AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2014WR016821

Key Points:

- Increased savings of water, energy and GHG when energy costs are included
- We obtained water and energy own and cross-price elasticities
- Our results encourage water and energy utilities to work together

Correspondence to:
A. Escriva-Bou,
alesbou@gmail.com.

Citation:
Escriva-Bou, A., J. R. Lund, and M. Pulido-Velazquez (2015), Optimal residential water conservation strategies considering related energy in California, *Water Resour. Res.*, *51*, doi:10.1002/2014WR016821.

Received 21 DEC 2014
Accepted 21 MAY 2015
Accepted article online 24 MAY 2015

Optimal residential water conservation strategies considering related energy in California

Alvar Escriva-Bou[1,2], Jay R. Lund[1], and Manuel Pulido-Velazquez[2]

[1]Center for Watershed Sciences, University of California, Davis, Davis, California, USA, [2]Research Institute of Water and Environmental Engineering, IIAMA, Universitat Politècnica de València, Valencia, Spain

Abstract Although most freshwater resources are used in agriculture, residential water use is a much more energy intensive user. Based on this, we analyze the increased willingness to adopt water conservation strategies if energy cost is included in the customers' utility function. Using a Water-Energy-CO_2 emissions model for household water end uses and probability distribution functions for parameters affecting water and water-related energy use in 10 different locations in California, this research introduces a probabilistic two-stage optimization model considering technical and behavioral decision variables to obtain the most economical strategies to minimize household water and water-related energy bills and costs given both water and energy price shocks. Results can provide an upper bound of household savings for customers with well-behaved preferences, and show greater adoption rates to reduce energy intensive appliances when energy is accounted, resulting in an overall 24% reduction in indoor water use that represents a 30% reduction in water-related energy use and a 53% reduction in household water-related CO_2 emissions. Previous use patterns and water and energy rate structures can affect greatly the potential benefits for customers and so their behavior. Given that water and energy are somewhat complementary goods for customers, we use results of the optimization to obtain own-price and cross-price elasticities of residential water use by simulating increases in water and energy prices. While the results are highly influenced by assumptions due to lack of empirical data, the method presented has no precedent in the literature and hopefully will stimulate the collection of additional relevant data.

1. Introduction

Water conservation is often the most cost effective *source* of additional water supply for water stressed urban regions to maintain supply reliability with increasing population and/or demands, or shorter-term droughts. In the city of Los Angeles total water demands between 2005 and 2010 were about the same as they were in 1980, despite a 38% of population increase [*LADWP*, 2010], and conservation campaigns during droughts have proven to be quite effective [*Pint*, 1999; *Reed and Lund*, 1990; *Valinas*, 2006].

There is much debate on the cost effectiveness of demand side management policies (DSMP) [*Olmstead and Stavins*, 2009; *Renwick and Green*, 2000]. Price-related DSMP have focused on behavioral incentives to reduce consumption, and nonprice DSMP accounts for various instruments: command-and-control (CAC) strategies such as building codes or plumbing standards, public campaigns, education, the value of information, or rationing. But fewer conservation studies recognize that residential water use is the one of the most energy intensive types of water use omitting a factor that can increase the benefits of water savings from energy savings.

Econometric models to predict water use as a function of price, income and other variables are common in the literature (for review, see *Arbués et al*. [2003]) and they have been used to test conservation policies as well [*DeOreo et al*., 2011; *Renwick and Archibald*, 1998]. More mechanistic engineered models use water end use data to estimate potential conservation by assuming replacement rates of improved appliances [*Cahill et al*., 2013] or even measured savings from retrofitting household's appliances [*Mayer et al*., 2003]. Finally another approach uses probability distributions from empirical data to characterize technological, behavioral, and socioeconomic parameters that affect water use and estimate consumption and potential conservation by modifying those variables through technological change or behavioral modification induced by price increases—assuming well-behaved preferences—using Monte Carlo simulations [*Cahill et al*., 2013;

Rosenberg et al., 2007]. This latest approach is used in this paper to include water-related energy consumption and how this variable can affect user decisions.

Although most freshwater resources are used in agriculture, residential water use is a much more energy intensive user [*Rothausen and Conway*, 2011]. Residential water-energy studies are in an early stage, and they have focused mostly on quantifying water-related energy consumption for each household appliance and end use. Some studies also present some kind of engineered procedure to analyze potential energy conservation: *Fidar et al*. [2010] assessed the variability of energy and carbon emissions of different water efficiency target/levels depending on the composite strategies of water end use savings in England; *Beal et al*. [2012] evaluated the potential conservation of energy and greenhouse gas emissions from resource-efficient household stock using empirical data and detailed stock specifications for homes in Queensland, Australia; *Kenway et al*. [2013] estimated the average water, water-related energy, CO_2 emission and economic savings by simulating technological and behavioral changes in a model based on a metered house in Brisbane, Australia; *Morales et al*. [2013] developed a methodology that uses parcel-level estimates of water use and optimization methods to determine the cost-effectiveness of water conservation practices based on the amount of water saved when savings in energy and wastewater treatment are included; finally *Abdallah and Rosenberg* [2014] obtained the energy elasticity of some technological and behavioral household modifications.

All these studies estimate potential conservation values without accounting for a budget constraint that could prevent customers from adopting these strategies. Another issue is that even if potential conservation strategies have long run benefits, some factors inhibit customers' adoption of these actions sometimes called the efficiency gap concept [*Jaffe and Stavins*, 1994]. Here the lack of information, the cost to get that information and uncertainty of future prices might explain nonadoption of seemingly beneficial strategies. In this paper, we try to bridge the efficiency gap a little using engineered technological and social modeling.

To include variability in costs and benefits we use a stochastic optimization model with recourse (or two-stage stochastic programming) that includes uncertainty in prices and water availability—increasing water prices and potential rationing during droughts and monthly variation of energy prices—and allows household dwellers to select among a variety of long-term and short-term actions to minimize their annual water and energy costs. Decisions are based on data available at the time the decisions are made accounting for stochastic presentation of events. No other study seems to have analyzed the residential water and energy use with this optimization approach, including technological and behavioral actions and inluding heterogeneity in household characteristics, stocks and patterns of consumption.

This approach also permits analysis of changes in water and energy prices and estimation of potential water and energy savings that are economically desirable assuming well-behaved preferences and complete information. Given that water and energy are complementary goods in this context, price elasticities and cross-price elasticities can be obtained. As far as we know only *Hansen* [1996] obtained the energy cross-price elasticity using an econometric model of residential water demand derived from a model of household production of final consumption goods taking water, energy and an aggregate of other goods as inputs.

The research expands a previous approach applied to water conservation [*Cahill et al*., 2013; *Rosenberg et al*., 2007] to include the water-related costs and benefits of a variety of water and energy conservation actions. A system analysis is applied to households using a previous water-energy-CO_2 model [*Escriva-Bou et al*., 2015] for 10 cities in California following this procedure: (i) identifying potential long and short-term conservation actions; (ii) modeling water, energy and economic savings due to these technological and behavioral modifications and its costs accounting for water and energy variable prices; (iii) obtaining the composite of actions that minimize the annual water-energy cost for each household; and (iv) considering uncertainty through Monte Carlo simulation for a wide variety of household conditions (adapted from *Alcubilla and Lund* [2006] and *Rosenberg et al*. [2007]). Finally one last run considering only water costs was done to obtain the increased willingness to adopt conservation actions from adding consideration of embedded energy.

The paper is organized as follows: section 2 explores the economics behind the model. Section 3 presents briefly the water-energy-CO_2 model, identifies the conservation actions, develops the models used to obtain savings through technological or behavioral changes, states the probabilistic two-stage optimization model, explains the Monte Carlo simulations and presents the elasticities assessment. Section 4 presents the results of all those parts. In section 5, a discussion about the results obtained and the limitations and potential improvement of the method is developed. Finally, section 6 presents conclusions.

2. The Economics Behind the Model

The model presented here tries to capture the increased willingness to adopt water conservation actions if the embedded energy is included in the water costs of the household. Although the results are obtained with empirical data, the model is built on some basic economic assumptions explained below.

The main demand assumption is that residential water and water-related energy are complementary goods. But only energy used by the water heater and indoor hot water are complementary, being the remaining consumption of both goods is independent.

Figure 1 shows an indifference curve, where customers would be equally satisfied with different quantities of water and energy use, although relative prices and the budget constraint determines the actual quantities consumed. Current water and energy consumption in a household (point 0) cam be broken down into outdoor water, indoor cold water and indoor hot water uses (horizontal green, blue and red arrows respectively) and water heating, space heating, appliances and air conditioned consumption (vertical red, green, orange and purple arrows respectively).

If a good's price changes, the substitution effect causes a reallocation of the consumption pattern to equate the marginal rate of substitution to the new price ratio keeping utility constant [*Nicholson and Snyder*, 2012]. If water price relative to energy price increases (from 0 to 1 in the graphic), there is a reduction in water use (mostly in outdoor water use because larger elasticity) and an increase in each of the energy uses but water heating, that decreases because of complementarity with indoor hot water. The opposite might be said if energy price relative to water price increases, moving from 0 to 2 where total energy decreases but energy used to heat water increases.

As our model only accounts for energy used to heating water, the assumption is that hot water and energy used for heating water are complements, given that customers have adequate information about hot water and energy used to heat water quantities and prices. The complementary assumption is given by the following formulae:

$$\frac{dW_{hot\ \ indoor}}{dp_{energy}} < 0 \tag{1}$$

$$\frac{dE_{heating\ \ water}}{dp_{water}} < 0 \tag{2}$$

$$\left.\frac{dW_{indoor\ \ hot}}{dp_{energy}}\right|_{U=constant} = \left.\frac{dE_{heating\ \ water}}{dp_{water}}\right|_{U=constant} \tag{3}$$

On the supply side a water utility has alternative water sources with different marginal costs and reliability, and it is operating as a regulated natural monopoly. We are assuming that current demand is 70% likely to be covered with a water supply with a very low marginal cost (e.g., surface water); 20% of the months surface water is shorted and the supply has to be completed with a secondary supply (e.g., groundwater) with a 10% increase in marginal cost; the remaining 10% of the times, main water supply has larger shortages and besides the secondary supply, the water utility has to find a tertiary water supply (e.g., buy water rights from water markets) with 20% increase in marginal cost Figure 2. As a result, an increase in prices to customers and a reduction of total demand is expected. Although this is an hypothetical case that we have applied equally for each of the water utilities using their actual water rate structures as a base price, we have used temporal water price increases basing our assumptions in the EBMUD 2008–2009 Drought Management Plan [*EBMUD*, 2011].

Accounting for energy supply, as most of the water heaters in California are gas-fired, we included the volatility in annual prices by setting three different prices for natural gas. In 80% of the months, the price ranges 90–110% of the average price. In 10% of the months, price exceeds 110% of the average price (assuming

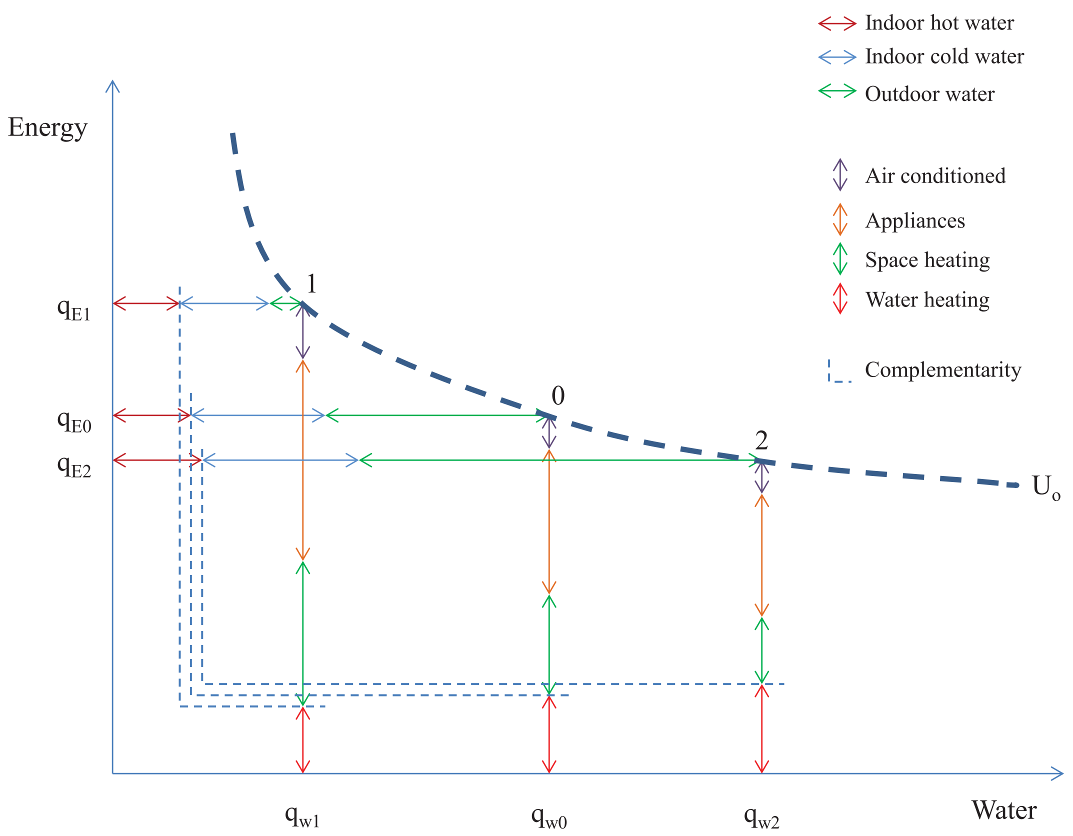

Figure 1. Indifference curve and break down of residential water and energy consumption.

115% of average price) and 10% of the months has lower prices (assuming 85% of average price; the average price is obtained from the actual prices for each location as explained in section 3.1). As seen in the residential natural gas price data from 2009 to 2014 (Figure 3), this is a fair assumption.

Customers pay close attention to price fluctuation to change their patterns of consumption, thus utilities can achieve moderated reductions in aggregate demand by modest price increases [*Renwick and Green*, 2000]. By including energy price and volatility we are increasing the price elasticity of water consumption to meet supply and demand. As we are taking this theoretical approach using real data from different cities, we will use both supply assumptions—water and energy price shocks—for all the locations in order to compare the results and obtain potential policy implications from the different performance.

Probably the most important economic assumption here is that customers have adequate information: they know exactly their water and energy use—even how much are they using in each end-use—and the prices and the likelihood and the amount of prices volatility; they also know all the potential water and energy conservation actions, their costs and effectiveness. Accounting for all these factors, household dwellers will adopt conservation actions that maximize their benefit or minimize their costs over time.

3. Methods

3.1. Water-Energy-CO_2-Costs Model

In a previous study, we developed a model to assess water and water-related energy, greenhouse gas (GHG) emission and costs for 10 cities in California [*Escriva-Bou et al.*, In press]. The study is based on a deductive approach that includes household heterogeneity in water use using probability distributions for each step. For conciseness the framework is only briefly described here.

Starting from a single family household water end use survey [*DeOreo et al.*, 2011], a model was built using probability distributions for parameters affecting water use. Total household water use is the sum of eight

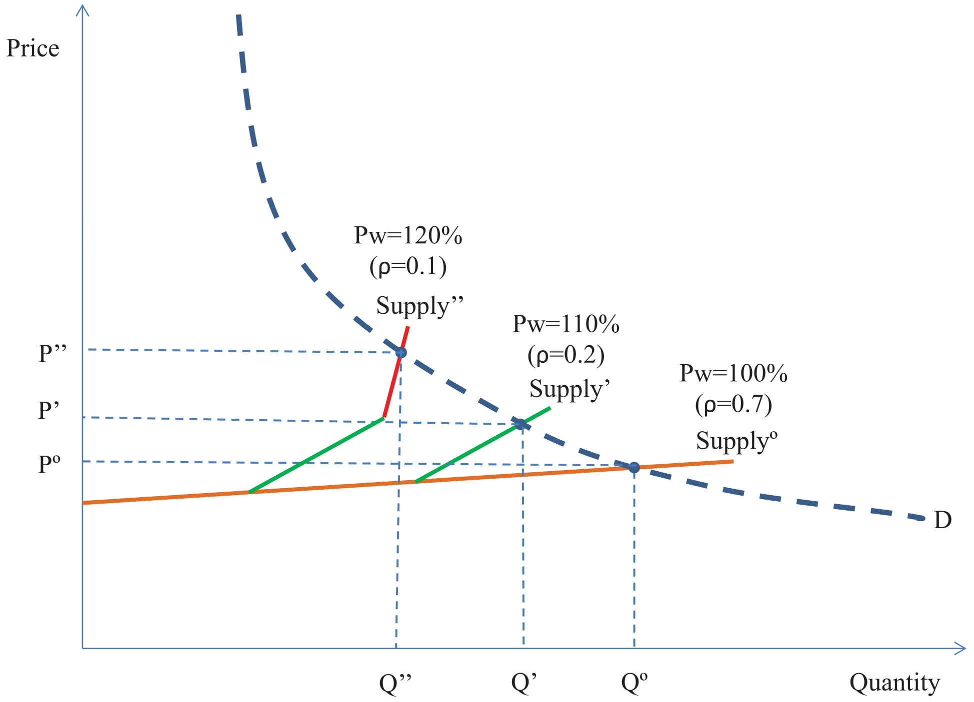

Figure 2. Theoretic water supply and demand curves accounting for alternative supply sources.

end-uses—toilet, shower, bath, faucet, dishwasher, clotheswasher, leaks/other, and outdoor use—each calculated separately as a function of household characteristics, users' behavior and external factors randomly sampled from parameter probability distributions.

Water-related energy next is estimated by calculating hot water shares for each end-use using probability functions from the literature [*Mayer et al*., 2003] and then assessing the energy used by the water heater using the Water Heater Analysis Model (WHAM) equation [*Lutz et al*., 1998]. The WHAM equation permits the user to minimally describe both the operating conditions—characterized by daily draw volume, thermostat setpoint temperature, inlet water temperature and ambient air temperature—and the water heater—described by the recovery efficiency (RE), standby heat loss coefficient (UA), and rated input power (Pon). The amount of energy used is obtained as the sum of the energy content of water drawn from the water heater plus the energy expended to recover from standby losses. We included the variability of water heaters and climate by assigning different values according to the probability distributions for each location using several data sources [*USDOE*, 2009; *USEIA*, 2009].

GHG emissions then are calculated using emission factors as a function of the type of water heater (electric or gas-fired) and the utility that provides the energy. Finally, the costs incurred by each household in water and water-related energy use are calculated using the different water and energy rate structures for each city.

3.2. Conservation Actions

Given a composition and a location of a household, water and water-related energy consumption depends on technological and behavioral factors. Usually technological improvements are long-term investments, whereas behavioral modification can occur in the short-run—as a reaction of a temporal price increase or supply rationing—but also can react to educational campaigns or increased environmental consciousness [*Gilg and Barr*, 2006; *Willis et al*., 2011] as either a short or long-term strategy

The model includes seven technological and eight behavioral modifications related directly with water use, and four technological and one behavioral adaptations over water-related energy appliances, as shown in Table 1.

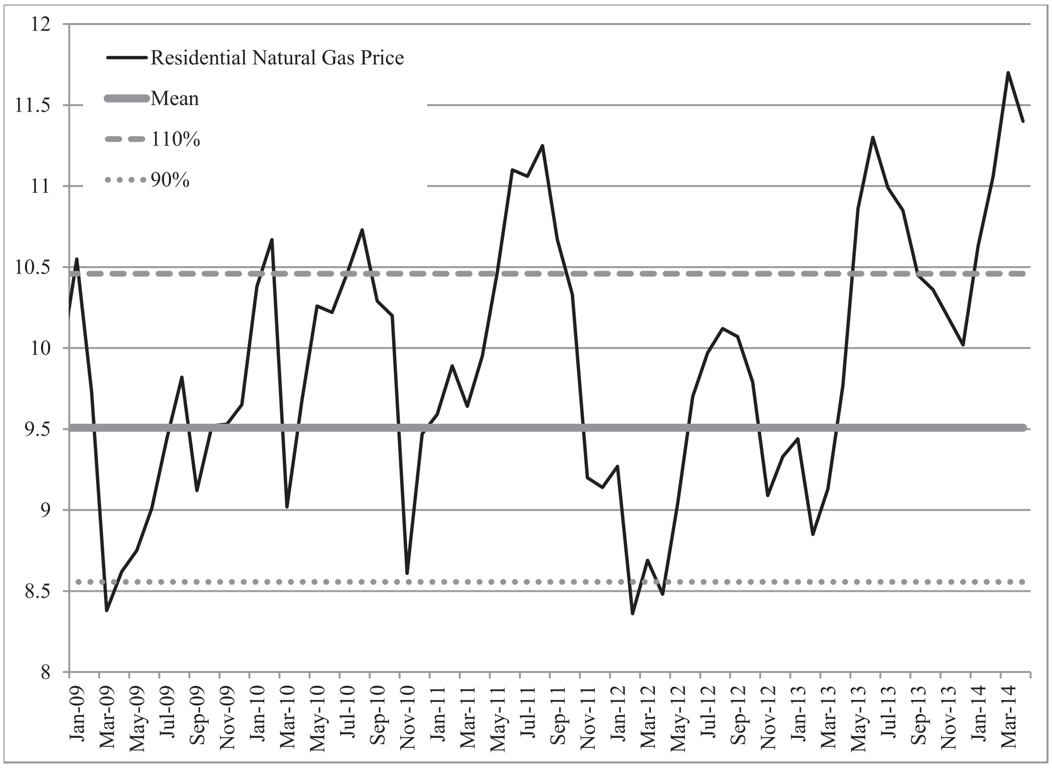

Figure 3. Average statewide residential natural gas price from January 2009 to April 2014 in California (real prices in 2009 dollars per thousand cubic feet). Source: Nominal prices from *USEIA* [2015].

3.3. Modeling Savings and Costs of Actions

3.3.1. Technological Improvements

Water savings from retrofitting appliances is represented by probability distributions of appliance water use with and without retrofit from field survey data [*DeOreo et al*., 2011], with potential savings randomly sampled if the appliance is retrofitted. Because the model explicitly includes household heterogeneity, it could obtain "negative" savings because there is a chance that the preretrofit flow would be lower than the postretrofit. Figure 4 shows an example of these distributions taken from surveyed households.

Because of the lack of real data of retrofitted water heaters, we used a different approach for their retrofitted performance: retrofitted water heaters are given a fixed efficiency level and recovery efficiency taken from commercial distributors, but we still permitted a variation in the other parameters.

The costs of long-term actions have been taken either from the literature or from commercial distributors, as shown in Table 1.

3.3.2. Behavioral Savings

Using behavioral parameters from household surveys—such as shower length, dishwasher use frequency—we simulated behavioral savings as a function of two factors: potential conservation and willingness to adopt conservation actions. Potential conservation accounts for current habits per person related to the main statistics of the surveyed households, assuming that users closer to minimum consumption are less likely to decrease their consumption than larger users. Willingness to adopt conservation actions relates with the awareness that household dwellers have to save water or energy and is represented by the "consciousness factor," that is a unique value per household.

For each household *j* the *i* behavioral parameter in the stage 1 will be given by the following expressions:

$$B_{ij}{}^{1} = B_{ij}{}^{0} \cdot (1 - RF_{ij}) \tag{4}$$

Table 1. Actions Available to Households to Save Water and Water-Related Energy[a]

Stage	Resource		Action	Capital Cost	Installation Cost	Unit	Lifespan
Long-Term Actions	Water	wlt1	Retrofit toilet	170	250	$	25
		wlt2	Retrofit showerheads	20	80	$	10
		wlt3	Retrofit dishwasher	650	170	$	10
		wlt4	Retrofit washing machine	500	170	$	10
		wlt5	Install artificial turf	3.5	100	$/sq. feet	10
		wlt6	Install xeriscape	2.5	0.5	$/sq. feet	15
		wlt7	Install smart irrigation controllers	140	160	$	15
	Energy	elt1	New gas-fired water heater intermediate efficiency (Avg. EF=0.63)	634.00	775.00	$	11.6
		elt2	New gas-fired water heater high efficiency (Avg. EF=0.75)	895.00	1033.00	$	11.6
		elt3	New electric water heater intermediate efficiency (Avg. EF=0.92)	304.19	329.82	$	11.6
		elt4	New electric water heater high efficiency (Avg. EF=2.35)	1163.28	539.37	$	11.6
Stage	Resource	Action		Hassle Cost		Unit	
Short-Term Actions	Water	wst1	Reduce toilet flushes	0.02		$/d	
		wst2	Reduce shower length	0.05		$/d	
		wst3	Reduce shower frequency	0.05		$/d	
		wst4	Reduce bath frequency	0.05		$/d	
		wst5	Reduce faucet use	0.05		$/d	
		wst6	Reduce laundry frequency	0.05		$/d	
		wst7	Leaks detection and fixing	0.05		$/d	
		wst8	Stress irrigation	0.05		$/d	
	Energy	est1	Decrease water heater setpoint temperature	0.05		$/d	

[a] Source: costs and lifespan for long-term water actions taken from *Cahill et al.* [2013]; costs and lifespan for long-term energy actions from *USEPA* [2015]; costs for short-term actions are engineering estimations. Values of the costs for short-term actions are the parameters P_i described in section 3.3.2. Efficiency for water heaters obtained from USEPA (2015), being high efficient electric water heaters a heat pump water heater that can achieve an efficiency value of 2.35, three times that of a common electric water heater.

$$RF_{ij}=\begin{cases}\left[\dfrac{B_{ij}{}^{0}-\min(b_i)}{median(b_i)-\min(b_i)}\cdot\left(\dfrac{\max(rf_i)}{2}\right)\right], & B_{ij}{}^{0}\leq\ median(b_i)+min(b_i)\\ CF_j\cdot\max(rf_i) & ,\ B_{ij}{}^{0}>median(b_i)+min(b_i)\end{cases}\tag{5}$$

where B_{ij}^{k} is the value for the behavioral parameter i for the household j in the stage k (usually events/day person); RF_{ij} the reduction factor for the parameter i for the household j (there is a previously defined

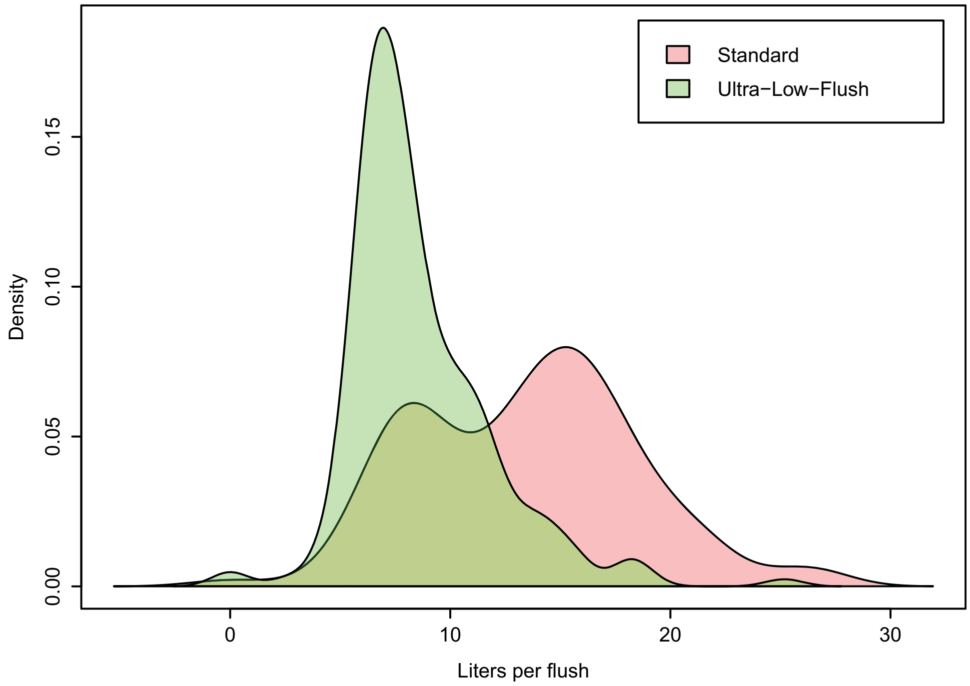

Figure 4. Flow per flush kernel density plots for standard and ultra-low-flush toilets obtained from surveyed households.

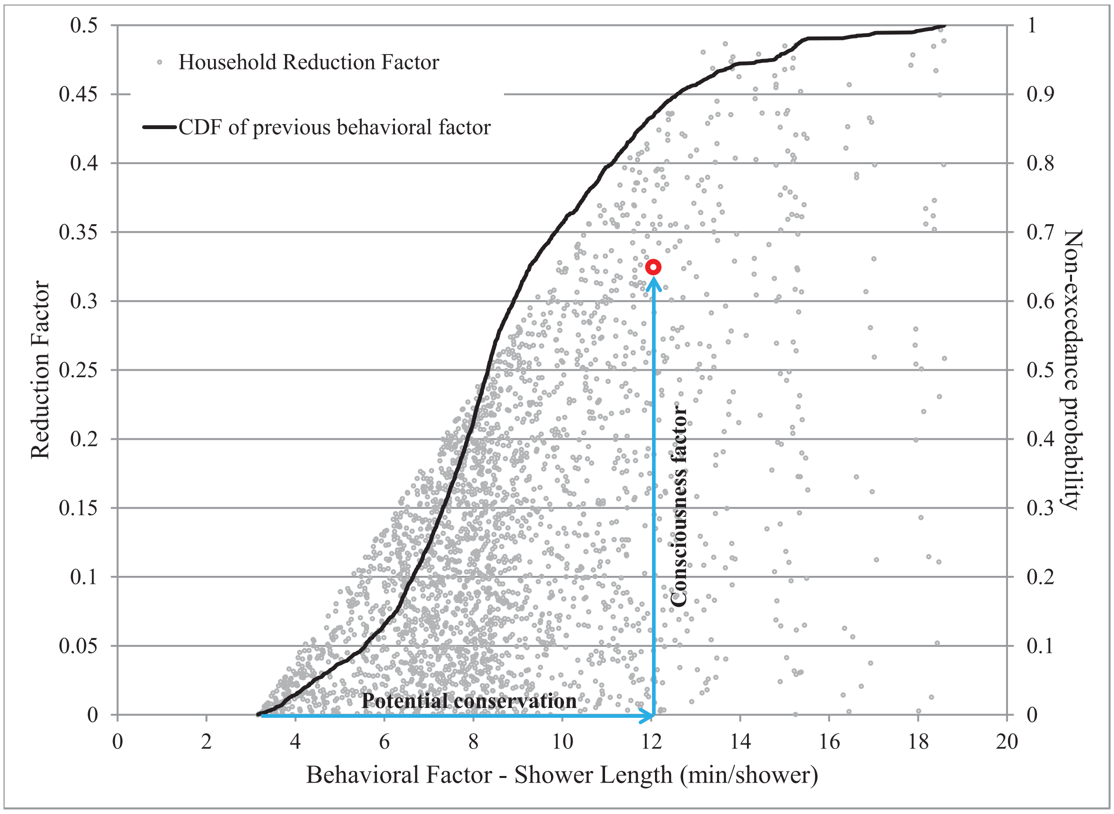

Figure 5. Reduction function for shower length distribution as a function of previous behavioral factor and a uniformly random consciousness factor.

$max(rf_i)$ parameter that accounts for the maximum reduction expected over the sample); and CF_j the consciousness factor for the household j.

The consciousness factor is a random factor given by a uniform distribution defined over the range [0, 1] that tries to capture the personal attitude or willingness to adopt conservation strategies. Although the use of a uniform distribution should seem naïve, *Gregory and Di Leo* [2003] reported that there is little or no correlation between general awareness of water conservation issues and household consumption, but their findings substantiate the role of personal involvement and habit formation. Because of the novelty of the research on environmental psychology on the link of reasoned and unreasoned influence on behavior, we have not found any empirical-based function in the literature that could capture this personal involvement and habit formation on water savings that could perform better than the uniform distribution for the consciousness factor.

Each point in Figure 5 presents the results of the reduction factor (RF_{ij}) for the 10,000 households obtained by Monte Carlo simulations for the shower length. The maximum *RFij* ranges from 0 to 0.5 as a lineal function of the current behavioral factor with a slope given by the median and the min of the sample. The consciousness factor includes a second variability because different attitudes toward conservations resulting that, even with very large potential conservation, a household can keep the current consumption if the consciousness factor is 0.

As behavioral changes have no financial costs, we included behavioral hassle costs [*Dolnicar and Hurlimann*, 2010; *Rosenberg et al*., 2007] that reflect inconvenience costs to household dwellers and that we have linked to income, because of decreasing income-elasticity of demand, and again to the consciousness factor, assuming that consciousness decreases hassle costs. The behavioral cost for the action i in the household j is given by the following expression:

$$C_{short-term_{ij}} = P_i \cdot \frac{I_j}{365 \cdot 24} \cdot \left(1 - \frac{CF_j}{2}\right) \quad (6)$$

where P_i is an engineering estimated parameter for the hourly hassle cost of action *i* given in Table 1; I_j the annual income of the household *j*; and CF_j the consciousness factor for the household *j*.

3.3.3. Interaction Among Actions

When a long-term action is implemented, the conditions for short-term actions are already changed to sometimes reduce the expected savings from behavioral changes. The same can be said about interaction between water and energy actions: water actions affect energy consumption, and then the energy savings of energy actions will depend on previous water long-term and short-term actions. Therefore, to calculate the correct expected water and energy savings we have to account for combinations of long-term and short-term water and energy actions separately, but then introduce the interaction among those actions as a constraint in the optimization model to avoid double counting of water or energy savings and/or costs.

This is the so-called "demand hardening" concept that can be explained by a decreasing elasticity of water demand as long-term actions are implemented. As shown in *Lund* [1995], if the implementation of low-flow toilets and xeriscaping increases, although normal water use decreases, the potential for water savings during shortages decreases, increasing user inconvenience and cost of achieving short-term conservation from these uses.

3.4. Probabilistic Two-Stage Optimization Model

Given adequate information, customers with well-behaved preferences will adopt the mix of conservation actions that minimize their water and energy costs selecting among the whole set of short and long-term actions available. Mathematically this is formulated as a two-stage mixed-integer nonlinear stochastic modelwith two dimensions of actions and costs—water and energy.

In the first stage households decide to retrofit appliances to reduce water and energy for the long-run, whereas in the second stage, water and energy prices and/or availability change with supply conditions and customers can decide daily to adopt behavioral actions to reduce consumption in the short-run.

This optimization model expands a series of previous works mainly focused on water systems [*Alcubilla and Lund*, 2006; *Cahill et al*., 2013; *Rosenberg et al*., 2007] to include water-related energy actions and costs on the residential scale. The program will be applied to 10 cities in California, but it is readily adapted to other locations and type of users.

3.4.1. Decision Variables

There are four arrays with different dimensions of binary variables acting as decision variables:

1. $\mathbf{X_{WLT}}$ = implementation of an action defined in the set of water long-term actions *wlt*;
2. $\mathbf{X_{WSTwe,ee}}$ = implementation of an action defined in the set water short-term actions *wst* in the water billing event *we* and energy billing event *ee*;
3. $\mathbf{X_{ELT}}$ = implementation of an action defined in the set of energy long-term actions *elt*;
4. $\mathbf{X_{ESTwe,ee}}$ = implementation of an action defined in the set of energy short-term actions *est*, in the water billing event *we* and energy billing event *ee*.

3.4.2. Objective Function

Customers with adequate information will minimize their total expected economic cost, including the costs of conservation actions and water and water-related energy bills. The objective function is:

$$\begin{aligned}Minimize\ \ Z= & \sum_{wlt} C_{wlt}\cdot X_{wlt}+\sum_{elt} C_{elt}\cdot X_{elt}+i\\ & \cdot\left[\sum_{we} p_{we}\cdot\left(\sum_{ee} p_{ee}\cdot\left\{j\cdot\left(\sum_{wst} C_{wst}\cdot X_{wst_{we,ee}}+\sum_{est} C_{est}\cdot X_{est_{we,ee}}\right)+B_{W_{we}}+B_{E_{ee}}\right\}\right)\right]\end{aligned} \tag{7}$$

where C_{wlt} and C_{elt} are the annualized long-term water and energy action costs ($/yr) respectively whereas C_{wst} and C_{est} are the short-term water and energy action costs ($/d); p_{we} and p_{ee} are the probabilities of each water and energy billing event; Bw_{we} and Be_{ee} are the cost of water and water-related energy bill each billing period; *i* is the number of billing periods (6 or 12 depending on the local utility conditions) and *j* is the number of days per billing period (30 or 60 depending on the local utility conditions). Note that even different time step data are used because facility of use (daily for short-term actions and costs and annually for long-term action, costs, and bills), the model is run in an annual basis using a stochastic approach to include water and energy cost variability.

3.4.3. Complementary Use Equations

Water and water-related energy use are equal to the base consumption minus the savings due to conservation actions accounting for the interdependence among actions:

$$W_1 = W_0 - W_{sav} \tag{8}$$

$$W_{sav} = \sum_{wlt} X_{wlt} \cdot W_{sav_{wlt}} + \sum_{we} p_{we} \cdot \sum_{ee} p_{ee} \cdot \sum_{wst} X_{wst_{we,ee}} \cdot W_{sav_{wst}}(we, ee|wlt) \tag{9}$$

$$E_1 = E_0 - E_{sav} \tag{10}$$

$$\begin{aligned} E_{sav} = {} & \sum_{wlt} X_{wlt} \cdot E_{sav_{wlt}} + \sum_{elt} X_{elt} \cdot E_{sav_{elt}} | wlt + \sum_{we} p_{we} \cdot \sum_{ee} p_{ee} \\ & \cdot \left(\sum_{wst} X_{wst_{we,ee}} \cdot E_{sav_{wst}}(we, ee|wlt, elt) + \sum_{est} X_{est_{we,ee}} \cdot E_{sav_{est}}(we, ee|wlt, elt, wst \right) \Bigg) \end{aligned} \tag{11}$$

Once the actions are taken and the water and energy use are obtained, the bills per billing event can be calculated. The water-related energy bill is obtained by multiplying the consumption by a simple averaged marginal energy cost per CCF (or kWh for electric water heaters) for each utility. The water bill is obtained using the local increasing block rate structures for each utility.

3.4.4. Constraints

1. Decision variables are binary
2. Maximum effectiveness: water and energy saved cannot exceed the initial water and water-related energy use:

$$W_{sav} \leq W_0 \tag{12}$$

$$E_{sav} \leq E_0 \tag{13}$$

3. Mutually exclusive actions: some actions, like different changes of outdoor landscaping or to retrofit the water heater, cannot be implemented simultaneously:

$$\sum_{wlt^*} X_{wlt} \leq 1; \quad \sum_{wst^*} X_{wst} \leq 1; \quad \sum_{elt^*} X_{elt} \leq 1; \quad \sum_{est^*} X_{est} \leq 1 \tag{14}$$

   where * denotes a subset of the mutually exclusive actions of the set of available actions.

4. Interdependence among actions: some actions' effectiveness depends on previous implementation of other actions (short-term actions depend on long-term actions, and effectiveness of energy-related actions depend on water-related actions). To show how these interrelations have been assessed we show the calculation of a short-term water related savings given an interdependence among wlt_1 and wst_1 in equation (15):

$$W_{sav_{wst_1}} = X_{wst_1} \cdot \{ X_{wlt_1} \cdot (W_{sav_{wst_1}} | wlt_1 = 1) + (1 - X_{wlt_1}) \cdot (W_{sav_{wst_1}} | wlt_1 = 0) \} \tag{15}$$

3.5. Monte Carlo Realizations

Based on a previous work that used 10,000 Monte Carlo simulations for water, water-related energy and costs for households in 10 cities in California [*Escriva-Bou et al.*, In press] (obtained from randomly sampling the parameter probabilistic distributions for household water and water-related energy and costs), we have derived the optimal set of conservation actions for each "sampled" household. This has been done by building a model that links an Excel spreadsheet with a GAMS optimization program. The information of each household is taken from that database, obtaining water and water-related energy savings and costs of each combination of actions. Then the mixed integer nonlinear program determines the optimal solution and gets the results back into the spreadsheet for each of the 10,000 households

3.6. Elasticities

The last step was to obtain price-elasticities and cross-price elasticities for residential water and water-related energy for each household. We artificially increased water and energy marginal prices by 10% for each city and then we reran the model for the 10,000 households again. The elasticities were calculated using the common expressions:

$$\varepsilon_{ww}=\frac{dW}{dP_w}\cdot\frac{P_w}{W};\quad \varepsilon_{ee}=\frac{dE}{dP_E}\cdot\frac{P_E}{E};\quad \varepsilon_{we}=\frac{dW}{dP_E}\cdot\frac{P_E}{W};\quad \varepsilon_{ew}=\frac{dE}{dP_w}\cdot\frac{P_E}{W} \tag{16}$$

4. Results

4.1. Water and Water-Related Energy Savings

Averaged optimization model results show total water savings between 8 and 36%, averaging 19% among utilities. Most water savings are from reducing outdoor use (averaging 25%), with indoor water savings between 5 and 16% (averaging 9%). Finally, because most indoor water savings are related to energy-intensive appliances, water-related energy savings are higher, between 21 and 28% (averaging 24%) Table 2.

Results also show that actions in different cities have a similar adoption rate and average savings per household, with some particularities given previous user rates or prices: lower outdoor use in San Francisco reduces the potential adoption of outdoor actions, whereas lower electricity prices in Los Angeles decrease the attractiveness of electric water heaters as shown in Figures 6 and 7.

For water use, Figure 6 shows that outdoor actions have the largest water conservation potential, whereas toilet and shower long and short-term actions have relatively high market penetration. On the long-term side, retrofit the clothes washer presents the second largest water savings amount but with lower adoption rates, whereas the rest of the actions are almost never adopted, because of low water savings for dishwasher retrofitting and expensive investment costs for artificial turf and xeriscaping. Among the other short-term actions, finding and fixing leaks has a high water savings potential, whereas laundry and toilet frequency are among the largest impact actions (besides shower and toilet retrofits).

For energy side, shower-related actions have the highest market penetration with large energy savings, followed by clothes washer actions, and although market penetration is low because of low initial values, reduced bath frequency could save a nonnegligible amount of energy. An interesting result from the actions related with water heaters is that high efficiency electric water heaters have a large market penetration, with Los Angeles MWD being an outlier due to low electricity rates, whereas gas-fired water heater adoption rates are almost negligible. Reducing water heater temperature is an interesting action for households that set temperatures above 120°F (a 40% of them).

Figure 8 shows total water and water-related energy savings per household for each utility depending on the market penetration of conservation actions, ordering the customers from highest to lowest conservation potential. Whereas water conservation potential is highly variable due to outdoor use across utilities, water-related energy savings are quite similar among utilities and with a steep and almost linear increase below 30% of market penetration, meaning that most energy savings potential comes from a small share of households.

Table 2. Averaged outdoor and Indoor Water and Water-Related Energy Use and Conservation for Various Cities in California (BAU stands for business-as-usual)

	Total Water (L·hh/d)			Indoor Water (L·hh/d)			Energy (kWh·hh/d)		
Utility	Water Use BAU	Water Savings	% Savings	Water Use BAU	Water Savings	% Savings	Energy Use BAU	Energy Savings	% Savings
Davis	1659	206	12%	575	28	5%	9.7	2.3	24%
SCWA	1012	107	11%	588	60	10%	11.3	2.4	21%
SFPUC	708	58	8%	633	56	9%	13.5	3.2	24%
EBMUD	1092	120	11%	591	40	7%	11.7	2.8	24%
Redwood	1084	134	12%	608	37	6%	12.6	3.3	26%
Las Virgenes MWD	3131	1127	36%	772	57	7%	12.4	3.3	26%
Los Angeles DWP	1628	370	23%	607	74	12%	9.9	2.1	21%
IRWD	1638	372	23%	639	52	8%	11.9	3.0	25%
San Diego City	1181	317	27%	509	70	14%	7.5	1.9	25%
San Diego County	1787	498	28%	668	109	16%	11.8	3.3	28%

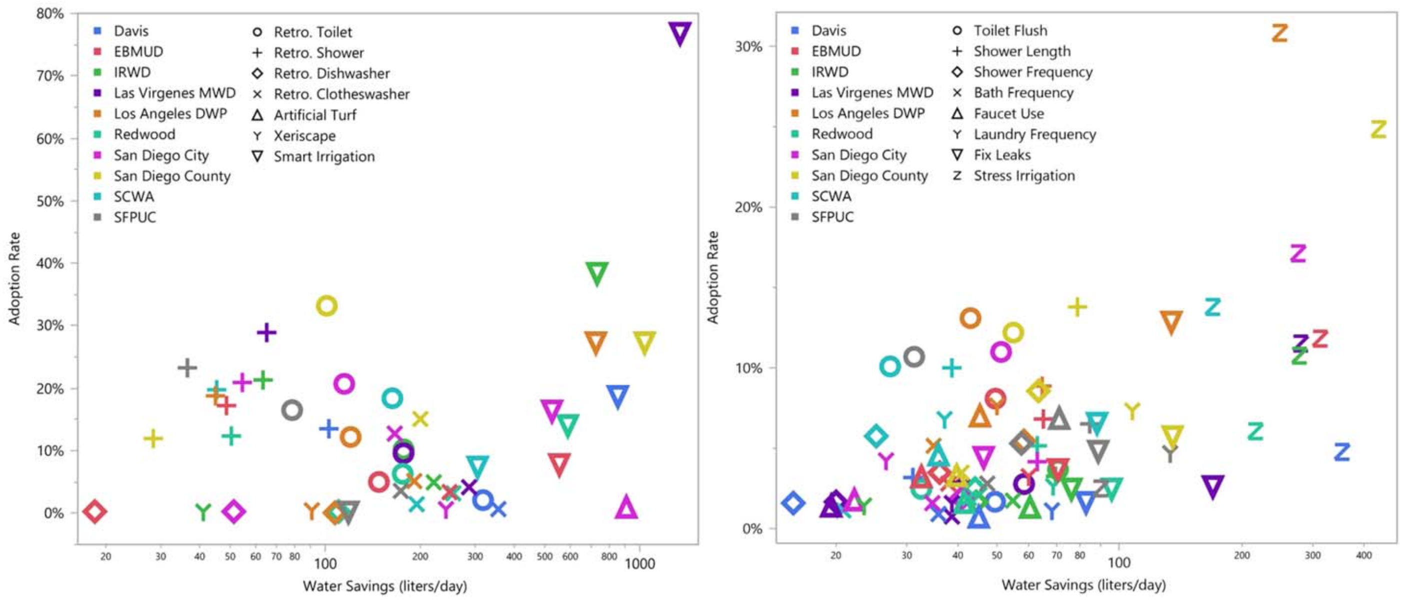

Figure 6. Optimized market penetration and average water savings for (left) long-term or technological actions and (right) short-term or behavioral actions presented in Table 1. Please, notice different *x* and *y* scales in both graphs.

4.2. Increased Willingness to Adopt Conservation Actions

We ran our model with and without considering benefits from water-related energy savings and then compared the results in Table 3. Energy intensive appliances such as shower or clothes washer, increase their adoption rates significantly, whereas cold-water appliances actions are largely unaffected.

Because large outdoor consumption in California, outdoor actions save most of the water. But if we consider only indoor use, the water and water-related energy and CO_2 emissions savings from incorporating related energy costs are huge. As shown in Table 4, indoor water savings grow by 10–44%, averaging 24%, energy savings increase between 3 and 60 %, averaging 30%, whereas water-related CO_2 emissions fall by 21–98%, averaging 53%—the huge difference between energy and CO_2 savings is because retrofitting the water heater reduces the effect of energy savings in the water-and-energy model, whereas in the CO_2 savings we

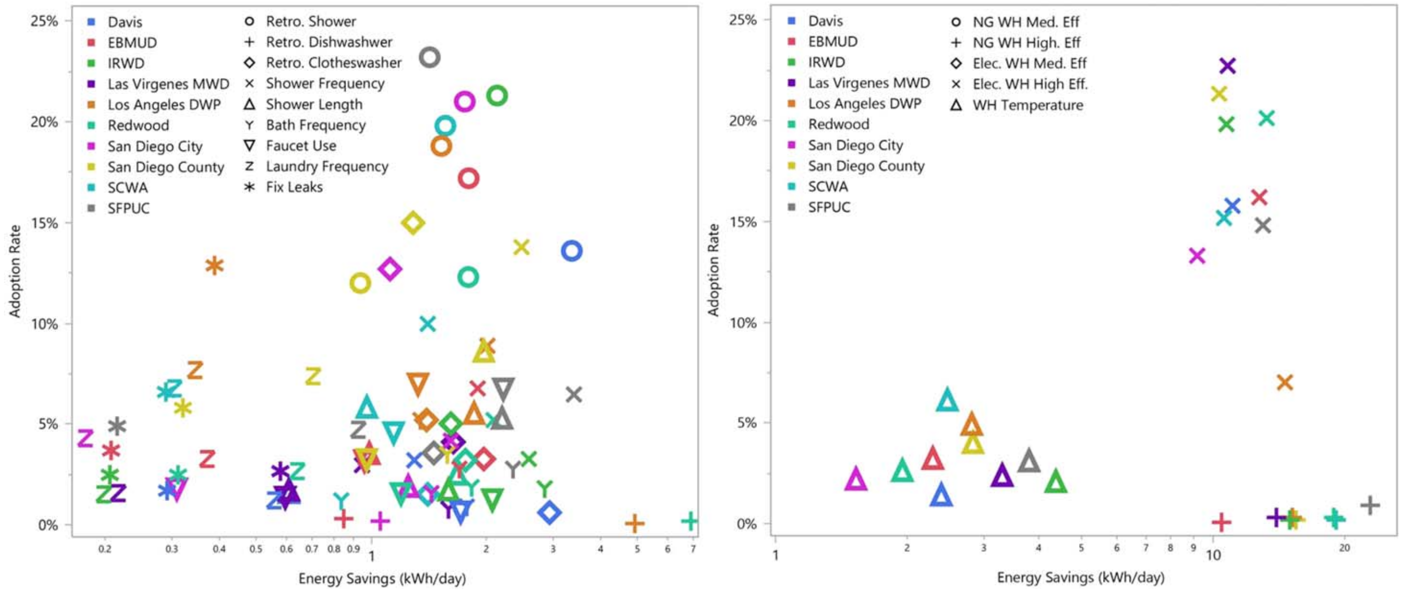

Figure 7. Market penetration and average energy savings for (left) water and (right) energy actions presented in Table 1.

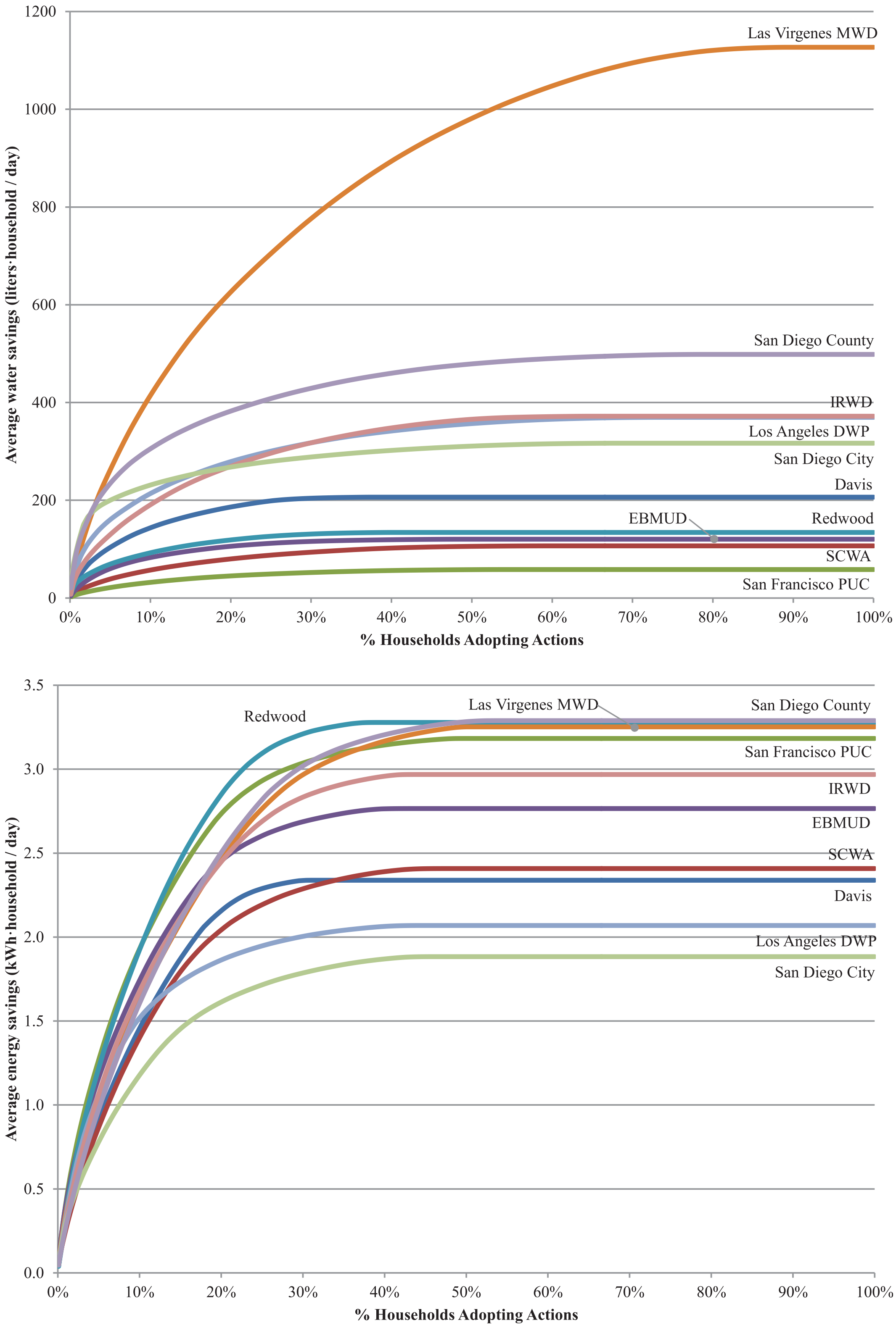

Figure 8. Total potential water (up) and water-related energy (down) conservation. *x* axis is ordered by customers from highest to lowest conservation potential.

Table 3. Increased Willingness to Adopt Conservation Actions if Embedded Energy is Considered

	Long-Term Actions							Short-Term Actions							
Utility	Retrof. Toilet	Retrof. Shower	Retrof. Dishwasher	Retrof. Clothes Washer	Artificial Turf	Xeriscape	Smart Irrigation	Toilet Frequency	Shower Lenght	Shower Frequency	Bath Frequency	Faucet Use	Laundry Frequency	Fix Leaks	Stress Irrigation
Davis	−0.2%	9.4%	0.0%	0.6%	0.0%	0.0%	0.6%	−0.2%	2.9%	1.5%	0.9%	0.5%	0.8%	0.7%	0.2%
SCWA	0.3%	10.2%	0.1%	0.8%	0.0%	0.0%	0.1%	−0.6%	6.1%	3.6%	0.6%	2.8%	1.9%	0.2%	0.5%
SFPUC	−0.4%	3.7%	0.0%	0.7%	0.0%	0.0%	0.0%	0.2%	2.1%	2.8%	1.2%	2.7%	0.9%	0.2%	−0.1%
EBMUD	−0.3%	8.3%	0.3%	1.3%	0.0%	0.0%	−0.1%	−0.2%	4.7%	2.8%	2.2%	2.6%	1.4%	0.9%	0.3%
Redwood	0.1%	7.4%	0.1%	2.0%	0.0%	0.0%	0.7%	0.1%	3.4%	1.4%	1.4%	1.1%	0.7%	0.7%	0.7%
Las Virgenes MWD	0.0%	12.5%	0.0%	2.3%	0.0%	0.0%	−0.1%	0.1%	1.9%	1.2%	0.7%	1.2%	0.8%	0.3%	−0.5%
Los Angeles DWP	−0.1%	6.0%	0.1%	1.7%	0.0%	0.0%	−0.1%	0.3%	3.8%	1.8%	2.8%	2.9%	1.0%	1.3%	0.2%
IRWD	−0.3%	11.6%	0.0%	1.7%	0.0%	0.0%	0.0%	−0.1%	2.4%	1.5%	1.7%	1.1%	1.0%	1.0%	0.8%
San Diego City	−0.1%	4.3%	0.1%	3.9%	0.1%	−0.1%	0.0%	−0.1%	2.1%	0.7%	0.9%	1.4%	1.7%	0.6%	0.9%
San Diego County	−0.3%	4.7%	0.0%	2.5%	0.0%	0.1%	−0.3%	−0.1%	6.8%	4.4%	2.5%	1.8%	1.8%	0.5%	−0.2%
Median	−0.2%	7.9%	0.1%	1.7%	0.0%	0.0%	0.0%	−0.1%	3.2%	1.7%	1.3%	1.6%	1.0%	0.7%	0.3%

assessed only the difference of hot water used without including water heater effects. Households manage conservation differently if embedded energy is included; conservation actions affecting the most energy intensive actions increase the benefits for the same amount of financial or hassle costs.

4.3. Elasticities and Demand Function

If water and energy use reductions from the set of optimal actions are very significant, as shown above, the short-term behavioral savings represented by price- and cross-price elasticities are very low, as shown in Table 5. The water price elasticities vary from −0.03 to −0.09, averaging −0.05; the energy price elasticities vary from −0.01 to −0.04, averaging −0.03. The effect of water price on energy use is merely significant (3^{rd} column), whereas the energy price effect on water use is negligible (4^{th} column). Despite low values, the negativity of the cross-price elasticities obtained confirm the assumption of economic complementarity between water and water-related energy, with energy prices affecting water use more than water price effects on energy use.

Another result from the model is the water demand function for each water utility given increases of 10 and 20% in marginal price. As expected from the results of the elasticities shown above, the water demand hardly decreases as marginal price increases (Figure 9).

5. Discussion

The two-stage optimization model is a basic cost-minimizing problem that might be seen as myopic from an economic point of view because it is not looking for income and substitution effects that arise from the water and energy cost savings and that could affect consumption of water, energy and other goods. But our focus is to increase the information available to select the most efficient CAC actions including the embedded energy of water appliances trying to reduce the efficiency gap, at the same time that we are modeling the economic behavior of people allowing reaction to short run prices changes.

Table 4. Optimized Increased Indoor Water and Water-Related Energy Use and CO_2 Emissions Reductions if Embedded Energy is Considered for 10 California utilities

	Water Reduction (L·hh/d)			Energy Reduction (kWh·hh/d)			CO_2 Emissions Reduction (kg·hh/d)		
Utility	Only Water	Water+Energy	% Increase	Only Water	Water+Energy	% Increase	Only Water	Water+Energy	% Increase
Davis	19.42	27.70	43%	0.41	0.57	37%	27.80	45.42	63%
SCWA	50.10	60.22	20%	0.41	0.63	52%	28.44	49.21	73%
SFPUC	49.89	56.27	13%	0.88	0.99	12%	60.53	76.53	26%
EBMUD	28.76	40.36	40%	0.40	0.64	60%	27.08	53.58	98%
Redwood	25.41	36.52	44%	0.33	0.52	56%	22.28	42.22	89%
Las Virgenes MWD	47.08	56.53	20%	0.66	0.72	9%	45.97	59.57	30%
Los Angeles DWP	66.80	73.80	10%	0.78	0.88	14%	56.01	71.30	27%
IRWD	41.29	52.23	27%	0.51	0.73	45%	34.90	57.73	65%
San Diego City	62.80	69.59	11%	0.63	0.65	3%	43.57	52.60	21%
San Diego County	97.35	108.64	12%	0.83	0.97	18%	55.68	78.32	41%

Table 5. Water and Energy Own and Cross-Price Elasticities

Utility	ε_{WW}	ε_{EE}	ε_{WE}	ε_{EW}
Davis	−0.04	−0.01	−0.01	−0.001
SCWA	−0.08	−0.03	−0.04	−0.01
SFPUC	−0.04	−0.04	−0.03	−0.01
EBMUD	−0.09	−0.03	−0.03	−0.01
Redwood	−0.06	−0.03	−0.04	−0.01
Las Virgenes MWD	−0.04	−0.01	−0.01	−0.001
Los Angeles DWP	−0.04	−0.03	−0.03	−0.003
IRWD	−0.05	−0.03	−0.02	−0.003
San Diego City	−0.06	−0.01	−0.02	−0.002
San Diego County	−0.03	−0.04	−0.03	−0.01

As mentioned before, this research assumes adequate information (and foresight) of water and water-related energy prices and costs of actions for household dwellers. Given that we are not trying to capture the real customer behavior, but rather the economic potential of conservation campaigns given variability of local conditions.

Nevertheless, a difference exists between long-term and short-term actions' assessment and costs: whereas long-term actions assessments are based on real data from a water end use survey [*DeOreo et al.*, 2011] and the costs were obtained from the literature, short-term actions' savings are obtained based in physical and behavioral relations with engineered-based assumptions, but without empirical data to test this assumption, alike the costs that have been assigned to these actions. Therefore, results on market penetration for long-term actions are more reliable than results obtained for the short-term actions.

More research and monitoring of short-term behavioral modifications on water and energy consumption could extend the current research to understand the factors that affect demand and how it could be managed more economically for customers and utilities.

The price elasticity of water use are much lower than those in the literature [*Dalhuisen et al.*, 2003; *Espey et al.*, 1997] and that is directly related with assumptions made on the behavioral savings and costs, and probably because of the limited number of conservation actions accounted. Therefore, these results cannot be directly taken as actual measures of price elasticities; thus, the method presented has to be further implemented, primarily obtaining and using empirical data, to improve the accuracy of the results. As aforementioned water and energy cross-price elasticities have been barely studied (see *Hansen* [1996]) probably

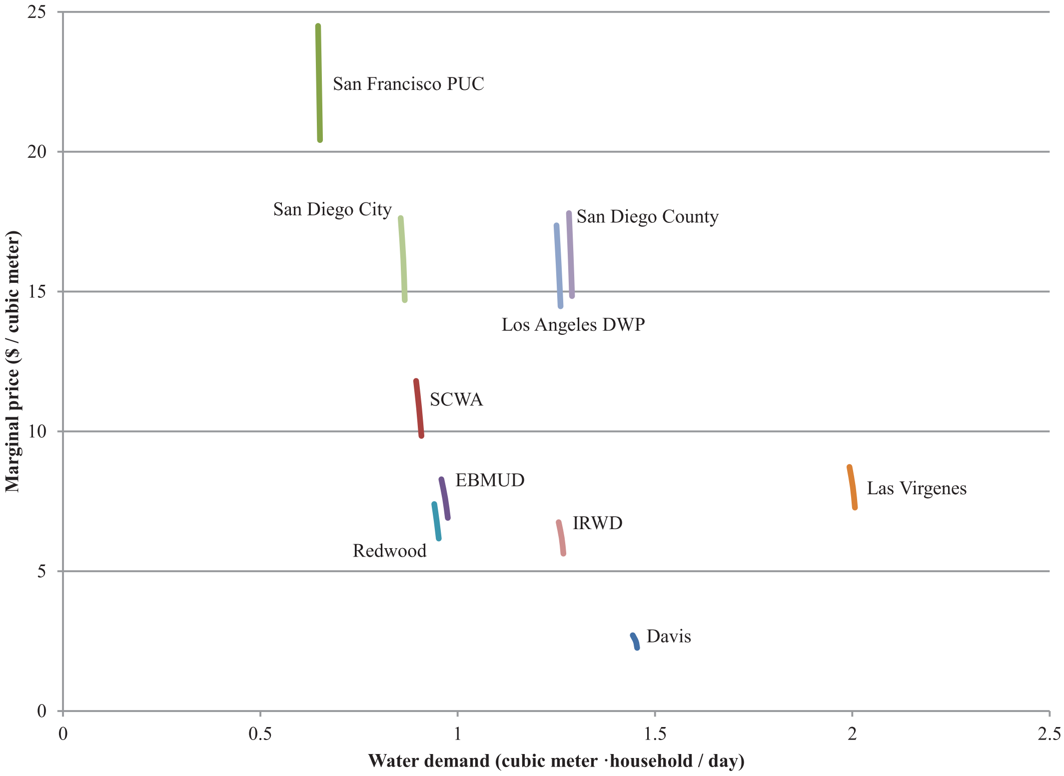

Figure 9. Average demand function given marginal water price increase for each utility.

because the lack of good data, but probably also because if customers do not have enough information to understand this interaction is almost impossible to them to react to cross price fluctuations. Increasing the availability of data and improving information for customers can result in a new understanding of the issue to reduce water and energy use.

6. Conclusions

A stochastic optimization model with recourse provides the minimum expected annual cost accounting for long and short-term conservation actions and stochastic variability in water and energy prices and availability. This paper demonstrates the increased willingness to adopt conservation actions and savings, and changes in the set of actions selected if energy costs are included in the water customers' objective function. The total increase in water savings is small (3%), reflecting large outdoor use in California, but is significant for indoor water use, increasing indoor water savings by 24%, water-related energy savings by 30% and water-related GHG emissions savings by 53% on average.

The results of the optimization model show that some outdoor conservation actions (smart irrigation and stress plants) have the highest potential for water conservation, because of the high economic benefits from large reductions in water use with small investments, whereas other outdoor actions, such as artificial turf or xeriscaping, are usually too costly to obtain benefits with the current water prices. Among the indoor actions, toilet and shower actions have the highest market penetrations: toilets, because of water savings, and showers, because of energy savings.

The long-term saving estimation is based on empirical data, but the short-term savings and costs have been derived from a less detailed economic-engineering model assuming that previous patterns of consumption, household income and environmental consciousness affect largely the adoption of conservation actions because of behavioral changes. Therefore, although both results have been obtained with a unique optimization model, long-term results should be more reliable than short-term results. The development of this model might be extended theoretically including more variables and calibrated with empirical data as water end use monitoring grows, obtaining additional insights from users' behavior and helping to better understand consumer utility functions.

The cost-minimizing function posed using the stochastic variability in water and energy prices allows identification of the most beneficial long-term investments from the customers point of view, and the second stage allows users to change their behavior with changes in prices and availability, providing a new approach to model customer behavior. This method also allows assessment of water and water-related price and cross-price elasticities, confirming the assumption that water and water-related energy are complementary goods.

Trying to reduce the efficiency gap, sometimes blamed for excessive optimism by residential command and control conservation promoters, we link traditional engineering conservation and economic modeling. The results show potential savings from residential retrofits, and how budget constraints and consumer behavior limit the conservation potential. We also have included the energy consumption of water use, which has the potential to significantly increase indoor water conservation and reduce GHG emissions because of the change in the optimal set of conservation actions for California households.

Acknowledgments
This paper has been developed as a result of a mobility stay funded by the Erasmus Mundus Programme of the European Commission under the Transatlantic Partnership for Excellence in Engineering—TEE Project. Water end-use data were kindly provided by Aquacraft Inc. who are able to release the data under private agreements and to whom we are very grateful.

References

Abdallah, A., and D. Rosenberg (2014), Heterogeneous residential water and energy linkages and implications for conservation and management, *J. Water Resour. Plann. Manage.*, *140*(3), 288–297.

Alcubilla, R. G., and J. R. Lund (2006), Derived willingness-to-pay for household water use with price and probabilistic supply, *J. Water Resour. Plann. Manage.*, *132*(6), 424–433.

Arbués, F., M. a. Á. García-Valiñas, and R. Martínez-Espiñeira (2003), Estimation of residential water demand: A state-of-the-art review, *J. Socio-Econ.*, *32*(1), 81–102.

Beal, C. D., E. Bertone, and R. A. Stewart (2012), Evaluating the energy and carbon reductions resulting from resource-efficient household stock, *Energy Buildings*, *55*, 422–432.

Cahill, R., J. R. Lund, B. DeOreo, and J. Medellin-Azuara (2013), Household water use and conservation models using Monte Carlo techniques, *Hydrol. Earth Syst. Sci.*, *17*(10), 3957–3967.

Dalhuisen, J. M., R. J. G. M. Florax, H. L. F. de Groot, and P. Nijkamp (2003), Price and income elasticities of residential water demand: A meta-analysis, *Land Econ.*, *79*(2), 292–308.

DeOreo, W. B., P. W. Mayer, L. Martien, M. Hayden, A. Funk, M. Kramer-Duffield, and R. Davis (2011), California single-family water use efficiency study, report, Aquacraft Inc. Water Eng. and Manage, Boulder, Colo.

Dolnicar, S., and A. Hurlimann (2010), Australians' Water Conservation Behaviours and Attitudes [online], *Aust. J. Water Resour.*, *14*(1), 43–53. [Available at http://search.informit.com.au/documentSummary;dn=242006012315522;res=IELENG.]

EBMUD (2011), *Urban Water Management Plan 2010*, Water Resour. Plann. Div. [Available at https://ebmud.com/water-and-wastewater/water-supply/urban-water-management-plan, last accessed 12 Feb 2015.]

Escriva-Bou, A., J. R. Lund, and M. Pulido-Velazquez (2015), Modeling residential water and related energy, carbon footprint and costs in California, *Environ. Sci. Policy*, *50*, 270–281, doi:10.1016/j.envsci.2015.03.005.

Espey, M., J. Espey, and W. D. Shaw (1997), Price elasticity of residential demand for water: A meta-analysis, *Water Resour. Res.*, *33*(6), 1369–1374.

Fidar, A., F. A. Memon, and D. Butler (2010), Environmental implications of water efficient microcomponents in residential buildings, *Sci. Total Environ.*, *408*(23), 5828–5835.

Gilg, A., and S. Barr (2006), Behavioural attitudes towards water saving? Evidence from a study of environmental actions, *Ecol. Econ.*, *57*(3), 400–414.

Gregory, G. D., and M. Di Leo (2003), Repeated behavior and environmental psychology: The role of personal involvement and habit formation in explaining water consumption, *J. Appl. Soc. Psychol.*, *33*(6), 1261–1296.

Hansen, L. G. (1996), Water and energy price impacts on residential water demand in Copenhagen, *Land Econ.*, *72*(1), 66–79.

Jaffe, A. B., and R. N. Stavins (1994), The energy-efficiency gap—What does it mean, *Energy Policy*, *22*(10), 804–810.

Kenway, S. J., R. Scheidegger, T. A. Larsen, P. Lant, and H. P. Bader (2013), Water-related energy in households: A model designed to understand the current state and simulate possible measures, *Energy Buildings*, *58*, 378–389.

LADWP (2010), *Urban Water Management Plan*, Los Angeles, Calif. [Available at http://www.water.ca.gov/urbanwatermanagement/2010uwmps/Los%20Angeles%20Department%20of%20Water%20and%20Power/LADWP%20UWMP_2010_LowRes.pdf.]

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

Lutz, J., C. D. Whitehead, A. Lekov, D. Winiarski, and G. Rosenquist (1998), WHAM: A simplified energy consumption equation for water heaters (3AD), in *Proceedings of the American Council for and Energy-Efficient Economy (ACEEE) 1998 Summer Study on Energy Efficiency in Buildings*, vol. 1, ACEEE, Washington, D. C. [Available at http://aceee.org/files/proceedings/1998/data/papers/0114.PDF.]

Mayer, P. W., B. deOreo, E. Towler, and D. M. Lewis (2003), Residential indoor water conservation study: Evaluation of high efficiency indoor plumbing fixture retrofits in single-family homes in the East Bay Municipal Utility District service area, report, East Bay Munic. Utility Dist., Boulder, Colo.

Morales, M. A., J. P. Heaney, K. R. Friedman, and J. M. Martin (2013), Parcel-level model of water and energy end use: Effects of indoor water conservation, *J Am Water Works Assoc.*, *105*(9), 83–84.

Nicholson, W., and C. Snyder (2012), *Microeconomic Theory: Basic Principles and Extensions*, vol. xxi, 11th ed., 758 pp., South-Western/Cengage Learning, Mason, Ohio.

Olmstead, S. M., and R. N. Stavins (2009), Comparing price and nonprice approaches to urban water conservation, *Water Resour. Res.*, *45*, W04301, doi:10.1029/2008WR007227.

Pint, E. M. (1999), Household responses to increased water rates during the California drought, *Land Econ.*, *75*(2), 246–266.

Reed, R. U., and J. R. Lund (1990), Transferable rations for drought management, *Optim. Resour. Water Manage.*, *726-730*.

Renwick, M. E., and S. O. Archibald (1998), Demand side management policies for residential water use: Who bears the conservation burden?, *Land Econ.*, *74*(3), 343–359.

Renwick, M. E., and R. D. Green (2000), Do residential water demand side management policies measure up? An analysis of eight California water agencies, *J. Environ. Econ. Manage.*, *40*(1), 37–55.

Rosenberg, D. E., T. Tarawneh, R. Abdel-Khaleq, and J. R. Lund (2007), Modeling integrated water user decisions in intermittent supply systems, *Water Resour. Res.*, *43*, W07425, doi:10.1029/2006WR005340.

Rothausen, S. G. S. A., and D. Conway (2011), Greenhouse-gas emissions from energy use in the water sector, *Nat. Clim. Change*, *1*(4), 210–219.

USDOE (2009), *Energy Efficiency Standards for Pool Heaters, Direct Heating Equipment And Water Heaters (EE-2006-STD-0129)*, Energy Efficiency and Renewable Energy Off. [Available at http://www.regulations.gov/#!documentDetail;D=EERE-2006-STD-0129–0170, last accessed 14 Apr 2014.]

USEIA (2009), *Residential Energy Consumption Survey 2009*. [Available at http://www.eia.gov/consumption/residential/index.cfm, last accessed 14 Apr 2014.]

USEIA (2015), *California Price of Natural Gas Delivered to Residential Customers*. [Available at http://www.eia.gov/dnav/ng/hist/n3010ca3M.htm, last accessed 20 Mar 2015.]

USEPA (2015), *Energy Star*. [Available at http://www.energystar.gov/, last accessed 23 Mar 2015.]

Valinas, M. D. A. G. (2006), Analysing rationing policies: Drought and its effects on urban users' welfare (Analysing rationing policies during drought), *Appl. Econ.*, *38*(8), 955–965.

Willis, R. M., R. A. Stewart, K. Panuwatwanich, P. R. Williams, and A. L. Hollingsworth (2011), Quantifying the influence of environmental and water conservation attitudes on household end use water consumption, *J Environ. Manage.*, *92*(8), 1996–2009.