Modeling integrated water user decisions in intermittent supply systems

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[1] 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.

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1. Introduction

[2] 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. They also 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].

[3] The literature on water use modeling and user behaviors has developed in two directions. First, regression models (for reviews, see *Hanemann* [1998], *Young* [2005], and *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.

[4] 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.

[5] This paper 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 (Figure 1). We also embed uses that accommodate different water qualities (Figure 2). 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.

[6] 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:

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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

Figure 1. Potential management actions for water users in Amman, Jordan.

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

Figure 2. Water quality associated with end uses; "a" indicates water is available for reuse outdoors.

[7] 1. Identify a wide range of potential long- and short-term user actions (Figure 1).

[8] 2. Characterize each action in terms of a financial cost, effective water quantity added or conserved, and water quality affected [*Rosenberg et al.*, 2007].

[9] 3. Describe interdependencies among actions (demand hardening, supply enhancement, and mutual exclusivity).

[10] 4. Characterize the events through which the user must manage water (source availabilities, uses, and likelihoods).

[11] 5. Identify the actions and associated use that minimize the user's costs across all events (stochastic optimization with recourse decisions).

[12] 6. Repeat for a wide variety of user conditions (Monte Carlo simulations).

[13] We identify and characterize actions and events in the study area using prior empirical work, our own surveys and questionnaires [*Rosenberg et al.*, 2007], and prior estimates of conservation action effectiveness [*Rosenberg*, 2007]. 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. 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.

[14] 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 paper is organized as follows. Section 2 reviews systems analysis for an individual water user. Section 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 and 5 describe Monte Carlo simulations and model calibration. Sections 6 and 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 8 concludes.

2. Systems Analysis for Water Users

[15] 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.

2.1. Identify Actions

[16] 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.

[17] For water users, long-term actions can include developing new supplies, expanding local storage, or installing appliances that improve water quality or use efficiency (Figure 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 toward a long-term action depends on the water user's expectation of capital cost, lifespan, discount rate, and future water availability, reliability, and quality.

2.2. Characterize Actions

[18] 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 [*Rosenberg*, 2007], 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.

2.3. Describe Interdependencies Among Actions

[19] 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 (1) water saved by taking shorter or less frequent showers and (2) gray water available for reuse outdoors. Alternatively, a customer must install roof down-

spouts and storage before collecting and using rainwater. A user can install a water-efficient semiautomatic or automatic laundry machine, not both. Interdependencies critically depend on the actions under consideration. In the Amman, Jordan example, we consider 42 interdependencies.

2.4. Characterize Events for Which the System Must Adapt

[20] 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.

[21] 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 (Figure 2) often force users to seek alternative sources when availability is limited. Event characteristics typically differ among users.

2.5. Suggest Mixes of Actions

[22] 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.

3. Stochastic Optimization With Recourse Decisions

[23] 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).

[24] 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. As water availability or reliability decreases, water users adopt increasingly expensive short-term actions.

[25] 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 (Figure 1); a variety of drinking, indoor, and outdoor water uses that accommodate different water qualities (Figure 2); interdependencies among actions; limited source availability and reliability; and nonlinear costs.

[26] These extensions reflect actions, uses, conditions, and costs (Appendix A) 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.

3.1. Decision Variables

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

[28] 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 $\mathbf{L}$, $\mathbf{S}$, and $\mathbf{X}$.

3.2. Model Formulation

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

$$\text{Minimize} \quad Z = c_1(\mathbf{L}) + a \cdot \sum_e p_e \cdot c_{2,e}(\mathbf{S}). \tag{1}$$

[30] 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.

[31] The objective function (equation (1)) is subject to several constraints.

[32] 1. Water supplies, $s_{u,e}$ ($\mathbf{S}$, $\mathbf{X}$) (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, $h_{u,e}$ ($\mathbf{L}$, $\mathbf{S}$) (m^3 event^{-1}),

$$s_{u,e}(\mathbf{S},\mathbf{X}) \geq d_{u,e} - h_{u,e}(\mathbf{L},\mathbf{S}), \quad \forall e \forall u. \tag{2}$$

[33] 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 ($d_{u,e}$).

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

$$L_{lt} \leq u_{lt}, \ \forall lt. \tag{3}$$

[35] 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, $g_{st,e}$ ($\mathbf{L}$, $\mathbf{S}$, $\mathbf{X}$) (m^3 event^{-1}), on the basis of interdependencies with other actions,

$$S_{st,e} \leq u_{st,e} + g_{st,e}(\mathbf{L},\mathbf{S},\mathbf{X}), \quad \forall e \ \ \forall st. \tag{4}$$

[36] Intermittently available sources have different upper limits ($u_{st,e}$) in different events e. The interdependency function, $g_{st,e}$, is an $n \times 1$ vector, n = rank ($\mathbf{L}$) + rank ($\mathbf{S}$) + rank ($\mathbf{X}$), 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 $u_{st,e}$.

[37] 4. 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,

$$\sum_{u} X_{u,e} \leq \sum_{st \in PSSs} S_{st,e}, \quad \forall e. \tag{5}$$

[38] 5. Local storage capacity, v_{stor} (**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,

$$\sum_{st \in PSs} X_{st,e} \leq v_{stor}(\mathbf{L}), \quad \forall e. \tag{6}$$

[39] 6. Finally, all decision variables must be positive:

$$L_{lt} \geq 0, \forall lt; \; S_{st,e} \geq 0, \; \forall st \forall e; \; X_{u,e} \geq 0, \; \forall u \forall e. \tag{7}$$

3.3. Model Discussion

[40] In the Amman, Jordan example, equations (1)–(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. Monte Carlo Simulations

[41] 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.

[42] First, we develop an empirical basis of water user behaviors and conditions from 9 prior studies in Amman, Jordan [*Theodory*, 2000; *Iskandarani*, 2002; *Snobar*, 2003; *Interdisciplinary Research Consultants*, 2004; *Rosenberg et al.*, 2007] (see also Jordan Meteorological Department (JMD), Rainfall, 2000, http://met.jometeo.gov.jo/; Center for Study of the Built Environment, Water conserving landscapes, 2004, http://www.csbe.org/water_conserving_landscapes/index.html; and Department of Statistics (DOS), Amman, Jordan, Urban agriculture survey, 1999, http://www.dos.gov.jo/sdb/env/env_e/home.htm and The preliminary results of the population and housing census, 2004, http://www.dos.gov.jo; and Academy for Educational Development, 2001, Capacity building project in Amman, Irbid, and Aqaba, report, 12 pp., Water Efficiency and Public Information for Action, U.S. Agency for International Development, Amman, Jordan, http://pdf.dec.org/pdf_docs/PNADB469.pdf). Absent other data, we make engineering estimates [*Rosenberg*, 2007]. Second, we use the empirical data to develop probability distributions for some 126 parameters that influence a customer's water use, water availability or reliability, effectiveness of one or more conservation actions, or action costs (Appendix A). 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 in explicit ways 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.

[43] 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.

[44] 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 [*Rosenberg et al.*, 2007] (Appendix A). 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 *Rosenberg et al.* [2007]).

[45] 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

$$d_{BathFaucet} = \frac{7}{1000}(P_N)(P_Y)(P_G), \tag{8}$$

where P_N = the flow rate of the existing bathroom faucet (l min^{-1}), P_Y = wash time (min person^{-1} d^{-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; that is, P_N, means the parameter is uncertain. Before sampling, use is also uncertain. Appendix A describes the parameters. Hereafter, P_N, refers to parameter N in Appendix A; 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.

[46] We use previously reported effectiveness functions for seven long-term conservation actions [*Rosenberg*, 2007]. For example, the water saved when retrofitting a bathroom faucet with a faucet aerator, $W_{FaucetRetroBath}$ (m^3 customer^{-1} yr^{-1}) is

$$W_{Faucet\,RetroBath} = \frac{365}{1000}(P_N - P_{AN})(P_Y)(P_G), \tag{9}$$

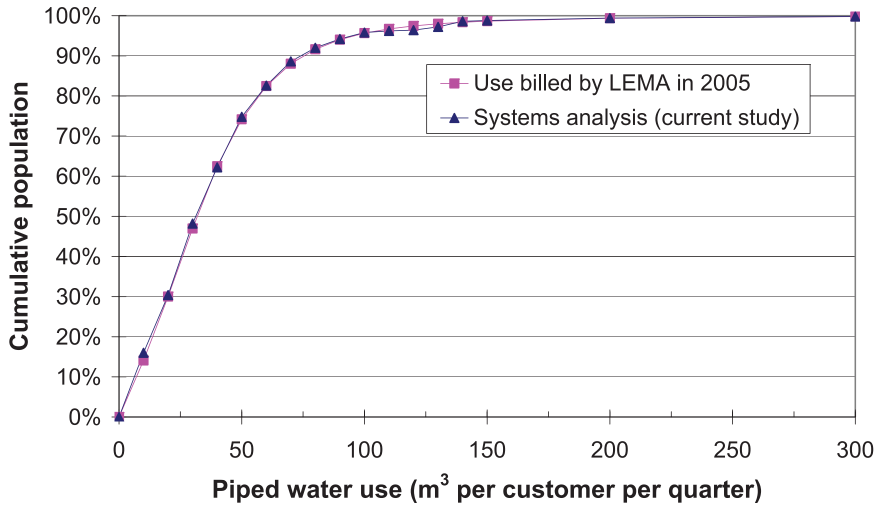

Figure 3. Model calibration against cumulative distribution of billed residential water use in 2005 for residential customers in Amman, Jordan.

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

[47] 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 (first 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 semiautomatic 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 [*Rosenberg et al.*, 2007] 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.

[48] In the Amman example, we consider three events: weeks of summer use with (1) limited and (2) unlimited piped water availability, and (3) 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:

$$p_{\textit{Summer Limited Availability}} = \frac{(P_C)}{a} \tag{10a}$$

$$p_{\textit{Summer Unlimited Availability}} = \frac{(P_B) - (P_C)}{a} \tag{10b}$$

$$p_{\textit{Winter}} = 1 - p_{\textit{Summer Unlimited Availability}} - p_{\textit{Summer Limited Availability}}. \tag{10c}$$

[49] Equations (8)–(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 (8) and (9) for faucet use and related conservation actions). Regression or customer preference models do not typically include these details or interdependencies.

5. Model Calibration

[50] We calibrate the cumulative distribution of modeled piped water use to use billed by Amman residential customers in 2005 (Figure 3). Calibration included 500 Monte Carlo simulated customers and set upper limits for all long-term conservation actions to zero (u_{lt} = 0 in equation (3)). This setting represents current conditions with limited adoption of long-term conservation actions (limited adoption is still represented by low sample values for technological parameters). 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

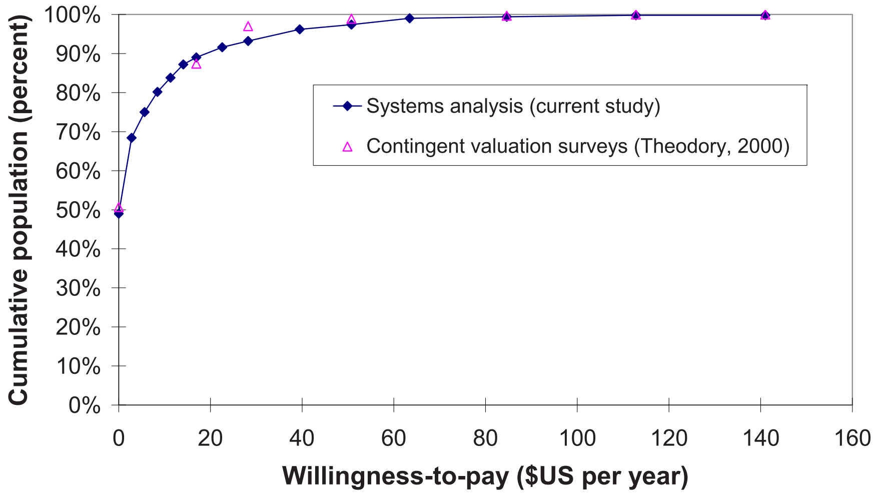

Figure 4. Cumulative distributions of willingness-to-pay to avoid shortage.

(K-S Test) between the billed and modeled water use distributions.

[51] Occupancy was chosen as the calibration parameter since the number of residential connections (customers) differs from the census of total and vacant housing units (O. Maghrabi, personal communication, 2006; and Department of Statistics, Amman, Jordan, The preliminary results of the population and housing census, 2004, http://www.dos.gov.jo). 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.

[52] 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 3). Both distributions skew heavily toward 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%.

6. Results for Parametric Changes

[53] 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.

6.1. Municipal Water Availability

[54] 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). 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).

6.2. Demand Response to Water Pricing

6.2.1. Alternative Water Sources

[55] 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 5). 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 nonelastic response near an average price of $US 2.5 per m^3. This switch point is also the current average price for tanker water.

6.2.2. Municipal Piped Water

[56] 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 1). 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.

[57] 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 1, columns titled "Short Term").

6.3. Conservation Campaign

[58] Releasing constraints on upper limits for long-term conservation actions (equation (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 2, second and third columns). Simulating

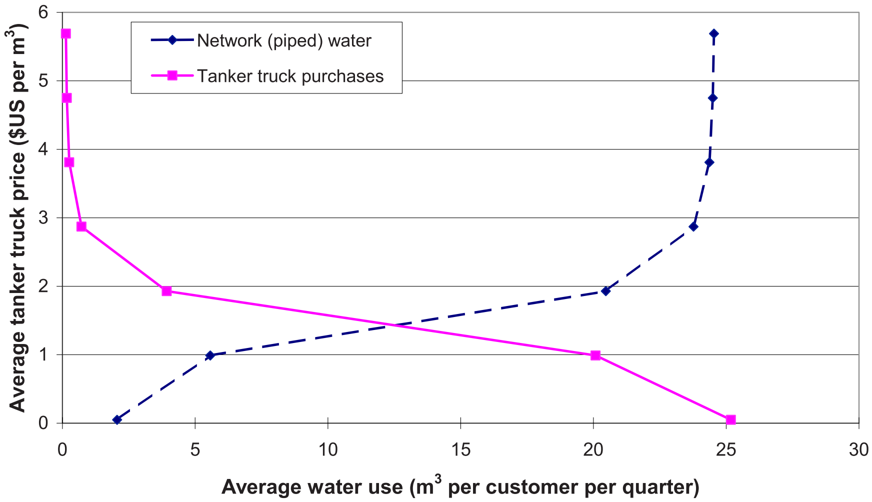

Figure 5. Elasticity and cross elasticity of tanker truck water price.

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 1, columns titled "Long Term"). This analysis provides a way to differentiate short- and long-term demand curves (i.e., before and after adopting 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)!

[59] Interestingly, a small fraction of customers with very significant water savings drive reductions in piped water use (Figure 6). 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.

[60] 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 7). 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.

7. Discussion

[61] 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, gray 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

Table 1. Demand Response Simulating Piped Water Use for Different Historical Rate Structures[a,b]

Demand Curve Component	Short Term, Before Conservation			Long Term, With Conservation		
	1997	2001	2006	1997	2001	2006
Piped water use per average household per year, m^3	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	

[a]Representative price equals total utility revenues divided by total billed water use.
[b]Long- and short-term curves plot at same representative prices.

Table 2. Average Responses to Conservation Efforts

Indicator	Short Term, Before Conservation	Long Term, After Conservation
Piped water use m^3 customer^{-1} yr^{-1}	152.0	100.7
Tanker truck use m^3 customer^{-1} yr^{-1}	9.2	1.5
Rainwater collected, m^3 customer^{-1} yr^{-1}	0.0	4.7
Gray water reused, m^3 customer^{-1} yr^{-1}	0.0	3.9
Expenditures, $US customer^{-1} yr^{-1}	232.1	149.3
Utility revenues, $US customer^{-1} yr^{-1}	101.8	41.2

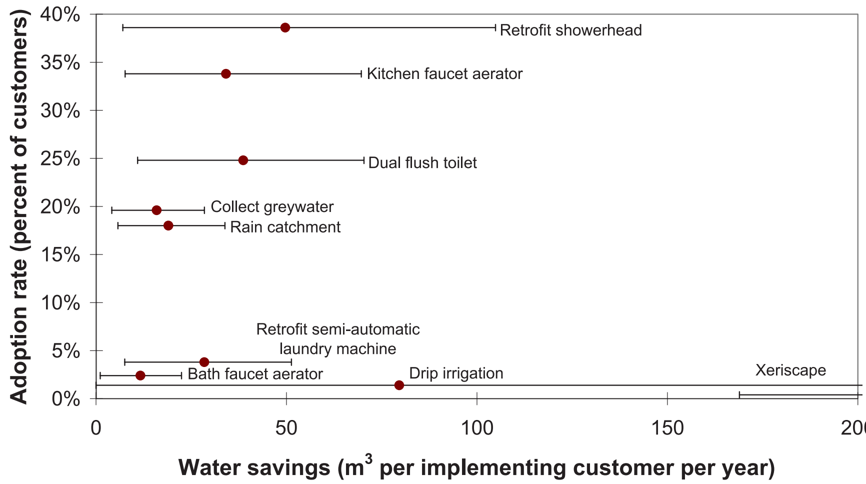

Figure 6. Estimated market penetration and water savings for conservation actions in Amman, Jordan. Circles show average, and error bars show 10th and 90th percentiles of Monte Carlo simulations.

results plus limitations. We emphasize that the price and conservation results still require empirical verification.

7.1. Increased Availability and Willingness to Pay

[62] 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). An advantage of systems analysis is ability to post facto specify and respecify 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 (Appendix A) excluded hassle, so customers may have greater WTP than suggested by the model or the prior survey.

7.2. Price Elasticity of Demand

[63] 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

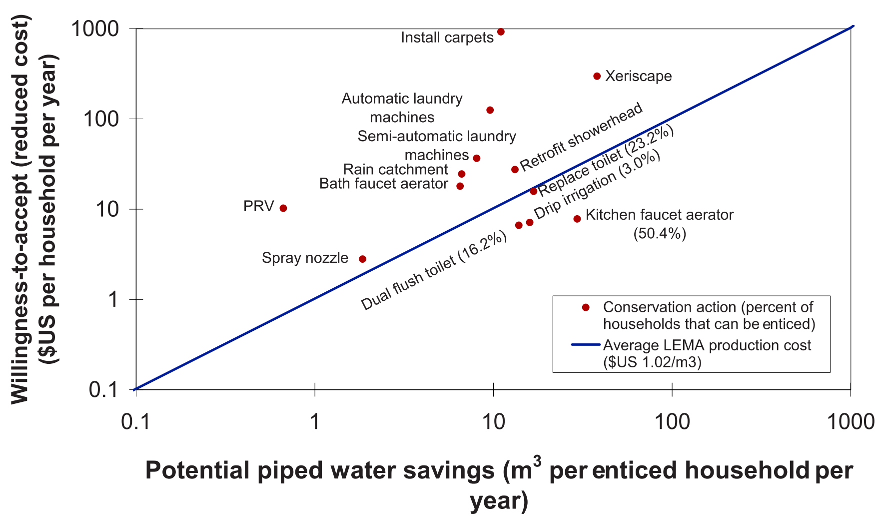

Figure 7. Average subsidies required to entice additional customers to install water-efficient appliances. For actions below LEMA production cost curve, percent indicates fraction of households that are potentially enticed.

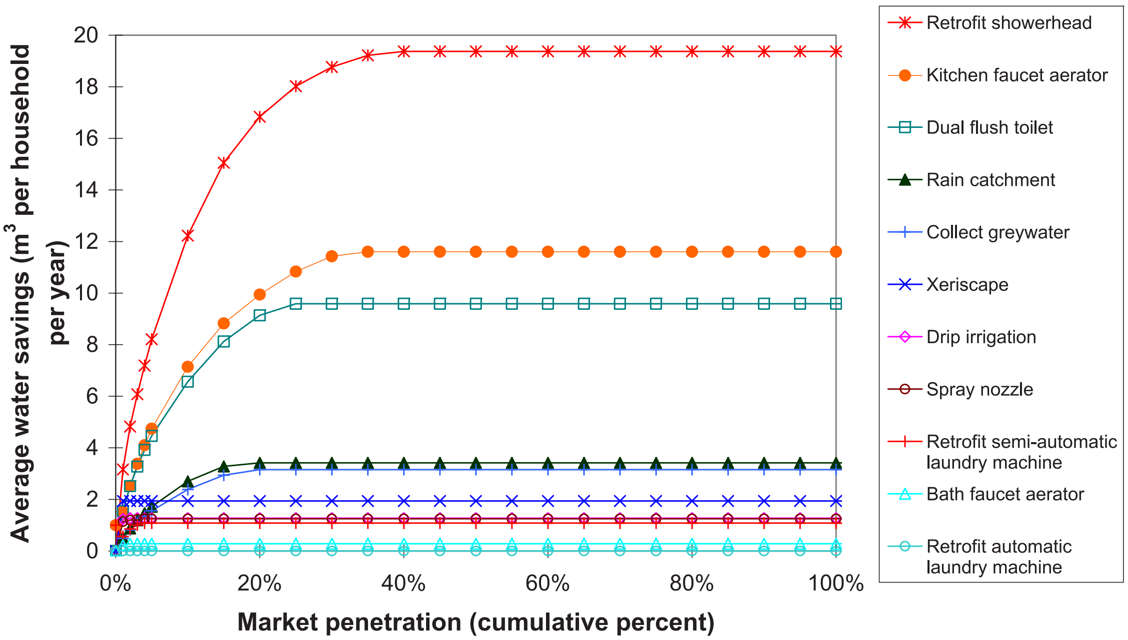

Figure 8. Sizing curves for water conservation programs. *X* axis is ordered by customers from highest to lowest conservation action effectiveness.

existing schedule, and (3) method to calculate a "representative" price for the schedule.

[64] 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.

[65] 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.

7.3. Conservation Campaigns

[66] 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 semiautomatic 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. *Rosenberg* [2007] suggests using surrogate data indicators, customer surveys, and water audits to identify high potential customers and actions.

[67] Numerically integrating the distributions of water savings shown in Figure 6 gives conservation program sizing curves (Figure 8). The curves suggest the minimal market penetration needed to meet a conservation objective [*Rosenberg*, 2007]. Minimal market penetration is achieved by ordering customers (x axis in Figure 8) 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 (1) average water savings for implementing customers and (2) the market penetration rate shown in Figure 6). Here, average effectiveness estimates by systems analysis are much lower than estimates for individual actions that ignore implementation costs and interdependencies [*Rosenberg*, 2007]. For example, *Rosenberg* [2007] reports 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.

[68] 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.

7.4. Further Methodological Limitations

[69] 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 misspecified. 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 uncalibrated 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.

[70] Second, initial estimates of water use set upper bounds for the optimal use (equations (2) and (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.

[71] 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 data set, specifying a regression model, and teasing apart diverse and potentially interdependent responses. These tasks require significant effort beyond the scope of the current study.

[72] Fourth, significant unaccounted-for and nonrevenue 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).

[73] 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.

8. Conclusions

[74] This paper 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 as follows.

[75] 1. The modeling approach reproduces both the existing average and distribution of piped water use for residential customers in Amman, Jordan.

[76] 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.

[77] 3. Price response is highly inelastic. However, the rate structure (block spaces, fixed and variable charges) complicates interpretation of price response.

[78] 4. In Amman, a conservation campaign may significantly reduce piped water use.

[79] 5. Campaigns should target select customers that show the most potential to save water and money.

[80] 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.

[81] 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.

[82] 8. Results for pricing and conservation efforts still require empirical verification. Including hassle, time, and other factors may reduce adoption rates.

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

Appendix A: Parameter Descriptions

[84] This appendix describes the parameters influencing initial estimates of water use and conservation action effectiveness (Table A1) and action costs (Table A2).

Notation

a number of events per year.

c_1 annual cost of long-term actions, \$ yr^{-1}.

$c_{2,e}$ cost of short term actions in event e, \$ event^{-1}.

$d_{u,e}$ initial estimate of water quality use u in event e, m^3 event^{-1}.

Table A1. Parameters Influencing Initial Estimates of Water Use and Conservation Action Effectiveness

Parameter	Units	Low Value	High Value	Average	Standard Deviation	Distribution[a]	Reference[b]
				Geographic			
A. Annual rainfall	mm/yr	110.0	550.0	269.7	93.5	FG	JMD (78 years)
B. Irrigation season	weeks/yr	20.0	35.0	-	-	UN	engineering estimate
C. Network shortages	weeks/yr	0.5	-	3.0	-	ED	AED (344 households)
D. Rainfall events	number/yr	1.0	6.0	-	-	UN	engineering estimate
				Demographic			
E. Roof area of building	m^2	100.0	-	206.1	-	ED	DS99 (1,800 households)
F. Households sharing building	number/building	1.0	-	2.7	-	ED	DS04 (383,000 households)
G. Household size	persons	3.0	-	5.1	-	ED	DS04 (383,000 households)
H. Drinking water random effects	l/event	(43.4)	19.9	(0.0)	67.1	NM	R07 (c. 28 persons)
I. Occupancy	fraction	-	1.0	-	-	HS (3)	calibrated
				Technological			
J. Garden area	m^2	-	300.0	111.3	103.2	FG	DS99 (1,800 households)
K. Number cars	number of cars	-	-	1.3	0.5	FG	AED (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	IRC (c. 10 devices)
N. Faucet flow rate - current device	l/min	5.5	20.0	-	-	UN	IRC (c. 10 devices)
O. Toilet tank volume - current device	l/flush	5.5	15.0	-	-	HS (6)	AED (344 households)
P. Laundry water use - current device	l/kg	-	-	-	-	NM	ARD (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	IRD (c. 20 devices)
				Behavioral			
T. Length of shower (current)	min	1.5	-	8.5	-	ED	IRC (c. 10 devices)
T. Length of shower – currernt	min	1.5	-	8.5	-	ED	IRC (c. 10 devices)
U. Shower frequency – summer	number/week	1.0	-	3.6	-	ED	R07 (c. 28 persons)
V. Shower frequency – winter	number/week	1.0	-	0.4	-	NM	R07 (c. 28 persons)
W. Toilet flushes	number/person/d	2.0	-	4.0	-	ED	S03 (30 households)
X. Flushes requiring full flush	fraction of flushes	0.3	0.7	-	-	UN	engineering estimate
Y. Faucet use	min/d/person	0.1	-	0.6	-	ED	S03 (30 households)
Z. Car wash time	min/use	5.0	15.0	-	-	UN	AED (344 households)
AA. Car washes	washes/week	-	-	1.6	1.0	FG	AED (344 households)
AB. Irrigation frequency	number/week	0.2	-	1.7	-	ED	AED (344 households)
AC. Floor wash frequency	number/week	1.0	7.0	-	-	UN	engineering estimate
AD. Irrigation applications	hrs/week	0.2	-	1.7	-	ED	R07 (c. 28 pers.)
AE. Bucket application to car	number 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/d	1.0	-	14.4	-	ED	S03 (30 households)
AH. Borrow	m^3/event	0.1	0.3	-	-	UN	I02 (200 households)
AI. Car wash method	(1 = auto, 2 = bucket, 3 = hose)	1.0	3.0	1.9	-	HS (3)	AED (344 households)
AJ. Laundry wash method	(1 = hand, 2 = semi, 3 = auto)	1.0	3.0	2.3	-	HS (3)	AED (344 households)
AK. Laundry weight	kg/person/week	0.6	-	3.9	-	UN	R07 (c. 28 pers.)
				Technological Modifications			
AM. Shower flow rate - retrofit device	l/min	6.0	9.0	-	-	UN	IRC (c. 10 devices)
AN. Faucet flow rate - retrofit device	l/min	5.5	6.5	-	-	UN	IRC (c. 10 devices)
AO. Toilet flush rate - retrofit, full	l/flush	5.5	6.5	-	-	UN	IRC (c. 20 devices)
AP. Toilet flush rate - retrofit, half	l/flush	2.0	3.0	-	-	UN	engineering estimate

Table A1. (continued)

Parameter	Units	Low Value	High Value	Average	Standard Deviation	Distribution[a]	Reference[b]
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	number misters/50 m^2	3.0	10.0	-	-	UN	engineering estimate
AT. Water use - cons semi-auto laundry	l/kg	3.3	-	5.1	1.5	NM	IRC (c. 20 devices)
AU. Drinking water treatment efficiency	fraction	0.3	0.8	-	-	UN	R07 (c. 28 pers.)
AV. Toilet bottle size	l/bottle	0.5	1.5	-	-	UN	engineering estimate
AW. Toilet bottles installed	number	1.0	2.0	-	-	UN	engineering estimate
			Behavior Modification				
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	number/week	0.5	-	0.8	-	ED	engineering estimate
BA. Faucet wash time saved	min/person/d	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	min/use	0.5	-	3.0	-	ED	engineering estimate
BD. Reduced irrigation time - stress irr.	min/use	1.0	-	10.0	-	ED	engineering estimate

[a]ED = exponential decay, FG = fitted gamma, HS(x) = histogram with *x* categories, NM = normal, UN = uniform, and FV = fixed value (constant).
[b]Sample size is given in parentheses. JMD, Jordan Meteorological Department (2000); AED, Academy for Educational Development (2001); DS99, Department of Statistics (1999); DS04, Department of Statistics (2004); R07, *Rosenberg et al.* [2007]; IRC, Interdisciplinary Research Consultants (2004); S03, *Snobar* [2003]; I02, *Iskandarani* [2002].

Table A2. Parameters Influencing Action Costs

Parameter	Units	Low Value	High Value	Average	Standard Deviation	Distribution[a]	Reference[b]
			Capital Costs for Long-Term Actions				
BE. Network connection	$US	-	-	324.3	-	FV	R07
BF. Roof tanks - 2 m3 size	$US	91.7	-	104.3	14.3	NM	R07 (c. 4 stores)
BG. Roof tanks - 1 m3 size	$US	53.6	-	64.2	8.9	NM	R07 (c. 4 stores)
BH. Ground tanks - 2 m3 size	$US	97.3	-	110.0	14.3	NM	R07 (c. 4 stores)
BI. Cistern	$US	620.4	-	972.9	641.5	NM	R07 (c. 28 persons)
BJ. Rainwater collection system	$US	141.0	-	282.0	141.0	NM	R07 (c. 4 stores)
BK. Grey-water system	$US	-	-	80.4	77.6	NM	R07 (c. 4 stores)
BL. Drill well	$US	7,614.0	-	14,523.0	6,186.9	NM	H05
BM. Install in-home water treatment	$US	197.4	-	296.1	134.3	NM	R07 (c. 4 stores)
BN. Low-flow showerhead	$US	7.1	-	81.8	112.5	NM	IRC (c. 10 devices)
BO. Low-flow bathroom faucet	$US	2.8	-	4.2	1.2	NM	IRC (c. 10 devices)
BP. Low-flow kitchen faucets	$US	2.8	-	4.2	1.2	NM	IRC (c. 10 devices)
BQ. Toilet dual-flush mechanisms	$US	5.6	-	19.7	13.0	NM	IRC (c. 20 devices)
BR. Low-flush toilet	$US	39.5	-	86.7	37.9	NM	IRC (c. 20 devices)
BS. Low-flow automatic laundry	$US	521.7	-	779.0	154.9	NM	IRC (c. 20 devices)
BT. Low-flow semi-automatic laundry	$US	112.8	-	193.9	143.5	NM	IRC (c. 20 devices)
BU. Low water consuming landscape	$US	423.0	-	2,961.0	2,308.3	NM	R07 (c. 4 stores)
BV. Drip irrigiation system	$US	21.2	-	25.4	4.1	NM	R07 (c. 4 stores)
BW. Spray nozzle on hoses	$US	1.4	-	4.2	2.1	NM	R07 (c. 4 stores)
BX. Permanent carpet on floors	$US	423.0	-	4,371.0	5,683.0	NM	R07 (c. 4 stores)
BY. Pressure reducing valve	$US	42.3	-	49.4	10.0	NM	R07 (c. 4 stores)
			Life Spans for Long-Term Action				
BZ. Network connection	years	10	30	-	-	UN	engineering estimate
CA. Roof tanks - 2 m3 size	years	3	7	-	-	UN	engineering estimate
CB. Roof tanks - 1 m3 size	years	3	7	-	-	UN	engineering estimate
CC. Ground tanks - 2 m3 size	years	3	7	-	-	UN	engineering estimate
CD. Cistern	years	10	30	-	-	UN	engineering estimate
CE. Rainwater collection system	years	5	15	-	-	UN	engineering estimate
CF. Grey-water system	years	5	20	-	-	UN	engineering estimate
CG. Drill well	years	10	30	-	-	UN	engineering estimate
CH. Install in-home water treatment	years	2	5	-	-	UN	engineering estimate

Table A2. (continued)

Parameter	Units	Low Value	High Value	Average	Standard Deviation	Distribution[a]	Reference[b]
CI. Low-flow showerhead	years	3	8	-	-	UN	engineering estimate
CJ. Low-flow bathroom faucet	years	3	8	-	-	UN	engineering estimate
CK. Low-flow kitchen faucets	years	3	8	-	-	UN	engineering estimate
CL. Toilet dual-flush mechanisms	years	3	8	-	-	UN	engineering estimate
CM. Low-flush toilet	years	5	15	-	-	UN	engineering estimate
CN. Low-flow automatic laundry	years	3	15	-	-	UN	engineering estimate
CO. Low-flow semi-automatic laundry	years	3	15	-	-	UN	engineering estimate
CP. Low water consuming landscape	years	5	30	-	-	UN	engineering estimate
CQ. Drip irrigiation system	years	2	5	-	-	UN	engineering estimate
CR. Spray nozzle on hoses	years	1	3	-	-	UN	engineering estimate
CS. Permanent carpet on floors	years	5	10	-	-	UN	engineering estimate
CT. Pressure reducing valve	years	3	10	-	-	UN	engineering estimate
BZ. Network connection	years	10	30	-	-	UN	engineering estimate
CA. Roof tanks - 2 m3 size	years	3	7	-	-	UN	engineering estimate
CB. Roof tanks - 1 m3 size	years	3	7	-	-	UN	engineering estimate
CC. Ground tanks - 2 m3 size	years	3	7	-	-	UN	engineering estimate
CD. Cistern	years	10	30	-	-	UN	engineering estimate
CE. Rainwater collection system	years	5	15	-	-	UN	engineering estimate
CF. Grey-water system	years	5	20	-	-	UN	engineering estimate
CG. Drill well	years	10	30	-	-	UN	engineering estimate
CH. Install in-home water treatment	years	2	5	-	-	UN	engineering estimate
CI. Low-flow showerhead	years	3	8	-	-	UN	engineering estimate
CJ. Low-flow bathroom faucet	years	3	8	-	-	UN	engineering estimate
CK. Low-flow kitchen faucets	years	3	8	-	-	UN	engineering estimate
CL. Toilet dual-flush mechanisms	years	3	8	-	-	UN	engineering estimate
CM. Low-flush toilet	years	5	15	-	-	UN	engineering estimate
CN. Low-flow automatic laundry	years	3	15	-	-	UN	engineering estimate
Operational Costs for Short-Term Actions							
CU. Drink rainwater	$US/m^3	-	-	0.0	-	FV	engineering estimate
CV. Collect rainwater	$US/m^3	-	-	0.0	-	FV	engineering estimate
CW. Buy water from water store	$US/m^3	56.4	-	64.9	7.7	NM	R07 (c. 4 stores)
CX. Buy bottled water	$US/m^3	146.6	-	215.9	79.9	NM	R07 (c. 4 stores)
CY. Buy water from tanker truck	$US/m^3	2.5	-	3.4	1.1	NM	R07 (c. 4 stores)
CZ. Borrow from neighbor	$US/m^3	-	-	0.0	-	FV	R07 (c. 28 pers.)
DA. Draw water from well	$US/m^3	-	-	0.0	-	FV	R07
DB. Boil water in home to drink	$US/m^3	0.6	-	4.8	4.6	NM	engineering estimate
DC. Treat water in home to drink	$US/m^3	-	-	0.0	-	FV	engineering estimate
DD. Store water	$US/m^3	-	-	0.0	-	FV	engineering estimate
DE. Draw water from storage	$US/m^3	-	-	0.0	-	FV	engineering estimate
DF. Collect and apply grey-water	$US/m^3	-	-	0.0	-	FV	engineering estimate
DG. Install bags or bottles in toilets	$US/m^3	-	-	0.0	-	FV	engineering estimate
DH. Find and fix leaks	$US/m^3	2.8	-	6.9	3.2	NM	R07 (c. 28 persons)
DI. Reduce landscape irrigation	$US/m^3	-	-	0.0	-	FV	engineering estimate
DJ. Turn off faucets while washing	$US/m^3	-	-	0.0	-	FV	engineering estimate
DK. Partially open faucet	$US/m^3	-	-	0.0	-	FV	engineering estimate
DL. Reduce shower length	$US/m^3	-	-	0.0	-	FV	engineering estimate
DM. Reduce shower-taking frequency	$US/m^3	-	-	0.0	-	FV	engineering estimate
DN. Reduce laundry-washing frequency	$US/m^3	-	-	0.0	-	FV	engineering estimate
DO. Sweep rather than wash floors	$US/m^3	-	-	0.0	-	FV	R07 (c. 28 persons)
DP. Wash car with buckets	$US/m^3	-	-	3.5	5.0	NM	R07 (c. 28 persons)
DQ. Wash car at gas station	$US/m^3	1.4	-	2.1	0.7	NM	engineering estimate
CU. Drink rainwater	$US/m^3	-	-	0.0	-	FV	engineering estimate
CV. Collect rainwater	$US/m^3	-	-	0.0	-	FV	engineering estimate
CW. Buy water from water store	$US/m^3	56.4	-	64.9	7.7	NM	R07 (c. 4 stores)
CX. Buy bottled water	$US/m^3	146.6	-	215.9	79.9	NM	R07 (c. 4 stores)
CY. Buy water from tanker truck	$US/m^3	2.5	-	3.4	1.1	NM	R07 (c. 4 stores)
CZ. Borrow from neighbor	$US/m^3	-	-	0.0	-	FV	R07 (c. 28 persons)
DA. Draw water from well	$US/m^3	-	-	0.0	-	FV	R07
DB. Boil water in home to drink	$US/m^3	0.6	-	4.8	4.6	NM	engineering estimate
DC. Treat water in home to drink	$US/m^3	-	-	0.0	-	FV	engineering estimate
DD. Store water	$US/m^3	-	-	0.0	-	FV	engineering estimate
DE. Draw water from storage	$US/m^3	-	-	0.0	-	FV	engineering estimate
DF. Collect and apply grey-water	$US/m^3	-	-	0.0	-	FV	engineering estimate
DG. Install bags or bottles in toilets	$US/m^3	-	-	0.0	-	FV	engineering estimate
DH. Find and fix leaks	$US/m^3	2.8	-	6.9	3.2	NM	R07 (c. 28 persons)
DI. Reduce landscape irrigation	$US/m^3	-	-	0.0	-	FV	engineering estimate
DJ. Turn off faucets while washing	$US/m^3	-	-	0.0	-	FV	engineering estimate
DK. Partially open faucet	$US/m^3	-	-	0.0	-	FV	engineering estimate
DL. Reduce shower length	$US/m^3	-	-	0.0	-	FV	engineering estimate
DM. Reduce shower-taking frequency	$US/m^3	-	-	0.0	-	FV	engineering estimate

Table A2. (continued)

Parameter	Units	Low Value	High Value	Average	Standard Deviation	Distribution[a]	Reference[b]
			Rate Structure for Piped Water Use				
DR. Use less than 20 m3/quarter	\$US (fixed charge)	-	-	4.89	-	FV	R07
DS. Use between 20 and 40 m3/quarter	\$US/m^3 (variable charge)	-	-	0.25	-	FV	R07
DT. Use between 40 and 130 m3/quarter	\$US/m^6 (quadratic charge)	-	-	0.01	-	FV	R07
DU. Use between 40 and 130 m3/quarter	\$US/m^3 (variable charge)	-	-	0.82	-	FV	R07
DV. Use above 130 m3/quarter	\$US/m^3 (variable charge)	-	-	1.75	-	FV	R07

[a]ED = exponential decay, FG = fitted gamma, HS(x) = histogram with *x* categories, NM = normal, UN = uniform, and FV = fixed value (constant).
[b]Sample size is given in parentheses. R07, *Rosenberg et al.* [2007]; H05, Hadidi, personal communication, 2005; IRC, Interdisciplinary Research Consultants (2004).

$g_{st,e}$ interaction function for short-term action *st* in event *e*, m^3 event^{-1}.
$h_{u,e}$ water savings for use *u* in event *e* from conservation actions, m^3 event^{-1}.
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^{-1}, (parameter *N* in Appendix A).
$S_{st,e}$ water volume implied by short-term action *st* in event *e*, m^3 event^{-1}.
$s_{u,e}$ water supply enhancement function for use *u* in event *e*, m^3 event^{-1}.
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^{-1}.
v_{stor} local water storage capacity, m^3.
W_{Faucet} water savings (effectiveness) to retrofit faucets, m^3 yr^{-1}.
$X_{u,e}$ supply volume allocated to use *u* in event *e*, m^3 event^{-1}.
Z objective function value, \$ yr^{-1}.

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