Water management with water conservation, infrastructure expansions, and source variability in Jordan

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[1] A regional hydroeconomic model is developed to include demand shifts from nonprice water conservation programs as input parameters and decision variables. Stochastic nonlinear programming then jointly identifies the benefit-maximizing portfolio of conservation and leak reduction 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 that (1) water conservation by urban users generates substantial regional benefits and can delay infrastructure expansions; (2) some rationing and conjunctive use operations smooth operations during droughts; (3) a broad mix of source developments, conveyance expansions, and leak reduction programs can forestall the need for desalination; (4) the Disi carrier to Amman should include a large branch to Karak; and (5) increasing conveyance from Ma'an, Irbid, and Mafraq can avert impending crises in the neighboring districts of Tafelah, Ajloun, and Zarqa.

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1. Introduction

[2] Regional water managers are challenged to 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 price changes can influence the optimal path of expansions and associated benefits for a single utility serving a growing city [*Gysi and Loucks*, 1971; *Dandy et al.*, 1984].

[3] More recent hydroeconomic models consider price demand responses and operations for entire river basins or regions [*Rosegrant et al.*, 2000; *Gillig et al.*, 2001; *Cai et al.*, 2003; *Draper et al.*, 2003; *Fisher et al.*, 2005]. For example, *Rosegrant et al.* [2000] optimize benefits for agricultural, urban, and 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 for all of California. And *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.

[4] Most recent applications use linear or nonlinear 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. These analyses work well for individual changes with deterministic flows and static hydrology but prove cumbersome for identifying an optimal portfolio of long-term supply, infrastructure expansion, and conservation program developments such as those listed in Figure 1. Analysis is further complicated by variable rainfall and runoff from year to year as typically seen in arid regions where hydroeconomic models are often applied.

[5] *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 nonprice water conservation and leak reduction programs, conveyance, wastewater treatment, and desalination facility expansions. Further, we identify optimal balances of intertemporal transfers, rationing, infrastructure expansions, and unused capacity to respond to stochastic water availability.

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Stage	New Supplies	Conservation	Political to encourage implementation
Long-term (Infrastructure expansion and program development)	• Expand surface and groundwater storage and extraction facilities • Build seawater desalination plants • Expand wastewater treatment plants • Expand conveyance pipelines and canals	• Reduce distribution system leaks – 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)	• Use surface and groundwater • Inter-district transfers • Desalination operations • Treat wastewater for reuse	• Ration to meet demands • Reallocate among sectors	• Import food • Pass and enforce groundwater use laws

Figure 1. Regional-scale water management actions in Jordan.

[6] Nonprice conservation programs are an important aspect of regional water management and are typically absent from hydroeconomic models. Hydroeconomic models usually integrate the area under user demand curves to quantify water use benefits and assume movement along the curves represents water users' conservation efforts (both short-term behavior changes and long-term appliance retrofits) in response to increased water prices. This emphasis follows the long-running focus on price elasticity of demand in the econometrics literature [*Howe and Linaweaver*, 1967; *Carver and Boland*, 1980; *Espey et al.*, 1997; *Young*, 2005]. Yet econometric studies show significant nonprice effects on water use related to family size, 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 [*A & N Technical Services, Inc.*, 2005; *U.S. Environmental Protection Agency* (*USEPA*), 2005]. Nonprice conservation efforts include education, awareness, outreach, rebates, subsidies, retrofit kits, rationing, and use restrictions undertaken or offered by the water service provider to encourage users to modify behaviors or retrofit appliances. These nonprice conservation programs shift the demand curve inward [*Michelsen et al.*, 1999]. Shifts reduce aggregate use 1–4% per individual educational or retrofit program [*Michelsen et al.*, 1999; *Renwick and Green*, 2000], are greater when installing ultralow-flow appliances [*A & N Technical Services, Inc.*, 2005; *USEPA*, 2005], and are potentially greater still for installations targeted to users who will save the most water and money [*Rosenberg et al.*, 2007]. For hydroeconomic models, the challenge is to include these demand-shifting nonprice 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 that of *Cai et al.* [2003], who postcalculate local and basin-wide water use efficiency rates under different allocation scenarios.

[7] Here we extend *Fisher et al.*'s [2005] single-year water allocation system model (single-year WAS) to include nonprice water conservation efforts, leak reduction 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 nonprice 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 nonprice conservation and leak reduction programs, surface and groundwater developments, conveyance, wastewater treatment, and desalination facility expansions.

[8] The paper summarizes the key methods and findings of a regional systems analysis for Jordan [*Rosenberg*, 2008, chapter 6], which is available online at http://cee.engr.ucdavis.edu/faculty/lund/students/RosenbergDissertation.pdf, and proceeds as follows. Section 2 reviews the single-year WAS and presents modifications to develop the stochastic two-stage program. Section 3 describes the application to the water system serving urban, industrial, and agricultural uses of over 6 million people in the Hashemite Kingdom of Jordan. Sections 4 and 5 present and discuss model results. Section 6 presents the conclusions.

2. Background and Methods

2.1. Single-Year Water Allocation System Model

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

[10] 1. Water is a scarce resource and has value. This value reflects the benefit from 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.

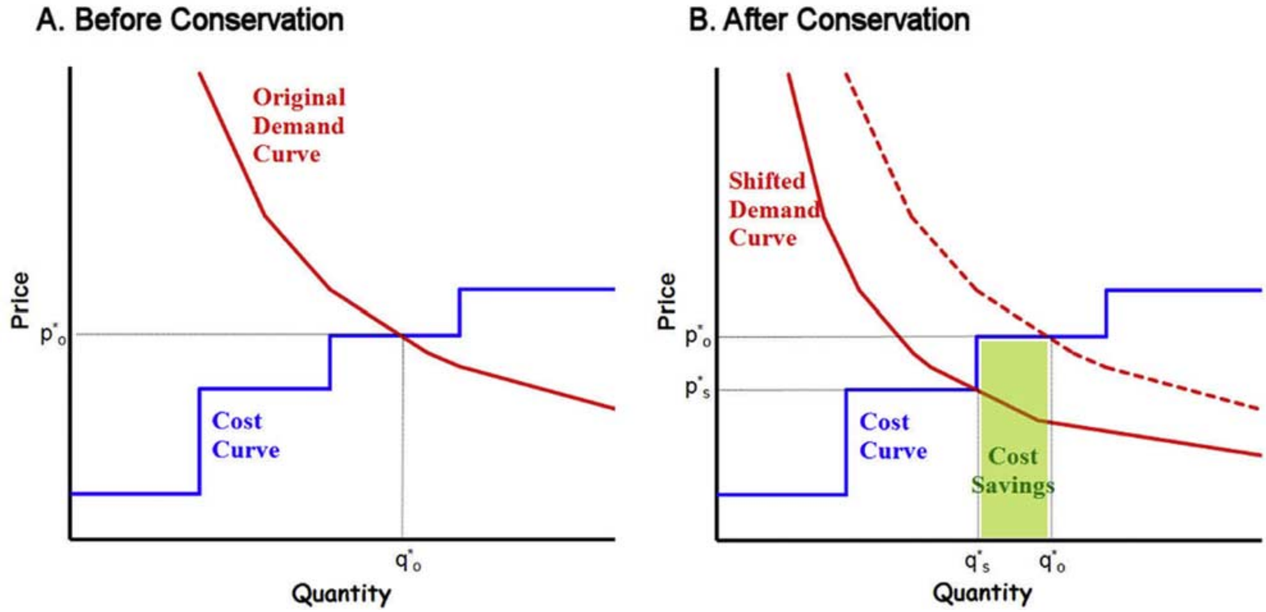


Figure 2. Demand curves and optimal allocations (a) before and (b) after implementing water conservation programs for users. Shaded area in Figure 2b shows the cost savings from implementing conservation programs.

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

[12] The project developed a steady state, deterministic optimization program for a single year that we term the single-year WAS (to distinguish it from the multiyear version that the team is currently developing and a stochastic version described here). The 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 the area between the demand and cost curves (the curves that represent benefits that water sectors derive from water use and costs to extract, treat, and convey water to where it is used, respectively; Figure 2a). The optimal allocation is the quantity (q_o^* in Figure 2a) 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, water imported from and exported to other districts, wastewater treated for reuse, and losses from leaks that cannot otherwise be put to economical use.

[13] The single-year WAS is a powerful tool that includes many supply, infrastructure, leak reduction, social, and economic policies for water management. The program models a single year, so users must compare results from successive runs: one run with the infrastructure, policy, or water availability in place and a second run without. For example, compare 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. In sections 2.2 and 2.3, we demonstrate methods for including capacity expansions, nonprice water conservation and leak reduction programs, and variable water availabilities in a stochastic formulation at the national level.

2.2. Nonprice Water Conservation Programs

[14] The demand curve in Figure 2a 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 [*Howe and Linaweaver*, 1967; *Carver and Boland*, 1980]. In the short term, water users may buy more expensive, privately vended water or temporarily reduce the length or frequency of their showers, 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 rainwater and gray 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 [*Rosenberg et al.*, 2007].

[15] However, many nonprice factors such as income, education, and conservation programs initiated by the water service provider also encourage users to modify behaviors or install water-efficient appliances to reduce their water use [*Michelsen et al.*, 1999; *Renwick and Green*, 2000; *A & N Technical Services, Inc.*, 2005; *USEPA*, 2005]. For example, *Renwick and Green* [2000] examined mean monthly single-family water use data for eight 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 from −0.08 to −0.34. Others report similar

decreases, although these values may understate actual shifts. *Rosenberg et al.* [2007] used mathematical programming to deduce price and nonprice demand responses for individual household water users in Amman, Jordan. They considered more than 39 separate long- and short-term supply and conservation actions and found (1) that the inelastic short-term price response was similar to the response used for the urban demand curve in the single-year WAS and (2) that 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%.

[16] In summary, price responses indicate movement along the demand curve, whereas nonprice conservation programs shift the whole demand curve and its shape. On the basis of prior empirical data for targeted installations of water-efficient appliances [*Rosenberg et al.*, 2007], we consider just a percentage shift inward with no change in shape (Figure 2b).

[17] The single-year WAS can accommodate and even calculate optimal allocations for a shifted demand curve (q_s^* in Figure 2b). 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 nonprice conservation programs that improve physical water use efficiency are always uneconomical. The correction employed here works as follows.

[18] 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, a clean car, an attractive landscape, urine disposal, or feces removal. Further, we note that water-related services, rather than water use per se, provide value to users. Nonprice conservation programs that install water-efficient appliances amount to a technology change that reduces the water input needed to provide those services. For example, in Jordan, water users who would retrofit an existing showerhead (9–20 L/min) with a low-flow showerhead (6–9 L/min) could shower for the same amount of time and as often and still get clean [*Rosenberg et al.*, 2007]. Yet those households would reduce their water use by 5–100 m^3/a. Nonprice conservation programs that improve physical water use efficiency reduce the quantity of water use but maintain the value associated with those uses.

[19] We therefore distinguish a demand for water-related services in each district i, SD_i, from the demand for water use, WU_i. The two demands differ by the physical efficiency improvement from installing water efficient appliances. We call this fractional improvement in district i $pcon_i$, so that

$$WU_i = SD_i \cdot (1 - pcon_i), \ \forall i. \tag{1}$$

Figure 2b distinguishes demands for water service (original demand curve) and water use (shifted demand curve) by the dashed and solid curves, respectively.

[20] Second, we optimize allocations to maximize net benefits. Net benefits (consumer surplus, Z) are the benefits of water-related service minus costs to supply the actual water used and costs for conservation activities:

$$\max Z = \sum_i \frac{b_i}{\alpha_i + 1} (SD_i)^{\alpha_i + 1} - \sum_i c_i \begin{pmatrix} Q_{\text{local sources}\,i}, Q_{\text{imports}\,i}, Q_{\text{exports}\,i}, \\ Q_{\text{treated wastewatert}\,i}, \text{pcon}_i, \text{pleak}_i \end{pmatrix}, \tag{2}$$

where b_i indicates the position of the service demand curve for district i; α_i indicates the demand curve elasticity for district i, assuming constant elasticity along the demand curve to give an exponential service demand curve; and c_i indicates the cost function in district i for using volumes from local water sources, $Q_{\text{local sources}\ i}$; volumes imported from other districts, $Q_{\text{imports}\ i}$; volumes exported to other districts, $Q_{\text{exports}\ i}$; wastewater treated for reuse, $Q_{\text{treated wastewater}\ i}$; and achieving physical efficiency rates in water use, $pcon_i$, and in distribution system leakage, $pleak_i$. The net benefits are subject to continuity on water use in each district:

$$WU_i = \left(Q_{\text{local sources}\,i} + Q_{\text{imports}\ i} - Q_{\text{exports}\ i} + Q_{\text{treated wastewater}\,i}\right) \cdot (1 - \text{pleak}_i), \ \forall i. \tag{3}$$

The shaded area in Figure 2b shows the cost savings (additional net benefits) from nonprice demand-shifting water conservation programs.

[21] Finally, with no efficiency improvements ($pcon_i = 0$), water use equals the demand for water-related service, the original and shifted demand curves coincide, there are no cost savings, and we have the situation shown in Figure 2a. In section 4, we show the net gain for targeted water-efficiency improvement programs in Amman and Jordan.

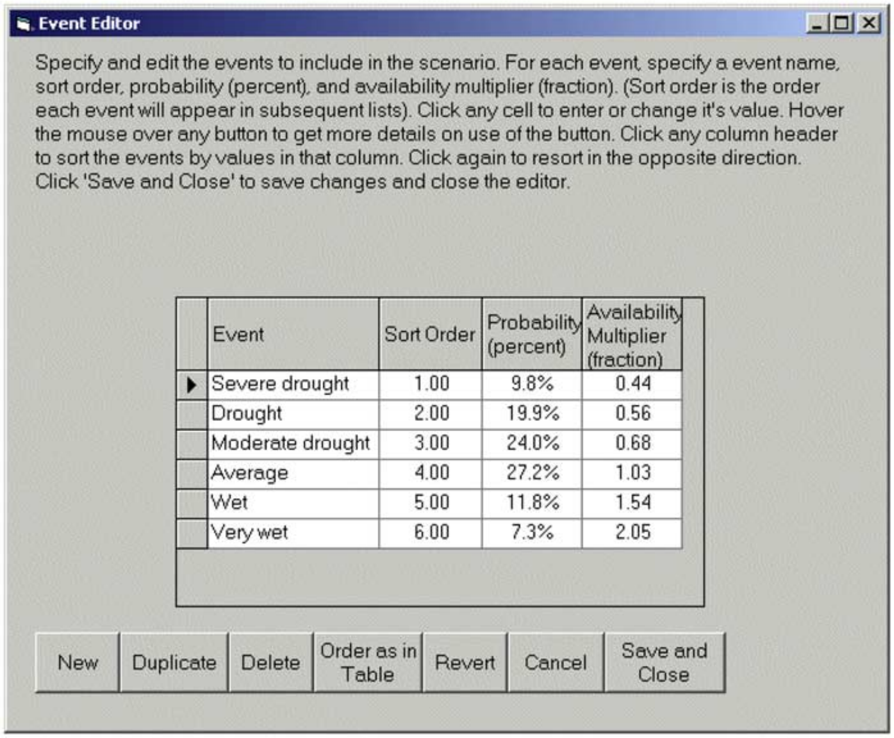
2.3. Integrating Variable Water Availability and Infrastructure Expansions

[22] 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: making long-term investments that expand infrastructure to improve water system reliability or implementing short-term emergency measures and coping strategies that reduce use when water supply availability is limiting? What is the appropriate balance between long- and short-term strategies?

[23] Here we use stochastic optimization with recourse (staged programming) to recommend infrastructure expansions given uncertainties in resource availability (for reviews, see *Sen and Higle* [1999] and *Sahinidis* [2004]). The technique works as follows.

[24] First, we list 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.

[25] Second, we partition decisions. Long-term (primary-stage) decisions include infrastructure expansions and nonprice conservation and leak reduction program developments. Short-term (recourse stage) operational decisions



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 3. Data entry for stochastic water availability events.

consider water source use, conveyance, demand allocations, and wastewater treatment and are specific for each event. Together, long-term actions plus sets of short-term actions for each event constitute a decision portfolio to respond to the stochastic distribution of water availabilities.

[26] Third, we optimize to identify the mix of long- and short-term decisions that maximize 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 nonprice conservation and leak reduction programs implemented. Thus, the program uses an expected value criterion to determine the optimal mix of long- and short-term actions.

[27] The expected net benefits are subject to constraints to balance water supply and demand at every location in every event (equation (3)); infrastructure use within existing (or expanded) capacity limits; and social, political, and other policies imposed by the user. Policies can include quota systems, taxes or subsidies on water use, limitations on use of some water qualities, water reserved for environmental or other purposes, minimum required allocations to some water use sectors, and use of common pool resources shared among multiple districts or countries.

[28] See *Rosenberg* [2008, chapter 6, appendix A] for the mathematics for the stochastic WAS program. The formulation is solved as a nonlinear program. Further, when only one event is specified, the event is assigned a probability of 1, infrastructure expansions are limited to their existing capacities, and the stochastic program reduces to the single-year WAS model.

2.4. Limitations

[29] Limitations of the stochastic WAS program include the following. (1) An expected value objective function gives risk-neutral rather than risk-adverse decisions. (2) Decision staging focuses on long-term drought planning policies. (3) Event independence ignores effects of event timing or sequence and precludes modeling storage or groundwater-banking decisions. For details and workarounds, see *Rosenberg* [2008].

2.5. Model Implementation

[30] The stochastic WAS is a Visual Basic application that links modules for data entry, storage, optimization, and results visualization. Users first define the regional layout of countries, districts, water use sectors, water qualities, local resources, and conveyance links to include in an analysis. Then, they enter required demand, supply, infrastructure, and policy data for those components. To optimize, the program queries the database and formats inputs for use by the optimization module. Afterward, users view the results.

[31] Figure 3 shows the form where the user defines the water availability events to include in a study. The optimization module is the General Algebraic Modeling System (GAMS) and solves the nonlinear program with CONOPT [*Brooke et al.*, 1998]. Solution time is generally less than 1 min on a Pentium laptop.

3. Example Application in Jordan

[32] We now demonstrate use of the stochastic WAS model for 12 governorates (districts) in Jordan. We summarize the national water budget and future prospects, describe potential infrastructure expansions and conservation program options, and characterize current water availability.

In section 4, we present and discuss optimization results. Unless otherwise noted, we use the WAS model data for Jordan developed and presented by *Fisher et al.* [2005, chapter 6].

3.1. National Water Budget and Prospects

[33] Jordan's current applied water use is approximately 1 billion m^3/a. Use is typically served by 300 million m^3 of renewable surface water and 550 million m^3 of renewable groundwater with the remaining deficit covered by groundwater overdraft. Use is split approximately 69, 27, and 4% among agricultural, urban, and industrial uses, respectively [*Abu Qdais and Batayneh*, 2002; *Al-Salihi and Himmo*, 2003; *Scott et al.*, 2003; *Taha and Magiera*, 2003; *Fisher et al.*, 2005].

[34] Jordan has few existing water supplies, a fast growing population (2–3%/a), and limited, expensive options for developing 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 [*Water Efficiency and Public Information for Action*, 2000; *Interdisciplinary Research Consultants*, 2004]. But efforts have not yet systematically integrated these components into a single framework for analysis and action.

[35] National-scale modeling can help identify promising new supply and conservation options for improving water system performance. It can further show the regional impacts of local water user [*Rosenberg et al.*, 2007] and city [*Rosenberg and Lund*, 2008] conservation efforts. And it also can confirm and justify actions that 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.

3.2. Potential Actions

[36] Figure 1 lists 15 infrastructure expansion and nonprice conservation and leak reduction program development options currently under consideration by MWI and the water utilities serving each district. Short-term actions in Figure 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 Figure 1 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.

[37] 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 [*Nuaimat and Ghazal*, 2006; *Rosenberg*, 2006; *Abdelghani et al.*, 2007]. When estimates differ among sources, we use averaged values. See *Rosenberg* [2008, chapter 6] for quantitative and qualitative descriptions of options for developing new fresh or brackish surface or groundwater sources originating in a district, desalinating seawater, treating urban or industrial wastewater for reuse in agriculture, building canals or pipelines to convey water between districts, and reducing leakage in district distribution systems and nonprice conservation programs that target installation of water-efficient appliances to select urban users who will save the most water and money.

3.3. Water Availability Events

[38] We sort the 65-year record of total runoff between 1937 and 2002 from Jordan's 12 major watersheds [*Taha and Magiera*, 2003] in increasing order and then characterize the distribution of water availability into a discrete set of six 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. 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 3 shows event probabilities and availability factors entered in the model. This approach treats runoff variability as homogenous across the study area and representative of surface water availability. These assumptions suffice for demonstration purposes.

3.4. Additional Data

[39] A 5% interest rate annualizes capital costs. *Fisher et al.* [2005, chapter 7] present water use projections for 2020 and the other model inputs, which include demand elasticities of −0.2, −0.33, and −0.5 for the urban, industrial, and agricultural sectors, respectively.

4. Results

[40] Table 1 summarizes model scenario results. The scenarios include verification runs, with targeted installations of water-efficient appliances for select urban users, and optimal infrastructure expansions and nonprice conservation and leak reduction program developments. We also study the scenarios of diverting some Disi water to Karak and Madaba along the conveyance route to Amman, improving water use efficiency for agricultural users, and management-absent targeted installations of water-efficient appliances for urban users.

4.1. Verification Runs

[41] Two initial runs verify that the stochastic formulation reproduces results of the single-year WAS program. These runs excluded the Zara-Ma'een project, did not allow infrastructure expansions or nonprice conservation or leak reduction program developments, 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 1) 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.

4.2. Targeted Installations of Water-Efficient Appliances

[42] Installing water-efficient appliances for select urban users in Amman to reduce overall urban sector use by 33% (see *Rosenberg et al.* [2007] for details) generates substantial benefits (Table 1). Benefits grow when select urban

Table 1. Net Benefits for Different Model Scenarios

Scenario	Net Benefits (million dollars/a)	
	Single Event	Stochastic
Verification run	2740	–
Targeted installations of water-efficient appliances by select urban users in Amman	5704	–
Targeted installations of water-efficient appliances by select urban users throughout Jordan	6397	–
Current conditions with Zara Ma'een project	5101	–
Optimal expansions and developments	6906	6830
Optimal expansions and developments and Disi carrier branches to Madaba and Karak	–	6893
Optimal expansions and developments, Disi branches, and water use efficiency by agricultural users	–	6910
Optimal expansions and developments without targeted installations of water-efficient appliances	6549	6489

users throughout the country install water-efficient appliances (Table 1). These nonprice water conservation programs would reduce water scarcity values across the country (Figure 4). Reductions are most pronounced in districts where water is scarce (Amman, Zarqa, and Ajloun).

[43] The net benefits from targeted water conservation for urban users in Amman exceed the gain from building the Zara-Ma'een project (Table 1). But the capital expenditure for nonprice conservation programs (including retrofit costs) is slightly more than the Zara-Ma'een project cost. All subsequent scenarios include the Zara-Ma'een project to reflect current conditions.

4.3. Optimal Expansions and Variable Water Availability

[44] Allowing the program to select from the infrastructure expansions and nonprice conservation and leak reduction programs listed by *Rosenberg* [2008, chapter 6] further increases net benefits (Table 1). Here we see the benefit in building or developing a mix of source expansion, conveyance, and nonprice conservation and leak reduction programs constituting annualized capital expenditures of about $50 million. The program does not select the Disi carrier or seawater desalination in Aqaba or Balqa.

[45] When facing a stochastic distribution of surface water availability, the program expands wastewater treatment for Amman and increases conveyance (Table 2). These changes increase annualized capital expenditures by $1 million/a but do not explain the larger reduction in net benefits. This reduction is related to reduced allocations and higher scarcity values in districts and events where surface water availability is limited. The effect is most pronounced

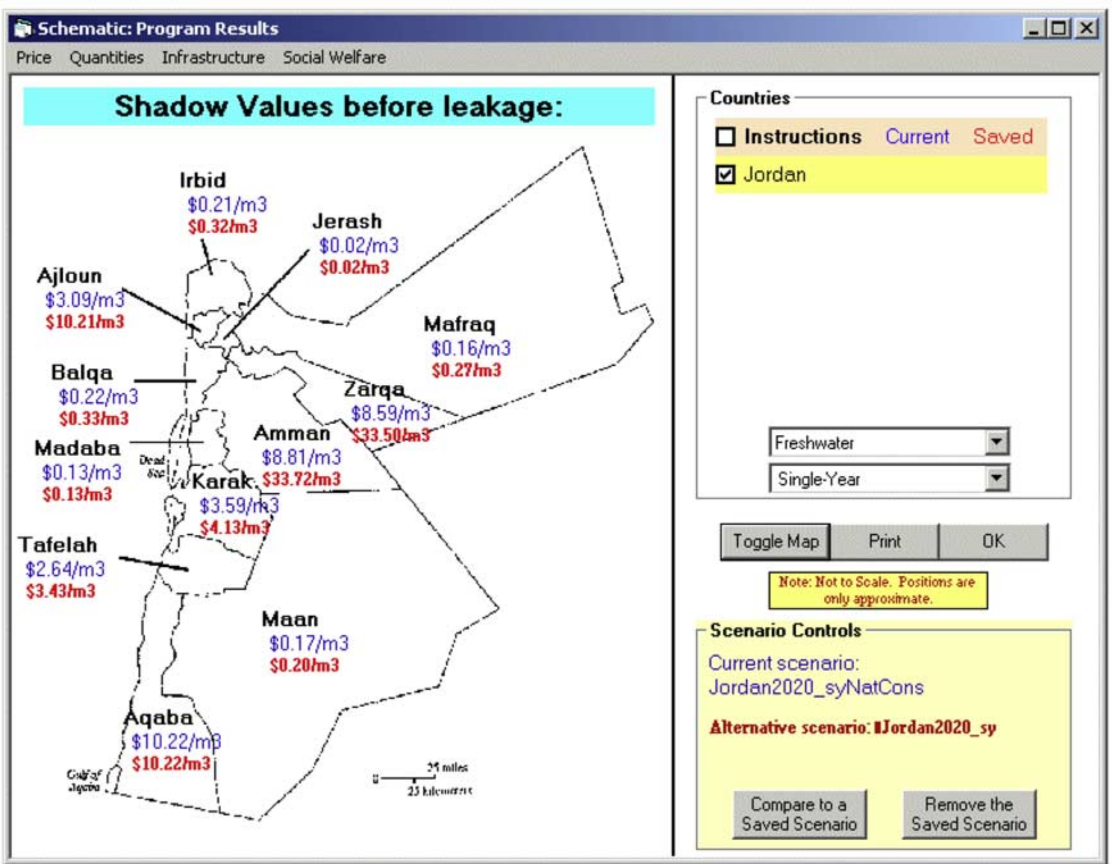


Figure 4. Shadow values in dollars/m^3 for freshwater in each district for scenarios with (top values) and without (bottom values) targeted installations of water-efficient appliances for select urban users.

Table 2. Optimal Long-Term Infrastructure Expansions and Conservation Program Development Actions

District (Project)	Initial Capacity (10^6 m^3)	Maximum Expansion (10^6 m^3)	Infrastructure Capacity Expansion (10^6 m^3): Optimal Expands, Single Event[a]	Optimal Expands, Stochastic Events[b]	Disi Branches[c]	No Water Use Efficiency[d]
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
Ma'an (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 (reverse osmosis plant)	–	7.5	–	–	–	3.5
Wastewater treatment plants						
Amman (As-Samra expansion)	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						
Ma'an to Aqaba (Disi expansion, phases 1 and 2)	–	14.0	14.0	14.0	12.8	12.8
Ma'an 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 (%): Optimal Expands, Single Event[a]	Optimal Expands, Stochastic Events[b]	Disi Branches[c]	No Water Use Efficiency[d]
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	–
Ma'an	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
Ma'an	25	14	−11	−11	−11	−11
Tafelah	25	14	−11	−11	−11	−11
Aqaba	25	14	−11	−11	−11	−11

[a]Annualized capital expenditure, \$49 million/a; annualized net benefit, \$6906 million/a.
[b]Annualized capital expenditure, \$50 million/a; annualized net benefit, \$6830 million/a.
[c]Annualized capital expenditure, \$54 million/a; annualized net benefit, \$6893 million/a.
[d]Annualized capital expenditure, \$52 million/a; annualized net benefit, \$6549 million/a.

in districts like Ajloun, Karak, and Tafelah that rely principally on surface water and is 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.

4.4. Disi Carrier Branches to Karak and Madaba

[46] 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 (Figure 5, bottom values). This difference suggests that additional conveyance may be beneficial [*Fisher et al.*, 2005]. Thus,

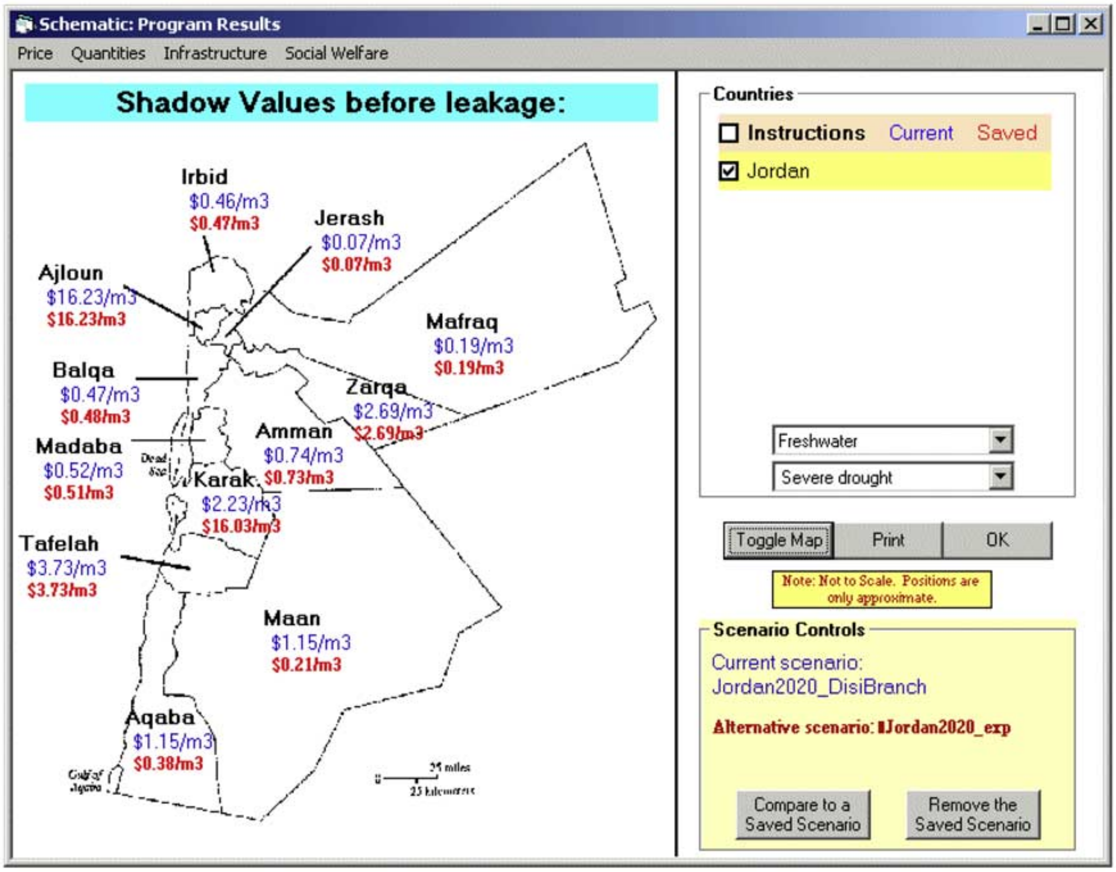


Figure 5. Shadow values in dollars/m^3 for water in each district for scenarios with (top values) and without (bottom values) a Disi carrier branch to Karak.

we consider Disi carrier branches from an intermediary node to Karak and Madaba.

[47] Results show the Disi well field is expanded, the carrier and Karak branch are built, and there is an improvement in annual net benefits of about $60 million/a (Disi Branches column in Table 2), and a drastic reduction in the scarcity value of water in Karak (Figure 5, top values). These gains are offset by modest increased scarcity values in Aqaba and Ma'an as these districts also compete for the Disi water (Aqaba develops wells in Wadi Araba). Still, the overall benefit for Karak makes the Disi project worthwhile.

4.5. A Further Look at Nonprice Water Conservation

[48] Two final runs consider (1) nonprice conservation programs to improve physical water use efficiency by 15% for agricultural users and (2) expansions required without nonprice water conservation for urban users. Improving applied water use efficiency by agricultural water users marginally decreases scarcity values for water, adds small net benefits (Table 1, seventh row), and reduces agricultural water use by only 15×10^6 m^3/a. In Jordan, agriculture water use is already of low value and elastic. Other activities cannot profitably make use of treated urban wastewater. Small benefits reflect the small increased economic productivity for agricultural users.

[49] Finally, without targeted installations of water-efficient appliances for urban water users, there is little change in capital expenditures with an almost $350 million/a loss in net benefits (Table 1). 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 (No Water Use Efficiency column in Table 2). These results highlight a trade-off between physical infrastructure expansions and nonprice water conservation programs. Nonprice water conservation programs can substitute for and delay infrastructure expansions.

5. Discussion

[50] Stochastic programming is used to integrate infrastructure capacity expansions, nonprice water conservation and leak reduction programs, and variable water availability in a regional water allocation model. Results show that a broad mix of targeted installations of water-efficient appliances, leak reduction, infrastructure expansions, and conjunctive operations can respond to growing projected water use forecasted for Jordan through 2020. In sections 5.1 and 5.2, we list and discuss key findings. We also contrast these findings with MWI's current actions and results from prior studies.

5.1. Key Findings

[51] 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 nonprice conservation programs significantly reduce scarcity costs compared to infrastructure projects and can delay or forestall the need for them. These regional findings quantify and substantiate off-site benefits often ascribed to water conservation and demand management [*Baumann et al.*, 1998]. Substantial regional benefits should also motivate and justify nonstructural government efforts listed in Figure 1 to encourage water conservation.

[52] 2. Some rationing is economical in response to limited water availability. Stochastic optimization identifies an economical balance between expanding infrastructure and rationing under variable water availability. This balance reflects the magnitude and likelihood of events when availability is limiting, economic costs of rationing, minimum allocations users can sustain, and opportunity costs of unused infrastructure. Users enter these parameters and policies so that recommended expansions and allocations maximize economic efficiency subject to prevailing social and political requirements.

[53] 3. A Disi carrier branch to Karak should be included. Several runs show that Disi water can significantly reduce water scarcity in Karak. 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 and Amman.

[54] 4. Desalination is not urgent. Small desalination plants in Aqaba and Balqa are indicated only in one run that excluded nonprice 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.

[55] 5. There are impending crises for Tafelah, Ajloun, and Zarqa. The most favorable modeling scenarios still indicate high scarcity values for Tafelah, Ajloun, and Zarqa that are much higher than values in neighboring districts (Figure 5). In part, this result reflects an absence of infrastructure projects considered for those districts. However, low scarcity values in neighboring districts suggest that additional conveyance from Ma'an, Irbid, and Mafraq to Tafelah, Ajloun, and Zarqa, respectively, can help manage impending crises in the latter districts.

5.2. Comparing to Actions Already Underway and Prior Studies

[56] Model results support MWI efforts to rebuild the Amman distribution network, finish the Unity Dam on the Yarmouk River, expand Zai plant capacity, tender proposals to build the Disi conveyor, and, with funding from the U.S. Agency for International Development, start a second kingdom-wide water conservation program and expand the Al-Samra wastewater treatment plant. The Aqaba Zone Economic Mobilization is still studying recommendations to expand conveyance from Disi to Aqaba, rehabilitate the Wadi Yutum wells, and expand tertiary wastewater treatment.

[57] Although MWI is developing plans to convey Red Sea water to the Dead Sea, our results show that the desalination portion is only used in the most water-scarce event and absent nonprice water conservation programs for urban users. A wide mix of other infrastructure expansions and nonprice conservation and leak reduction programs can forestall development of large-scale desalination. However, absent these efforts, large-scale desalination of Red-Dead Canal water may be justified.

[58] 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), to reduce leakage, and to build the Zara-Ma'een project and Disi carrier. Leak reduction, targeted installations of water-efficient appliances for urban users, 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, leak reduction, and nonprice conservation program decisions helps the model to identify an optimal portfolio of expansions in one go rather than through numerous simulations.

[59] 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 Aqaba and use mixed integer programming to identify the cost-minimizing timing of capacity expansion to meet growing projected water needs through 2020. They similarly recommend expanding the Wadi Yutum well field, adding a Disi pipeline to Aqaba, and building a wastewater treatment plant. However, they also suggest building a desalination plant. Their study does not consider competition for scarce Disi water, stochastic water availability, leak reduction, or nonprice water conservation options. These factors can forestall or delay desalination.

[60] Finally, we assume that the demand curves for water-related service and water use have the same shape; further research should explore effects of demand hardening for a more inelastic demand curve with conservation programs in place. Further, as with the single-year WAS model, our methods and findings leave out optimal storage operations and sequencing through time of capacity expansions, leak reduction, and nonprice conservation programs with growing, uncertain demands. We suspect that economic analysis would show that nonprice 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.

6. Conclusions

[61] An integrated hydroeconomic analysis considers a very diversified portfolio of options for a diverse set of demands in an extensive geographic setting. Stochastic programming identifies an optimal mix of infrastructure expansions and nonprice water conservation and leak reduction programs plus operational allocations and rationing to respond to a stochastic distribution of surface water availability. We build on recent empirical and theoretical work and show how to include shifts in demand from nonprice conservation programs as an input parameter and decision in a hydroeconomic regional water model. We shift the demand curve that describes user value. 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).

[62] Application of the integrated regional water model in Jordan shows the following.

[63] 1. Targeted installations of water-efficient appliances for urban users can generate significant benefits with small capital investments. These benefits match or better gains from infrastructure projects and delay or avoid their considerable expense. MWI and the Jordan government should promote nonprice water conservation efforts.

[64] 2. Rationing and conjunctive use operations are economical responses to stochastic water availability.

[65] 3. A broad mix of other infrastructure expansion projects and leak reduction programs can substitute for and forestall desalination in Aqaba and Balqa.

[66] 4. The Disi carrier to Amman should include a large branch to Karak.

[67] 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.

[68] 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, conveyance, wastewater treatment for reuse, leak reduction, and nonprice conservation programs and expansion efforts can mitigate these effects. Implementing these actions will require large capital investments. But the expected benefits should be larger still.

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