(S^-_{j,s,e}\right) \quad (5.4a)$$

Subject to

$$\sum_{i=1}^{I} sf^{+}_{i,s,e} L^{\pm}_{i} + \sum_{j=1}^{J}\left(1-al_j\right)\cdot S^{-}_{j,s,e} \geq d^{-}_{s,e},\ \forall s,e. \quad (5.4b)$$

$$L^{\pm}_{i} \leq l_{\max i},\ \forall i. \quad (5.4c)$$

$$S^{-}_{j,s,e} \leq s^{+}_{\max j,s,e} + \sum_{i=1}^{I} g^{+}_{i,j} sf^{+}_{i,s,e} L^{\pm}_{i},\ \forall j,s,e. \quad (5.4d)$$

$$\sum_{m=1}^{M} S^{-}_{m,s,e} \leq CAP_{s,e} + sf^{+}_{i,s,e} L^{\pm}_{i},\ \forall s,e, \text{where } i = \text{expand capacity,} \quad (5.4e)$$

$$S^{-}_{j,s,e} \leq t^{+}_{s} \cdot \sum_{k=1}^{K} S^{-}_{k,s,e},\ \forall s,e,\ \text{where } j = \text{reuse treated wastewater, and} \quad (5.4f)$$

$$L^{\pm}_{i} \geq 0,\ \forall i;\quad S^{-}_{j,s,e} \geq 0,\ \forall j,s,e. \quad (5.4g,h)$$

Lower-bound sub-model (5.4) has point numerical inputs and is solved as a deterministic mixed integer program. The solution identifies optimal long-term actions (L_i^*) and short-term action levels ($S_{j.s.e}^-$) that minimize cost under favorable economic conditions. Long-term levels become inputs to the upper-bound sub-model.

Step 2. Set up and solve the upper bound sub-model to identify Z_3^+. Use objective function coefficients and constraint values that require large expenditures and increase the need for short-term actions ($S_{j.s.e}^+$) [i.e., large capital and operational costs (c_1^+ and c_2^+), small water savings when adopting long-term conservation actions (sf^-), large shortage levels (d^+), small upper limits for short-term actions (s_{max}^-), interactions that decrease upper limits of short term actions (g^-), and small treated wastewater availability for reuse (t^-)]. The upper-bound sub-model excludes constraints (c) and (g) as long-term decisions (L_i^*) were previously fixed. The sole decisions are short-term action levels ($S_{j,s,e}^+$) that minimize expenditures with unfavorable economic conditions. The upper-bound sub-model is:

$$\text{Minimize } Z_3^+ = \sum_{i=1}^{I} c_{1,i}^+ \left(L_i^*\right) + \sum_{s=1}^{S} \sum_{e=1}^{E} p_e \sum_{j=1}^{J} c_{2,j,s}^+ \left(S_{j,s,e}^+\right) \tag{5.5a}$$

Subject to

$$\sum_{i=1}^{I} sf_{i,s,e}^- L_i^* + \sum_{j=1}^{J} \left(1 - al_j\right) \cdot S_{j,s,e}^+ \geq d_{s,e}^+, \ \forall s, e \,. \tag{5.5b}$$

$$S_{j,s,e}^+ \leq s_{\max j,s,e}^- + \sum_{i=1}^{I} g_{i,j}^- sf_{i,s,e}^- L_i^*, \ \forall j, s, e \,. \tag{5.5d}$$

$$\sum_{m=1}^{M} S_{m,s,e}^+ \leq CAP_{s,e} + sf_{i,s,e}^- L_i^*, \ \forall s, e, \text{where } i = \text{expand capacity,} \tag{5.5e}$$

$$S_{j,s,e}^+ \leq t_s^- \cdot \sum_{k=1}^{K} S_{k,s,e}^+, \ \forall s, e, \ \text{where } j = \text{reuse treated wastewater, and} \tag{5.5f}$$

$$S_{j,s,e}^+ \geq S_{j,s,e}^-, \ \forall j, s, e \,. \tag{5.5h}$$

Upper-bound sub-model (5.5) also has point numerical inputs and is solved as before.

Step 3. Solutions to sub-models (5.4) and (5.5) span stable, feasible ranges for the objective function and decision variables. These ranges are $Z_{3\ opt}^{\pm} = [Z_3^-, Z_3^+]$, L_i^*, and $S^{\pm}_{j,s,e\ opt} = [S^-_{j,s,e}, S^+_{j,s,e}]$ where Z_3^-, L_i^*, and $S^-_{j,s,e}$ are solutions to lower-bound sub-model (4) and Z_3^+ and $S^+_{j,s,e}$ are solutions to upper-bound sub-model (5.5).

5.2.3.2. *Discussion*

Grey number optimization incorporates parameter intervals directly in the model formulation. Decomposing and solving the two interacting deterministic sub-models requires minimal computational effort and identifies stable, feasible ranges for the objective function and short-term decisions. Decision makers can then select short-term action levels within the feasible ranges to develop policy alternatives.

5.2.4. Best / worst-case formulation

Best / worst-case analysis has a long history of use in optimization to help judge a system's capability to realize a desired goal. It solves a deterministic-equivalent program twice for the combinations of parameter values that represent the most- (best) and least- (worst) favorable conditions. This formulation nearly resembles the grey-number approach minus interaction among the sub-models. In a cost minimization application, the best case is identical to the lower-bound grey-number sub-model(5.4). The worst case modifies the upper-bound sub-model (5.5) to (i) allow separate long-term decisions for the worst case (L_i^+) and (ii) relax lower-limits on short-term decisions.

$$\text{Minimize } Z_3^+ = \sum_{i=1}^{I} c_{1,i}^+ \left(L_i^+\right) + \sum_{s=1}^{S}\sum_{e=1}^{E} p_e \sum_{j=1}^{J} c_{2,j,s}^+ \left(S_{j,s,e}^+\right) \tag{5.6a}$$

Subject to

$$\sum_{i=1}^{I} sf_{i,s,e}^- L_i^+ + \sum_{j=1}^{J} \left(1 - al_j\right) \cdot S_{j,s,e}^+ \ge d_{s,e}^+, \ \forall s,e. \tag{5.6b}$$

$$L_i^+ \le l_{\max i}, \ \forall i. \tag{5.6c}$$

$$S_{j,s,e}^+ \le s_{\max j,s,e}^- + \sum_{i=1}^{I} g_{i,j}^- sf_{i,s,e}^- L_i^+, \ \forall j,s,e. \tag{5.6d}$$

$$\sum_{m=1}^{M} S_{m,s,e}^+ \le CAP_{s,e} + sf_{i,s,e}^- L_i^+, \ \forall s,e, \text{where } i = \text{expand capacity}, \tag{5.6e}$$

$$S_{j,s,e}^+ \le t_s^- \cdot \sum_{k=1}^{K} S_{k,s,e}^+, \ \forall s,e, \ \text{where } j = \text{reuse treated wastewater, and} \tag{5.6f}$$

$$L_i^+ \ge 0, \ \forall i; \ S_{j,s,e}^+ \ge 0, \ \forall j,s,e. \tag{5.6g,h}$$

Here, L_i^+ [integer] and $S_{j,s,e}^+$ [m^3 $event^{-1}$] represent long- and short-term decision variable values for the worst case. Best and worst-case sub-models (5.4) and (5.6) have point numerical inputs and are solved as separate deterministic mixed integer programs.

5.2.5. Model Limitations

Limitations of stochastic linear optimization for shortage management are well described (Garcia-Alcubilla and Lund 2006; Lund 1995; Wilchfort and Lund 1997). These limitations and potential workarounds are:

1. *Expected value decisions*. In the objective function, weighting short-term action costs by event probabilities gives an expected-value, risk-neutral decision criteria. However, decision makers are generally risk-adverse. Risk aversion can be accommodated in two ways: 1) revise upward probabilities for extreme shortage events (above their hydrologic likelihood), or 2) modify the robust objective

function to minimize cost variance across data scenarios, for example,

$$\text{Minimize } Z_2{}' = \sum_{d=1}^{D}\left(Z_d - \frac{1}{D}\sum_{d=1}^{D} Z_d\right)^2 .$$

2. *Drought triggers*. Stochastic programming is a planning tool to respond to shortages of long duration and recurrent frequency. However, for systems that face occasional shortages of a few days or weeks duration (such as in the eastern United States), trigger rules may play a more critical role in optimizing shortage responses. Yet, once an event is triggered or identified, a simplified version of the stochastic program resembling upper bound sub-model (5.4) can identify the optimal mix of short-term actions to respond to the shortage event.

3. *Event independence*. The approach assumes shortage events occur independently of one-another ignoring effects of event timing or sequence. This assumption precludes actions such as groundwater banking or reservoir storage that allow temporal water transfers (i.e., from wet to dry periods). Jenkins and Lund (2000) work around this limitation by simulating different reservoir storage or re-operation policies, calculating the resulting shortage probability distributions, and then optimizing for each simulation run.

4. *Cost minimization rather than benefit maximization*. Shortage management minimizes costs subject to meeting specified shortage levels. Benefit maximization would allow answering the related and important economic question: *how much* water to allocate in a shortage? Or, to what extent should operators ration (restrict) supplies to cope with shortages? But benefits (particularly the utility water users derive from increased availability) are elusive to specify. Specification is further complicated when users value different levels of reliability, face complex price structures for municipal water, and have already adopted alternative long- and short-term strategies to cope with existing rationing. Yet, benefit maximization reduces to cost minimization when benefits are constant or linear with respect to the volume of water use.

5.3. Example Application for Amman, Jordan

We now apply the different stochastic optimization approaches to the Amman, Jordan water system. First, we summarize current system operations, introduce the shortage problem, describe potential management actions, and develop events for which the system must deliver water. Then we present and discuss results.

5.3.1. System operation and problem identification

Currently, the Amman system delivers about 133 Mm^3 per year of groundwater and imported surface water to 2.2 million persons through 360,000 residential and 40,000 non-residential connections. Figure 5.2 shows a schematic of existing and proposed supply and wastewater works. Water is generally available through the pipe network to customers for between 24 and 72 hours per week.

However, nearly 45% of deliveries is non-revenue water from real and apparent losses such as physical leaks, meter reader errors, unauthorized use (theft), or meter under-registration (Figure 5.3). Moreover, the system overdrafts local groundwater to meet existing demands, expects increased demands fueled by 2.8% annual population growth, has limited ability to tap new local supplies, faces high costs to acquire and import water from distant sources, and periodically endures droughts that diminish the availability of existing surface water supplies. Jordan has also seen several sudden and large immigration waves that coincide with regional crisis (Hussein 2000). Approximately 2 million transients passed through Jordan during the 1990-1991 Gulf War of which 400,000 became permanent residents. Many more followed the 2003 U.S. invasion of Iraq, and still others arrived in July 2006 with the Israel and Hizbollah war. New arrivals increase demand on an already stretched water supply system.

Jordan was the focus of a major regional optimization effort (Fisher et al. 2005) and has seen several efforts to reduce residential and commercial water use (Abu-Taleb and Murad 1999; Faruqui and Al-Jayyousi 2002; IdRC 2004; WEPIA 2000). But no work has systematically compared customer conservation actions with new supply or loss reduction alternatives.

An integrated modeling effort at the utility scale can help identify a cost-effective mix of new supplies and conservation actions to bridge the expected demand-supply gap. Such analysis could also confirm and justify actions the Ministry of Water and Irrigation (MWI) and Suez Lyonnaise des Eaux/Arabtech Jardaneh and Montgomery Watson (LEMA, the management contractor for the Amman system) are planning and implementing to address existing and expected shortages.

5.3.2. Potential Actions

Table 5.2 and Table 5.3 summarize 16 long-term and 7 short-term actions the utility can take to develop new supplies or reduce system use (including decreasing billed use, real losses, or apparent losses). We classify actions as either long- or short-term. Long-term actions require a one-time (and generally large) capital investment and establish infrastructure for supply or conservation. These actions must be taken well in advance of any actual water delivery or use reduction. Short-term actions can be implemented when needed. They can flexibly respond to crisis or events as they occur and do not require advance planning unless conditioned on long-term infrastructure.

Information is summarized from handwritten notes, electronic files, and paper documents taken or shared during meetings, interviews, and follow-up visits in Amman between November, 2005 and January, 2006 with more than 20 managers who work for MWI, Jordan Valley Authority (JVA), Water Authority of Jordan (WAJ), LEMA, U.S. Agency for International Development (USAID), and private consultants. In general, meetings focused on the particular action within a manager's expertise. Several times, managers identified additional actions and person(s) with whom to discuss them. Ranges listed in Table 5.2 and Table 5.3 for costs, life spans, and water quantities gained or saved represent reported lower and upper bounds for existing or planned projects or plants.

For several conservation actions (customer education and awareness program, rebates to customers to adopt conservation technologies, re-price water, and restrict outdoor water use), costs and quantities are aggregate results from a detailed integrated study of residential water use in Amman (Chapter 4). This study linked Monte-Carlo simulations of household water management choices to stochastic optimization and calibrated against the existing distribution of billed residential water use. Thus, ranges represent the 10th and 90th percentiles of estimated effectiveness and cost distributions for Amman households. Below, we review potential actions to cope with shortages.

5.3.2.1. Supply enhancement

Long term supply enhancement

Long-term actions establish water supply infrastructure, access to sources, or develop yields.

New surface water. Dams exist on nearly all of Jordan's natural streams. Here, capital costs and quantities represent small impoundments across desert wadis to recharge groundwater. The volume stored is available later by extraction through existing wells.

New local groundwater. Amman area groundwater is severely over-drafted. It is infeasible to pump additional large quantities of groundwater. Instead, reported ranges represent costs and quantities to drill, pump, and biologically treat a new well with production capacity from 10 and 50 m^3 per hour. We allow development of 5 new wells.

New distant groundwater. MWI has recently tendered proposals to pump the Disi fossil aquifer along the southern border with Saudi Arabia and convey the water more than 200 km north to Amman (El-Nasser 2005; Nuaimat and Ghazal 2006; Taha and Magiera 2003). However, this mega-project has also previously seen financial backers withdraw and criticism about the impacts on aquifer safe yield from pumping by overlying landowners—both Jordanian and Saudi. One incidental project benefit not considered here is ability to simultaneously deliver water to and alleviate scarcities in the cities of Ma'an, Karak, and Madaba along the conveyance route to Amman.

Desalinate seawater. A second mega project envisions conveying Red Sea water more than 300 km north from Aqaba to the Dead Sea. The 400-meter elevation drop between the two seas can generate hydropower to desalinate the seawater (El-Nasser 2005; Nuaimat and Ghazal 2006; Taha and Magiera 2003). Desalinated seawater (potable freshwater) would then be pumped uphill to Amman. Costs reflect current estimates to deliver potable water to Amman. These estimates exclude environmental benefits to use desalination brine waste to restore the declining Dead Sea level.

Desalinate local brackish water. A third mega project will collect brackish waters from the Mujib, Zara, and Ma'een rivers, desalinate it by reverse osmosis, and convey treated water uphill to Amman (Nuaimat and Ghazal 2006; Taha and Magiera 2003). The Zara-Ma'een project is scheduled to begin deliveries in late Summer 2006. Costs reflect recent estimates to treat and deliver potable water to Amman.

Desalinate distant brackish water. Since 2000, MWI has built more than 10 brackish water desalination plants throughout Jordan with treatment capacities ranging from 4 to 2,500 m^3 per hour. These plants convert brackish water with TDS up to 10,000 ppm into potable water by reverse osmosis (WAJ, 2005). More brackish water is available and additional plants can be built (Mohsen and Al-Jayousi 1999). Capacities and costs are for an individual plant and ranges reflect low and high values seen for existing plants. Operation costs include conveyance to Amman.

Mobile desalination units. MWI recently purchased and currently operates 3 mobile desalination units. Units sit on flatbed trucks and can treat brackish water with TDS up to 4,000 ppm by reverse osmosis. MWI could purchase additional units. Operational costs include conveyance to Amman.

Tanker trucks. LEMA currently owns 19 tanker trucks with individual capacities from 6 to 12 m^3. The trucks operate from 4 groundwater filling stations around Amman and deliver water to the storage tanks of customers who lack service through the pipe network or have exhausted storage between rationing periods. LEMA can purchase additional tanker trucks to expand capacity to flexibly deliver water to customers. The range of water quantities reflects annual deliveries recorded between 1999 and 2005. Operational costs reflect gas, personnel, maintenance, telephone, and administrative costs logged by LEMA in 2005.

Expand treatment and conveyance capacity. Imported surface water is treated at the Zai treatment plant and pumped uphill to Amman. Currently, the plant operates at its capacity of 123,000 m^3 per day and operations cost JD 0.16 / m^3 (Fisher et al. 2005, Chp. 7). The plant and pumping capacity will need expansion to import additional surface water from the Jordan Valley. Data values are from a proposal to double Zai's capacity.

Expand wastewater treatment and reuse. Expanding wastewater treatment capacity and exchanging treated wastewater for fresh surface water used by Jordan Valley farmers can increase the freshwater available to Amman. Currently, some 56% to 78% of Amman customers have sewerage and generate about 71 to 79 Mm^3 wastewater per year. Raw influent is reduced to between 50 and 51 Mm^3 per year of secondary treated wastewater at 4 plants in and around Amman (despite plant capacities totaling only 33 Mm^3 per year). Treated wastewater is released back into Jordan River tributaries and used by downstream farmers. Ranges for water quantities and costs represent an Al-Samra plant expansion, new treatment plants for Wadi Zarka and South Amman, and include wastewater treatment and conveyance losses.

Short-term supply enhancement

Short-term supply actions have an immediate and therefore flexible effect on system supply. They can be implemented when needed, in response to particular events.

Buy agricultural water. The JVA has a long-standing program to rent agricultural land from Jordan Valley farmers during drought years. The JVA solicits participants in January or February of a year. Participants take payment of between JD 800 and 1,200 per farm unit (1 farm unit = 40,000 m^2) and forgo delivery of their water allocation. Water is instead conveyed to Amman for urban use. The program operated in 1990, 2001, and 2002 and involved 320 farm units (about 6.4 Mm^3 per year). Participants either fallow their land or substitute saline shallow groundwater or polluted Jordan River water. Operational costs include payments, treatment, and conveyance to Amman.

Enhance precipitation. Pilot studies in north Jordan in the early 1990s showed that seeding clouds with silver iodide or dry ice to enhance ice particle nucleation and rainfall had the potential to increase existing winter surface runoff by 12% (Taha and Magiera 2003). Operation costs were estimated for airplane sorties, computers, equipment, and materials, and also include conveyance to Amman.

Rent tanker trucks. Many companies, institutions, and individual owners operate tanker trucks from private wells. LEMA can rent trucks for about JD 500 per month to flexibly expand capacity to deliver water to customers. The upper limit on deliveries is the same as for LEMA-owned trucks.

5.3.2.2. Conservation

Conservation actions can reduce physical losses, billed water use, or apparent losses. Reducing billed water use also reduces utility revenues whereas reducing apparent losses increases revenues but does not change the existing level of water use.

Long-term conservation

Long-term conservation actions must be taken well in advance of reductions seen in water use. These actions generally involve modifying the distribution system, water meters, or customer water use appliances.

Reduce physical losses. MWI has completed about 67% of a 5-year Capital Improvement Project to restructure the Amman water distribution system to reduce physical water loss. Improvements include dividing the network into separate pressure zones, installing bulk meters, primary tanks, and gravity fed distribution for each zone, optimizing flows, and reducing system pressure. Tests show between 18% and 35% reduction in water loss that amounts to water savings between 24 and 46 Mm^3 per year.

Targeted water conservation program. Detailed modeling of Amman residential water customer behaviors showed that targeting specific customers to install water efficient appliances can reduce aggregate residential water use nearly 33% (Chapter 4). Several customers can benefit financially by installing toilet dual flush mechanisms, low-flow showerheads, faucet aerators, drip irrigation, water efficient laundry machines and landscapes, etc. The crux is to identify customers with potential to save water and money, determine which specific action(s) those customers should adopt, and find engaging ways to promote and motivate adoption. Here, we estimate capital costs for education, awareness, and administration but exclude retrofit costs based on the USAID budget for a prior Jordan water conservation program. Customers pay to install water efficient appliances and reduce their piped water charges. These avoided costs represent lost revenues or operational costs to the utility.

Rebate programs. The detailed Amman study simultaneously identified the subsidies a further subset of residential customers might require to install water efficient appliances (Chapter 4). Toilet dual flush mechanisms, kitchen faucet aerators, and drip irrigation showed large water savings for small subsidy amounts and are thus included here. Cost and water savings (Table 5.3) ranges represent the 10th and 90th percentiles for Amman households willing to accept. The work did not show piped water charges avoided by accepting customers; instead, we use the median marginal price (JD 0.5/m^3) to estimate the lost revenue or utility operation cost.

Re-price water. The detailed Amman study also showed an inelastic residential price response with elasticity estimated at between –0.025 and –0.035 (Chapter 4). This elasticity means that doubling the average charge for piped water would only reduce piped water use by about 2.5%. As a conservation program, re-pricing water may achieve small water savings. However, raising prices represents an opportunity to increase revenues and pass more production, treatment, and delivery costs onto customers. In Amman, instituting a new price schedule requires approval by parliament and is politically difficult. We include this action primarily for demonstration purposes. We estimate capital costs for publicity, accounting, and staff retraining.

Increase meter registration. Bench top tests show that “rolled” class B water meters (improperly rotated by up to 90 degrees to ease reading) under-register customer water use by 11% to 14% (Griffen 2004). Retrofitting the estimated 10% of rolled meters with any-position meters can increase registration and utility revenue but will not save water. We estimate capital costs based on an installation charge of JD 25 per meter.

Meter illegal connections. Unauthorized use (theft) is a significant (but unknown) component of apparent losses. Installing meters on illegal connections could increase utility revenues and slightly reduce use. Here, we assume metering would counteract 10% to 15% of existing apparent losses, that thieving and legitimate customers consume similar water volumes, and that thieving customers will maintain their use patterns after metering. The life span is lower (compared to increasing meter registration) since thieving customers are more likely to subvert meter installations.

Short-term conservation

Short-term conservation actions have an immediate and therefore flexible effect to reduce system water use. They can be implemented as needed, in response to events.

Reduce response time to fix leaks. Reducing the time to fix reported leaks can save significant water volumes. Given LEMA’s recent efforts in this area, we assume an annual budget of JD 1 million could mobilize savings between 5% and 10% of the current system physical leakage. Note, restructuring the distribution system will reduce spontaneous leakage and the water saved by faster leak repair.

Restrict outdoor water use. Many cities have significantly reduced water use in droughts by restricting outdoor watering (Kenny et al. 2004). In Amman, few customers have gardens or lawns, the utility has never imposed restrictions, outdoor water use is primarily to wash cars and irrigate landscaping and is a small part of aggregate water use. We use results from the detailed Amman study (Chapter 4) to set seasonal upper limits when restricting outdoor water use. Operation costs are lost revenues and reflect the range of piped water costs avoided by customers with outdoor use should restrictions become active. A customer conservation program and rebates to install drip irrigation will reduce water saved by restricting outdoor water use.

Disconnect illegal connections. Currently, LEMA employs 40 staff to visit customers with unpaid bills and disconnect those who refuse to pay (Griffen 2004). The team also uses maps and other means to identify and disconnect households with illegal connections or customers who bypass their meters. The team disconnects about 700 households per month with reported real water savings of 7 Mm^3/year and operation costs reflecting salaries and durables to support the team. However, the lasting effects are short. Disconnection may motivate a customer to make another illegal connection; the fraction of repeat offenders is unknown.

Ration service. The utility can significantly reduce customer piped water use by rationing the time water is available in the distribution system. Rationing is also an extreme form of pressure management to reduce physical leakage and apparent losses. Customers respond by using alternative sources (rainwater, grey-water, or vendors who sell water from private wells) or adopting long- and/or short-term conservation behaviors. Currently, the Amman utility rations water so it is available to customers for only 24 to 60 hours per week. Here, we divide rationing into two tiers. Tier 1 represents normal rationing with limited customer responses. In this tier, operation costs are nil (input as a very small, positive number) and the upper limit is 15% to 25% of the total system input, or the estimated untapped demand not met because of existing rationing. Tier 2 represents severe rationing that requires drastic customer responses, and is the "action of last resort". In tier 2, the upper limit is unlimited, but operation costs skyrocket to the exorbitant prices charged by private tanker trucks to customers during the most severe water shortages on record. In actuality, customers—rather than the utility—bear these costs. However, the tier 2 rationing cost should be interpreted as the "penalty" the utility incurs when it otherwise fails to balance supplies and demand.

5.3.3. Shortage Events

We develop shortage events for year 2020 from uncertain (i) surface water runoff, and (ii) forecasts of municipal water demand. Here, we use 65 years (1937 to 2002) of modeled runoff in the North Rift side wadis, Yarmouk, and Amman-Zarqa basins (Taha and Magiera 2003) to characterize the probability distribution of uncertain surface water availability to Amman. We describe uncertain demands for Amman as a uniform probability distribution between 191 and 251 Mm^3/year reflecting high and low demand forecasts reported in the Jordan water literature for 2020 (Alkhaddar et al. 2005; Al-Salihi and Himmo 2003; Fisher et al. 2005; Mohsen and Al-Jayousi 1999; Taha and Magiera 2003). In select cases, Kingdom-wide demand forecasts (all sectors) were prorated by 27% to obtain municipal sector demand and by 34.6% to obtain demand for Amman. Convoluting the difference between uncertain demand forecast, uncertain surface water availability, existing fixed groundwater availability, and the additional fixed untapped demand not met because of existing rationing gives the probability distribution of annual shortages (Appendix A). We characterize the shortage distribution using a discrete set of 6 annual shortage levels and mass probabilities to represent explicit shortage events (Table 5.4). In the modeling, we prorate each annual shortage level into seasonal volumes (summer and winter) based on average seasonal allocations to Amman reported over the past decade (WAJ, 1994-2004). We include unmet demand due to existing rationing as part of shortages (and allow it be met at no cost by tier 1 rationing) so that we can later parametrically reduce the upper limit on tier 1 rationing to study impacts on water availability.

5.3.4. Solution method

The stochastic programs were coded in the Generic Algebraic Modeling System (GAMS) and solved with BDMLP (Brooke et al. 1998). The deterministic-equivalent program used point values that were the midpoints of the ranges reported in Table 5.2 through Table 5.4. The robust program used 20 data scenarios. Each parameter value was randomly and independently sampled in GAMS from a uniform distribution between reported ranges. These ranges were also inputs for the grey-number and best/worst case formulations.

A base case used uncertain demand forecasts for year 2020. Input data was organized and managed in Excel, then written to text files read by GAMS. Optimization results were written out to Excel for post processing and visualization. Run time for all models was less than 2 minutes on a Pentium laptop.

5.4. Results and Discussion

We present base case results for 2020 and draw comparisons among the four approaches to include uncertainties (Table 5.5 and Table 5.6). Two parametric extensions also show effects of (i) increasing shortage levels to levels forecast for 2040 (Figure 5.4) and (ii) decreasing the upper limit of tier 1 rationing (Figure 5.5). Discussion highlights suggestions to expand capacity over time and increase water availability to customers. We compare these suggestions to current and planned MWI and LEMA actions and results from a prior regional optimization study (Fisher et al. 2005).

5.4.1. Base case: coping with shortages in 2020

The four modeling approaches recommend a nearly identical mix of long-term supply enhancement and conservation actions (Table 5.5). Particularly, that implementing most conservation actions combined with maximum allowable new surface and local groundwater supplies, building small plants to desalinate distant brackish waters, purchasing additional mobile desalination units, and expanding capacity at Zai to treat and convey additional surface water to Amman can forestall the mega projects (Red-Dead seawater desalination, distant Disi groundwater pumping, and desalinating the brackish Zara-Ma'een waters). Expected annual costs are consistent but large—implying, minimally, present value investments of JD 660 to 800 million to cope with shortages.

The robust and deterministic-equivalent solutions differ only in that the robust solution builds one additional plant to desalinate distant brackish waters and purchases one more mobile desalination unit. These additions constitute about JD 7 million/year difference in expected annual costs.

Expected annual costs for the deterministic-equivalent and robust solutions fall within the ranges indicated by the best / worst case analysis. However, the grey number solution does not. In fact, the upper-bound grey-number solution is JD 280 million per year—higher (worse) than the worst-case analysis! This result occurs for three reasons. First, the grey-number solution recommends a smaller program of long-term actions to reduce costs under favorable economic conditions. This program is also recommended by the best-case analysis and builds fewer plants to desalinate distant brackish water, does not purchase mobile desalination units, or implement the Capital Investment Program to curtail physical water loss. Second, the grey-number approach must implement the same reduced program of long-term actions under unfavorable conditions to maintain feasible ranges for decisions across sub-models. This sub-model interaction means the grey-number approach has fewer options to cope with larger shortfalls. It requires many additional and more costly short-term actions (see severe rationing (R2) in Table 5.6). And third, the worst-case analysis is not similarly constrained. Under unfavorable conditions, the worst-case basis for long-term actions switches to exclude many conservation actions and increase use of distant groundwater, local and distant brackish waters, and mobile desalination units. Therefore, the grey-number solution potentially incurs significant costs (above worst case estimates) to maintain a stable, feasible range of solutions.

In sum, the long-term action results highlight several important distinctions among the four approaches to consider uncertainties. First, the grey-number solution is risk prone. Second, the best / worst-case analysis can suggest conflicting—rather than systematic—responses. And third, deterministic-equivalent and robust approaches seem to offer single, coherent responses at moderate costs.

Otherwise, the four approaches recommend similar mixes of and levels for short-term actions (Table 5.6). All formulations suggest regularly disconnecting illegal users, not renting tanker trucks, and increasing levels of implementation for the other short-term actions as shortage events become more severe. They also show good agreement regarding the shadow values of constraints on Zai treatment and conveyance capacity [Eqs. (5.1e), (5.2e), and (5.3e); results not shown]. Namely, capacity (even with expansion) is still limited or nearly limited in the largest shortage events (the events that require tier 2 rationing). These results suggest that expanding Zai capacity beyond the planned upgrade can further reduce shortage costs. This expansion becomes more cost effective should more Jordan Valley surface water become available.

5.4.2. Parametric Analysis

5.4.2.1. Capacity expansion over time

Resolving the deterministic-equivalent optimization program for the shortages with uncertain demands predicted for 2040 (Al-Salihi and Himmo 2003) shows the capital investments required to accommodate future expanded shortages (Figure 5.4). Four main trends over time are apparent.

1. *Fast rising costs.* Expected annual costs rise from about JD 33 million per year through 2020 to more than JD 132 million per year in 2040. The expected annual shortage level triples whereas costs quadruple. In later years, only expensive new supply options are still available.

2. *Growing importance of conservation*. Water saved by reducing physical leakage and targeting customers to install water efficient appliances grows as demand increases. These actions show important economies of scale and significantly dampen cost trend #1 above. Investing early in water conservation makes it possible to later reap expanded savings as demand grows with little added cost.

3. *Delayed need for mega projects for new supply*. Pumping distant groundwater (Disi Conveyor) and desalinating local brackish water (Zara Ma'een) only become cost-effective options to cope with shortages in 2040.

4. *Little role for seawater desalination.* Even the worst-case analysis does not suggest building the Red-Dead Canal. Instead, a wide mix of other, less expensive options are available and should provide required water volumes and reliabilities through 2040. However, further sensitivity analysis shows that the Red-Dead Canal may become feasible should it's capital cost decrease to JD 56 million (82% to 98% reduction). This large reduction is partly related to the project's high operational costs. We can also interpret the sensitivity results to mean: build the Red-Dead Canal if the project's environmental, hydropower, and other non-Amman water supply related benefits instead justify the project costs.

5.4.2.2. Increasing water availability to customers

A second set of runs resolved the base case deterministic-equivalent formulation with a higher water demand level while parametrically decreasing the upper limit for tier 1 rationing to zero. This analysis identifies costs and actions to increase water availability to customers (Figure 5.5). We post-calculate availability by reworking the component analysis (Figure 5.3) considering the new actions to secure supplies and reduce real and apparent losses. Availability is then billed use divided by forecast number of customers.

Figure 5.5 shows expected annual costs double as availability increases from the base case level of 200 towards 260 m^3 per customer per year. Several new supplies increase availability: first the Zara-Ma'een project, later the Disi aquifer conveyor, and finally both. However, both projects are expensive. Real and accounting losses are significant and consume part of the new supplies. This shows a steep water-supply function.

5.4.3. Comparing to actions already underway and results from a prior study

MWI and LEMA will shortly open the Zara-Ma'een project to desalinate and convey nearby brackish water and have nearly completed the project to reduce physical water loss from the Amman distribution network. MWI plans to expand Zai plant capacity and is tendering proposals to build the Disi aquifer conveyor. Elsewhere, MWI and USAID are jointly tendering proposals for a second Kingdom-wide water conservation program while LEMA has aggressively pursued a physical and accounting loss reduction program. The program has reduced response time to fix reported leaks, retrofitted "rolled" meters, and metered or disconnected illegal connections.

Our results show each action is an important long-term investment for MWI and LEMA to proactively address current and future water shortages. The Zai expansion, physical and accounting water loss reduction programs, and conservation targeted to customers are urgently needed. Zara-Ma'een desalination and Disi groundwater are needed later on. The parametric results confirm that Zara-Ma'een is the low-cost option to increase availability to Amman.

Although MWI is developing plans to desalinate and convey Red Sea water via the Dead Sea, our results show this project is a less urgent and a more costly way to address shortages through 2040. Desalinating distant brackish waters, targeting conservation programs to specific customers, restructuring the network, reducing the response time to fix reported leaks, and other actions should provide sufficient water quantities at suitable reliabilities and lower costs. However, the Red-Dead Canal may merit consideration if its other non-water supply benefits justify nearly all the capital costs.

Our findings also largely affirm and expand upon results from a prior regional-scale, single-year, benefit-maximizing, deterministic optimization study for Jordan (Fisher et al. 2005, chapter 7). Namely, urgent needs to (i) expand the Zai treatment and conveyance capacity (Balqa to Amman conveyor), (ii) reduce physical water loss (intra-district leakage), and (iii) only build the Red-Dead canal should environmental and other benefits justify the capital costs. Fisher et al. (2005) show that the Zara-Ma'een and Disi mega projects can reduce scarcity costs in Amman, but do not resolve project timings. Their regional focus also show effects in other districts whereas our utility-scale focus permits including systematic effects of uncertainties and conservation actions like reducing accounting losses, targeting select customers to install water efficient appliances, and offering rebates to motivate additional installations. We leave for further study comparing these actions with other new supply and conservation actions potentially taken at the regional scale (actions like tax incentives to encourage customers to install water efficient appliances, import restrictions on water-wasting appliances, labeling water-efficient appliances, etc).

5.5. Conclusions

Stochastic programming identifies an optimal mix of long- and short-term supply enhancement and conservation actions to cost-effectively respond to a distribution of water shortages. Deterministic-equivalent, robust, grey-number, and best/worst case formulations showcase different approaches to systematically include uncertainties.

The four approaches offer remarkably similar suggestions to address shortages forecast for Amman, Jordan in 2020. Key differences are (i) the grey-number solution is risk-prone—potentially gives higher costs than the worst-case analysis, and (ii) best / worst-case analysis offers conflicting strategies. Further research should identify new grey-solution algorithms that are risk-adverse.

The results also suggest four strategies to help Amman managers cope with shortages:

1. Conserve water now. Reduce physical leakage, target awareness to select customers to install water efficient appliances, and offer rebates to motivate other customers to follow suit. Water savings should grow over time at little added cost as demand increases.

2. Delay implementing mega projects for new supplies such as desalinating the brackish Zara-Ma'een waters and pumping the Disi aquifer to later years,

3. Significantly delay desalinating seawater (Red-Dead Canal) given the availability of cheaper new supplies and alternatives to reduce billed water use, physical, and accounting losses.

4. Build the Zara-Ma'een project as the low-cost option to increase water availability to customers.

Overall, our analysis shows that shortages pose a major and growing problem in Amman. Addressing shortages will require significant capital investments. Increasing water availability to customers will require still further investments.

Appendix A. Probability Distribution of Shortages

This appendix derives the probability distribution of uncertain shortages from uncertain demand forecasts and uncertain surface water availability. It also shows how the distribution is modified slightly by constant offsets and how a finite set of shortage values and probabilities can approximate the shortage distribution.

Shortages in future year *t*, SH_t [$\text{m}^3\ \text{year}^{-1}$], occur from increases in forecasted water demand, decreases in available surface water supplies, or additional untapped demand not met because of existing rationing,

$$SH_t = (D_t - d_0) + (w_0 - W_t) + r_t \, . \tag{5.A.1}$$

Here, D_t is the uncertain water demand forecast in year *t*, d_0 is the current known demand, w_0 is the current known surface water availability, W_t is the uncertain future surface water availability in year *t*, and r_t is the known untapped demand in year *t* not met because of rationing (all have units [$\text{m}^3\ \text{year}^{-1}$]). (The capital letters *SH*, *D*, and *W* reflect notation common to the probability literature where a capital letter, i.e. *D,* means the parameter is uncertain. The lower case counterpart, i.e., *d*, refers to a particular value that the uncertain parameter may take. And $p_D(d)$ is the probability density function of *D* or the probability that *D* will take a value in the local neighborhood of *d*).

When existing surface water use and current groundwater use, g_0 [m^3 year^{-1}] meet current demand and groundwater use is fixed, Eq. (5.A.1) simplifies to

$$SH_t = D_t - W_t - g_0 + r_t\,. \tag{5.A.2}$$

The shortage is the difference of two uncertain parameters offset by constants. Therefore, shortage is uncertain and will be distributed according to the *convolution* of the uncertain parameters (Jaynes 2003, p. 677). Taking (D_t - g_0 + r_t) as the first uncertain parameter and (W_t) as the second uncertain parameter, the probability distribution for shortage is:

$$p_{SH_t}(sh) \equiv \int_{-\infty}^{\infty} p_{D_t - g_0 + r_t}(y) \cdot p_{W_t}(y - sh) \cdot dy\,. \tag{5.A.3}$$

We note that subtracting a fixed quantity from an unknown parameter is equivalent to left-shifting the domain of the unknown parameter's probability distribution, i.e., $p_{D_t - g_0 + r_t}(y - g_0 + r_t) = p_{D_t}(y)$ or equivalently $p_{D_t - g_0 + r_t}(y) = p_{D_t}(y + g_0 - r_t)$. Substituting the second expression and $x = y + g_0 - r_t$ into Eq. (5.A.3) gives

$$p_{SH_t}(sh) \equiv \int_{-\infty}^{\infty} p_{D_t}(x) \cdot p_{W_t}(x - sh - g_0 + r_t) \cdot dx\,. \tag{5.A.4}$$

Another domain substitution gives

$$p_{SH_t}(sh + g_0 - r_t) \equiv \int_{-\infty}^{\infty} p_{D_t}(x) \cdot p_{W_t}(x - sh) \cdot dx \tag{5.A.5}$$

Eq. (5.A.5) is also interpreted as the probability distribution of the difference D_t - W_t shifted by the constant offsets.

Evaluating convolution integral (5.A.5) depends on the distributions of the uncertain parameters. Chapter 3 gives analytical results for two uniform distributions, two exponential decay distributions, and an exponential decay distribution subtracted from a uniform distribution. When D_t and W_t are both normally distributed with means, respectively, μ_D and μ_W and variances, respectively, σ_D^2 and σ_W^2, their difference will also be normally distributed with mean μ_D - μ_W and variance σ_D^2 + σ_W^2. In other cases, the convolution integral can be evaluated numerically.

To develop the shortage events (shortage volumes and mass probabilities), we simply select a finite set of the shortages (sh_0, sh_1, …, sh_i), and integrate the shortage probability density function in the neighborhood of each shortage,

$$P_{sh_i} = \int_{x=b_i}^{x=b_{i+1}} p_{SH}(x) \cdot dx \approx \sum_{x_j \geq b_i}^{x_j < b_{i+1}} \frac{1}{2}\left[p_{SH}(x_{j+1}) + p_{SH}(x_j)\right] \cdot \left[x_{j+1} - x_{j+1}\right], \forall sh_i \qquad (5.A.6)$$

Here, b_i is the lower limit of integration for shortage sh_i and is also the midpoint of the previous shortage interval (i.e., $b_i = (sh_i + sh_{i-1}) / 2$), b_{i+1} is the upper limit of integration, and the right side of the approximation sign represents trapezoid rule approximation with index j denoting all points x_j within the current interval where the convolution integral was numerically evaluated. The mass probability, P_{sh_i}, is also the difference between the cumulative density function for the shortage distribution evaluated at the lower and upper limits of interval i.

5.6. References

Abu-Taleb MF, Murad MM (1999) Use of focus groups and surveys to evaluate water conservation campaign. Journal of Water Resources Planning and Management-Asce 125(2):94-99

Alkhaddar RM, Sheehy WJS, Al-Ansari N (2005) Jordan's Water Resources: Supply and Future Demand. Water International 30(3):294-303

Al-Salihi AH, Himmo SK (2003) Control and Management Study of Jordan's Water Resources. Water International 28(1):1-10

Brooke A, Kendrick D, Meeraus A et al (1998) GAMS, a user’s guide, GAMS Development Corporation, Washington, D.C.

El-Nasser H (2005), Amman, Jordan

Faruqui N, Al-Jayyousi O (2002) Greywater reuse in urban agriculture for poverty alleviation - A case study in Jordan. Water International 27(3):387-394

Fisher FM, Huber-Lee A, Amir I et al (2005) Liquid Assets: An economic approach for water management and conflict resolution in the Middle East and beyond. Resources for the Future, Washington, D.C.

Garcia-Alcubilla R, Lund JR (2006) Derived willingness-to-pay for household water use with price and probabilistic supply. Journal of Water Resources Planning and Management-Asce 132(6)

Griffen R (2004) Management of Water Losses Due to Commercial Reasons: A Study in Amman. Paper presented at the International Water Demand Management Conference, Dead Sea, Jordan, June 2 2004.

Huang GH, Baetz BW, Patry GG (1994) Grey Dynamic-Programming for Waste-Management Planning under Uncertainty. Journal of Urban Planning and Development-Asce 120(3):132-156

Huang GH, Baetz BW, Patry GG (1995) Grey Integer Programming - an Application to Waste Management Planning under Uncertainty. European Journal of Operational Research 83(3):594-620

Huang GH, Loucks DP (2000) An inexact two-stage stochastic programming model for water resources management under uncertainty. Civil Engineering and Environmental Systems 17(2):95-118

Hussein IAJ (2000) Managing water supply systems under sudden disasters: Jordan during the Gulf War (1990-1991). Water International 25(2):232-237

IdRC (2004) A Survey of Home Appliances and Toilets in the Jordanian Markets, Academy for Educational Development: Water Efficiency for Public Information and Action (WEPIA) Program, Amman, Jordan

Ishibuchi H, Tanaka H (1990) Multiobjective Programming in Optimization of the Interval Objective Function. European Journal of Operational Research 48(2):219-225

Jaber JO, Mohsen MS (2001) Evaluation of non-conventional water resources supply in Jordan. Desalination 136(1-3 SU):83-92

Jaynes ET (2003) Probability Theory: the logic of science. Cambridge University Press, Cambridge, United Kingdom

Jenkins MW, Lund JR (2000) Integrating yield and shortage management under multiple uncertainties. Journal of Water Resources Planning and Management-Asce 126(5):288-297

Joench-Clausen T, Fugl J (2001) Firming up the Conceptual Basis of Integrated Water Resources Management. International Journal of Water Resources Development 17(4):501-510

Kenny DS, Klien RA, Clark MP (2004) Use and effectiveness of municipal water restrictions during drought in Colorado. Journal of the American Water Resources Association 40(1):77-87

Li YP, Huang GH, Nie SL (2006) An interval-parameter multi-stage stochastic programming model for water resources management under uncertainty. Advances in Water Resources 29(5):776-789

Lund JR (1995) Derived estimation of willingness to pay to avoid probabilistic shortage. Water Resources Research 31(5):1367-1372

Maqsood M, Huang GH (2003) A two-stage interval-stochastic programming model for waste management under uncertainty. Journal of the Air & Waste Management Association 53(5):540-552

Mohsen MS, Al-Jayousi OR (1999) Brackish water desalination: an alternative for water supply enhancement in Jordan. Desalination 124:163-174

Mulvey JM, Vanderbei RJ, Zenios SA (1995) Robust optimization of large-scale systems. Operations Research 43(2):264-281

Nuaimat K, Ghazal M (2006) Water will be in abundance by 2020 - minister. Jordan Times, Amman

Sahinidis NV (2004) Optimization under uncertainty: state-of-the-art and opportunities. Computers & Chemical Engineering 28(6-7):971-983

Scott CA, El-Haser H, Hagan RE et al (2003) Facing Water Scarcity in Jordan: Reuse, Demand Reduction, Energy, and Transboundary Approaches to Assure Future Water Supplies. Water International 28(2):209-216

Sen S, Higle JL (1999) An introductory tutorial on stochastic linear programming models. Interfaces 29(2):33-61

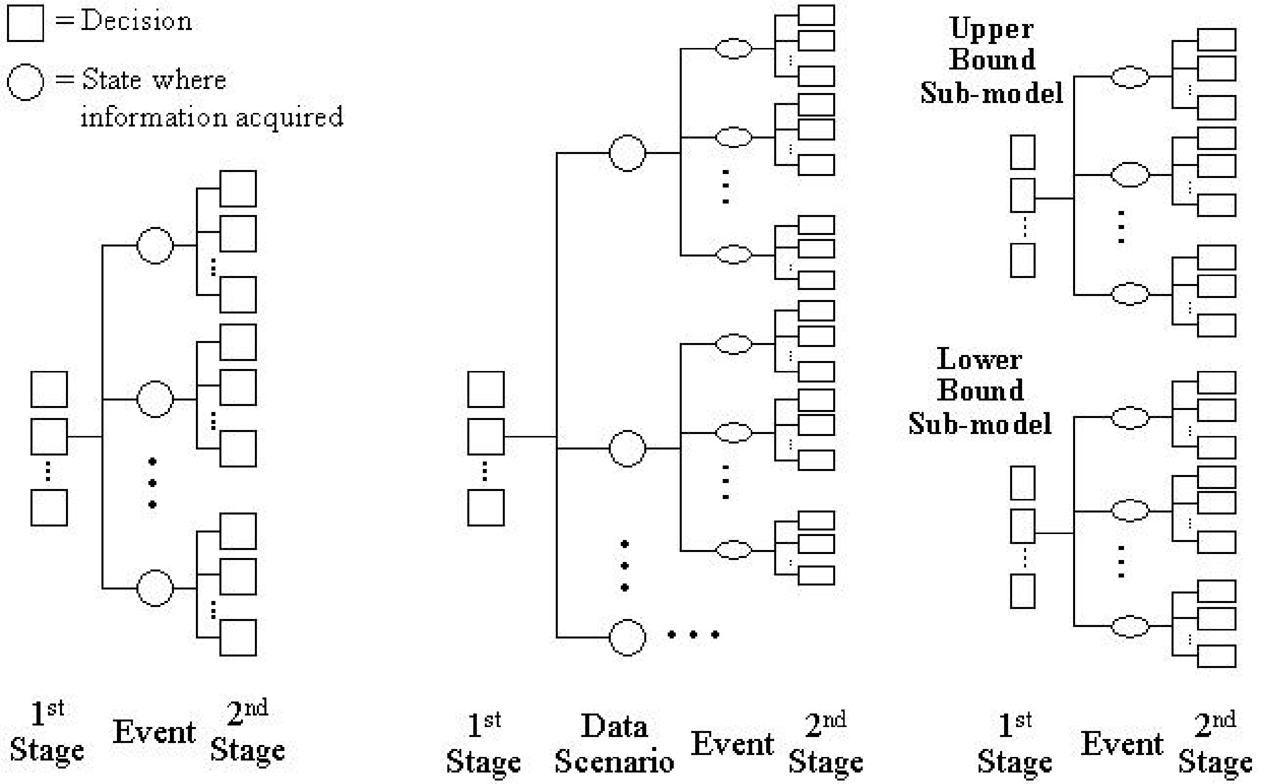
Taha S, Magiera P (2003) National Water Master Plan: Water Resources in Jordan, Ministry of Water and Irrigation, Amman, Jordan

Thomas JS, Durham B (2003) Integrated Water Resource Management: looking at the whole picture. Desalination 156(1-3):21-28

WEPIA (2000) Assessment of Water Saving Devices Sector in Jordan, Amman, Jordan

Wilchfort O, Lund JR (1997) Shortage management modeling for urban water supply systems. Journal of Water Resources Planning and Management 123(4):250-258

Wolf AT, Murakami M (1995) Techno-political decision making for water resources development: the Jordan River watershed. Water Resources Development 11(2):147-161



A. Deterministic Formulation

B. Robust Formulation

C. Grey Number Formulation

Figure 5.1. Decision trees for stochastic programs with recourse

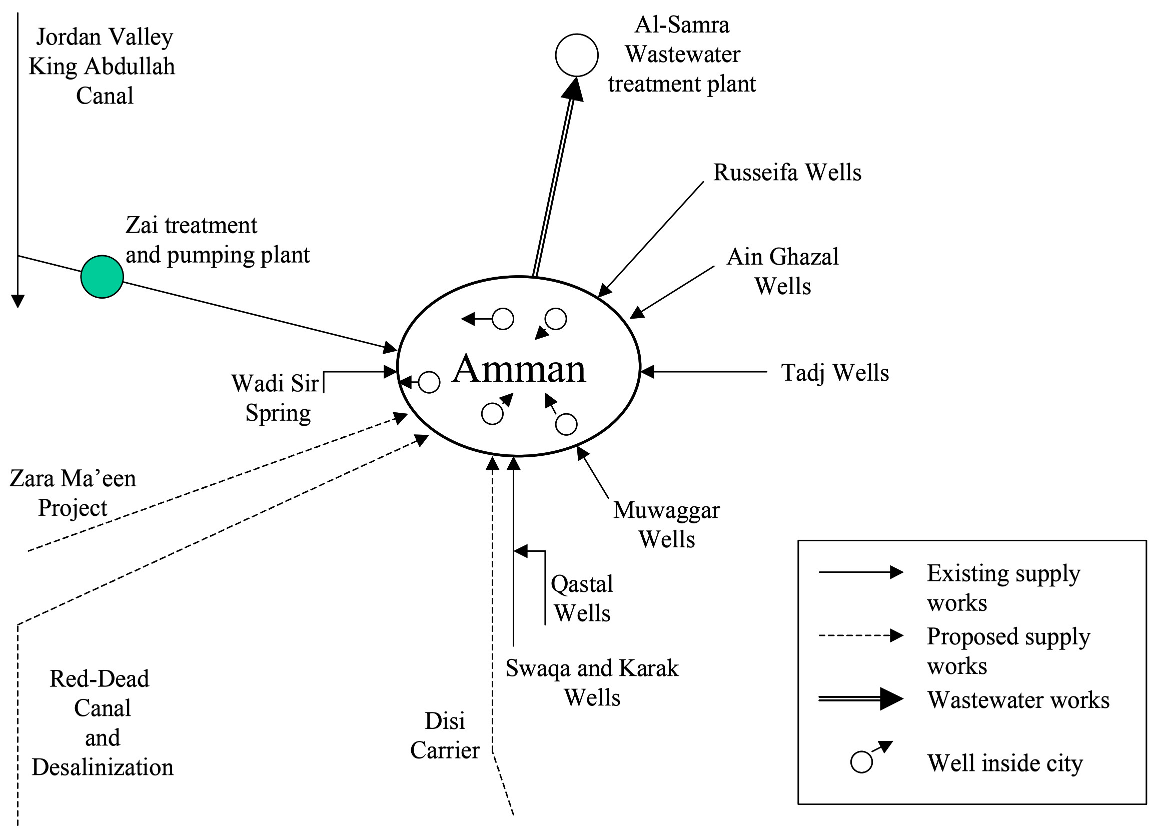


Figure 5.2. Schematic of existing and proposed main water supply and wastewater works for Amman

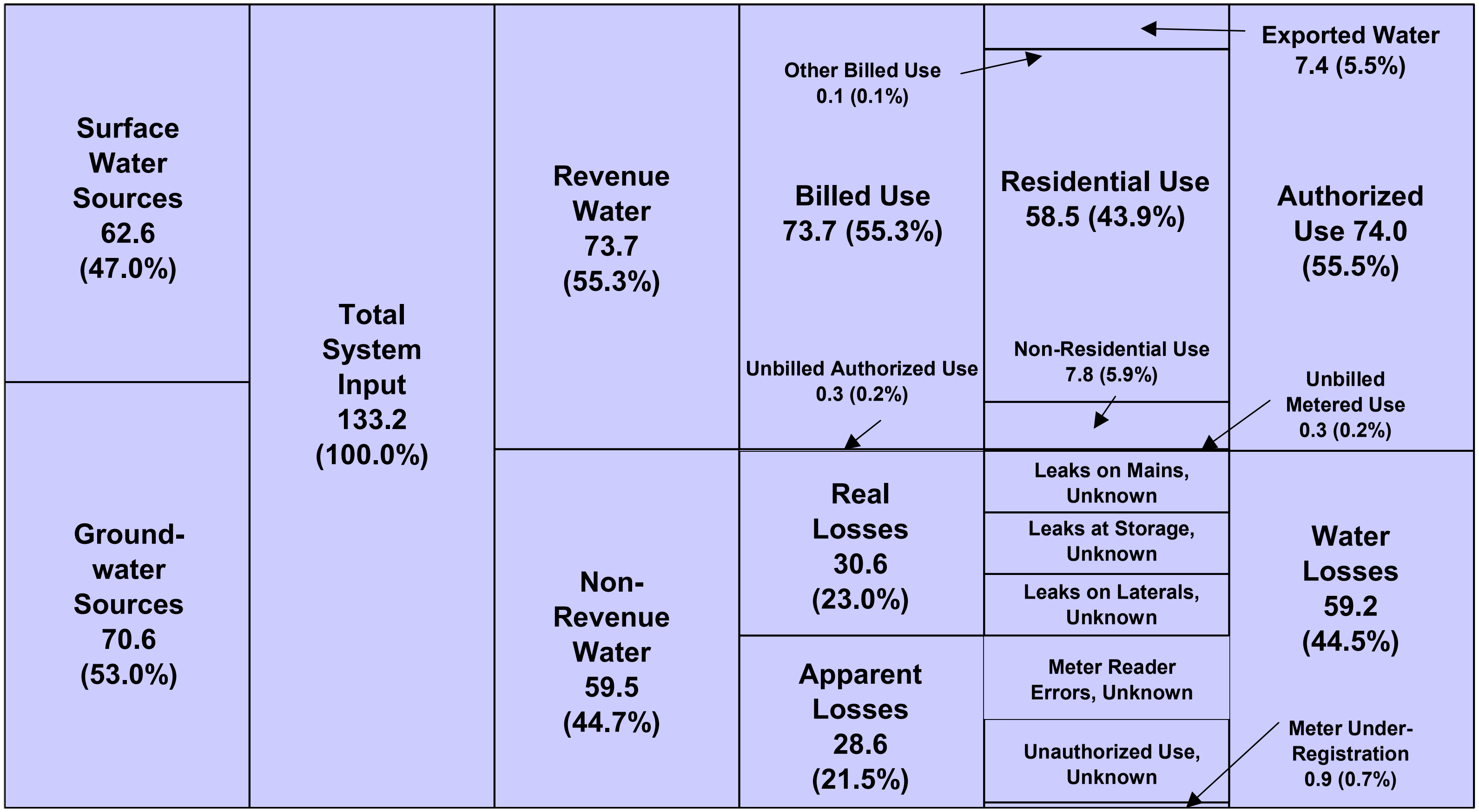


Figure 5.3. Component analysis for Amman, Jordan water system in 2005. Mm^3 per year (% of total system input)

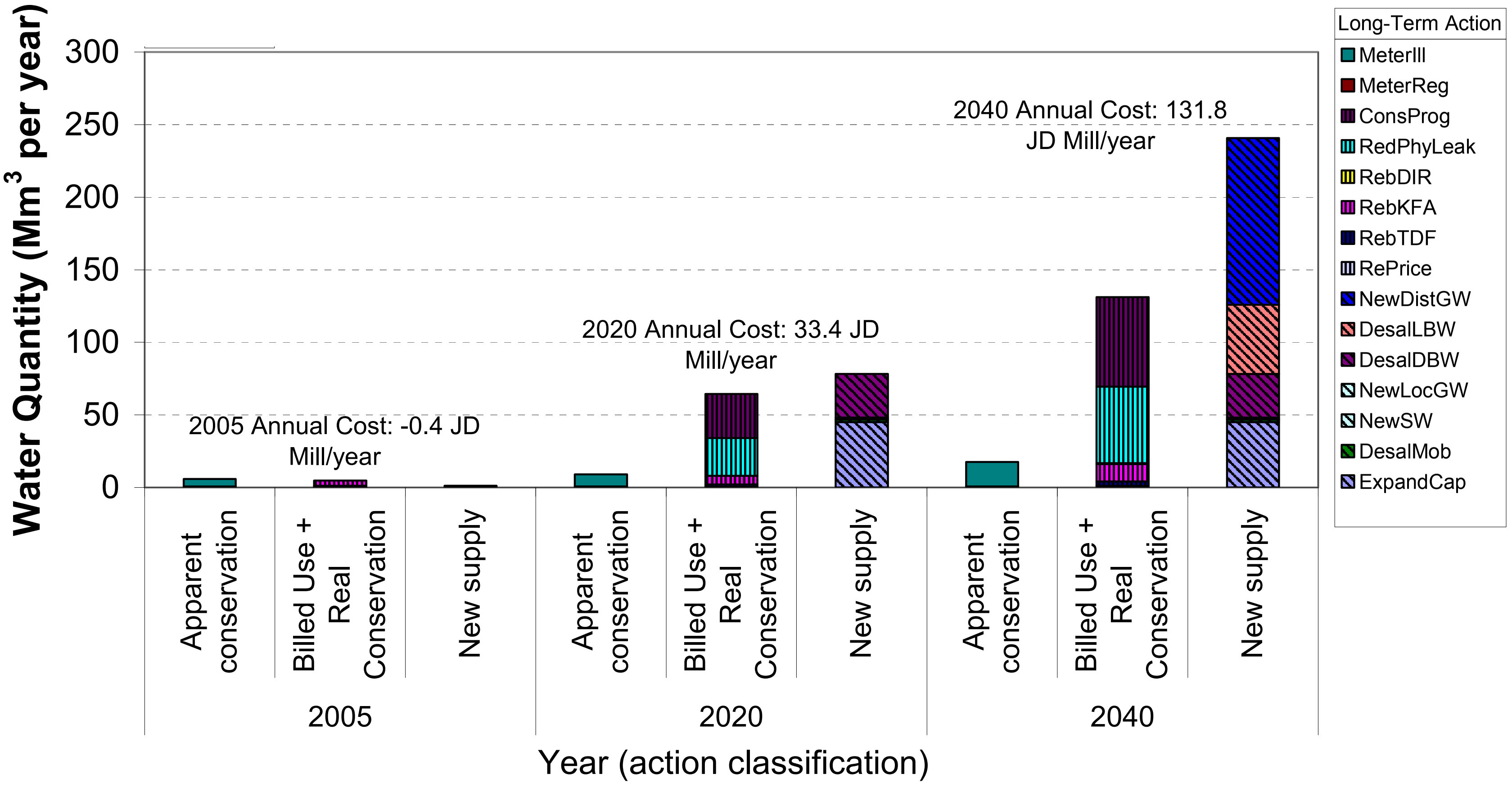


Figure 5.4. Capacity expansion and expected costs to cope with shortages over time

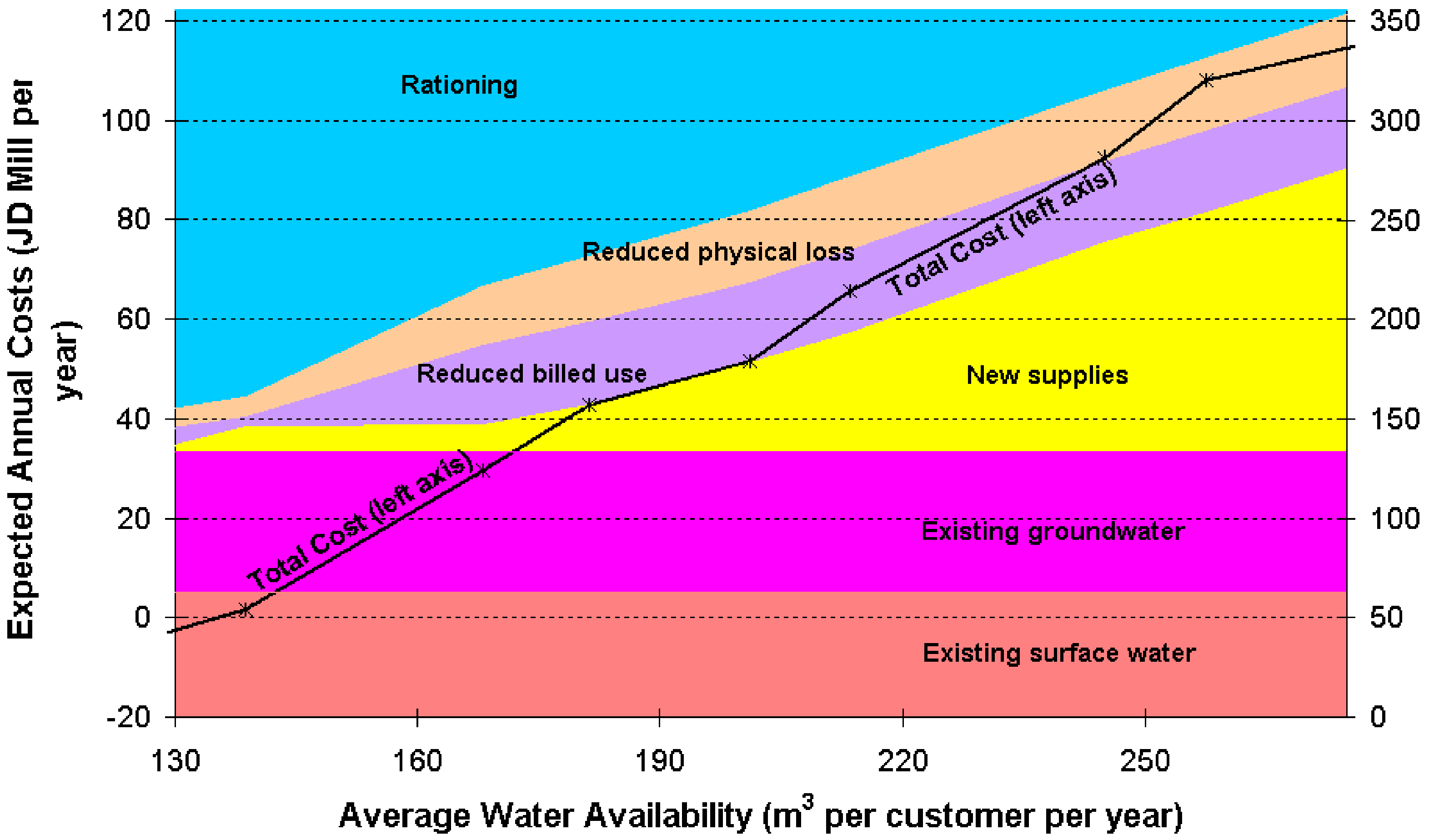


Figure 5.5. Costs associated with increasing water availability to customers

Table 5.1. Utility scale shortage management actions

Stage	Supply Enhancement	Conservation / Demand Reduction		
		Real Losses	Billed Use	Apparent Losses
Long-term	• Expand wastewater recycling and reuse capacity • Develop new surface water (dams) • Develop new local groundwater • Develop new distant groundwater • Expand system storage, conveyance, and treatment • Build desalination plants • Seawater • Brackish waters • Mobile units – Purchase tanker trucks	• Restructure distribution system – Lower operating pressure – Optimize and control flows	• Promote water efficient landscaping and appliances, grey-water reuse, and rainwater collection • Rebates to customers to install water efficient appliances • Re-price water	• Retrofit under-registering meters • Incentives to meter-readers and bill collectors • Install meters on illegal connections
Short-term	• Buy Agricultural water during droughts or shortages (fallowing) • Enhance precipitation • Deliver water by tanker truck – Trucks owned by utility – Rent trucks • Use surface water • Use local groundwater • Use distant groundwater • Reuse wastewater • Use desalination plants (seawater, brackish waters, mobile units)	• Detect and repair network leaks • Decrease response time to fix leaks • Ration service – Tier 1 – Tier 2	• Disconnect illegal users • Restrict outdoor water uses – Car washing – Irrigation • Ration service – Tier 1 – Tier 2	• Ration service – Tier 1 – Tier 2

Table 5.2. Potential long-term actions for Amman, Jordan

Action	Capital Cost (JD Mill)	Lifespan (Years)	Water Quantity (MCM/year)	Operating Cost (JD/m^3)	Notes	Source
Water Supply Enhancement						
1. New surface water sources	0.01 to 0.04	15 to 30	0.01 to 0.04	0.02 to 0.18	Only small, distant desert impoundments	JVA, 2005
2. New local groundwater sources	0.005 to 0.045	5 to 15	0.1 to 0.4	0.035 to 0.05	Per well; Drilling, pumping, and bacteological treatment	WAJ, 2004
3. New distant groundwater sources	600	20 to 30	80 to 150	0.21	Disi aquifer pumping and pipeline	El-Nasser, 2005; Nuaimat and Ghazal, 2006
4. Build sea-water desalination plant	1,420 to 2,130	15 to 25	850	1.15	Red-Dead project	El-Nasser, 2005; Nuaimat and Ghazal, 2006
5. Desalinate local brackish water	125	10 to 20	35 to 60	0.30 to 0.33	Zara Ma'een project	WAJ, 2005; Nuaimat and Ghazal, 2006
6. Desalinate distant brackish waters	0.1 to 3.5	10 to 20	0.6 to 6.1	0.30 to 0.40	Per plant; as for existing plants	WAJ, 2005
7. Buy mobile desalination unit	0.088 to 0.090	5 to 15	0.438	0.32 to 0.37	Per unit; salinity up to 4000 PPM	WAJ, 2005
8. Buy new water tanker truck	0.033 to 0.045	5 to 15	0.006 to 0.015	0.76 to 2.02	Per truck; as for existing trucks	LEMA, 2006
9. Expand capacity to store, convey, and treat water	45 to 71	10 to 20	45	0.16	Zai pumping and treatment plant expansion	Fisher et al, 2005; USAID, 2005
10. Expand capacity to recycle and reuse wastewater	49 to 108	10 to 20	7 to 58	0.01 to 0.26	Al-Samra expansion, Wadi Zarka, and South Amman treatment plants	WAJ, 2004; Taha and Magiera, 2003
Water Demand Management						
11. Physical loss reduction[a]	142	10 to 30	10.7 to 20.7	0.05 to 0.19	Capital Improvement Project to restructure Amman network	MWI, 2005
12. Customer water conservation program[a]	2 to 9	2 to 10	10.5 to 26.3	0.14 to 1.13	Target water efficient appliances to customers with potential to save most water and money	Rosenberg et al., 2006
13. Offer rebates to customers who adopt conservation technologies						
- Dual flush toilets[a,b]	0.04 to 0.47	3 to 7	0.3 to 1.5	0	Ranges from 10th and 90th percentiles of Monte-Carlo simulated Amman households	Rosenberg et al., 2006
- Kitchen faucet aerators[a,b]	0.10 to 2.12	3 to 5	0.3 to 6.9	0		Rosenberg et al., 2006
- Drip irrigation[a,b]	0.02 to 0.09	3 to 7	0.0 to 0.4	0		Rosenberg et al., 2006
14. Re-price water[a]	0.5 to 1.5	2 to 5	0.1 to 0.5	-7.2 to -13.4	Uses reported elasticity and average aggregate price increase from JD 0.02 to 0.10 per m3. Politically difficult	Rosenberg et al., 2006
15. Increase meter registration	0.8 to 0.9	3 to 10	0.7 to 0.8	-0.45 to -0.55	Retrofit rolled meters; JD 25 / meter	LEMA, 2004; 2005; 2006
16. Meter illegal connections[a,b]	0.7 to 0.9	1 to 5	4.3 to 5.7	-0.45 to -0.55	JD 25 / meter	LEMA, 2005

Notes:

a. Water quantity scales with demand forecast

b. Capital cost scales with demand forecast

Table 5.3. Potential short-term actions for Amman, Jordan

Action	Upper Limit (MCM/year)		Operating Cost (JD/m^3)	Notes	Source
	Summer	Winter			
Water Supply Enhancement [a]					
1. Buy agricultural water during drought	6.4	0	0.20 to 0.22	Rent land from Jordan valley farmers (fallowing program)	JVA, 2005
2. Enhance precipitation	0	30.48	0.25 to 0.26	Pilot cloud seeding tests in N. Jordan in 1992; assume increase SW by 12%	Taha and Magiera, 2003
3. Rent tanker trucks	0.003 to 0.008	0.003 to 0.008	0.40 to 1.07	Per truck	LEMA, 2005
Water Demand Management					
4. Reduce response time to repair leaks[b]	1.8 to 3.7	1.2 to 2.4	0.16 to 0.33	per recent LEMA efforts	LEMA, 2005
5. Restrict outdoor water use[b,c]	3.2 to 5.5	0.8 to 1.4	0.56 to 0.62	Landscape irrigation, car washing	Rosenberg et al., 2006
6. Disconnect illegal connections[c]	1.1 to 4.2	0.7 to 2.8	-0.48 to -0.39	per recent LEMA efforts	Griffin, 2004; LEMA, 2006
7. Ration service					
- Current (Step 1)[c]	12.0 to 20.0	8.0 to 13.3	0.00	Existing rationing; untapped demand	LEMA, 2006
- Drastic (Step 2)	1000	1000	3.00 to 4.00	unlimited; action of last resort; penalty	

Notes:

a. Only lists actions with fixed upper limits

b. Upper limit can decrease if long-term conservation actions implemented

c. Upper limit scales with demand forecasts

Table 5.4. Shortage events with demand forecasts for year 2020

Event Description		Probability	Shortage level	
Demand Level	Available surface water	(%)	(Mm^3/year)	(% of 2005 demand)
1. Small	Large	4.1%	47.0 to 75.0	35.3% to 56.3%
2. Below average	Above median	11.4%	75.0 to 105.0	56.3% to 78.8%
3. Slightly below average	Slightly above median	27.8%	105.0 to 132.5	78.8% to 99.5%
4. Slightly above average	Slightly below median	33.8%	132.5 to 157.5	99.5% to 118.2%
5. Above average	Below median	20.1%	157.5 to 182.5	118.2% to 137.0%
6. Large	Small	1.7%	182.5 to 192.2	137.0% to 144.3%

Table 5.5. Optimized costs and implementation for long-term actions through 2020

Long-Term Action	Model Solution Approach			
	Determ.-Equiv. (point values)	Robust[a] (data scenarios)	Grey Number[b] (risk prone)	Best / Worst[c] (case anal.)
Supply Enhancement				
1. New surface water sources (desert check dams)	5	5	5	5
2. New local groundwater sources	5	5	5	5
3. New distant groundwater sources (Disi)				<0, 1>
4. Sea-water desalination (Red-Dead Canal)				
5. Desalinate local brackish water (Zara-Ma'een)				<0, 1>
6. Desalinate distant brackish waters	9	10	6	<6, 7>
7. Buy mobile desalination unit	4	5		<0, 5>
8. Buy new water tanker truck				
9. Expand capacity to convey and treat water (Zai)	1	1	1	1
10. Expand capacity to recycle and reuse wastewater				
Conservation				
11. Reduce physical losses (Capital Improvement Proj.)	1	1		
12. Targeted customer water conservation program	1	1	1	<1, 0>
13. Rebates to customers who install				
- Dual flush toilets	1	1	1	<1, 0>
- Kitchen faucet aerators	1	1	1	<1, 0>
- Drip irrigation			1	<1, 0>
14. Re-price water	1	1	1	1
15. Increase meter registration (retrofit rolled meters)	1	1	1	<1, 0>
16. Meter illegal connections	1	1	1	1
Expected Annual Costs (JD Mill/year)				
- For long-term actions	34	(22, 36, 49)	[6, 54]	<6, 78>
- For short-term actions	-1	(-11, 4, 30)	[-21, 226]	<-21, 34>
- Total	33	(19, 40, 66)	[-15, 281]	<-15, 112>

Notes:

a. Costs show lowest, average, and largest of 20 random, independently-sampled data scenarios

b. Grey-number approach only gives single, deterministic value for long-term decisions. Costs in brackets show stable, feasible range corresponding to solutions from lower- and upper-bound submodels.

c. Brackets show best followed by worst case values when the two values differ

Table 5.6. Implementation levels for short-term actions in shortage events (Mm^3/year)

Model Solution Approach	**Short-Term Action**[b]	**Shortages** Shortage level [Mm^3/year] (Probability [%])					
		54.5 (4.1%)	90.0 (11.4%)	118.8 (27.8%)	145.0 (33.8%)	170.0 (20.1%)	187.3 (2.8%)
Deterministic-Equivalent (average parameter values)	B			1.9	6.4	6.4	6.4
	C				8.3	18.0	22.4
	RT						
	D	7.3	7.3	7.3	7.3	7.3	7.3
	RL				3.9	3.9	3.9
	RO				5.2	5.2	5.7
	R1	8.8	43.4	44.1	44.1	44.1	44.1
	R2					3.3	15.8
Robust[c] (data scenarios)	B		0.5	2.4	6.1	6.4	6.4
	C			2.7	9.2	19.1	21.9
	RT						
	D	7.4	6.8	7.9	7.2	7.2	7.0
	RL		0.3	0.6	2.8	3.3	3.4
	RO		0.2	0.6	3.1	5.4	6.1
	R1	13.8	41.1	44.4	45.2	44.7	45.6
	R2				1.4	8.6	20.8
Grey Number[d] (risk prone)	B	[0, 6.4]	[0, 6.4]	[0, 6.4]	[0, 6.4]	[6.4, 6.4]	[6.4, 6.4]
	C	[0, 7.5]	[0, 19.1]	[0, 22.5]	[0, 22.5]	[7.2, 22.5]	[17.0, 22.5]
	RT						
	D	[11.6, 3.0]	[11.6, 3.0]	[11.6, 3.0]	[11.6, 3.0]	[11.6, 3.0]	[11.6, 3.0]
	RL	[0, 1.8]	[0, 1.8]	[0, 3.0]	[3.6, 3.0]	[6.1, 3.0]	[6.1, 3.0]
	RO	[0, 4.1]	[0, 4.1]	[0, 4.6]	[0, 4.6]	[5.9, 4.6]	[5.9, 4.6]
	R1	[0, 33.1]	[3.4, 33.1]	[33.4, 33.1]	[55.2, 33.1]	[55.2, 33.1]	[55.2, 33.1]
	R2		[0, 17.1]	[0, 39.5]	[0, 64.5]	[0, 89.5]	[2.2, 99.2]
Best / Worst[e] (case analysis)	B		<0, 2.1>	<0, 6.4>	<0, 6.4>	<6.4, 6.4>	<6.4, 6.4>
	C				<0, 6.5>	<7.2, 16.2>	<17.0, 20.0>
	RT						
	D	<11.6, 3.0>	<11.6, 3.0>	<11.6, 3.0>	<11.6, 3.0>	<11.6, 3.0>	<11.6, 3.0>
	RL			<0, 1.8>	<3.6, 1.8>	<6.1, 1.8>	<6.1, 1.8>
	RO				<0, 5.3>	<5.9, 5.3>	<5.9, 5.3>
	R1	<0, 33.1>	<3.4, 33.1>	<33.4, 33.1>	<55.2, 33.1>	<55.2, 33.1>	<55.2, 33.1>
	R2					<0, 15.2>	<2.2, 21.2>

Notes:

a. Blank indicates zero value
b. B = Buy ag. water, C = Cloud seeding, RT = Rent tanker trucks, D = Disconnect illegal connections, RL = Reduce leak fix time, RO = Restrict outdoor water use, R1 = Normal rationing, R2 = Severe rationing
c. Average of 20 random, independently-sampled, data scenarios
d. Numbers in brackets show stable, feasible ranges spanning solutions to lower- and upper-bound submodels
e. Numbers in brackets show solutions for best and then worst cases

Part III

Management and Modeling for a Region

Chapter 6

Regional Water Management with Water Conservation, Infrastructure Expansions, and Source Variability

Abstract – A regional hydro-economic model is developed to include non-price demand shifts from water conservation programs as input parameters and decision variables. Stochastic non-linear programming then jointly identifies the benefit-maximizing portfolio of conservation programs, infrastructure expansions, and operational allocations under variable water availability. We present a detailed application for 12 governorates in the Hashemite Kingdom of Jordan. It considers targeted installations of water efficient appliances, leak reduction in the distribution system, surface and groundwater development, seawater desalination, conveyance, and wastewater treatment projects. Results show: (i) Water conservation by urban users generates substantial regional benefits and can delay infrastructure expansions. (ii) Some rationing and conjunctive use operations smooth operations during droughts. (iii) A broad mix of source developments, conveyance expansions, and leak reduction programs can forestall the need for desalination. (iv) The Disi carrier to Amman should include a large branch to Karak. And (v) increasing conveyance from the Ma'an, Irbid, and Mafraq can avert impending crises in the neighboring districts of Tafelah, Ajloun, and Zarqa.

6.1. Introduction

Regional water managers often develop, allocate, or suggest more efficient use of scarce water supplies for multiple purposes across wide spatial and temporal scales. Managers have long recognized that these activities require integrating engineering, economic, social, and political considerations. For example, water price and other factors influence the volume of water used (and vice versa), and price-modulated demand can encourage conservation and beneficially forestall infrastructure expansions (Howe and Linaweaver 1967). Further, rate structure, revenue generation requirements, or limits on changes in prices can influence the optimal path of expansions and associated benefits (Dandy et al. 1984; Gysi and Loucks 1971). Many early applications used dynamic programming to identify profitable expansions for one utility serving growing urban users. An early regional application (Armstrong and Willis 1977) used quadratic mixed-integer programming to simultaneously identify expansions for and allocations among multiple sources and water use sectors in neighboring sub-areas of two California counties.

More recently, hydro-economic models consider price-demand responses and operations for entire river basins or regions (Cai et al. 2003; Draper et al. 2003; Fisher et al. 2002; Fisher et al. 2005; Gillig et al. 2001; Jenkins et al. 2004; Rosegrant et al. 2000). For example, Rosegrant et al. (2000) optimize benefits for agricultural, urban, environmental uses considering the network of conveyance, storage, demands, and return flows in the Maipo River Basin in Chile. Gillig et al. (2001) consider source expansions with stochastic water availability in the Edwards Aquifer, Texas. Draper et al. (2003) focus on conjunctive surface and groundwater management, environmental flows, conveyance, wastewater reuse, water market transfers, and return flows that minimize scarcity losses to agricultural and urban users across the California water system. Fisher et al. (2005) include supply, conveyance, desalination, wastewater reuse, pricing, and sector use policies to inform water conflict resolution in Israel, Palestine, and Jordan.

Most recent applications each use linear or non-linear programming to solve the *allocation* problem for a single-year or time series of monthly flows. They then use sensitivity analysis or examine the shadow values (Lagrange multipliers) of binding model constraints to identify beneficial *expansions*. A shadow value is an optimization output that reports the objective function slope at a binding constraint and indicates the improvement when the constraint is relaxed one unit. These analyses work well for individual changes with deterministic flows or static hydrology. But it proves cumbersome to identify an optimal package of long-term supply, infrastructure expansion, and conservation program developments such as those listed in Table 6.1. Analysis is further complicated by variable rainfall and runoff from year-to-year as typically seen in arid regions where hydro-economic models are often applied.

Gillig et al. (2001) use mixed integer stochastic programming with recourse to identify an optimal portfolio of surface and groundwater source expansions and operations under variable hydrology. Here, we extend their approach to allow water conservation and leak reduction programs, conveyance, wastewater treatment, and desalination facility expansions. Further, we identify optimal balances of inter-temporal transfers, rationing, infrastructure expansions, and unused capacity to respond to stochastic water availability.

Conservation programs are an important aspect of regional water management and are absent from hydro-economic models. Hydro-economic models usually integrate the area under user demand curves to quantify water use benefits. This emphasis follows the long-running (and almost singular) focus on price elasticity of demand in the econometrics literature (Howe and Linaweaver 1967; Young 2005). Economists typically distinguish short-term (i.e., practices) and long-term (appliance retrofit) user responses to price changes but dispute their relative importance (Carver and Boland 1980; Espey et al. 1997). Yet, econometric studies show significant non-price effects on water use related to family size, household income, yard area, etc., and (in the instances when they have been examined) voluntary conservation program (Michelsen et al. 1999; Renwick and Green 2000) or water efficient appliance retrofits (CUWCC 2005; USEPA 2005). These non-price factors shift the demand curve inward (Michelsen et al. 1999). Shifts reduce aggregate use 1% to 4% per individual educational or retrofit program (Michelsen et al. 1999; Renwick and Green 2000), are greater when installing ultra-low flow appliances (CUWCC 2005; USEPA 2005), and potentially greater still for targeted installations to users who will save the most water and money (Chapter 4). For hydro-economic models, the challenge is to include these demand shifting conservation program options with *input* parameters and *decision* variables. This proactive approach to include physical water use efficiency and evaluate when such water conservation is economical contrasts with Cai et al. (2003) who post-calculate local and basin-wide efficiencies under different water transfer scenarios (allocations).

Here, we extend Fisher et al's (2005) single-year Water Allocation System model (henceforth, Single-Year WAS) to include water conservation programs and infrastructure expansions with variable water availability. We specify a demand curve for water-related service, shift that demand curve to represent the reduction in water use associated with a conservation program, and embed the shifted curves and allocation model in a stochastic two-stage program that allows for and identifies the net benefit maximizing mix of conservation and leak reduction programs, surface and groundwater developments, conveyance, wastewater treatment, and desalination expansions.

The chapter proceeds as follows. Section 6.2 reviews the Single-Year WAS model and presents modifications to develop the stochastic two-stage program. Section 6.3 describes an application to the water system serving urban, industrial, and agricultural uses of over 6 million people in the Hashemite Kingdom of Jordan. Sections 6.4 and 6.5 present and discuss model results. Section 6.6 concludes.

6.2. Background and Methods

6.2.1. Single-Year Water Allocation System model

A team of Israeli, Jordanian, Palestinian, American, and Dutch experts have collaborated for over 10 years on the Water Economics Project (Fisher et al. 2002; Fisher et al. 2005). The project used several economic and engineering principles to identify opportunities for regional water cooperation. Namely,

1. Water, as a scarce resource, has value. This value reflects the benefit from water use, costs to procure, treat, and convey water to the point of use, and benefits foregone by using water in one place rather than somewhere else.

2. Currently, seawater desalination plus conveyance to the point of use places an upper bound on water value (as the most expensive supply option).

The project developed a steady-state, deterministic optimization program for a single-year that we term "Single-Year WAS" (to distinguish it from the multi-year version the team is currently developing and a stochastic version that we describe later). Single-Year WAS maximizes net benefits from water use subject to physical, environmental, social, and political constraints on water availability, use, reuse, costs, movement, and prices. The net benefit is defined as the area between the demand and cost curves (respectively, the curves that represent benefits water sectors derive from water use and costs to extract, treat, and convey water to where it is used) (Figure 6.1a). The optimal allocation is the quantity (q^*_{st} in Figure 6.1a) associated with the point where the two curves intersect (when private values match social values). Constraints are specified for the countries, districts within the countries, and water-use sectors included in the analysis. For example, as a physical limitation in each district i, the quantity demanded must balance with the water extracted from local sources, imported from and exported to other districts, wastewater treated for reuse, and losses from leaks that can not otherwise be put to economical use.

Some important findings from application of Single-Year WAS in Israel, Palestine, and Jordan included:

- Ability to bring three parties together to work on common water problems,
- The value of water in the Mountain Aquifers in dispute between Israel and Palestine is very small—significantly less than the cost to purchase one fighter jet to control or defend those water rights, and
- There is significant benefit to private and cooperative efforts to develop infrastructure. Examples include Jordan expanding its pipeline to Amman from the Jordan Valley and Gaza building a wastewater treatment plant to sell its wastewater to Israeli farmers for reuse in the Negev desert.

Single-Year WAS is a powerful tool that includes many supply, infrastructure, leak reduction, social, and economic policies related to water management. The program considers a single-year, so model users must compare results from successive runs--one run with the infrastructure, policy, or water availability in place and a second without it. For example, comparing a scenario with "normal" year hydrology to a second scenario with "drought" conditions. Combining more options and option levels requires analyzing a multiplicatively expanding number of alternatives. Below, we introduce and then demonstrate methods to include water conservation programs, capacity expansions, and variable water availabilities in a stochastic formulation at the national level or large region.

6.2.2. Water Conservation Programs

The demand curve in Figure 6.1a summarizes the benefits users derive from water use. The curve also shows the price response or the reduction in use when price increases. Price response generally has two components (Carver and Boland 1980; Howe and Linaweaver 1967). In the short-term, water users may buy more-expensive privately vended water or temporarily reduce the length or frequency of their shower, dishwashing, landscape irrigation, and other water uses. Over the long-term and with better information, users may continue behavior changes or purchase and install more water efficient appliances. In Jordan, urban users may purchase and install rain- and grey-water collection systems, low-flow showerheads, low-flush toilets, dual-flush toilet mechanisms, drip irrigation systems, low water-use landscapes, and other water-saving devices (Chapter 2).

However, many non-price factors such as income, education, or conservation programs also encourage users to modify their behaviors or install water efficient appliances to reduce their water use (CUWCC 2005; Michelsen et al. 1999; Renwick and Green 2000; USEPA 2005). For example, Renwick and Green (2000) examined mean monthly single-family water use data for 8 water utilities in California over 8 years and reported short-term reductions in water use significant at the 99% level for public information campaigns, distributing retrofit kits, rationing, and water use restrictions programs. Short-term elasticity responses were in the range –0.08 to –0.34. Others report similar decreases although these values may understate actual shifts. Averaged water use data overlooks the skewed distribution of water savings among individual households. Further, inter-correlated geographic, demographic, technologic, behavioral, and attitudinal factors also affect water savings and are difficult to include in econometric analysis.

In Chapter 4, we used mathematical programming to include the above factors and deduce price and non-price demand responses for individual household water users in Amman, Jordan. We considered some 39+ separate long- and short-term supply and conservation actions, and found an (i) inelastic short-term price response similar to the response used for the urban user demand curve in Single-Year WAS, and (ii) targeted installations of water efficient appliances (to the small number of users who have the most to gain) gave a similar price-response, but reduced *overall* water use nearly 33%.

In sum, price responses indicate movement *along* the demand curve whereas non-price conservation programs shift the whole demand curve inward and in shape. Based on prior empirical data (Chapter 4), we consider just a shift inward with no change in shape (Figure 6.1b).

Single-Year WAS can accommodate and even calculate optimal allocations for a shifted demand curve (q^{*}_{lt} in Figure 6.1b). However, the calculation of net benefits needs correction. Calculating net benefits directly from the shifted demand curve will give a net benefit that is *smaller* than the net benefit calculated from the original demand curve and incorrectly suggests that conservation program that improve physical water use efficiency are *always* uneconomical. The correction employed here works as follows.

First, we note that water use combines inputs of water, time, and technology to achieve a water-related service such as a bathed body, clean dishes, clean laundry, clean car, attractive landscape, urine disposal, or feces removal. Further, we posit that water-related services—rather than water use per se—provide value to users. Conservation programs that install water efficient appliances amount to a technology change that reduces the water input needed to provide those services. Water efficient technologies simply use less water to maintain these services and values. For example, in Jordan, water users who retrofit a water-wasting showerhead (9 to 20 liters/minute) with a low flow showerhead (6 to 9 liters/minute), shower for the same time, as often, and still get clean (Chapter 4). Yet these households can potentially reduce their water use by 5 to 100 m^3 per year. Conservation programs that improve physical water use efficiency reduce the quantity of water use but maintain the value associated with those uses.

We therefore distinguish a demand for water related services from the demand for water use. The two demands differ by the physical efficiency improvement from installing water efficient appliances. We call this percentage improvement in district *i* $pcon_i$, so that

$$\text{Water Use}_{\text{i}} = \text{Service Demand}_{\text{i}} \cdot (1 - pcon_i),\ \forall i. \qquad (6.1)$$

Figure 6.1b distinguishes demands for water service (original demand curve) and water use (shifted demand curve) by, respectively, the dashed and solid curves.

Second, we optimize allocations to maximize net benefits. Net benefits (consumer surplus) are the benefits of water related service minus costs to supply the actual water used and costs for conservation activities. With b_i indicating the position of the service demand curve for district *i*, α_i the demand curve elasticity for district *i*, and assuming constant elasticity along the demand curve to give a service demand curve in exponential form, the net benefits are:

$$\begin{matrix}\text{Max}\\ \text{(Net Benefits)}\end{matrix} = \sum_i \frac{b_i}{\alpha_i + 1}\left(\text{Service Demand}_i\right)^{\alpha_i + 1} - \text{Costs}\begin{pmatrix}\text{Local Sources, Imports,}\\ \text{Exports, Wastewater}\\ \text{Treatment, Conservation}\end{pmatrix} \tag{6.2}$$

and are subject to continuity on water use in each district

$$\text{Water Use}_i = \begin{pmatrix}\text{Local Sources}_i + \text{Imports}_i\\ - \text{Exports}_i + \text{Treated Wastewater}_i\end{pmatrix}\cdot\left(1 - \text{Loss Rate}_i\right),\ \forall i \tag{6.3}$$

The shaded area in Figure 6.1b shows the costs savings (additional net benefits) from non-price demand shifting water conservation programs.

Finally, with no efficiency improvements ($pcon_i = 0$), water demand equals the demand for water related service, the original and shifted demand curves coincide, there is no cost savings, and we have the situation shown in Figure 6.1a. Later, we show the net gain for targeted water efficiency improvement programs in Amman and in Jordan.

6.2.3. Integrating Variable Water Availability and Infrastructure Expansions

Variable availability reflects uncertainty about rainfall, runoff, or groundwater available to serve water demands. This uncertainty presents an important question for planners. Which is preferable: make long-term investments that expand infrastructure to improve water system reliability? Or, implement short-term emergency measures and coping strategies that cut back demand in the instances when water supply availability is limited? What is the appropriate balance between long- and short-term strategies?

The fields of production planning, facilities location, energy investment, environmental management, water management, agriculture, telecommunications, design of chemical processes, and finance often use stochastic optimization with recourse (staged programming) to recommend infrastructure expansions in the face of uncertainties regarding resource availability (for reviews, see Sahinidis 2004; Sen and Higle 1999). The technique, which we adopt here, works as follows.

First, we list out discrete stochastic states for the system. In the context of water management, these states are water availability events described by an availability level (fraction of average annual available rainfall, runoff, and groundwater flow) and likelihood (probability). Together, event probabilities must sum to 1.

Second, we partition decisions into two types. First, we make long-term (primary-stage) decisions for infrastructure expansions or conservation program development. Then, for each event, we make short-term (recourse-stage) operational decisions regarding water source use, conveyance, demand allocations, and wastewater treatment. These operational decisions are event-specific and reflect limitations imposed by long-term decisions plus the water availability level. Together, long-term actions plus sets of short-term actions for each event constitute the decision portfolio to respond to the stochastic distribution of water availabilities.

Third, we optimize to identify the mix of long- and short-term decisions that maximizes expected net benefits over all events. Expected net benefits are the net benefits for each event (value from water use minus costs to extract, treat, and convey water) weighted by the event probability. From the event-probability-weighted net benefits, we subtract capital costs for long-term infrastructure expansions and conservation programs implemented. Thus, the program uses an expected value criterion to determine the optimal mix of long- and short-term actions.

The expected net benefits are subject to constraints to balance water supply and demand at every location in every event, infrastructure use within existing (or expanded) capacity limits, and social, political and other policies imposed by the user. Policies can include paid- and unpaid-for water, limitations on use of certain water qualities, water reserved for environmental or other purposes, minimum required allocations to certain water use sectors, and use of common pool resources shared among multiple districts or countries.

Appendix A provides the mathematics for the stochastic WAS program. This formulation is solved as a non-linear program. Further, when only one event is specified, the event is assigned a probability of one, and infrastructure expansions are limited to their existing capacities, the stochastic program reduces to the Single-Year WAS model (Fisher et al 2005).

6.2.4. Limitations

Limitations of the stochastic WAS program include:

1. *An expected value objective function gives risk-neutral rather than risk-adverse decisions.*

2. *Decision staging focuses on long-term drought planning policies*. Stochastic programming typically helps plan responses to droughts of long duration and recurrent frequency, for example, at the inter-annual time scale. However, systems that face short droughts of a few days or weeks (such as in the eastern United States) may only require rationing, water use restrictions, or planned shortages. Stochastic WAS allows users to define the event length and short-term operational policies such as event-specific demand elasticity and multipliers such as from demand hardening, minimum required allocations (or lack thereof), and

penalties when minimum allocations go unmet. Together, these event-specific inputs can be used to test the economic impacts of short-term drought response policies on long-term net benefits.

3. *Event independence ignores effects of event timing or sequence and precludes modeling storage or groundwater banking decisions*. Marques (2004) allows groundwater banking but assumes groundwater storage is infinitely large. This condition does not hold in Jordan: surface water reservoirs are small and groundwater is over-drafted.

    However, Stochastic WAS can still elicit the economic impacts of temporal transfers and identify advantageous conjunctive use policies. First, water source availability in a particular event need not represent just natural availability. Availability can include human management that stores or draws-down sources in different events. After optimizing, examining the shadow values associated with the constraints on source availability will indicate whether increasing human-managed availability is advantageous.

    Second, we can also penalize use of a particular source in a particular event. We can add a usage charge to the operational cost for using a particular source,

$$\text{Source Cost}_{\text{ise}} = \text{Operational Cost}_{\text{is}} + \text{Usage Charge}_{\text{ise}},\ \forall i,s,e. \tag{6.4}$$

    Here, all terms are in \$ per m^3 and the indexes *i*, *s*, and *e* represent, respectively, the district, source, and event as defined in Appendix A. The usage charge is the additional penalty to use resource *s* in event *e* rather than leave it *in-situ* for use in a later event. The usage charge can represent the modeler's judgment or be estimated using dynamic, inter-temporal analysis. (Howitt et al. (2005) describe a dynamic value iteration approach). In sum, stochastic programming cannot generally identify optimal allocations across events; however, we can still specify and study water storage and drawdown policies.

For further details and work-arounds for these problems, see Jenkins and Lund (2000), Chapter 4, and Chapter 5.

6.2.5. Model Implementation

The stochastic version of WAS is a Visual Basic application that links modules for data storage, optimization, and results visualization (Figure 6.2). Users first define the regional layout of countries, districts, water use sectors, water qualities, local resources, and conveyance links to include in a scenario. Then, they enter required demand, supply, infrastructure, and policy data for those components. To optimize, the program queries the database and formats data for use by the optimization module. Afterwards, users view results for any or all components.

Modularity separates the input data from the application forms, events, and methods that solicit, query, and optimize using the input data and display results. Separation permits:

- Model users to flexibly define, enter data for, and study circumstances for Jordan, any other country, or group of countries.

- Model developers to reuse code to develop alternative model formulations. Alternative formulations can even have different input data and data structures. For example, Single-Year WAS requests a demand elasticity for each district and water use sector (2 dimensions) whereas Stochastic WAS needs an elasticity for each district, sector, and water availability event (3 dimensions).

Figure 6.3a,b show forms where the user defines the districts and water availability events to include in a study. Figure 6.3c is the form served to enter demand elasticity for those districts and events. The optimization module uses the Generic Algebraic Modeling System (GAMS) language and solves the non-linear program with CONOPT (Brooke et al. 1998). Solution time is generally less than 1 minute on a Pentium laptop.

6.3. Example Application in Jordan

We now demonstrate use of the WAS models for the Jordan water system. Jordan is divided into 12 *governorates* or water management districts (Figure 6.4). Below, we summarize the national water budget and future prospects, describe potential infrastructure expansions and conservation program options, characterize current water availability, and estimate usage charges on water sources. Later in section 6.4, we present and discuss optimization results. Unless otherwise noted, we use WAS model data for Jordan developed and presented by Fisher et al. (2005, chapter 6).

6.3.1. National Water Budget and Prospects

Jordan's current water demand is approximately 1 billion m^3 per year. This demand is typically served by 300 million m^3 of renewable surface water, 550 million m^3 of renewable groundwater, with the remaining deficit of 150 million m^3 covered by overdraft of groundwater. Use is split approximately 69%, 27%, and 4%, respectively, among agricultural, urban, and industrial uses. Breakdowns by districts and further details are discussed by (Abu Qdais and Batayneh 2002; Al-Salihi and Himmo 2003; Fisher et al. 2005; Scott et al. 2003; Taha and Magiera 2003) and others.

Jordan's water problems date back 20 years (Al-Weshah 1992) and further. Jordan has few existing water supplies, a fast growing population (2% to 3% per year), and limited, expensive options to develop new supplies. Much excellent work has identified ways to bridge the supply / demand gap, including characterizing water availability and potential options (Taha and Magiera 2003), regional optimization (Fisher et al. 2005, chapter 6), and improving residential and commercial water use efficiency (IdRC 2004; WEPIA 2000). But, to date, efforts have yet to systematically integrate these components in a single framework for analysis and action.

Integrated modeling at the national scale can help identify promising new supply and conservation options to improve water system performance. It can further show the regional impacts of local water user (Chapter 4) and city (Chapter 5) conservation efforts.

And, it can also confirm and justify actions the Jordan Ministry of Water and Irrigation (MWI) and cities of Amman, Zarqa, Irbid, and Aqaba are planning and implementing to improve water system performance.

6.3.2. Potential Actions

Table 6.1 to Table 6.3 characterize 15 infrastructure expansion and conservation program development options currently under consideration by MWI and the water utilities serving each district. Short-term actions in Table 6.1 are implemented when needed and can flexibly respond to events as they occur. They do not require advance planning (unless conditioned on long-term infrastructure). Long-term actions in Table 6.1 to Table 6.3 require a one-time (and generally large) capital investment and establish infrastructure for supply or conservation. Long-term actions must be taken well in advance of any actual supply provision or use reduction. Descriptions, below, highlight implementation.

We use operational costs and initial capacities for short-term actions as described by Fisher et al (2005, chapter 7). We gathered information on long-term infrastructure options during meetings with Jordanian water managers during January, 2006, and from subsequently published reports (Abdelghani et al. 2007; Nuaimat and Ghazal 2006; Rosenberg 2006). When estimates differ among sources, we use averaged values.

6.3.2.1. Source Development

These projects develop fresh or brackish surface or groundwater originating in a district.

Zara Ma'een project. The Zara Ma'een project collects brackish waters from the Mujib, Zara, and Ma'een rivers, desalinates it by reverse osmosis, and pumps the treated water more than 1000 meters uphill to Amman (Nuaimat and Ghazal 2006; Taha and Magiera 2003). Operations started in Summer 2006. We list the project to draw comparisons to conservation efforts that are still in the planning phase.

Yarmouk river. MWI is currently constructing the Unity Dam to raise the capacity to store and withdraw water on the Yarmouk River in Irbid (Rosenberg 2006). The project only recently went forward in 2001 after Jordan and Syria signed a 3rd agreement on use of the shared Yarmouk waters. However, the agreement does not discuss water allocations between countries. There is also uncertainty whether Syria, the upstream riparian, will release or make available sufficient water to fill the dam. Here, the maximum capacity includes existing use of Yarmouk waters plus the volume Jordanian managers hope the dam will capture.

Disi aquifer. MWI has tendered proposals to increase pumping capacity from Disi fossil groundwater in Ma'an (El-Nasser 2005; Nuaimat and Ghazal 2006; Taha and Magiera 2003). Costs reflect only extraction and treatment; conveyance to Amman and Aqaba is considered later. The Disi project has already seen financial backers withdraw and criticism about the impacts on aquifer yield from pumping by overlying landowners—both Jordanian and Saudi.

Wadi Yutum rehabilitation. This project would repair 7 existing wells in Wadi Yutum, build a local holding reservoir, and tie into the Aqaba water network (Abdelghani et al. 2007). The Wadi Yutum wells were the primary water source for Aqaba but fell into disuse after the city switched to the more plentiful (but distant) Disi aquifer.

Wadi Araba brackish water. This project would install 15 wells in Wadi Araba, extract brackish groundwater with salinity concentrations up to 1000 ppm, treat the water with nano-filtration, then pump the water 18 km to Aqaba (Abdelghani et al. 2007). Although the project capital and operating costs are larger than other options for Aqaba, the project may be cost effective or necessary in the context of regional water management.

6.3.2.2. Seawater Desalination

Jordan has only 22 km of seacoast located in the far south on the Gulf of Aqaba (part of the Red Sea). Still, two proposals exist to desalinate seawater.

Reverse Osmosis for Aqaba. The first proposal involves building a small reverse osmosis (RO) desalination plant for Aqaba (Abdelghani et al. 2007). Capital and operating costs reflect recent RO experiences in Israel, Gaza, and Saudi Arabia. However, it is difficult to determine all capital costs prior to designing the plant. Further, recent Mediterranean experiences with RO are for much larger plants that likely have economies of scale. Still, desalination research shows that RO costs will decrease significantly over time.

Red-Dead Canal and desalination. This mega project would convey Red Sea water more than 300 km from Aqaba to the Dead Sea near Balqa (El-Nasser 2005; Nuaimat and Ghazal 2006; Taha and Magiera 2003). The 400-meter elevation drop between the two seas would generate hydropower and the penstock releases would help restore the declining Dead Sea level. Further, part of the penstock releases could be desalinated and pumped uphill to Amman. Here, we do not count capital expenditures, operating costs, and benefits for the Red-Dead conveyance, hydropower generation, and environmental restoration portions of the project. We only consider capital and operating costs to desalinate seawater at Balqa. Conveyance to Amman is addressed later.

6.3.2.3. Wastewater Treatment

These projects will develop or expand capacity to treat urban and industrial wastewater and reuse the treated effluent for agricultural production. Operational costs consider the *additional* expense incurred (above the cost to safely dispose of wastewater to the environment) to treat wastewater to a quality suitable for agricultural use.

As-Samra expansion. The Al-Samra wastewater treatment plant currently serves Amman and Zarka but operates significantly above the plant's design capacity. MWI, with financial support from USAID, seeks to expand treatment capacity to 267,000 m^3 per day, of which up to 66% (after treatment and evaporative losses) would be available for reuse by agricultural users in Amman, Zarka, or Balqa.

Wadi Zarka plant. MWI also desires to build a second wastewater treatment plant for Zarka. As a new plant, this project has slightly higher capital and operating costs than the As-Samra expansion.

Tertiary treatment for Aqaba. Based on recent estimates by the Aqaba Water Company, the wastewater treatment plant in Aqaba can be expanded by 4.4 million m^3 (MCM) per year (Abdelghani et al. 2007). The higher operational cost includes tertiary treatment.

6.3.2.4. Conveyance

These projects build or expand pipes or aqueducts to transport water between districts.

Zai plant expansion. Currently, the Zai treatment plant and pumps operate at their capacity of 123,000 m^3 per day to move surface water 1000 meters uphill from Balqa to Amman (Fisher et al. 2005, Chp. 7). Capital costs represent an MWI proposal to double Zai plant capacity. Although Red-Dead Sea desalinated water would be conveyed to Amman though a separate pipeline, we treat Zai expansion as representative of the capital and operational costs for subsequent conveyance of desalinated water to Amman.

Disi carrier to Amman. As part of the project to extract fossil water from the Disi aquifer in Ma'an, MWI is tendering proposals to convey the water 200+ km to Amman (El-Nasser 2005; Nuaimat and Ghazal 2006; Taha and Magiera 2003). Conveyance represents more than 80% of the total $600 million capital costs for the project. At first, we consider only a direct link between Ma'an and Amman. Later, we examine potential benefits for branches to Karak and Madaba along the route to Amman.

Expanding the Disi carrier to Aqaba. The Aqaba Special Economic Zone (ASEZ) proposes building a parallel pipe to expand capacity by 14 MCM per year to convey Disi aquifer water from Ma'an to Aqaba (Abdelghani et al. 2007). The existing pipeline from Disi has a physical capacity of 21.5 MCM per year, but regulations limited conveyance to 17.5 MCM per year. However, MWI relaxed these regulations in 2006. Further, we exclude the $\$0.25/m^3$ surcharge MWI charges ASEZ for use of Disi water as done by Fisher et al. (2005).

6.3.2.5. Targeted Installations of Water Efficient Appliances

Targeted installations for select urban users in Amman. Detailed modeling of Amman residential water user behaviors showed that targeting *select* customers to install water efficient appliances can reduce *overall* residential water use nearly 33% (Chapter 4). A small number of customers can save significant water and money by installing toilet dual flush mechanisms, low-flow showerheads, faucet aerators, drip irrigation, water efficient laundry machines and landscapes, etc. The crux is to identify customers with potential to save water and money, determine which specific action(s) those customers should adopt, and find engaging ways to promote and motivate adoption. We estimate capital costs of $47 million for education, administration, and retrofits.

Targeted installations for select urban users in other districts. We postulate effects of a targeted water-use efficiency program in other districts based on the estimates for

Amman. We use the same maximum reduction rate for the urban districts of Zarka, Mafraq, and Irbid, but reduce the maximum rate for other districts with larger rural populations. In all districts, we use population forecasts to prorate program capital costs.

6.3.2.6. Leak Reduction Programs

Capital Improvement Project in Amman. MWI has nearly completed a 5-year project to restructure the Amman urban water distribution system to reduce physical water loss. Improvements include dividing the network into separate pressure zones, installing bulk meters, primary tanks, and gravity fed distribution for each zone, optimizing flows, and reducing system pressure. Preliminary results show reductions of 24 to 46 MCM per year that constitute approximately 11% of urban, industrial, and agricultural deliveries in Amman. We express reductions from restructuring the network as a percentage of deliveries since the absolute volume of reductions will continue to grow as demand served by the restructured system increases.

Leak Reduction in other districts. We draw on the experience in Amman to postulate effects for leak reduction in other districts. Population forecasts serve as indicators of distribution system size and to prorate program capital costs.

6.3.3. Water Availability Events

We use the 65-year record of runoff between 1937 and 2002 in Jordan’s 12 major watersheds (Taha and Magiera 2003) to develop a discrete set of stochastic water availability events. We calculate the total Kingdom-wide runoff for each year, sort these annual runoff values in increasing order, then characterize the distribution of water availability into a discrete set of 6 annual availability levels and mass probabilities that represent explicit events. We divide each availability level by the mean observed runoff to obtain an event-specific availability factor. And finally, we multiply surface water source availabilities by event-specific availability factors to estimate source availability in each event (availabilities for groundwater sources are the same across all events). Figure 6.3b shows the event probabilities and availability factors entered in the Stochastic WAS model.

This approach treats runoff variability as homogenous across the study area and representative of surface water availability. These assumptions suffice for demonstration purposes given the limited available data. More detailed runoff and groundwater data would allow individual analysis to capture some of the spatial correlation patterns.

Users can further differentiate demands and select policies across events; however this feature was not used in the analysis for Jordan. Values for demand elasticity, multipliers, base year use, and policies that specify set-aside quantities, unpaid use, costs to safely dispose of wastewater, and additional costs to reuse treated wastewater were the same for each event and matched values used by Fisher et al (2005, chapter 7).

6.3.4. Additional Data

A 5% interest rate annualizes capital costs. Fisher et al. (2005, chapter 7) present prior water use projections for 2020 and the other model inputs which include demand elasticities of –0.2, -0.33, and –0.5, respectively, for the urban, industrial, and agricultural sectors.

6.4. Results

Table 6.4 summarizes model scenario results. The scenarios include verification runs, water use efficiency, and optimal infrastructure expansions and conservation program developments. We also study diverting some Disi water to Karak and Madaba along the conveyance route to Amman, improving water use efficiency for agricultural users, conjunctive use operations, and management without water use efficiency improvements.

6.4.1. Verification Runs

Two initial runs verify that the stochastic formulation reproduces results of the Single-Year WAS program. These runs did not allow infrastructure expansions, conservation program developments, excluded the Zara-Ma'een project, only specified a single-event with a water availability level and probability of 1, and were made for water use observed in 1995 and unrestricted use projected for 2020. Annualized net benefits (Table 6.4, Row 1, Column C) match results presented for this case by Fisher et al. (2005, chapter 7). Net benefits and shadow values in each district and all short-term decision levels also match.

6.4.2. Targeted Installations of Water Efficient Appliances

Installing water use appliances for *select* urban users in Amman to reduce *overall* urban sector use by 33% generates substantial benefits (Table 6.4, Row 2). Benefits grow even further when select urban users throughout the country install water efficient appliances (Table 6.4, Row 3). Such water conservation programs would reduce water scarcity values across the country (Figure 6.5). Reductions are most pronounced in districts where water is scarce (Amman, Zarqa, and Ajloun).

However, scarcity reduction does not indicate a uniform distribution of benefits. Users in Mafraq, Balqa, and Madaba benefit from water use efficiency, but these districts still see a reduction in their overall net benefits (Figure 6.6). These districts have low scarcity values, relative water abundance, and export (sell) supplies to neighboring districts where water is scarce and users pay premiums for additional water. Improved water use efficiency by users in water scarce districts reduces their imports. Water abundant districts must find new customers.

Overall, the net benefits from targeted water conservation for urban users in Amman exceed the gain from building the Zara-Ma'een project (Table 6.4, Row 4). But, the capital expenditure for conservation programs (including retrofit costs) is slightly more than the Zara-Ma'een project cost. Below, all subsequent scenarios include the Zara-Ma'een project to reflect current conditions.

6.4.3. Optimal Expansions and Variable Water Availability

Allowing the program to select from the infrastructure expansions and conservation programs listed in Table 6.2 and Table 6.3 further increases net benefits (Table 6.4, Row 5, Column C). Here, the program sees benefit to build or develop a mix of source expansion, conveyance, physical water use efficiency, and leak reduction programs constituting annualized capital expenditures of about $50 million. The program does not see benefits for the Disi carrier or seawater desalination in Aqaba or Balqa.

When facing a stochastic distribution of surface water availability as described in Figure 6.3b, the program expands wastewater treatment for Amman, and increases conveyance (Table 6.5, Column E). These changes increase annualized capital expenditures by $1 million/year but do not explain the larger reduction in net benefits. This reduction is related to reduced allocation and higher scarcity values in districts and events where surface water availability is limited (Table 6.6). This effect is most pronounced in districts like Ajloun, Karak, and Tafelah that rely principally on surface water and less pronounced in districts like Zarqa, Mafraq, and Aqaba that use only local or imported groundwater. Scarcity costs imposed in the water scarce events are less than the additional capital and operating costs needed to build infrastructure to serve unmet peak demand for a short time. From an expected net benefits perspective, it is preferable to ration in the few, infrequent events where water availability is limited rather than build additional infrastructure. Event-specific rationing should be studied further.

6.4.4. Disi Carrier Branches to Karak and Madaba

Karak has very high water scarcity values in many events with limiting water availability while nearby districts like Ma'an and Madaba have lower scarcity values (Table 6.6). This difference suggests additional conveyance may be beneficial (Fisher et al. 2002). Thus, we consider Disi Carrier branches to Karak and Madaba. To model these branches, we introduce an intermediary node between Ma'an and Amman, specify a primary conveyance link from Ma'an to the node, and then secondary conveyance links from the node onward to Karak, Madaba, and Amman. We assign the Disi project costs and capacity to the primary link and allow the secondary links to operate with unlimited capacity, no operating or capital costs.

Results show the Disi wellfield is expanded, the carrier is built, an improvement in annual net benefits of about $60 million/year (Table 6.5, Column F), and a drastic reduction in the scarcity value of water in Karak (Figure 6.7). These gains are offset by modest increased scarcity values in Aqaba and Ma'an as these districts also compete for the Disi water (Aqaba finds it necessary to develop wells in Wadi Araba). Still, the overall benefit for Karak makes the Disi project worthwhile.

6.4.5. A Further Look at Water Conservation

Two final runs consider (i) conservation programs to improve water use efficiency for agricultural users by 15% and (ii) expansions required without physical water-use efficiency improvements for urban users.

Improving water use efficiency by agricultural water users marginally decreases scarcity values for water and adds small net benefits (Table 6.4, Row 7). On average, agricultural water use drops only 15 MCM/year with most of the decrease from reuse of treated wastewater. In Jordan, agriculture water use is already low value and relatively elastic. Other activities cannot profitably make use of the treated urban wastewater. Small benefits reflect the small increased economic productivity for agricultural users.

Finally, without targeted installations of water efficient appliances for urban water users, the program finds little change in capital expenditures with an almost $350 million/year loss in net benefits (Table 6.4, Row 8). Capital expansions now include desalination plants for Aqaba and Balqa, more conveyance from Balqa to Amman, and expansions for the Disi aquifer, Yarmouk river, and As-Samra treatment plant (Table 6.5, Column G). These results highlight a tradeoff between physical infrastructure expansions and water conservation programs. Water conservation programs can substitute for and delay infrastructure expansions.

6.5. Discussion

Stochastic programming is used to integrate water conservation programs, infrastructure capacity expansions, and variable water availability in a regional water allocation model. Results show that a broad mix of water use efficiency, leak reduction, infrastructure expansions, and conjunctive operations can respond to growing projected water use forecast for Jordan through 2020. Below, we list and discuss key findings. We also contrast these findings to MWI's current actions and results from prior studies.

6.5.1. Key Findings

1. *Targeted conservation programs for urban water users yield substantial regional benefits.* Several model runs show that improving physical water use efficiency by targeting select urban users to install water efficient appliances allows existing supplies and facilities to serve a growing demand. And, these programs significantly reduce scarcity costs compared to infrastructure projects (Figure 6.8) and can delay or forestall the need for those projects. These regional findings quantify and substantiate off-site benefits often ascribed to water conservation and demand management (Baumann et al. 1998; Dziegielewski and Baumann 1992).

   The substantial regional benefits should also motivate and justify non-structural government efforts to encourage water conservation. Examples include fund research to develop water efficient appliances. Limit the manufacture and import of inefficient water appliances. Better label appliance water and energy use (and likely operating costs) so customers can make more-informed purchases. Improve and better enforce water-efficient plumbing regulations. Raise awareness about water use efficiency among users, plumbers, mechanics, maintenance crews, landscape architects, gardeners, and nursery owners. In Jordan, urban water users and water utilities already have financial incentives to install and encourage use of water efficient appliances (Chapter 4 and Chapter 5); here, regional results show the Jordanian government also has substantial incentives to encourage these activities.

2. *Some rationing is economical in response to limited water availability.* Stochastic optimization provides a way to quantify and identify the appropriate balance between expanding infrastructure and rationing under variable water availability given the correct economic information and representation of scarcity responses. This balance depends on the magnitude and likelihood of events when availability is limiting, economic costs or (consequences) of rationing, minimum allocations users can sustain, and opportunity costs of unused infrastructure. Users can enter these parameters and policies into Stochastic WAS so that recommended expansions and allocation maximize economic efficiency subject to prevailing social and political requirements.

3. *The Disi Carrier to… Karak*. Several runs show that Disi water can significantly reduce water scarcity in Karak. Water is conveyed only in events where surface water availability is limited. With increased availability and the pipeline existing, Disi water is instead sent to Amman. Other runs that do not consider the branch to Karak avoid building the Disi carrier. These findings suggest that the Disi project should emphasize supplying Karak rather than Amman.

4. *Desalination not urgent*. Small desalination plants in Aqaba and Balqa are indicated only in one run that did not specify water conservation programs for urban water users. Water was desalinated only in one event when surface water availability was most limited. Employing a broad mix of other infrastructure expansions and leak reduction programs can forestall more expensive desalination.

5. *Impending crises for Tafelah, Ajloun, and Zarqa.* The most favorable scenario with infrastructure expansions, conservation programs, and the Disi Branch to Karak still indicates high scarcity values for Tafelah, Ajloun, and Zarqa (Figure 6.8). These scarcity values are much higher than values in neighboring districts. In part, this result reflects an absence of infrastructure projects considered for those districts. However, low scarcity values in neighboring districts suggests that additional conveyance from Ma’an, Irbid, and Mafraq to, respectively, Tafelah, Ajloun, and Zarqa can help manage impending crises in the later districts.

6.5.2. Comparing to actions already underway and prior studies

MWI has nearly completed the project to rebuild and reduce leaks in the Amman distribution network and mostly finished the Unity Dam on the Yarmouk river. MWI plans to expand Zai plant capacity and is tendering proposals to build the Disi aquifer conveyor. Elsewhere, MWI, with funding from the U.S. Agency for International Development, has contracted for a second Kingdom-wide water conservation program and to expand the Al-Samra wastewater treatment plant. AZEM is still studying recommendations to expand conveyance from Disi to Aqaba, rehabilitate the Wadi Yutum wells, and expand tertiary wastewater treatment.

Our results show each action is an important long-term investment for MWI and the district water managers. These infrastructure projects and conservation programs can improve overall system performance plus maintain and expand benefits across a distribution of water availabilities.

Although MWI is developing plans to convey Red Sea water to the Dead Sea, our results show the desalination portion is only used in the most water scarce event and absent water conservation programs for urban users. A wide mix of other infrastructure expansions and conservation programs can forestall development of large-scale desalination. However, absent these efforts, large-scale desalination of Red-Dead Canal water may be justified.

Our findings further affirm and expand upon results from the Single-Year WAS in Jordan (Fisher et al. 2005, chapter 7). Namely, urgent needs to expand the Zai plant (Balqa to Amman conveyor), reduce leakage, build the Zara-Ma'een project and the Disi Carrier. Urban water conservation programs and other options for Aqaba significantly reduce scarcity costs to levels that avoid the need for desalination. Including stochastic surface water availability somewhat depresses overall net benefit while allowing long-term capacity expansion and conservation program decisions allow the model to identify an optimal portfolio of expansions in one go rather than through numerous simulations.

Our findings also partially verify and significantly expand on results for a recent water supply study for Aqaba (Abdelghani et al. 2007). Abdelghani et al. (2007) include a MWI imposed surcharge on water delivered through the pipeline from Disi to Amman, consider expanding the pipeline, developing wellfields in Wadis Yutum and Araba, expanding wastewater treatment, and building a small RO desalination plant. They use mixed integer programming to identify the cost-minimizing timings of capacity expansion to meet growing projected water needs through 2020. They similarly recommend expanding the Wadi Yutum wellfield, Disi pipeline to Aqaba, and wastewater treatment plant. However, they also suggest building a desalination plant. Their study does not consider competition for scarce Disi water, stochastic water availability, or water conservation options. These factors permit forestalling or delay of desalination.

Finally, we assume the demand curves for water related service and water efficient use have the same shape; further research should explore affects of demand hardening or a more inelastic demand curve with water use efficiency. Further, as with the Single-Year WAS model, our methods and findings leave aside optimal storage operations and sequencing through time of capacity expansions and conservation programs with growing, uncertain demands. We suspect that economic analysis should show conservation programs—which have lower capital costs and commensurate net benefits—are better implemented first. However, this determination requires further study with mixed integer or dynamic programming analysis.

6.6. Conclusions

An integrated hydro-economic analysis considers a very diversified portfolio of options for a very diverse set of demands in an extensive geographic setting. Stochastic programming identifies an optimal mix of water conservation programs and infrastructure expansions plus operational allocations to respond to a stochastic distribution of surface water availability. We build on recent empirical and theoretical work and show how to include non-price shifts in demand from conservation programs as an input parameter and decision in a hydro-economic regional water model. We include efficiency by shifting the demand curve that describes user benefits. We lower demand for actual water use but still count the benefits associated with maintaining the level of water related service. Installing water efficient appliances allows users to do the same with less water (or do more with the same water).

Application of the integrated regional water model in Jordan shows:

1. Targeted installations of water efficient appliances for urban users can generate significant benefits with small capital investments. Benefits match gains from infrastructure projects and delay or avoid their considerable expense. The findings suggest that MWI and the Jordan government should promote water conservation.

2. Rationing and conjunctive use operations are economical responses to stochastic water availability.

3. A broad mix of other infrastructure expansion projects and leak reduction programs can substitute for and forestall desalination in Aqaba and Balqa.

4. The Disi carrier to Amman should include a large branch to Karak, and

5. Impending water scarcities in Tafelah, Ajloun, and Zarqa should be better managed by increasing conveyance from the neighboring districts of Ma’an, Irbid, and Mafraq where water is more available.

Overall, the analysis shows that a growing population and expanding water uses will significantly increase costs and competition for water. However, a broad mix of supply, infrastructure expansions, and conservation programs can mitigate these effects. Implementing these actions will require large capital investments. But the expected benefits should be larger still.

Appendix A. Stochastic Model Formulation

A stochastic version of the Single-Year WAS model is presented here in the standard form for optimization: the objective function followed by constraints. This stochastic formulation incorporates modifications to (i) make the model more general (so users can define the relevant districts, intermediary nodes, sectors, and water quality types for the study region), and (ii) allow water use efficiency, variable water availability, and capacity expansions. We adopt Fisher et al’s. (2005, pp. 41-3) notation with 5 changes:

1. Introduce the index *q* to denote water quality and aggregate variables, parameters, equations, and terms that they define separately for fresh and recycled waters;
2. Substitute the variable QTW_{idq} (quantity of wastewater from sector *d* treated to quality *q* in district *i*) for their variable QRY_{id} (quantity recycled from use *d* in district *i*);
3. Introduce the index *n* to denote intermediary nodes that are potential start or end points for conveyance links but at which no demand, supply, or wastewater treatment is allowed;
4. Introduce the indexes *p* and *j* to represent the union of all districts and nodes; and
5. Allow users to specify a minimum required flow in a conveyance link.

Further additions (below) permit water use efficiency, variable water availability, capacity expansions, and operations within expanded capacity limits.

The Objective Function is:

$$\begin{aligned} Max\,Z = \sum_e prob_e \cdot & \left[\sum_i \sum_d \frac{b_{ide}\left(\sum_q QD_{idqe}\right)^{\alpha_{ide}+1}}{\alpha_{ide}+1} - \sum_i \sum_q \sum_s cs_{iqse} QS_{iqse} - \sum_p \sum_{j \neq p} \sum_q ctr_{qpje} QTR_{qpje} \right. \\ & \left. - \sum_i \sum_d \sum_q cr_{idqe} QTW_{idqe} - \sum_i \sum_d ce_{ide}\left(\sum_q QDC_{idqe}\right) \right] \\ & - \sum_p \sum_{j \neq p} \sum_q cxtr_{qpj} XTR_{qpj} - \sum_i \sum_q \sum_s cxs_{iqs} XS_{iqs} - \sum_i \sum_q \left(cxtw_{iq} XTW_{iq} + cxl_{iq} XL_{iq}\right) \\ & - \sum_i \sum_d cxcon_{id} XCON_{id} \end{aligned}$$

Subject to:

1. Continuity on actual water at each district for each quality in each event

$$\sum_d QDC_{idqe} = \left(\sum_s QS_{iqse} + \sum_d QTW_{idqe} + \sum_p QTR_{qpie} - \sum_p QTR_{qipe} \right) \cdot \left(1 - dl_{0iq} + XL_{iq}\right),\ \forall i, q, e$$

2. Continuity on actual water at each node for each quality in each event

$$\sum_p QTR_{qpne} = \sum_p QTR_{qnpe},\ \forall n, q, e$$

3. Treated wastewater comes from actual water demands

$$\sum_q QTW_{idqe} = PR_{ide} \sum_q QDC_{idqe},\ \forall i, d, e$$

4. Lower limit on demand for water related service by each sector, district, and event

$$\sum_q QD_{idqe} \geq \left(\frac{p_{\max}}{b_{ide}} \right)^{\frac{1}{\alpha_{ide}}},\ \forall i, d, e$$

5. Existing and expanded water user efficiency relates demands for water related service and actual water

$$QDC_{idqe} = QD_{idqe} \cdot \left(1 - pcon_{0\ id} - XCON_{id}\right),\ \forall i, d, q, e$$

With the following bounds

$$QS_{iqse} \le qs_{0\ iqs} + XS_{iqs} \le qs_{\max\ iqs},\ \forall i, q, s, e$$

$$\sum_{d} QTW_{idq} \le qtw_{0\ iq} + XTW_{iq} \le qtw_{\max iq},\ \forall i, q$$

$$QTR_{qpje} \le qtr_{0\ qpj} + XTR_{qpj} \le qs_{\max qpj},\ \forall q, p, j, e$$

$$pcon_{0\ id} + XCON_{id} \le pcon_{\max\ id},\ \forall i, d$$

$$dl_{0\ iq} + XL_{iq} \le dl_{\max\ iq},\ \forall i, q$$

$$QS_{iqse} \le qs_{avail\ iqse},\ \forall i, q, s, e$$

$$PR_{ide} \le pr_{\max\ id},\ \forall i, d, e$$

$$QTR_{qpje} \ge qtr_{\min\ qpj},\ \forall q, p, j, e$$

and all variables positive.

Variables are:

Z = net expected benefit from water in millions of dollars;
QS_{iqse} = quantity supplied by source *s* of quality *q* in district *i* in event *e* in 10^6 m^3;
QD_{idqe} = demand for water related service of quality *q* by sector *d* in district *i* in event *e* in 10^6 m^3;
QDC_{idqe} = quantity demanded after conservation in 10^6 m^3;
QTR_{qpje} = quantity of water quality *q* transferred from point *p* to *j* in event *e* in 10^6 m^3;
QTW_{idqe} = sector *d* wastewater treated to quality *q* in district *i* in event *e* in 10^6 m^3;
PR_{ide} = percent of sector *d* wastewater treated in district *i* in event *e* in fraction;
XS_{iqs} = Supply capacity expansion for source *s* of quality *q* in district *i* in 10^6 m^3;
XTR_{qpj} = Conveyance capacity expansion from point *p* to *j* of quality *q* in10^6 m^3;
XTW_{id} = Wastewater reuse plant capacity expansion in district *i* for quality *q* 10^6 m^3;
XL_{iq} = Leak reduction program expansion in district *i* for quality *q* in fraction;
$XCON_{id}$ = Water use efficiency improvement in district *i* for quality *q* in fraction;

Indices are:

p = point (districts and nodes);
i = district;
n = node;
d = water use sector (urban, industrial, or agricultural);
s = supply source or step;
q = water quality type (fresh, recycled water);
e = event (water supply availability / demand)

Parameters are:

α_{ide} = exponent of inverse demand function for demand *d* in district *i* in event *e*;
b_{ide} = coefficient of inverse demand curve for demand *d* in district *i* in event *e*;
ce_{ide} = unit environmental cost of water discharged by demand sector *d* in district *i* in event *e* in \$ m^{-3};
cr_{idqe} = unit cost to treat sector *d* waste in district *i* to quality *q* in event *e* in \$ m^{-3};

cs_{iqse} = unit cost to supply new water of quality *q* from source *s* in district *i* in event *e* in \$ m^{-3};

ctr_{qpje} = unit cost to transport water quality *q* from point *p* to *j* in event *e* in \$ m^{-3};

cxs_{iqs} = annualized capital cost to expand source *s* of quality *q* in district *i* in \$ m^{-3};

$cxtr_{iqs}$ = annualized capital cost to expand conveyance capacity of quality *q* from point *p* to *j* in \$ m^{-3};

$cxtw_{iq}$ = annualized capital cost to expand wastewater treatment capacity to quality *q* in district *i* in \$ m^{-3};

$cxcon_{id}$ = annualized capital cost to expand user conservation program in district *i* for sector *d* in \$ $fraction^{-1}$;

cxl_{iq} = annualized capital cost to expand leak reduction program in district *i* for quality *q* in \$ $fraction^{-1}$;

p_e = probability of event *e* in fraction;

$p_{max\ id}$ = maximum price of water from demand sector *d* in district *i* in \$ m^{-3};

$pr_{max\ id}$ = maximum percent of waste from demand sector *d* in district *i* that can be treated in fraction;

$qs_{0\ iqs}$ = existing capacity of source *s* in district *i* of quality *q* in 10^6 m^3;

$qs_{avail\ iqse}$ = availability of source *s* in district *i* of quality *q* in event *e* in 10^6 m^3;

$qs_{max\ iqs}$ = maximum capacity for source *s* of quality *q* in district *i* in 10^6 m^3;

$qtr_{0\ qpj}$ = existing conveyance capacity for quality *q* from point *p* to *j* in 10^6 m^3;

$qtr_{max\ qpj}$ = maximum capacity after expansions for conveyance of quality *q* from point *p* to *j* in 10^6 m^3;

$qtr_{min\ qpj}$ = minimum required flow of quality *q* from point *p* to *j* in 10^6 m^3;

$qtw_{0\ iq}$ = existing capacity to treat water to quality *q* at district *i* in 10^6 m^3;

$qtw_{max\ iq}$ = maximum capacity after expansions to treat water to quality *q* at district *i* in 10^6 m^3;

$pcon_{0\ id}$ = reduction in use associated with existing conservation programs for sector *d* in district *i* in fraction;

$pcon_{max\ id}$ = maximum reduction in use from conservation programs for sector *d* in district *i* in fraction;

$dl_{0\ iq}$ = existing leak rate for quality *q* in district *i* in fraction;

$dl_{max\ iq}$ = maximum reduction in leakage rate for quality *q* in district *i* in fraction;

Optional user policies, when selected, generate the following additional constraints:

6. Actual water demand consists of paid water ($QD_{paid\ idqe}$) and unaccounted-for losses
$QDC_{idqe} = QD_{paid\ idqe} + r_{iqe}pr_{unpaid\ ide}$, $\forall i, d, q, e$.

7. Demand for certain water quality types must be less than the specified quantity
$\sum_{d} QDC_{idqe} \le q_{rec\max\ iq}$, $\forall i, q, e$

8. Demand for certain water quality types must be less than a specified percentage of total demand.
$\sum_{d} QDC_{idqe} \le p_{rec\max\ iq} \sum_{d,q2} QD_{id,q2,e}$, $\forall i, q, e$

9. Use from a pool of shared sources must be less than a specified quantity

$$\sum_{iqs} indcp_{ciqs} QS_{iqse} \leq q_{shared\ ce},\ \forall c, e$$

10. Minimum required allocation to each sector

$$\sum_{q} QDC_{idqe} \geq q_{required\ ide},\ \forall i, d, e$$

6.7. References

Abdelghani, E., Dweiri, S., Fernandez, D., and Kent, P. (2007). "A Water Resource Planning Model for Aqaba." United States Agency for International Development and Aqaba Zone for Economic Mobilization, Aqaba, Jordan. http://www.azem-aqaba.com/pdf/march07_water_resource.pdf.

Abu Qdais, H. A., and Batayneh, F. (2002). "The Role of Desalination in Bridging the Water Gap in Jordan." *Desalination*, 150(2), 99-106.

Al-Salihi, A. H., and Himmo, S. K. (2003). "Control and Management Study of Jordan's Water Resources." *Water International*, 28(1), 1-10.

Al-Weshah, R. A.-M. (1992). "Jordan's Water Resources: Technical Perspective." *Water International*, 17(3), 124-132.

Armstrong, R. D., and Willis, C. E. (1977). "Simultaneous Investment and Allocation Decisions Applied to Water Planning." *Management Science*, 23(10), 1080-1088.

Baumann, D. D., Boland, J. J., and Hanemann, W. M. (1998). *Urban Water Demand Management and Planning*, McGraw-Hill, Inc., New York.

Brooke, A., Kendrick, D., Meeraus, A., and Raman, R. (1998). "GAMS, a user's guide." GAMS Development Corporation, Washington, D.C. http://www.gams.com/.

Cai, X. M., Rosegrant, M. W., and Ringler, C. (2003). "Physical and economic efficiency of water use in the river basin: Implications for efficient water management." *Water Resources Research*, 39(1).

Carver, P. H., and Boland, J. J. (1980). "Short-Run and Long-Run Effects of Price on Municipal Water-Use." *Water Resources Research*, 16(4), 609-616.

California Urban Water Conservation Council (CUWCC). (2005). "A Guide to Data and Methods for Cost-Effectiveness Analysis of Urban Water Conservation Best Management Practices." l, Sacramento, CA, 142 pp.

Dandy, G. C., McBean, E. A., and Hutchinson, B. G. (1984). "A Model for Constrained Optimum Water Pricing and Capacity Expansion." *Water Resources Research*, 20(5), 511-520.

Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R., and Howitt, R. E. (2003). "Economic-engineering optimization for California water management." *Journal of Water Resources Planning and Management-Asce*, 129(3), 155-164.

Dziegielewski, B., and Baumann, D. D. (1992). "The benefits of managing urban water demands." *Environment*, 34(9), 7-11, 35-41.

Espey, M., Espey, J., and Shaw, W. D. (1997). "Price elasticity of residential demand for water: A meta-analysis." *Water Resources Research*, 33(6), 1369-1374.

Fisher, F. M., Arlosoroff, S., Eckstein, Z., Haddadin, M. J., Hamati, S. G., Huber-Lee, A., Jarrar, A. M., Jayyousi, A. F., Shamir, U., and Wesseling, H. (2002). "Optimal water management and conflict resolution: The Middle East Water Project." *Water Resources Research*, 38(11), 25-1:17.

Fisher, F. M., Huber-Lee, A., Amir, I., Arlosoroff, S., Eckstein, Z., Haddadin, M. J., Hamati, S. G., Jarrar, A. M., Jayyousi, A. F., Shamir, U., and Wesseling, H. (2005). *Liquid Assets: An economic approach for water management and conflict resolution in the Middle East and beyond*, Resources for the Future, Washington, D.C.

Gillig, D., B. A. McCarl, and F. Boadu, An economic, hydrologic, and environmental assessment of water management alternative plans for the South Central Texas region, *Journal of Agricultural and Applied Economics*, *33*, 59-78, 2001.

Gysi, M., and Loucks, D. P. (1971). "Some Long Run Effects of Water-Pricing Policies." *Water Resources Research*, 7(6), 1371-&.

Howe, C. W., and Linaweaver, F. (1967). "Impact of Price on Residential Water Demand and Its Relation to System Design and Price Structure." *Water Resources Research*, 3(1), 13-26.

Howitt, R. E., Msangi, S., Reynaud, A., and Knapp, K. C. (2005). "Estimating intertemporal preferences for natural resource allocation." *American Journal of Agricultural Economics*, 87(4), 969-983.

Interdisciplinary Research Consultants (IdRC). (2004). "A Survey of Home Appliances and Toilets in the Jordanian Markets." Academy for Educational Development: Water Efficiency for Public Information and Action (WEPIA) Program, Amman, Jordan, 50 pp.

Jenkins, M. W., and Lund, J. R. (2000). "Integrating yield and shortage management under multiple uncertainties." *Journal of Water Resources Planning and Management-Asce*, 126(5), 288-297.

Jenkins, M. W., Lund, J. R., Howitt, R. E., Draper, A. J., Msangi, S. M., Tanaka, S. K., Ritzema, R. S., and Marques, G. F. (2004). "Optimization of California's water supply system: Results and insights." *Journal of Water Resources Planning and Management-Asce*, 130(4), 271-280.

Marques, G. (2004). "Economic Representation of Agricultural Activities in Water Resources Systems Engineering," PhD, University of California, Davis, Davis.

Michelsen, A. M., McGuckin, J. T., and Stumpf, D. (1999). "Nonprice water conservation programs as a demand management tool." *Journal of the American Water Resources Association*, 35(3), 593-602.

Nuaimat, K., and Ghazal, M. (2006). "Water will be in abundance by 2020 - minister." *Jordan Times*, June 20.

Renwick, M. E., and Green, R. D. (2000). "Do residential water demand side management policies measure up? An analysis of eight California water agencies." *Journal of Environmental Economics and Management*, 40(1), 37-55.

Rosegrant, M. W., Ringler, C., McKinney, D. C., Cai, X., Keller, A., and Donoso, G. (2000). "Integrated economic-hydrologic water modeling at the basin scale: the Maipo river basin." *Agricultural Economics*, 24(1), 33-46.

Rosenberg, D. E. (2006). "The Yarmouk River Agreements: Jordan-Syrian transboundary water management, 1953-2004." *Arab World Geographer*, 9(1), 23-39.

Sahinidis, N. V. (2004). "Optimization under uncertainty: state-of-the-art and opportunities." *Computers & Chemical Engineering*, 28(6-7), 971-983.

Scott, C. A., El-Haser, H., Hagan, R. E., and Hijazi, A. (2003). "Facing Water Scarcity in Jordan: Reuse, Demand Reduction, Energy, and Transboundary Approaches to Assure Future Water Supplies." *Water International*, 28(2), 209-216.

Sen, S., and Higle, J. L. (1999). "An introductory tutorial on stochastic linear programming models." *Interfaces*, 29(2), 33-61.

Taha, S., and Magiera, P. (2003). "National Water Master Plan: Water Resources in Jordan." Ministry of Water and Irrigation, Amman, Jordan. http://www.mwi.gov.jo/nwmp/NWMP/index.htm.

U.S. Environmental Protection Agency (USEPA). (2005). "Combined Retrofit Report, Volume 1: Water and Energy Savings from High Efficiency Fixtures and appliances in Singe Family Homes." Washington, D.C.

Water Efficiency and Public Information for Action (WEPIA). (2000). "Assessment of Water Saving Devices Sector in Jordan." Amman, Jordan, 39 pp.

Young, R. A. (2005). *Determining the Economic Value of Water: Concepts and Methods*, Resources for the Future, Washington, D.C.

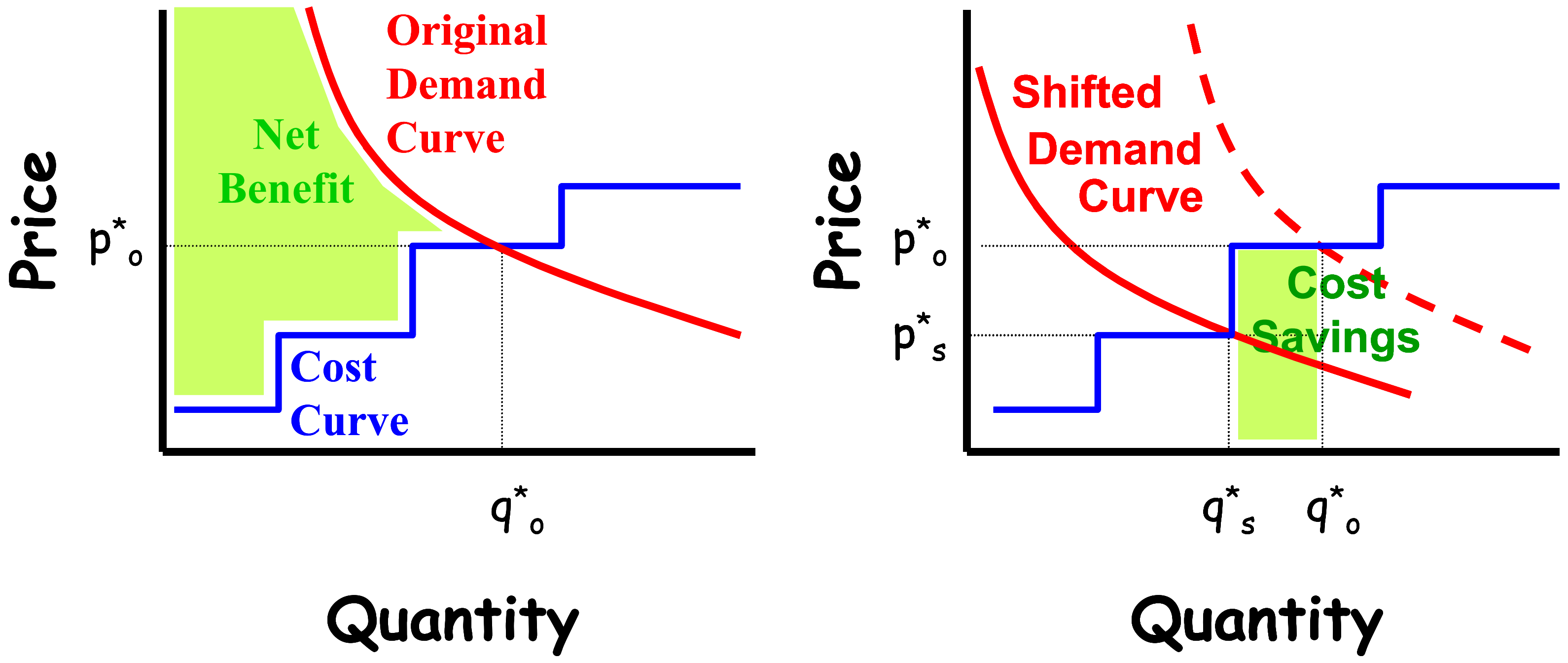


Figure 6.1. Demand curves and optimal allocations before (A) and after (B) implementing water conservation programs for users. Shaded area in (B) shows the cost savings from implementing conservation programs.

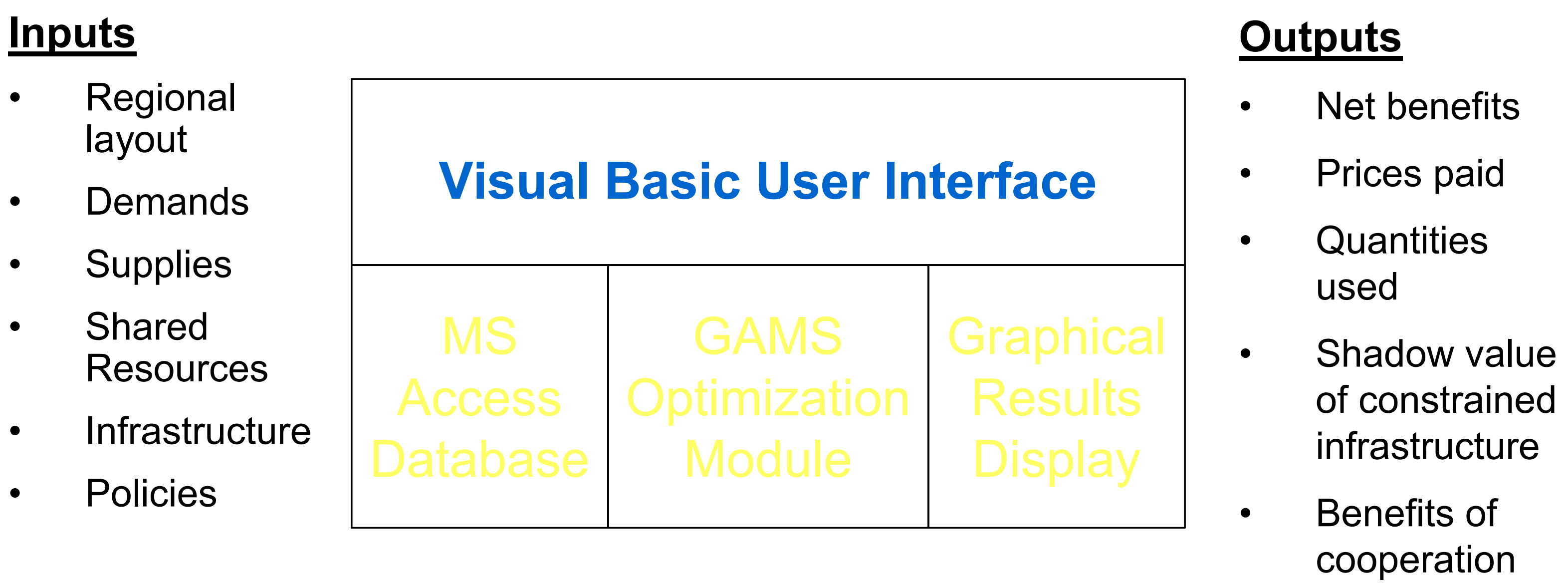
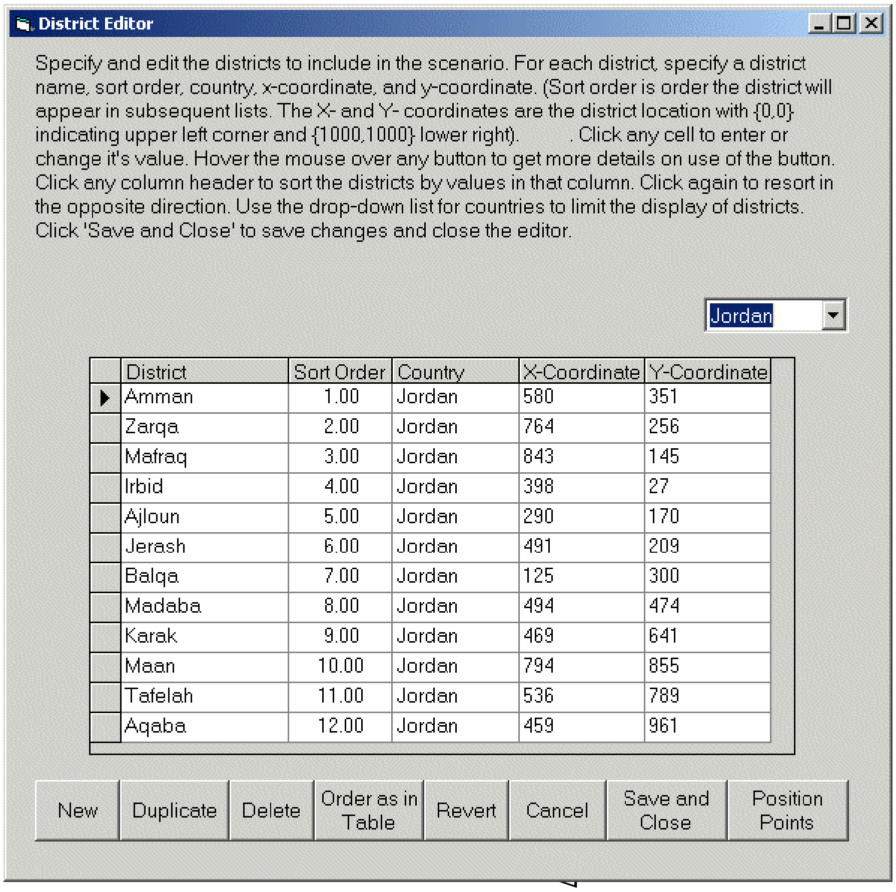


Figure 6.2. Stochastic WAS model architecture



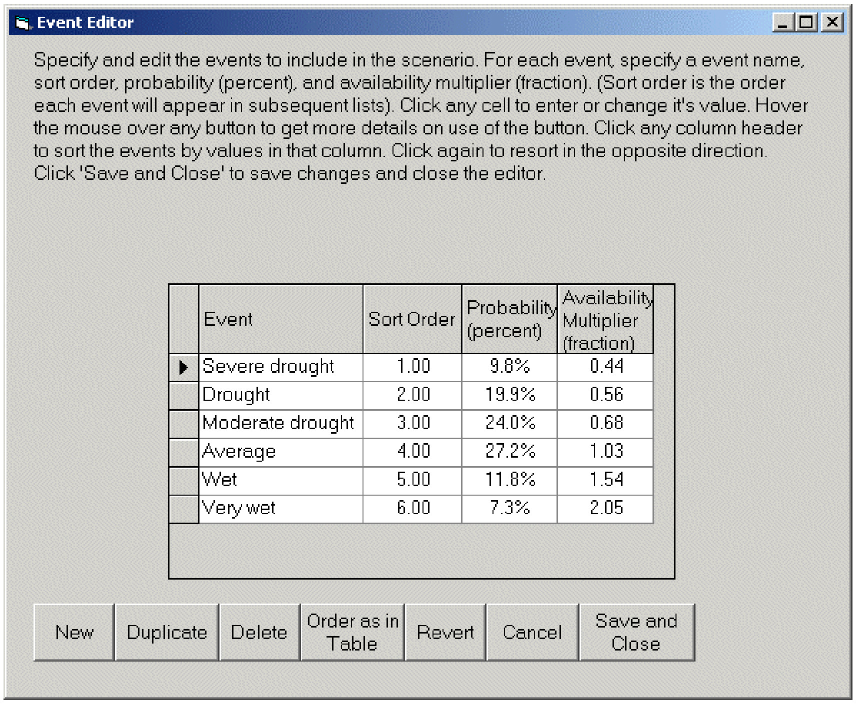
Specify and edit the districts to include in the scenario. For each district, specify a district name, sort order, country, x-coordinate, and y-coordinate. (Sort order is order the district will appear in subsequent lists. The X- and Y- coordinates are the district location with {0,0} indicating upper left corner and {1000,1000} lower right). . Click any cell to enter or change it's value. Hover the mouse over any button to get more details on use of the button. Click any column header to sort the districts by values in that column. Click again to resort in the opposite direction. Use the drop-down list for countries to limit the display of districts. Click 'Save and Close' to save changes and close the editor.

Jordan

District	Sort Order	Country	X-Coordinate	Y-Coordinate
Amman	1.00	Jordan	580	351
Zarqa	2.00	Jordan	764	256
Mafraq	3.00	Jordan	843	145
Irbid	4.00	Jordan	398	27
Ajloun	5.00	Jordan	290	170
Jerash	6.00	Jordan	491	209
Balqa	7.00	Jordan	125	300
Madaba	8.00	Jordan	494	474
Karak	9.00	Jordan	469	641
Maan	10.00	Jordan	794	855
Tafelah	11.00	Jordan	536	789
Aqaba	12.00	Jordan	459	961

A. Defining the Districts

B. Defining the Water Availability Events

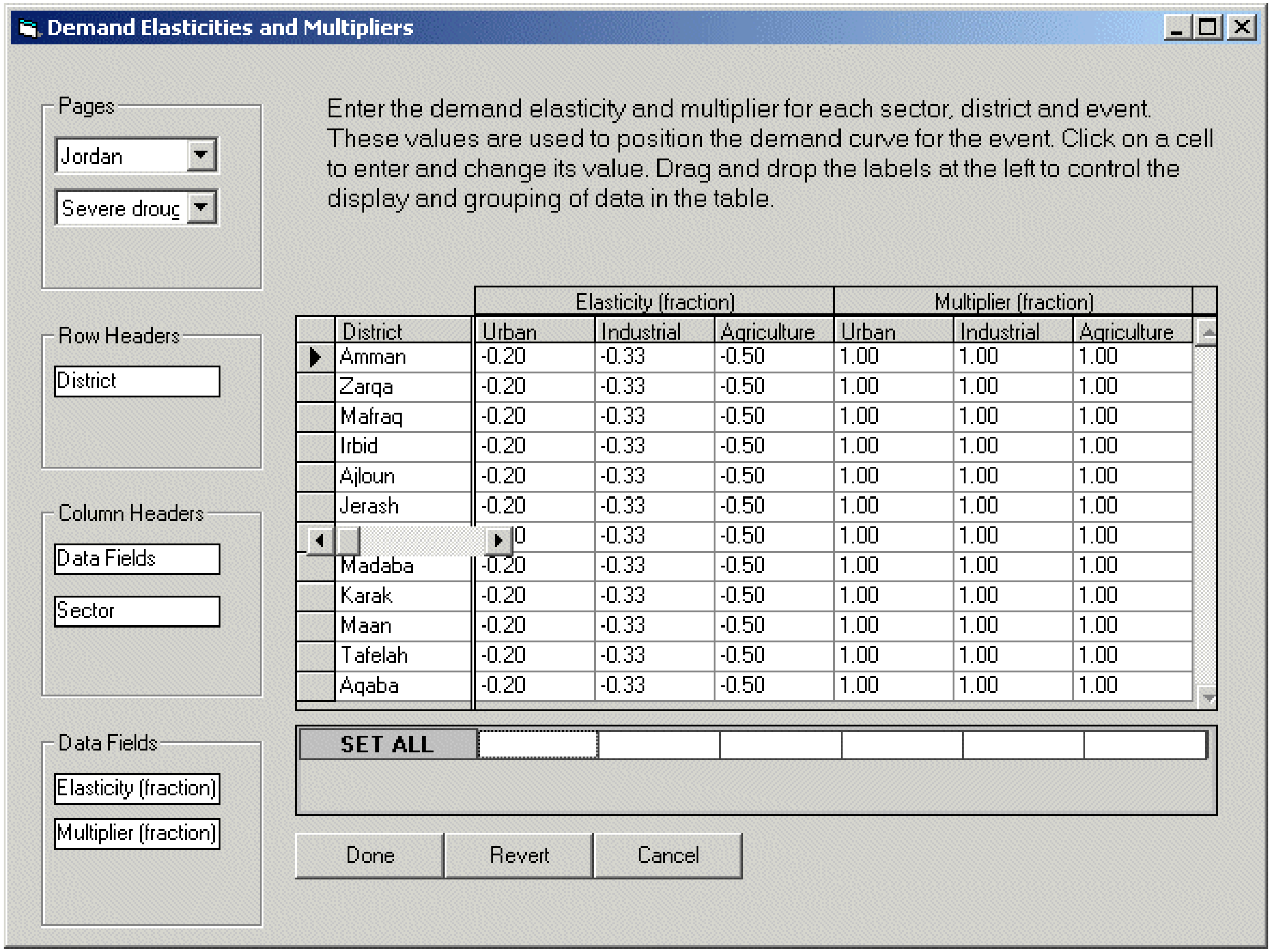


Specify and edit the events to include in the scenario. For each event, specify a event name, sort order, probability (percent), and availability multiplier (fraction). (Sort order is the order each event will appear in subsequent lists). Click any cell to enter or change it's value. Hover the mouse over any button to get more details on use of the button. Click any column header to sort the events by values in that column. Click again to resort in the opposite direction. Click 'Save and Close' to save changes and close the editor.

Event	Sort Order	Probability (percent)	Availability Multiplier (fraction)
Severe drought	1.00	9.8%	0.44
Drought	2.00	19.9%	0.56
Moderate drought	3.00	24.0%	0.68
Average	4.00	27.2%	1.03
Wet	5.00	11.8%	1.54
Very wet	6.00	7.3%	2.05

Figure 6.3. Stochastic WAS data entry

C. Entering Demand Curve Elasticity and Multiplier for each District, Sector, and Event.



Pages: Jordan; Severe droug

Row Headers: District

Column Headers: Data Fields; Sector

Data Fields: Elasticity (fraction); Multiplier (fraction)

Enter the demand elasticity and multiplier for each sector, district and event. These values are used to position the demand curve for the event. Click on a cell to enter and change its value. Drag and drop the labels at the left to control the display and grouping of data in the table.

	Elasticity (fraction)			Multiplier (fraction)		
District	Urban	Industrial	Agriculture	Urban	Industrial	Agriculture
Amman	-0.20	-0.33	-0.50	1.00	1.00	1.00
Zarqa	-0.20	-0.33	-0.50	1.00	1.00	1.00
Mafraq	-0.20	-0.33	-0.50	1.00	1.00	1.00
Irbid	-0.20	-0.33	-0.50	1.00	1.00	1.00
Ajloun	-0.20	-0.33	-0.50	1.00	1.00	1.00
Jerash	-0.20	-0.33	-0.50	1.00	1.00	1.00
[illegible]	[illegible]	-0.33	-0.50	1.00	1.00	1.00
Madaba	-0.20	-0.33	-0.50	1.00	1.00	1.00
Karak	-0.20	-0.33	-0.50	1.00	1.00	1.00
Maan	-0.20	-0.33	-0.50	1.00	1.00	1.00
Tafelah	-0.20	-0.33	-0.50	1.00	1.00	1.00
Aqaba	-0.20	-0.33	-0.50	1.00	1.00	1.00

Figure 3 (continued). WAS data entry

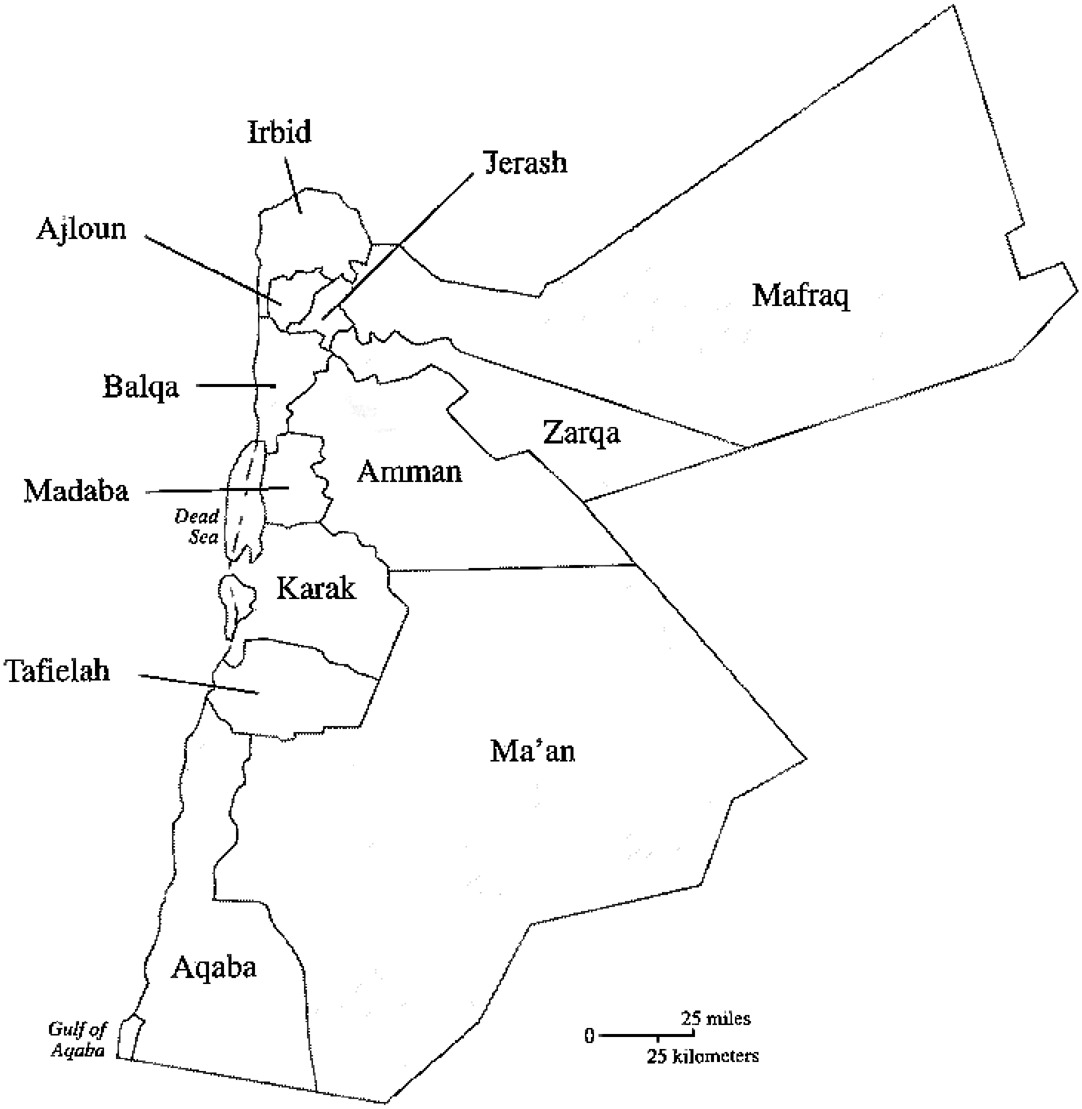
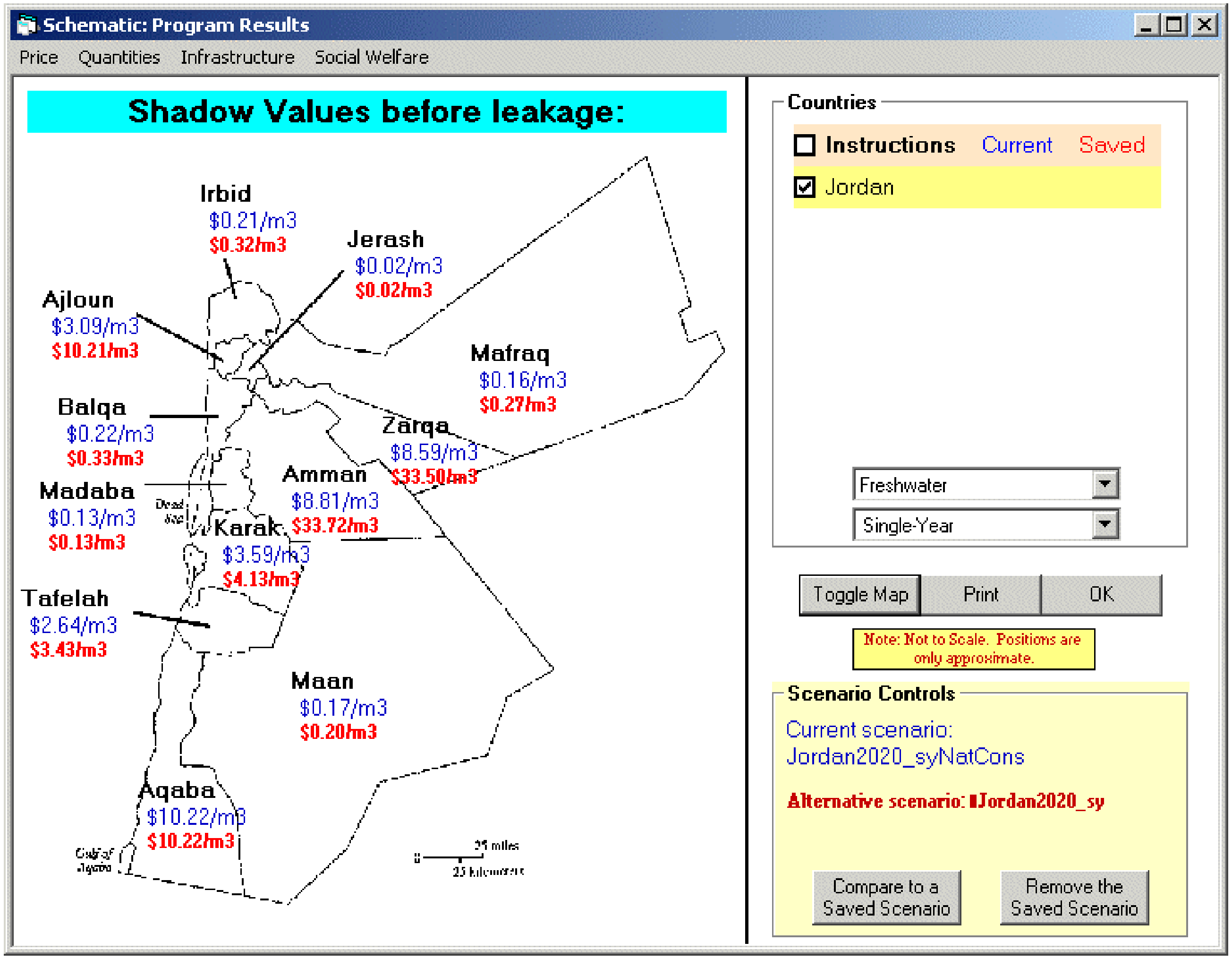


Figure 6.4. Jordan governorates (water districts) (adapted from Fisher et. al. [2005])



☐ Instructions

☑ Jordan

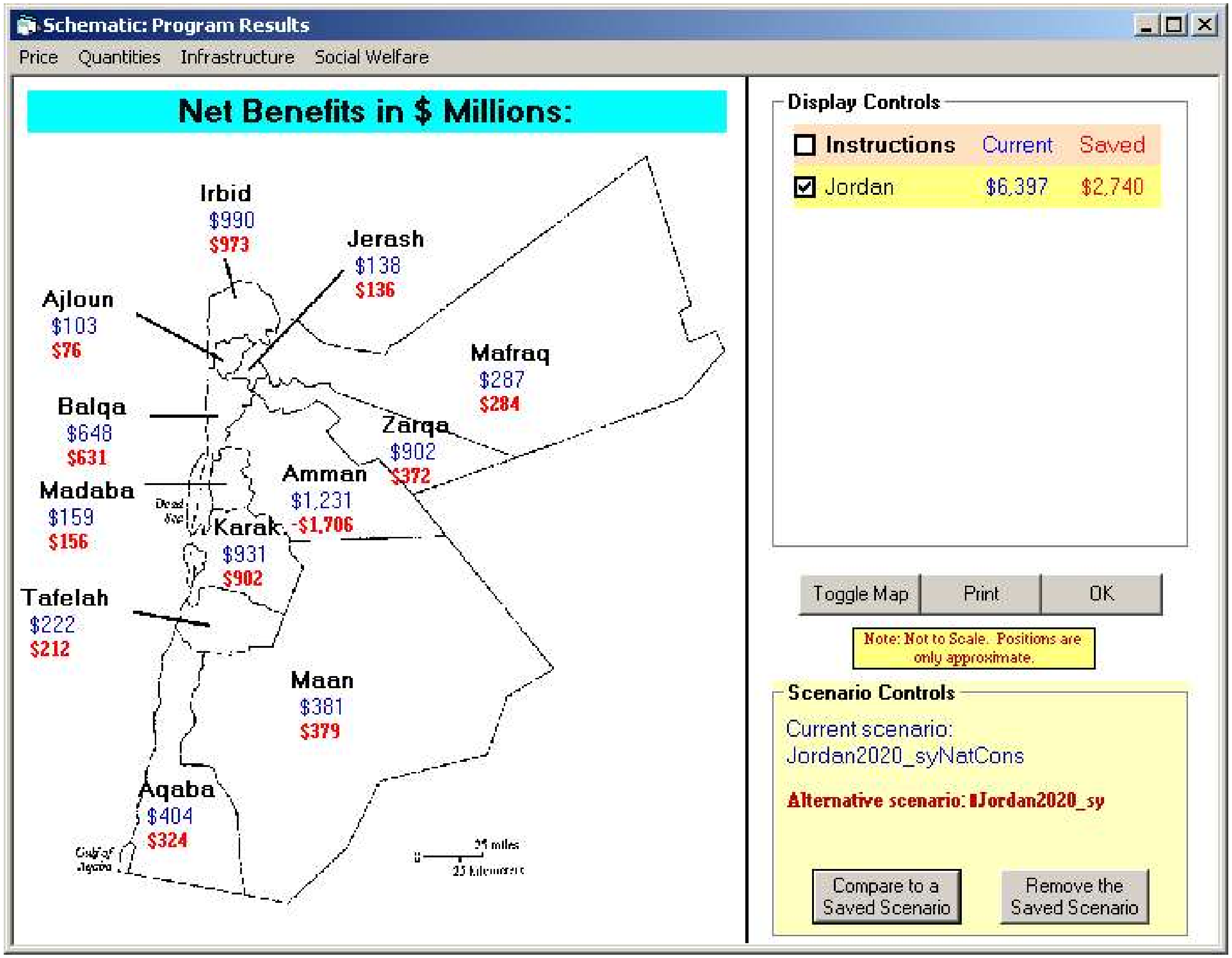
Freshwater

Single-Year

Current scenario:
Jordan2020_syNatCons

Alternative scenario: IJordan2020_sy

Figure 6.5. Shadow values in \$/m^3 for freshwater in each district with (top line) and without (bottom line) targeted installations of water efficient appliances for select urban users

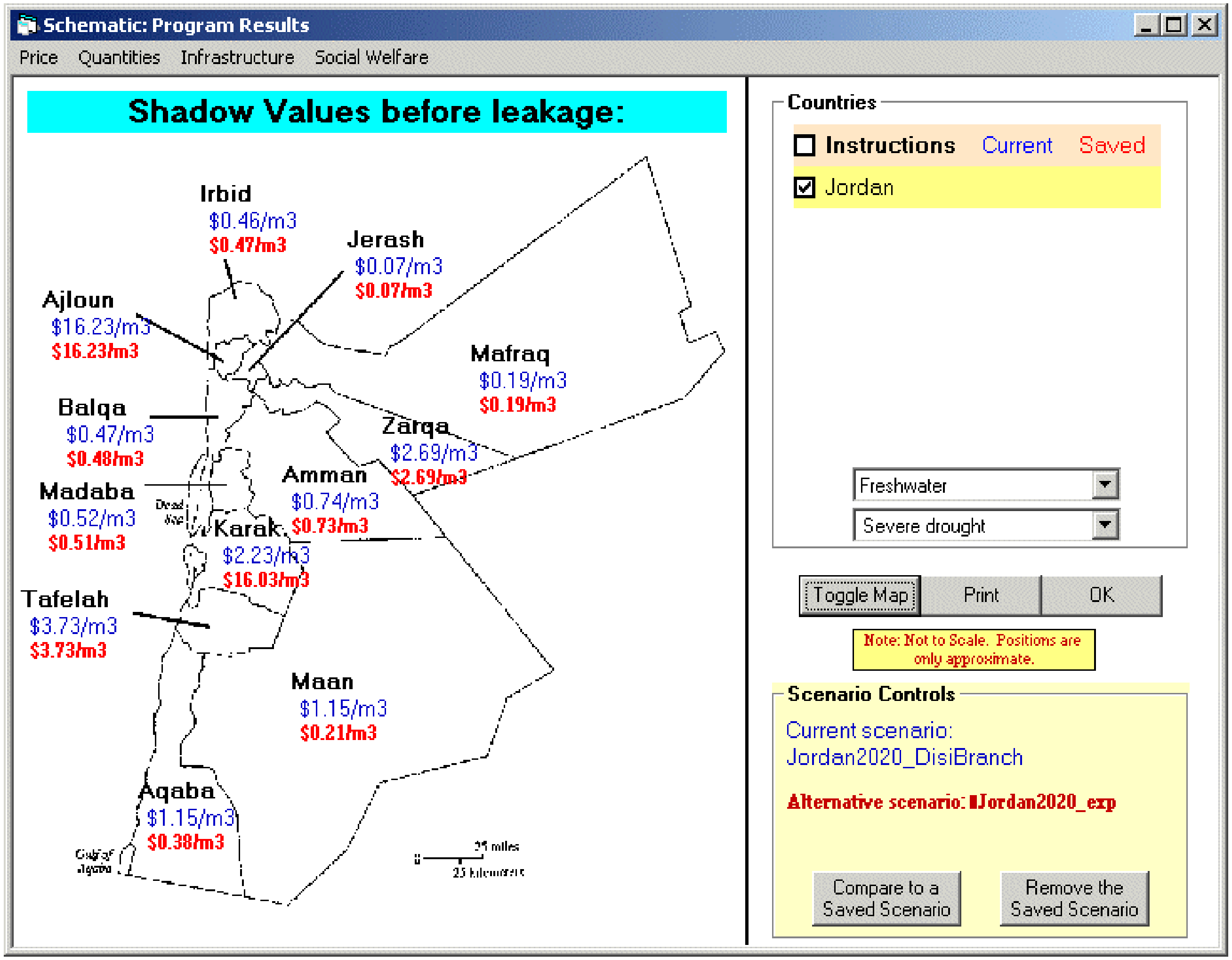


	Current	Saved
☐ Instructions		
☑ Jordan	$6,397	$2,740

Current scenario:
Jordan2020_syNatCons

Alternative scenario: ▮Jordan2020_sy

Figure 6.6. Annualized net benefits in $Millions/year with (top line) and without (bottom line) targeted installations of water efficient appliances for select urban users throughout the country

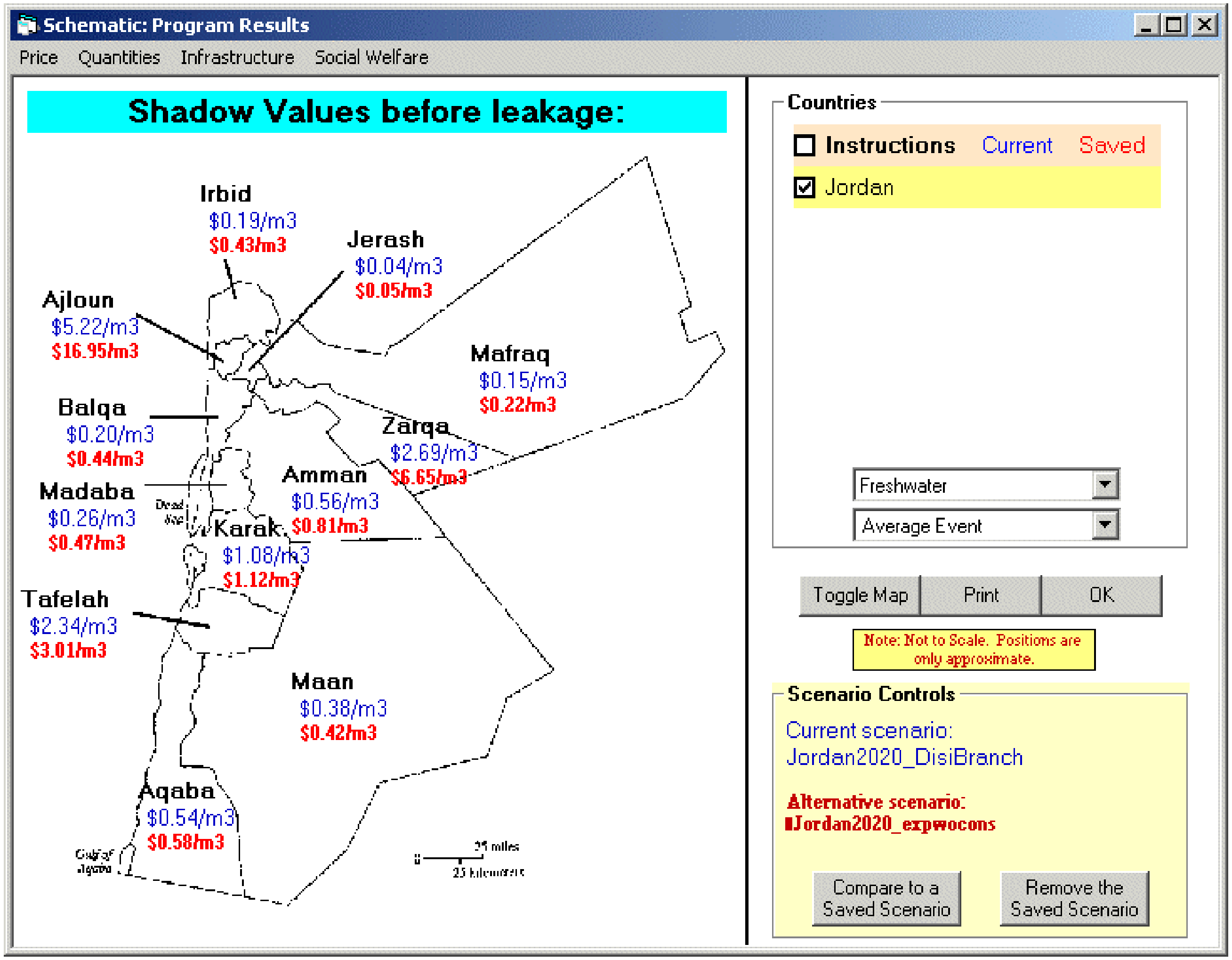


Note: Not to Scale. Positions are only approximate.

Current scenario: Jordan2020_DisiBranch

Alternative scenario: Jordan2020_exp

Figure 6.7. Shadow values in $\$/m^3$ with (top line) and without (bottom line) a Disi carrier branch to Karak



Note: Not to Scale. Positions are only approximate.

Current scenario:
Jordan2020_DisiBranch

Alternative scenario:
Jordan2020_expwocons

Figure 6.8. Shadow values in $/m^3 with (top line) and without (bottom line) targeted installations of water efficient appliances for select urban users

Table 6.1. Regional scale water management actions in Jordan

Stage	New Supplies	Conservation	Political actions to encourage implementation
Long-term (Infrastructure expansion and program development)	• Surface and groundwater storage and extraction facilities • Seawater desalination plants • Wastewater treatment pants • Expand conveyance pipelines and canals	• Restructure distribution system • Lower operating pressure • Optimize and control flows • Target installations of water-efficient appliances to users	• Negotiate water rights • Secure aid for infrastructure development • Restrict imports of inefficient water appliances • Establish and enforce water efficient plumbing codes • Fund research to develop conservation technologies • Give tax credits to users who install water efficient appliances
Short-term (annual operations)	• Surface and groundwater use • Inter-district transfers • Desalination operations • Treat wastewater for reuse	• Ration to meet demands • Reallocate among sectors	• Import food • Pass and enforce groundwater use laws

Table 6.2. Infrastructure expansion options for Jordan

District (Project)	Existing Capacity (MCM)	Expansion Cost ($Mill/MCM)	Maximum Capacity (MCM)	Operating Cost ($/m^3)	Operating Life (years)	Source
Local Source Development						
Amman (Zara Ma'een)	0	5.04	35	0.44	15	WAJ, 2005; Nuaimat and Ghazal, 2006
Irbid (Yarmouk River)	126	1.39	206	0.17	20	MWI, 2005
Ma'an (Disi Aquifer)	70	1.41	170	0.08	25	El-Nasser, 2005; Nuaimat and Ghazal, 2006
Aqaba (Wadi Yutum)	0	1.96	2.5	0.10	20	Abdelghani et al, 2007
Aqaba (Wadi Araba)	0	0.32	7.5	0.89	20	Abdelghani et al, 2007
Seawater Desalination Plants						
Balqa (Red-Dead Project)	0	0.27	850	0.92	20	El-Nasser, 2005
Aqaba (Reverse Osmosis)	0	2.67	7.5	0.37	20	Abdelghani et al, 2007
Wastewater Treatment Plants						
Amman (Al-Samra Expan.)	26	2.13	97.5	0.05	20	MWI, 2005
Zarka (Wadi Zarka Plant)	23	2.24	76.7	0.10	20	MWI, 2005
Aqaba (Tertiary Treatment)	2	2.25	6.38	0.10	25	Abdelghani et al, 2007
Conveyance Expansions						
Balqa to Amman (Zai Expansion)	45	1.82	90	0.23	15	Fisher et al, 2005; USAID, 2005
Ma'an to Amman (Disi Carrier)	0	7.05	100	0.22	20	El-Nasser, 2005; Nuaimat and Ghazal, 2006
Ma'an to Aqaba (Disi Expansion phases I & II)	0	2.32	14	0.08	20	Abdelghani et al, 2007

Table 6.3. Conservation program options for Jordan

District	Existing Rate (%)	Max. Achiev. Rate (%)	Capital Cost ($Mill/1% chg.)	Operating Life (years)	Source
Water Use Efficiency Programs					
Amman (targeted)	0%	33%	2.02	7	Rosenberg et al., in press
Zarka (prorated)	0%	33%	0.80	7	
Mafraq (prorated)	0%	33%	0.22	7	
Irbid (prorated)	0%	33%	0.95	7	
Ajloun (prorated)	0%	25%	0.13	7	
Jerash (prorated)	0%	25%	0.16	7	
Balqa (prorated)	0%	25%	0.35	7	
Madaba (prorated)	0%	25%	0.13	7	
Karak (prorated)	0%	25%	0.22	7	
Ma'an (prorated)	0%	25%	0.10	7	
Tafeliah (prorated)	0%	25%	0.09	7	
Aqaba (prorated)	0%	25%	0.11	7	
Leak Reduction Programs					
Amman (Capital Improvement)	25%	14%	17.8	20	MWI, 2005
Zarka (prorated)	25%	14%	7.0	20	
Mafraq (prorated)	25%	14%	1.9	20	
Irbid (prorated)	25%	14%	8.4	20	
Ajloun (prorated)	25%	14%	1.1	20	
Jerash (prorated)	25%	14%	1.4	20	
Balqa (prorated)	25%	14%	3.1	20	
Madaba (prorated)	25%	14%	1.1	20	
Karak (prorated)	25%	14%	1.9	20	
Ma'an (prorated)	25%	14%	0.9	20	
Tafeliah (prorated)	25%	14%	0.7	20	
Aqaba (prorated)	25%	14%	1.0	20	

Table 6.4. Net benefits for different model scenarios

Scenario (A)	**Net Benefits** ($ Millions/year) **Single-Event** (C)	 **Stochastic** (D)
1. Verification run	2,740	-
2. Targeted installations of water efficient appliances by select urban users in Amman	5,704	-
3. Targeted installations of water efficient appliances by select urban users throughout Jordan	6,397	
4. Current conditions with Zara Ma'een project	5,101	-
5. Optimal expansions and developments	6,906	6,830
6. Opt. exp. + develop. and Disi carrier branches to Madaba and Karak	-	6,893
7. Opt. Exp. + develop., Disi branches, and water use efficiency by agricultural users	-	6,910
8. Optimal expansions and developments without targeted installations of water efficient appliances	6,549	6,489

Table 6.5. Optimal long-term infrastructure expansions and conservation program development actions

District (Project) (A)	**Initial Capacity** (MCM) (B)	**Maximum Expansion** (MCM) (C)	**Infrastructure Capacity Expansion** (MCM)			
			Model Scenario			
			Optimal expands, single-event (D)	Optimal expands, stochastic-events (E)	Disi Branches (F)	No Water Use Efficiency (G)
Source Development						
Amman (Zara Ma'een)	35.0	35.0	-	-	-	-
Irbid (Yarmouk River)	128.0	208.0	80.0	11.8	11.8	41.3
Maan (Disi Aquifer)	55.0	155.0	6.5	5.8	38.9	43.9
Aqaba (Wadi Yutum)	-	2.5	2.5	2.5	2.5	2.5
Aqaba (Wadi Araba)	-	7.5	-	-	5.9	7.5
Seawater Desalination Plants						
Balqa (Red-Dead Canal)	-	850.0	-	-	-	29.9
Aqaba (RO plant)	-	7.5	-	-	-	3.5
Wastewater Treatment Plants						
Amman (As-Samra Exp.)	26.0	97.5	-	54.1	53.8	70.5
Zarqa (Wadi Zarka Plant)	23.0	76.7	-	-	-	-
Aqaba (Tertiary Treatment)	2.0	6.4	2.1	2.1	2.1	2.1
Conveyance Expansions						
Maan to Aqaba (Disi Exp., phases I & II)	-	14.0	14.0	14.0	12.8	12.8
Maan to Amman (Disi Carrier)	-	100.0	-	-	37.0	39.7
Balqa to Amman (Zai Expansion)	45.0	940.0	45.0	46.2	45.8	74.5

District	**Initial Rate** (%)	**Maximum Rate** (%)	**Conservation Program Development** (%)			
			Model Scenario			
			Optimal expands, single-event	Optimal expands, stochastic-events	Disi Branches	No Water Use Efficiency
Targeted Installations of Water Efficient Appliances to Urban Users						
Amman	0%	33%	33%	33%	33%	-
Zarqa	0%	33%	33%	33%	33%	-
Mafraq	0%	33%	33%	33%	33%	-
Irbid	0%	33%	33%	33%	33%	-
Ajloun	0%	25%	25%	25%	25%	-
Jerash	0%	25%	25%	25%	25%	-
Balqa	0%	25%	25%	25%	25%	-
Madaba	0%	25%	25%	25%	25%	-
Karak	0%	25%	25%	25%	25%	-
Maan	0%	25%	25%	25%	25%	-
Tafelah	0%	25%	25%	25%	25%	-
Aqaba	0%	25%	25%	25%	25%	-
Leak Reduction Programs						
Amman	25%	14%	-	-	-	-11%
Zarqa	25%	14%	-11%	-11%	-11%	-11%
Mafraq	25%	14%	-	-	-	-5%
Irbid	25%	14%	-	-	-	-
Ajloun	25%	14%	-11%	-11%	-11%	-11%
Jerash	25%	14%	-	-	-	-
Balqa	25%	14%	-2%	-	-	-5%
Madaba	25%	14%	-	-	-	-11%
Karak	25%	14%	-11%	-11%	-11%	-11%
Maan	25%	14%	-11%	-11%	-11%	-11%
Tafelah	25%	14%	-11%	-11%	-11%	-11%
Aqaba	25%	14%	-11%	-11%	-11%	-11%

Annualized Capital Expenditures ($ Mill/year)	**49**	**50**	**54**	**52**
Annualized Net Benefits ($ Mill/year)	**6,906**	**6,830**	**6,893**	**6,549**

Table 6.6. Scarcity values after optimal infrastructure expansion and conservation program developments (run 4, stochastic events)

District	**Water Availability Event** [availability level (probability)]					
	Severe Drought [0.44 (10%)]	Drought [0.56 (20%)]	Mod. Drought [0.68 (24%)]	Average [1.03 (27%)]	Wet [1.54 (12%)]	Very Wet [2.05 (7%)]
Amman	0.73	0.64	0.56	0.50	0.50	0.48
Zarqa	2.69	2.69	2.69	2.69	2.69	2.69
Mafraq	0.19	0.15	0.15	0.15	0.15	0.15
Irbid	0.47	0.20	0.18	0.15	0.11	0.09
Ajloun	16.23	9.30	5.59	1.49	0.19	0.09
Jerash	0.07	0.07	0.04	0.02	0.02	0.02
Balqa	0.48	0.21	0.19	0.16	0.12	0.10
Madaba	0.51	0.42	0.34	0.13	0.01	0.01
Karak	16.03	9.85	6.43	2.33	0.71	0.24
Maan	0.21	0.20	0.19	0.19	0.18	0.18
Tafelah	3.73	3.17	2.70	1.82	1.08	0.94
Aqaba	0.38	0.38	0.38	0.38	0.38	0.38

Chapter 7

Conclusions

7.1. Review of Problem and Solution Approach

Water shortages in Jordan are a major and growing problem. Water availability is usually just 12 to 72 hours per week yet there are several dozen or more potential options to improve availability (Table 7.1). What actions should individual households, the Amman water utility, and the national government take to reduce shortages or improve system performance?

This dissertation has developed and applied integrated systems analysis to identify promising actions to address shortages. The approach integrates diverse options including new supplies, conservation to more efficiently use existing supplies or alter the timing of uses to make them better coincide with supply availability, and improving the institutional and regulatory environments to encourage new supply or conservation efforts. The analyses also consider long- and short-term investments, multiple water qualities for different uses, and uncertainties in all of the above including in action costs, life spans, effectiveness, water availabilities, reliabilities, and user behaviors.

The systems analysis draws from the disciplines of engineering, economics, and operations research and works as follows:

1. Identify all potential options
2. Characterize each action by its cost, lifespan, and effectiveness,
3. Describe interdependencies among actions
4. Quantify the magnitude and likelihood of events for which the system must deliver water, and
5. Optimize to identify the cost-effective mix of actions that meet shortages over all expected events.

Stochastic optimization programs with recourse decisions identified the cost-effective mixes of actions. Further sensitivity analysis, analytical error propagation, Monte-Carlo simulations, robust, Best/Worst, and Grey-Number formulations considered uncertainties.

The analysis was repeated separately at three scales for individual households, the city of Amman, and all of Jordan. Promising actions identified at the household scale were included in the option mix for city and similarly at the regional scale.

Below, sections two through five summarize the key methodological contributions, management recommendations for Jordan, complementary scales for action, and recommendations for further work. Section six gives the overall findings.

7.2. Methodological Contributions

Systems analysis at household, city, and regional scales has yielded contributions for water conservation planning, water use estimation, uncertainty propagation, and applied engineering, economics, and operations research. Contributions include:

At the household scale:

1. New analytical and numerical approaches to estimate the distribution of water saved when a household adopts a conservation action,
2. Ability to integrate source, availability, quality, local storage, costs, conservation, and user behaviors to estimate household water use,
3. An empirically tested estimate for the distribution of water use among customers in Amman, while
4. Simultaneously predicting (i) adoption rates for conservation technologies, (ii) water use response to changes in water prices plus other factors, and (iii) household willingness-to-pay to avoid shortages.

At the city scale, modeling:

5. Integrates multiple supply and conservation options with uncertainties, and
6. Yields consistent results with different approaches to handle parameter uncertainties, however,
7. Shows grey-number solutions are risk-prone—give higher costs than from a worst-case analysis.

From regional scale work, we can now:

8. Represent non-price shifts in demand from water use efficiency in a hydro-economic model,
9. Integrate effects of user and utility actions identified at narrow spatial scales, and
10. Include infrastructure expansions and conservation program decisions along with stochastic water availability.

Combined, the above efforts also

11. Identify complementary actions taken by actors at different scales. Complementary scales for action are further discussed in Section 7.3.

7.3. Management Recommendations for Jordan

Results from the systems analysis made for Jordan further show:

For individual households in Amman:

- Households differ in their abilities to conserve water,
- Targeted campaigns can save significant water and money with reduced effort,

- Target installations of water-efficient appliances to households that will save the most money and water.

For the City of Amman:

- A wide mix of conservation, alternative supplies, and capacity expansion (Zai pumping plant) should help overcome shortages forecast through 2040.
- Conservation—both targeted conservation programs for select households and reducing distribution system leaks—play important and growing roles over time.
- There is a delayed need for mega-supply projects such as pumping the distant fossil Disi aquifer, and
- No role for seawater desalination and conveyance (Red-Dead Canal) as an economical water supply project.

Regional scale results show:

- Improved water use efficiency for urban water users generate substantial regional economic benefits and can forestall the need for infrastructure expansions.
- A broad mix of other infrastructure expansions projects and leak reduction programs can substitute for and forestall desalination in Aqaba and Balqa.
- The Disi carrier to Amman should include a large branch to Karak, and
- Impending water scarcities in Tafelah, Ajloun, and Zarqa should be better managed by increasing conveyance from the neighboring districts of Ma'an, Irbid, and Mafraq where water is more available.

7.4. Complementary Scales for Action

Several promising management actions summarized above are implemented at several scales. In particular, conservation appears repeatedly. Individual households—on their own accord—have financial incentives to install water efficient appliances. Further, city programs to encourage or subsidize households to install water efficient appliances represent a cost-effective option for the city to cope with shortages. Also, targeted installations of water efficient appliances all across Jordan will generate substantial regional benefits. These benefits can be used to fund or justify national government efforts to develop and enforce water efficient plumbing codes, better label appliance water use (so customers can make better-informed purchases), or restrict the manufacture or import of inefficient water-use appliances.

Table 7.2 organizes the promising options from each scale to better illustrate the complementary scales for action. Placement in Table 7.2 shows both who initiates / suggests the action (row header) and who implements the action (column header) to procure the additional water or reduce use. For example, the upper-right box shows the national government finds it beneficial to develop water efficient plumbing codes, restrict the manufacture and import of water wasting appliances, and offer tax incentives to customers who install water-efficient appliances. However, these regional initiated actions only reduce water use when individual water users purchase and install water efficient appliances. But, scrolling down the User column shows that the city also finds it beneficial to offer water audits to recommend water-efficient purchases for users or rebates to encourage those purchases. Further, users find benefit to install water efficient appliances and landscaping. These complementary listings illustrate the linkages across scales. Linkages are bi-directional and work both from the (i) top-down (as centralized command and control management described above), and (ii) bottom-up (as grass roots lobbying or organization). For example, users who see benefits to install water-efficient appliances can motivate their friends or family to likewise adopt or lobby or otherwise organize to encourage decision makers at city or regional scale help make those appliances more widely available.

7.5. Further work

The systems analyses work presented herein identifies numerous promising actions and complementary scales for implementation. Additional work is needed to better promote and disseminate promising options and verify their benefits.

For example, household surveys (Chapter 3) reveal that Amman residents can list conservation options, but lack specific knowledge such as what devices are water efficient, where they are purchased, their costs, how they are installed, or what benefits they might derive from them. Such limitations identify awareness, skill development and motivation as important to make targeted conservation programs successful.

We must also verify that water savings estimated herein translate to actual water savings when users install water efficient appliances. Verification first requires estimating water savings for individual households then monitoring households' aggregate and disaggregated water use before and after installation. A variety of non-intrusive, passive equipment is available to monitor components of household water use (Mayer et al. 1999; Vickers 2001). Verification studies could be made either in Jordan or the U.S.

At the city scale, improved employee accountability will help make efforts such as water audits for customers, rebates for installation of water efficient appliances, water meter retrofits, improved meter reading and billing effective and long-lasting. City and Regional scale stochastic modeling should also better represent water storage (both surface- and groundwater) across the stochastic water-availability events (inter-annual transfers). Marques (2004) includes inter-temporal transfers but does so by assuming groundwater storage capacity is very large compared to operational storage levels. This approach will not work in Jordan where surface and groundwater levels often hit the physical storage limits.

At the regional scale, further systems analyses should focus to resolve optimal sequencing of infrastructure capacity expansion and conservation program development over time with uncertain but growing demands. Optimal staging and timing can help identify when to start mega-supply projects like the Disi Aquifer or Red-Dead Canal, particularly since these projects have long (10+ year) lead times. Manne (1961), Bean et. al (1992), and others outline frameworks to examine project staging with uncertain demand. Additional important areas for regional study include optimal water management for environmental purposes, use of non-renewable resources (such as fossil groundwater), and integrated multi-objective management.

Finally, most of this dissertation focused on water supply and conservation for urban water users. In Jordan and many other places, agricultural water use is a large component of the regional water budget (70% in Jordan) and agricultural water conservation should present many promising new options. Much more research, modeling, applications, and verification are needed in this area.

7.6. Overall Findings

Overall, this work shows that modeling can integrate multiple source, reliability, conservation options, quality, costs, and explicit uncertainties to estimate water use and potential savings from adopting water efficient use practices. Integrating these multiple factors in a systems analysis further identifies promising actions to improve water availability in the face of shortages. Applications at different scales show multiple, complementary options for individual Jordanian households, the city of Amman, and region to improve water availability. Among these, urban water conservation—both reducing the leakage in the distribution system and motivating select households to install water efficient appliances—is very promising and should generate significant regional benefits. However, to improve availability, Jordan will require significant water sector investments over the next 20 years—more than $US 3 billion or about 10% of Jordan's annual gross domestic product.

7.7. Literature Cited

Bean, J. C., Higle, J. L., and Smith, R. L. (1992). "Capacity Expansion under Stochastic Demands." *Operations Research*, 40, S210-S216.

Manne, A. S. (1961). "Capacity Expansion and Probabilistic Growth." *Econometrica*, 29(4), 632-649.

Marques, G. (2004). "Economic Representation of Agricultural Activities in Water Resources Systems Engineering," PhD, University of California, Davis, Davis.

Mayer, P. W., DeOreo, W. B., Opitz, E. M., Kiefer, J. C., Davis, W. Y., Dziegielewski, B., and Nelson, J. O. (1999). "Residential End Uses of Water," American Water Works Association, Denver, Colorado. http://www.aquacraft.com/index.htm.

Vickers, A. L. (2001). *The handbook of water conservation*, WaterPlow Press, Amherst, Massachusetts. www.waterplowpress.com.

Table 7.1. Potential water management actions to cope with shortages in Jordan

Spatial Scale	New Supplies	Conservation
National or Regional	• Negotiate water rights • Inter-basin transfers • Secure aid to develop infrastructure	• Import food, reallocate among water sectors • Restrict imports on inefficient water appliances • Establish water efficient plumbing codes • Fund research to develop water efficient appliances • Give tax credits to persons who install water-efficient appliances
Utility or District	• Expand wastewater recycling and reuse • Develop new surface and groundwater resources • Seed clouds to enhance runoff • Expand system storage, conveyance, and treatment capacities • Desalinate seawater or brackish waters • Negotiate and exercise options to buy water during droughts or shortages • Purchase water on the spot market	• Detection and repair distribution system leaks • Optimize system flows • Reduce system operating pressure • Ration service • Restrict certain water uses (outdoor) • Reduce un-accounted for or illegal water use • Re-price water • Subsidize customers to install water-efficient appliances • Customer education and awareness programs
Water User or Customer	• Develop alternative, local sources (rainwater catchment, groundwater, springs) • Increase draw from distribution network • Collect and reuse grey-water • Purchase from water venders • Borrow or steal from others • Boil or treat water to drink	• Install water-efficient appliances • Landscape or grow low-water consuming plants or crops • Detect and repair leaks • Modify or reduce water-use behaviors

Table 7.2. Complementary scales for actions to improve water availability in Jordan

		Implements Action		
		National	**City**	**Users**
Initiates Action	**National**	✓ Negotiate compacts ✓ Fund research to develop water - efficient appliances	✓ Allocations + transfers ✓ Health, quality, and water rights regulations ✓ Appoint officials ✓ Grants / loans	✓ Plumbing codes ✓ Import restrictions ✓ Tax credits
	City	✓ Lobby ✓ Advise national authorities	✓ New supplies + convey. ✓ Desalinate ✓ Repair network ✓ Pressure control ✓ Train staff ✓ Reuse wastewater ✓ Buy drought options	✓ Water audits ✓ Water pricing ✓ Rebates to retrofit ✓ Awareness campaigns ✓ Ration ✓ Retrofit water meters
	User	✓ Voting ✓ Political donations ✓ Political demonstrations	✓ Pay bills ✓ Customer confidence ✓ Illegal water use ✓ Choose water source or vendor	✓ Install water efficient appliances ✓ Xeriscape ✓ Fix plumbing leaks ✓ Change use behaviors ✓ Peer pressure

Implies top – down management (command and control)

Implies bottom – up development (grass roots)