The Report Committee for Bruk M. Berhanu
Certifies that this is the approved version of the following report:

Feasibility of Water Efficiency and Reuse Technologies As Demand-Side Strategies for Urban Water Management

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor: ______________________________
Mary Jo Kirisits

Co-Supervisor: ______________________________
Sheila Olmstead

Feasibility of Water Efficiency and Reuse Technologies as Demand-Side Strategies for Urban Water Management

by

Bruk M Berhanu, B.S.E.

Report

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degrees of

Master of Science in Engineering

and

Master of Public Affairs

The University of Texas at Austin

August 2016

Acknowledgements

I would like to acknowledge several people for their contributions to this report as well as my graduate education. First, I would like to thank my former advisor, Dr. Michael Blackhurst, for supporting this research and exposing me to a system of thinking about sustainability and water issues that will forever shape my career. I wish you the best of luck in Pittsburgh and hope our paths cross again. I would also like thank Dr. Mary Jo Kirisits for lending her valuable time to mentoring and advising me throughout my graduate career. I would also like to thank Paulina Jaramillo, Derrick Carlson, and Miriam Hegglin of the Climate Impacts, Mitigation, and Adaptation research group at Carnegie Mellon University for their support with this research project. Finally, I would like to thank my classmates in the Department of Environmental and Water Resources Engineering in the Cockrell School of Engineering for making this graduate program as successful as it has been.

Abstract

Feasibility of Water Efficiency and Reuse Technologies as Demand-Side Strategies for Urban Water Management

Bruk M Berhanu, M.S.E.; M.P.Aff

The University of Texas at Austin, 2016

Supervisors: Mary Jo Kirisits and Sheila Olmstead

Potable residential water efficiency and reuse technologies have seen increasing adoption in recent years and have been estimated to reduce demands by up to 50%. This report present the results of an engineering economic model to estimate the technically feasible levelized cost of water provided by seven above-code water efficiency and reuse technologies within Texas Water Planning Region K, representing central Texas. Unlike other demand-side studies of residential water use, we model uncertainty and variation in technology adoption cost and performance; include reuse technologies; and differentiate between new construction and retrofits. A water efficiency and reuse supply curve was developed to compare the levelized cost of efficiency and reuse technologies with conventional supply-side water management strategies. Results show that efficiency and reuse in the residential sector can meet 85% of 50-year projected needs (the difference between projected demand and estimated supplies) for the LCRA service area. Lower levelized costs were estimated for immediate retrofits of most technologies, promoting incentives for early technology adoption. However, efficiency and reuse technology

performance demonstrates considerable uncertainty and variability. The fraction of demands met by demand-side strategies range from around 60% to 100%. Occupancy drives much of the variability because it significantly affects demand. These results promote designing incentives for adoption of water efficiency and reuse technologies based upon use. Finally, water-efficient showerheads and bathroom faucet aerators perform well over a variety of assumptions, indicating that these technologies should be a priority for municipalities seeking water demand reductions. The methods presented in this report provide a useful tool for water planners and managers who wish to compare demand- and supply-side water management strategies on an even basis, and introduces assessments of uncertainty and variability not previously seen in the relevant literature. This report has been modified for publication and has been published as a manuscript in the Journal of Industrial Ecology (DOI: 10.1111/jiec.12430).

Table of Contents

List of Tables

List of Figures

Introduction

U.S. water providers spent an estimated $473.7 billion on conventional drinking water supply projects between 1991 and 2005 (Anderson, 2007). However, many regions in the U.S. have increasing water scarcity, which strains traditional water supplies and challenges conventional water planning approaches. In response, demand-side water management strategies have seen increasing interest as a means to provide water supplies for the building sector.

Demand-side management strategies include price (e.g., "conservation-based pricing") and non-price interventions. Non-price interventions include command-and-control restrictions (e.g., outdoor watering limits) as well as adoption of "above-code" (water use efficiency beyond that required by building code) efficiency and reuse technologies, both of which have seen global adoption and promotion using a variety of policy mechanisms (Energy Policy Act, 2005; EPA, 2002). For example, the U.S. Environmental Protection Agency (EPA) actively promotes adoption of WaterSense® and ENERGY STAR® technologies, and many utilities provide incentives for technology adoption or free technology swaps. Similar government-managed water efficiency legislation and programs also exist in Australia and Canada (Water Efficiency Labelling and Standards Act, 2005; Canada Water Act, 2015).

Arguments for above-code efficiency and reuse are often based upon a priori estimates of technically feasible reductions in water demand (Chesnutt et al., 2007; NCDENR, 2004). For example, Hebeger et al. (2014) modeled indoor residential water consumption in California according to end-use and estimated ~50% reduction in residential demand with complete market penetration of above-code efficiency technologies (i.e., the technical potential is 50%). Others have emphasized the potential of efficiency and reuse technologies to offset conventional supply projects (EPA 2002; Texas Living Water Project, 2014; White and Howe, 1998; Woltemaide and Fuellhart, 2013). In a review of 16 demand-side management programs covering utilities in 14 states, the EPA estimated that the monetary municipal benefits of offsetting or delaying conventional supply projects exceeded the costs of each demand-side management program and reduced total (indoor plus outdoor) water consumption by 14 to 50% (EPA, 2002).

A posteriori studies of the effectiveness of water efficiency and reuse technologies also are available. For example, several studies have observed the effect of efficient technologies by applying statistical analyses to water consumption. Renwick and Archibald (1998) used regression to demonstrate that water-efficient showerheads, water-efficient toilets, and efficient irrigation systems reduced demand by 8%, 10%, and 11%, respectively, for Californian households. Kenney et al. (2008) and Renwick and Green (2000) found similar reductions associated with participation in water efficiency rebate programs. Additionally, several studies have used summary statistics to estimate a 6% to 16% reduction in residential water demand from adoption of efficient technologies (Lee et al., 2011, 2013; AWWA, 1999; DeOreo, 2011).

Conservation supply curves (CSCs) have long been used to integrate demand- and supply-side alternatives for energy planning. CSCs show the total technically feasible energy savings (shown on the abscissa) by rank-ordering technology performance by cost effectiveness or levelized cost of service (shown on the ordinate) (Meier, 1982; National Academy Press, 1992; Stoft, 1995). CSCs provide a consistent basis for comparing technology performance across consumers (demand side) and producers (supply side), thus facilitating the selection of economically efficient technology models. Similarly, CSCs can facilitate improved water management planning; in particular, CSCs can be used to compare demand-side interventions to supply-side methods and to integrate strategies into a single decision-support resource that a variety of stakeholders can understand. By considering the costs and benefits to municipalities and consumers, CSCs can help identify and quantify split incentives (i.e., who pays the marginal costs and who reaps the benefits) to facilitate technology adoption schemes.

Despite these advantages, only three other applications of CSCs to water provisions are available. Of these, only one examined the application of CSCs specifically to water efficiency and reuse technologies as well as other demand-side water management programs as part of a case study, though no comparison to supply-side strategies planned for the study area were considered (White and Fane, 2007). The other applications investigate the theoretical basis of CSCs for water supply planning (Smith, 2010) or provide previously constructed CSCs of only water efficiency technologies for consumer reference (Northwest Power and Conservation Council, 2014).

This work expands the use of CSCs by integrating supply- and demand-side strategies in a single resource using the Lower Colorado River Authority (LCRA), the water governance body for the Lower Colorado River Basin in central and southeast Texas, as a case study. Figure 1 shows the geographic location for the LCRA. In recent years, the majority of freshwater demand in the LCRA has shifted from agricultural to municipal water customers, as water scarcity has spurred interruption of service to agricultural customers (LCRA, 2014). Worsening drought conditions throughout much of Texas have prompted municipalities within the LCRA to enact water-use restrictions as a form of demand-side management (Austin Water Utility, 2014).

Figure 1. Lower Colorado River Authority (LCRA) service area boundary

The approach detailed in this report provides a single tool for water management planners to compare supply- and demand-side management strategies on a consistent basis, under a range of assumptions regarding technology performance and demographic characteristics of the study area. The stochastic treatment of uncertainty and variation in technology adoption is unique in the consideration of adoption schedule and technology cost and performance parameters. Using these methods can enable robust water resources decision-making under uncertain scenarios, and promotes design of effective incentive policies to achieve large-scale and cost-effective water demand reductions.

Methods

This report details the technically feasible water savings in the LCRA from 2010 to 2060 from five above-code efficiency technologies (WaterSense® water-efficient toilets, WaterSense® water-efficient showerheads, WaterSense® bathroom faucet aerators, ENERGY STAR® clothes washers, and ENERGY STAR® dishwashers) and two reuse technologies (household rainwater harvesting and integrated toilet-sink devices). Two technology deployment schemes were considered in which existing technologies are replaced immediately or as they retire, differentiating between growth (new construction) and retrofits. A water efficiency and reuse CSC was then constructed to compare demand-side technology performance to conventional supply-side approaches.

Levelized Cost of Performance Estimation

Equation (1) specifies the engineering economic model used to estimate the levelized cost of performance for each technology (where Table 1 details terms and definitions). In the energy efficiency literature, the cost of conserved energy is used as a measure of cost-effectiveness, calculated as the net present value of the life cycle costs of energy efficiency technology adoption, normalized by the lifetime energy savings produced (Meier, 1982). In this study, we modify the cost of conserved energy equation to assess the levelized cost of water efficiency and reuse technologies. We calculate the net present cost of basin-wide technology adoption and subsequent retrofits, normalized by the total estimated water savings over the planning horizon.

$$Levelized\ Cost = \frac{\left((C * CRF) - (P_E * S_E + P_W * S_W)\right)}{S_W} \qquad (1)$$

Future technology penetrations and their respective rates of technological change determine the basin-wide effectiveness of water efficiency and reuse. Here, two technology adoption schemes were; replace-immediately and replace-as-retire. In the replace-immediately scheme, existing and future homes are treated separately. For existing homes, immediate replacement of all existing technologies with above-code technologies was modeled, assuming the full capital cost of those technologies. For future installations of above-code technologies in new homes, only the marginal cost of above-code technologies when estimating the capital expenditures was considered. The model inherently assumes that no welfare loss occurs from adoption of above-code water efficiency and reuse technologies (i.e., the level of utility remains constant) and solely estimate monetary costs associated with technology adoption. However, it is worth noting the anecdotal evidence of loss of service level via decreased technology performance, associated with efficiency technology adoption. Table 1 summarizes the model differences between these two schemes.

Term	***Replace-Immediately Scheme***	***Replace-as-Retire Scheme***
C (Capital Expenditure, $)	Full cost of above-code technologies for early technology retirements	Marginal cost (difference in capital cost of above-code and current use models) of above-code technologies for replacements as technologies retire
CRF (Capital Recovery Factor)	$= \frac{\text{discount rate} * (1 + \text{discount rate})^{\text{service life}}}{(1 + \text{discount rate})^{\text{service life}} - 1}$	
P_E	Price of energy ($/GJ)	
S_E (Annual energy savings, GJ)	(Current Use) – (Above-Code Use) for first retrofit	(Minimum-Code Use) – (Above-Code Use) for new installations and subsequent retrofits
P_W	Price of water ($/cubic meter)	
S_W (Annual water savings, cubic meters)	(Current Use) – (Above-Code Use) for first retrofit OR Avoided potable use for reuse technologies	(Minimum-Code Use) – (Above-Code Use) for new installations and subsequent retrofits OR Avoided potable use for reuse technologies

Table 1. Levelized cost equation terms and definitions.

The replace-immediately scheme has a high capital cost burden, but monetary and resource savings begin immediately. These assumptions thus represent the technically feasible water savings given technology performance specifications. In the more realistic replace-as-retire scheme, future retirements and installations using above-code technologies are considered at the marginal cost of those technologies. The marginal cost was used instead of the full capital cost to reflect the consumer choice between at- and above-code technologies. Relative to the replace-immediately scheme, the replace-as-retire scheme has a lower capital cost burden but delays monetary and resource savings.

It is important to note that the engineering economic model in this analysis does not account for the salvage value or secondhand adoption of retired technologies. Additionally, a base-case discount rate of 10% was assumed, in accordance with EPA recommendations for assessing energy efficiency, with high and low values of 42.5% and 3.9%, respectively (National Action Plan for Energy Efficiency, 2008; Hausman, 1979; Wada et al., 2012; United States Office of Management and Budget, 2014).

TECHNOLOGY COST AND PERFORMANCE ESTIMATES

Table A1 in the appendix summarizes the seven efficiency and reuse technologies and their performance standards. We used ENERGY STAR® and WaterSense® performance standards, detailed in the Energy Policy Act of 2005, as above-code technology performance values for water-efficient toilets, clothes washers, dishwashers, and showerheads (Energy Policy Act, 2005). Further, we scraped online retail sales data using technology models recommended by the EPA's WaterSense® and ENERGY STAR® reference materials for over 100 models of each efficiency technology (U.S. EPA, 2014a; U.S. EPA, 2014b). These data were used to obtain the associated capital costs (C), as well as water and energy performance of at-code technology models (used to calculate resource savings).

For integrated toilet-sink devices, performance and capital cost data were collected from manufacturers across a range of models and devices and estimated water savings as the lesser of displaced demand from either toilet flushing or bathroom faucet use that could be provided by recycling greywater from bathroom faucet use.

For rainwater harvesting systems, the Texas Water Development Board Rainwater Harvesting Manual provides the design parameters (i.e., material costs, storage capacity, treatment cost, catchment area, and capture efficiency). These parameters were used to estimate the capital cost per liter of water stored, using median, 10th, and 90th percentiles of parameters values for the base-, low-, and high-cases respectively (Texas Water Development Board, 2005). Two water quality scenarios were employed; users could either leave water untreated specifically for outdoor use or treat to potable standards for indoor or outdoor use (at an additional treatment cost). These treatment scenarios are designated as -P and -NP (for potable and non-potable use, respectively). System sizing constraints due to intermittent rainfall by sizing rainwater harvesting tanks were modeled using the sequent-peak algorithm (Thomas and Burden, 1987), and selecting from available storage tank volumes based upon maximum annual storage needs over the planning horizon for each simulation.

To estimate water savings associated with efficiency interventions, data from the white and grey literature were used to calculate end-use demands and current market saturation rates (DeOreo, 2011; Mayer and DeOreo, 1999; U.S. EPA, 2014a; U.S. EIA, 2010). We do not assume that minimum-code regulations and performance of commercially available technologies will remain stagnant through the 50-year planning horizon; our model assumes similar technical gains between above-code and at-code technologies at similar marginal costs (difference in capital costs between technologies).

Uncertainty and Variability Modeling

To estimate basin-wide residential demand, household technology installations were scaled to the entire LCRA service area based on population projections through 2060 (assuming that current water service needs grow in proportion to population) with an uncertainty range of ±20%, in accordance with projections detailed in the 2012 State Water Plan for Texas (Texas Water Development Board, 2012). For individual technologies, parametric sensitivity analysis was performed to highlight model sensitivities associated with extreme input values.

Monte Carlo (MC) simulation with 100,000 trials was used to estimate levelized cost, total capital costs, total water savings, and net present value for all seven technologies. For dishwashers, clothes washers, and water-efficient toilets empirical distributions and parameter correlations for highly variable parameters (e.g., occupancy, technology demand, capital cost) were established. For each MC simulation, technology selection was treated as a random choice from commercially available technology models to prepare empirical distributions of capital costs and efficiency performance. The technology choice was applied to all households within the LCRA and percentage of annual retirements calculated as the inverse of the technology service life. Retirement of retrofits and new construction technologies were modeled in the same manner across adoption schemes. Therefore, the treatment of currently installed stock formed the difference in adoption schemes; the replace-immediately scenario represented immediate retrofitting of currently installed at-code models in 2010, while the replace-as-retire¬ scenario represented retrofits implemented at a rate of the inverse of the technology service life.

Further, discrete empirical household occupancy distributions were developed from state census data (Texas State Data Center, 2014). The number of clothes washer and dishwasher cycles, as well as bathroom faucet, shower, and toilet demands were estimated using household occupancy data and end-use demand estimates (U.S. EIA, 2010; American Water Works Association, 1999). Remaining model parameters were modeled using uniform distributions of low-, base-, and high-case values.

Using Equation 1 and the above technology performance assumptions, water savings, net present value, levelized cost of service, and total capital expenditures for the 2010-2060 planning horizon were calculated and probabilistic distributions of basin-wide estimates of the model outcomes specified in Equation 1 were prepared. Though most model parameters are shown in Figure 2, Tables A2 through A9 in the appendix provide a complete list of model parameters for each technology and the service area, as well as low-, base-, and high-case values or empirical distributions when applicable. Finally, the results of the demand-side strategies were compared with the water management strategies recommended by the Texas Water Development Board for the 2010-2060 planning horizon in a "water efficiency and reuse supply curve".

Results

SENSITIVITY OF LEVELIZED COST TO MODEL PARAMETERS

Figure 2 shows the results of the one-way sensitivity analysis for the levelized cost of service for each technology. For example, bathroom faucet aerators have the largest sensitivity to the price of water, showing high levelized costs in low water price scenarios and vice versa. In each sub-figure, the vertical dashed line represents the levelized cost when all model parameters are at base-case values. All levelized costs are reported in real 2010 $ per thousand cubic meters. For all figures, values shown in red and parentheses indicate net consumer savings and values in black indicate net consumer costs.

In general, the largest contributors to uncertainty and variation in levelized costs are the capital cost of above-code models and annual demand. Annual demand has the largest influence on levelized cost of service for clothes washers and dishwashers; however, the levelized cost for efficient fixtures (water-efficient showerheads, bathroom faucet aerators) are more sensitive to the unit price of water and discount rate. The figure shows that the levelized costs of service for clothes washers, water-efficient toilets, and dishwashers are highly sensitive to demand; this suggests that higher use (and therefore higher water savings) is required to offset high capital costs. Integrated toilet-sink devices are sensitive to capital and installation costs, service life, and the supply of reusable water, though they are relatively less sensitive to water prices. Similarly, rainwater harvesting systems (both potable and non-potable) are sensitive to the supply of water (in the form of catchment area and storage capacity).

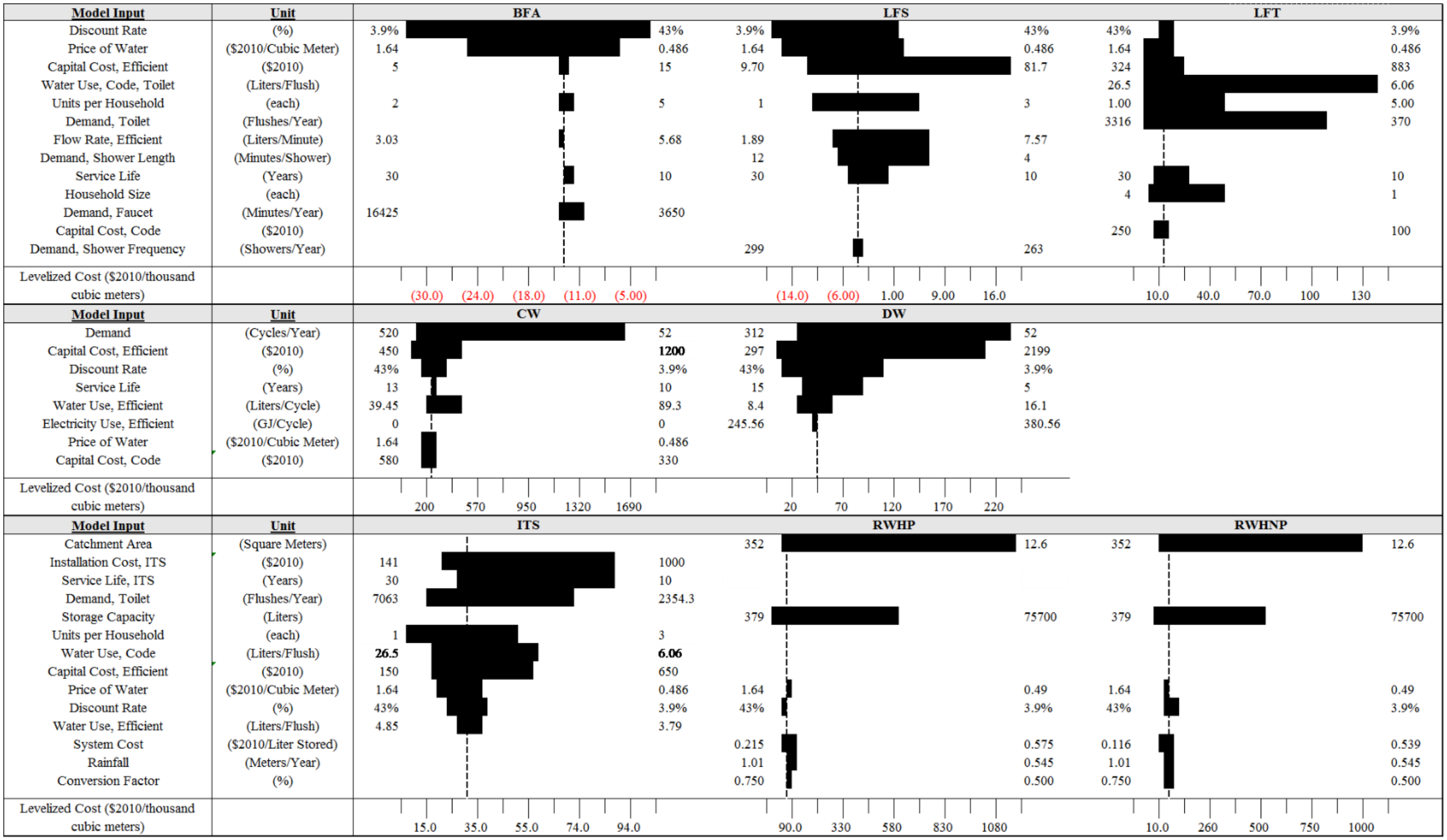

Figure 2. One-way sensitivity analysis of levelized cost for efficiency and reuse technologies.

Figure 2. One-way sensitivity analysis of levelized cost for efficiency and reuse technologies. The ordinate of each chart shows the inputs and associated uncertainty range values while the abscissa shows the levelized cost of service for each technology. Efficiency and reuse technologies are labeled along abscissa as follows: BFA – bathroom faucet aerators, LFS – water-efficient showerheads, LFT – water-efficient toilets, ITS – integrated toilet-sink devices, CW – clothes washers, DW – dishwashers, RWH-P/-NP – rainwater harvesting (potable and non-potable use, respectively). The dashed line in each chart represents the base-case levelized cost for the respective technology. Values shown in red and parentheses indicate net consumer savings and values in black indicate net consumer cost.

The monetary value of the difference in water saved between adoption schemes, using current rates, was \$28.3 million (difference of 317 million cubic meters) for net-benefit technologies, with a range of \$15.2 million for a difference of 153 million cubic meters to \$60.5 billion for a difference of 705 million cubic meters. When considering all technologies, the value of water saved was \$2.44 billion (difference of 2.73 billion cubic meters) for all technologies with a range of \$1.57 billion for a difference of 1.76 billion cubic meters to \$3.32 billion for a difference of 3.71 billion cubic meters. The difference in median capital costs between the two adoption schemes was \$13.9 million for net-benefit technologies (uncertainty range of \$9.78 million to \$7.67 million) and \$15.4 billion for all technologies (uncertainty range of \$10.2 billion to \$36.6 billion). These results indicate that immediate replacement of all technologies considered is not appropriate, though the immediate replacement of net benefit technologies produces considerably higher monetary benefits. However, from a policy development and implementation perspective, a replace-immediately scheme is highly likely due to the immense capital cost required to achieve instant retrofits. Therefore, the replace-immediately scheme represents the theoretical maximum of technically feasible water savings.

BREAKEVEN DISCOUNT RATE ANALYSIS OF ADOPTION SCHEMES

To understand how adoption scheme preferences vary over individual households, a breakeven analysis was to estimate the implicit discount rate at which a household would be indifferent between the two adoption schemes presented. Table 2 details the results of the breakeven discount rate analysis for each technology. For all technologies, households tend to prefer the replace-as-retire adoption scheme at implicit discount rates higher than the breakeven rate. Figure 3b, which compares the annual levelized costs for each technology and adoption scheme combinations, echoes these results. For example, water-efficient showerheads have equal levelized costs between adoption schemes at a discount rate of 239%, holding all other variables constant. Therefore, households with implicit discount rates less than or equal to 239% prefer the replace-immediately adoption scheme, and those with discount rates higher than 239% prefer the replace¬-as-retire scenario. In Figure 3b, the replace immediately scheme is also preferable for water-efficient showerheads, in terms of levelized cost. This preference hold true across the uncertainty range, because the value of the high case for the discount rate variable is less than 239%. This trend of adoption scheme preference holds true for all technologies considered. However, for integrated toilet-sink devices, the breakeven discount rate was much higher than any values observed in the relevant energy and water efficiency literature (i.e., greater than 50,000,000%). This result can be interpreted as if there is no discount rate at which households prefer the replace-as-retire discount rate for this technology.

These results can guide the interpretation of the implicit discount as it applies to water efficiency and reuse technologies. In the replace immediately adoption scheme, an individual bears the full capital costs burden of technology adoption. Therefore, when combined with a high implicit discount rate, the consumer will place much higher importance on present cash flows (i.e., capital cost expenditures) and lesser importance on future cash flows (i.e., monetary savings), leading them to prefer an adoption scheme that delays the capital cost expenditures. However, the replace-as-retire scheme also delays monetary savings from more efficient water and energy use. For low discount rate scenarios (in the replace immediately scheme), the relative importance of present and future cash flows are less disparate. Therefore, a consumer will be less reluctant to consider immediate technology adoption.

Beyond the implications of the individual discount rate, a consumer in the replace-as-retire adoption scheme only bears the marginal cost of efficiency technology adoption, or the difference in capital costs between an at-code and above-code models of a particular water end-use technology. However, a consumer under the replace-immediately adoption scheme must bear the full capital cost of adopting an above-code technology, because they are choosing to replace their technology before the end of the natural service life. Therefore, the replace-as-retire adoption scheme has an inherent advantage with respect to capital cost burden to the consumer. Combined with the results of the breakeven analysis, this advantage could explain the preference of the replace-as-retire scenario across all technologies at discount rates higher than the respective breakeven rates.

Technology	Breakeven Discount Rate
Water-Efficient Showerheads	239%
Bathroom Faucet Aerators	198%
Water-Efficient Toilets	10.6%
Rainwater Harvesting (Non-Potable)	12.0%
ENERGY STAR® Clothes Washers	4.17%
Rainwater Harvesting (Potable)	9.85%
Integrated Toilet-Sinks	51,600,000%
ENERGY STAR® Dishwashers	6.96%

Table 2. Breakeven discount rates between adoption schemes for water efficiency and reuse technologies.

For all technologies, households prefer the replace-as-retire adoption scheme for implicit discount rates higher than the breakeven rate.

WATER EFFICIENCY AND REUSE SUPPLY CURVE

Figure 4 shows the water efficiency and reuse supply curve for the 30 conventional water management strategies described in the 2012 State Water Plan for Texas and seven efficiency and reuse technologies in the LCRA basin, under the replace-immediately adoption scheme. For convenience, the 30 recommended water management strategies, as well as estimated water supplied over the planning horizon and expected capital and operating costs are included in Table A15 in the Appendix. The annual levelized costs of the water management strategies outlined in the 2012 Texas State Water Plan for Region K range from \$0.101 to \$26.8 per thousand cubic meters per year, and the total capital expenditure for all 30 projects is approximately \$1.63 billion (2010 base year). The estimated water supplied by each project ranges from 1.01 million to 3.23 billion cubic meters, with a total estimated supply of approximately 17.4 billion cubic meters by 2060.

Table 3 provides a summary of the total capital costs, net present costs, annual levelized costs of service, total water savings, displaced costs of traditional water management strategies (i.e., avoided cost from pursuing efficiency and reuse technology instead of supply-side strategies at the high end of the supply curve that would produce commensurate water savings/supplies), and total cost/savings (net present value + displaced cost) for net-benefit technologies and for all efficiency and reuse technologies considered for this study, as well as the extreme parameter values that contributed to uncertainty ranges. By "supplying" commensurate water provisions at lower levelized costs, technologies such as water-efficient toilets and bathroom faucet aerators could displace more expensive conventional water supply alternatives.

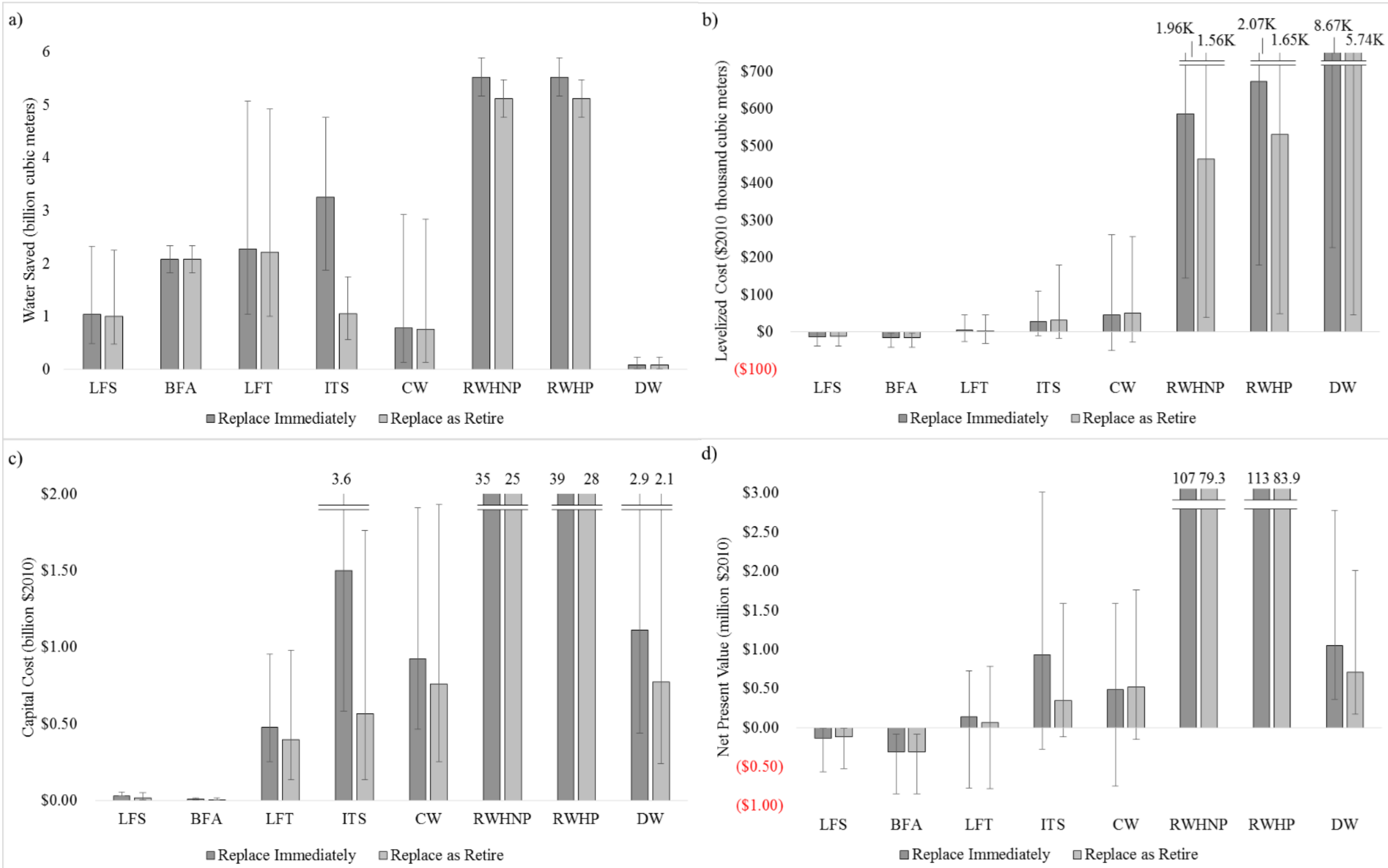

Figure 3. Comparison of replace-immediately and replace-as-retire adoption schemes.

Figure 1. Comparison of replace-immediately and replace-as-retire adoption schemes for: a) water saved in billions of cubic meters; b) annual levelized cost in $/billion cubic meters; c) capital costs in billion $2010; and d) net present value in billion $2010 of basin-wide water efficiency and technology adoption over the 50-year planning horizon. Values shown in red and parentheses indicate net consumer savings and values in black indicate net consumer costs. Error bars represent 10th and 90th percentiles of Monte Carlo simulation results.

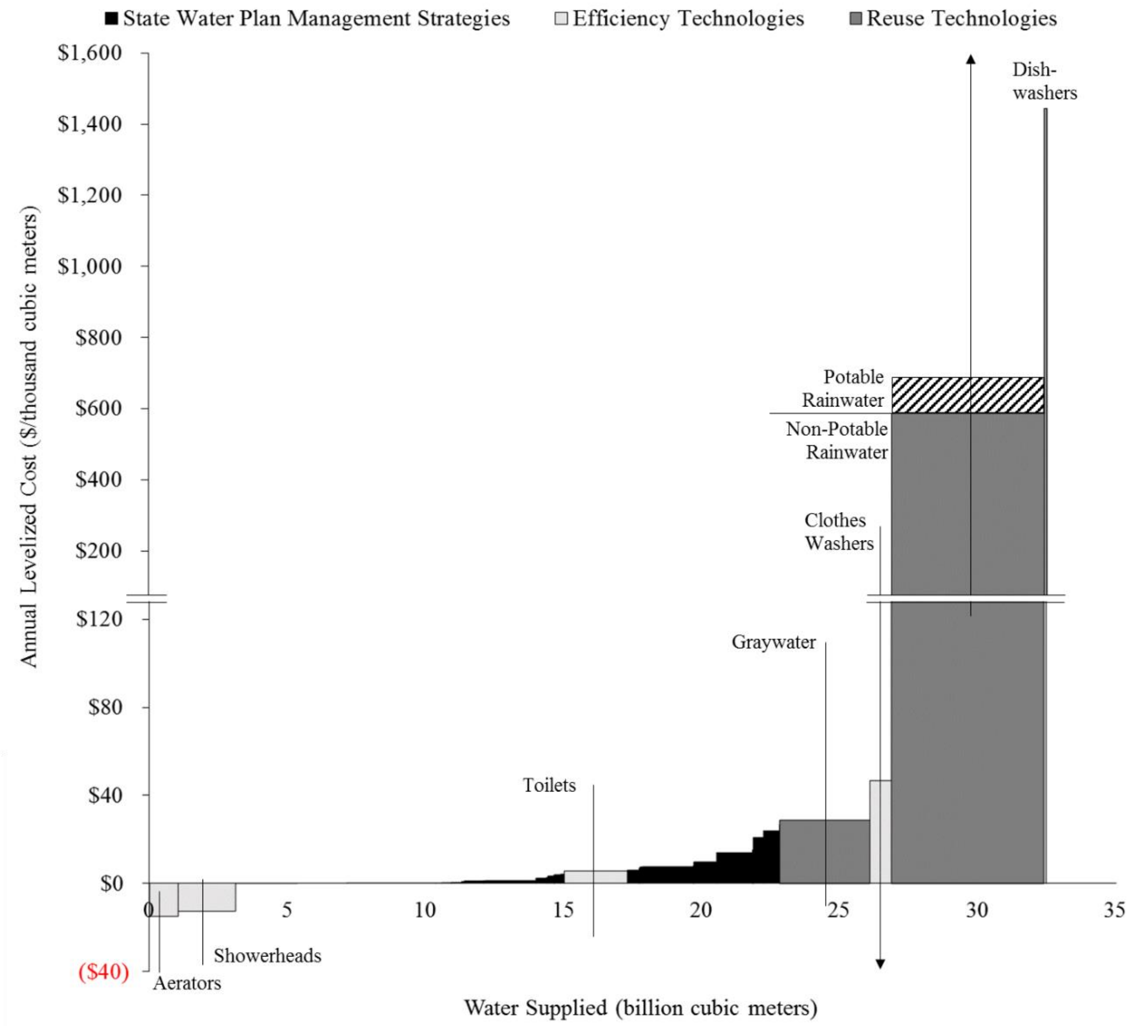

Figure 2. Water efficiency and reuse supply curves for demand- and supply-side strategies in the study area.

Supply-side strategies between 3 billion cubic meters and 11 billion cubic meters water supplied reflect levelized costs not visible on the given ordinate scale. Error bars represent 10th and 90th percentile values from Monte Carlo simulations. The patterned box above rainwater for non-potable use results represents the marginal levelized cost of additional treatment technology required for potable use of rainwater. Values shown in red and parentheses indicate net consumer savings and values in black indicate net consumer costs. Error bars represent 10th and 90th percentile ranges from Monte Carlo simulation results and arrows indicate values beyond vertical access scale.

From this figure, adoption of net-benefit technologies alone can provide 18% of projected water needs (approximately 3.12 billion cubic meters) for the LCRA service area (uncertainty range of 13% to 26%), translating to avoided capital costs of $1.06 billion (uncertainty range of $881 million to $1.06 million).

Clothes washers, rainwater harvesting systems (both potable use and non-potable use), integrated toilet-sink devices, and dishwashers have higher levelized costs of service and thus less potential to displace conventional projects. Both rainwater harvesting systems scenarios were found to be more expensive than all of the proposed water management strategies, though the levelized cost of a potable quality rainwater harvesting system is only about 6% higher than that of a non-potable rainwater harvesting system, while supplying equal volumes of water. This small marginal difference in cost is because the bulk of the cost is associated with the storage cistern rather than the treatment system. The result is a slightly larger capital and operating expenditure for potable water demand reduction by means of rainwater harvesting. In both cases, proper maintenance and upkeep of these systems is crucial to ensure that an increase in operating costs does not occur (Texas Water Development Board, 2005). Alternatively, non-potable water use (i.e., outdoor use and toilet flushing) can fulfill a large volume of household water demand without additional costs.

Still, full adoption of all seven technologies considered might substantially reduce the need for traditional supply projects; complete adoption can reduce projected water needs by 15 billion cubic meters, which is 85% of projected water needs for the LCRA service area (with an uncertainty range of 60-100% of water needs) though at a much higher capital investment in all cases. Table A14 in the Appendix provides the summary of base-case levelized costs and uncertainty ranges for all seven technologies considered in this study.

Model Outcome	Net-Benefit Technologies			All Technologies		
	Input Scenario			Input Scenario		
	Low	Base	High	Low	Base	High
Water Savings (billion cubic meters)	2.32	3.12	4.66	10.5	15.0	23.6
Capital Cost (billion $)	$0.017	$0.037	$0.071	$14.8	$43.3	$124
Net Present Cost (billion $)	($1.41)	($0.443)	($0.096)	$9.13	$40.6	$121
Levelized Cost of ($/thousand cubic meters/year)	($40.1)	($14.1)	($2.73)	$124	$382	$927
Monetary Savings from Displacing Supply-Side Strategies (billion $)	($0.881)	($0.881)	($1.06)	($1.60)	($1.62)	($1.63)
Total Cost/Savings (billion $)	($2.30)	($1.32)	($1.16)	$7.53	$39.0	$120

Table 3. Technology costs and water savings summary for demand-side alternatives, including base-case values and uncertainty ranges for *replace-immediately* adoption scheme.

Values shown in red and parentheses indicate net consumer savings and values in black indicate net consumer costs. “Low-”, “Base-”, and “High-” case labels represent 10th, 50th, and 90th, percentiles, respectively.

Discussion

MODEL RESULTS AND TECHNICALLY FEASIBLE WATER RESOURCE AND MONETARY SAVINGS

Adoption of net-benefit technologies alone can displace almost 20% of the recommended conventional supply projects for the LCRA. Additionally, the relatively large water savings associated with integrated toilet-sink devices suggests that there is a large unrealized benefit of greywater recycling technologies in Texas, specifically from devices that reduce demand from traditional end-uses. However, the large range of capital costs indicates that better understanding of costs is needed. Though current state regulations prohibit collection of greywater for indoor use (Texas State Legislature, 1989, 1992), our results indicate integrated toilet-sink devices might provide cost-effective water savings for indoor residential water demand.

Net-benefit technologies (i.e., water-efficient showerheads and bathroom faucet aerators) produce net monetary savings over their service life under a wide variety of assumptions, suggesting that these technologies should be a high priority for municipalities seeking demand reductions. Moreover, the marginal cost of the net-benefit technologies are relatively minor between adoption schemes ($13.9 million) and is smaller than the value of the difference in water savings between schemes ($28.4 million for 31.7 million cubic meters difference), which makes immediate replacement of these technologies preferable to delaying replacement until retirement.

TECHNICAL IMPLICATIONS FOR WATER PLANNING AND MANAGEMENT

Deeper demand reductions would require marginally more expensive technologies. Water-efficient toilets, integrated toilet-sink devices, and rainwater harvesting systems (potable use and non-potable use) all demonstrate potentially large demand reductions but at marginal costs that exceed the cost of all conventional supply projects. Additionally, the relatively large uncertainty ranges for both clothes washers and dishwashers, as well as the higher levelized costs in comparison to proposed supply-side strategies, suggest that basin-wide adoption might not be an appropriate adoption strategy for these technologies. Instead, the sensitivity of levelized costs of clothes washers and dishwashers to end-use demands could be leveraged by incentivizing adoption for high-demand consumers, such as large families or sites with multiple-user groups (e.g., an apartment complex). Several studies have investigated optimal retrofit/replacement of efficiency and conservation strategies in residential and commercial buildings to maximize environmental and monetary life cycle benefits (Kleine et al., 2011; Keoleian et al., 2001; Kim et al., 2006; Morrissey, 2014). Applying such methods to incentivized adoption of water efficiency and reuse technologies could maximize environmental benefits while minimizing cost to the consumer.

Though the relative rankings of water efficiency technologies are already known with respect to performance, the results of this study establish the relative rankings of these technologies with respect to cost-effectiveness on a basin-wide scale. The results also quantify the levelized cost of water saved for each technology and characterize the uncertainty of each levelized cost estimate and the impacts of individual household variables (e.g., discount rate, household demand) on levelized cost and preferred technology adoption scheme. Moreover, the results illustrate some of the nuances involved in the adoption of said technologies. For example, the level of demand for water services within a household are often the largest determinant of levelized cost for a high-cost technology (e.g., ENERGY STAR® clothes washers and dishwashers).

"Low-hanging fruit" strategies such as water-efficient showerheads and bathroom faucet aerators are typically the first options explored for reducing water demand, yet the results in this work show greater water savings for higher-cost technologies. Additionally, the result of relatively low rankings of rainwater harvesting and integrated toilet-sink devices among bathroom faucet aerators and water-efficient showerheads, toilets, clothes washers and dishwashers, by levelized cost, is a unique aspect of this study that warrants further investigation. Finally, the implicit discount rate for households can influence adoption scheme preferences. These results suggest that incentives will be required, effectively lowering the implicit discount rate, to motivate adoption of these technologies over implementation of the traditional supply-side strategies. However, depending on the preferred adoption scheme of a particular household, incentives that encourage early adoption of water efficiency and reuse technologies might be economically inefficient. Additionally, the cash flows associated with each technology can be scheduled in a manner that requires a lower discount rate to compensate for the delayed water savings associated with the replace-as-retire scheme.

ECONOMIC AND POLICY CONSIDERATIONS

The Efficiency Gap and Departures from Technically Feasible Water Savings

The results presented in this study highlight the technical feasibility of adoption of water efficiency and reuse technologies. Therefore, the costs and associated water savings for each technology represent the maximum water savings and costs borne by Region K residents to adopt each technology. However, these figures would likely diverge from actual costs paid and water saved from technology adoption for a variety of reasons. This divergence between the technically feasible water savings and costs and those realized are associated with the "efficiency gap", which has been described by Alcott and Greenstone (2012) as "a wedge between the cost-minimizing level of energy efficiency and the actual level realized". Though established in the context of energy efficiency technologies, it is reasonable to believe that the same phenomenon would occur for water efficiency and reuse technologies. That is to say, there might be a similar wedge between technically feasible and realized water efficiency savings, and/or their associated costs.

In the energy efficiency literature, the efficiency gap arises from the presence of one of at least two market failures: inefficient investment and externalities associated with energy use (Alcott and Greenstone, 2012). Backlund et al. (2012) suggest additional causes for the energy efficiency gap, both financial and behavioral. Other sources of the efficiency gap from the consumer's perspective include limited access to capital and inaccurate or incomplete information, which contribute to a barrier of bounded rationality (DeCanio, 1988). For example, inaccurate information of a consumer's current resource demands and potential for resource savings can inflate a customer's implicit discount rate if they do not believe that they are likely to recoup the capital cost of efficiency technology adoption. For the remainder of this section, investigate the causes of the efficiency gap that might limit the monetary and resource savings estimated in the Results section of this report are investigated.

Barriers to Diffusion of Technology and Technically Feasible Savings Realization

As mentioned previously, there are several possible reasons for the efficiency gap. From the consumer's (i.e., demand-side) perspective, these causes can be classified as either financial or behavioral. Economic market failures and rationally inconsistent choices can affect an individual's decision-making regarding efficiency technology adoption, by influencing their perception of costs and benefits of technology adoption. For example, previous results indicate that the cost-effectiveness of high capital cost technologies, such as an ENERGYSTAR® clothes washers, largely depends on the demand for service. However, lack of information about this sensitivity to demand for service might lead a consumer to rely on imperfect information such as anecdotal assessments of technology performance. To use a common economic analogy, the consumer would therefore leave the proverbial $20 bill on the ground, by adopting at- or below-code technologies.

Alcott and Greenstone (2012) identify three possible market failures as culprits of the efficiency gap: imperfect information, inattention and misoptimization, and negative externalities. Imperfect information is a general barrier to the enhanced diffusion of technologies, due to the uncertainty surrounding the expected returns on investment from a new or otherwise unproven technology. In the case of greywater and rainwater reuse technologies, this uncertainty might result in premiums attached to technology costs to ensure public health and safety through command-and-control policies. Examples of such policies include the former restrictions surrounding the household capture and use of rainwater in Colorado (Colorado Department of Natural Resources Division of Water Resources, 2016) or the recently lifted prohibition of the indoor use of greywater in Texas (Texas Commission on Environmental Quality, 2016). These policies limit the cost-effectiveness of water reuse technologies by preventing use of greywater and rainwater towards indoor demand reductions.

Inattention to complete information can arise if the consumer deems the cost of securing perfect information too high or if they possess a limited capacity to factor perfect information into their decision making; such inattention can change the purchasing patterns of a well-informed consumer (Alcott and Greenstone, 2012; Sallee, 2014; Sims, 2015). Complete knowledge of the variability in performance among several models of a particular technology might be available to a consumer but might not factor into their purchase decision-making. The implications of variable technology performance on levelized cost are nuanced and would require investigation that the consumer would not or could not perform at the time of the purchase decision. Therefore, the consumer might opt to ignore this information or use rules-of-thumb when purchasing a new efficiency technology model rather than using available evidence. This inattention can lead to misoptimization of consumer benefits, where an individual fails to recognize the marginal benefit of selecting a technology that has lower operating costs due to increased efficiency but has higher capital costs.

Uncertainty regarding the life-cycle costs of efficiency technology prevent the consumer from making well-informed purchasing decisions to maximize their economic benefit. In the case of water efficiency and reuse technologies, benefits occur both in the monetary savings from reduced water demand, as well as avoidance of future costs that would arise from the need for more marginally expensive water supplies. Due in part to temporal uncertainty surrounding the cost of future water supply projects, and how those costs are translated into water rates, an individual cannot account for the benefits of delaying or avoiding those projects from the purchase of above-code efficiency technologies. Moreover, if an individual tends to discount future cash flows hyperbolically, then the difference between present and future cash flows is even more pronounced than if they tended to discount cash flows linearly, while the difference between two sets of future cash flows would seem less dissimilar. As seen in Figure 2, the implicit discount rate of a consumer can influence the cost-effectiveness of low-cost water efficiency technologies, despite the tendency of these technologies to produce net monetary benefits over their lifetime under a variety of demand, cost, and water rate assumptions.

The rebound effect also presents possible reasons for an observed efficiency gap. In the energy efficiency literature, Sorrell and Dimitropoulos (2007) describe the rebound effect as an “efficiency elasticity of demand” for energy services. That is to say, increases in the efficiency of a particular energy service (e.g., space refrigeration or lighting) can lead to a corresponding decrease in the effective price paid for that service and subsequently increases in the demand for that, or a different, service (Greening, 2000). If a consumer effectively pays less for a service due to increased efficiency, then they might reinvest their monetary savings by increasing their demand for that service or other services. The rebound effect occurs in three categories: direct effects, indirect effects, and economy-wide effects (Sorrell and Dimitropoulos, 2009). Direct and indirect rebound refers to increased consumption of the same or other services, respectively, and affect the consumer most directly. For example, a direct rebound effect associated with adoption of a high-efficiency air-conditioner would be to increase the demand for cooling while an indirect rebound effect would occur if the consumer reinvested the monetary savings from increased home cooling efficiency into an additional energy end-use, such as a high-definition television. In the water efficiency sector, the direct rebound effect presents a clear possible cause of the efficiency gap and reduces the ability of basin-wide efficiency technology adoption to displace future water supply projects. However, the implications of indirect rebound are more nuanced and would require an investigation into the life-cycle water use associated with increased consumption from the indirect rebound effect.

This review of demand-side barriers to basin-wide adoption of water efficiency and reuse technologies provides several possible reasons for the existence of a water efficiency gap. Each of these factors represents an opportunity for departure from technically feasible water savings and monetary benefits but can be addressed with appropriate policies that aim to reduce the uncertainty surrounding the decision to purchase a particular water efficiency technology. These policies come from both water managers and planners, as well as the state and local jurisdictions in which efficiency technology adoption will take place. Federal policies, such as those enacted by the Energy Policy Act of 2005, can provide a backstop for states and municipalities to expand upon depending on their own economic circumstances and resource availability. Therefore, an examination of the barriers that water managers face in implementing water supply policies and a survey of the current relevant policy landscape might provide addition insight into possible solutions for the apparent efficiency gap.

Barriers to Implementation for Water Providers

The demand-side barriers to diffusion of water efficiency and reuse technologies are primarily financial and behavioral. From the water provider's perspective (i.e., the supply-side), barriers to implementation of demand-side water management strategies such as adoption of water efficiency and reuse technologies can be classified as technical, economic, or policy based. Water providers must estimate water demand across future planning horizons to ensure that sufficient water supplies will be secured in time to meet these demands. These estimates are often fraught with uncertainty for several reasons.

Most water providers lack high-resolution and consistent water use data from their customers. At best, most providers have a record of monthly water use from billing records, though these usage volumes are often comprised of both estimated and observed data. Obtaining daily or sub-daily water usage patterns can require advanced metering infrastructure that can replace or be retrofitted onto existing metering devices. Alternatively, utilities can choose to conduct home water audits or more frequent meter readings, though either option is often cost-prohibitive and time-consuming. However, high-resolution water usage data can provide previously unavailable information such as identification of water end-uses, time-of-use patterns, and accurate apportionment of monthly water demand to water end-uses (DeOreo et al., 1996). Disaggregating water demand by its end-use would allow water providers to better target customers with at- or below-code end-use technologies, rather than promoting blanket incentives for water and reuse technology adoption for all customers. By targeting incentives, water providers can improve the economic efficiency of utility-led conservation investments.

The question of who bears the cost burden associated with above-code efficiency and reuse technology adoption might have as much of an effect on the efficacy of said adoption as the technical performance of these technologies. From the customer's perspective, selection of a particular technology model, installation, maintenance, and end-of-life disposal are all transaction costs that increase their economic burden. The impact of these costs on the purchasing decision are in part a function of the individual's implicit discount rate, but these impacts can be mitigated by policies incentivizing technology adoption. In Region K, the two primary surface water providers (City of Austin and LCRA) offer several programs to promote both increased water use efficiency as well as water conservation (Lower Colorado River Authority, 2016; City of Austin, 2016). These programs include mechanisms for partial and full-cost rebates for above-code efficiency technologies as well as incentives for stormwater retention efforts and low water-demand landscapes. While the efficacy of these programs lies outside of the scope of this report, it is useful to discuss these programs within the context of water efficiency and reuse technology adoption in general terms.

Rebate programs to subsidize the cost of water efficiency and reuse technologies are typically offered in a blanket fashion, though an application process is usually required, and opportunities to target efficiency investments to high-demand customers are left unrealized. As demonstrated Section 3, the pattern of water use associated with a particular end-use has a large influence on the cost-effectiveness of that technology. Therefore, water providers might spend resources allocated to rebates for low-demand users more efficiently by identifying and seeking out high-water demand and/or low-income households that would not otherwise adopt above-code technologies (Bennear et al, 2013). Moreover, customers who are willing to pay a partially subsidized price for above-code water efficiency technologies would not require a full rebate, liberating resources for additional rebates. However, the cost associated with understanding customer willingness to pay for water efficiency might outweigh those savings that could be achieved.

In circumstances where the cost burden is shared between water providers and water customers, such as with a partial rebate, a homeowner bears some risk of stranded investment, occurring in cases of relocation or foreclosure. However, for water customers living in rental properties, the risk of stranded investment increases due to the relatively transient nature of rental property dwellers. In these cases, the renter has little incentive to adopt an above-code water efficiency technology, especially with higher capital cost technologies or knowledge of an imminent relocation. Likewise, the property owner has no incentive to bear the cost of above-code water efficiency adoption if the tenant pays water rates, as he or she will not realize any of the associated savings from reduced water demand. This issue of split-incentive between a tenant and property-owner is an example as the principal-agent¬ problem, which has been studied in the context of energy efficiency (International Energy Agency, 2007; 2008; Murtishaw and Sathaye, 2008; Davis, 2009; Blumstein, 2010; Gillingham et al., 2012). To my knowledge, investigations of the principal-agent problem in water efficiency do not exist in the literature, though useful parallels can be drawn between the issue in water efficiency and energy efficiency contexts.

Murtishaw and Sathaye (2008) characterized the principal-agent problem for different types of households, based upon whether the occupant is able to choose which technology models are installed as well as their method of energy payment (direct or indirect). They theorized that households without the ability to choose their end-use technology will tend to consume more energy if paying for their energy use indirectly, such as through a flat-rate fee structure. This overconsumption is due to the removal of the energy price signal to influence usage. However, households without the ability to choose their end-use technology but who pay for energy services directly, are likely to suffer from an "efficiency problem" in which the installed technology was selected solely on the basis of capital cost, rather than accounting for technical performance (i.e., efficiency). Therefore, these customers are more likely to overpay for energy services than to overconsume. Households with the ability to choose their end-use devices will suffer from a combination of the overconsumption and inefficiency if they pay for energy services indirectly, again due to the removal of the energy price signal and subsequent lack of incentive to increase end-use efficiency. Finally, households with the ability to choose end-use devices and who pay for energy services directly, will theoretically not face a principal-agent problem. Murtishaw and Sathaye (2008) go on to quantify the degree of overconsumption of primary energy due to the principal-agent problem, with estimates ranging from 10% to 59% among the three cases of the principal-agent problem explored. Their results indicate that price signals alone are a limited approach to promoting resource conservation, especially if consumers are shielded from price signal effects. Gillingham et al. (2012) similarly applied the principal-agent problem to renter-occupied households to examine both appliance efficiency and insulation practices. Their investigation introduced the nuance of increased exercise of control over energy consumption, rather than an overall lowering of consumption, which might result in reduction of unnecessary energy consumption (e.g., reducing air-conditioning demand when a dwelling is unoccupied) but does not translate to permanent behavioral changes.

Though this discussion of the principal-agent problem is by no means exhaustive, a exploration of the issue from the perspective of the water providers is useful for the purposes of this report. Water providers wishing to maximize efficiency technology adoption have the opportunity to implement policies designed for this specific issue: to mediate the split incentive between tenants and property owners. In cases like these, water providers might already have the necessary data to determine who bears the cost of water services within a particular property through billing data, though they do not know how indirect payments are determined or the schedule of these payments (e.g., monthly, quarterly, etc.). Therefore, they can tailor rebate programs to address the specific cases of principal-agent problem, based upon the ability to choose end-use technology and recipient of price signal. For households lacking the ability to choose specific end-use technology models, a provider may forgo tenant-oriented rebates in favor of directly appealing to the property owner. In the case of multifamily dwellings, where tenants typically do not have a choice of end-use technology, this practice would facilitate property-wide efficiency technology adoption. Likewise, for households with the ability to choose end-use models but who pay for water services indirectly, water providers might be better served by targeting rebates and other incentives directly to tenants. In all three cases of end-use technology choice and direct/indirect price signal interaction, the water provider has the opportunity to correct the issue of split incentives by providing compensation to the party that would otherwise "lose out" on the savings generated by above-code water efficiency adoption.

RELEVANT POLICY LANDSCAPE

Given the barriers to implementation discussed in this report, the role of federal, state, and local level policies from both the demand-side and supply-side perspectives are crucial in supporting such a large endeavor. Key policy areas to be discussed in this report include of water supply project and operations financing and water rate-making, though the influence of energy-related policies on water supply and availability is another area of interest. In each of these areas, a brief survey of the relevant landscape will be given to provide insight into gaps and confounding policies that might serve as additional barriers to complete adoption of water efficiency and reuse technologies.

Financing of water supply projects is typically accomplished through debt-financing mechanisms for large infrastructure projects, while smaller programs and incentives are typically funded out of a water provider's operating budget. The basin-wide adoption of water efficiency and reuse technologies could potentially fall under either of these categories, depending upon the perspective taken by the water provider. The immense capital outlay associated with water and reuse technology adoption might be perceived as an investment in infrastructure, though ownership of said infrastructure would rest with the property owner. Therefore, it is unclear as to whether a water provider is able to consider the incentivizing of service are-wide adoption of water efficiency and reuse technologies as capital spending or operating expenditures. This distinction has implications for the sources of funding available for these technologies.

Depending on the technology, complete and immediate replacement of all currently installed at- or below-code technologies within Region K could cost anywhere from $884 million $5.76 billion, as reported in Table 3. For reference, the City of Austin's water utility, Austin Water, received $154 million in FY2016 for capital spending purposes, primarily for "replacement and rehabilitation of critical assets throughout the water and wastewater systems, as well as the growth of reclaimed water assets" (City of Austin, 2015). Given the competition for resources within a particular organization, as well as decreasing revenues due to previously implemented water conservation policies in many cases, water providers might wish to use a debt-financing mechanism to achieve the goal of 100% uptake of above-code water efficiency and reuse technologies.

The state of Texas possesses several mechanisms by which to provide funding assistance for water projects, with several definitions of what a water project is (Texas Water Code Chapter 15, 1997). These funding sources are all administered by the state, specifically the Texas Water Development Board, though for a variety purposes such as conservation efforts or infrastructure projects. The largest source of funding comes from the Texas Water Development Fund, established in 1957, which has to date issued over $4 billion in general obligation bonds (Texas Comptroller of Public Accounts, 2014). Moreover, the passage of Proposition 6 in 2013 created the State Water Implementation and State Water Implementation Revenue Funds for Texas (SWIFT/SWIRFT), allocating $2 billion from general revenues into a revolving fund with the sole purpose of providing low-interest loans to fund the water management strategies published in the State Water Plan (Texas Water Code Chapter 15, 2013). At least 20% of SWIFT/SWIRFT funds must be used for "water conservation or reuse" strategies, highlighting the opportunity for application of SWIFT/SWIRFT funds to water efficiency and reuse technology adoption within Region K (Texas Water Code Chapter 15, 2013). However, state-wide competition for these resources indicate that securing sufficient funding for such an endeavor would be nearly impossible within one funding cycle. Therefore, immediate replacement of less efficient water efficiency technologies is unlikely, due to the immense capital outlays required. A replace-as-retire adoption scheme might prove easier to fund and implement given the delay in capital burden, lower net present value of investments and relatively small difference in water savings between adoption schemes, as seen in Figure 3. Overall, state-assisted funding of this endeavor is possible, but the outcome would not maximize cost-effectiveness due to the limited state resources dedicated to improving residential water efficiency.

Recalling the discussion surrounding the principal-agent problem, and acknowledging the body of literature surrounding water rate-making, one could argue that efficiency and reuse technologies would not be as necessary if water rates were set in a manner that reflect the nature of water as a commodity based upon scarcity. Ideally, an price signal would provide an economically-efficient incentive for water users to curtail their usage and the desired level of conservation would inform the specific water rate

(Chesnutt and Beecher, 1998; Renwick and Green, 2000; Olmstead and Stavins, 2009). However, the Public Utility Commission of Texas currently limits the authority of municipal and non-profit water providers to set rates above the sum of the cost of rendering service, return on invested capital, and allowable expenses (Texas Water Code Chapter 24, 2015). Therefore, any efforts to set water rates at levels designed to promote conservation are inherently limited.

Some utilities in Texas have overcome this obstacle by incorporating a form of marginal pricing, known as a tiered or block rate structure, into their water rates (City of Austin, 2016; City of San Antonio, 2016). Under a block rate structure, customers pay increasingly higher volumetric rates for water as their consumption reaches certain levels. For example, the City of Austin employs a block rate structure that increases the volumetric charge for water once a customer has reached 2,000 gallons, 6,000 gallons, 11,000 gallons and so on, of monthly consumption. The specific unit and fixed prices that makeup the water rate are designed to achieve both revenue stability and cost recovery for a utility (Howe and Linaweaver, 1967). The rationale behind the tiered rate structure is that large-volume water users influence peak (often seasonal) demands, and, by extension, infrastructure capacity more so than small-volume users; thus, this justifies their paying higher rates for marginal water use (Howe and Linaweaver, 1967; Chesnutt and Beecher, 1998).

Setting water rates for the ancillary purpose of indoor water conservation is limited not only by regulation, but also by the capacity to reduce indoor water demand. This limitation is in part due to the relatively price inelastic nature of indoor water demand, meaning that an increase of 1% in the price of water results in less than a 1% decrease in water demand. However, it is worth noting that estimates of price elasticity of total (indoor and outdoor) demand for water are more variable than estimates of price elasticity of only indoor demand in the relevant literature (Thomas and Syme, 1988; Espey et al., 1997; Chesnutt and Beecher, 1998; Renwick and Green, 2000; Dalhuisen et al., 2003; Olmstead and Stavins, 2009). Due to the price inelasticity of indoor demand, there is an inherent limit to the efficacy of an increasing block rate price structure in reducing indoor residential water demand.

Conclusions

This report presents the results of an engineering economic analysis of the basin-wide adoption of above-code water efficiency and reuse technologies in Texas State Water Planning Region K (the Lower Colorado River Basin). Basin-wide adoption of WaterSense® fixtures (showerheads, bathroom faucet aerators, and toilets), ENERGY STAR® appliances (clothes washers and dishwashers) and reuse technologies for indoor and outdoor use (rainwater harvesting and greywater recycling in the form of integrated toilet-sink devices) can produce technically feasible water savings equivalent to 85% of Region K's anticipated water needs through 2060. Moreover, adoption of several types of technologies provide more favorable levelized costs of water than the majority of water management strategies recommended for Region K in the 2012 Texas State Water Plan; showerheads and bathroom faucet aerators were found to produce economic benefits over their service life under a variety of parameter assumptions, also displacing the need for more marginally expensive water management strategies. Dishwashers and rainwater harvesting systems produced levelized costs higher than all recommended water management strategies under most scenarios and are not technically or economically attraction options for basin-wide technology adoption. Estimates of technically feasible water savings for all technologies range from 60% to 100% of anticipated water needs, while ranges of levelized costs estimates vary considerably among individual technologies. However, this study highlights the significant potential of 100% saturation of above-code water efficiency and reuse technologies for displacing costs of supply-side infrastructure.

Uncertainty in technical, financial, and behavioral parameters and variability of household characteristics within the service area and within technology types can substantially alter these technically feasible savings and costs, with the potential to increase the levelized cost of water for these technologies higher than several of the water management strategies recommended for Region K. Critical parameters vary across technologies, though capital costs, discount rates, household demand and technical performance were found to have the largest influence on levelized cost estimates, in general. Therefore, care should be taken to control or account for these parameters when designing policy to promote and incentivize technology adoption. For example, utilities might choose to target incentives and rebates to the party responsible for choosing end-use technologies, in the case of the principal-agent problem. Alternatively, rebates and incentives might be targeted to particular households that are more likely to observe water savings based upon results of the sensitivity analysis found in Figure 2.

Observed water savings and costs paid will likely differ from technically feasible results, due to the "efficiency gap" phenomenon. The efficiency gap is caused in part by the impact of financial and behavioral factors such as the price elasticity of water demand, the rebound effect, an individual's implicit discount rate, and the principal-agent problem and other market failures. Moreover, water providers face significant challenges in understanding indoor water demand at high resolution (temporally and with respect to end-use) when assessing economically efficient incentives. Access to capital, competition for state resources, price structure regulation, and evolution of state and local building codes all play substantial roles in promoting or deterring technology adoption. Therefore, these policy levers are important tools in achieving 100% saturation of above-code efficiency and reuse technologies throughout Region K.

This study quantifies the magnitude of monetary savings from efficiency and reuse technologies, in relation to the capital cost of adoption, and the relative levels of uncertainty associated with each technology. These factors are important considerations for water managers in assessing future water supply and demand scenarios. The CSC, when applied to water provisions, aggregates these considerations into a single tool for water planners to assess supply-side and demand-side water management strategies simultaneously. The main benefit of the CSC is an organized and comprehensive overview of the various types of provisions of water resources that also provides a formal ranking and illustrates the scale of these rankings. Therefore, the water planner can rank water efficiency and reuse technologies relative to each other as well as among more traditional water management approaches.

STUDY LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

The policy mechanisms supporting efficiency change and reuse (i.e., who bears the costs and benefits) can have just as substantial an effect on water use as does the technical change itself. This result presented in this report do not include the microeconomic implications (income, substitution, and redistribution) of aggressive water efficiency and reuse (Renwick and Archibald, 1998; Espey et al., 1997). Aside from these implications, savings from efficiency and reuse may be eroded by increased consumption due to the rebound effect, though Davis (2008) found negligible rebound for more efficient clothes washers. Moreover, Bennear et al, compared a priori and a posteriori estimates of household water use before and after participation of a high-efficiency toilet rebate program for 485 installations in Cary, NC, and found little evidence to suggest the occurrence of rebound (via divergence between engineering estimates and a difference-in difference estimate). Investigating the occurrence of the rebound effect would require an assessment of water demand before and after above-code technology adoption, to determine if a discrepancy exists between engineering estimates and observed consumption.

An environmental life cycle assessment would provide further insight into the environmental costs of supply- and demand-side strategies and could inform water management decisions. Of the 30 water management strategies presented in the 2012 State Water Plan for Texas, 21 strategies involve construction of reservoirs or expansion and development of groundwater resources, which have negative impacts (scopes 1, 2, and 3 emissions) as well as other direct/indirect environmental externalities (Howe, 2002; Rosenberg et al., 2000). The 2012 State Water Plan for Texas includes high-level assessments of environmental impacts of all recommended and alternate water management strategies for Texas. However, several strategies have been assessed using qualitative, rather than quantitative, classifications and would benefit from more rigorous analysis (Texas Water Development Board, 2012).

Efficiency and reuse technologies come with their own environmental externalities, which mainly occur indirectly (scopes 2 and 3 for greenhouse gas emissions) through their supply chain. Further investigation of the environmental externalities associated with both supply- and demand- side water projects can provide decision-makers with a more complete view of the full environmental costs of water management. For example, reduction of water demand volume from water efficiency technology adoption is associated with direct impacts on drinking water distribution and wastewater treatment plant operations (Stokes and Horvath, 2010, 2009, 2006; Alvarez- Gaitan et al., 2014; Lundie et al., 2004; Short et al., 2014). Indirect impacts from avoided importation, desalination, and recycling supply-side projects, which can be associated with higher energy-use intensity than are traditional water provisions, also must be estimated.

Water efficiency and reuse technologies provide a compelling avenue for household demand reduction. Based upon engineering estimates, lower levelized costs of service for complete basin adoption and robust performance under a wide range of technological and demographic parameters, for bathroom faucets aerators and low-flow showerheads, were observed. However, more expensive technologies such as low-flow toilets and ENERGYSTAR® clothes washers show larger uncertainty in levelized cost estimates and may exceed the levelized costs of supply-side water management strategies. Using an efficiency and reuse supply curve method, water planners can directly compare demand-side management options to traditional water supply provisions, accounting for uncertainties in technology adoption, cost, and performance. The insights gained from this supply curve can guide economically efficient incentive programs that achieve optimal water savings. The water savings associated with high capital-cost technologies, such as clothes washers and water-efficient toilets, do not suffer from delayed adoption as currently installed models retire; this implies less of a need for immediate adoption of these technologies. Therefore, efforts should be focused on immediate adoption of bathroom faucet aerators and low-flow showerheads (i.e., net-benefit technologies), which produce considerable water savings and simultaneously provide monetary savings to the consumer. The feasible water savings reported in this study provide a compelling argument for the consideration of above-code efficiency and reuse technology as a viable and cost-effective demand-side water management strategy.

Appendix

Table A1 shows the performance standards for minimum-code and above-code water service technologies, mandated by the Energy Policy Act of 2005 and ENERGY STAR® / WaterSense® product specifications, respectively.

Technology Performance	**Units**	**Energy Policy Act 2005 (minimum-code)**	**ENERGY STAR® / WaterSense® (above-code)**
Low-Flow Toilet (LFT)	gpf	1.6	1.28
Low-Flow Showerhead (LFS)	gpm	2.5	no specification
Bathroom Faucet Aerator (BFA)	gpm	2.2	1.5
ENERGY STAR® Clothes Washer (CW)	WF	WF $\leq$ 9.5	WF $\leq$ 6.0
ENERGY STAR® Dishwasher (DW)	gal/cycle	6.5 (standard) 4.5 (compact)	5.0 (standard) 3.5 (compact)
Household Rainwater Harvesting (RWH)	gal	n/a	n/a
Integrated Toilet-Sink Device (ITS)	gpf	n/a	n/a

Table A1. National water end-use efficiency standards.

(WF – water factor [(gallons/cycle/ft^3)], gpf – gallons/flush, gpm – gallons/min)

Table A summarizes the assumptions for household occupancy, energy and water prices, water heater efficiency, and energy sources for hot water. These assumptions were used to calculate the monetary benefit from energy and water savings, as well the energy savings for adoption of LFS, CW, and DW.

Parameter	Units	Low	Base	High	Reference
Household Size	members	1	2.5	4	(1)
Price of Water	$2010/gal	0.002	0.003	0.006	(2)
Price of Electricity	$2010/kWh	0.079	0.099	0.119	(3)
Price of Natural Gas	$2010/kWh	9.49	11.1	12.5	(4)
Hot Water Heating Efficiency (for NGWH)	n/a	0.006	0.008	0.010	(5)
Fraction of Households with elec. water heater (EWH)	n/a	0.422	0.528	0.634	(6)
Fraction of Households with natural gas water heater (NGWH)	n/a	0.316	0.395	0.474	(1)
Population Multiplier	n/a	80%	100%	120%	(7)

Table A2. LCRA service area model inputs, including base case and ranges.

(kWh – kilowatt-hour, EWH – percentage of households in LCRA with electric water heater, NGWH – percentage of households in LCRA with natural gas water heater, Population Multiplier – Scaling Factor used to estimate uncertainty in population projections)

Tables A**Error! Reference source not found.**3 through A9 detail the model parameters as well as base-case and uncertainty ranges for all water efficiency and reuse technologies, as well as model inputs for the LCRA service area. All inputs were used for both sensitivity analysis as well as Monte Carlo simulations. Low and high case values are 10^{th} and 90^{th} percentiles respectively, while base-case values are median estimates.

Parameter	Units	Low	Base	High	Reference
Capital Cost, Conventional, CW	$2,010	330	420	580	(8)
Capital Cost, EnergyStar, CW	$2,010	450	750	1200	(8)
Water Use, Conventional, CW	gal/cycle		35.2		(8)
Water Use, EnergyStar, CW	gal/cycle	10.4	14.4	23.6	(8)
Electricity Use, Conventional, CW	kWh/cycle	0.21	0.21	0.21	(8)
Electricity Use, EnergyStar, CW	kWh/cycle	0.08	0.11	0.15	(8)
Installation Labor Cost, EnergyStar, CW	$2,010	105	132	158	(9)
Current Market Share (efficient)	%		67.1%		(1)
Service Life	years	10	12	13	(10)
Units/Household	ea		1		(10)
Demand, CW	cycles/yr	52	312	520	(10)

Table A3. CW model parameters with base case and uncertainty ranges.

Parameter	Units	Low	Base	High	Reference
Capital Cost, Conventional, DW	$2010		260		(8)
Capital Cost, EnergyStar, DW	$2010	297	659	2199	(8)
Water Use, Conventional, DW	gal/cycle		6.5		(8)
Water Use, EnergyStar, DW	gal/cycle	2.22	3.61	4.25	(8)
Electricity Use, Conventional, DW	kWh/cycle		1.65		(8)
Electricity Use, EnergyStar, DW	kWh/cycle	0.88	1.27	1.37	(8)
Installation Labor Cost, EnergyStar, DW	$2010	124	127	129	(11)
Current Market Share (efficient)	%		64.9%		(1)
Service Life	years	5	10	15	(10)
Units/Household	ea	1	1	1	(1)
Demand, DW	cycles/yr	52.0	215	312	(10)

Table A4. DW model parameters with base case and uncertainty ranges.

Parameter	Units	Low	Base	High	Reference
Capital Cost, Conventional, Toilet	$2010	100	150	250	(8)
Capital Cost, Efficient, Toilet	$2010	324	564	883	(8)
Water Use, Conventional, Toilet	gpf	1.60	4.25	7.0	(8)
Water Use, Efficient, Toilet	gpf	1.00	1.10	1.28	(8)
Installation Labor Cost, Low-flow toilet	$2010	138	141	143	(12)
Current Market Share (efficient)	%		66%		(13)
Service Life	years	10	20	30	(14)
Units/Household	ea	1	2	5	(1)
Demand, Toilets	flush/capita/day	1.02	5.05	9.09	(15)
	flush/capita/yr	370	1840	3320	(15)

Table A5. LFT model parameters with base case and uncertainty ranges.

Parameter	Units	Low	Base	High	Reference
Capital Cost, Conventional Showerhead	$2010		5.00		(8)
Capital Cost, Efficient, Showerhead	$2010	9.70	28.0	81.7	(8)
Flow Rate, Conventional, Showerhead	gpm		2.50		(8)
Flow Rate, Efficient, Showerhead	gpm	0.96	1.50	2.00	(8)
Demand, shower length	min/shower	4.00	8.00	12.0	(13)
Installation Labor Cost, Efficient Shower-head	$2010		0.00		Assumed
Current Market Share (efficient)	%		68%		(13)
Service Life	yrs	10	20	30	(14)
Units/Household	ea	1	2	3	(1)
Demand, Shower frequency	showers/capita/day	0.72	0.75	0.82	(22)
Demand, Shower Frequency	showers/capita/yr	263	274	300	(22)

Table A6. LFS model parameters with base and uncertainty ranges.

Parameter	Units	Low	Base	High	Reference
Capital Cost, Aerator	$2010	5.00	10.0	15.0	(8)
Flow Rate, Conventional, Faucet	gpm		2.2		(8)
Flow Rate, Efficient, Faucet	gpm	0.80	1.50	1.50	(8)
Installation Labor Cost Aerator	$2010		0		Assumed
Current Market Share (efficient)	%		63%		(16)
Service Life	years	10	20	30	(14)
Units/Household	ea	2	3	5	(1)
Demand, Faucet	min/HH/day	10.0	24.8	45.0	(13)
	min/HH/yr	3650	9050	16400	Calculated

Table A7. BFA model parameters with base case and uncertainty ranges.

Parameter	Units	Lo w	Base	High	Reference
Capital Cost, Conventional, Toilet	$2010	100	150	250	(8)
Capital Cost, Conventional, Bathroom Sink	$2010	80.0	120	160	(8)
Capital Cost, Efficient, Combined	$2010	150	300	650	(17) – high case, (18) - base case, (19) – low case
Installation Labor Cost, Efficient, Combined	$2010	141	250	1000	(12)
Water Use, Conventional, Toilet	gpf	1.60	4.25	7.00	(8)
Water Use, Efficient, Combined	gpm	0.80	1.28	1.60	Same as LFT
Demand, ITS	flushes/capita/day	1.02	5.05	9.09	(13)
	flushes/capita/yr	370	1840	3320	(13)
Units/HH	ea	1	2	3	Same as LFT
Current Market Share	%	0			Assumed
Service Life	yrs	10	20	30	Same as LFT

Table A8. ITS model parameters with base case and uncertainty ranges.

Parameter	Units	Low	Base	High	Reference
Capital Cost, Rainwater Harvesting System, Potable Use	\$2010/gal stored	2.29	2.31	9.94	(20)
Capital Cost, Rainwater Harvesting System, Non-Potable Use	\$2010/gal stored	1.53	2.08	4.60	(20)
Storage Time	days	7.00	14.0	30.0	(20)
Current Market Share	%		0		Assumed
Service Life	years	10	12	15	(20)
Average LCRA Rainfall	ft/yr	2.29	2.82	3.31	(21)
Catchment Area	sq. ft.	625	1000	2500	(20)
Conversion Factor	%	0.5	0.623	0.75	(20)
Required Capacity	gal	77.0	426	3630	Calculated

Table A9. RWH System model parameters with base case and uncertainty ranges.

Technology		Low Demand	Base Demand	High Demand
CW	Per HH Demand (at-code)	30.1	12.0	7.5
	Per HH Demand (above-code)	8.91	4.93	5.04
	Volumetric Reduction	21.2	7.10	2.48
	% Total Reduction	32.2%	6.79%	0.690%
DW	Per HH Demand (at-code)	3.83	1.53	0.957
	Per HH Demand (above-code)	1.31	0.851	0.626
	Volumetric Reduction	2.52	0.681	0.331
	% Total Reduction	5.82%	1.46%	0.266%
LFT	Per HH Demand (at-code)	1.62	53.7	254
	Per HH Demand (above-code)	1.02	13.9	46.5
	Volumetric Reduction	0.609	39.8	208
	% Total Reduction	2.47%	51.3%	70.7%
LFS	Per HH Demand (at-code)	10.0	15.6	71.9
	Per HH Demand (above-code)	2.00	9.35	57.5
	Volumetric Reduction	8.00	6.23	14.4
	% Total Reduction	15.2%	14.9%	20.0%
BFA	Per HH Demand (at-code)	20.2	21.8	25.3
	Per HH Demand (above-code)	7.35	14.9	17.2
	Volumetric Reduction	12.9	6.94	8.04
	% Total Reduction	30.7%	20.9%	7.02%
All Technologies	Per HH Demand (at-code)	65.7	104.6	360.0
	Per HH Demand (above-code)	20.6	43.9	126.9
	Volumetric Reduction	45.2	60.7	233.1
	% Total Reduction	68.7%	58.0%	64.7%

Table A10. Estimates of household indoor demand reduction by end-use. All units in gallons per capita per day (gpd) unless otherwise indicated.

Table A10 shows the per household estimates of daily water demand for households with either all at-code end-use technologies or all above-code end-use technologies. We used the base-case household demand for each technology (from Tables A2 through A9) to generate the daily household demand estimates. Results simply represent the total potential demand reduction from adoption of above-code technologies, without consideration for cost of adoption or pattern of adoption.

Monte Carlo Model Description

Monte Carlo (MC) simulation was used to model adoption of efficiency technologies that demonstrated extreme uncertainty ranges under parametric treatment; LFT, CW, and DW. For each technology, a random model was chosen from online retail data and the corresponding cost and performance were used to calculate the levelized cost of service. A random household occupancy was generated using empirical occupancy distributions from 2010 Census data for all counties located within the LCRA. Once a household occupancy was selected, demand was then estimated based on empirical distributions for CW and DW, taken from the 2009 Residential Energy Consumption Survey. Because there was no empirical demand distribution available for LFT, we treated demand parametrically using the mean per capita use for toilets reported in the 1999 Residential End-Uses for Water Study as the base-case with plus or minus 1.5x the standard deviation for the high and low case, respectively. Additionally, the number of toilets was correlated to household occupancy (based on number of bathrooms reported in the 2009 RECS data) and was used for capital cost calculations.

For each technology and simulation, all other model parameters were treated as a random selection with uniform probability across low, base, and high case values. We ran 500,000 simulations for each technology and collected the results in the form of distributions for total water savings, total capital costs, net present value, and levelized cost for the LCRA service area. Tables S12 though S15 show the distribution used for each applicable parameter. Figures S2 through S4 show frequency distributions of levelized cost and total water savings for each technology modeled using MC simulation.

Table A16 shows the model outputs (i.e., levelized cost) for the base-case and uncertainty ranges. Additionally, the model parameters determining extreme value ranges are identified and their corresponding high and low values are specified. Finally, Table A17 shows the cost and water supply data for the Region K Recommended water management strategies, that were used for comparison against efficiency and reuse technologies.

Occupancy	Cumulative Probability Function (CDF)
1	0.29
2	0.62
3	0.77
4	0.90
5	0.96
6	0.98
7	1.00

Table A11. Occupancy Distribution for Households in the LCRA Service Area.

Demand (Cyc/Wk)	Occupancy CDF						
	1	2	3	4	5	6	7
1	0.251	0.064	0.027	0.016	0.010	0.029	0.010
3	0.871	0.602	0.394	0.272	0.225	0.185	0.158
7	0.986	0.946	0.889	0.796	0.664	0.591	0.485
13	0.998	0.994	0.983	0.964	0.926	0.856	0.847
15	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table A12. Demand and Occupancy Distribution Matrix for CW.

Demand (Cyc/Wk)	Occupancy CDF						
	1	2	3	4	5	6	7
0.5	0.251	0.064	0.027	0.016	0.010	0.029	0.010
1	0.871	0.602	0.394	0.272	0.225	0.185	0.158
2.5	0.986	0.946	0.889	0.796	0.664	0.591	0.485
5	0.998	0.994	0.983	0.964	0.926	0.856	0.847
7	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table A13. Demand and Occupancy Distribution Matrix for DW.

# of Toilets	Occupancy CDF						
	1	2	3	4	5	6	7
0	0.003	0.000	0.000	0.000	0.000	0.000	0.000
1	0.498	0.327	0.281	0.246	0.269	0.236	0.209
2	0.879	0.751	0.742	0.692	0.669	0.700	0.698
3	0.977	0.941	0.941	0.911	0.901	0.901	0.893
4	0.994	0.985	0.986	0.978	0.978	0.971	0.978
5	0.999	0.996	0.997	0.994	0.990	1.00	0.991
6	1.00	0.999	0.999	0.998	0.995	1.00	0.996
7	1.00	1.00	0.999	0.999	1.00	1.00	0.996
8	1.00	1.00	1.00	0.999	1.00	1.00	0.996
9	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	1.00	1.00	1.00	1.00	1.00	1.00	1.00
11	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table A14. Quantity and Occupancy Distribution Matrix for LFT.

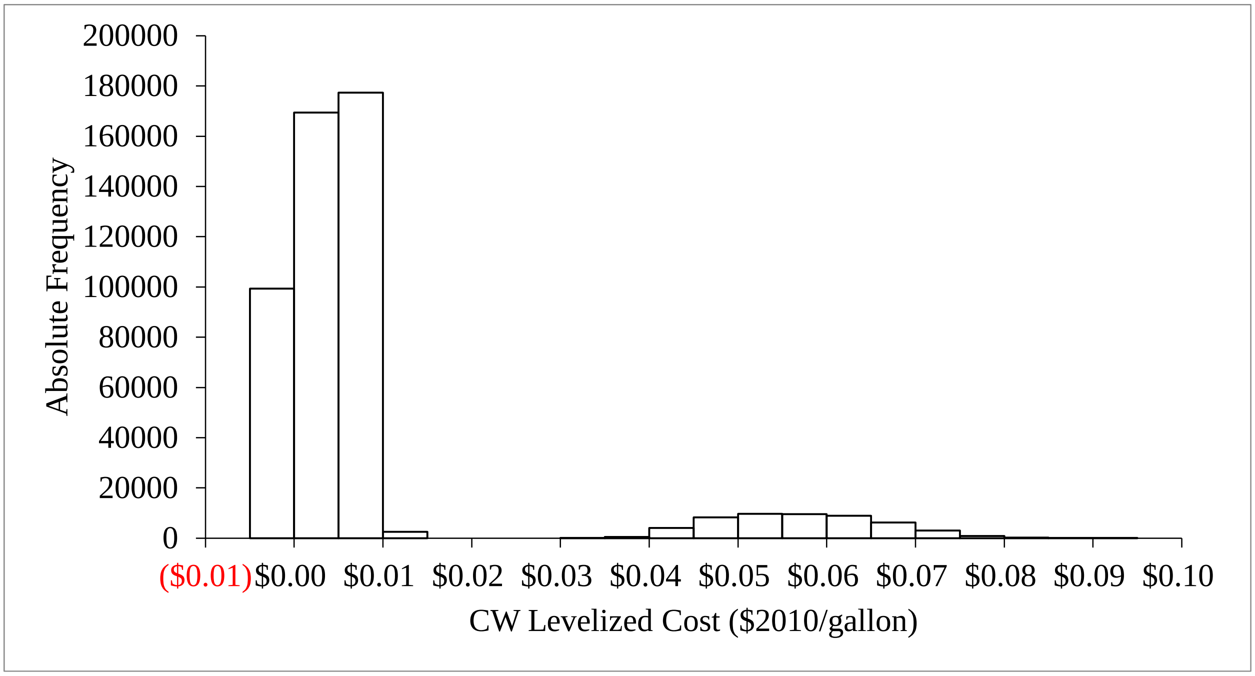

Figure A1. Distribution of CW Levelized Cost Results.

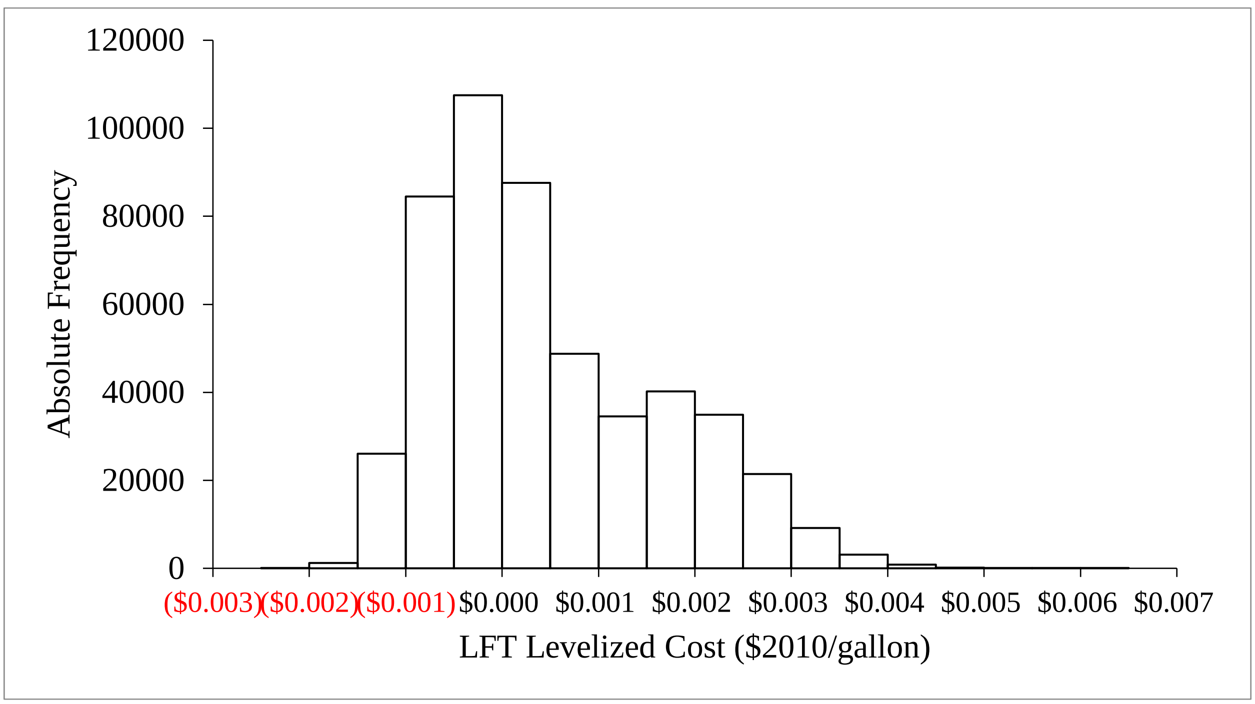

Figure A2. Distribution of LFT Levelized Cost Results.

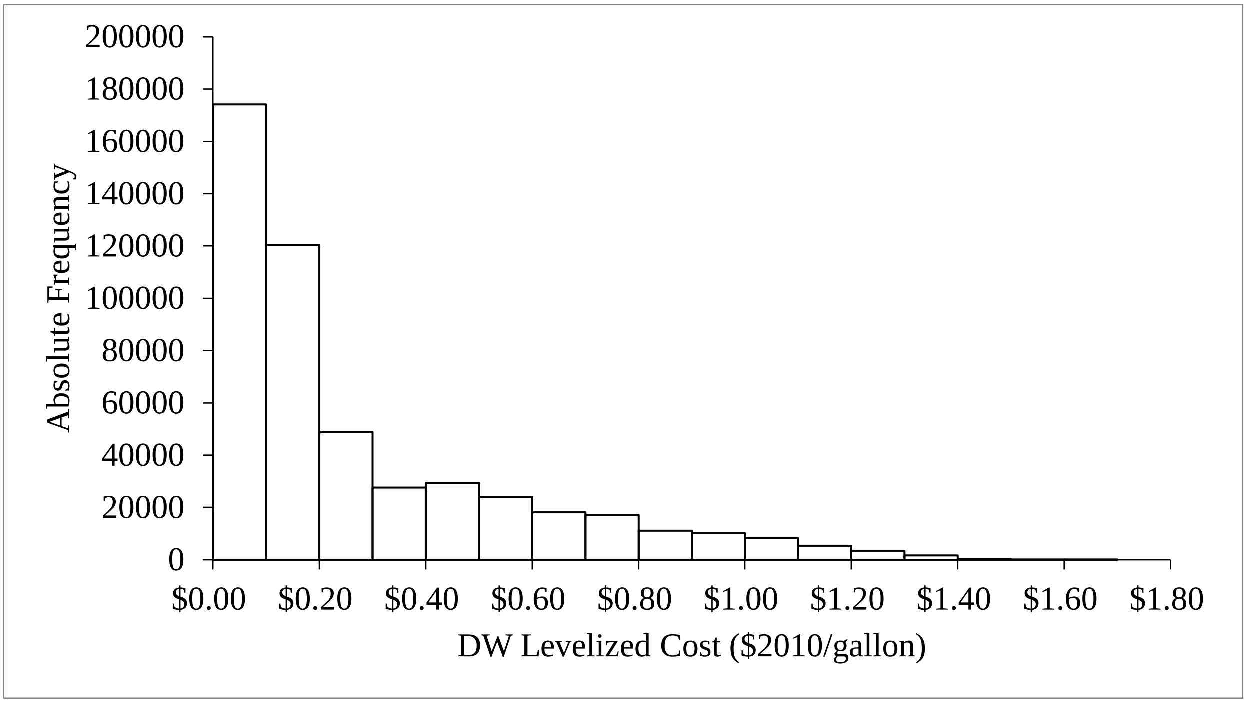

Figure A3. Distribution of DW Levelized Cost Results.

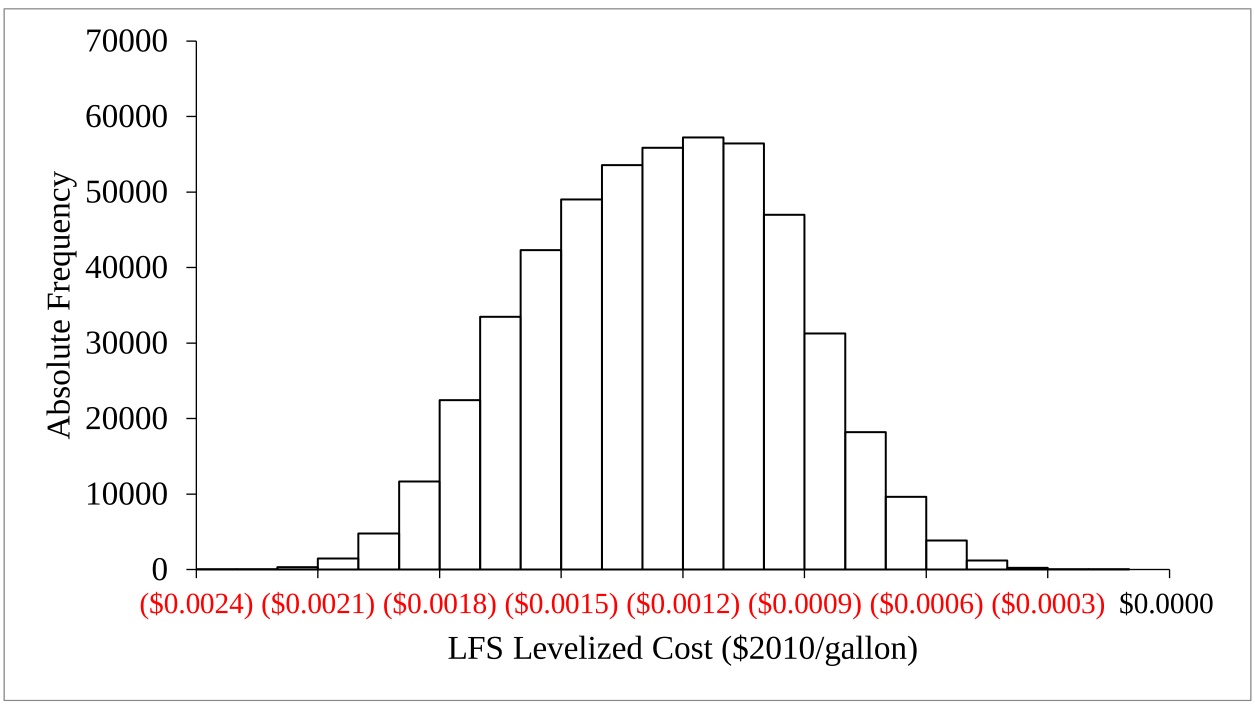

Figure A4. Distribution of LFS Levelized Cost Results

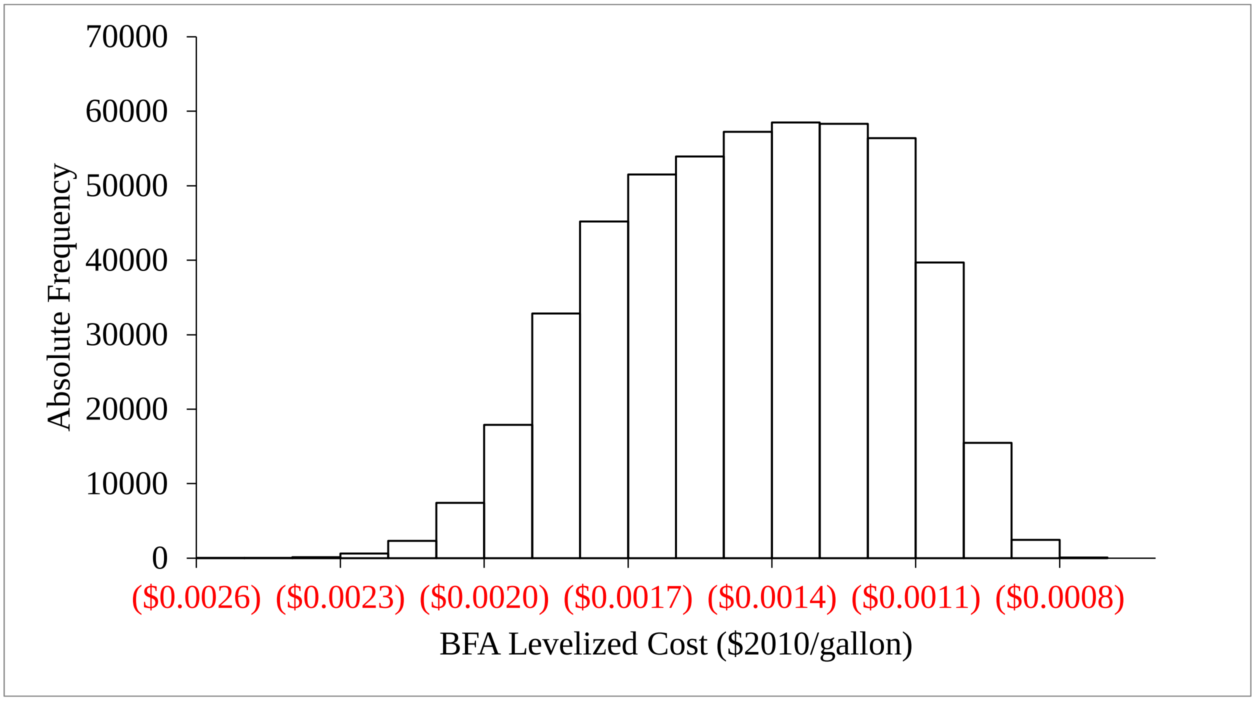

Figure A5. Distribution of BFA Levelized Cost Results

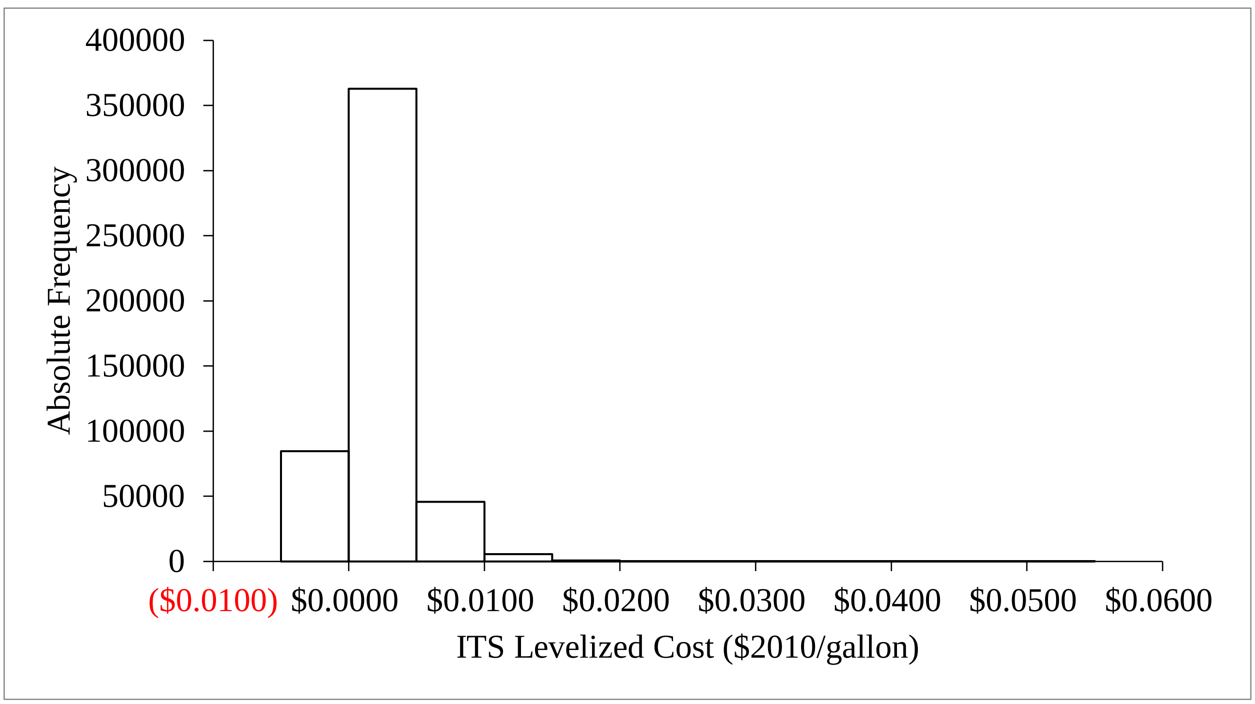

Figure A6. Distribution of ITS Levelized Cost Results

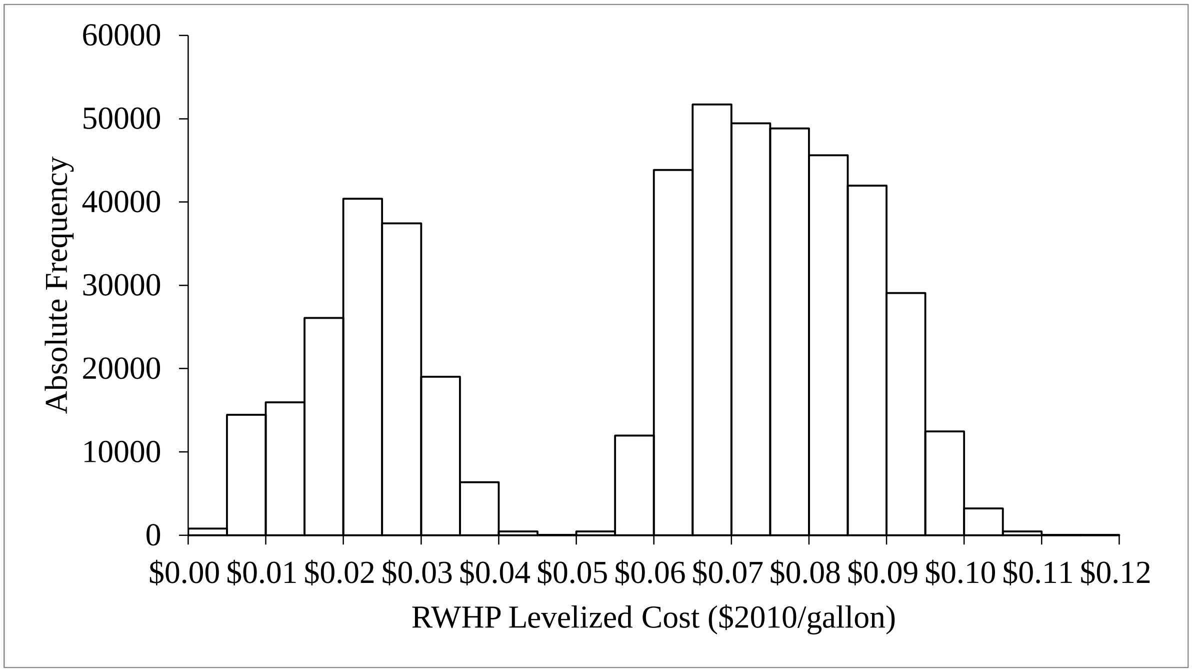

Figure A7. Distribution of RWHP Levelized Cost Results

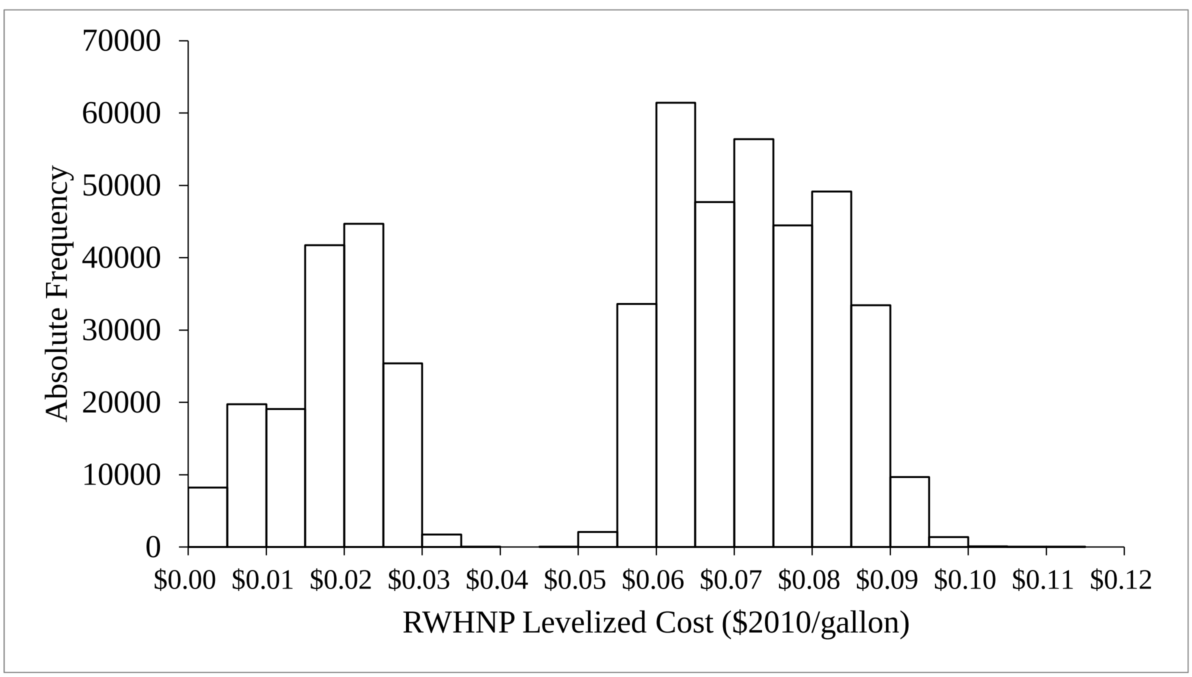

Figure A8. Distribution of RWHNP Levelized Cost Results

Technology	Water Saved (million acre-ft)			Annual Levelized Cost ($2010/million acre-ft)			Critical Inputs (Low Output, High Output)
	Low	Base	High	Low	Base	High	
BFA	1.483	1.684	1.898	($27.28)	($21.36)	($16.17)	Price of Water, Discount Rate
LFS	0.394	0.843	1.884	($24.88)	($18.55)	($12.83)	Price of Water
LFT	0.841	1.846	4.110	($12.35)	$2.32	$33.72	No. of Bathrooms, Code Model Performance
ITS	1.523	2.648	3.864	($4.27)	$20.20	$76.10	Units per HH, Installation and Labor
CW	0.109	0.631	2.367	($13.29)	$67.82	$125.89	No. of Bathrooms, Installation Cost
RWHNP	4.185	4.475	4.774	$229.79	$957.92	$1,258.66	Storage Capacity, Catchment Area
RWHP	4.185	4.474	4.772	$696.32	$1,015.26	$1,332.54	Storage Capacity, Catchment Area
DW	0.014	0.069	0.192	$696.32	$2,262.29	$11,105.11	Capital Cost (Above Code), Demand

Table A15. Conservation Supply Curve Results, including base-case values and uncertainty ranges. Inputs and corresponding values producing low- and high-case outputs are identified.

Recommended Water Management Strategy	Capital Cost ($2010M)	Water Supplied (million acre-ft)	Cost Effectiveness ($2010/million acre-ft)	Strategy Type
House Bill 1437 on-farm conservation	$3.82	0.558	$0.0012	Conservation
Development of other aquifer	$3.10	0.276	$0.0020	Groundwater
Alternative irrigation division delivery system improvements	$4.94	1.810	$0.0005	Transmission
Alternative on-farm conservation	$5.43	1.450	$0.0006	Conservation
Expansion of Gulf Coast Aquifer	$1.48	0.176	$0.0015	Groundwater
New LCRA contracts	$17.6	2.619	$0.0012	Reallocation
Off-channel storage in additional reservoirs	$53.4	1.500	$0.0062	Surface
Enhanced recharge of groundwater (Gulf Coast Aquifer)	$56.3	0.344	$0.0283	Groundwater
Expansion of Carrizo-Wilcox Aquifer	$16.9	0.543	$0.0054	Groundwater
Development of Gulf Coast Aquifer	$0.164	0.001	$0.0346	Groundwater
Reuse by Highland Lakes communities	$15.9	0.175	$0.0158	Reuse
Expansion of other aquifer	$1.72	0.074	$0.0040	Groundwater
Development of Carrizo-Wilcox Aquifer	$12.2	0.107	$0.0199	Groundwater
Expansion of Trinity Aquifer	$3.61	0.051	$0.0124	Groundwater
City of Austin direct reuse (municipal and manufacturing)	$302	1.478	$0.0354	Reuse
City of Austin direct reuse (steam-electric)	$302	0.469	$0.1116	Reuse
Purchase water from City of Austin	$2.28	0.066	$0.0060	Reallocation
Alternative conjunctive use of groundwater - includes overdrafts	$19.48	0.300	$0.0112	Groundwater
Development of saline zone of Edwards-Balcones Fault Zone Aquifer	$19.8	0.185	$0.0185	Groundwater
Development of Queen City Aquifer	$4.19	0.006	$0.1251	Groundwater
Desalination of Brackish Gulf Coast Aquifer	$178	0.672	$0.0458	Groundwater
Groundwater importation	$396	1.050	$0.0653	Groundwater
Goldthwaite Channel Dam	$1.84	0.018	$0.0177	Transmission
Development of Ellenburger-San Saba Aquifer	$5.60	0.030	$0.0326	Groundwater
Development of Hickory Aquifer	$4.70	0.022	$0.0371	Groundwater
Expansion of Ellenburger-San Saba Aquifer	$14.5	0.072	$0.0350	Groundwater
Desalination of Ellenburger-San Saba Aquifer	$6.29	0.015	$0.0709	Groundwater
Aquifer storage and recovery	$169	0.300	$0.0974	Groundwater
Expansion of Hickory Aquifer	$0.61	0.004	$0.0285	Groundwater
Development of Trinity Aquifer	$4.08	0.010	$0.0725	Groundwater
TOTAL	$1,626.56	14.4		

Table A16. Region K Recommended Water Management Strategies[20]

References

Alcott, H.; Greenstone, M. 2012. Is There An Energy Efficiency Gap?. *J Econ Perspect.* 26:1 3-28.

Alvarez-Gaitan, J.P.; Short, M.D.; Peters, G.M.; MacGill, I.; Moore, S. 2014. Consequential Cradle-To-Gate Carbon Footprint of Water Treatment Chemicals Using Simple and Complex Marginal Technologies For Electricity Supplies. *Int J Life Cycle Assess*.19: 1974-1984.

Anderson, R. 2007. *Who Pays for the Water Pipes, Pumps and Treatment Works? – Local Government Expenditures on Sewer and Water - 1991 to 2005*; Mayors Water Council: 75th Annual Conference of Mayors: p. 19.

Austin Water Utility. Stage 2 Watering Restrictions | Austin Water Utility | AustinTexas.gov - The Official Website of the City of Austin http://austintexas.gov/department/stage-2-watering-restrictions (accessed Aug 26, 2014).

Austin Water Utility. 2016. *2015-2016 Water & Wastewater Rates.* http://www.austintexas.gov/sites/default/files/files/Water/Rates/ResidentialWaterRates_2016.pdf

Austin Water Utility. 2016. *Water Conservation – Rebates*. http://www.austintexas.gov/department/water-conservation-rebates

Australian Capital Territory Parliamentary Council. 2005. Water Efficiency Labelling and Standards Act 2005: A2005-10.

AWWA Research Foundation. 1999. *Residential end uses of water*. Mayer, P. W.; DeOreo, W. B., Eds.; AWWA Research Foundation and American Water Works Association: Denver, CO.

Backlund, S.; Thollander, P.; Palm, J.; Ottosson, M. 2012. Extending the Energy Efficiency Gap. *Energy Policy.* 51: 392-396.

Barton, J. Energy Policy Act of 2005; 2005.

Blumstein, C. 2010. Program Evaluation and Incentives for Administrators of Energy-Efficiency Programs: Can Evaluation Solve the Principal/Agent Problem? *Energy Policy*. 38: 6232-6239.

Chesnutt, T.W.; Beecher, J.A. 1998. Conservation Rates in the Real World. *J Am Water Works Assoc*. 90:2 60-70.

Chesnutt, T. W.; Fiske, G.; Beecher, J. A.; Pekelney, D. M. 2007. *Water Efficiency Programs for Integrated Water Management: Efficient and Customer-Responsive Organization*. Water Efficiency Programs for Integrated Water Management; Case Study 1P-4.5C-91149-01/07-NH; American Water Works Association Research Foundation: AWWA Research Foundation, Denver, CO: p. 252.

City of Austin. 2016. *2016-2017 Austin, TX Proposed Budget: Volume One.* https://assets.austintexas.gov/budget/16-17/downloads/FY17_Proposed_Budget_Vol_1.pdf

Colorado Department of Natural Resources Division of Water Resources. 2016. *Rainwater Collection*. http://water.state.co.us/SurfaceWater/RainwaterCollection/Pages/default.aspx

Committee on Science, Engineering, and Public Policy. 1992. Policy implications of greenhouse warming: mitigation, adaptation, and the science base (Appendix C); *National Academy Press*: Washington, D.C,

Dalhuisen, J.M.; Florax, R.J.G.M.; de Groot, H.L.F.; Nijkamp, P. 2003. Price and Income Elasticities of Residential Water Demand: A Meta-Analysis. *Land Econ.* 79:2 292-308.

Davis, L. W. 2008. Durable Good and Residential Demand for Energy and Water: Evidence from a Field Trial. *Rand Journal of Economics.* 39: 530–546.

Davis, L.W. 2010. Evaluating the Slow Adoption of Energy Efficient Investments: Are Renters Less Likely To Have Energy Efficient Appliances?. *National Bureau of Economic Research*. Working Paper 16114. http://www.nber.org/papers/w16114

DeCanio, 1998. The Efficiency Paradox: Bureaucratic and Organizational Barriers to Profitable Energy-Saving Investments. *Energy Policy*. 26:5 441-454.

De Kleine, R.D.; Keoleian, G.A.; Kelly, J.C. 2011. Optimal Replacement of Residential Air Conditioning Equipment to Minimize Energy, Greenhouse Gas Emissions, and Consumer Cost in the US. *Energy Policy*. 39: 3144-3153.

DeOreo, W.B.; Heaney, J.P.; Mayer, P.W. 1996. Flow Trace Analysis to Assess Water Use. *J Am Water Works Assoc.* 88:1 79-90.

DeOreo, W. B. 2011. *Analysis of Water Use in New Single Family Homes; Water Efficiency Benchmarks for New Single-Family Homes.* Aquacraft Inc.: p. 156.

Division of Water Resources; Division of Soil and Water Conservation; Division of Pollution Prevention and Environmental Assistance. 2004. *Report on Water Conservation and Water Use Efficiency As Required by House Bill 1215 (Session*

*Law 2002-167), Section 5*North Carolina Department of Environment and Natural Resources: North Carolina: p. 22.

Espey, M.; Espey, J.; Shaw, W. D. 1997. Price Elasticity of Residential Demand for Water: A Meta-Analysis. *Water Resources Research*.33: 1369–1374.

EPA Water Resources Center. *Cases In Water Conservation: How Efficiency Programs Help Water Utilities Save Water and Avoid Costs; Cases In Water Conservation*. 2002. Case Study EPA832-B-02-003; Unites States Environmental Protection Agency: U.S. EPA Office of Water, Washington, D.C.: p. 54.

Gillingham, K.; Harding, M.; Rapson, D. 2012. Split Incentives in Residential Energy Consumption. *The Energy Journal*. 33:2 37-62.

Greening, L.A.; Greene, D.L.; Difiglio, C. 2000. Energy Efficiency and Consumption – the Rebound Effect – a Survey. *Energy Policy*. 28: 389-401.

Hausman, J. 1979. Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables. *The Bell Journal of Economics*.10:(1) 33-54

Heberger, M.; Cooley, H.; Gleick, P. 2014. *Urban Water Conservation and Efficiency Potential in California; The Untapped Potential of California's Water Supply*. Case Study 14-05-D. Pacific Institute and Natural Resources Defense Council: California,: p. 12.

Howe, C. W. 2002. Policy Issues and Institutional Impediments in The Management of Groundwater: Lessons From Case Studies. *Environment and Development Economics*.. 7: 17.

Howe, C.W.; Linaweaver, F.P. 1967. The Impact of Price on Residential Water Demand and Its Relation to System Design and Price Structure. *Water Resources Research.* 3:1 13-32.

International Energy Agency. 2007. *Mind the Gap: Quantifying Principal-Agent Problems in Energy Efficiency.* International Energy Agency. Paris, France.

International Energy Agency. 2008. *Promoting Energy Efficiency Investments: Case Studies in the Residential Sector.* International Energy Agency. Paris, France.

Kenney, D. S.; Goemans, C.; Klein, R.; Lowrey, J.; Reidy, K. 2008. Residential Water Demand Management: Lessons from Aurora, Colorado. *Journal of the American Water Resources Association*.44: 192–207.

Keoleian, G.A.; Blanchard, S.; Reppe, P. 2001. Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House. *Journal of Industrial Ecology*., 4:(2) 135-156.

Kim, H.C; Keoleian, G.A.; Horie, Y.A. 2006. Optimal Household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. *Energy Policy*.34: 2310-2323.

Lower Colorado River Authority. "LCRA Board will consider proposed new water rates" www.lcra.org/water/water-supply/drought-update/Pages/Water-rates.aspx (accessed August, 2014).

Lee, M.; Tansel, B.; Balbin, M. 2011. Influence of Residential water Use Efficiency Measures on Houshold Water Demand: A Four Year Longitudinal Study. *Resources, Conservation and Recycling*.56: 1–6.

Lee, M.; Tansel, B.; Balbin, M. 2013. Urban Sustainability Incentives for Residential Water Conservation: Adoption of Multiple High Efficiency Appliances. *Water Resource Management*.27: 2531–2540.

Lower Colorado River Authority. 2014. How Does 2013 Compare? LCRA Water Use Summary 2013; LCRA Water Use Summary; Summary; Lower Colorado River Authority: Lower Colorado River Basin; p. 2.

Lower Colorado River Authority. 2012. LCRA Water Conservation Incentives Program; Lower Colorado River Authority.; p. 16.

Lundie, S.; Peters, G.M.; Beavis, P.C. 2004. Life Cycle Assessment for Sustainable Metropolitan Water Systems Planning. *Environmental Science and Technology*., 38: 3465-3473.

Meier, A. K. 1982. Supply Curves of Conserved Energy. Ph.D. Thesis, University of California: Lawrence Berkeley Laboratory.

Morrissey, J.; Dunphy, N.; MacSweeney, R. 2014. Energy efficiency in commercial buildings: capturing added-value of retrofit. *Journal of Property and Investment Finance*. 32:(4), 396-414.

Murtishaw,S; Sathaye, J. 2008. Quantifying the Effect of the Principal-Agent Problem on U.S. Residential Energy Use. *Proceedings of the 2008 ACEEE Summer Study on Energy Efficiency in Buildings.* 9: 293-304.

National Action Plan for Energy Efficiency. 2008. *Understanding Cost-Effectiveness of Energy Efficiency Programs: Best Practices, Technical Methods, and Emerging Issues for Policy-Makers*. Energy and Environmental Economics, Inc. and Regulatory Assistance Project.. www.epa.gov/eeactionplan

Northwest Power Council. Conservation Supply Curve Files www.nwcouncil.org/energy/powerplan/6/supply-curves/ (accessed August, 2014).Olmstead, S.M.; Stavins, R.N. 2009. Comparing Price and Nonprice

Approaches to Urban Water Conservation. *Water Resources Research.* 45: W04301.

Renwick, M. E.; Archibald, S. O. 1998. Demand Side Management Policies for Residential Water Use: Who Bears the Conservation Burden? *Land Economics*.74: 343.

Renwick, M. E.; Green, R. D. 2000. Do Residential Water Demand Side Management Policies Measure Up? An Analysis of Eight California Water Agencies. *Journal of Environmental Economics and Management*., 40: 37–55.

Rosenberg, D. M.; Mccully, P.; Pringle, C. M. 2000. Global-Scale Environmental Effects of Hydrological Alterations: Introduction. *BioScience*. 50: 746.

Sallee, J.M. 2014. Rational Inattention and Energy Efficiency. *J of Law and Econ.* 57: 781-820.

San Antonio Water System. 2016. *Residential Water Service.* http://www.saws.org/service/rates/Resident.cfm

Sims, C.A. 2015. Rational Inattention and Monetary Economics. *Handbook of Monetary Policy.* P. 155-181.

Short, M.; Saint, C.; Regel, R.; van den Akker, B. 2014. *An Integrated Approach for Performance Benchmarking of Water Recycling Operations*. Australian Water Recycling Centre for Excellence.

Smith, M. 2010. *Water Transformed: Sustainable Water Solutions for Climate Change Adaptation - Module C*, The Natural Edge Project (TNEP), Griffith University, and Australian National University, Australia.

Stoft, S. E. 1995. The Economics of Conserved-Energy “Supply” Curves. *Energy Journal*. 16: 109–137.

Stokes, J.R.; Horvath, A. 2010. Supply-Chain Environmental Effects of Wastewater Utilities. *Environmental Resources Letters*., 5:014015-014022.

Stokes, J.R.; Horvath, A. 2009. Energy and Air Emission Effects of Water Supply. *Environmental Science and Technology*., 43: 2680-2687.

Stokes, J.; Horvath, A. 2006. Life Cycle Energy Assessment of Alternative Water Supply Systems. *Int. Journal of Life Cycle Assessment*.11:(5) 335-343.

Sorrell, S.; Dimitropoulos, J. 2008. The Rebound Effect: Microeconomic Definitions, Limitations, and Extensions. *Ecological Economics*., 65: 636–649.

Texas Commission on Environmental Quality. 2016. *Beneficial Re-Use of Graywater*. https://www.tceq.texas.gov/permitting/wastewater/graywater

Texas Comptroller of Public Accounts. 2014. *Texas Water Report: Going Deeper for the Solution*. http://www.comptroller.texas.gov/specialrpt/water/96-1746.pdf#24.

Texas Living Water Project. 2014. Water Conservation Works | Texas Living Waters Project http://texaslivingwaters.org/water-conservation/main-water-conservation/ (accessed August 2014).

Texas State Data Center. 2014. Projections of the Population of Texas and Counties in Texas by Age, Sex and Race/Ethnicity for 2010-2050. The Office of the State Demographer. http://txsdc.utsa.edu/Data/TPEPP/Projections/Methodology.pdf (accessed September 2013).

Texas State Legislature. 1992.*Texas Health and Safety Code*;. Vol. Title 5. Subtitle B. Chapter 372., p. 2.

Texas State Legislature. 1989. *Texas Health and Safety Code*; Vol. Title 5. Subtitle B. Section 341.039, p. 1.

Texas State Legislature. 2007. *Texas Water Code*, Title 2. Subtitle C. Chapter 15. Subchapter A.

Texas Water Development Board. 2005.*The Texas Manual on Rainwater Harvesting*; Third Edition; Texas Water Development Board: Austin, Texas,

Texas Water Development Board. 2012. *Water For Texas 2012 State Water Plan*; Texas Water Development Board: Texas, p. 314.

Thomas, J.F.; Syme, G.J. 1988. Estimating Residential Price Elasticity of Demand for Water: A Contingent Valuation Approach. *Water Resources Research*. 24:11 1847-1857.

U.S. Energy Information Administration. 2009. Residential Energy Consumption Survey (RECS) - Data http://www.eia.gov/consumption/residential/data/2009/ (accessed August 2014).

U.S. Energy Information Administration. 2013. Levelized Cost of Electricity and Levelized Avoided Cost of Electricity Methodology Supplement.. www.eia.gov/renewable/workshop/gencosts/pdf/methodology_supplement.pdf (accessed September 2015).

U.S. Environmental Protection Agency. 2014. ENERGY STAR Certified Products | EPA ENERGY STAR; https://data.energystar.gov/ (accessed August, 2014).

U.S. Environmental Protection Agency. 2014. WaterSense Labeled Products | WaterSense | USEPA; www.epa.gov/watersense/products/index.html (Accessed August 2014)

U.S. Office of Management and Budget, Washington, D.C. 2014. *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs* http://www.whitehouse.gov/omb/circulars_a094/ (accessed August 2014).

Vogel, R.M. and Stedinger, J.R. 1987. Generalized Storage-Reliability-Yield Relationships. *Journal of Hydrology*.89: 303-327.

Wada, K.; Akimoto, K.; Sano, F.; Oda, J.; Homma, T. 2012, Energy Efficiency Opportunities in the Residential Sector and Their Feasibility. *Energy*. 48: 5-10.

White, S. B.; Howe, C. 1998. Water Efficiency and Reuse: A Least Cost Planning Approach. Paper presented at the 6th NSW Recycled Water Seminar; Institute for Sustainable Futures: Sydney, AU. p. 6.

White, S. B.; Fane, S. A. 2007. Designing Cost Effective Water Demand Management Programs in Australia. *Water Science and Technology*. 46: 225-232.

Woltemaide, C.; Fuellhart, K. 2013. Economic Efficiency of Residential Water Conservation Programs in a Pennsylvania Public Water Utility. *Prof. Geogr.*, 65: 116–129.

Appendix References

(1) U.S. Energy Information Administration. Residential Energy Consumption Survey (RECS) – Data http://www.eia.gov/consumption/residential/data/2009/.

(2) U.S. Office of Management and Budget, Washignton, D.C. Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs http://www.whitehouse.gov/omb/circulars_a094/.

(3) Austin Water Utility. Water Service Rates - Residential Customers, 2013.

(4) Energy Information Administration. 2012 Utility Bundled Retail Sales - Residential.

(5) Texas Natural Gas Prices http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_STX_a.htm.

(6) How much coal, natural gas, or petroleum is used to generate a kilowatthour of electricity? - FAQ - U.S. Energy Information Administration (EIA) http://www.eia.gov/tools/faqs/faq.cfm?id=667&t=2.

(7) Texas Water Development Board. *Water For Texas 2012 State Water Plan*; Texas Water Development Board: Texas, 2012; p. 314.

(8) ENERGY STAR Certified Products | EPA ENERGY STAR https://data.energystar.gov/.

(9) Cost to Install Washing Machine - 2014 Cost Calculator (ZipCode based) http://www.homewyse.com/services/cost_to_install_washing_machine.html.

(10) http://www.homewyse.com/services/cost_to_install_washing_machine.html.

(11) Office of Energy & Renewable Energy. Energy and Cost Savings Calculators for Energy-Efficient Products | Department of Energy http://www.energy.gov/eere/femp/energy-and-cost-savings-calculators-energy-efficient-products.

(12) Cost to Install Dishwasher - 2014 Cost Calculator (ZipCode based) http://www.homewyse.com/services/cost_to_install_dishwasher.html.

(13) Cost to Install Toilet - 2014 Cost Calculator (ZipCode based) http://www.homewyse.com/services/cost_to_install_toilet.html.

(14) DeOreo, W. B. *Analysis of Water Use in New Single Family Homes*; Water Efficiency Benchmarks for New Single-Family Homes; Analysis; Aquacraft Inc.: Arizona, California, Colorado, Nevada, Oregon, Utah, and Florida, 2011; p. 156.

(15) Seiders, D.; Ahluwalia, G.; Melman, S.; Quint, R.; Chaluvadi, A.; Liang, M.; Silverberg, A.; Bechler, C. *Study of Life Expectancy of Home Components*; Case Study; National Association of Home Builders: United States, 2007; p. 19.

(16) AWWA Research Foundation. *Residential end uses of water*; Mayer, P. W.; DeOreo, W. B., Eds.; AWWA Research Foundation and American Water Works Association: Denver, CO, 1999.

(17) Guy, E. *Lavatory Faucets and Faucet Accessories*; California Energy Commission 2013 Pre-Rulemaking Appliance Efficiency: Invitation to Participate; Study 12-AAER-2C; California Energy Commission: California, U.S., 2013; p. 17.

(18) *Price List, North America, June 2012*; Caroma North American Price List; Price Listing; Caroma, 2012; p. 32.

(19) STORE « SinkPositive | The Water-Saving, Patented, Multipurpose Accessory Sink That Fits on the Tank of your Toilet http://sinkpositive.com/web/store/.

(20) Texas Water Development Board. *The Texas Manual on Rainwater Harvesting*; Third.; Texas Water Development Board: Austin, Texas, 2005.

(21) Climate at a Glance: Time Series | National Climatic Data Center (NCDC) http://www.ncdc.noaa.gov/cag/time-series/us.

(22) AWWA Research Foundation. Residential end uses of water; Mayer, P. W.; DeOreo, W. B., Eds.; AWWA Research Foundation and American Water Works Association: Denver, CO, 1999.