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Key Points:
- We assess energy and carbon dioxide emissions related to the urban water cycle
- We analyze the consequences of water demand management policies on energy and carbon dioxide emissions
- Some demand management policies show significant economic impacts for water and energy utilities

Supporting Information:
- Supporting Information S1

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Saving Energy From Urban Water Demand Management

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Abstract Water use directly causes a significant amount of energy use in cities. In this paper we assessed energy and carbon dioxide emissions related to each part of the urban water cycle and the consequences of some water demand management policies in terms of water, energy, and CO_2 emissions in urban water users, water and energy utilities, and the environment. First, we developed an hourly model of urban water uses by customer category, including water-related energy consumption. Next, using real data from the East Bay Municipal Utility District in California, we calibrated a model of the energy used in water supply, treatment, pumping, and wastewater treatment by the utility, obtaining also energy costs. Then, using data from the California Independent System Operator, we obtained hourly costs of energy generation and transport to the point of use for the energy utility. Finally, using average emission factors reported by energy utilities, we estimated greenhouse gas emissions for the entire urban water cycle. Results for East Bay Municipal Utility District show that water end uses account for almost 95% of all water-related energy use; however, the remaining 5% of energy used by the utility still costs over USD12 million annually. The carbon footprint of the urban water cycle is 372 kg CO_2/person/year, representing approximately 4% of the total per capita emissions in California. Several simulations analyze the consequences of different water demand management policies, resulting in significant economic impacts for water and energy utilities and environmental benefits by reducing CO_2 emissions.

1. Introduction

Mature water economies are characterized by sharply rising incremental costs of water supply, more direct and intense competition among different kinds of users, and greatly increased interdependencies among water uses (Randall, 1981). Similarly, electric utilities started to perceive potential long-term shortages in energy supply in the 1970s (Loughran & Kulick, 2004). These increased economic and physical difficulties to obtain new supplies of water and energy turned managers and policymakers to focus on demand management strategies. Traditionally, water and energy resources have been managed separately, but a growing body of scientific literature is showing the multiple linkages between water and energy. Although many papers have described and assessed these relations, there is a gap on how managing water demands can save energy and reduce greenhouse gas (GHG) emissions providing benefits for both water and energy utilities, providing also public benefits.

Generally speaking, water-related energy use can be classified into two categories: the energy used by water infrastructure (water supply and conveyance, treatment, distribution, wastewater collection, treatment and discharge, and recycled water treatment and distribution) and the energy used by the end uses of water (agricultural, residential, commercial, and industrial water pumping, heating, cooling, evaporation, softening, removal, treatment, and other energy used directly in water processes; California Energy Commission (CEC), 2005).

Large-scale water-energy-GHG emission assessments have been conducted in recent years at the regional, national, and even at a supranational level. In the United States the energy use in the residential, commercial, industrial, and power sectors for direct water and steam services was approximately 12.6% of the 2010 annual primary energy consumption (Sanders & Webber, 2012). In California, the assessment of the relationship reported larger figures: up to 20% of electricity use and 30% of natural gas are related with water uses (CEC, 2005). The previous figures included both the energy used in water infrastructure and energy used for end uses of water. Without accounting for the energy used in end uses of water, Hardy et al. (2012) obtained that in Spain approximately 5.8% of total electricity demand is due to the water sector, whereas Reffold et al. (2008) estimated that 5.5% of GHG emissions in the UK are from urban water use. Although these results have highlighted the importance of analyzing the water-energy nexus, these studies do not provide clear strategies for decision makers to reduce water-related energy and GHG emissions.

More detailed urban water-energy studies have focused either on water utilities—that is, supply, treatment, conveyance, wastewater collection, and treatment—or on residential water use. Some studies have focused on the development of a representative range of energy intensities (energy consumption by unit of water use) by identifying patterns in the amount and timing of energy used by water and wastewater agencies across agencies (California Public Utilities Commission, 2010) or analyzing the geographical and seasonal variability within an agency service area (Spang & Loge, 2015). It is also crucial to evaluate the impact of current and various future water supply portfolios on energy demand, GHG emissions, and costs while considering the current and future regional energy grid mix (Mo et al., 2014). On the residential side, some studies have quantified the energy consumption and carbon emissions of household water uses analyzing the effects of water conservation options (Abdallah & Rosenberg, 2014; Fidar et al., 2010; Kenway et al., 2013).

Although end uses of water consume most of the energy in the water cycle, they are not usually considered in water and energy management and policy (Rothausen & Conway, 2011). The energy consumption of these end uses of water, along with the energy used by water supply infrastructures to meet these water demands, contributes to daily energy peaks. Therefore, there are opportunities for collaboration among water customers, water utilities, and energy utilities to reduce energy peaks, saving money and improving the efficiency of the electricity market. Furthermore, reducing water peaks can deliver substantial savings in infrastructure capacity and operations (Cole et al., 2012). As far as we know there are no previous studies that have analyzed water and water-related energy use at an hourly time step, capable of estimating the potential benefits of changes in intradaily water use patterns for both water and energy utilities.

The objective of this study is to model urban water and water-related energy uses at an intradaily scale from available data in the East Bay Municipal Utility District (EBMUD), a utility that provides water services to over 1.3 million people in the San Francisco Bay, California. We couple end uses of water and their water-related energy with energy consumption from water supply, treatment, and wastewater infrastructure to develop a model with an hourly time step. Our model can assess total water-related energy use and CO_2 emissions from each element of the urban water cycle and analyze how changes in water use patterns affect water and energy utilities. By generating different scenarios, we also estimate the potential benefits for water and energy utilities from conservation and demand-response policies applied to water use.

2. Methods

We developed a model that uses an hourly time scale to analyze (1) urban water uses and (2) energy use in urban water end uses. Once calibrated, the model is used to run sensitivity analyses focused on the impact of various water-demand management policies. We use EBMUD data to calibrate our model and show how residential conservation strategies and demand response interventions can decrease water and energy demands and carbon dioxide emissions. Figure 1 shows a flow diagram of the methods indicating the main steps described in detail below.

As an example, we apply the methodology to a case study in EBMUD (California). This utility serves approximately 1.34 million, based on 2010 census data, within a 860 squared kilometers area including the major cities of Oakland, Berkeley, Walnut Creek, and San Ramon. About 90% of the water delivered to EBMUD customers comes from the Mokelumne River watershed. From Pardee Reservoir, the Mokelumne Aqueducts convey water across the Sacramento-San Joaquin River Delta to local storage and treatment facilities. EBMUD has six water treatment plants and one wastewater treatment plant (EBMUD, 2011).

Because of the size of the service area, we selected a subset of the EBMUD network that accounts for roughly 27% of the total water serviced (which would represent roughly 355,000 inhabitants assuming similar per capita use throughout the service area) and that can be assessed independently. The area under study included part of Alamo city and the cities of Danville and San Ramon. The water from the Mokelumne Aqueducts is treated in two water treatment plants—Lafayette and Walnut Creek—and pumped through many different pumping plants to ensure adequate pressure until the water is used. Wastewater is then collected and treated. EBMUD provided a complete data set of water flows and water-related energy use for each of the main elements of the urban water cycle for the years of 2009 and 2010. Although the

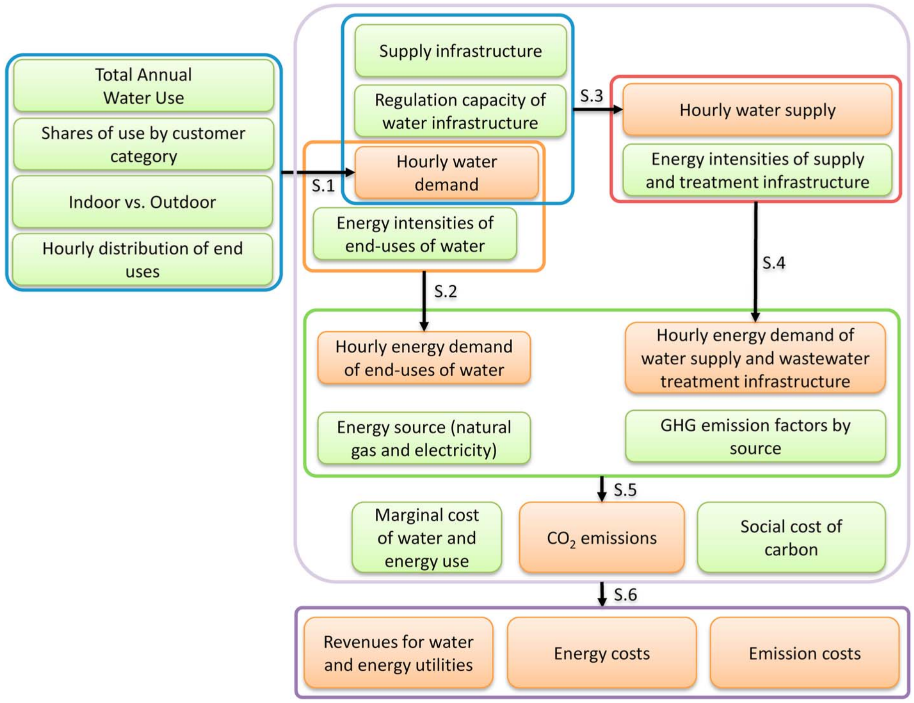

Figure 1. Flow diagram of the modeling procedure. The arrows with numbers represent the main steps followed. Green boxes represent input data, and orange boxes represent results from the model.

wastewater of this area is treated by the Central Contra Costa Sanitary District Office, we assume that the energy intensity of the wastewater treatment is similar to the data that we have from EBMUD's wastewater treatment plant. A schematic of the case study is provided in the supporting information.

2.1. Step 1: Hourly Water Demands

The objective of this section is to obtain hourly water demands. If these hourly demands are obtained by customer category—residential, institutional, commercial, industrial, and irrigation—and including the share of indoor versus outdoor uses, the assessment of water-related energy use that we show in the next step will be more accurate.

In the presence of hourly data per customer category and the share of indoor and outdoor uses, this step would be straightforward. But these data were not available in our case, as it happens with most water utilities currently, so there is a need for intermediate calculations.

The first step is to obtain daily water use and indoor versus outdoor consumption. Annual indoor and outdoor shares are obtained from the Urban Water Management Plan (EBMUD, 2011), and daily data of water supply from the water treatment plant are also available, where we can see a sharp seasonality. We assume that indoor water use is fixed throughout the year and the seasonality is driven by outdoor uses. The calculation of the daily demands by indoor versus outdoor use is obtained using the following expressions:

$$w_{\text{supply wtp},i} = w_{i_{\text{indoor}}} + w_{i_{\text{outdoor}}} \tag{1}$$

$$w_{i_{\text{indoor}}} = \min\left(\frac{\%_{\text{indoor\_total}} \cdot \sum_{i=1}^{365} w_{\text{supply wtp},i}}{365}, w_{\text{supply wtp},i}\right) \tag{2}$$

$$w_{i_{\text{outdoor}}} = w_{\text{supply wtp},i} - w_{i_{\text{indoor}}} \tag{3}$$

where for each day i, $w_{\text{supply wtp}}$ is the water supplied from the water treatment plant (s), w_{indoor} is the water used for indoor purposes, w_{outdoor} is the water used for outdoor purposes, and $\%_{\text{indoor\_total}}$ is the share of annual water used for indoor purposes.

Once we have daily water demands by indoor versus outdoor use, we allocate these demands by customer category using the shares included in the Urban Water Management Plan (UWMP), and finally we obtain hourly use for each category assigning hourly percentages based on data from Funk and deOreo (2011).

$$w_{i,j,k_{\text{indoor}}} = \%_k \cdot \%_{j_k} \cdot w_{i_{\text{indoor}}} \forall i, j, k \tag{4}$$

$$w_{i,j,k_{\text{outdoor}}} = \%_k \cdot \%_{j_k} \cdot w_{i_{\text{outdoor}}} \forall i, j, k \tag{5}$$

where for each day i, each hour j, and each customer category k, $\%_k$ is the share of water use by customer category with respect to the total water use, and $\%_{jk}$ is the hourly share for the category k.

For the indoor residential uses, we further broke them down by water appliances—toilet, shower, bath, faucet, dishwasher, clothes washer, and leaks/other uses—which allowed us later to obtain the benefits for water and energy utilities of residential demand-response by simulating changes in water use patterns.

The data used in this section and some graphic analysis are provided in the supporting information.

2.2. Step 2: Hourly Energy Demand of End Uses of Water

Water-related energy use for end uses is obtained from different sources. In all cases we rely on *energy intensity* factors—amount of energy consumed per unit of water use—obtained from the literature. Residential water-related energy is obtained from Escriva-Bou et al. (2015a) accounting for the different energy intensities of each residential water end use. Energy intensity of commercial and institutional uses were obtained from CEC (2005). Finally, because of the lack of data from other data sources, we assumed that 1% of institutional water use is used in faucets within public buildings. As the energy use from outdoor water end uses is almost negligible compared to the indoor water end uses, energy use is obtained multiplying the energy intensity factors by indoor water use, as follows:

$$e_{i,j,k} = e\_\text{int}_k \cdot w_{i,j,k_{\text{indoor}}} \forall i, j, k \tag{6}$$

where $e_{i,j,k}$ is the hourly energy demand, and e_int_k is the energy intensity of the end use k. Detailed information of the energy intensities for end uses is provided in the supporting information.

2.3. Step 3: Hourly Water Supply

Although water demands have a continuous variation over time, the water treatment, distribution, and wastewater collection and distribution can be accommodated to work when energy costs are lower depending on the regulation capacity of the system. For instance, a water utility can have reservoirs located in the higher parts of a city where water is pumped during off-peak hours and released during peak hours. As a result, water regulation capacity makes possible to separate the timing between water demands and supplies.

Metered data at EBMUD show this capacity of regulation: utility managers operate the system minimizing energy costs at peak hours. This is especially noticeable during summer peak hours, when the greatest differences between peak and off-peak energy prices exist. Figure 2 shows how pump flow is almost 0 during *on-peak hours* and minimized in *partial-peak hours*. To meet higher daytime demand, operators overpressurize the network before starting partial-peak hours, and they do it again before starting on-peak hours if needed.

As we lack hourly water use data, we modeled that pattern by matching our hourly estimated demand with actual hourly supply from pumping plants, and we obtained the share of total daily demand supplied on peak and off-peak hours as follows:

$$\%\text{pump}_{\text{partial\_peak,summer}} = \frac{1}{n} \cdot \sum_i \frac{w_{\text{pump}_{i,\text{partial\_peak,summer}}}}{w_{\text{pump}_{i,\text{total,summer}}}} \approx 35\% \tag{7}$$

$$\%\text{pump}_{\text{off\_peak,summer}} = \frac{1}{n} \cdot \sum_i \frac{w_{\text{pump}_{i,\text{off\_peak,summer}}}}{w_{\text{pump}_{i,\text{total,summer}}}} \approx 65\% \tag{8}$$

$$\%\text{pump}_{\text{peak,winter}} = \frac{1}{n} \cdot \sum_i \frac{w_{\text{pump}_{i,\text{peak,winter}}}}{w_{\text{pump}_{i,\text{total,winter}}}} \approx 45\% \tag{9}$$

$$\%\text{pump}_{\text{off\_peak,winter}} = \frac{1}{n} \cdot \sum_i \frac{w_{\text{pump}_{i,\text{off\_peak,winter}}}}{w_{\text{pump}_{i,\text{total,winter}}}} \approx 55\% \tag{10}$$

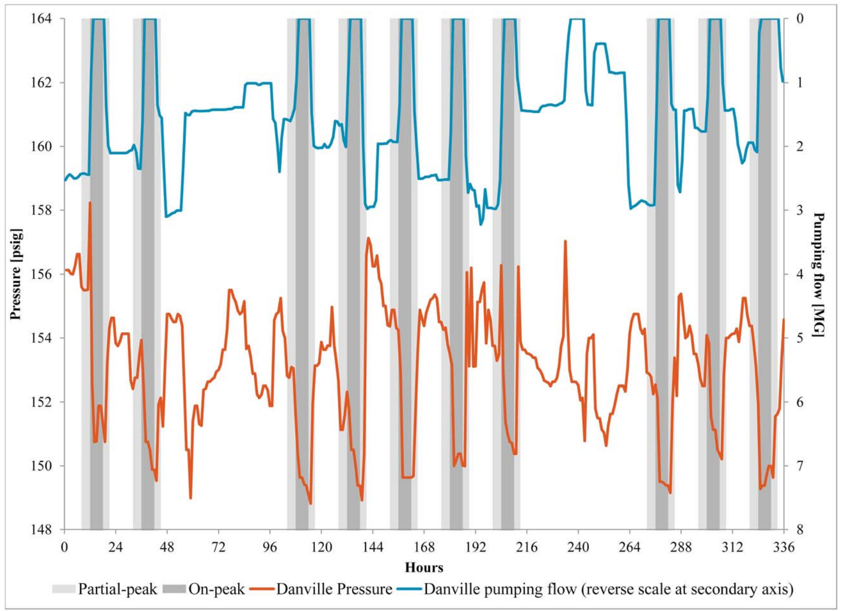

Figure 2. Pressure, pumping flow, and time-of-use hours at Danville pumping station (1 to 14 July 2010). Note that the pumping flow is in the secondary axis using a reverse scale.

where $\%pump_l$ is the share of daily water pumped for the energy price period *l*, and *n* is the total number of days for the season (summer or winter). From there, we obtain hourly water supply from pumps by

$$w_{pump_{i,j}} = \frac{\%pump_l}{{n_l}/{24}} \cdot w_{i,j} \forall i, j \tag{11}$$

where $w_{pump\ i,j}$ is the total water pumped for the day *i* and the hour *j*, n_l is the number of hours per day where the energy price period *l* is applied, and $w_{i,j}$ is the total hourly water demand downstream of the pump. More details are provided in the supporting information.

We found no evidence in the data that there were capacity regulations on the water treatment plants, and we only have monthly data for the wastewater treatment plants, so we assume that their hourly variation follows the same distribution that the water demands. It is also important to notice that in this study we did not include reservoir regulation or water supply from groundwater pumping or pumping from external sources. This is because we are assuming that water is conveyed by gravity to the service area. The method presented would work with other type of supply elements.

2.4. Step 4: Hourly Energy Demand of Water Supply and Treatment

At the urban scale, water-related energy use of the water utility is determined by the energy used to treat water in water treatment plants, distribute pressurized water using pumping plants, and convey and treat sewage in wastewater treatment plants.

The energy intensity can be obtained by fitting linear regressions of the energy consumption as a function of water treated or pumped in the supply infrastructure. Figure 3 shows that the linear models fit well with the relationship of water supply and water-related energy for the infrastructure considered.

Then, the energy used in the water supply infrastructure ($e_{i,j,m}$) can be calculated as follows:

$$e_{i,j,m} = e\_int_m \cdot w_{i,j,m} \forall i, j, k \tag{12}$$

where e_int_m is the energy intensity obtained for the element *m* of the water supply infrastructure from the linear regressions, and $w_{i,j,m}$ is the water treated/pumped in the day *i*, hour *j*, and element *m*.

2.5. Step 5: CO_2 Emissions

To account for CO_2 emissions, we first obtained the source of energy for each water-related energy use. Following data from the Residential Energy Consumption Survey (U.S. Energy Information Administration,

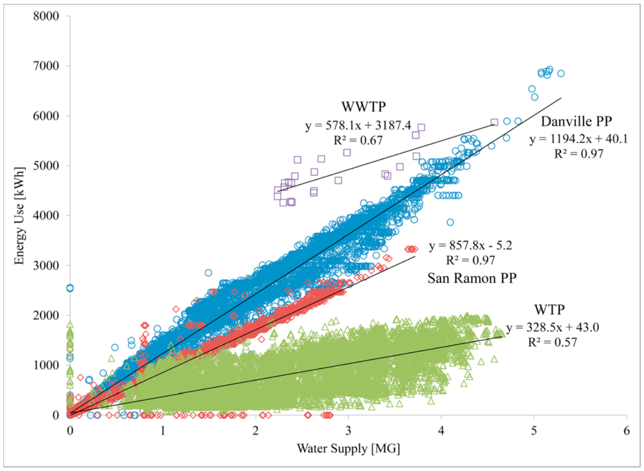

Figure 3. Linear fitting of water-related energy supply infrastructure. WTP stands for water treatment plant; PP for pumping plant; and WWTP means wastewater treatment plant.

2009), 91% of California households use natural gas water heaters, whereas the remaining 9% use electric water heaters. We assumed that the remaining water-related energy uses and energy for the water utility are supplied by the electricity grid.

Knowing the energy source and use, emission factors are used to calculate CO_2 emissions. According to the California Registry Power/Utility Workgroup, PG&E (the electricity supplier) emits 0.24 kg CO_2/kWh of electricity served (California Registry Power/Utility Workgroup, 2009). For natural gas, because roughly 85% of natural gas used in California is imported, we used the weighted national average of 5.31 kg CO_2/therm or 0.18 kg CO_2/kWh (U.S. Energy Information Administration, 2011).

2.6. Step 6: Revenues, Energy Costs, and Social Cost of CO_2

We obtain some economic parameters—revenues, energy costs, and the social cost of CO_2—to compare the results of the scenarios.

As we are interested in how changes in water and energy affect sales, we preferred to obtain variable revenues—defined as the marginal price per unit sold multiplied by the total amount of units sold—instead of obtaining total revenues which include a significant part of revenues attributable to fixed costs. To obtain water revenues, we use the marginal price for multifamily homes of $2.89 per hundred cubic feet, which is similar to the average rate for the different tiers for single-family homes, obtained from EBMUD UWMP. For energy revenues, we use $0.1927/kWh for winter and $0.24730 for summer uses for electricity (PG&E, 2017) and $1.82/Therm for natural gas (California Public Utilities Commission, 2017).

We obtained energy costs by using current hourly prices for both the water and energy utilities:

1. The water utility buys electricity from PG&E, with prices varying according to a Time-of-Use tariff. From November to April, the tariff has two steps (partial-peak from 8:30 a.m. to 9:30 p.m. and off-peak for the remaining hours of the day), whereas in summer the tariff has an additional step from noon to 6 p.m. (On-peak). Prices in summer are higher than in winter due to higher demand. To obtain the total costs for our case study, we multiplied the hourly energy use in each element obtained from our model ($e_{i,j,m}$ in equation (12)) by the hourly cost. Details about Time-of-Use tariff electricity tariff for EBMUD are provided in the supporting information.
2. The energy utility works as a retailer buying its electricity from the wholesale market (California Independent System Operator, CAISO) and then distributing this energy to customers with their own distribution infrastructure. We used the locational marginal price for 2009 and 2010 for the VallyVW_1_N001 node —the closest node to the Alamo/Danville area of EBMUD—obtained from the CAISO Open Access Same-time Information System. Hourly locational marginal prices for the VallyVW_1_N001 node are presented in the supporting information.

Finally, we assessed the costs of the water-related CO_2 emissions assigning a value of $43/metric ton (the central estimate for 2015 at 3% discount rate adjusted in 2017 dollars obtained by the Interagency Working Group on Social Cost of Greenhouse Gases of the United States Government; United States Environmental Protection Agency, 2016) to obtain the benefits of reducing emissions.

2.7. Validation

One way to validate the hourly results obtained from the model is to compare the energy consumption to real data of energy consumption and costs. In our case we only have data from the water utility supply infrastructure (obtained from EBMUD), but we did not have access to data on water-related energy consumption of water end uses. Therefore, as we do not have the option to validate the model for end uses, there is more uncertainty on these estimates.

2.8. Simulations

Several simulations analyzed how different changes in water use or water use patterns can affect total energy consumption and CO_2 emissions. We also analyzed the consequences for the water and energy utilities in terms of energy costs of these changes in water use. The simulations are summarized below:

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1. *Business-as-usual scenario*. The scenario includes the model results of the case study, including both end uses of water and water treatment, supply, and wastewater treatment operations.
2. *Residential optimal conservation*. Escriva-Bou et al. (2015b) obtained optimal conservation strategies considering different water and energy pricing strategies and technological and behavioral actions—based on effectiveness and costs—to reduce water and water-related energy use for households in water utilities in California. Using an optimization method, each household can decide to retrofit water appliances or change behaviors if the benefits provided by the savings in water and energy bills are larger than the costs of taking the options. The optimal solution can provide an upper bound of household savings for customers with well-behaved preferences. For EBMUD, the optimal solutions yielded an average water use reduction of 11% in single-family homes (from 291 to 259 gallons per day, GPD, per household) and 6% in multifamily homes (from 180 to 169 GPD per household). For single-family homes 66% of the savings were from outdoor uses, 12% in showers, 9% in toilet, 8% in clothes washer, and the remaining 4% shared in the other uses. In multifamily homes 35% of savings come from showers, 28% from toilets, 25% from clothes washers, and the remaining 12% from the remaining uses.
3. *Demand response*. Demand response programs are designed to change use patterns by customers in response to changes in the price of a particular good over time. Although these measures have been applied in electricity markets, we foresee a potential to apply demand response programs to water use. By reducing daily water peaks, water utilities could reduce their energy bill. Also, energy utilities could benefit from changes in water use by shaving energy peaks, given the cheaper energy prices but also the economic savings that could arise from reduced needs in energy infrastructure capacity. Our model can estimate just some of the benefits from demand response programs. We simulated a simple hypothetical case where all outdoor and residential dishwasher and washing machine uses occur in *off-peak* hours. In this case we did not simulate any reduction in water use but only a change of time of use.

The current share of electric and gas-fired water heaters in California weakens the connection between residential water use and the electricity wholesale market, but in other states—like Florida—most water heaters are electric. Thus, a second set of simulations was exactly the same as before but changing the share of electric water heaters to 90% and the remaining 10% gas-fired. Therefore, we have three scenarios for two different cases: the gas-fired heating (90% of gas-fired water heaters and 10% electric water heaters) and the electric heating (90% electric water heaters and 10% of gas-fired water heaters).

To compare the simulations, we show water and energy use, the CO_2 emissions, and the economic parameters for each scenario.

3. Results

All the results presented below were obtained for the subset of the EBMUD utility (27% of the total EBMUD water consumption). Note that we are obtaining the results assuming that per capita water use and the share of use per customer category is similar throughout the service area.

3.1. Validating the Model

The results of the validation of the hourly supply infrastructure (shown in the supporting information) show that annual energy consumption for each stage of the urban water cycle is close—less than 1% of difference—to metered data. The modeled energy cost can be understood as an indicator of the accuracy of hourly supply because their hourly price is variable and is also similar to the measured data.

3.2. Energy, CO_2 Emissions, and Energy and Emission Costs of the Urban Water Cycle

From water uses per customer category, we obtain water-related energy use and GHG emissions. Figure 4 shows that almost 95% of the energy consumption in the urban water cycle for EBMUD is from end uses, with residential end uses responsible for more than 70% of all water-related energy use, followed in importance by industrial end uses. Energy used by the water utility—water treatment, pumping, and wastewater treatment—accounts for only 5.1% of total energy use but represents more than $3.3 million per year, for 27% of the EBMUD network. This result is consistent with the total electricity expenditures of the water utility, which are over $12 million per year, representing approximately 3.5% of EBMUD costs according to its annual budget.

As a consequence of the differential emission factors from direct use of natural gas versus electricity, the share of GHG emissions from residential end uses is a little lower than its energy consumption—67%

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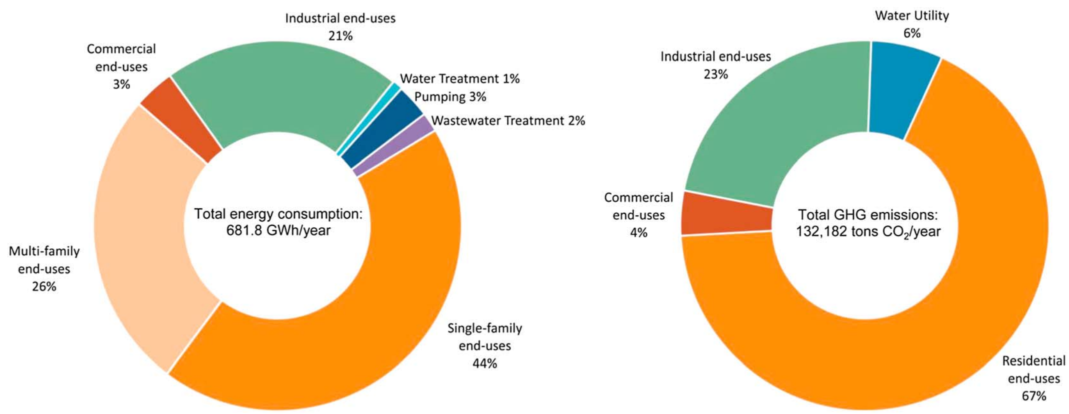

Figure 4. Annual water-related energy consumption (left) and CO_2 emissions (right) in the urban water cycle for the subset of EBMUD for the BAU scenario. EBMUD = East Bay Municipal Utility District; BAU = business as usual.

versus 70%—whereas the shares of the remaining sectors grow a little bit (Figure 4). Accounting for the total GHG emissions obtained and the estimated population in the area (355,000), the carbon footprint of the urban water cycle including end uses is 372 kg CO_2/person/year, representing approximately 4% of the total per capita GHG emission in California. Note again that the population was estimated assuming similar per capita use throughout the service area.

In terms of energy and CO_2 per unit of water (usually referred to as energy and carbon intensity), the urban water cycle uses 38.73 MWh/Mgal (or 12.62 MWh/af) and 7.51 t CO_2/Mgal (or 2.44 t CO_2/af).

Hourly water-related energy profiles (shown for a summer day in Figure 5) show that the largest share of water-related energy use is from water end uses, whereas water utility energy consumption is small. The figure also shows different time patterns of consumption, especially between residential end uses—with two peaks just before and after normal working times—and industrial and commercial end uses—centered on working hours. The figure shows in a secondary axis the average annual wholesale price of electricity in

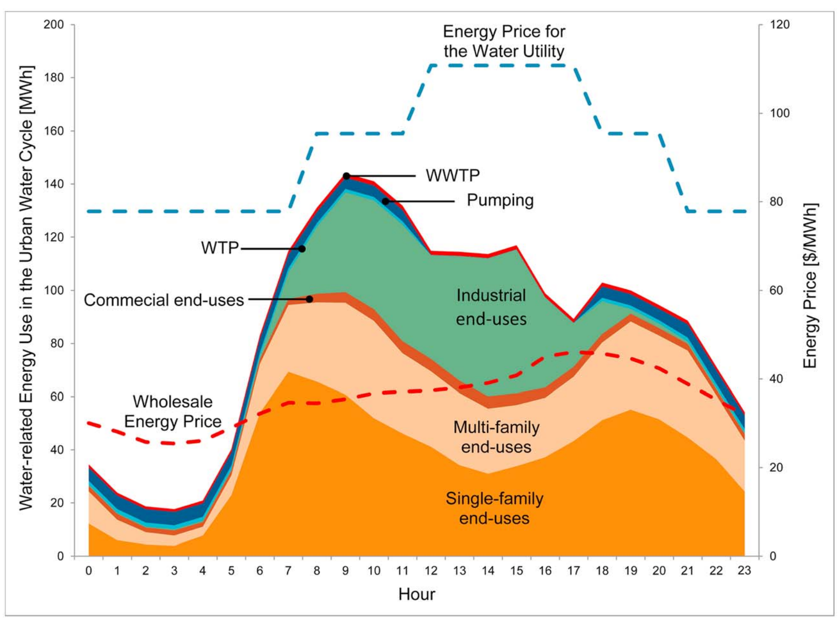

Figure 5. Hourly water-related energy profile for the different elements of the urban water cycle in a summer day in EBMUD (stacked areas). The lines show in a secondary axis the average hourly electricity wholesale prices that the energy provider pays and the average hourly electricity price for the water utility. EBMUD = East Bay Municipal Utility District.

Table 1
Results of Annual Water, Water-Related Energy and GHG Emissions and Energy Costs for the Water and Energy Utilities for the Scenarios Considered

			Gas-fired heating scenario		
			BAU	ROC	DR
Variable	Parameter	Unit	Value	Value (reduction %)	Value (reduction %)
Water use	Annual demand	(Mgal/year)	17,606	16,542 (6.0%)	17,605 (0.0%)
Energy	Water utility	(MWh/year)	37,862	36,108 (4.6%)	37,861 (0.0%)
	Residential demand	(MWh/year)	518,830	483,771 (6.8%)	518,829 (0.0%)
	Rest end uses demand	(MWh/year)	125,131	125,131 (0.0%)	125,131 (0.0%)
	Total energy demand	(MWh/year)	681,823	645,010 (5.4%)	681,821 (0.0%)
	Electric demand	(MWh/year)	46,176	43,056 (6.8%)	46,176 (0.0%)
	Natural gas demand	(MWh/year)	635,647	601,954 (5.3%)	635,645 (0.0%)
CO_2	Water utility	(t/year)	9,087	8,666 (4.6%)	9,087 (0.0%)
	Residential end uses	(t/year)	96,741	90,204 (6.8%)	96,741 (0.0%)
	Remaining end uses	(t/year)	26,354	26,354 (0.0%)	26,354 (0.0%)
	Total emissions	(t/year)	132,182	125,224 (5.3%)	132,181 (0.0%)
Water utility	Revenues from water sales	($/year)	67,976,404	63,872,266 (6.0%)	67,974,656 (0.0%)
	Total Energy Cost	($/year)	3,263,116	3,121,923 (4.3%)	3,163,236 (3.1%)
Energy Utility	Revenues from energy sales	($/year)	56,405,441	53,467,038 (5.2%)	56,405,381 (0.0%)
	Total energy cost	($/year)	3,068,793	2,893,119 (5.7%)	2,969,247 (3.2%)
Social Cost of CO_2	Total emissions cost	($/year)	5,683,824	5,384,626 (5.3%)	5,683,804 (0.0%)

Note. GHG = greenhouse gas; BAU = business as usual; ROC = residential optimal conservation; DR = demand response.

the market ranging from $25.44/MWh at 3 a.m. to $46.06/MWh at 5 p.m., and the annual average hourly energy price of electricity served to EBMUD, which ranges from $77.80/MWh in off-peak hours to $110.75/MWh in summer peak hours.

3.3. Residential Water Conservation Effects

We simulated an 11% reduction in single-family homes and a 6% reduction in multifamily homes, resulting in 6% of the total annual water conservation for the entire utility when other water uses remain constant. Conservation causes a decrease in water utility revenues or $4.1 million per year, but the energy consumption costs decrease by 4.3%, almost $150,000 per year (Table 1). The energy utility decreases its revenues by $2.9 million, but the operating costs will be reduced by over $175,000 per year, representing 5.7% of its raw energy costs. Finally, GHG emissions would also be reduced by 5.3%, saving almost 7,000 t of CO_2 per year—and over $264,000, accounting for the social cost of carbon emissions.

3.4. Demand Response Program Effects

By switching outdoor, dishwasher, and washing machine water use to off-peak hours, water use remains equal but water-related energy peaks are shaved to reduce energy costs. As water and energy sales are the same, there is not a reduction on revenues. There is a reduction in energy cost for the water utility of ~$100,000 per year (3.1%), and a decrease of 3.2% in energy costs for the energy utility of the same amount from the *gas-fired heating scenario* (Table 1).

When there is a higher share of electric water heaters (what we called the *electric heating scenario*), the savings for the energy utility would increase to almost $500,000 per year. When adding up the benefits for both the water and energy utilities, there is a total benefit of almost $600,000 per year (more details are included in the supporting information). This means a total benefit per capita of $1.69 per year.

3.5. Sensitivity Analysis

We conducted a sensitivity analysis of some of the parameters that are likely to affect the final results the most: indoor versus outdoor use, and the energy intensities of water utility infrastructure and urban end uses.

The results in Table 2 show that a decrease of 10% of the indoor share of residential water use would affect energy use of end uses by the same amount showing the lineal dependence of energy and indoor uses. Also, the energy used by the water utility would decrease because less water would be treated and pumped and also less wastewater would be treated. Energy savings translate proportionally into reductions in CO_2

Table 2
Sensitivity Analysis of the Main Parameters Affecting the Model

			BAU	Indoor decrease 10%	Energy intensities water utility decreased 10%	Energy intensities end uses decreased 10%
Energy	Water utility	(MWh/year)	37,862	37,467	34,902	37,862
	Reduction	(%)	—	1.0%	7.8%	0.0%
	Urban end uses	(MWh/year)	643,961	579,565	643,961	579,565
	Reduction	(%)	—	10.0%	0.0%	10.0%
	Total energy	(MWh/year)	681,823	617,032	678,863	617,427
	Reduction	(%)	—	9.5%	0.4%	9.4%
CO_2 Emissions	Total emissions	(t/year)	132,182	119,778	131,471	119,872
	Reduction	(%)	—	9.4%	0.5%	9.3%
Energy Cost for Water Utility	Total energy cost	($/year)	$ 3,263,116	$ 3,213,326	$ 3,012,112	$ 3,263,116
	Reduction	(%)	—	1.5%	7.7%	0.0%
Energy Cost for Electric Utility	Total energy cost	($/year)	$ 3,068,793	$ 2,871,709	$ 2,966,898	$ 2,893,420
	Reduction	(%)	—	6.4%	3.3%	5.7%
Social Cost of CO_2	Total emissions cost	($/year)	$ 5,022,914	$ 4,551,549	$ 4,995,916	$ 4,555,152
	Reduction	(%)	—	9.4%	0.5%	9.3%

Note. BAU = business as usual.

emissions and costs. The decrease of 10% of energy intensities of water utility infrastructure reduces the energy used by the water utility and its energy costs by nearly 8% because some infrastructure has fixed energy use nonrelated with water use, but the reduction in total energy and CO_2 emissions and costs is relatively small. Conversely, reduction of energy intensities of end uses decreases almost proportionately the total energy consumption and CO_2 emissions, whereas the water utility is not affected at all.

The effects of the different parameters on the cost of wholesale electricity are variable. It is more sensitive to indoor water uses and to energy intensities of end uses, because of the larger level of electric demand from end uses of water. But its sensitivity to the energy intensities of the water utility is also significant.

Whereas the utility supply infrastructure and residential end use energy intensity parameters are based on metered data, energy intensity parameters of nonresidential end uses of water are not based on metered data, increasing the uncertainty of these estimates.

4. Discussion and Policy Implications

Traditional analysis of water demand management policies focus on increasing the ability of the water utility to meet current or future demands with available supplies. But water demand management policies have some *unintended* effects on energy consumption of end users of water—households, industries, and commercial and institutional activities—that affect directly energy providers. This research, with the innovative hourly analysis, shows that saving water or switching patterns of consumption from peak to off-peak hours can result in economic impacts for users, water and energy utilities, and also for the environment.

In EBMUD service area, 95% of water-related energy and 94% of the water-related CO_2 emissions of the urban water cycle are from end uses of water (mainly residential water heating), whereas the rest are related to treating and pumping water and wastewater. These results, which include end uses of water, show that EBMUD is a low energy-intensive water utility, mostly because its water is from surface reservoirs conveyed by gravity, but they still spend more than $12 million per year for electricity. The total carbon footprint per capita of the urban water cycle including end uses is 372 kg CO_2/year representing approximately 4% of the total CO_2 emissions per capita in California. Therefore, water conservation can be adapted as a policy to reduce CO_2 emissions, especially in those places with higher water use per capita and/or energy generation sources with higher emission intensities.

Given the hourly variability in energy prices for both the water and energy utilities, demand-response on water use can become a way to reduce costs. By shifting some residential end uses to off-peak hours, we obtained that both water and energy utilities could be reduced roughly by 3% their energy costs. It is worth noting that the economic benefits for the energy utility are even larger than the benefits for the water utility, result not reported before in the literature, suggesting that energy utilities should be involved in encouraging water demand management policies, as is already happening in California (California Department of Food and Agriculture, 2017; CEC, 2017). The benefit for the energy utilities increases as the share of electric water heaters rises, because the link between water use and electricity peaks becomes more significant.

As obtained in the results, the total per capita benefits of the demand response programs are below $2 per year. That yields a significant result: whereas these benefits can create economic incentives for water and energy utilities to change the patterns of consumption of their water customers, these economic benefits are not large enough to incentivize these changes by using economic incentives in end users (i.e., time-of use pricing). Therefore, demand response programs might not be justified by reductions in cost of water-related energy. However, the benefits on the water and energy utilities can justify other types of education campaigns that can be aligned with other purposes (for instance, decreasing outdoor irrigation during peak hours could also decrease water losses by evaporation).

Water and energy demand management policies are already being used widely because they are able to defer, or even avoid, the need to expand capacity to meet peak water or energy demands (Cole et al., 2012). Note here that we did not include in our assessment the potential benefits from the avoidance or deferment in infrastructure investments. The deferment of capital costs would potentially provide the greatest savings for utilities especially in high-density residential areas (Gurung et al., 2014). While we are not assessing these potential larger benefits, in this study we are pointing out that direct energy savings from water demand policies for both water and energy utilities are added benefits that have not been usually accounted for in these policies.

Finally, it is important to notice that the social cost of carbon is usually not accounted for in most water policy analysis. This cost has been included in recent policy in different parts of the world as carbon taxes or cap-and-trade markets. In California's latest cap-and-trade auctions the cost per ton is $13.57 per metric ton (LAO, 2017), whereas in Europe it is under $10 per metric ton (Ellerman et al., 2016). These costs are much lower than the social cost of carbon proposed by the Interagency Working Group on Social Cost of Carbon (United States Environmental Protection Agency, 2016). Our results show that the social benefits in terms of CO_2 reductions from water demand management policies are significant and even larger than the economic benefits of energy savings for water and energy utilities. This suggests that more emphasis should be devoted to analyzing the economic benefits of CO_2 emissions reductions from water demand management policies.

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