The Water-Energy Nexus: a bottom-up approach for basin-wide management

Ph.D. Thesis by

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Als meus pares, Pepe i Isabel, per dedicar tota una
vida a tractar d'acomplir els nostres somnis

(To my parents, Pepe and Isabel, because they worked the whole life
only to see our dreams becoming real)

A Marcieta, perquè mai et podré tornar tot el que tu m'has donat

(To Marcieta, because I won't be able to pay you back all what you already gave me)

Per a tots els que han cregut que l'educació ha de ser un dret universal,
per a aquells que lluitaren per aconseguir que l'escola i la universitat foren publiques,
i per als que creuen que totes les persones hauríem de tenir dret a les mateixes
oportunitats sense importar en quin lloc i en quines condicions hàgem nascut.
Sense ells possiblement jo no estaria hui escrivint estes línies

(To all those who have believed that education has to be a universal right,
to all those who fought to got public schools and universities,
and to all those who believe that all persons must have the right to have the same
opportunities no matter where and how they were born.
Without them, possibly I would not be writing these lines today)

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Abstract

Most individual processes relating water and energy interdependence have been assessed in many different ways over the last decade, but there is still a need for integrating these results in management by providing actual tools for decision-makers to effectively understand the tradeoffs between water and energy from management options and scenarios.

The final goal of this dissertation is to develop a basin-scale hydroeconomic model for water management including the water balance and the water-related energy dependency in the entire water cycle that can assess the effects on water, energy and GHG emissions of different policies and management options. To achieve that goal I use a result-oriented bottom-up approach starting by analyzing the residential water-energy relationship, developing later an urban model that builds up on the previous results, and finally describing and applying a basin-scale model.

First chapter uses California's drought to identify the economic threats of water scarcity on food, energy and environmental systems as a way to introduce the multiple interactions between these resources, reviewing the literature on the on the water-energy relationship and presenting the objectives and structure of the dissertation.

Because most of the water-related energy is used in the urban water cycle, I focus later the attention in the urban water-related energy consumption. Second chapter develops an end-use model for water use and related energy and carbon footprint using probability distributions for parameters affecting water consumption in 10 local water utilities in California. Statewide single-family water-related CO_2 emissions are 2% of overall per capita emissions, and locally variability is presented. The impact of several com-

mon conservation strategies on household water and energy use are assessed simulating different scenarios.

Based on the this model, Chapter 3 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 percent reduction in water-related energy use and a 53 percent reduction in household water-related CO_2 emissions.

To complete the urban water cycle, Chapter 4 develops first an hourly model of urban water uses by customer category including water-related energy consumption and next I calibrate a model of the energy used in water supply, treatment, pumping and wastewater treatment by the utility, using real data from East Bay Municipal Utility District in California. Hourly costs of energy for the water and energy utilities are assessed and GHG emissions for the entire water cycle estimated. Results show that water end-uses account for almost 95% of all water-related energy use, but the 5% managed by the utility is still worth over $12 million annually. Several simulations analyze the potential benefits for water demand management actions. The total carbon footprint per capita of the urban water cycle is 405 kg CO_2/year representing 4.4% of the total GHG emissions per capita in California.

Accounting for the results obtained in Chapters 2 to 4, Chapter 5 describes a simple but powerful decision support system for water management that includes water-related energy use and GHG emissions not solely from the water operations, but also from final water end uses, including demands from cities, agriculture, environment and the energy sector. The DSS combines a surface water management model with a simple groundwater model, accounting for their interrelationships, and also includes explicitly economic data to optimize water use across sectors during shortages and calculate return flows from different uses. Capabilities of the DSS are demonstrated on a case study over California's intertied water system over the historic period and some simulations are run to highlight water and energy tradeoffs. Results show that urban end uses account for most GHG emissions of the entire water cycle, but large water conveyance produces significant peaks over the summer season. The carbon footprint of the entire water cycle during this period, according to the model, was 21.43 millions of tons of CO_2/year, what was roughly 5% of California's total GHG emissions.

The last two chapters discus and summarize the thematic and methodological contributions and looks for further research presenting and discussing the research gaps and research questions that this dissertation left open.

Resum

La majoria dels processos relacionats amb la interdependència entre aigua i energia han estat evaluats en gran varietat de maneres durant l'última dècada, però existix la necessitat d'integrar eixos resultats en la gestió proporcionant ferramentes reals per a la presa de decisions entenent integralment el consum d'aigua i d'energia per a diferent opcions de gestió i múltiples escenaris.

L'objectiu final d'esta tesi es el de desenvolupar un model hidro-econòmic a escala de conca per a la gestió de recursos hídrics incloent la dependència energètica del cicle integral de l'aigua que siga capaç d'estimar els efectes en aigua, energia i generació d'emissions de gasos d'efecte hivernacle (GEH) associats al consum d'aigua de diferents polítiques i opcions de gestió. Per a aconseguir eixe objectiu utilitze una metodologia "de baix cap amunt" i orientada a resultats començant per l'anàlisi de la relació d'aigua i energia a escala residencial, desenvolupant més endavant un model urbà que s'alimentarà dels resultats anteriors, per a finalment descriure i aplicar un model a escala de conca.

El primer capítol utilitza la sequera de Califòrnia per a identificar les amenaces econòmiques de l'escassesa d'aigua en els sistemes de producció d'aliments, energètic i mediambiental per a presentar les múltiples interaccions entre estos recursos. La segona part del primer capítol centra l'objectiu de la tesi, la relació entre l'aigua i l'energia, presenta la revisió de la literatura identificant els buits, descriu els objectius i les qüestions que busca respondre esta recerca, explica la metodologia seguida, i descriu la organització de la tesi.

Al segon capítol es desenvolupa un model d'usos finals d'aigua, comptant amb l'energia i les emissions de GEH associats utilitzant distribucions de probabilitat per als paràmetres que afecten a l'ús de l'aigua en 10 ciutats en Califòrnia. Com a resultats

principals s'obté que les emissions de GEH associades al consum residencial d'aigua representen el 2% del total d'emissions per càpita, i es presenta la variabilitat deguda a les condicions locals. Els impactes d'algunes pràctiques comunes d'estalvi d'aigua i energia són calculades simulant diferent escenaris.

Basat en eixe model, al Capítol 3 es presenta un model d'optimització probabilístics en dos períodes considerant variables de decisió de modificacions tècniques i de comportament en relació al consum d'aigua per a obtindre les estratègies més econòmiques per a minimitzar les factures d'aigua i energia. Els resultats proporcionen un límit superior per a l'estalvi domèstic, i mostren majors taxes d'adopció per a reduir usos d'aigua que són més intensius en consum energètic quan l'energia es incluïda, resultant en una reducció del 24% d'ús d'aigua a dins de les cases, que representa un 30% en reducció d'energia i un 53% d'emissions de GEH, ambdós relacionats amb el consum d'aigua.

Per a completar el cicle urbà de l'aigua, el Capítol 4 desenvolupa primer un model horari d'usos d'aigua incloent l'energia associada i després es calibra un model d'aigua i energia en l'abastiment, tractament i bombeig d'aigua i al tractament d'aigua residual, utilitzant dades reals de East Bay Municipal Utility District en Califòrnia. Els costs horaris d'energia per a les companyies d'aigua i energia, així com les emissions de GEH són estimades. Els resultats mostren que els usos finals són responsables del 95% de l'energia relacionada amb l'ús de l'aigua, però que el 5% restant té un cost de 12 milions de dolars anualment. Algunes simulacions analitzen els beneficis econòmics potencials de mesures de gestió de demanda d'aigua. La petjada de carbó total del cicle urbà de l'aigua s'estima en 405 kg CO_2/any representant el 4.4% de les emissions per càpita en Califòrnia.

Tenint en compte els resultats obtesos en els capítols 2, 3 i 4, el Capítol 5 descriu un sistema de suport de decisió (SSD) per a gestió de recursos hídrics incloent energia i emissions de GEH no sols de la gestió de l'aigua, sinó també del úsos finals de l'aigua, incloent demandes urbanes, agrícoles, ambientals i del sector energètic. El SSD combina un model d'aigua superficial amb un d'aigua subterrànea, incloent les seues interrelacions, i també inclou explícitament dades econòmiques per a optimitzar l'ús de l'aigua durant períodes de sequera. Les possibilitats del SSD són demostrades en un cas d'estudi aplicat a un model simplificat del sistema de recursos hídrics de Califòrnia. Els resultats mostren que els usos finals de l'aigua en zones urbanes són responsables de la majoria de les emissions de GEH, però que les grans infrastructures de transport d'aigua produïxen important pics a l'estiu. D'acord amb el model, la petjada de carbó del cicle de l'aigua a Califòrnia és de 21.43 milions de tones de CO_2/any, el que significa aproximadament el 5% del total d'emissions de GEH a l'estat.

Els últims dos capítols resumeixen i discuteixen les contribucions temàtiques i metodològiques d'esta tesi, presentant noves línies d'investigació que es deriven d'este treball.

Resumen

La mayoría de los procesos relacionado con la interdependencia entre agua y energía han sido evaluados en gran variedad de modos durante la última década, pero aún existe la necesidad de integrar esos resultados en la gestión proporcionando herramientas para la toma de decisiones comprendiendo integralmente el consumo de agua y energía para diferentes opciones de gestión y múltiples escenarios.

El objetivo final de esta tesis es el desarrollar un modelo hidro-económico a escala de cuenca para la gestión de recursos hídricos incluyendo la dependencia energética del ciclo integral del agua que sea capaz de estimar los efectos en agua, energía y generación de emisiones de gases de efecto invernadero (GEI) asociados al consumo de agua de diferentes políticas y opciones de gestión. Para conseguir ese objetivo utilizo una metodología "de abajo hacia arriba" y orientada a resultados empezando por el análisis de la relación de agua y energía a escala residencial, desarrollando más adelante un modelo urbano que se alimentará de los resultados anteriores, para finalmente describir y aplicar un modelo a escala de cuenca.

El primer capítulo utiliza la sequía de California para identificar las amenazas económicas de la escasez de agua en los sistemas de producción de alimentos, energético y medioambiental para presentar las múltiples interacciones entre estos recursos. La segunda parte del primer capítulo centra el objetivo de la tesis, la relación entre el agua y la energía, presenta la revisión de la literatura identificando los vacíos, describe los objetivos y las cuestiones que busca responder esta investigación, explica la metodología seguida, y describe la organización de la tesis.

En el segundo capítulo se desarrolla un modelo de usos finales de agua, contando con la energía y las emisiones de GEI asociados utilizando distribuciones de probabilidad para los parámetros que afectan al uso del agua en 10 ciudades en California. Como

resultados principales se obtiene que las emisiones de GEI asociadas al consumo residencial de agua representan el 2% del total de emisiones per cápita, y se presenta la variabilidad debida a las condiciones locales. Los impactos de algunas prácticas comunes de ahorro de agua y energía son calculadas simulando diferente escenarios.

Basado en ese modelo, el Capítulo 3 se presenta un modelo de optimización probabilísticos en dos periodos considerando variables de decisión de modificaciones técnicas y de comportamiento en relación al consumo de agua para obtener las estrategias más económicas para minimizar las facturas de agua y energía. Los resultados proporcionan un límite superior para el ahorro doméstico, y muestran mayores tasas de adopción para reducir usos de agua que son más intensivos en consumo energético cuando la energía se incluye, resultando en una reducción del 24% de uso de agua adentro de las casas, que representa un 30% en reducción de energía y un 53% de emisiones de GEI, ambos relacionados con el consumo de agua.

Para completar el ciclo urbano del agua, el Capítulo 4 desarrolla primero un modelo horario de usos de agua incluyendo la energía asociada y después se calibra un modelo de agua y energía en el abastecimiento, tratamiento y bombeo de agua, y el tratamiento de agua residual, utilizando datos reales de East Bay Municipal Utility District en California. Los costes horarios de energía para las compañías de agua y energía, así como las emisiones de GEI son estimadas. Los resultados muestran que los usos finales son responsables del 95% de la energía relacionada con el uso del agua, pero que el 5% restante tiene un coste de 12 millones de dólares anualmente. Algunas simulaciones analizan los beneficios económicos potenciales de medidas de gestión de demanda de agua. La huella de carbón total del ciclo urbano del agua se estima en 405 kg CO_2/año representando el 4.4% de las emisiones per cápita en California.

Teniendo en cuenta los resultados obtenidos en los capítulos 2, 3 y 4, el Capítulo 5 describe un sistema de apoyo de decisión (SSD) para gestión de recursos hídricos incluyente energía y emisiones de GEI no sólo de la gestión del agua, sino también de usos finales del agua, incluyendo demandas urbanas, agrícolas, ambientales y del sector energético. El SSD combina un modelo de agua superficial con uno de agua subterráneo, incluyendo sus interacciones, y también incluye explícitamente datos económicos para optimizar el uso del agua durante periodos de sequía. Las posibilidades del SSD son demostradas en un caso de estudio aplicado a un modelo simplificado del sistema de recursos hídricos de California. Los resultados muestran que los usos finales del agua en zonas urbanas son responsables de la mayoría de las emisiones de GEH, pero que las grandes infrastructures de transporte de agua producen importante picos en verano. De acuerdo con el modelo, la huella de carbón del ciclo del agua en California es de 21.43 millones de toneladas de CO_2/año, lo que significa aproximadamente el 5% del total de emisiones de GEI del estado.

Los últimos dos capítulos resumen y discuten las contribuciones temáticas y metodológicas de esta tesis, presentando nuevas líneas de investigación que se derivan de este trabajo.

List of publications

Chapter 2: Escriva-Bou, A., Lund, J. R., & Pulido-Velazquez, M. (2015). Modeling residential water and related energy, carbon footprint and costs in California. Environmental Science & Policy, 50(0), 270-281. doi: http://dx.doi.org/10.1016/j.envsci.2015.03.005

Chapter 3: Escriva-Bou, A., Lund, J. R., & Pulido-Velazquez, M. (2015). Optimal residential water conservation strategies considering related energy in California. Water Resources Research, n/a-n/a. doi: 10.1002/2014WR016821.

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PART I: INTRODUCTION

Chapter 1

Introduction

Abstract

The water cycle is energy intensive, and most energy sources require some amount of water; food production on irrigated croplands depends on intensive water and energy use; and finally energy use of the water cycle and food production releases greenhouse emissions. The economic consequences of these connections are non-trivial and sometimes very complex to understand and assess.

Defining and understanding the interactions of all these interrelated is the first step to address the policy challenges that water, energy and food systems will increasingly face as population and water, energy and food demands rise.

In the first part of this chapter I use the current California's drought to present the magnitude of the water-energy-food nexus on the different sectors of the economy, showing some general results of the effects of the drought and how the scientific community is assessing and approaching this topic.

In the second part, I focus on the water-energy relationship demonstrating the necessity of better models for managing the nexus. First, reviewing the existing literature, I identify the main research gaps that I am trying to address and, based on them, I define the objectives of the research. Finally the structure of the dissertation is presented.

1.1. The Californian water-energy-food-environment relationship

1.1.1. Introduction

California is currently suffering one of the driest periods on record and, as a persistently water-stressed region, all the alarms have been activated[1]. If the drought persists, there may be serious economic consequences for California's agriculture, which may suffer from a rise in unemployment. Water scarcity will decrease hydropower generation affecting electricity prices and indirectly lead to an increase in greenhouse gas emissions from substitutive sources. More broadly, the current drought will affect the living standards of most Californian residents, as urban water conservation strategies are implemented through water price increases or even water rationing.

The widespread consequences of this severe drought have led to greater attention from both scientists and policy-makers, as it is becoming increasingly clear that water, food, energy and climate systems are highly interdependent. The water cycle is energy intensive and most energy sources require some water inputs. Food production relies on irrigated croplands, which uses large amounts of energy and water. The energy consumption of the water cycle and food production combined results in the daily release of many tons of greenhouse gases. The economic consequences of these connections are huge and sometimes complex to understand, making their assessment challenge.

Traditionally, professionals of each of these fields have worked in isolation, often making many assumptions regarding data from other fields. Fortunately the scientific community has come to realize the potential benefits of shared approaches (Scholten et al., 2007), and recent studies have begun to assess the important relationships between water and energy, food and water, and energy and climate change (CEC, 2005). While simple assessments of an individual aspect of this problem are essential as a foundation, more integrative approaches considering all aspects of this problem will be required to determine the most economically efficient policies for tackling water stress in the future.

In the remainder of the chapter I first summarize the main features of California's water, energy and food production systems, accounting for their economic implications and their consequences on the environment. After that, I describe the objectives of the dissertation, presenting a summary of the literature reviewed and the thesis structure.

1.1.2. Water itself

California has a Mediterranean climate with rainy winters, dry summers and huge temporal and spatial variability in water availability and demand. Among other conse-

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[1] Gov. Brown proclaimed on January 17, 2014, a State of Emergency to exist throughout the State of California due to severe drought conditions; on April 25, 2014, proclaimed a Continued State of Emergency; and on April 1, 2015, directed first-ever statewide mandatory water reductions through Executive Order B-29-15.

quences, this has resulted in significant investment in the hydraulic infrastructure that exists in the state today. Normally 75 percent of California's average precipitation occurs between November and March (DWR, 2012). Although 70 percent of runoff occurs north of the Sacramento-San Joaquin Delta, 75 percent of the state's demand lies to the south (Hanak et al., 2011), especially for irrigation of the high-value croplands, with peak usage falling within the dry season.

In an average year, California uses roughly 80 million acre-foot of water to irrigate crops, supply potable water to cities and maintain ecosystems. According to the California Water Plan (DWR, 2009) 49 percent (39 MAF) of total freshwater is used for environmental purposes, 41 percent (33 MAF) is consumed by the agricultural sector and only 10 percent (8 MAF) is diverted to urban areas.

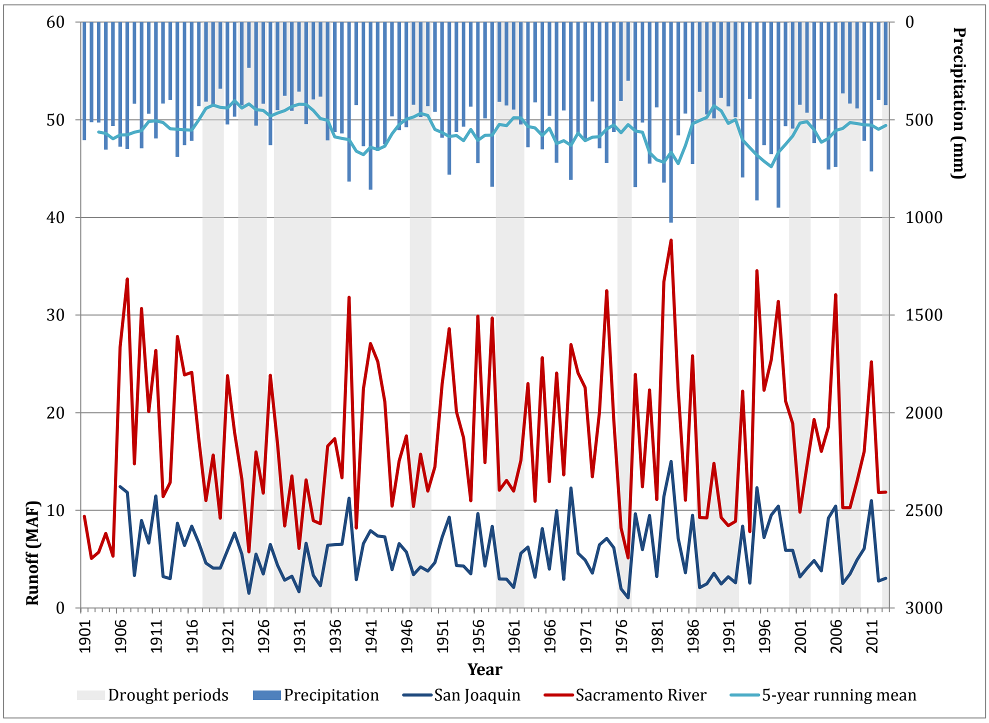
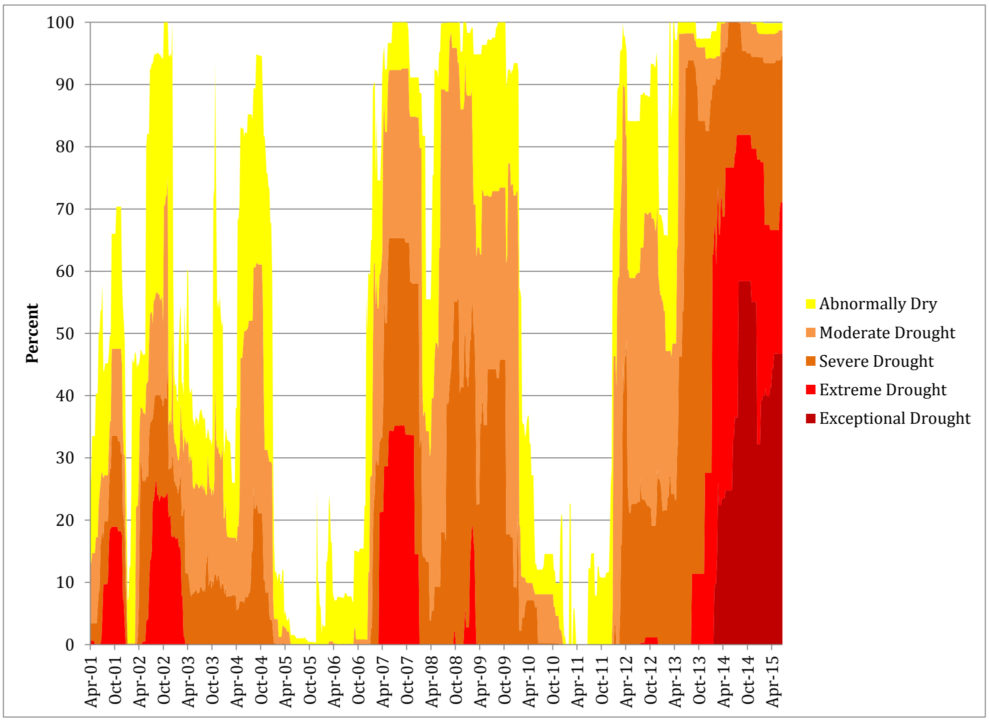


Figure 1.1: California historic statewide precipitation, main rivers' runoff and drought periods.

Another feature of California's climate is the multi-year hydrological cycles that alternate between wet periods and droughts (Figure 1.1). Even though there is only limited evidence for an increased trend globally in drought or dryness since the middle of the 20th century (Hartmann et al., 2013), changes in population and economic development over the next 25 years will dictate the future relationship between water supply and demand to a much greater degree than will changes in climate (Vorosmarty, Green, Salisbury, & Lammers, 2000). These two factors —multi-year uncertainty in resources and increasing demands— represent the greatest challenges currently facing water management researches and decision-makers in California.

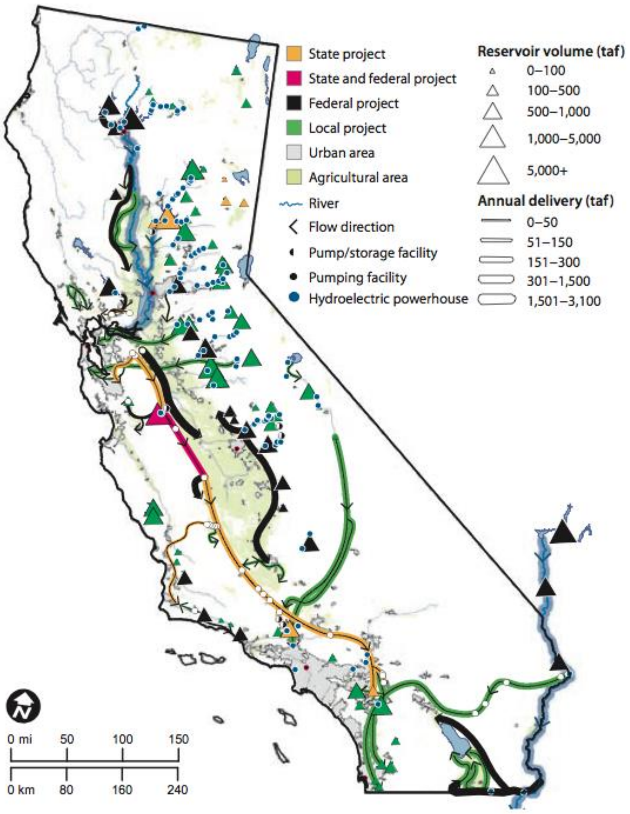
Considering all this information, the rainy season is ended and 2015 has been almost as dry as 2014. Considering that 2013 was also dry, water management is garnering much attention and many minds are focused in developing the best-response actions under an uncertain future. As is shown in Figure 1.2, for the first time since the beginning of this century, a significant percentage of the state is classified within the *Exceptional Drought* category according to U.S. Drought Monitor, and the whole state is below normal levels of humidity.



Source: Data from Fuchs (2015)

Figure 1.2: California statewide percentage area in U.S. Drought Monitor Categories.

Despite these pressing problems, California is well placed to overcome them. The extensive, integrated and flexible water system that was built mostly during the 20th century has the ability to transfer water between almost any two locations across the state, regardless of distance. As is shown in Figure 1.3, local, state and federal projects have connected the relatively wet and unpopulated north with the agricultural regions in the Central Valley and the populous cities of southern California, using the delta of the Sacramento and San Joaquin rivers as a water hub.

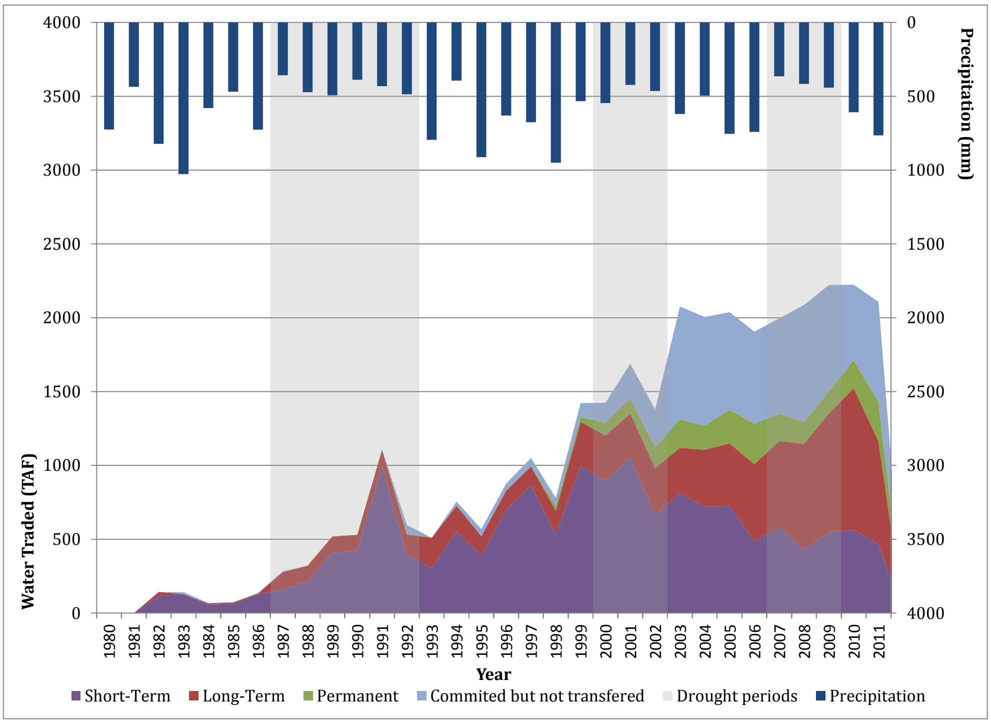


Source: Hanak et al. (2011)

Figure 1.3: California's water network: conveyance and storage infrastructure.

By learning from historical dry events and taking advantage of an intertied water network, California's water users have diversified its water source portfolio to improve its reliability. Most agricultural water users can switch from surface to groundwater sources when the former is scarce, but what is more impressive is the variety of water sources available to some urban water utilities —especially those traditionally more vulnerable to drought. One such case is that of San Diego County Water Utility that sources water from its reservoirs, pumping from aquifers, reusing recycled water, importing water from northern California or from the Colorado River, and in the future through a desalination plant.

Another strength of California's system which is a result of its integrated network combined with the varying economic profitability of water uses and a proper regulation of water institutions, is the water market that has been extraordinarily helpful during periods of drought. As shown in Figure 1.4 water transfers have grown substantially since the early 1980s with different phases in its development (Hanak & Stryjewski, 2012). First, in the late 1980s, short-term purchases triggered the water market to alleviate the effects of the 1987-1992 drought. Later, by the end of the 1990s water markets were driven by environmental concerns. Finally, in most of the 2000s it can be seen how long-term agreements have taken the place of short-term transfers as a long-run strategy, while at the same time, a significant part of the water committed in these long-term agreements has not been transferred. As water transfers demonstrate, water has an economic value as a commodity and, as far as it is possible through water infrastructure connections, urban utilities and high-value farms can buy water from lower-value producers.



Source: Data from Hanak and Stryjewski (2012)

Figure 1.4: Water transfers in California depending on their nature.

Therefore, what can be expected from drought? Because agricultural yields depend on applied water, and only some annual crops will survive reduced irrigation, most farmers will maintain this practice to sustain their profits, unless offered incentives, such as revenues from water transfers, to switch crops. As in 2014, if there are cutoffs in surface water, farmers will switch to groundwater if they can, meaning that most surface water shortages will be replaced by groundwater. This will increase production costs for farmers, and in overexploited aquifers, the current situation will worsen, with potential risk that further falls in the groundwater levels will strand some wells.

For urban water use, demand-side management policies (DSMP) have become essential when short-term events such as droughts drastically reduce water reliability and it is hard or expensive to find temporary new water supplies. Therefore, it can be expected that policies such as increases in urban water rates, non-economic strategies such as public campaigns, or even water rationing if the situation deteriorates, will be more commonly used.

In the last few years, a significant proportion of transfers bought in the water market have been committed but not transferred, thus both urban and high-value agricultural producers, especially growers of perennial crops with a risk of high losses, will transfer these commitments. If the drought persists, I expect an increase in the number of short-terms agreements. This will increase water prices for both urban and agricultural sectors.

1.1.3. Water as an energy consumer

Energy is needed to pump, treat, transport, heat, cool and recycle water. According to the California Energy Commission 54 TWh of electricity and 4,284 million therms of natural gas are consumed annually in the entire water management cycle. These amounts are 21 and 32 percent of the state's total use respectively (CEC, 2005), and they are the main components of what is understood in this dissertation as water-related energy.

Whereas environmental and agricultural sectors are the vast majority of total water consumption, urban water end-uses are responsible for 58% of total water-related electricity and 98% of total water-related natural gas consumption. Furthermore, urban water supply and treatment, and wastewater treatment accounts for nearly 20% of water-related electricity use. Meanwhile agricultural supply, treatment and end-use account for an additional 22% of all water-related electricity consumption. These results, presented in absolute terms in Table 1.1, were assessed for the year 2000. There are some posterior studies (CEC, 2007; Wolff & Wilkinson, 2011) that have arrived to similar overall results, however some concerns about the original methodology have been raised[2] and corrected.

Table 1.1: California water and water-related energy use per sector.

		Urban	**Agriculture**	**Environment**	**Total Statewide**
Water Use [MAF in 2010]		8	33	39	80
Water-Related Electricity [GWh/year]	Supply and Treatment	9,566	3,188	0	250,494
	End-Uses	27,887	7,372		
Water-Related Natural Gas [Million Therms/year]	Supply and Treatment	19	-	0	13,571
	End-Uses	4,220	18		

Source: CEC (2005)

As described above, spatial variations in precipitation and water demands across California necessitated the creation of huge water conveyance systems that are now some of the largest *single user* of electricity in the state. For example, the State Water Project consumed an average of 7.81 GWh of electricity per year between 2005 and 2009 (more than 3% of the state's total electricity consumption), although during this period, it also generated 4.99 GWh of hydropower per year. Despite the high energy intensity of these conveyance systems, more energy is used every year to pump groundwater locally to supply water.

Considering these facts, and given that urban water use is the principal water-related energy user (Fidar, Memon, & Butler, 2010), it is likely that urban demand management policies to reduce residential water consumption per capita during drought through technological and attitudinal changes would decrease water-related energy use. A significant proportion of residential water savings will come from outdoor reductions, and given that outdoor water is unheated, the reductions in water-related energy will not be very large as might be expected from Table 1.1. Savings in indoor water use translates more directly to a significant reduction in residential energy use. Overall residential energy use would increase during periods of high temperatures because of greater air conditioning use (Scanlon, Duncan, & Reedy, 2013).

In agriculture, as surface water becomes limited, an increase in energy use from pumping groundwater to farms that have the ability to switch their water source must be expected. Although only studied during a short range of time, between 2006 and 2012 non-residential electricity consumption for two of the most important agricultural counties in California —Fresno and Tulare— shows that electric consumption is inversely proportional to precipitation. In 2014, this is likely to be exacerbated because the drought is more severe than previous ones. The same trend should be expected if high-value croplands and urban utilities buy water through the market increasing water

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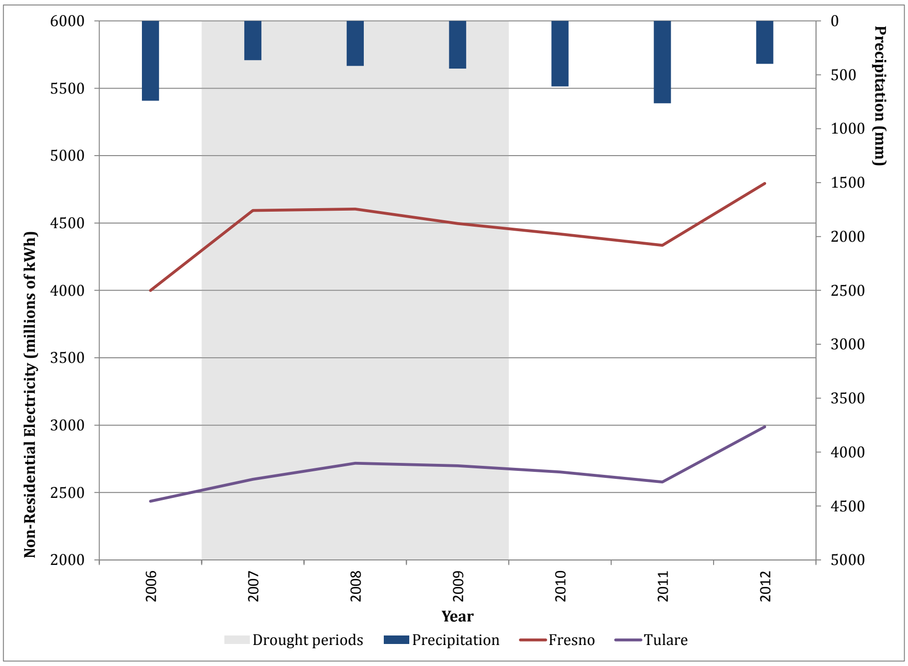
[2] Wolff and Wilkinson (2011) presented a potential double-counting issue in the CEC (2005) report because natural gas used to generate electricity was also counted as an industrial water-related end-use.

transfers: again agricultural users who are able to switch between water sources will sell surface water and energy use will increase from greater groundwater pumping.

The final consequence is that delta exports to the Central Valley and Southern California will be reduced. Therefore the State Water Project (SWP) and the Central Valley Project (CVP) will reduce their energy consumption. As I mentioned previously, the SWP is the largest single user of electricity, thus a considerable amount of energy will be saved.



Source: Data from CEC (2015)

Figure 1.5: Non-residential electricity use in Fresno and Tulare counties.

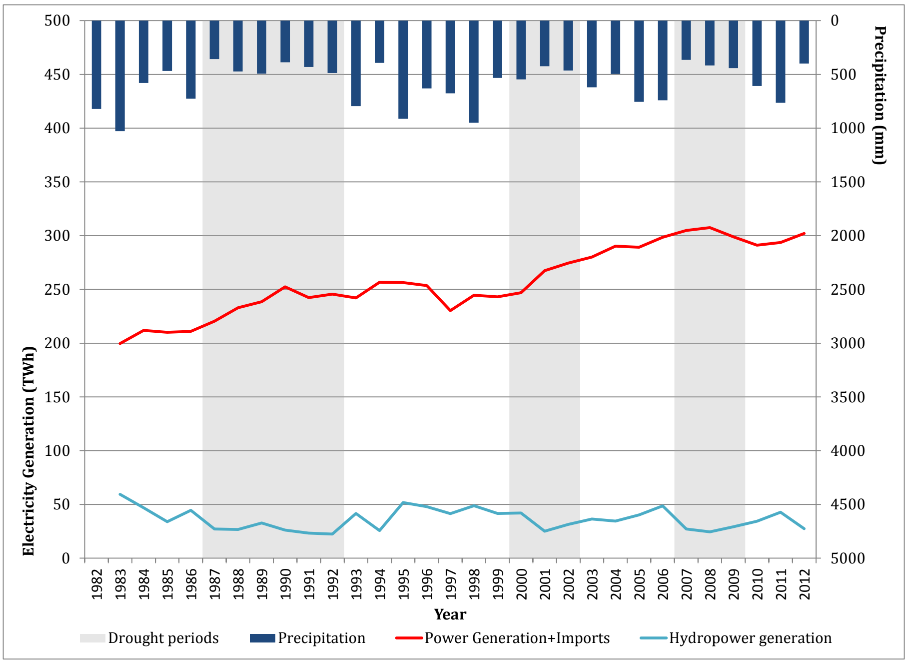
1.1.4. Water as an energy source

California produces roughly 70 percent of its electricity from power plants in the state or outside the state but owned by California utilities, whereas 30 percent is imported from the Pacific Northwest and the American Southwest. On average 54% of within-state electricity production is natural gas-fired, 16% is from hydropower, 15% from nuclear plants, 6% from geothermal, and the remaining 9% is shared between renewables —wind and solar—, coal, biomass and other sources (CEC, 2014).

Most of these energy sources need water in different ways. Hydropower completely depends on water availability, but consumes only a negligible part through reservoir evaporation. Thermoelectric power plants, including natural gas and nuclear plants, remove heat from the cycle with a condenser using cooling water (Torcellini, Long, & Judkoff, 2003). Even though thermoelectric generation accounts for ~40% of water withdrawals and 3% of freshwater use in the US (Scanlon et al., 2013) and thus competes directly with other freshwater users in California, most generators use saline water and so are unaffected by water scarcity.

As shown in Figure 1.6, hydropower generation has fallen significantly during droughts, averaging 28.12 TWh in drought years versus 41.51 TWh/year in non-drought years in the last three decades. Accounting for differences in comparative costs of electricity generation obtained from Klein (2010), hydropower has a levelized cost of $70.04 /MWh whereas the potential substitute, Advanced Combined Cycle (CC), would cost $114.36 /MWh, thus the average loss amounts to $593 million /year.

Another potential concern is if the decrease in hydropower generation has a direct effect on electricity prices. As Figure 1.6 also shows, the relative share of hydropower as a proportion of California's total energy generation has been decreasing, meaning that any drought effect on electricity prices will be relatively small because of reduced dependence on hydropower.



Source: Data from CEC (2015)

Figure 1.6: Total in-state power generation plus imports (electricity consumption) vs. hydropower generation.

1.1.5. Water and energy as food inputs

Although California's economic growth today is more reliant on other sectors, its agricultural economic output remains the highest in the U.S. and this sector, which accounts for 80 percent of total water withdrawals, is highly competitive in international agricultural markets. Nowadays the agricultural sector generates 1.3 percent of the Gross State Product (GSP) and employs 6.7 percent of the state's private sector labor force (AIC, 2013). These are statewide aggregate data, but focusing on agricultural regions such as the Central Valley, the share of the gross production and agricultural labor market is much larger for some counties, and more importantly, is usually correlated with poorer regions which are home to more vulnerable inhabitants. Therefore, while the potential impacts on the agricultural sector may not significantly affect the state's economy as a whole, the effects in agricultural regions can be intense.

As noted previously, water scarcity will have direct consequences on food production inputs:

i. Water shortages could reduce sources available for crops, meaning that if no alternative supplies exists, producers will have to apply less water, decreasing yields, switch to a less water-consuming crops which will likely be less profitable, or reduce the area planted.

ii. If the producer has an alternative water source, they will get substitute water but with an increase in production costs because of the energy required to pump groundwater or because water must be purchased through a water transfer scheme. Both situations decrease total profits *ceteris paribus*.

Extrapolating these local implications statewide scale, a drought reduces total revenues and agricultural GSP, and the labor market will be damaged, especially in regions dependent on agricultural. Howitt, MacEwan, and Medellin-Azuara (2011) estimated that $370 million was lost in gross revenue as a result of the 2009 drought, implying 7,500 job losses.

California agriculture is driven by the interactions between technology, resources and market demands (Medellin-Azuara, Howitt, MacEwan, & Lund, 2011). Technological improvements are reflected by the increasing linear trend of agricultural gross state product (GSP), whereas the variations above and below this trend are dependent on international market prices —because only a few California crops have market power— and resource availability.

For all these reasons, it is difficult to foresee the effects of the present drought on overall agriculture revenues but it is certain that it will increase production costs as water becomes expensive during times of shortage and more energy is used to pump from aquifers. Final effects on net revenues will depend largely on prices determined by the international trade.

Regarding food prices, there will not be any effect on the internationally traded market goods such as grain, rice or corn because California is a price taker. In the California-specific crops such as berries or nuts the effects will be uncertain because of the many other variables involved. *Ceteris paribus* some increase in prices would be expected that will reflect the increase of input costs.

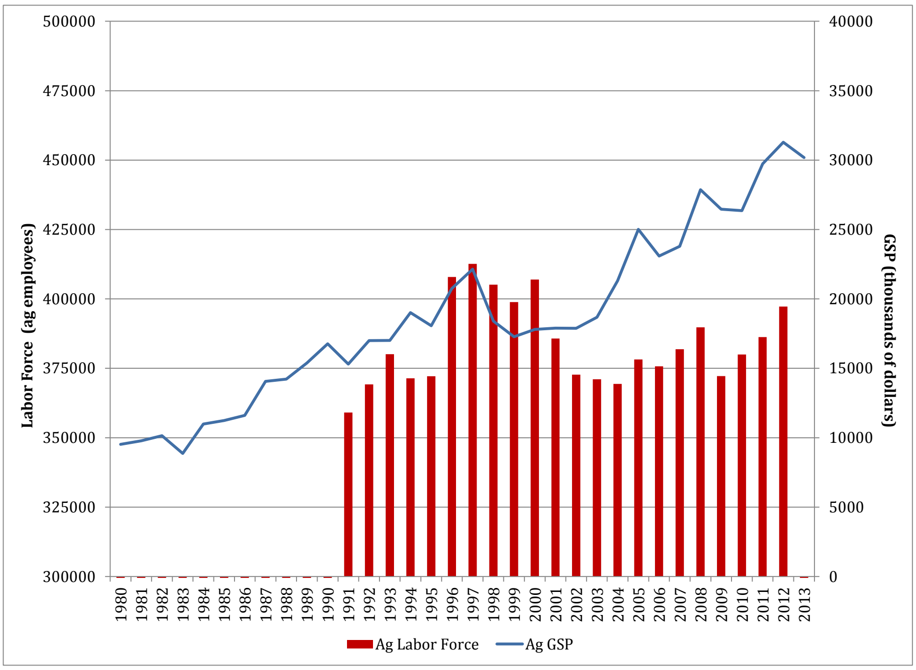


Figure 1.7: Agricultural labor force and agricultural gross state product.

1.1.6. Water, energy, food and the environment

Direct consequences of water scarcity on the environment are obvious: as a water-stressed region, traditional *economic* demands will try to get as much water as they can, thus environmental flows will compete with other uses and it is expected that aquatic species will be severely damaged. However, because of California's unique water system configuration where the Delta plays a main role as a water hub and is susceptible to salinity (Knowles & Cayan, 2002, 2004) even in driest years requires a minimum outflow to maintain salty water far from water exports sources in the south delta. This economic positive effect of environmental flows helps prevent rivers running dry, even during droughts, but there will still be negative effects on aquatic habitats to be managed.

The indirect effects of water scarcity will depend on the variations of energy use associated with water use, and their consequent greenhouse gas (GHG) emissions. Summarizing the variations on water-related energy production and consumption mentioned above the main effects on GHG will be:

i. An increase in GHG emissions due to the substitution from hydropower to thermoelectric electricity generation is expected. Using an emission factor of 499.1 g CO_2e/kWh (Spath & Mann, 2000) it would result in an average 6.68 millions of tons of CO_2e per year accounting to the difference between average hydropower generation in normal and drought-period years, that it will have an economic value of $75.75 million given the current price of the GHG allowances.

ii. If urban water use decreases following demand-side drought management policies, a reduction in urban water-related energy use and greenhouse gases would be expected, that could be significant, considering that that most of the state's water-related energy consumption is for urban uses, especially heating water. Residential water uses are intensive energy uses, therefore saving indoor water uses is a way to significantly reduce GHG.

iii. Finally, increased groundwater pumping to substitute for surface water shortages increase GHG emissions that should be directly related to food production. The same effect would be expected in urban water utilities which have the ability to shift from surface water to groundwater sources.

The variation of GHG emissions related with the water cycle is at least very symbolic since water systems in arid and semi-arid regions are increasing their vulnerability with global warming (Hartmann et al., 2013).

1.1.7. From local conclusions to global considerations

California's intertied water network improves the robustness of statewide water supplies and its economic profits to protect against potential short-term shocks such as droughts and even long-term trends such as climate change. One of the main features of the system is that most demands have diversified their water source portfolio to increase their economic reliability, even creating institutional tools water markets.

But when water supplies fail, normality is altered, hydropower generation diminishes, the agricultural sector uses more energy to pump or convey water, raising GHG emissions at the same time, and food production input costs increases. Only through urban demand-side policies can water be saved without direct costs —just a temporary loss in the living-standards utility function— and achieving a significant water-related energy and GHG emissions savings.

These interrelations have non-trivial economic implications: from the perspective of the ordinary citizen, urban water rates would increase if DSMP are implemented, and energy, water and food prices would have some price effect due to reduced hydropower production, increase pumping from groundwater, and increased input costs for the food production sector; water and energy utilities will incur some extra costs because of the drought, but they will be relatively small due to improved water and energy source portfolios; from the agricultural sector, and assuming that prices will vary slightly because of international trade, the increased input costs will cause significant economic losses and a reduction in the employment, especially in those counties that depend on agriculture; and finally accounting for statewide general consequences, GHG emissions will increase from reduced hydropower production and increased urban and agricultural pumping and conveyance, whereas the expected decrease will depend on the effectiveness of the urban conservation policies taken.

The conclusions above are strictly determined by local water, energy and food production systems in California today, but from these arguments some final thoughts might be developed relevant for other water-stressed regions where some of the assumptions do not hold exactly as in California:

- Less developed countries with a greater share of the gross product determined by the agricultural sector should expect larger impacts of economic and labor market losses from water scarcity.
- Countries highly dependent on hydropower could suffer significant problems of energy supply due to water shortages, and a severe drought could imply a significant effect on final energy prices. Therefore, improvements of the energy portfolio should be a priority for countries with uncertain climate projections.
- Agricultural regions not shaped and buffered by the international trade are expected to suffer high price volatility for food commodities.
- Less integrated water systems or those dependent on a unique water source will be more vulnerable to droughts.

Therefore, integrated approaches are essential to assess the interrelated effects of water, food production, energy and environment systems in more vulnerable regions to minimize economic losses and potential damages.

1.2. The water-energy nexus: a "bottom-up" approach for basin wide management

1.2.1. Introduction

Given the importance of the water-energy-food relationship interconnections shown in the previous section, I decide to focus this dissertation in a significant part of it: the energy use (and related GHG emissions) of the anthropogenic water cycle.

As stated in "California's water-energy relationship" report by the California Energy Commission (CEC, 2005):

> *"A major portion of the solution is closer coordination between the water and energy sectors. A meaningful solution cannot be reached in the current regulatory environment where water utilities value only the cost of acquisition, conveyance, treatment, and delivery; wastewater utilities value only the cost of collection, treatment, and disposal; electric utilities value only saved electricity; and natural gas utilities value only saved natural gas. The state must both develop and expand best practices and existing programs to realize the substantial incremental benefits of joint water and energy resources and infrastructure management".*

Because the novelty of this field most of the identified research has focused in pure assessment of the water-energy nexus, either the quantification of water-related energy in different water uses or the water necessities of different power generation facilities. A big gap still exists in assessing the outputs for different stakeholders from different changes in water use and management options because the lack of models capable to predict the consequences of these complex systems. Therefore, and following the CEC report recommendations, the focus of this research is to build models that using previous published water-energy assessments, can predict the effects in energy use and GHG emissions of different policy and management strategies in different phases of the anthropogenic water cycle.

In the remainder of the chapter I review the state of the art of the water-energy nexus identifying the main research gaps in the field, later I set forth the objectives of the research, and finally the structure and approach of the dissertation is described.

1.2.2. The water-energy nexus literature

Although in each of the chapters I include a more extensive literature review for the purpose of the chapter, here I summarize the milestones of the literature reviewed in the water-energy interrelationship highlighting the research gaps.

To improve the quality of the review I divide the section in the most common topics found in the literature: energy use of urban water end-uses; the urban water-energy relationship; energy consumption of agricultural water use; water use for energy generation; and the large scale water-energy nexus.

1.2.2.1. Energy use of urban water end-uses

Urban end-uses are the highest energy-intensive water use, but the heterogeneity of these uses makes difficult their assessment. The improvement in high-definition monitoring has eased the quantification of water consumption of different end-uses and has been applied specially to residential water use (Cominola, Giuliani, Piga, Castelletti, & Rizzoli, 2015). From water end-uses, different approaches have been taken to obtain energy use focusing mostly in energy and GHG savings from water conservation strategies.

As a precursor in the field, deMonsabert and Liner (1998) developed a model (WATERGY) to identify water conservation options with simple payback periods of 10 years of less that calculates both direct and indirect savings associated with a water conservation effort. Although a really interesting approach, model accuracy was not tested empirically because the lack of data in these early years, so its reliability is undetermined.

The Appendix B of the California Energy Commission report (CEC, 2005) enumerates (without any explanation) the attribution of energy consumption of the water end-uses. Although their approach is really simplistic, using the total energy used by the end-use and multiplying this total energy use by a percentage of water-related energy, it is almost the unique study that reports all the water-related energy consumption of the water-end uses (residential, commercial, industrial, mining and transportation).

Following the recommendations of the CEC report (CEC, 2005), the California Public Utilities Commission (CPUC) developed an embedded Water-Energy Measure Calculator composed by three different studies. Within this framework, Funk and DeOreo (2011) developed the End-use Water Demand Profile, that was designed to provide accurate hourly water use profile data that may be used alongside concurrent studies' information to update the CPUC Water-Energy Measure Calculator. Although that study did not include energy consumption, was the basis for the other studies to calculate the embedded energy of the urban water end-uses.

Fidar et al. (2010) developed a methodology to quantify and analyze the energy consumption and associated carbon emissions resulting from achieving the carious water efficiency levels set out in the Code for Sustainable Homes (CSD) in England. Their results confirmed that significant fractions of water-related energy use and associated carbon emissions are attributed to in-house water consumption, and also confirmed that many composite strategies, whilst saving water do not necessarily save energy or reduce carbon emissions.

Kenway, Scheidegger, Larsen, Lant, and Bader (2013) applied a model for water use, water-related energy and related CO_2 emissions and costs that provided a system understanding of water-related household activities. The study showed that technical improvements alone result in a less that about 15 percent reduction in energy and CO_2

and that behavioral changes have the potential to be very effective in terms of water saving and reduction of water-related energy and GHG emissions.

Morales, Heaney, Friedman, and Martin (2013) presented a parcel-level methodology to estimate water and energy savings associated with indoor water conservation best management practices. Their results showed that energy costs are seen to have a major effect on the benefits that customers can obtain if they install more efficient retrofits.

Abdallah and Rosenberg (2014) developed an integrated approach to model heterogeneous household water and energy use and their linkages using a large dataset, analyzing how different parameters affect water and energy consumption. Among others outputs, their results show that household behaviors are similar across study sites whereas appliance technological performances differ.

With a really different approach based on an econometric analysis, Hansen (1996) estimated the water demand function including both water and energy prices as dependent variables, and found a significant negative energy cross-price elasticity of -0.2 (larger than the water own-price elasticity of -0.1 or less). This result is really interesting, but any other study has been found in this topic.

There is a growing literature on the energy consumption and GHG emissions of water use that has focused mostly in assessments of water-related energy and GHG emissions and potential benefits from water conservation. Most of the studies obtain the benefits by multiplying potential conservation actions on average results, undermining their capacity to assess actual results from a population of heterogeneous water users. The study of Abdallah and Rosenberg (2014) is an exception in this sense, using heterogeneity in the parameters of their model.

Residential water-use depends on the price paid by customers, geographic conditions, household composition, water using appliance technology and other behavioral characteristics. Although, the studies cited above do not explicitly examine the effects of geography and pricing on customer water-use and water-related energy and GHG emissions. Therefore, to conduct a regional study it must be included these differences in geographic and price conditions that have not been analyzed before.

Another significant gap is that all the studies presented 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 & Stavins, 1994). Here, the lack of information, the cost to get that information and uncertainty of future prices might explain non-adoption of seemingly beneficial strategies.

Given that there is only one study found about water and energy cross-price elasticities (Hansen, 1996) much more has to be done in this field to understand the potential cross effects of water and energy prices.

Finally it has to be mentioned that exists a significant gap on the commercial, industrial and rest of urban water end-uses, mostly because the lack of comprehensive datasets, both on the water and energy side, to estimate the energy consumption of a huge variety of industrial, commercial and the remaining of non-residential end-uses.

1.2.2.2. The urban water-energy relationship

Probably the most researched side of the water-energy relationship is that related to the urban cycle of water. Different water supply options, treatment and distribution operations, and wastewater collection and treatment have different energy necessities that are largely recorded in the literature.

Raluy, Serra, Uche, and Valero (2004) analyzed the evolution of environmental impact by means of the Life-Cycle Assessment (LCA) technique caused by the most common commercial desalination technologies used worldwide. Following a similar approach, a hybrid LCA, Stokes and Horvath (2009) explored air emission effects of supplying water obtaining that for the typically sized U.S. utility analyzed, recycled water is preferable to desalination and comparable to importation.

Reffold (2008) examined the difference in GHG gas emissions associated with a variety of options for supplying water and using it more efficiently plus methods and products to reduce and manage households' water demand. One of the key findings is that all supply side measures result in an increase in carbon emissions, because the more efficient ones are already being used, so demand management options result in reductions of the carbon footprint of the water supply.

Within the framework of the California Public Utilities Commission (CPUC) following the recommendations of the CEC report (CEC, 2005), Park and Bennett (2010) characterized and quantified the relationships between water and energy use by water and wastewater agencies, and determined the range of magnitudes and key drivers of embedded energy in water. This is one of the largest surveys conducted in the supply side of the water cycle.

Kenway, Lant, and Priestley (2011) considered connections between water and energy in the provision and consumption of water in cities, as well as in the management of wastewater obtaining that water-related energy in a hypothetical Australian city of 1,000,000 people accounted for 13 percent of national electricity use, 18 percent of natural gas use and 9 percent of primary energy use, amounting for 8 percent of total national GHG emissions.

Mo, Zhang, Mihelcic, and Hokanson (2011) analyzed with and input-output based hybrid analysis the embodied energy in a groundwater supply system (Kalamazoo, Michigan) and a surface water supply system (Tampa, Florida). Some years later, a similar approach to estimate embodied energy, GHG emissions and energy costs but considering new water sources in Tampa Bay, Florida and San Diego, California was conducted (Mo, Wang, & Zimmerman, 2014).

Following the supply-side of the urban nexus, Nair, George, Malano, Arora, and Nawarathna (2014) presented a literature review and assessment of knowledge gaps related to water-energy-greenhouse gas nexus studies, analyzing also the energy intensity of decentralized water systems and various water end-uses together with the major tools and models used.

The approach taken by Spang and Loge (2015) is kind of newfangled because their objective was to map energy intensity within a water utility finding significant variations in the energy intensity of delivered potable water resulting from seasonal and topographic effects. As a main conclusion they state that “understanding when and where water is being used is essential for understanding the energy impacts of water consumption, or conversely, for estimating the linked energy benefits of conserving water”.

Most of the studies cited assess either some parts —especially water supply sources— or the entire urban water-energy nexus, and only some studies assessed with really low-level of detail —because they use average values— the effects of changes in water demand on the entire urban nexus. Furthermore, although end uses often have the highest energy use of all water-sector elements, it has not traditionally been seen as a direct part of the water sector and is often unaccounted for in water and energy management and policy (Rothausen & Conway, 2011). Therefore there is a significant gap in coupled end-use and utility-scale models to assess the energy and carbon footprint of the urban water cycle to assess demand side management policies to reduce GHG emissions, as seen from customer, water and energy utilities, and state or national perspectives.

Another interesting gap identified is that there is not any study about the effects on both water and energy utilities of water demand management actions. Because some elements of the water cycle are large energy consumers (mainly urban users), there is the potential collaboration for water customers and water utilities with energy utilities to reduce energy peaks, saving money and improving efficiency in the electricity market. Furthermore, reducing water peaks can deliver substantial savings in infrastructure capacity and operations (Cole, O'Halloran, & Stewart, 2012).

1.2.2.3. Energy consumption of agricultural water use

There are few references about the energy consumption of agricultural water use, being the CEC report on California Agricultural Water Electrical Energy Requirements (CEC, 2003) one of the most comprehensive contributions on the field. This study assessed the energy use for agricultural water by water destinations (i.e. irrigation district surface and groundwater pumping, on-farm groundwater and booster pumping, and conveyance to irrigation districts), calculated the energy embedded in transferring historical agricultural water to other destinations, estimated potential future energy requirements and finally analyzed potential impacts of different policies.

With a broader approach Schnepf (2004) assessed direct —fuel or electricity to operate machinery and equipment, to heat or cool buildings, and for lighting on the farm— and indirect —fertilizers and chemicals produced off the farm— energy used in the agriculture in the United States. The author provided information relevant to the U.S. agricultural sector on energy use, emerging issues, and related legislation. Whereas relevant because the lack of information on the agricultural side of the nexus, the water-related energy use was not explicitly considered.

Although their simplistic approach, it is wort to note that the Appendix B of the California Energy Commission report (CEC, 2005) enumerates (without any explanation) the attribution of energy consumption of the water end-uses including the agricultural supply.

Jackson, Khan, and Hafeez (2010) conducted a comparative analysis of water application and energy consumption of different irrigation technologies in Australia. Among others, one of their key results show that converting from flood to pressurized systems resulted in a reduction in water application of between 10 percent and 66 percent, however the increase in energy consumption was up to 163 percent. In a groundwater dependent region, their assessment showed that the total energy consumption was reduced by 12 to 44 percent when converting from flood to pressurized systems.

There are many other references that analyze the energy consumption of different crops under different conditions or scenarios (see Table 2 in Rothausen and Conway (2011) for a review) but they are actually far away from the objectives of this dissertation.

Therefore, although there are some studies about the energy consumption of water use in agriculture the field is still needed of more references to analyze it in a proper way. I found an important gap at the larger scale, beyond the field level, on how the effects of converting flood to pressure irrigation is decreasing the recharge so affecting the groundwater level at a larger scale what could increase total energy consumption. Beyond this issue, and because most of the studies cited focus on assessments of the energy consumption of water use, there is a need for larger scale models that include water and energy consumption and the effects of agricultural practices on water resource systems and the environment.

1.2.2.4. Water use for energy generation

Water use for energy generation facilities is becoming more important especially in water stressed regions. In the United States above 50 percent of the water withdrawals are related with thermoelectric power generation (Healy, Alley, Engle, McMahon, & Bales, 2015) although most of these withdrawals are returned to the water system without being actually consumed.

There is a high variability of water-related uses from power generation, but it is possible to extract the water-intensity of the different power generation facilities using data from recent studies. Macknick, Newmark, Heath, and Hallett (2012) provided estimates of operational water withdrawal and water consumption factors for electricity generating technologies in the United States that were collected from published primary literature.

Using a similar approach, Mielke, Diaz Anadon, and Narayanamurti (2010) collected an overview of water consumption for different sources of energy, including extraction, processing and conversion of resources, fuels and technologies. Whereas their primary focus was consumptive use of water for different sources of energy, levels of water withdrawals were also discussed, especially in the context of cooling of thermoelectric power plants.

Tidwell, Kobos, Malczynski, Klise, and Castillo (2012) estimated the potential impact of water availability on future expansion of thermoelectric power generation. Specifically, both the extent and location of thermoelectric development at risk due to limited fresh water-supply was estimated for a variety of alternative energy futures that differ according the assumed mix of fuels utilized in new plant construction.

What is really interesting from the point of view of the water and energy management challenges is that some periods with high temperatures can concur with drought conditions, resulting in an increase in energy demands for residential use and water demands for energy generation, at the same time that reduced water availability. Scanlon et al. (2013) analyzed this fact in Texas using an extreme drought in 2011, quantifying water and electricity demand and supply for power plants during the drought relative to 2010, and obtained that even that water use for gas production is controversial, water saved by using natural gas combined cycle plants relative to coal steam turbine plans is 25-50 times greater than the amount of water used in hydraulic fracturing to extract the gas.

Another topic that has attracted a lot of attention is the water use for biofuel production. Using a life-cycle analysis, de Fraiture, Giordano, and Liao (2008) explored the land and water implications of increased biofuel production globally, focusing in China and India, concluding that local and regional impact could be substantial. With a similar approach Galan-del-Castillo and Velazquez (2010) showed the strong nexus between water and energy in biofuel production estimating the virtual water and the water footprint from the raw material production that were needed to reach the Spanish targets for biofuel consumption by 2010.

Although many are the approaches and papers that have assessed the water consumption of the power generation facilities, as far as the author know, none of these studies have included the energy generation in more general water resource system models. Therefore a gap still exists in this topic.

1.2.2.5. The large-scale water-energy nexus

Finally, the last topic in the literature of the water-energy nexus is related to the studies that try to summarize and add up all the previous results in a regional, national or supra-national scale. This was the goal of the report in the Californian context (CEC, 2005), and also of the work conducted later by Wolff and Wilkinson (2011), and there are many replications in different ways of this methodology that uses available data to summarize water-related energy consumption and/or water necessities of energy generation.

In 2006 the Department of Energy release a report to the U.S. Congress on the interdependency of energy and water (DoE, 2006). This report stated that in a business-as-usual scenario, consumption of water in the electric sector could grow substantially, therefore, the U.S. should carefully consider carefully energy and water development and management so that each resource is used according to its full value.

Using similar regional, national or supra-national approaches, Siddiqi and Anadon (2011), Hardy, Garrido, and Juana (2012), Sanders and Webber (2012) and Tidwell, Moreland, and Zemlick (2014) explored the energy footprint of water use for the Middle East and North Africa, Spain, the United States and the western United States respectively.

Although all these studies are really interesting because the insights that they are providing for large-scale policy analysis, they are less interesting from the management side of the current systems. Therefore, there is a significant gap in large-scale modeling to understand the effects of different management options and policies on the energy consumption of water resource systems, and also to know how the water use of the power sector is increasing the competition for water use.

Even though that is not estimating the water-energy nexus in specific location, the work of Plappally and Lienhard (2012) is included in this section because their intention is to provide energy intensities in most water uses that could result in a large-scale analysis. They surveyed the available literature on energy intensity for water use in the municipal and agricultural sectors and separated the processes into several stages obtaining representative values of the energy consumed per unit water for a broad range of processes.

Finally it is worth to notice some studies that are assessing the water-energy relationship of large infrastructure. The study of CPUC within the framework of the Water-Energy Measure Calculator (CPUC, 2010) collected detailed water and energy data from nine large or wholesale water agencies —including large conveyance of the State Water Project in California—, estimation of the total amount of energy used in the supply and conveyance segment of the water cycle, and developed a predictive model for estimating the range of energy impacts under a variety of scenarios. Another interesting work was conducted by Munoz, Mila-i-Canals, and Fernandez-Alba (2010) analyzing the tradeoffs in different large-scale supply options in Spain using a life-cycle assessment approach.

Both latest approaches are really interesting to obtain data to develop large-scale modelling of water resource systems accounting for energy use of the water cycle.

1.2.3. Research objectives

The main objective of this research is *to develop a hydro-economic model of water management at the basin-scale including water balance (traditional models) and the water-related energy consumption and GHG emissions of the entire water cycle, including urban, agricultural, environmental and energy-related water demands.*

To develop this goal I followed a bottom-up approach trying to address the most significant sides of the water-energy nexus while filling the gaps that I have identified in the previous section.

As it has been aforementioned in review of the literature, most of the studies analyzing the water-energy nexus focused on pure assessments of this relationship, either of the water use of energy generation or the energy use of the water cycle. Therefore it is a transversal objective for each chapter in this dissertation to develop economic models that will be able to analyze the results on water, and related energy and GHG emissions of different policy and management options.

The specific objectives conducting to the development of the main goal of this research and the research questions that I am trying to answer are:

- **Objective 1**: Develop a residential water end-use model assessing related energy and GHG emissions in California. The model will explicitly account for heterogeneity in water and water-related energy use, geographic parameters affecting use, and variability in costs due to different water and energy rate structures.
    - How much energy and GHG emissions are associated with residential water end-uses?
    - How spatial variability and heterogeneity in consumption affects water and energy use?
    - How different water and energy rate structures can incentive/disincentive water and energy conservation?
- **Objective 2:** Develop an economic optimization model to obtain the optimal conservation strategies that Californian households can take to save water, and related energy and GHG emissions.
    - Based on variability of water and energy prices in different locations, what are the optimal strategies to save water and related energy in households?
    - How including energy costs in customer’s perception of water use can increase water conservation attitudes?
    - How significant are water and energy own- and cross-price elasticities?

- **Objective 3:** Develop an urban-scale water and energy model that can assess heterogeneous water demand side management policies and the effects of these policies on households, water and energy utilities, and the environment.
    - How much energy and GHG emissions are embedded in the urban water cycle and who is the final responsible of them?
    - What are the economic effects of water conservation on water and energy utilities?
    - Are there synergies for water and energy utilities to work together?
- **Objective 4:** Develop a basin-scale water model including water-related energy and GHG emissions from water operations and from end-uses, including demands from cities, agriculture, environment and the energy sector.
    - How much energy and GHG emissions are embedded in the water cycle?
    - How increased demand is affecting energy and GHG emissions from water use?
    - What are the effects of large-scale water management options in energy consumption and greenhouse gas emissions?
    - Is the energy sector a real competitor for other water uses in California?

1.2.4. Research approach

To achieve the main goal of the research a bottom-up approach is used with three main levels: an end-use model, an urban model, and finally a basin-scale model.

The end-use model focused on the residential water-energy nexus because it is the largest water end-use contributor to total water-related energy and GHG emissions (CEC, 2005). For this model water data use from a survey of more than 700 single-family households across ten different locations in California was obtained from Aquacraft Inc. (DeOreo et al., 2011), whereas the energy parameters where obtained from the Residential Energy Consumption Survey (USEIA, 2009).

The second stage was to build the urban water-energy model. For this model I used the results of the residential end-use model as a main input, but because the lack of data or the non-residential urban end-uses (commercial, institutional, and industrial & petroleum) I obtained energy-intensities for these other uses from the literature. Once all the urban end-uses were characterized, I used water-related energy data for water supply, treatment, pumping, and wastewater treatment from East Bay Municipal District in California, and energy prices form the California Independent System Operator.

The last stage was to develop a hydro-economic basin-scale water model including related energy and GHG emissions. For this model I used the previous urban model to represent all the main populated areas just changing the population parameters for each urban area represented. I developed another end-use model for agricultural water-related energy use accounting for different supply sources and irrigation technologies. Environmental and power generation water demands were also included, assessing their energy consumption depending on their water source. Once all the water and water-related energy demands were characterized, the final step was to assemble the water resource model. Because the many and diverse sources of information used in this stage, I refer to Chapter 5 for a more comprehensive understanding.

1.2.5. Organization of the dissertation

This dissertation comprises seven chapters, which are organized in the following manner:

In **Chapter 2**, starting from a household water end-use data survey, a model for residential water use and water-related energy and GHG emissions is presented, accounting for heterogeneity in consumption and spatial variability. Water and energy costs are also included accounting for different water and energy rate structures. Finally, simulation runs assess the impact of several common conservation strategies on residential water and energy use.

Based on the previous results, **Chapter 3** develops an optimization model to assess increased residential water and energy savings when energy is included in the traditional water management conservation strategies including short- and long-term strategies to deal with water and energy price variability. Methodologically this chapter contributes also with water and energy economics by presenting a new approach to obtain water and energy own- and cross-price elasticities.

Using both final water end-use and related energy data and water-related energy use from urban services, **Chapter 4** develops a coupled end-use and utility-scale water-energy model with an hourly time step. This model is capable to assess the total water-related energy use and GHG gas emissions from each of the parts of the urban water cycle including final end-uses, and to analyze how changes in water consumption patterns affect water and energy utilities.

In **Chapter 5** a basic decision support system of water resource system management is described accounting for water-related energy and GHG emissions and water-dependent energy generation that includes an interrelation of surface water and groundwater systems. The model is applied using a simplification of the California intertied water system using available data from different sources in the period 1984 to 2003 obtaining water and water-related energy and GHG emissions results for the historic data with the historic conditions, and then I run several simulations of different scenarios.

Chapter 6 summarizes of the results' discussion for each chapter, and then a general discussion of the results is presented.

Finally, all the thematic and methodologic conclusions are summarized in **Chapter 7**.

1.3. References

Abdallah, A., & Rosenberg, D. (2014). Heterogeneous Residential Water and Energy Linkages and Implications for Conservation and Management. *Journal of Water Resources Planning and Management, 140*(3), 288-297. doi: doi:10.1061/(ASCE)WR.1943-5452.0000340

AIC. (2013). The measure of California agriculture. Highlights. University of California, Davis. Agricultural Issues Center. Available at http://aic.ucdavis.edu/publications/moca/MOCAbrochure2013.pdf. Accessed 21/4/2014.

CEC. (2003). California Agricultural Water Electrical Energy Requirements. ITRC Report No. R 03-006. California Energy Commission. Sacramento. December 2003.

CEC. (2005). California's Water - Energy Relationship. Prepared in Support of the 2005 Integrated Energy Policy Report Proceeding. California Energy Commission. November 2005. CEC-700-2005-011-SF.

CEC. (2007). *Refining Estimates of Water-related Energy Use in California: PIER Final Project Report.*: California Energy Commission.

CEC. (2014). Energy Almanac. The California Energy Commission. Available at http://energyalmanac.ca.gov/electricity/. Accessed 21/4/2014.

CEC. (2015). Electric Generation Capacity & Energy. Energy Almanac. California Energy Commission. Online resource available at: http://www.energyalmanac.ca.gov/. Accessed on June 19, 2015.

Cole, G., O'Halloran, K., & Stewart, R. A. (2012). Time of use tariffs: implications for water efficiency. *Water Science and Technology-Water Supply, 12*(1), 90-100. doi: Doi 10.2166/Ws.2011.123

Cominola, A., Giuliani, M., Piga, D., Castelletti, A., & Rizzoli, A. E. (2015). Benefits and challenges of using smart meters for advancing residential water demand modeling and management: A review. *Environmental Modelling & Software, 72*, 198-214.

CPUC. (2010). Embedded Energy in Water Studies. Study 1: Statewide and Regional Water-Energy Relationship. Prepared by GEI Consultants/Navigant Consulting, Inc. California Public Utilities Commission. August 31, 2010.

de Fraiture, C., Giordano, M., & Liao, Y. S. (2008). Biofuels and implications for agricultural water use: blue impacts of green energy. *Water Policy, 10*, 67-81. doi: Doi 10.2166/Wp.2008.054

deMonsabert, S., & Liner, B. L. (1998). Integrated energy and water conservation modeling. *Journal of Energy Engineering-Asce, 124*(1), 1-19. doi: Doi 10.1061/(Asce)0733-9402(1998)124:1(1)

DeOreo, W. B., Mayer, P. W., Martien, L., Hayden, M., Funk, A., Kramer-Duffield, M., & Davis, R. (2011). California single-family water use efficiency study. Aquacraft, Inc. Water Engineering and Management. July 20, 2011.

DoE, U. (2006). Energy demands on water resources: Report to Congress on the interdependency of energy and water. *Washington DC: US Department of Energy*, 1.

DWR. (2009). California Water Plan. Update 2009. Available at http://www.waterplan.water.ca.gov/cwpu2009/. Accessed 20/4/2014.

DWR. (2012). Drought in California. California Department of Water Resources. Natural Resources Agency. State of California . Fall 2012.

Fidar, A., Memon, F. A., & Butler, D. (2010). Environmental implications of water efficient microcomponents in residential buildings. *Science of the Total Environment, 408*(23), 5828-5835. doi: DOI 10.1016/j.scitotenv.2010.08.006

Fuchs, B. (2015). United States drought monitor. National Drought Mitigation Center. Available at http://droughtmonitor.unl.edu/. Accessed June 25, 2015.

Funk, A., & DeOreo, W. B. (2011). Embedded Energy in Water Studies, Study 3: End-use Water Demand Profiles. *Prepared by Aquacraft, Inc. for the California Public Utilities Commission Energy Division, Managed by California Institute for Energy and Environment, CALMAC Study ID CPU0052*.

Galan-del-Castillo, E., & Velazquez, E. (2010). From water to energy: The virtual water content and water footprint of biofuel consumption in Spain. *Energy Policy, 38*(3), 1345-1352. doi: http://dx.doi.org/10.1016/j.enpol.2009.11.015

Hanak, E., Lund, J., Dinar, A., Gray, B., Howitt, R., Mount, J., . . . Thompson, B. (2011). Managing California's Water: From Conflict to Reconciliation. San Franciso, CA: Public Policy Institue of California.

Hanak, E., & Stryjewski, E. (2012). California´s water market, by the numbers: Update 2012. Public Policy Institute of California.

Hansen, L. G. (1996). Water and energy price impacts on residential water demand in Copenhagen. *Land Economics, 72*(1), 66-79. doi: Doi 10.2307/3147158

Hardy, L., Garrido, A., & Juana, L. (2012). Evaluation of Spain's Water-Energy Nexus. *International Journal of Water Resources Development, 28*(1), 151-170. doi: Doi 10.1080/07900627.2012.642240

Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y., . . . Zhai, P. M. (2013). 2013: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Healy, R. W., Alley, W. M., Engle, M. A., McMahon, P. B., & Bales, J. D. (2015). The water-energy nexus—An earth science perspective: U.S. Geological Survey Circular 1407, 107 p., http://dx.doi.org/10.3133/cir1407.

Howitt, R. E., MacEwan, D. J., & Medellin-Azuara, J. (2011). "Droughts, Jobs and Controversy: Revisiting 2009." Agricultural and Resources Economics Update 15(6): 1-4.

Jackson, T. M., Khan, S., & Hafeez, M. (2010). A comparative analysis of water application and energy consumption at the irrigated field level. *Agricultural Water Management, 97*(10), 1477-1485. doi: DOI 10.1016/j.agwat.2010.04.013

Jaffe, A. B., & Stavins, R. N. (1994). The Energy-Efficiency Gap - What Does It Mean. *Energy Policy, 22*(10), 804-810. doi: Doi 10.1016/0301-4215(94)90138-4

Kenway, S. J., Lant, P., & Priestley, T. (2011). Quantifying water-energy links and related carbon emissions in cities. *Journal of Water and Climate Change, 2*(4), 247-259. doi: 10.2166/wcc.2011.005

Kenway, S. J., Scheidegger, R., Larsen, T. A., Lant, P., & Bader, H. P. (2013). Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings, 58*, 378-389. doi: DOI 10.1016/j.enbuild.2012.08.035

Klein, J. (2010). Comparative costs of California central station electricity generation. California Energy Commission. Final Staff Report. January 2010.

Knowles, N., & Cayan, D. R. (2002). Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. *Geophysical Research Letters, 29*(18). doi: Artn 1891 Doi 10.1029/2001gl014339

Knowles, N., & Cayan, D. R. (2004). Elevational dependence of projected hydrologic changes in the San Francisco Estuary and watershed. *Climatic Change, 62*(1-3), 319-336. doi: Doi 10.1023/B:Clim.0000013696.14308.B9

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters, 7*(4). doi: Artn 045802 Doi 10.1088/1748-9326/7/4/045802

Medellin-Azuara, J., Howitt, R. E., MacEwan, D. J., & Lund, J. R. (2011). Economic impacts of climate-related changes to California agriculture. *Climatic Change, 109*, 387-405. doi: DOI 10.1007/s10584-011-0314-3

Mielke, E., Diaz Anadon, L., & Narayanamurti, V. (2010). Water consumption of energy resource extraction, processing, and conversion. Energy Technology Innovation Policy Research Group. Harvard Kennedy School. Belfer Center for Science and International Affairs. October 2010.

Mo, W. W., Wang, R. R., & Zimmerman, J. B. (2014). Energy-Water Nexus Analysis of Enhanced Water Supply Scenarios: A Regional Comparison of Tampa Bay, Florida, and San Diego, California. *Environmental Science & Technology, 48*(10), 5883-5891. doi: Doi 10.1021/Es405648x

Mo, W. W., Zhang, Q., Mihelcic, J. R., & Hokanson, D. R. (2011). Embodied energy comparison of surface water and groundwater supply options. *Water Res, 45*(17), 5577-5586. doi: 10.1016/j.watres.2011.08.016

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

Munoz, I., Mila-i-Canals, L., & Fernandez-Alba, A. R. (2010). Life Cycle Assessment of Water Supply Plans in Mediterranean Spain. *Journal of Industrial Ecology, 14*(6), 902-918. doi: DOI 10.1111/j.1530-9290.2010.00271.x

Nair, S., George, B., Malano, H. M., Arora, M., & Nawarathna, B. (2014). Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resources Conservation and Recycling, 89*, 1-10. doi: 10.1016/j.resconrec.2014.05.007

Park, L., & Bennett, B. (2010). Embedded Energy in Water Studies-Study 2: Water Agency and Function Component Study and Embedded Energy-Water Load Profiles. *Sacramento, CA: California Public Utilities Commission*.

Plappally, A. K., & Lienhard, J. H. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable & Sustainable Energy Reviews, 16*(7), 4818-4848. doi: 10.1016/j.rser.2012.05.022

Raluy, R., Serra, L., Uche, J., & Valero, A. (2004). Life-cycle assessment of desalination technologies integrated with energy production systems. *Desalination, 167*, 445-458.

Reffold, E. (2008). *Greenhouse gas emissions of water supply and demand management options*: Environment Agency.

Rothausen, S. G. S. A., & Conway, D. (2011). Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change, 1*(4), 210-219. doi: Doi 10.1038/Nclimate1147

Sanders, K. T., & Webber, M. E. (2012). Evaluating the energy consumed for water use in the United States. *Environmental Research Letters, 7*(3). doi: Artn 034034

Doi 10.1088/1748-9326/7/3/034034

Scanlon, B. R., Duncan, I., & Reedy, R. C. (2013). Drought and the water-energy nexus in Texas. *Environmental Research Letters, 8*(4). doi: Artn 045033

Doi 10.1088/1748-9326/8/4/045033

Schnepf, R. D. (2004). *Energy use in agriculture: Background and issues*.

Scholten, H., Kassahun, A., Refsgaard, J. C., Kargas, T., Gavardinas, C., & Beulens, A. J. M. (2007). A methodology to support multidisciplinary model-based water management. *Environmental Modelling & Software, 22*(5), 743-759. doi: http://dx.doi.org/10.1016/j.envsoft.2005.12.025

Siddiqi, A., & Anadon, L. D. (2011). The water-energy nexus in Middle East and North Africa. *Energy Policy, 39*(8), 4529-4540. doi: DOI 10.1016/j.enpol.2011.04.023

Spang, E. S., & Loge, F. J. (2015). A High-Resolution Approach to Mapping Energy Flows through Water Infrastructure Systems. *Journal of Industrial Ecology, 19*(4), 656-665. doi: 10.1111/jiec.12240

Spath, P. L., & Mann, M. K. (2000). Life cycle assessment of a natural gas combined-cycle power generation system. National Renewable Energy Laboratory. U.S. Department of Energy.

Stokes, J. R., & Horvath, A. (2009). Energy and Air Emission Effects of Water Supply. *Environmental Science & Technology, 43*(8), 2680-2687. doi: 10.1021/es801802h

Tidwell, V. C., Kobos, P. H., Malczynski, L. A., Klise, G., & Castillo, C. R. (2012). Exploring the Water-Thermoelectric Power Nexus. *Journal of Water Resources Planning and Management-Asce, 138*(5), 491-501. doi: Doi 10.1061/(Asce)Wr.1943-5452.0000222

Tidwell, V. C., Moreland, B., & Zemlick, K. (2014). Geographic Footprint of Electricity Use for Water Services in the Western US. *Environmental Science & Technology, 48*(15), 8897-8904. doi: Doi 10.1021/Es5016845

Torcellini, P., Long, N., & Judkoff, R. (2003). Consumptive water use for U.S. power production. National Renewable Energy Laboratory. U.S. Deparment of Energy. December 2003.

USEIA. (2009). *Residential Energy Consumption Survey 2009. U.S. Energy Information Administration. Available at http://www.eia.gov/consumption/residential/index.cfm. Accessed 4/14/2014.*

Vorosmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science, 289*(5477), 284-288. doi: DOI 10.1126/science.289.5477.284

Wolff, G., & Wilkinson, R. (2011). Statewide Assessment of Water-Related Energy Use for the Year 2000. California Energy Commission, PIER Energy-Related Environmental Research Program: Sacramento: Californian Energy Commission.

PART II:
RESEARCH PAPERS

Chapter 2

Modeling residential water and related energy, carbon footprint and costs in California[1]

Abstract

Starting from single-family household water end-use data, this study develops an end-use model for water-use and related energy and carbon footprint using probability distributions for parameters affecting water consumption in 10 local water utilities in California. Monte Carlo simulations are used to develop a large representative sample of households to describe variability in use, with water bills for each house for different utility rate structures.

The water-related energy consumption for each household realization was obtained using an energy model based on the different water end-uses, assuming probability distributions for hot-water-use for each appliance and water heater characteristics. Spatial variability is incorporated to account for average air and household water inlet temperatures and price structures for each utility. Water-related energy costs are calculated using averaged energy price for each location. CO_2 emissions were derived from energy use using emission factors.

Overall simulation runs assess the impact of several common conservation strategies on household water and energy use. Results show that single-family water-related CO_2

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emissions are 2% of overall per capita emissions, and that managing water and energy jointly can significantly reduce state greenhouse gas emissions.

2.1. Introduction

The increasing awareness of the high consumption of energy in the water sector has attracted considerable attention to water-energy interdependences. Most attention has focused on individual large consumers such as inter-basins transfers or energy-intensive water pumping or desalination. However, most overall water-related energy consumption happens inside households (Reffold, Leighton, Choufhoury, & Rayner, 2008), a large and heterogeneous group of small users. Water-related residential end-uses are responsible of 5.4% of all electricity and 15.1% of all natural gas used in California (CEC, 2005). Most of this energy is for heating water. This implies that a significant proportion of total per capita GHG emissions are directly related to household water end-uses.

Water scarcity is attracting attention to conservation programs as a cost-effective *source* of water. California's Senate Bill X7-7 sets an overall goal of reducing per capita urban water-use by 20% by 2020. At the same time, Assembly Bill No. 32 would require the state to adopt a statewide greenhouse gas emissions limit equivalent to statewide GHG emissions in 1990 to be achieved by 2020. Even with the realization of water and energy linkages, no strategy has directly linked residential water and energy conservation synergies.

Advances in metering for residential water-uses has increased attention to how and when households use water (DeOreo, Heaney, & Mayer, 1996). We can now observe, predict and assess the end-use consequences of conservation policies and rebate programs (Cahill, Lund, DeOreo, & Medellin-Azuara, 2013; Rosenberg, 2007). Water end-use measurements also support energy consumption calculations for household microcomponents, and from energy use and emission factors, greenhouse gas emissions can be assessed. Few studies have dealt with this issue: Fidar, Memon, and Butler (2010) presented a method to quantify and analyze energy consumption and carbon emissions from increasing water efficiency in England; Beal, Bertone, and Stewart (2012) assessed the energy demand and related carbon emissions from residential appliances and fixtures using data from 252 households in Australia; Kenway, Scheidegger, Larsen, Lant, and Bader (2013) calibrated a model for water, water-related energy, CO_2 emissions and costs for a specific family household in Brisbane, Australia; and Abdallah and Rosenberg (2014) modeled the heterogeneity of residential water and energy linkages for four different datasets in the United States (US) with different appliance efficiency levels.

Residential water-use depends on the price paid by customers, geographic conditions, household composition, water using appliance technology and other behavioral characteristics (Arbués, García-Valiñas, & Martínez-Espiñeira, 2003). Although the studies cited above do not explicitly examine the effects of geography and pricing on customer water-use and water-related energy and greenhouse gas emissions. Accounting for heterogeneity in household water and water-related energy use due to household characteristics, technology, users' behaviors and external factors —such as weather or water rates—, this study develops a model of household water end-uses, water-related energy and greenhouse gas emissions, including water and energy costs paid by customers, to estimate overall values locally and for the state of California. The study also evaluates the potential of several water and energy conservation actions under different objectives and for different locations.

In Section 2 of the paper we present the proposed methods for assessing water end-use, water-related energy, and GHG emission models, and the scenarios considered; Section 3 presents the results for each model output; Section 4 presents the discussion of results; and lastly we present overall conclusions.

2.2. Methods

2.2.1. Overall description

The model was built in four steps, as shown in Figure 2.1. First, probability distributions for parameters affecting water-use were obtained for 10 California cities. A water end-use model (described in Table 2.1) was used for Monte Carlo simulations of a large sample (2500 households) for each location.

With probability distributions for parameters affecting water-related energy use —water heater characteristics— and from the water end-uses obtained before, by applying hot water probability distributions, we estimated water-related energy use for each household through Monte Carlo simulations.

From end-uses for each customer, water and water-related energy costs were obtained applying different rates for each city. Finally, GHG emissions were estimated for each water end-use for each household in each city using GHG emission factors reported by each energy utility. Each step and method is described in detail below.

2.2.2. Water end-use model

Using water end-uses patterns from a sample of over 700 single-family homes across ten water utilities throughout California collected by Aquacraft Inc. (DeOreo et al., 2011) we built a Monte Carlo-based model using probability distributions for parameters affecting end water-uses (Cahill et al., 2013). Total household use (Equation 1 in Table 2.1) was then adjusted for each water utility to match local annual average use because the houses from which we extracted the probability distributions do not represent perfectly local average household use.

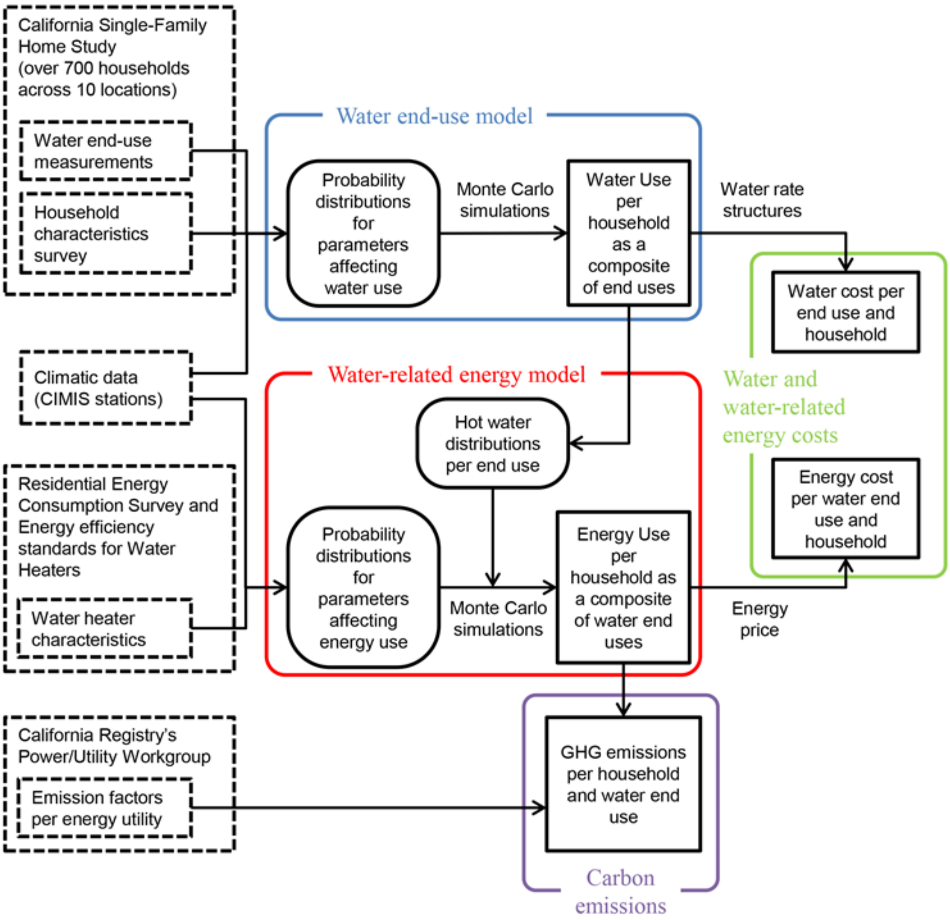

Figure 2.1: Flow diagram of the water-energy-GHG emissions model. (Legend: colored boxes show the main steps of the framework; black dashed lines represent input data from previous studies; black rounded boxes denote intermediate models, and black squared boxes outputs from the models.

Each factor in the end-use models (Equations 2 to 9 in Table 2.1) was randomly sampled for each household using probability distributions given by their histograms for each water utility to capture local water-use variability. Parameters included: i) household characteristics such as number of residents, technological values for appliances or outdoor areas, etc.; ii) users' behaviors such as shower length, number of dishwasher cycles per week, etc.; iii) climatic data is included to estimate irrigation necessities for outdoor use. Final results came from 2500 Monte Carlo household simulations[2] for each utility.

Table 2.1: Water end-use model equations for major water-uses.

$$(1)\ Q_{household} = Q_{toilet} + Q_{shower} + Q_{bath} + Q_{faucet} + Q_{dishwasher} + Q_{clotheswasher} + Q_{other} + Q_{outdoor}$$

$$(2)\ Q_{toilet} = \left(\frac{\#StdToilet \cdot \left(\frac{gal}{flush}(StdToilet)\right) + \#ULFToilet \cdot \left(\frac{gal}{flush}(ULFToilet)\right)}{\#Toilets\ in\ house} \right) \cdot \left(\frac{flushes}{day \cdot person}\right) \cdot \left(\frac{persons}{house}\right)$$

$$(3)\ Q_{shower} = \left(\frac{\#StdShw \cdot \left(\frac{gal}{min}(StdShw)\right) + \#LowFlowShw \cdot \left(\frac{gal}{min}(LowFlowShw)\right)}{\#Showers\ in\ house} \right) \cdot \left(\frac{minutes}{shower}\right) \cdot \left(\frac{showers}{day \cdot person}\right) \cdot \left(\frac{persons}{house}\right)$$

$$(4)\ Q_{bath} = (BooleanBathUse) \cdot \left(\frac{gal}{bath}\right) \cdot \left(\frac{bath}{day \cdot person}\right) \cdot \left(\frac{persons}{house}\right)$$

$$(5)\ Q_{faucet} = \left(\frac{gal}{min}\right) \cdot \left(\frac{events}{day \cdot person}\right) \cdot \left(\frac{persons}{house}\right)$$

$$(6)\ Q_{dishwasher} = (BooleanDishwasherUse) \cdot \left(\frac{gal}{cycle}\right) \cdot \left(\frac{cycle}{week \cdot person}\right) \cdot \left(\frac{1\ week}{7\ days}\right) \cdot \left(\frac{persons}{house}\right)$$

$$(7)\ Q_{clotheswasher} = (BooleanCWUse) \cdot \left(\frac{\frac{gal}{load}\ (TopCW) \cdot \#TopCW + \frac{gal}{load}(FrontCW) \cdot \#FrontCW}{\#Clotheswashers\ in\ house} \right) \cdot \left(\frac{load}{week \cdot person}\right) \cdot \left(\frac{1\ week}{7\ days}\right) \cdot \left(\frac{persons}{house}\right)$$

$$(8)\ Q_{other} = (BooleanLeaks) \cdot \left(\frac{gal}{day}(leaks)\right) + (BooleanOtherUses) \cdot \left(\frac{gal}{day}(other\ uses)\right)$$

$$\begin{aligned}(9)\ Q_{outdoor} = {} & (BooleanIrrigation) \cdot (ET) \cdot (LawnArea \cdot Kc_{lawn} + GardenArea \cdot Kc_{garden} \\ & + XeriscapeArea \cdot Kc_{xeriscape} + SwimingpoolArea \cdot Kc_{swpool}) \cdot (ApplicationRatio)\end{aligned}$$

2.2.3. Water-related energy model

Our energy model only accounted for energy used by the household water heater because this is the main household water-related energy use. Energy used by the utility to

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[2] 2500 samples were taken because it was a relative large amount of samples to obtain consistent results —same main statistics— with different runs, and at the same time that keep a reasonable computational time.

procure water for the household can be estimated separately. So the first step was to obtain the hot water draws for water end-uses.

A few studies have analyzed household hot water-use patterns. We used a probability distribution of hot water draws from data by Mayer, deOreo, Towler, and Lewis (2003) on East Bay Municipal Utility District (details provided in Supporting Information).

With these hot water end-uses, water heater energy use was estimated using the Water Heater Analysis Model (WHAM) equation (Lutz, Whitehead, Lekov, Winiarski, & Rosenquist, 1998) defined as the summed energy content of hot water drawn from the heater plus energy expended to recover from standby losses.

$$(10)\ Q_{in} = \frac{vol \cdot den \cdot Cp \cdot (T_{tank} - T_{in})}{\eta_{re}} \cdot \left(1 - \frac{UA \cdot (T_{tank} - T_{amb})}{P_{on}}\right) + 24 \cdot UA \cdot (T_{tank} - T_{amb})$$

Being Q_{in} the total water heater energy consumption (Btu/day); η_{re} the recovery efficiency; P_{on} the rated input power (Btu/hr); UA the standby heat loss coefficient (Btu/hr·^{o}F); T_{tank} the thermostat setpoint temperature (^{o}F); T_{in} the inlet water temperature (^{o}F); T_{amb} the temperature of the air around the water heater (^{o}F); *vol* the volume of water drawn in 24 hours (gal/day); *den* the density of water (lb/gal); and C_p the specific heat of water (Btu/lb·^{o}F).

The WHAM equation includes the same three types of parameters used for the water end-use models: i) household technological characteristics of the water heater; ii) users' behaviors as the (setpoint temperature); iii) climatic data (temperature of the air and the inlet water temperature). Probability distributions of each parameter were derived from the Residential Energy Consumption Survey 2009 (USEIA, 2009) for single-houses in California and from Energy Efficiency Standards for Water Heaters (USDOE, 2009). Temperature and evapotranspiration parameter values are from the California Irrigation Management Information System (CIMIS).

Finally we obtained the water-related energy consumption for each of 2500 Monte Carlo simulated households for each of the 10 water utilities. We used the WHAM equation over the hot water volume computed from the water end-uses with probabilistic hot water percentages for each appliance. We also randomly sampled all parameters for each household water heater from their probability distributions.

2.2.4. Carbon emissions

From energy consumption CO_2 emissions were calculated, accounting for the type of the energy used —electric or gas-fired water heaters— and the energy utility that provided it.

The California Registry's Power/Utility Workgroup reports greenhouse emission factors for electric power generation, transmission and delivery (CRPUW, 2009). CO_2 emissions ranged from 0.24 kg·CO_2/kWh to 0.58 kg·CO_2/kWh (complete CO_2 emission factors for each utility are provided in the Supporting Information)

Roughly 85 percent of natural gas used in California is imported from the American Southwest, Rocky Mountains and Canada; the remaining 15 percent is produced in-state. The variability of emission factors from different sources is quite low, so we used the weighted national average of 5.31 kg CO_2/therm (USEIA, 2011).

2.2.5. Water and Water-Related Energy Costs

The water bill for each house was calculated using the water rate structure for each utility for 2006, the year of the California Single-Family Water Use Efficiency Study (DeOreo et al., 2011).

Regarding energy rates, we used an overall energy price for each utility. Electricity prices range from $0.105/kWh in LADPW to $0.166/kWh in San Diego Gas & Electric. The natural gas price is $11.79 per thousand cubic feet ($0.0115 per thousand Btu) from the Energy Almanac of the California Energy Commission.

More details of water and energy rate structures are provided in the Supporting Information.

2.2.6. Scenarios

Several simulations were run to analyze the effects of different scenarios —technological improvements, behavioral modifications, and an overall water-use reduction— on water and energy use, GHG emissions and water and water-related energy costs. Technological-based simulations were used to analyze potential impacts of command-and-control policies, behavioral-based simulations were run to analyze the effects of reductions for each behavioral parameter.

Technology improvements —retrofit toilet, retrofit shower, retrofit dishwasher, retrofit washing machine, substitution of natural turf for artificial turf or xeriscape, and installation of smart irrigation controllers— were simulated by changing technological parameter values from the initial probability distributions with a new probability distribution assuming that all appliances are retrofitted.

To simulate behavioral modifications —reductions in toilet flushes, shower length, shower frequency, bath frequency, leaks detection and fixing and stress irrigation— we assumed a reduction for each behavioral parameter to analyze which parameters have more impact on water and water-related energy use for each city. A sensitivity analysis of these parameters is done by analyzing results from 1 to 20 of use reduction.

On the energy side, we simulated the installation of a new water heater —using two types of electric and two types of natural gas commercial water heaters, one in the intermediate and other in the high range of efficiency[3] values for each energy source—

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[3] High efficiency electric water heater is a heat pump water heater that can achieve an efficiency value of 2.2, three times that of a common electric water heater.

and a behavioral action to decrease the water heater setpoint temperature to 120ºF for households that have a setpoint temperature above this value.

Finally, we simulated an overall water-use decrease of 10% for each household in order to analyze the differences among locations based on the heterogeneity of residential water and energy linkages that the model captures.

2.3. Results

2.3.1. Water end-use model

The goodness of fit of the end-use model was formally tested using the Kolmogorov-Smirnov two-sample test (Smirnov, 1948) failing to reject in all the cases the null hypothesis that modeled and metered data have the same underlying distribution. Figure 2.2 shows an example comparison of the cumulative histograms for the results obtained with the water end-uses models and the real data metered in the city of Davis, with a p-value for the K-S two-sample test of 0.28.

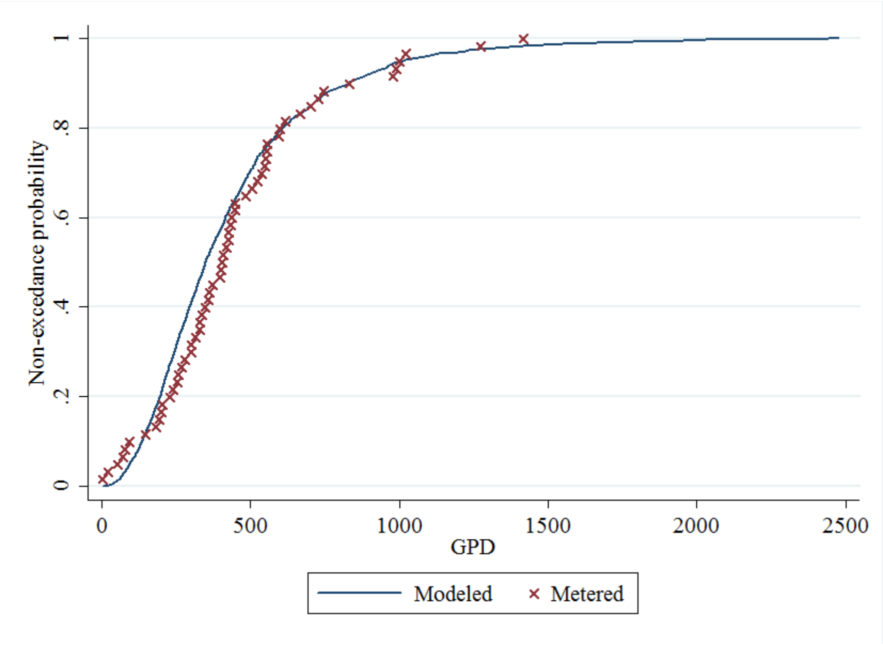

Figure 2.2: Comparison of the cumulative histograms for metered and modeled total water-use in Davis (as a sum of the end-use models).

2.3.2. Water-related energy model

For water-related energy we compared the results of our model with a sample of 1088 single-family houses in California from the 2009 Residential Energy Consumption Survey (USEIA, 2009). Even though the comparison of the descriptive statistics (Table 2.2) shows that the results differ and the K-S two-sample test reject that the samples have the same underlying distribution, they have a similar range and demonstrate that the model developed is close to others obtained with different models[4].

Table 2.2: Descriptive statistics for water-related energy and costs for California households obtained with our model vs RECS model.

	Source	**Observations**	**Mean**	**Std. deviation**	**Skewness**
Energy Use (kWh/day)	RECS	1088	14.94	10.11	3.50
	Model	25000	11.15	9.91	5.21
Energy Cost ($/month)	RECS	1088	17.82	12.28	2.58
	Model	25000	15.24	14.54	4.89

2.3.3. California overall results

Assuming the 10 utilities analyzed are representative of the total population of single-family homes in California, we estimate overall results for the state as a weighted average accounting for the total number of households in each utility included in the study.

Figure 2.3 shows overall results for a representative household in California: average household water-use is 364 GPD, 207 (57%) is outdoor use and 157 (43%) is indoor, with 51 GPD passing through the water heater (14% of the total, and 32% of indoor use). The water heater uses 10.4 kWh per day, emitting 728.1 kg CO_2/year or 245 kg/person·year, roughly 2% of total emissions per capita in California. Considering costs of water and energy, an average household pays $79.8/month for water and $13.9/month for water-related energy, totaling $93.7/month.

Outdoor use is the largest water-use amounting to $44.3/month (56% of water costs and 47% of total cost). Shower (8.2% of water costs and 13.1% of total costs) and faucet (8.5% of water costs and 13% of total costs) uses are second and third in cost be-

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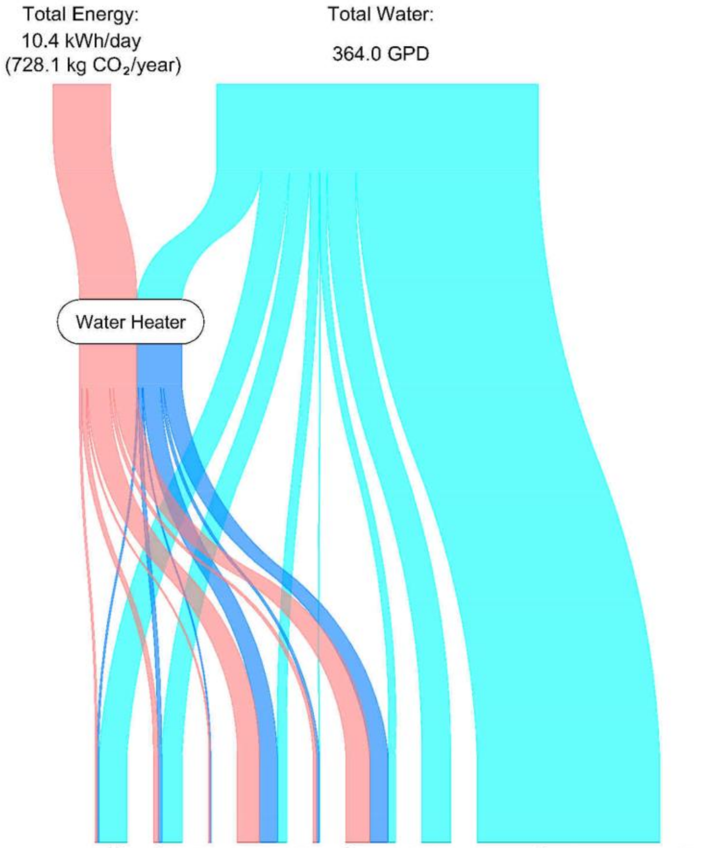
[4] Notice that the RECS model lacks metered data for the water heater, so their results are estimated as well. RECS use different models (space heating, air-conditioning, water heating, refrigerators, and other purposes) to estimate the household energy consumption and adjust their models to fit real billing data.

cause of high shares of hot water-use. Toilet, leaks/other, and clothes washer are less important although they use a similar amount of water than shower and faucet. Finally bath and dishwasher end-uses are only minor shares of the total uses, emissions and costs.

Notice that water and water-related energy costs are similar in energy-intensive end-uses such as faucet, shower, bath or dishwasher.



	L/O	CW	DW	Faucet	Bath	Shower	Toilet	Outdoor	Total
Cold Water (GPD)	31.7	23.1	0.0	10.6	0.4	8.1	32.5	206.6	313.0
Hot Water (GPD)	1.8	4.2	1.1	19.9	3.0	20.9	0.0	0.0	51.0
Energy (kWh/day)	0.4	0.8	0.2	4.0	0.6	4.3	0.0	0.0	10.4
CO_2 (kg/year)	26.2	58.8	16.2	283.4	42.6	300.8	0.0	0.0	728.1
Water cost ($/month)	7.3	6.2	0.3	6.8	0.7	6.5	7.5	44.3	79.8
Energy cost ($/month)	0.5	1.1	0.3	5.4	0.8	5.8	0.0	0.0	13.9
Total cost ($/month)	7.8	7.3	0.6	12.2	1.6	12.6	7.5	44.3	93.7

Figure 2.3: Water, water-related energy and CO_2 flows, and water and water-related energy costs per end-use in a representative single family household in California.

2.3.4. Heterogeneity in consumption and variability in location

2.3.4.1. Water use

In agreement with previous studies (DeOreo et al., 2011), Figure 2.4 shows how high variability in outdoor water-use affects total water-use variability among locations whereas indoor uses are quite similar.

For indoor water, shown in Figure 2.5, toilet, shower, faucet, clothes washer and leaks/other have a similar share of the total indoor water-use, varying some among locations. Bath and dishwasher water end-uses are almost negligible.

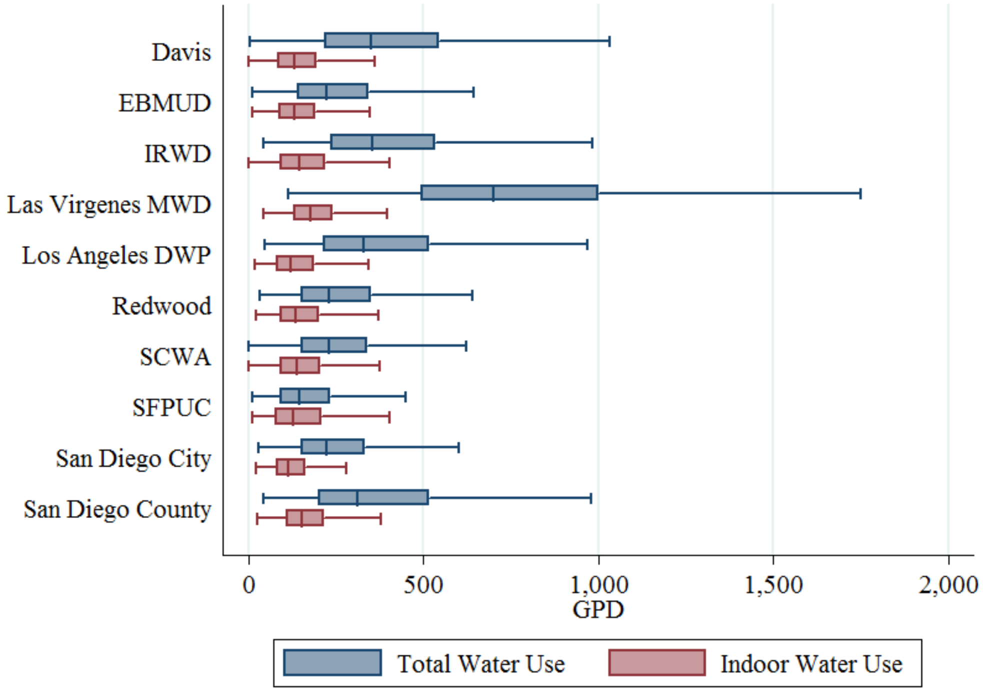


Figure 2.4: Box and whisker plots for total and indoor residential water-use for each utility.

2.3.4.2. Water-related energy use

Most water-related energy use is from shower and faucet end-uses (roughly 80% of total) whereas bath, dishwasher, clothes washer and leaks/other end-uses are a minority of the total water-related household energy use (Figure 2.5). Even though the average indoor water-use in southern California households is larger (170 vs. 157 GPD), northern households use slightly more water-related energy (11.7 vs 10.6 kWh/day).

We applied a multivariate regression analysis to the Monte Carlo simulation results, obtaining that 88% of the variability of water-related energy consumption can be explained with the sum of faucet and shower uses (Figure SI.1 in the Supporting Information). Including the rest of the variables (end-uses, water heater characteristics and temperatures) the model explains 98% of variability of water-related energy variability, obtaining the coefficients in Table 2.3.

Table 2.3: Parameter estimates for the regression analysis of water-related energy.

Variable	**Estimated Parameters**	**t statistic**
Constant	-2.31***	(-4.53)
Faucet use [GPD]	0.10***	(253.30)
Shower use [GPD]	0.11***	(275.05)
Bath use [GPD]	0.14***	(98.18)
Dishwasher use [GPD]	0.18***	(48.53)
Clothes washer use [GPD]	0.03***	(76.22)
Leaks/Other use [GPD]	0.01***	(41.41)
Electric water heater dummy	0.44***	(3.64)
Efficiency	0.44***	(3.35)
Pon	0.000004***	(5.01)
RE	-11.06***	(-20.65)
UA	0.42***	(141.01)
Temp. air [^{0}F]	-0.09***	(-6.98)
Temp inlet [^{0}F]	-0.12***	(-9.64)
Temp. tank [^{0}F]	0.20***	(126.83)

N = 25000; $R^2 = 0.9760$; *** means p-value<0.001

2.3.4.3. GHG emissions

Residential water-related CO_2 emissions, in Figure 2.6, show that shower and faucet use cause most water-related CO2. Total GHG emissions rank from 535 kg CO2/year in San Diego City to almost 900 kg CO_2/year in San Francisco. Results of emissions per end-use and variability among locations are very similar to water-related energy presented in Figure 2.5.

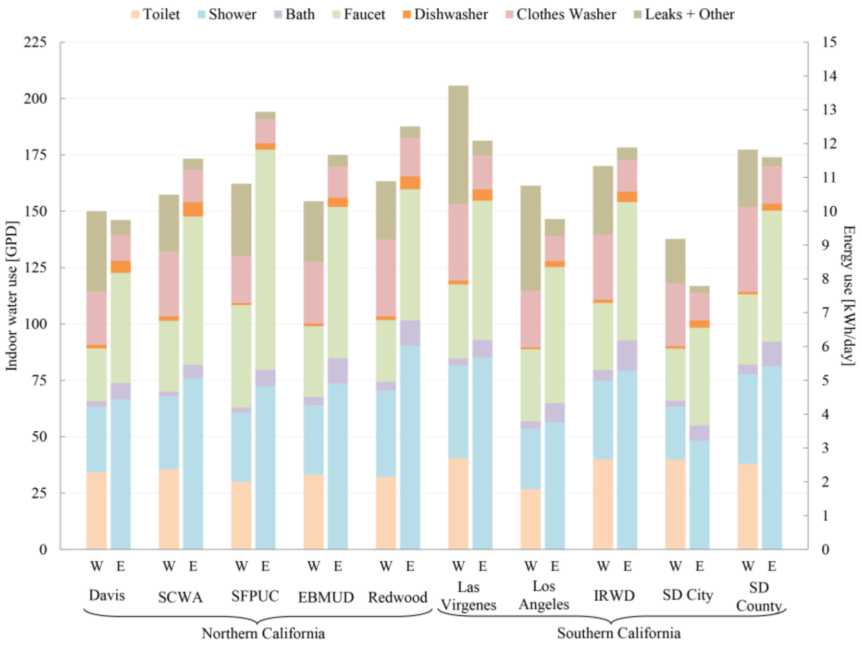


Figure 2.5: Household daily indoor water and energy uses for each utility.

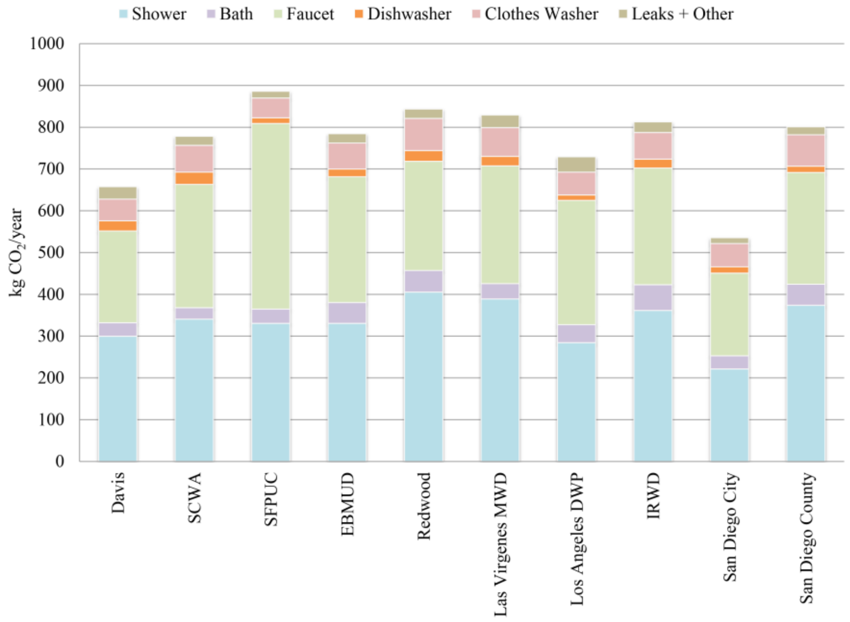


Figure 2.6: Annual CO_2 emissions per end-use and per utility.

2.3.4.4. Water and water-related energy costs

Huge differences in water rate structures across water utilities cause large water bill variations, whereas smaller differences in energy prices make the water-related energy bill less variable (Figure 2.7).

Water and water-related energy costs for each end-use show that water costs are determined by the local water rate structures, driven largely by outdoor use —75% in Las Virgenes, 62% in Los Angeles and San Diego County and 60% in Irvine, but only 10% in San Francisco—, whereas energy costs are related with total consumption for each water end-use using hot water.

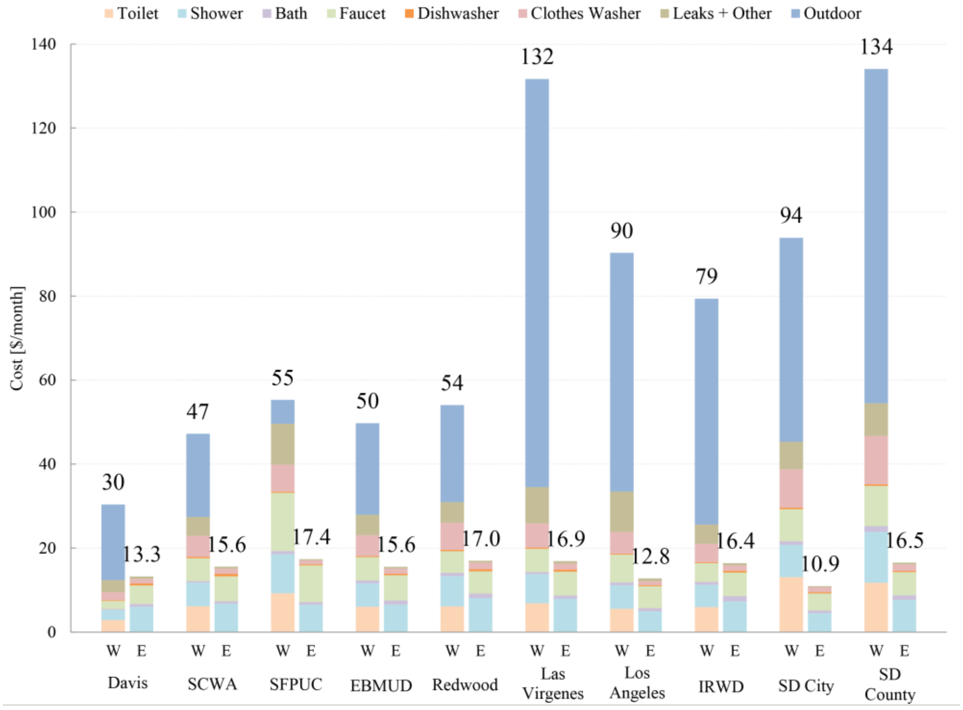


Figure 2.7: Water and water-related energy bills per end-use for each utility.

2.3.4.5. Results from scenario simulations

Fourteen simulations were run to affect water-use and five that affect only energy consumption obtaining water, energy, CO_2 and economic savings. Finally we estimate the California wide reduction for each simulation (Table 2.4). For behavioral parameters a sensitivity analysis has been conducted, presenting the results for changes in the parameters ranging from 1 to 20 percent in use reduction.

As expected, simulations that only save cold water such as “retrofit toilet” or the modifications in outdoor irrigation, affect only the water side, whereas improvements in water heaters cause only energy and CO_2 savings, but savings on water end-uses with a significant proportion of hot water have both water and water-related energy savings. Outdoor changes and water heater retrofitting have the largest benefits on water and water-related energy respectively, but they are also the most expensive investments. As water cost is the largest share of total cost, water savings has more effect on total cost, as demonstrated by the lower total cost savings of water heater retrofits, even with their large energy savings. Lastly, high performance electric water heaters have less energy use and GHG emissions than gas-fired heaters.

2.4. Insights for management and policy

Below we present and discuss some results from selected simulations that support some interesting insights for management and policy:

2.4.1. Differences in willingness to adopt conservation strategies

Pre-conservation water consumption patterns determined mainly by technological, behavioral and external factors, determine the potential water savings from a conservation action. However, water and energy rates drive the economic benefits to customers from conservation actions. So, previous conditions and rates together cause significant differences in customer willingness to adopt conservation strategies.

Figure 2.8 shows that customers from Davis probably have newer houses or have retrofitted showers according to local building codes and cannot reduce significantly water-use with this action, whereas other cities could. Big differences on economic incentives depend on water and energy rates, ranging from Las Virgenes (low water rates and high consumption) to San Francisco (high water rates).

2.4.2. Targeting

A small proportion of households accounts for a disproportionate share of water and water-related energy use. A water utility that focuses attention on these *high users* —in the higher quartile of water and energy consumption— and using advanced metered technology available, can increase returns from conservation strategies considerably.

Taking the results from the 10% overall water reduction simulation for median users and the higher quartile of users, obtaining that in average water savings increase twice, energy and CO_2 savings increase 2.4 times, and economic benefits for customers increase 2.3 times (Figure 2.9).

High-use customers should be more receptive to conservation measures because of their increased economic benefits, increasing the likelihood of conservation campaign success. The overall water-use reduction impact for a utility will be significantly larger than the same campaign with normal-use customers.

Table 2.4: Results of total water, water-related energy and CO_2 savings and economic water and energy benefits for each simulation.

	Water			Energy			CO_2			Water Cost			Energy Cost			Total Cost		
	GPD	Reduction (%)		kWh/day	Reduction (%)		kg/year	Reduction (%)		$/month	Reduction (%)		$/month	Reduction (%)		$/month	Reduction (%)	
Business as usual	364	-	-	10.4	-	-	728	-	-	79.8	-	-	13.9	-	-	93.7	-	
Ret. Toilet	358	2%	++	10.4	0%	Ø	728	0%	Ø	78.5	2%	++	13.9	0%	Ø	92.5	1%	++
Ret. Shower	361	0.7%	+	10.0	4%	++	701	4%	++	79.2	0.7%	+	13.4	4%	++	92.7	1%	++
Ret. Dishwasher	363	0.2%	+	10.2	1.5%	++	718	1.4%	++	79.6	0.2%	+	13.7	1.4%	++	93.4	0.4%	+
Ret. Clotheswasher	355	2%	++	10.1	3%	++	709	3%	++	78.0	2%	++	13.6	3%	++	91.6	2%	++
Artificial Turf	170	53%	+++	10.4	0%	Ø	728	0%	Ø	41.3	48%	+++	13.9	0%	Ø	55.2	41%	+++
Install Xeriscape	243	33%	+++	10.4	0%	Ø	728	0%	Ø	54.9	31%	+++	13.9	0%	Ø	68.9	27%	+++
Smart Irrigation	324	11%	+++	10.4	0%	Ø	728	0%	Ø	71.1	11%	+++	13.9	0%	Ø	85.1	9%	+++
Red. Toilet Flushes (1% to 20%)	358-364	0.1% - 1.8%	++	10.4	0%	Ø	728	0%	Ø	78.5 - 79.8	0.1% - 1.6%	++	13.9	0%	Ø	92.4 - 93.6	0.1% - 1.4%	++
Red. shower length (1% to 20%)	358-364	0.1% - 1.6%	++	9.5-10.3	0.4% - 8.2%	+++	671-728	0.4% - 8.2%	+++	78.7 - 79.8	0.1% - 1.4%	++	12.8 - 13.9	0.4% - 8.2%	+++	91.4 - 93.6	0.1% - 2.5%	++
Red. shower frequency (1% to 20%)	358-364	0.1% - 1.6%	++	9.5-10.3	0.4% - 8.2%	+++	671-728	0.4% - 8.2%	+++	78.7 - 79.8	0.1% - 1.4%	++	12.8 - 13.9	0.4% - 8.2%	+++	91.4 - 93.6	0.1% - 2.5%	++
Red. Frequency Bath (1% to 20%)	363-364	0.0% - 0.2%	Ø	10.2-10.3	0.1% - 1.2%	++	722-728	0.1% - 1.2%	++	79.7 - 79.8	0.0% - 0.2%	Ø	13.7 - 13.9	0.1% - 1.2%	++	93.4 - 93.7	0.0% - 0.3%	+
Red. Frequency Faucet (1% to 20%)	358-364	0.1% - 1.7%	++	9.5-10.3	0.4% - 7.8%	+++	673-728	0.4% - 7.8%	+++	78.6 - 79.8	0.1% - 1.5%	++	12.8 - 13.9	0.4% - 7.8%	+++	91.4 - 93.6	0.1% - 2.5%	++
Red. Laundry Frequency (1% to 20%)	359-364	0.1% - 1.5%	++	10.2-10.3	0.1% - 1.6%	++	719-728	0.1% - 1.6%	++	78.8 - 79.8	0.1% - 1.3%	++	13.7 - 13.9	0.1% - 1.6%	++	92.4 - 93.6	0.1% - 1.4%	++
Fix Leaks (1% to 20%)	358-364	0.1% - 1.6%	++	10.3	0% - 0.7%	+	726-728	0% - 0.7%	+	78.7 - 79.8	0.1% - 1.5%	++	13.8 - 13.9	0% - 0.7%	++	92.4 - 93.6	0.1% - 1.3%	++
Stress irrigation (1% to 20%)	323-362	0.6% - 11.4%	+++	10.4	0%	Ø	728	0%	Ø	71.2 - 79.4	0.6% - 10.9%	+++	13.9	0%	Ø	85.0 - 93.3	0.5% - 9.3%	+++
10% Overall Reduction	348	10%	+++	9.3	10%	+++	655	10%	+++	72.4	9%	+++	12.5	10%	+++	84.9	9%	+++
Nat Gas WH Good Eff.	364	0%	Ø	10.1	3%	++	728	0%	Ø	79.8	0%	Ø	12.0	14%	+++	91.8	2%	++
Nat Gas WH High Eff.	364	0%	Ø	8.4	18%	+++	623	14%	+++	79.8	0%	Ø	10.1	28%	+++	89.8	4%	++
Electric WH Good Eff.	364	0%	Ø	6.8	34%	+++	496	32%	+++	79.8	0%	Ø	26.8	-92%	Ø	106.6	-14%	Ø
Electric WH High Eff.	364	0%	Ø	2.7	74%	+++	195	73%	+++	79.8	0%	Ø	10.5	24%	+++	90.3	4%	++
WH Setpoint Temperature	364	0%	Ø	9.7	6%	+++	684	6%	+++	79.8	0%	Ø	13.1	6%	+++	92.9	1%	+

+++ = High reduction (>5%); ++ = Medium reduction (>1% and ≤5%); + = Low reduction (≤1%); Ø = Null.

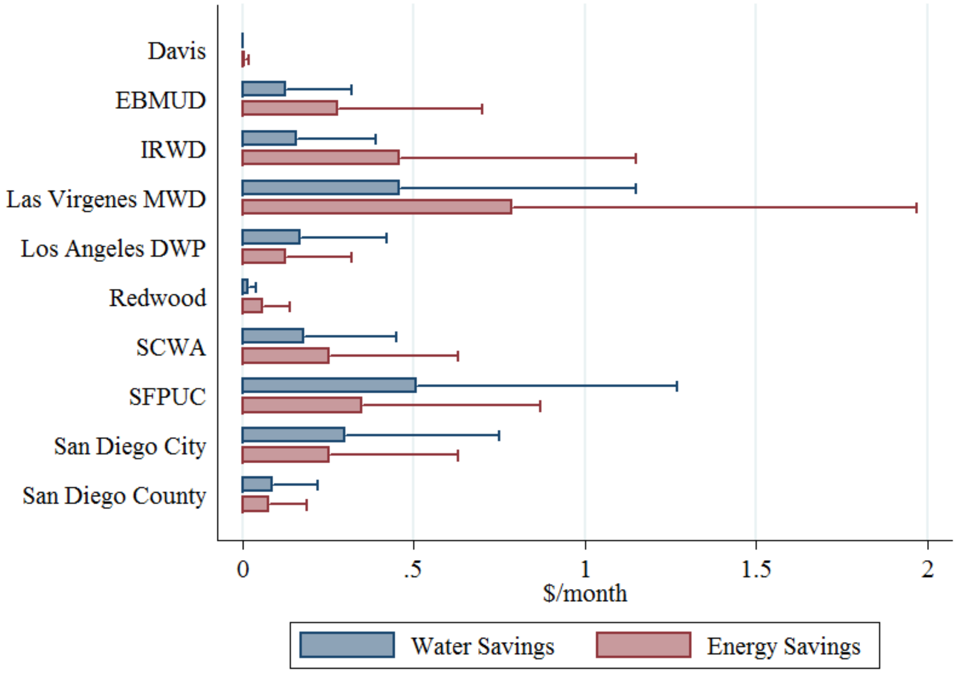
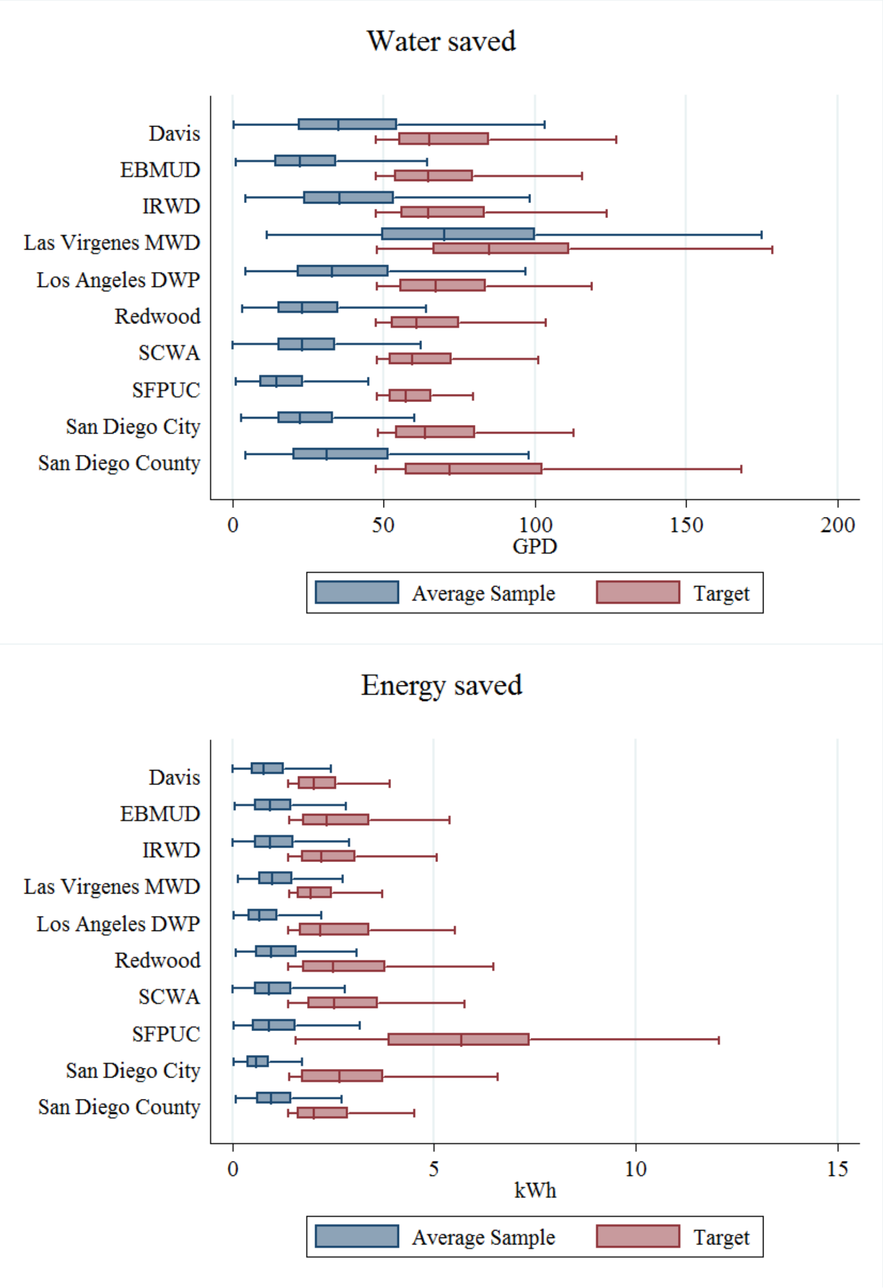


Figure 2.8: Economic savings from retrofitting shower per utility.

2.4.3. Efficiency over the planning scales

The efficiency of a conservation action depends on the planning objective. For example: the state of California could try to reduce the total amount of GHG emissions by retrofitting water heaters, installing new electric water heaters that have high efficiency with a CO_2 reduction of 533 kg/year per household on average, whereas natural gas water heaters only reduce 105 kg CO_2/year per household (Figure 2.10). But if customers seek only to reduce their costs, electric water heaters will only be meaningful in Los Angeles (because of cheaper electric rates), whereas in every other location, lower natural gas rates will always overcome electric water heaters' energy costs.


Water saved
Davis
EBMUD
IRWD
Las Virgenes MWD
Los Angeles DWP
Redwood
SCWA
SFPUC
San Diego City
San Diego County
0
50
100
150
200
GPD
Average Sample
Target
Energy saved
Davis
EBMUD
IRWD
Las Virgenes MWD
Los Angeles DWP
Redwood
SCWA
SFPUC
San Diego City
San Diego County
0
5
10
15
kWh
Average Sample
Target

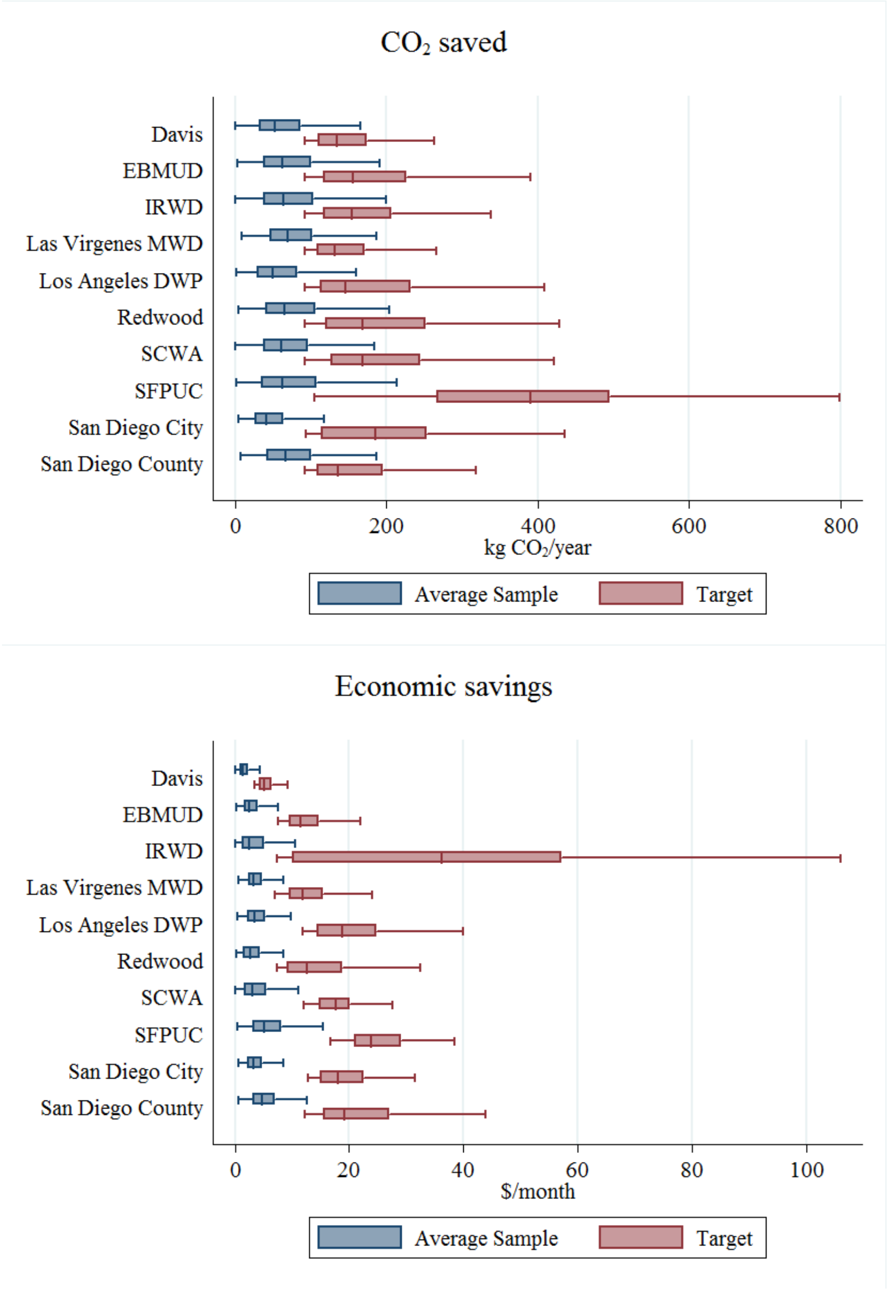


Figure 2.9: Comparison for water, water-related energy, CO2 emissions and costs reduction assuming a 10% decrease in water-use between average users and targeting customers for each utility.

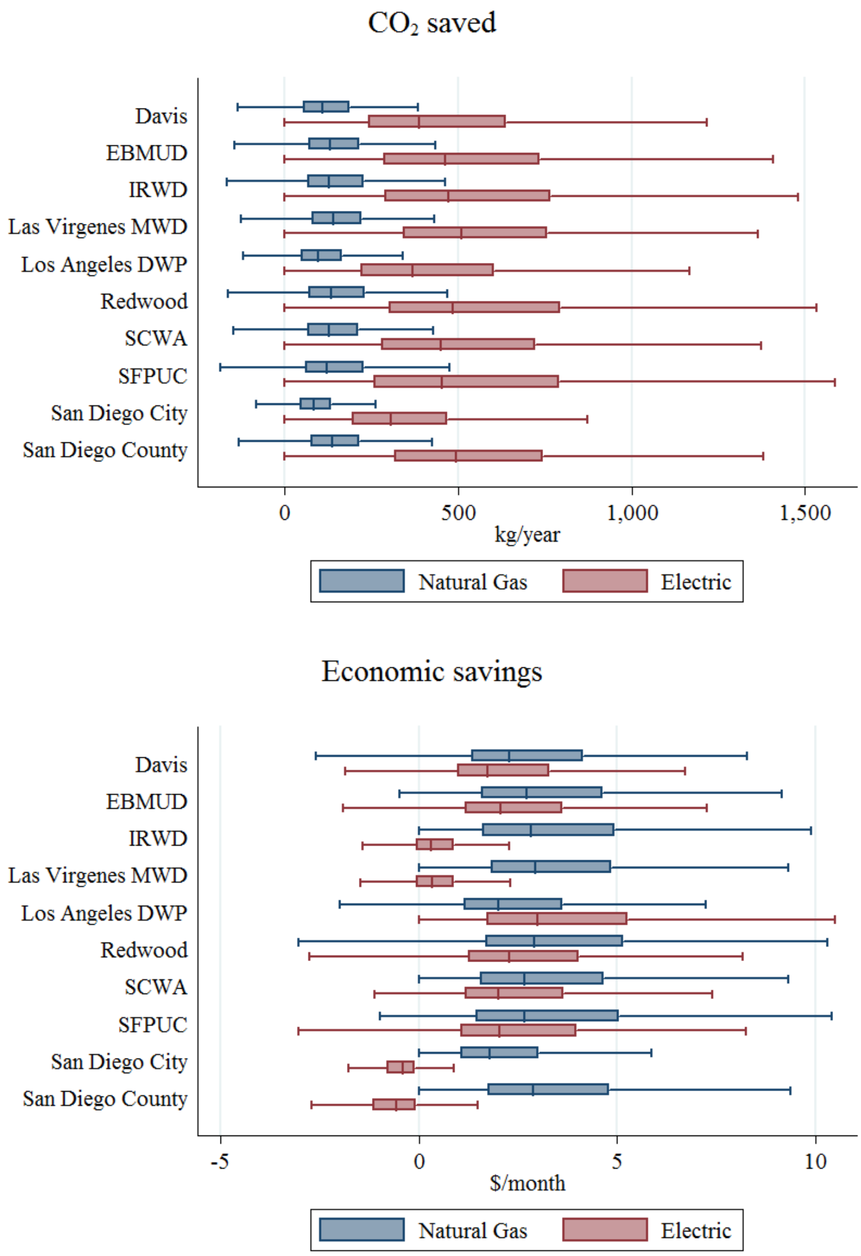


Figure 2.10: Comparison of CO_2 and economic savings between gas-fired and electric water heater retrofitting per utility.

2.5. Discussion

The water end-use model fits metered data well because the probability distributions were drawn from metered households, whereas we lack metered data to test the water-related energy end-use model, although the model results are close to the RECS results. Our results also are consistent with previous studies: water-related energy used was slightly higher than results of Abdallah and Rosenberg (2014), probably because we are including losses with the WHAM formulation, and slightly lower than those from Kenway et al. (2013) because we are not including energy used directly by appliances (although their results for total gas use, hot water + losses, are slightly lower than ours).

Total water-use variability is driven by variability in outdoor water-use. Cheaper water rates and inland climates in Las Virgenes and Davis imply a high outdoor use, meanwhile relatively small lots in San Francisco cause less total water-use, although indoor water-use is similar to other locations.

Regression analysis results from households show that hot water-use and water heater characteristics are the main drivers of energy consumption, but outside and inlet temperatures also are important in energy consumption: even though the average indoor water-use in southern California households is larger, northern households use slightly more water-related energy due to lower winter temperatures.

Interestingly although electric water heaters are more efficient heating water than gas-fired heaters, the overall performance comparison depends on the main energy source of electricity generation. Electricity generation using natural gas in a combined plant could have a loss of two thirds of the main energy source including efficiency in generation and distribution losses when the electricity is used in a house. But most electric utilities have a diversified portfolio to generate electricity, so this variability in electric generation has to be considered in overall performance. We included this point using different emission factors for natural gas and electric water heaters, but as most water heaters in California are gas-fired, the effect on final results is tiny. This should not have to be the case in other regions with a higher share of electric water heaters, where the main driver of the GHG emission factors will be the energy source of the electric utility.

From the simulation runs we obtain that total water, water-related energy and greenhouse gas emissions savings for each utility depends on conditions of consumption given by technological, behavioral and external factors, whereas household economic benefits from savings rely on the water and energy rates of each utility. Water end-uses with a higher share of hot water receive more economic benefit by saving water because of the reduced energy cost. On the other side, technology or behavior improvements that only affect the energy side, i.e. retrofit water heaters or modify the setpoint temperature, lead to economic benefit only by energy savings. The results of the simulation runs presented in Table 2.4 seems to suggest that on a cost basis, users would be more willing to adopt conservation actions that have higher savings (i.e. outdoor water use), but users have to consider their costs taking those actions (i.e. retrofit costs). Therefore the point made in this study is that there are added savings when energy is accounted, but a cost-benefit analysis needs to be conducted to analyze which of these strategies could be more successful from the customer perspective.

Including energy and CO_2 emissions and their costs in the conceptualization of water-use can improve people's knowledge about their actual expenses and environmental footprint, helping to incentivize potential conservation strategies. Moreover, throughout the analysis of spatial variability, we show that water and energy rates, energy sources available for customers and different energy portfolios of power companies can cause high variability in energy, cost and emission results with customers' water-use held constant. Customers' behavior, in reacting to bills and local, regional and national policies, can change outcomes depending on local conditions such as water and energy rates or temperature.

2.6. Conclusions

A framework is developed to model heterogeneous and geographically variable residential water end-uses, water-related energy consumption and greenhouse emissions while accounting for water and water-related costs to customers.

Using the method, we assessed water and water-related energy and GHG emissions and costs. Outdoor water-use accounts for more than 50 percent of water-use in California but most water-related energy and GHG emissions are from shower and faucet end-uses (roughly 80% of the total). Water-related energy cost represents a third of water cost in northern cities whereas in much less representative in the south. This is partially due to large water consumption and higher water prices in southern California, but also because outside and inlet temperatures play an important role in reducing energy consumption.

Include avoided energy cost can increase the proneness to water conservation. For energy-intensive appliances —faucet, shower, bath and dishwasher— water and energy costs of use are similar. Inlet temperature plays an important role in water-related energy consumption, what open the possibility for utilities to efficiently manage water supply from different sources to reduce energy consumption in households.

Heterogeneity among households in water and water-related energy and GHG emissions is significant. So selective options targeting high-use households and effective conservation policies —outdoor uses for water, and faucet and shower end-uses for energy consumption and CO_2 reductions— have high potential for cost-effective water, energy and CO_2 emission savings.

Residential water-related carbon footprint depends both on household water heater performance and on the electric generation portfolio of the regional utility. Water-related CO_2 emissions average about 730 kg/year per household, representing 2% of per capita greenhouse gas emissions in California. This result does not include other embedded energy in water supply, conveyance, treatment, pumping or wastewater collection and treatment. Therefore, total energy and GHG emissions related with residential water-use would be larger, a study being conducted as an extension of this research.

Assessments of residential water-related energy conservation also can vary for different planning scales. From a state perspective, managing water and water-related energy jointly can reduce greenhouse gas emissions significantly in California. For water and energy utilities, joint water and energy conservation programs could reduce the net cost of some strategies as retrofit campaigns or managing energy peaks and reducing carbon footprint. This is a motivation to give users incentives to save water, energy and per capita carbon footprint and to reduce their water and energy bills simultaneously.

2.7. References

Abdallah, A., & Rosenberg, D. (2014). Heterogeneous Residential Water and Energy Linkages and Implications for Conservation and Management. *Journal of Water Resources Planning and Management, 140*(3), 288-297. doi: doi:10.1061/(ASCE)WR.1943-5452.0000340

Arbués, F., García-Valiñas, M. a. Á., & Martínez-Espiñeira, R. (2003). Estimation of residential water demand: a state-of-the-art review. *The Journal of Socio-Economics, 32*(1), 81-102. doi: http://dx.doi.org/10.1016/S1053-5357(03)00005-2

Beal, C. D., Bertone, E., & Stewart, R. A. (2012). Evaluating the energy and carbon reductions resulting from resource-efficient household stock. *Energy and Buildings, 55*, 422-432. doi: DOI 10.1016/j.enbuild.2012.08.004

Cahill, R., Lund, J. R., DeOreo, B., & Medellin-Azuara, J. (2013). Household water use and conservation models using Monte Carlo techniques. *Hydrology and Earth System Sciences, 17*(10), 3957-3967. doi: DOI 10.5194/hess-17-3957-2013

CEC. (2005). California's Water - Energy Relationship. Prepared in Support of the 2005 Integrated Energy Policy Report Proceeding. California Energy Commission. November 2005. CEC-700-2005-011-SF.

CRPUW. (2009). Power/Utility Reporting Protocol (PUP). The California Registry Power/Utility Workgroup. Available at http://www.climateregistry.org/tools/protocols/industry-specific-protocols/power-utility.html. Accessed 4/14/2014.

DeOreo, W. B., Heaney, J. P., & Mayer, P. W. (1996). Flow trace analysis to assess water use. *Journal American Water Works Association, 88*(1), 79-90.

DeOreo, W. B., Mayer, P. W., Martien, L., Hayden, M., Funk, A., Kramer-Duffield, M., & Davis, R. (2011). California single-family water use efficiency study. Aquacraft, Inc. Water Engineering and Management. July 20, 2011.

Fidar, A., Memon, F. A., & Butler, D. (2010). Environmental implications of water efficient microcomponents in residential buildings. *Science of the Total Environment, 408*(23), 5828-5835. doi: DOI 10.1016/j.scitotenv.2010.08.006

Kenway, S. J., Scheidegger, R., Larsen, T. A., Lant, P., & Bader, H. P. (2013). Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings, 58*, 378-389. doi: DOI 10.1016/j.enbuild.2012.08.035

Lutz, J., Whitehead, C. D., Lekov, A., Winiarski, D., & Rosenquist, G. (1998). WHAM: A Simplified Energy Consumption Equation for Water Heaters. (3AD). WHAM: A Simplified Energy Consumption Equation for Water Heaters. Proceeedings of the ACEEE 1998 Summer Study on Energy Efficiency in Buildings, 1. Washington, DC: ACEEE. .

Mayer, P. W., deOreo, B., Towler, E., & Lewis, D. M. (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. East Bay Municipal Utility District (EBMUD) and The United States Environmental Protection Agency (USEPA). July 2003.

Reffold, E., Leighton, F., Choufhoury, F., & Rayner, P. (2008). Greenhouse gas emissions of water supply and demand management. Science Report No SC070010. Environment Agency; 2008.

Rosenberg, D. E. (2007). Probabilistic estimation of water conservation effectiveness. *Journal of Water Resources Planning and Management-Asce, 133*(1), 39-49. doi: Doi 10.1061/(Asce(0733-9496(2007)133:1(39)

Smirnov, N. (1948). Table for Estimating the Goodness of Fit of Empirical Distributions. *Annals of Mathematical Statistics, 19*(2), 279-279. doi: DOI 10.1214/aoms/1177730256

USDOE. (2009). Energy efficiency standards for Pool Heaters, Direct Heating Equipment and Water Heaters (EE-2006-STD-0129). Energy Efficiency and Renewable Energy Office (EERE). U.S. Department of Energy (DOE). Available at http://www.regulations.gov/#!documentDetail;D=EERE-2006-STD-0129-0170. Accessed 4/14/2014.

USEIA. (2009). *Residential Energy Consumption Survey 2009. U.S. Energy Information Administration. Available at http://www.eia.gov/consumption/residential/index.cfm. Accessed 4/14/2014.*

USEIA. (2011). Voluntary reporting of greenhouse gases program (Voluntary reporting of greenhouse gases program fuel carbon dioxide emission coefficients). U.S. Energy Information Administration. Available at http://www.eia.gov/oiaf/1605/coefficients.html. Last updated January 31, 2011. Accessed 4/14/2014.

Appendix: Supporting information

This supplement contains the following materials:

A.1. Efficiency over the planning scales

Table SI.1: Parameters influencing water use for each location

Table SI.2: Air and inlet temperatures used in the energy assessment. Source: Temperatures from closest CIMIS stations; $\Delta(T_{INLET} - T_{AVG})$ from USDOE (2009).

Table SI.3: Water heater setpoint temperature. Source: Abdallah and Rosenberg (2014).

Table SI.4: Primary water heating fuel in single-family homes in California. Source: USEIA (2009).

Table SI.5: Water heater sizes per primary water heating fuel. Source: USEIA (2009).

Table SI.6: Distribution of basecase efficiency by tank size for natural gas water heaters. Source: USDOE (2009).

Table SI.7: Distribution of basecase efficiency by tank size for electric water heaters. Source: USDOE (2009).

Table SI.8: Rated input power (P_{ON}) distribution by rated volume for natural gas water heaters. Source: USDOE (2009).

Table SI.9: Rated input power (P_{ON}) distribution by rated volume for electric water heaters. Source: USDOE (2009).

Table SI.10: Hot water vs. total water use (Source: Mayer et al. (2003)) and assumed distribution functions for hot water end uses.

Table SI.11: Emission factors reported by electric utilities in California. Source: CRPUW (2009).

Table SI.12: Water rate structure for each water utility analyzed in the study. Own construction from Mayer et al. (2003).

Table SI.13: Electricity prices for California power utilities.

A.2. Results

A.2.1. Water, water-related energy and GHG and costs per utility and end-use

Table SI.14: Average water use, water-related energy use, water-related GHG emissions, water costs, water-related energy costs and total costs per utility and end-use.

A.2.2. Regression of water-related energy use with indoor water use

Figure SI.1: Daily water-related energy consumption as a function of the sum of faucet and shower water end uses.

A.2.3 Simulation results

Figure SI.2: Results of total water, water-related energy and CO_2 savings and economic water and energy benefits obtained for each simulation

Table SI.1: Parameters influencing water use for each location

Davis

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	2.83	1.42	0	6
Toilet	#Toilets	Integer	2.23	0.57	1	3
	#StdToilet	Integer	1.27	0.98	0	3
	#ULFToilet	Integer	1.07	1.07	0	3
	FlushStdToilet	gal/flush	4.03	1.49	1.85	5.63
	FlushULFToilet	gal/flush	2.16	0.43	1.67	2.74
	ToiletFrequency	flushes/day·person	5.14	1.82	2.31	9.08
Shower	#Shower	Integer	1.90	0.55	1	3
	#StdShower	Integer	0.90	0.92	0	3
	#LowFlowShower	Integer	1.20	0.96	0	3
	FlowStdShower	gal/minute	2.36	1.33	1.53	5.33
	FlowLowFlowShower	gal/minute	1.95	0.40	1.55	2.83
	LengthShower	minutes/shower	8.78	2.26	3.94	14.39
	ShowerFrequency	showers/day·person	5.44	2.08	0.00	8.88
Bath	BooleanBathUse	Boolean	0.33	0.48	0	1
	GallonsPerBath	gal/bath	24.56	11.16	8.77	43.34
	FrequencyBath	baths/day·person	0.85	0.84	0.13	2.42
Faucet	FaucetFlow	Boolean	1.00	0.00	1.00	1.00
	FaucetFrequency	events/day·person	20.77	18.30	0	108.31
Dishwasher	BooleanDishwasherUse	Boolean	0.58	0.50	0	1
	GallonsPerCycle	gal/cycle	7.72	3.45	3.32	17.84
	FrequencyDishwasher	cycle/week·person	0.83	1.02	0	4.375
Clotheswasher	BooleanClotheswasherUse	Boolean	0.92	0.28	0	1
	#TopLoadedCW	Integer	0.60	0.50	0	1
	#FrontLoadedCW	Integer	0.44	0.51	0	1
	#CW	Integer	1	0.26	0	2
	GallonsPerLoadTopCW	gal/load	45.54	13.66	19.94	71.12
	GallonsPerLoadFrontCW	gal/load	21.19	6.71	12.31	37.99
	FrequencyClotheswasher	loads/week·person	2.42	1.53	0	5.65
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	37.14	60.64	0.68	307.87
	BooleanOtherUse	Boolean	0.35	0.48	0	1
	GallonsPerDayOtherUse	gal/day	8.93	8.57	0.05	26.62
Outdoor	BooleanIrrigation	Boolean	0.88	0.32	0	1
	ET_0	inches/year	43.49	0.00	43.49	43.49
	LawnArea	square feet	4330.8 (100%)*	2668.33	533.00	13865.00
	GardenArea	square feet	549.0 (6%)*	84.87	500.00	647.00
	XeriscapeArea	square feet	656.6 (10%)*	375.34	118.00	1100.00
	SwimmingpoolArea	square feet	NoData (0%)*	NoData	NoData	NoData
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	1.47	0.99	0.09	5.44

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

Sonoma County Water Authority

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	2.55	1.22	0	6
Toilet	#Toilets	Integer	2.35	0.54	1	3
	#StdToilet	Integer	0.85	1.08	0	3
	#ULFToilet	Integer	1.59	1.16	0	3
	FlushStdToilet	gal/flush	4.68	1.09	3.44	6.94
	FlushULFToilet	gal/flush	2.07	0.81	1.21	4.80
	ToiletFrequency	flushes/day·person	5.36	3.08	1.12	15.69
Shower	#Shower	Integer	2.06	0.35	1	3
	#StdShower	Integer	0.82	0.85	0	3
	#LowFlowShower	Integer	1.37	0.76	0	2
	FlowStdShower	gal/minute	2.17	0.55	1.82	2.99
	FlowLowFlowShower	gal/minute	2.06	0.82	1.06	3.87
	LengthShower	minutes/shower	8.88	3.64	2.75	27.47
	ShowerFrequency	showers/day·person	4.40	2.83	0.00	12.92
Bath	BooleanBathUse	Boolean	0.36	0.48	0	1
	GallonsPerBath	gal/bath	23.31	7.18	11.13	37.75
	FrequencyBath	baths/day·person	0.64	0.42	0.15	1.48
Faucet	FaucetFlow	Boolean	1.00	0.00	1.00	1.00
	FaucetFrequency	events/day·person	24.88	22.01	0	110.19
Dishwasher	BooleanDishwasherUse	Boolean	0.78	0.42	0	1
	GallonsPerCycle	gal/cycle	7.51	3.04	2.72	20.02
	FrequencyDishwasher	cycle/week·person	0.60	0.79	0	4.08
Clotheswasher	BooleanClotheswasherUse	Boolean	0.95	0.22	0	1
	#TopLoadedCW	Integer	0.97	0.18	0	1
	#FrontLoadedCW	Integer	0.10	0.31	0	1
	#CW	Integer	1	0.25	0	2
	GallonsPerLoadTopCW	gal/load	36.86	8.10	9.91	53.77
	GallonsPerLoadFrontCW	gal/load	29.18	9.07	18.82	35.72
	FrequencyClotheswasher	loads/week·person	2.21	1.44	0	5.83
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	24.04	39.05	0.32	203.53
	BooleanOtherUse	Boolean	0.37	0.49	0	1
	GallonsPerDayOtherUse	gal/day	3.73	5.94	0.07	19.88
Outdoor	BooleanIrrigation	Boolean	0.80	0.41	0	1
	ET_0	inches/year	33.76	0.60	32.91	34.58
	LawnArea	square feet	4114.7 (100%)*	3035.62	955.00	13109.00
	GardenArea	square feet	325.3 (7%)*	79.05	238.00	392.00
	XeriscapeArea	square feet	1178.5 (19%)*	1004.57	146.00	2619.00
	SwimmingpoolArea	square feet	292.6 (28%)*	226.27	50	672
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	0.91	0.67	0.00	2.97

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

San Francisco Public Utility Commission

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	3.72	2.11	1	9
Toilet	#Toilets	Integer	2.09	1.31	1	7
	#StdToilet	Integer	0.74	1.21	0	5
	#ULFToilet	Integer	1.41	0.91	0	3
	FlushStdToilet	gal/flush	3.15	0.48	2.45	3.45
	FlushULFToilet	gal/flush	2.12	0.72	1.24	3.55
	ToiletFrequency	flushes/day·person	4.17	2.03	0.23	9.21
Shower	#Shower	Integer	2.00	1.28	1	7
	#StdShower	Integer	0.78	1.24	0	5
	#LowFlowShower	Integer	1.47	0.77	0	3
	FlowStdShower	gal/minute	2.34	0.00	2.34	2.34
	FlowLowFlowShower	gal/minute	1.92	0.52	1.39	3.16
	LengthShower	minutes/shower	9.08	2.92	3.28	19.17
	ShowerFrequency	showers/day·person	4.19	3.30	0.29	15.46
Bath	BooleanBathUse	Boolean	0.37	0.49	0	1
	GallonsPerBath	gal/bath	26.35	11.57	4.91	46.10
	FrequencyBath	baths/day·person	0.53	0.45	0.08	1.18
Faucet	FaucetFlow	Boolean	1.00	0.00	1.00	1.00
	FaucetFrequency	events/day·person	29.79	29.65	5.04	154.06
Dishwasher	BooleanDishwasherUse	Boolean	0.51	0.51	0	1
	GallonsPerCycle	gal/cycle	6.57	2.20	3.03	11.86
	FrequencyDishwasher	cycle/week·person	0.33	0.52	0	1.75
Clotheswasher	BooleanClotheswasherUse	Boolean	0.84	0.37	0	1
	#TopLoadedCW	Integer	0.74	0.45	0	1
	#FrontLoadedCW	Integer	0.36	0.49	0	1
	#CW	Integer	1.09	0.29	1	2
	GallonsPerLoadTopCW	gal/load	31.10	12.28	9.58	50.06
	GallonsPerLoadFrontCW	gal/load	29.32	11.84	18.50	48.11
	FrequencyClotheswasher	loads/week·person	2.08	3.09	0	15.75
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	19.73	36.19	0.23	197.98
	BooleanOtherUse	Boolean	0.55	0.50	0	1
	GallonsPerDayOtherUse	gal/day	29.21	58.79	0.02	257.50
Outdoor	BooleanIrrigation	Boolean	0.49	0.51	0	1
	ET$_0$	inches/year	29.75	1.17	25.35	30.04
	LawnArea	square feet	1195.6 (98%)*	695.10	461.00	2906.00
	GardenArea	square feet	364.0 (6%)*	0.00	364.00	364.00
	XeriscapeArea	square feet	NoData (0%)*	NoData	NoData	NoData
	SwimmingpoolArea	square feet	NoData (0%)*	NoData	NoData	NoData
	K$_c$Lawn	Dimensionless	0.8	0.8	0.8	0.8
	K$_c$Garden	Dimensionless	0.5	0.5	0.5	0.5
	K$_c$Xeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K$_c$Swimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	1.25	1.38	0.00	5.63

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

East Bay Metropolitan Utility District

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	3.07	1.47	1	7
Toilet	#Toilets	Integer	2.19	0.81	1	5
	#StdToilet	Integer	1.24	1.08	0	3
	#ULFToilet	Integer	1.15	1.18	0	4
	FlushStdToilet	gal/flush	2.98	0.98	1.59	5.09
	FlushULFToilet	gal/flush	2.77	1.25	1.44	6.65
	ToiletFrequency	flushes/day·person	4.80	3.11	0.31	14.36
Shower	#Shower	Integer	1.90	0.76	1	4
	#StdShower	Integer	1.05	0.97	0	3
	#LowFlowShower	Integer	0.96	0.98	0	3
	FlowStdShower	gal/minute	2.22	0.68	1.16	3.57
	FlowLowFlowShower	gal/minute	2.18	0.58	1.49	3.43
	LengthShower	minutes/shower	8.75	2.88	3.15	18.61
	ShowerFrequency	showers/day·person	4.19	2.72	0.00	15.56
Bath	BooleanBathUse	Boolean	0.41	0.49	0	1
	GallonsPerBath	gal/bath	23.13	8.37	10.35	44.61
	FrequencyBath	baths/day·person	1.05	1.32	0.11	7.18
Faucet	FaucetFlow	Boolean	1.00	0.00	1.00	1.00
	FaucetFrequency	events/day·person	20.48	20.29	0.41	150.21
Dishwasher	BooleanDishwasherUse	Boolean	0.51	0.50	0	1
	GallonsPerCycle	gal/cycle	6.54	2.08	1.85	10.82
	FrequencyDishwasher	cycle/week·person	0.56	1.03	0	7
Clotheswasher	BooleanClotheswasherUse	Boolean	0.87	0.34	0	1
	#TopLoadedCW	Integer	0.86	0.35	0	1
	#FrontLoadedCW	Integer	0.25	0.44	0	1
	#CW	Integer	1.08	0.27	1	2
	GallonsPerLoadTopCW	gal/load	40.43	8.88	10.03	60.37
	GallonsPerLoadFrontCW	gal/load	30.66	11.24	15.66	49.55
	FrequencyClotheswasher	loads/week·person	1.95	1.48	0	8.88
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	25.57	44.77	0.34	290.14
	BooleanOtherUse	Boolean	0.51	0.50	0	1
	GallonsPerDayOtherUse	gal/day	5.72	11.64	0.03	77.10
Outdoor	BooleanIrrigation	Boolean	0.85	0.36	0	1
	ET_0	inches/year	34.90	3.19	29.68	43.92
	LawnArea	square feet	2143.5 (97%)*	1924.30	191.00	12491.00
	GardenArea	square feet	288.0 (1%)*	0.00	288.00	288.00
	XeriscapeArea	square feet	1966.8 (23%)*	1534.40	178.00	5886.00
	SwimmingpoolArea	square feet	440.5 (7%)*	402.78	50	946
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	2.00	2.00	0.00	12.19

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

Redwood City

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	2.86	1.57	1	9
Toilet	#Toilets	Integer	2.23	1.06	1	5
	#StdToilet	Integer	0.94	0.94	0	3
	#ULFToilet	Integer	1.36	1.34	0	4
	FlushStdToilet	gal/flush	3.15	1.22	1.24	4.86
	FlushULFToilet	gal/flush	2.09	0.64	1.20	3.24
	ToiletFrequency	flushes/day·person	4.76	2.03	0.85	9.25
Shower	#Shower	Integer	1.91	1.01	1	5
	#StdShower	Integer	0.89	0.87	0	3
	#LowFlowShower	Integer	1.13	1.18	0	4
	FlowStdShower	gal/minute	1.96	0.75	0.92	3.23
	FlowLowFlowShower	gal/minute	2.39	0.98	1.51	5.21
	LengthShower	minutes/shower	9.77	3.57	3.58	22.36
	ShowerFrequency	showers/day·person	5.42	2.74	1.46	13.46
Bath	BooleanBathUse	Boolean	0.51	0.50	0	1
	GallonsPerBath	gal/bath	29.25	17.81	8.26	86.56
	FrequencyBath	baths/day·person	0.73	0.59	0.12	1.88
Faucet	FaucetFlow	Boolean	1.00	0.00	1.00	1.00
	FaucetFrequency	events/day·person	27.94	27.09	3.25	110.63
Dishwasher	BooleanDishwasherUse	Boolean	0.76	0.43	0	1
	GallonsPerCycle	gal/cycle	7.31	2.84	2.44	14.96
	FrequencyDishwasher	cycle/week·person	1.01	1.86	0	10.5
Clotheswasher	BooleanClotheswasherUse	Boolean	0.98	0.13	0	1
	#TopLoadedCW	Integer	0.74	0.45	0	1
	#FrontLoadedCW	Integer	0.33	0.48	0	1
	#CW	Integer	1.03	0.17	1	2
	GallonsPerLoadTopCW	gal/load	40.03	9.85	25.24	63.66
	GallonsPerLoadFrontCW	gal/load	28.38	16.16	16.84	68.09
	FrequencyClotheswasher	loads/week·person	2.60	1.67	0.93	7.00
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	26.02	52.31	0.04	334.72
	BooleanOtherUse	Boolean	0.32	0.47	0	1
	GallonsPerDayOtherUse	gal/day	4.88	8.43	0.02	24.69
Outdoor	BooleanIrrigation	Boolean	0.93	0.25	0	1
	ET_0	inches/year	38.25	0.00	38.25	38.25
	LawnArea	square feet	3526.9 (100%)*	3093.73	361.00	16126.00
	GardenArea	square feet	NoData (0%)*	NoData	NoData	NoData
	XeriscapeArea	square feet	1392.1 (16%)*	1253.66	239.00	3807.00
	SwimmingpoolArea	square feet	NoData (0%)*	NoData	NoData	NoData
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	1.22	1.31	0.04	7.54

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

Las Virgenes Municipal Water District

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	2.73	1.36	1	8
Toilet	#Toilets	Integer	3.20	1.21	2	6
	#StdToilet	Integer	1.37	1.54	0	5
	#ULFToilet	Integer	1.83	1.32	0	4
	FlushStdToilet	gal/flush	3.20	1.03	1.99	4.55
	FlushULFToilet	gal/flush	2.14	0.58	1.55	3.24
	ToiletFrequency	flushes/day·person	5.82	2.87	0.62	14.08
Shower	#Shower	Integer	2.87	1.41	1	8
	#StdShower	Integer	1.43	1.45	0	4
	#LowFlowShower	Integer	1.59	1.15	0	4
	FlowStdShower	gal/minute	2.12	0.58	1.55	2.91
	FlowLowFlowShower	gal/minute	1.76	0.35	1.33	2.43
	LengthShower	minutes/shower	9.12	2.31	4.56	13.85
	ShowerFrequency	showers/day·person	5.02	2.85	0.00	11.85
Bath	BooleanBathUse	Boolean	0.63	0.49	0	1
	GallonsPerBath	gal/bath	19.38	6.97	8.50	43.03
	FrequencyBath	baths/day·person	0.70	0.75	0.13	2.69
Faucet	FaucetFlow	Boolean	0.98	0.13	0.00	1.00
	FaucetFrequency	events/day·person	22.90	15.82	0	70.08
Dishwasher	BooleanDishwasherUse	Boolean	0.83	0.38	0	1
	GallonsPerCycle	gal/cycle	6.31	2.50	1.94	13.90
	FrequencyDishwasher	cycle/week·person	0.68	0.61	0	2.15
Clotheswasher	BooleanClotheswasherUse	Boolean	0.95	0.22	0	1
	#TopLoadedCW	Integer	0.67	0.48	0	1
	#FrontLoadedCW	Integer	0.37	0.49	0	1
	#CW	Integer	1	0.00	1	1
	GallonsPerLoadTopCW	gal/load	41.34	13.82	24.56	90.30
	GallonsPerLoadFrontCW	gal/load	24.74	14.34	12.88	64.19
	FrequencyClotheswasher	loads/week·person	2.42	1.31	0	4.85
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	44.70	71.26	0.13	500.79
	BooleanOtherUse	Boolean	0.78	0.42	0	1
	GallonsPerDayOtherUse	gal/day	15.05	72.38	0.02	490.00
Outdoor	BooleanIrrigation	Boolean	1.00	0.00	1	1
	ET_0	inches/year	46.80	0.00	46.80	46.80
	LawnArea	square feet	4769.0 (100%)*	2838.96	698.30	15202.80
	GardenArea	square feet	NoData (0%)*	NoData	NoData	NoData
	XeriscapeArea	square feet	28129.0 (2%)*	0.00	28129.00	28129.00
	SwimmingpoolArea	square feet	467.9 (60%)*	153.6324704	160.9	915.5
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	2.05	0.94	0.48	4.67

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

Los Angeles Department of Water and Power

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	2.98	2.05	1	17
Toilet	#Toilets	Integer	2.33	0.88	1	6
	#StdToilet	Integer	0.66	1.02	0	4
	#ULFToilet	Integer	1.84	1.11	0	4
	FlushStdToilet	gal/flush	4.05	1.69	1.47	7.04
	FlushULFToilet	gal/flush	2.26	0.79	0.69	4.77
	ToiletFrequency	flushes/day·person	5.38	4.33	0.16	25.00
Shower	#Shower	Integer	2.02	0.78	1	5
	#StdShower	Integer	0.87	0.99	0	3
	#LowFlowShower	Integer	1.31	0.94	0	4
	FlowStdShower	gal/minute	2.44	0.79	1.47	4.40
	FlowLowFlowShower	gal/minute	2.16	0.71	1.12	4.70
	LengthShower	minutes/shower	7.55	2.42	2.01	16.44
	ShowerFrequency	showers/day·person	5.15	7.26	0.00	71.08
Bath	BooleanBathUse	Boolean	0.62	0.49	0	1
	GallonsPerBath	gal/bath	20.32	9.08	5.28	57.01
	FrequencyBath	baths/day·person	0.79	0.67	0.03	2.92
Faucet	FaucetFlow	Boolean	0.98	0.14	0.00	1.00
	FaucetFrequency	events/day·person	25.47	25.47	0	200.88
Dishwasher	BooleanDishwasherUse	Boolean	0.46	0.50	0	1
	GallonsPerCycle	gal/cycle	8.02	7.46	2.67	55.39
	FrequencyDishwasher	cycle/week·person	0.38	0.60	0	2.96
Clotheswasher	BooleanClotheswasherUse	Boolean	0.90	0.30	0	1
	#TopLoadedCW	Integer	0.81	0.39	0	1
	#FrontLoadedCW	Integer	0.31	0.47	0	1
	#CW	Integer	1.05	0.26	0	2
	GallonsPerLoadTopCW	gal/load	38.48	8.81	18.55	61.38
	GallonsPerLoadFrontCW	gal/load	26.74	9.99	12.62	48.02
	FrequencyClotheswasher	loads/week·person	2.32	1.79	0	8.40
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	47.56	102.78	0.01	686.51
	BooleanOtherUse	Boolean	0.69	0.46	0	1
	GallonsPerDayOtherUse	gal/day	6.76	16.89	0.02	91.78
Outdoor	BooleanIrrigation	Boolean	1.00	0.00	1	1
	ET_0	inches/year	41.57	0.00	41.57	41.57
	LawnArea	square feet	3226.8 (100%)*	2249.40	240.00	11659.70
	GardenArea	square feet	NoData (0%)*	NoData	NoData	NoData
	XeriscapeArea	square feet	793.9 (1%)*	0.00	793.90	793.90
	SwimmingpoolArea	square feet	470.8 (26%)*	182.0945969	45.9	785.1
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	1.87	2.01	0.18	18.43

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

Irvine Ranch Water District

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	3.11	1.57	0	7
Toilet	#Toilets	Integer	3.00	1.10	1	7
	#StdToilet	Integer	1.66	1.18	0	3
	#ULFToilet	Integer	1.48	1.53	0	4
	FlushStdToilet	gal/flush	3.38	1.06	1.54	5.41
	FlushULFToilet	gal/flush	2.50	1.02	1.56	4.96
	ToiletFrequency	flushes/day·person	5.35	3.00	0.21	16.00
Shower	#Shower	Integer	2.77	1.10	1	7
	#StdShower	Integer	1.63	1.18	0	4
	#LowFlowShower	Integer	1.38	1.43	0	4
	FlowStdShower	gal/minute	2.19	0.71	1.38	4.11
	FlowLowFlowShower	gal/minute	2.00	0.37	1.61	2.92
	LengthShower	minutes/shower	8.50	2.69	3.06	23.14
	ShowerFrequency	showers/day·person	4.81	3.14	0.00	14.29
Bath	BooleanBathUse	Boolean	0.73	0.45	0	1
	GallonsPerBath	gal/bath	16.78	5.92	6.85	45.61
	FrequencyBath	baths/day·person	1.19	1.22	0.12	4.58
Faucet	FaucetFlow	Boolean	1.00	0.00	1.00	1.00
	FaucetFrequency	events/day·person	17.20	12.45	0	77.69
Dishwasher	BooleanDishwasherUse	Boolean	0.66	0.48	0	1
	GallonsPerCycle	gal/cycle	7.01	2.48	2.31	15.79
	FrequencyDishwasher	cycle/week·person	0.54	0.57	0	3.21
Clotheswasher	BooleanClotheswasherUse	Boolean	0.95	0.22	0	1
	#TopLoadedCW	Integer	0.77	0.43	0	1
	#FrontLoadedCW	Integer	0.32	0.47	0	1
	#CW	Integer	1.04	0.20	1	2
	GallonsPerLoadTopCW	gal/load	39.25	8.40	24.36	66.92
	GallonsPerLoadFrontCW	gal/load	19.50	6.86	12.89	37.11
	FrequencyClotheswasher	loads/week·person	2.43	2.09	0	10.50
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	30.07	49.46	0.09	378.34
	BooleanOtherUse	Boolean	0.67	0.47	0	1
	GallonsPerDayOtherUse	gal/day	2.85	5.15	0.01	26.89
Outdoor	BooleanIrrigation	Boolean	0.99	0.09	0	1
	ET_0	inches/year	47.92	0.58	46.25	48.12
	LawnArea	square feet	2210.6 (100%)*	1608.63	159.20	8778.00
	GardenArea	square feet	NoData (0%)*	NoData	NoData	NoData
	XeriscapeArea	square feet	453.3 (10%)*	492.68	90.50	1532.70
	SwimmingpoolArea	square feet	361.5 (11%)*	206.8474774	32.3	769.6
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	1.87	1.22	0.00	7.16

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

San Diego City

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	2.74	1.84	1	12
Toilet	#Toilets	Integer	2.57	0.90	1	5
	#StdToilet	Integer	0.86	1.11	0	3
	#ULFToilet	Integer	2.03	1.22	0	4
	FlushStdToilet	gal/flush	3.87	1.05	2.30	5.24
	FlushULFToilet	gal/flush	2.43	0.69	1.58	4.20
	ToiletFrequency	flushes/day·person	6.22	3.57	1.08	16.00
Shower	#Shower	Integer	2.11	0.70	0	4
	#StdShower	Integer	0.97	1.01	0	3
	#LowFlowShower	Integer	1.35	1.05	0	4
	FlowStdShower	gal/minute	2.25	0.82	1.27	3.43
	FlowLowFlowShower	gal/minute	1.73	0.46	0.46	2.36
	LengthShower	minutes/shower	8.09	2.67	4.38	17.22
	ShowerFrequency	showers/day·person	4.91	3.02	0.54	15.62
Bath	BooleanBathUse	Boolean	0.57	0.50	0	1
	GallonsPerBath	gal/bath	18.72	7.78	7.14	38.60
	FrequencyBath	baths/day·person	0.95	1.05	0.10	4.45
Faucet	FaucetFlow	Boolean	1.00	0.00	1.00	1.00
	FaucetFrequency	events/day·person	20.71	10.95	5.54	48.62
Dishwasher	BooleanDishwasherUse	Boolean	0.59	0.50	0	1
	GallonsPerCycle	gal/cycle	6.79	2.92	3.03	13.81
	FrequencyDishwasher	cycle/week·person	0.55	0.68	0	2.33
Clotheswasher	BooleanClotheswasherUse	Boolean	0.97	0.18	0	1
	#TopLoadedCW	Integer	0.76	0.43	0	1
	#FrontLoadedCW	Integer	0.30	0.47	0	1
	#CW	Integer	1	0.00	1	1
	GallonsPerLoadTopCW	gal/load	42.30	10.82	29.22	65.48
	GallonsPerLoadFrontCW	gal/load	20.36	2.90	16.11	25.75
	FrequencyClotheswasher	loads/week·person	1.91	1.02	0	4.38
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	18.58	26.87	0.33	123.76
	BooleanOtherUse	Boolean	0.69	0.47	0	1
	GallonsPerDayOtherUse	gal/day	3.47	9.31	0.07	57.97
Outdoor	BooleanIrrigation	Boolean	0.97	0.18	0	1
	ET_0	inches/year	46.88	1.94	43.08	54.33
	LawnArea	square feet	2451.1 (98%)*	1495.13	142.00	6781.30
	GardenArea	square feet	NoData (0%)*	NoData	NoData	NoData
	XeriscapeArea	square feet	605.6 (4%)*	105.50	531.00	680.20
	SwimmingpoolArea	square feet	320.8 (14%)*	217.6123913	17.1	597.5
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	1.48	2.92	0.00	21.01

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

San Diego County

	Parameter	Units	Average	Std. Deviation	Low Value	High Value
	# Residents	Integer	2.74	1.25	1	6
Toilet	#Toilets	Integer	2.54	1.20	1	5
	#StdToilet	Integer	1.15	1.28	0	4
	#ULFToilet	Integer	1.38	1.45	0	4
	FlushStdToilet	gal/flush	4.38	0.41	3.93	4.86
	FlushULFToilet	gal/flush	2.30	0.53	1.77	3.00
	ToiletFrequency	flushes/day·person	5.08	2.59	1.54	13.33
Shower	#Shower	Integer	2.38	1.12	1	5
	#StdShower	Integer	0.92	0.95	0	3
	#LowFlowShower	Integer	1.46	1.27	0	4
	FlowStdShower	gal/minute	1.93	0.44	1.33	2.38
	FlowLowFlowShower	gal/minute	2.38	1.06	1.75	4.26
	LengthShower	minutes/shower	9.17	2.82	3.46	16.60
	ShowerFrequency	showers/day·person	4.91	2.92	0.83	10.79
Bath	BooleanBathUse	Boolean	0.71	0.46	0	1
	GallonsPerBath	gal/bath	18.39	5.24	7.29	29.08
	FrequencyBath	baths/day·person	0.89	0.89	0.13	3.50
Faucet	FaucetFlow	Boolean	1.00	0.00	1.00	1.00
	FaucetFrequency	events/day·person	19.21	13.14	4.09	53.00
Dishwasher	BooleanDishwasherUse	Boolean	0.52	0.50	0	1
	GallonsPerCycle	gal/cycle	6.55	1.99	2.83	9.88
	FrequencyDishwasher	cycle/week·person	0.57	0.70	0	2.55
Clotheswasher	BooleanClotheswasherUse	Boolean	0.96	0.19	0	1
	#TopLoadedCW	Integer	0.82	0.40	0	1
	#FrontLoadedCW	Integer	0.42	0.51	0	1
	#CW	Integer	1.08	0.28	1	2
	GallonsPerLoadTopCW	gal/load	35.32	13.62	11.82	56.67
	GallonsPerLoadFrontCW	gal/load	23.20	11.57	12.00	42.16
	FrequencyClotheswasher	loads/week·person	2.39	1.64	0.5	5.95
Leaks/Other	BooleanLeaks	Boolean	1	0	1	1
	GallonsPerDayLeaks	gal/day	24.38	50.10	0.34	367.96
	BooleanOtherUse	Boolean	0.71	0.46	0	1
	GallonsPerDayOtherUse	gal/day	3.25	6.05	0.05	28.93
Outdoor	BooleanIrrigation	Boolean	0.96	0.19	0	1
	ET_0	inches/year	47.70	1.61	46.69	54.33
	LawnArea	square feet	3413.7 (96%)*	3494.50	76.30	16222.80
	GardenArea	square feet	NoData (0%)*	NoData	NoData	NoData
	XeriscapeArea	square feet	2263.7 (13%)*	3223.72	133.70	9478.30
	SwimmingpoolArea	square feet	417.1 (30%)*	285.5087627	34.3	1315.1
	K_cLawn	Dimensionless	0.8	0.8	0.8	0.8
	K_cGarden	Dimensionless	0.5	0.5	0.5	0.5
	K_cXeriscape	Dimensionless	0.3	0.3	0.3	0.3
	K_cSwimmingpool	Dimensionless	1.25	1.25	1.25	1.25
	ApplicationRatio	Dimensionless	1.72	2.11	0.00	12.76

*Values in the parentheses show the percentage of houses over the total of the sample that have these areas.

Table SI.2: Air and inlet temperature used in the energy assessment. Source: Temperatures from closest CIMIS stations; Δ(TINLET – TAVG) from USDOE (2009).

Water Agency	T_{MAX}	T_{AVG}	T_{MIN}	$\Delta\ (T_{INLET}-T_{AVG})$
Davis	73.9	60.2	46.5	10.4
SCWA	74.7	59.7	44.7	10.4
SFPUC	65.1	58.3	51.4	10.4
EBMUD	66.2	58.1	49.9	10.4
Redwood	70.0	58.6	47.1	10.4
Los Angeles DWP	75.6	66.2	56.6	9.5
IRWD	67.6	61.7	55.8	9.5
San Diego City	70.8	64.4	58.1	11.8
Las Virgenes MWD	75.6	66.2	56.6	9.5
San Diego County	70.8	64.4	58.1	11.8

Table SI.3: Water heater setpoint temperature. Source: Abdallah and Rosenberg (2014).

Temperature (ºF)	Percentage
120	60.0%
[120 - 140]	40.0%

Table SI.4: Primary water heating fuel in single-family homes in California. Source: USEIA (2009)[5]

Water Heater Fuel	Percentage
Natural Gas	87.6%
Propane/LPG	3.3%
Fuel Oil	0.1%
Electricity	8.6%
Other Fuel	0.4%

Table SI.5: Water heater sizes per primary water heating fuel. Source: USEIA (2009).

Size	Natural Gas	Electricity
Small (<30)	13.9%	15.7%
Medium ([30,50])	52.5%	51.7%
Large (>50)	33.6%	32.6%

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[5] In our model we only used natural gas and electric water heaters adjusting the percentages shown above.

Table SI.6: Distribution of basecase efficiency by tank size for natural gas water heaters. Source: USDOE (2009).

Tank Size	30		40		50		65		75	
Eff. Level	EF	%	EF	%	EF	%	EF	%	EF	%
0	0.6	92.0%	0.6	63.9%	0.58	57.3%	0.6	58.9%	0.5	41.7%
1	0.6	1.7%	0.6	23.4%	0.6	4.6%	0.6	13.4%	0.6	26.0%
2	0.6	0.0%	0.6	1.6%	0.62	24.1%	0.6	8.0%	0.6	20.8%
3	0.7	0.0%	0.6	4.8%	0.63	7.8%	0.6	13.4%	0.6	0.0%
4	0.7	0.0%	0.7	0.0%	0.65	0.0%	0.6	0.0%	0.6	5.2%
5	0.7	5.3%	0.7	5.3%	0.66	5.3%	0.6	5.3%	0.6	5.3%
6	0.8	1.0%	0.8	1.0%	0.76	1.0%	0.8	1.0%	0.7	1.0%

Table SI.7: Distribution of basecase efficiency by tank size for electric water heaters. Source: USDOE (2009).

Tank Size	30		40		50		66		80		119	
Eff. Level	EF	%	EF	%	EF	%	EF	%	EF	%	EF	%
0	0.9	80.2%	0.9	7.3%	0.9	29.8%	0.9	30.2%	0.9	42.6%	0.8	12.7%
1	0.9	0.0%	0.9	51.2%	0.91	16.8%	0.9	8.6%	0.9	0.0%	0.8	25.3%
2	0.9	0.0%	0.9	0.0%	0.92	11.2%	0.9	8.6%	0.9	0.0%	0.8	12.7%
3	0.9	11.9%	0.9	23.8%	0.93	26.1%	0.9	34.5%	0.9	26.2%	0.8	6.3%
4	1.0	0.0%	0.9	7.3%	0.94	7.5%	0.9	4.3%	0.9	19.7%	0.9	38.0%
5	1.0	3.0%	1.0	5.5%	0.95	3.7%	0.9	8.6%	0.9	6.6%	0.9	0.0%
6	2.0	4.0%	2.0	4.0%	2	4.0%	2.0	4.0%	2.0	4.0%	1.9	4.0%
7	2.4	1.0%	2.4	1.0%	2.35	1.0%	2.3	1.0%	2.3	1.0%	2.3	1.0%

Table SI.8: Rated input power (PON) distribution by rated volume for natural gas water heaters. Source: USDOE (2009).

Input Rating	30 Gallon	40 Gallon	50 Gallon	65 Gallon	75 Gallon
(kBtu/h)	(>35 Gal)	(>=35 to <45 Gal)	(>=45 to <55 Gal)	(>=55 to <70 Gal)	(>=70 Gal)
30	59.3%	1.1%	0.0%	0.0%	0.0%
32	27.8%	1.1%	0.0%	0.0%	0.0%
33	0.0%	0.6%	0.0%	0.0%	0.0%
34	1.9%	9.5%	0.7%	0.0%	0.0%
35.5	9.3%	2.2%	2.0%	0.0%	0.0%
36	0.0%	11.7%	5.9%	0.0%	0.0%
38	0.0%	12.8%	6.6%	2.6%	0.0%
40	1.9%	55.3%	44.1%	5.3%	0.0%
42	0.0%	1.1%	8.6%	2.6%	5.6%
45	0.0%	0.0%	0.7%	0.0%	0.0%
48	0.0%	1.7%	2.0%	0.0%	0.0%
50	0.0%	2.8%	11.8%	15.8%	0.0%
52	0.0%	0.0%	0.0%	2.6%	0.0%
55	0.0%	0.0%	0.0%	7.9%	5.6%
60	0.0%	0.0%	4.6%	0.0%	11.1%
62.5	0.0%	0.0%	0.7%	0.0%	0.0%
65	0.0%	0.0%	10.5%	55.3%	0.0%
67	0.0%	0.0%	2.0%	0.0%	0.0%
70	0.0%	0.0%	0.0%	7.9%	22.2%
75	0.0%	0.0%	0.0%	0.0%	55.6%

Table SI.9: Rated input power (PON) distribution by rated volume for electric water heaters. Source: USDOE (2009).

Input Rating	30 gallons	40 gallons	50 gallons	66 gallons	80 gallons	119 gallons
kW	%	%	%	%	%	%
1.5	3.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1.7	3.0%	0.0%	0.0%	0.0%	0.0%	0.0%
3	3.0%	1.9%	5.6%	0.0%	3.3%	11.8%
3.8	9.1%	15.4%	13.0%	4.2%	6.7%	11.8%
4.5	81.8%	82.7%	81.5%	91.7%	86.7%	76.5%
5.5	0.0%	0.0%	0.0%	4.2%	3.3%	0.0%

Table SI.10: Hot water vs. total water use (Source: Mayer et al. (2003)) and assumed distribution functions for hot water end uses.

	Study values				Assumed distribution		
End-Use	Hot Water (GPD)	95% CI	Total Water Use (GPD)	95% CI	Mean	Standard Deviation	Distribution Function
Toilet	0.0	0.0	21.4	1.8	0.0%	0.0%	—
Shower	6.9	1.2	9.6	1.6	71.9%	7.1%	Normal
Bath	1.7	0.7	1.9	0.8	89.5%	3.5%	Truncated Normal
Faucet	8.6	0.9	13.2	1.5	65.2%	5.5%	Normal
Dishwasher	1.4	0.3	1.4	0.4	100.0%	—	Fixed Value
Clothes-Washer	1.9	0.6	12.4	3.0	15.3%	3.7%	Normal
Leak	0.7	0.1	11.2	2.6	6.3%	1.0%	Normal
Other	0.0	0.0	0.0	0.0	0.0%	0.0%	—
Outdoor	0.0	0.0	0.0	0.0	0.0%	0.0%	—

Table SI.11: Emission factors reported by electric utilities in California. Source: CRPUW (2009).

Power Utility	kg CO_2/kWh
PG&E	0.24
San Francisco City and County	0.30
San Diego Gas & Electric	0.32
Los Angeles Department of Water and Power	0.58
Southern California Edison	0.30

Table SI.12: Water rate structure for each water utility analyzed in the study. Own construction from Mayer et al. (2003).

Utility	Billing Frequency	Fixed Charge	First Tier (CCF)	Marginal Cost Tier 1	Second Tier (CCF)	Marginal Cost Tier 2	Third Tier (CCF)	Marginal Cost Tier 3	Fourth Tier (CCF)	Marginal Cost Tier 4	Fifth Tier (CCF)	Marginal Cost Tier 5	Fixed Sewer Charge	Marginal Sewer Cost per CCF
Los Angeles DWP	Bimonthly	$0.00	[0,53.14]	$2.18	>53.14	$3.18	—	—	—	—	—	—	$0.00	$2.85
IRWD	Monthly	$5.45	[0,7]	$0.91	[7,16]	$1.27	[16,24]	$2.86	[24,31]	$4.80	>31	$9.84	$10.00	$0.00
San Diego City and County	Monthly	$15.87	[0,7]	$1.73	[7,14]	$2.16	>14	$2.37	—	—	—	—	$11.32	$3.12
EBMUD	Monthly	$9.25	[0,7]	$1.65	[7,16]	$2.05	>16	$2.51	—	—	—	—	$9.33	$0.47
Davis	Bimonthly	$6.22	[0,36]	$0.77	>36	$0.86	—	—	—	—	—	—	$26.69	$0.00
SFPUC	Bimonthly	$4.60	>0	$2.14	—	—	—	—	—	—	—	—	$0.00	$5.07
Las Virgenes MWD	Bimonthly	$14.05	[0,12]	$1.90	[12,24]	$2.03	[24,115]	$2.63	>115	$3.20	—	—	$58.73	$0.00
Redwood	Bimonthly	$24.00	[0,10]	$1.18	[10,25]	$2.16	[25,50]	$2.74	>50	$3.53	—	—	$26.27	$0.00
SCWA	Bimonthly	$5.00	[0,20]	$2.28	>20	$5.28	—	—	—	—	—	—	$21.83	$0.00

Table SI.13: Electricity prices for California power utilities

Power Utility	$/kWh
PG&E	0.129
San Francisco City and County	0.129
San Diego Gas & Electric	0.166
Los Angeles Department of Water and Power	0.105
Southern California Edison	0.153

Table SI.14: Average water use, water-related energy use, water-related GHG emissions, water costs, water-related energy costs and total costs per utility and end-use.

Water use per utility and end-use [GPD]

Utility	Toilet	Shower	Bath	Faucet	Dishwasher	Clothes Washer	Leaks + Other	Outdoor	Total
Davis	34.33	28.92	2.51	23.38	1.67	23.61	35.59	282.38	432.39
SCWA	35.58	32.31	2.09	31.41	2.01	28.72	25.20	112.21	269.53
SFPUC	30.07	30.40	2.51	45.42	0.88	20.93	32.01	18.56	180.78
EBMUD	33.19	30.76	3.77	31.29	1.23	27.38	26.81	136.52	290.95
Redwood	32.17	38.32	3.94	27.29	1.74	34.08	25.77	128.41	291.71
Las Virgenes MWD	40.59	41.00	3.11	32.82	1.73	34.10	52.34	610.82	816.51
Los Angeles DWP	26.71	26.89	3.35	31.83	0.91	25.10	46.49	267.78	429.05
IRWD	39.97	34.88	4.79	29.66	1.46	28.98	30.31	260.13	430.18
San Diego City	39.90	23.46	2.65	23.06	1.15	27.71	19.77	166.29	303.99
San Diego County	38.03	39.63	4.28	31.22	1.13	37.68	25.34	294.74	472.05

Water-related energy yse per utility and end-use [kWh/day]

Utility	Toilet	Shower	Bath	Faucet	Dishwasher	Clothes Washer	Leaks + Other	Outdoor	Total
Davis	0.00	4.44	0.48	3.26	0.35	0.77	0.44	0.00	9.74
SCWA	0.00	5.06	0.40	4.38	0.43	0.95	0.32	0.00	11.55
SFPUC	0.00	4.82	0.50	6.50	0.19	0.69	0.23	0.00	12.94
EBMUD	0.00	4.91	0.75	4.47	0.27	0.93	0.33	0.00	11.66
Redwood	0.00	6.02	0.76	3.88	0.38	1.14	0.33	0.00	12.51
Las Virgenes MWD	0.00	5.66	0.54	4.11	0.33	1.00	0.44	0.00	12.08
Los Angeles DWP	0.00	3.75	0.58	4.02	0.18	0.74	0.50	0.00	9.77
IRWD	0.00	5.28	0.90	4.09	0.31	0.93	0.37	0.00	11.89
San Diego City	0.00	3.22	0.45	2.89	0.22	0.81	0.20	0.00	7.79
San Diego County	0.00	5.41	0.73	3.87	0.22	1.09	0.28	0.00	11.60

Water-related GHG emissions per utility and end-use [kg CO_2/year]

Utility	Toilet	Shower	Bath	Faucet	Dishwasher	Clothes Washer	Leaks + Other	Outdoor	Total
Davis	0.00	299.72	32.44	219.60	23.99	52.23	29.46	0.00	657.43
SCWA	0.00	340.59	27.24	295.33	29.34	64.12	21.69	0.00	778.31
SFPUC	0.00	330.68	33.87	444.57	13.33	47.45	16.00	0.00	885.90
EBMUD	0.00	330.40	50.12	300.75	18.41	62.41	22.38	0.00	784.46
Redwood	0.00	405.35	51.52	261.67	25.74	76.70	22.62	0.00	843.60
Las Virgenes MWD	0.00	388.91	36.76	281.70	22.80	68.81	30.09	0.00	829.06
Los Angeles DWP	0.00	284.40	43.01	297.51	13.01	54.42	36.87	0.00	729.22
IRWD	0.00	361.34	61.77	279.31	21.05	63.77	25.65	0.00	812.89
San Diego City	0.00	221.46	31.36	198.00	15.04	55.66	14.18	0.00	535.70
San Diego County	0.00	373.76	50.26	267.77	14.85	75.37	19.07	0.00	801.08

Water cost per utility and end-use [$/month]

Utility	Toilet	Shower	Bath	Faucet	Dishwasher	Clothes Washer	Leaks + Other	Outdoor	Total
Davis	2.89	2.40	0.22	1.95	0.14	1.94	2.86	18.01	30.39
SCWA	6.16	5.62	0.36	5.45	0.35	4.99	4.49	19.78	47.21
SFPUC	9.24	9.31	0.77	13.84	0.27	6.40	9.80	5.67	55.30
EBMUD	6.04	5.56	0.68	5.59	0.23	4.97	4.88	21.79	49.74
Redwood	6.12	7.23	0.76	5.16	0.33	6.45	4.90	23.11	54.05
Las Virgenes MWD	6.86	6.91	0.53	5.52	0.29	5.76	8.67	97.13	131.67
Los Angeles DWP	5.54	5.61	0.69	6.60	0.19	5.19	9.63	56.84	90.29
IRWD	5.96	5.30	0.71	4.44	0.21	4.42	4.55	53.78	79.37
San Diego City	13.08	7.70	0.88	7.61	0.38	9.11	6.58	48.55	93.89
San Diego County	11.76	12.13	1.33	9.61	0.35	11.54	7.80	79.54	134.05

Water-related Energy Cost per utility and end-use [$/month]

Utility	Toilet	Shower	Bath	Faucet	Dishwasher	Clothes Washer	Leaks + Other	Outdoor	Total
Davis	0.00	6.03	0.66	4.42	0.49	1.05	0.60	0.00	13.26
SCWA	0.00	6.79	0.55	5.94	0.59	1.29	0.43	0.00	15.59
SFPUC	0.00	6.51	0.66	8.70	0.26	0.93	0.32	0.00	17.38
EBMUD	0.00	6.57	0.99	5.97	0.36	1.24	0.44	0.00	15.57
Redwood	0.00	8.12	1.07	5.29	0.51	1.54	0.46	0.00	16.99
Las Virgenes MWD	0.00	7.95	0.75	5.71	0.46	1.40	0.63	0.00	16.91
Los Angeles DWP	0.00	4.97	0.76	5.23	0.23	0.96	0.65	0.00	12.80
IRWD	0.00	7.31	1.25	5.63	0.43	1.28	0.53	0.00	16.42
San Diego City	0.00	4.54	0.65	4.01	0.30	1.14	0.30	0.00	10.93
San Diego County	0.00	7.71	1.04	5.54	0.30	1.55	0.40	0.00	16.53

Total water and water-related energy cost per utility and end-use [$/month]

Utility	Toilet	Shower	Bath	Faucet	Dishwasher	Clothes Washer	Leaks + Other	Outdoor	Total
Davis	2.89	8.43	0.88	6.37	0.63	2.99	3.46	18.01	43.65
SCWA	6.16	12.42	0.91	11.39	0.95	6.27	4.92	19.78	62.80
SFPUC	9.24	15.82	1.43	22.54	0.54	7.33	10.11	5.67	72.68
EBMUD	6.04	12.13	1.67	11.56	0.59	6.20	5.32	21.79	65.32
Redwood	6.12	15.35	1.83	10.45	0.85	7.99	5.36	23.11	71.04
Las Virgenes MWD	6.86	14.87	1.28	11.23	0.76	7.16	9.29	97.13	148.58
Los Angeles DWP	5.54	10.59	1.45	11.83	0.42	6.15	10.28	56.84	103.09
IRWD	5.96	12.61	1.96	10.07	0.63	5.70	5.07	53.78	95.80
San Diego City	13.08	12.24	1.52	11.63	0.68	10.25	6.87	48.55	104.82
San Diego County	11.76	19.84	2.36	15.14	0.65	13.09	8.19	79.54	150.59

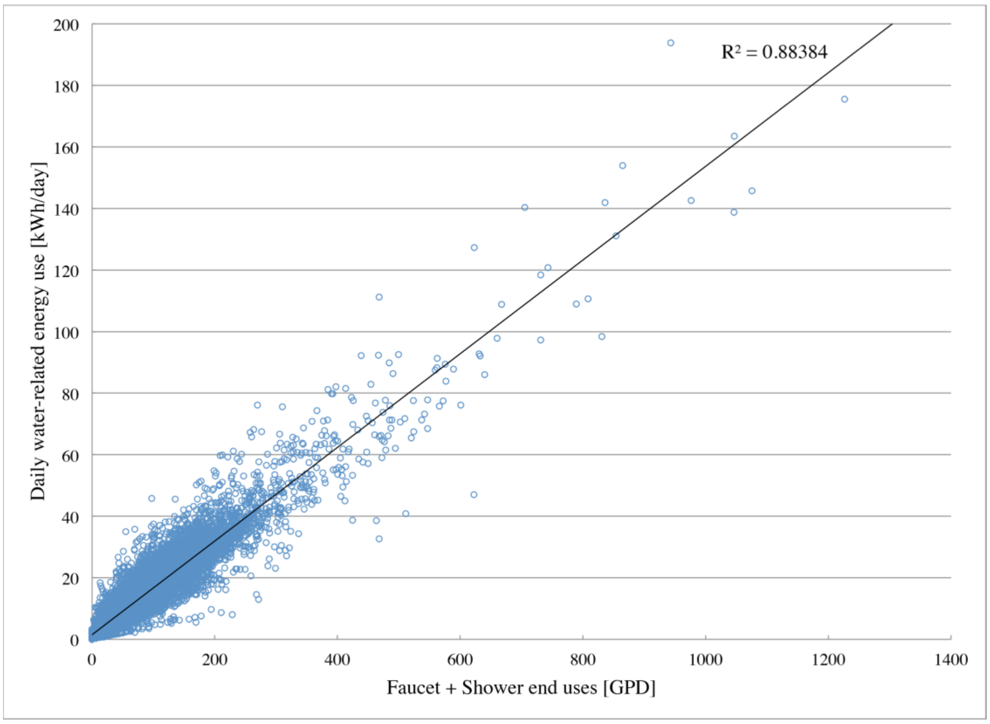

Figure SI.1: Daily water-related energy consumption as a function of the sum of faucet and shower water end uses.

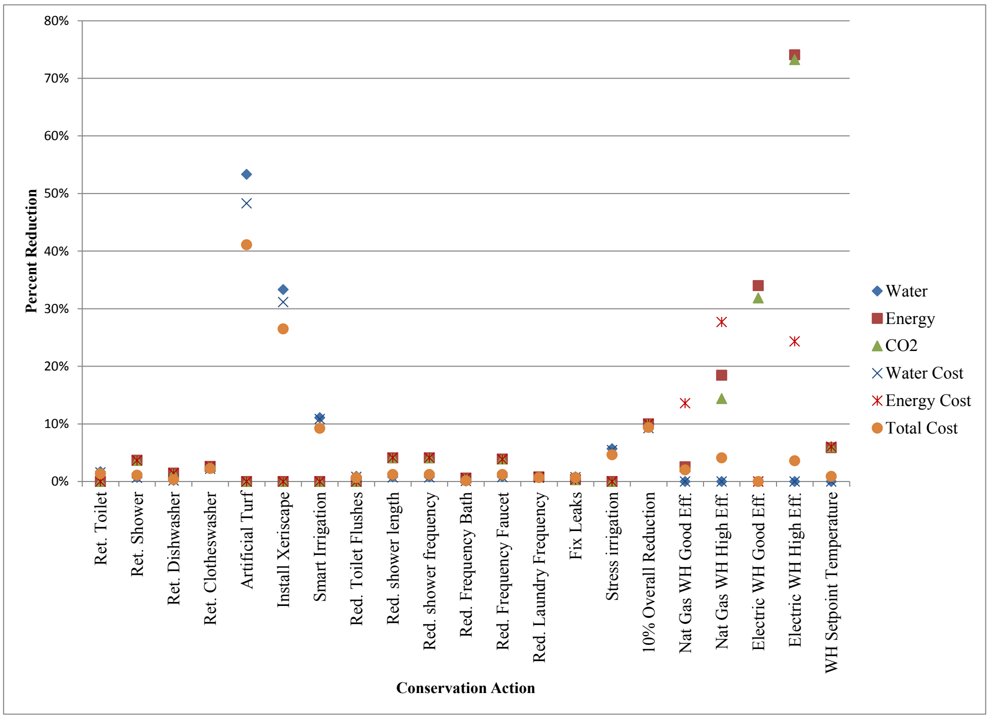

Figure SI.2 : Results of total water, water-related energy and CO2 savings and economic water and energy benefits obtained for each simulation

Chapter 3

Optimal residential water conservation strategies considering related energy in California[1]

Abstract

Although most freshwater resources are used in agriculture, residential water use is responsible of a large share of water-related energy consumption (Fidar, Memon, & Butler, 2010). 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-GHG 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 likely to be 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 percent reduction in water-related energy use and a 53 percent reduction in household water-

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related GHG 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

3.1. 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 & Lund, 1990; Valinas, 2006).

There much debate on the cost effectiveness of demand side management policies (DSMP) (Olmstead & Stavins, 2009; Renwick & Green, 2000). Price-related DSMP have focused on behavioral incentives to reduce consumption, and non-price 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 consumption, 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 (see the review Arbués, García-Valiñas, and Martínez-Espiñeira (2003)) and they have been used to test conservation policies as well (DeOreo et al., 2011; Renwick & Archibald, 1998). More mechanistic engineered models use water end use data to estimate potential conservation by assuming replacement rates of improved appliances (Cahill, Lund, DeOreo, & Medellin-Azuara, 2013) or even measured savings from retrofitting household’s appliances (Mayer, deOreo, Towler, & Lewis, 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, Tarawneh, Abdel-Khaleq, & Lund, 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 & 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, Bertone, and Stewart (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, Scheidegger, Larsen, Lant, and Bader (2013) estimated the average water, water-related energy, GHG emission and economic savings by simulating technological and behavioral changes in a model based on a metered house in Brisbane, Australia; Morales, Heaney, Friedman, and Martin (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 & Stavins, 1994). Here, the lack of information, the cost to get that information and uncertainty of future prices might explain non-adoption 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-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-GHG emissions model (Alvar Escriva-Bou, Lund, & Pulido-Velazquez, 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 (adapting (Alcubilla & Lund, 2006; 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-GHG emissions 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 exposes 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.

3.2. 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 3.1 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 determine 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).

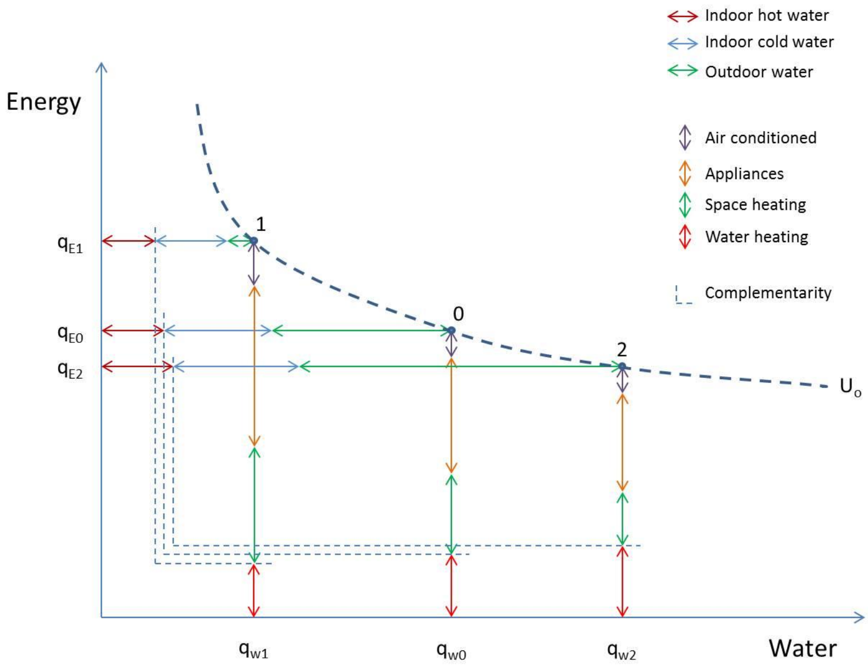

Figure 3.1: Indifference curve and break down of residential water and energy consumption.

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 & 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:

$$\frac{dW_{hot\ indoor}}{dp_{energy}} < 0 \qquad \textbf{Equation 1}$$

$$\frac{dE_{heating\ water}}{dp_{water}} < 0 \qquad \textbf{Equation 2}$$

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

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 percent likely to be covered with a water supply with a very low marginal cost (for example surface water); 20 percent of the months surface water is shorted and the supply has to be completed with a secondary supply (for example groundwater) with a 10 percent increase in marginal cost; the remaining 10 percent of the times, main water supply has larger shortages and besides the secondary supply, the water utility has to find a tertiary water supply (for example buy water rights from water markets) with 20 percent increase in marginal cost (Figure 3.2). 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).

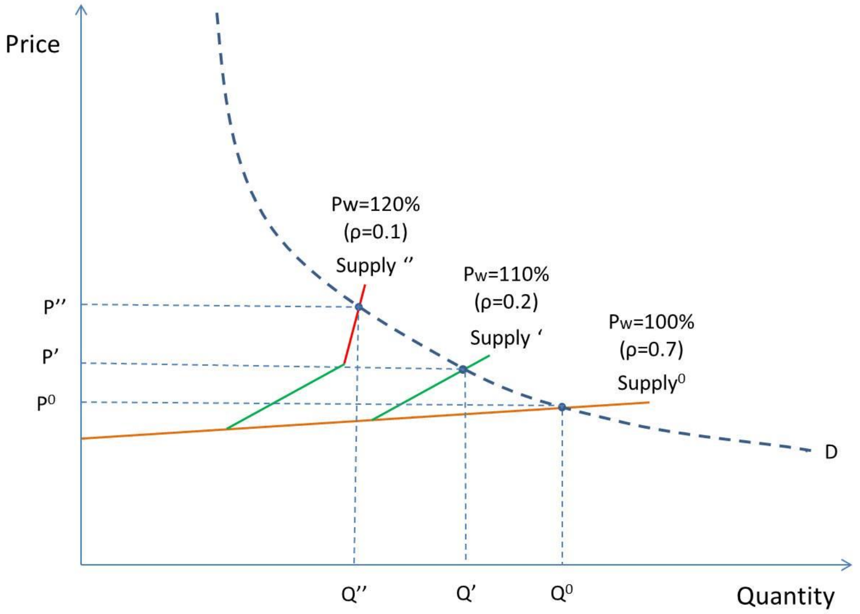

Figure 3.2: Theoretic water supply and demand curves accounting for alternative supply sources.

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 percent of the months, the price ranges 90%-110% of the average price. In 10 percent of the months, price exceeds 110% of the average price (assuming 115% of average price) and 10 percent of the months has lower prices (assuming 85% of average price)[2]. As seen in the residential natural gas price data from 2009 to 2014 (Figure 3.3), this is a fair assumption.

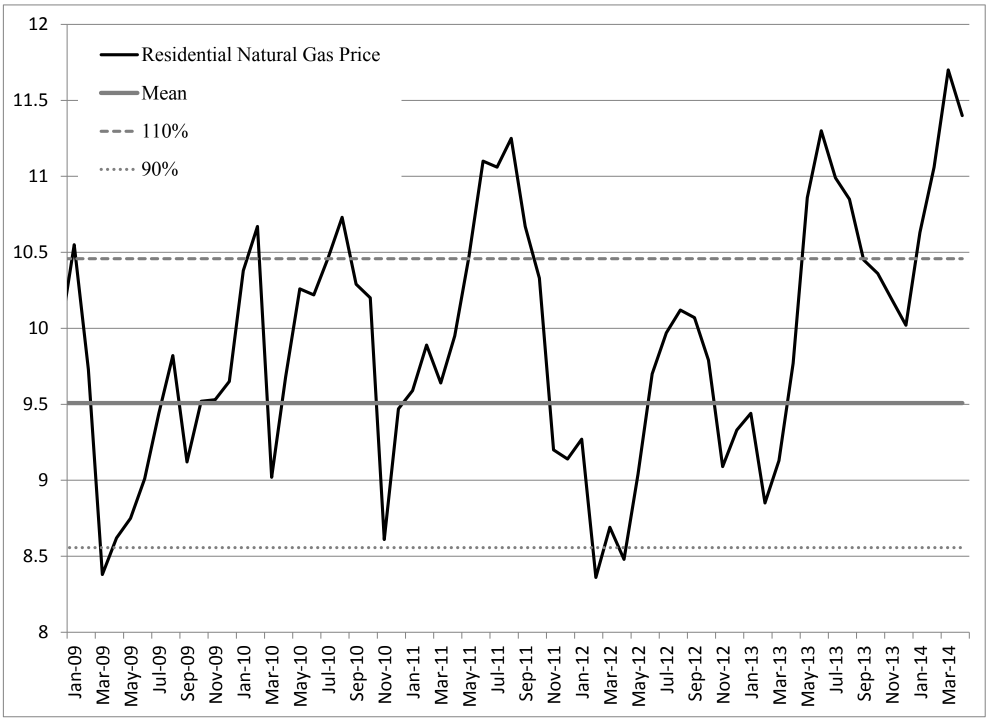

Figure 3.3: Average statewide residential natural gas price from January 2009 to April 2014 in California (real prices in 2009 dollars per thousand cubic feet). Source: Nominal prices from USEIA (2015).

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 & Green, 2000). By including energy price and volatility we are increasing the price elasticity of water consumption to meet supply and demand. As

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[2] The average price is obtained from the actual prices for each location as explained in Section 3.1

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.

3.3. Methods

3.4.1. Water-Energy-GHG Emissions-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 (A. Escriva-Bou, Lund, & Pulido-Velazquez, In press). The study is based on a deductive approach that includes household heterogeneity in water consumption 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 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, Whitehead, Lekov, Winiarski, & Rosenquist, 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.

3.4.2. 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 & Barr, 2006; Willis, Stewart, Panuwatwanich, Williams, & Hollingsworth, 2011) as either a short or long-term strategy

The model includes 7 technological and 8 behavioral modifications related directly with water use, and 4 technological and 1 behavioral adaptations over water-related energy appliances, as shown in Table 3.1.

Table 3.1: Actions available to households to save water and water-related energy. 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[3].

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	1,033.00	$	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)	1,163.28	539.37	$	11.6
Stage	**Resource**	**Action**		**Hassle Cost**		**Unit**	
Short-Term Actions	Water	wst1	Reduce toilet flushes	0.02		$/day	
		wst2	Reduce shower length	0.05		$/day	
		wst3	Reduce shower frequency	0.05		$/day	
		wst4	Reduce bath frequency	0.05		$/day	
		wst5	Reduce faucet use	0.05		$/day	
		wst6	Reduce laundry frequency	0.05		$/day	
		wst7	Leaks detection and fixing	0.05		$/day	
		wst8	Stress irrigation	0.05		$/day	
	Energy	est1	Decrease water heater setpoint temperature	0.05		$/day	

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[3] 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.

3.4.3. Modeling savings and costs

3.3.3.1. 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 pre-retrofit flow would be lower than the post-retrofit. Figure 3.4 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 3.1.

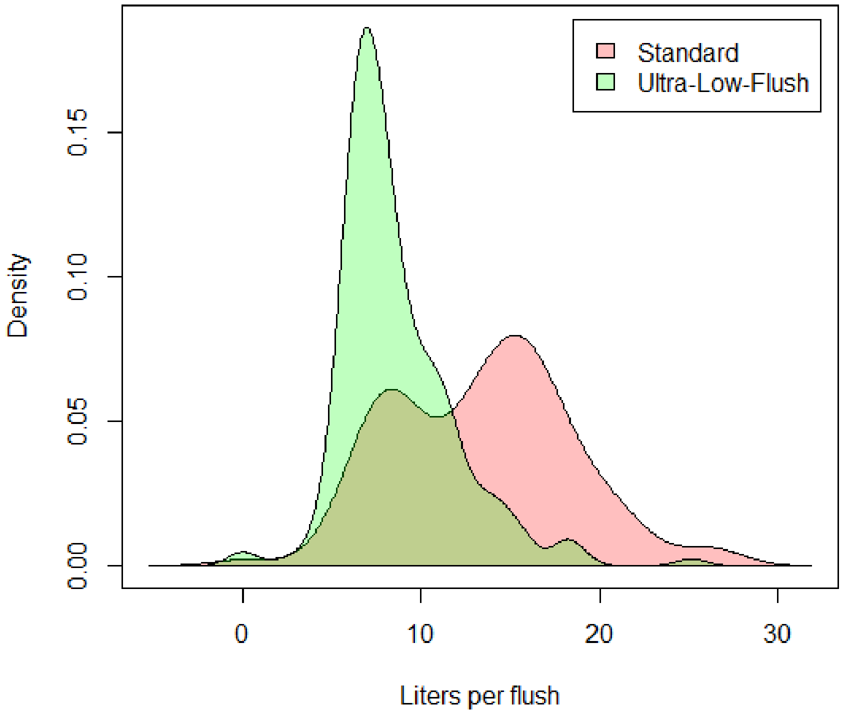

Figure 3.4 Flow per flush kernel density plots for standard and ultra-low-flush toilets obtained from surveyed households.

3.3.3.2. 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:

$$\boldsymbol{B_{ij}}^{\mathbf{1}} = \boldsymbol{B_{ij}}^{\mathbf{0}} \cdot (\mathbf{1} - \boldsymbol{RF_{ij}}) \qquad \textbf{Equation 4}$$

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

Where B_{ij}^{k} is the value for the behavioral parameter *i* for the household *j* in the stage *k* (usually events/days·person); RF_{ij} the reduction factor for the parameter *i* for the household *j* (there is a previously defined $max(rf_i)$ 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 3.5 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 towards 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 & 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:

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

Where P_i is an engineering estimated parameter for the hourly hassle cost of action *i* given in Table 3.1; I_j the annual income of the household *j*; and CF_j the consciousness factor for the household *j*.

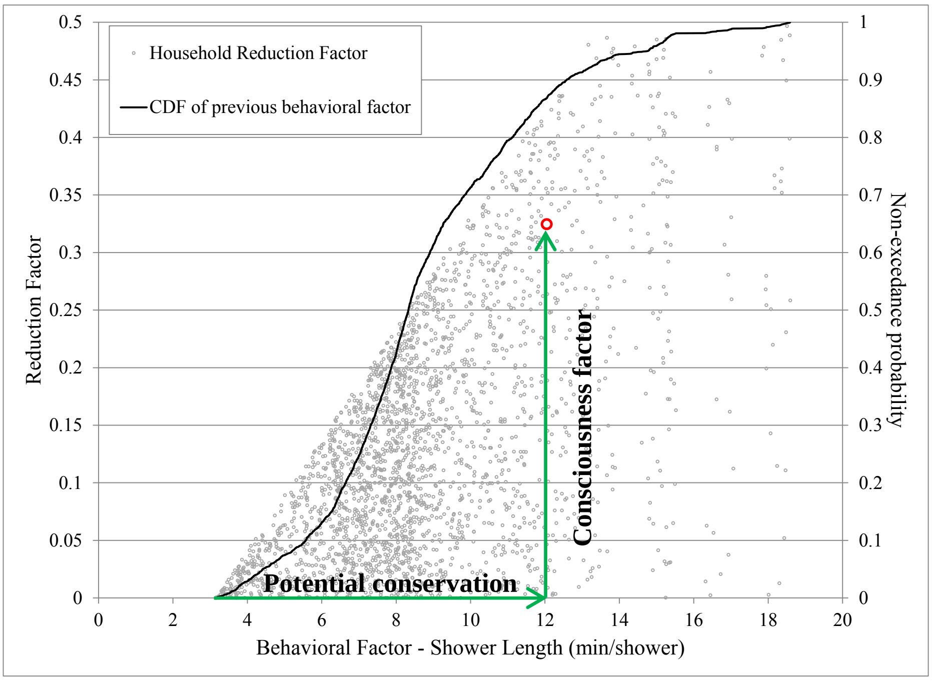

Figure 3.5: Reduction function for shower length distribution as a function of previous behavioral factor and a uniformly random consciousness factor.

3.3.3.3. Interactions 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.

3.4.4. 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 non-linear 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 & 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.

3.3.4.1. Decision variables

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

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

3.3.4.2. 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:

$$\boldsymbol{Minimize\ Z} = \sum\nolimits_{wlt} \boldsymbol{C_{wlt}} \cdot \boldsymbol{X_{wlt}} + \sum\nolimits_{elt} \boldsymbol{C_{elt}} \cdot \boldsymbol{X_{elt}} + \boldsymbol{i} \cdot \left[\sum\nolimits_{we} \boldsymbol{p_{we}} \cdot \right.$$

$$\left.\left(\sum\nolimits_{ee} \boldsymbol{p_{ee}} \cdot \left\{\boldsymbol{j} \cdot \left(\sum\nolimits_{wst} \boldsymbol{C_{wst}} \cdot \boldsymbol{X_{wst_{we,ee}}} + \sum\nolimits_{est} \boldsymbol{C_{est}} \cdot \boldsymbol{X_{est_{we,ee}}}\right) + \boldsymbol{B_{W_{we}}} + \boldsymbol{B_{E_{ee}}}\right\}\right)\right] \qquad \textbf{Equation 7}$$

Where: C_{wlt} and C_{elt} are the annualized long-term water and energy action costs ($/year) respectively whereas C_{wst} and C_{est} are the short-term water and energy action costs ($/day); 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)[4].

3.3.4.3. 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:

$$\boldsymbol{W_1} = \boldsymbol{W_0} - \boldsymbol{W_{sav}} \qquad \textbf{Equation 8}$$

$$\boldsymbol{W_{sav}} = \sum\nolimits_{wlt} \boldsymbol{X_{wlt}} \cdot \boldsymbol{W_{sav_{wlt}}} + \sum\nolimits_{we} \boldsymbol{p_{we}} \cdot \sum\nolimits_{ee} \boldsymbol{p_{ee}} \cdot \sum\nolimits_{wst} \boldsymbol{X_{wst_{we,ee}}} \cdot \boldsymbol{W_{sav_{wst}}}(\boldsymbol{we, ee|wlt}) \qquad \textbf{Equation 9}$$

$$\boldsymbol{E_1} = \boldsymbol{E_0} - \boldsymbol{E_{sav}} \qquad \textbf{Equation 10}$$

$$\boldsymbol{E_{sav}} = \sum\nolimits_{wlt} \boldsymbol{X_{wlt}} \cdot \boldsymbol{E_{sav_{wlt}}} + \sum\nolimits_{elt} \boldsymbol{X_{elt}} \cdot \boldsymbol{E_{sav_{elt}}} \big| \boldsymbol{wlt} + \sum\nolimits_{we} \boldsymbol{p_{we}} \cdot \sum\nolimits_{ee} \boldsymbol{p_{ee}} \cdot \Big(\sum\nolimits_{wst} \boldsymbol{X_{wst_{we,ee}}} \cdot$$

$$\boldsymbol{E_{sav_{wst}}}(\boldsymbol{we, ee|wlt, elt}) + \sum\nolimits_{est} \boldsymbol{X_{est_{we,ee}}} \cdot \boldsymbol{E_{sav_{est}}}(\boldsymbol{we, ee|wlt, elt, wst})\Big) \qquad \textbf{Equation 11}$$

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.

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[4] Note that even different time step data is 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.

3.3.4.4. Constraints

i. *Decision variables are binary*

ii. *Maximum effectiveness*: water and energy saved cannot exceed the initial water and water-related energy use:

$$\boldsymbol{W_{sav} \leq W_0} \qquad \textbf{Equation 12}$$

$$\boldsymbol{E_{sav} \leq E_0} \qquad \textbf{Equation 13}$$

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

$$\textstyle\sum_{wlt^*} \boldsymbol{X_{wlt} \leq 1}\ ;\sum_{wst^*} \boldsymbol{X_{wst} \leq 1}\ ;\sum_{elt^*} \boldsymbol{X_{elt} \leq 1}\ ;\sum_{est^*} \boldsymbol{X_{est} \leq 1} \qquad \textbf{Equation 14}$$

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

iv. *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 wlt1 and wst1 in equation 15:

$$\boldsymbol{W_{sav_{wst_1}} = X_{wst_1} \cdot \left\{ X_{wlt_1} \cdot \left(W_{sav_{wst_1}} \middle| wlt_1 = 1 \right) + \left(1 - X_{wlt_1}\right) \cdot \left(W_{sav_{wst_1}} \middle| wlt_1 = 0 \right) \right\}} \textbf{Equation 15}$$

3.3.4.5. 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 (A. 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 non-linear program determines the optimal solution and gets the results back into the spreadsheet for each of the 10,000 households

3.3.4.6. 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 percent for each city and then we re-ran the model for the

10,000 households again. The elasticities were calculated using the common expressions:

$$\varepsilon_{ww} = \frac{dW}{dP_w} \cdot \frac{P_w}{W}\,;\ \varepsilon_{ee} = \frac{dE}{dP_E} \cdot \frac{P_E}{E}\,;\ \varepsilon_{we} = \frac{dW}{dP_E} \cdot \frac{P_E}{W}\,;\ \varepsilon_{ew} = \frac{dE}{dP_w} \cdot \frac{P_E}{W} \qquad \textbf{Equation 16}$$

3.4. Results

3.4.1. *Water and water-related energy savings*

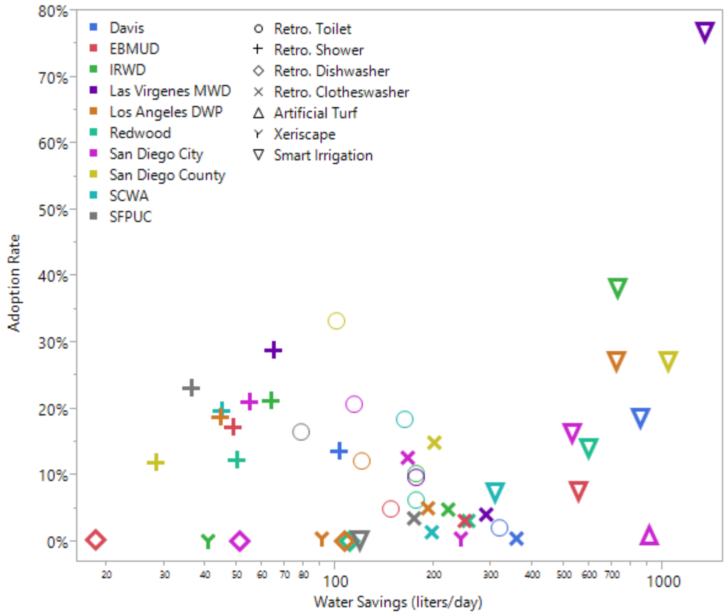
Averaged optimization model results show total water savings between 8 and 36 percent, averaging 19% among utilities. Most water savings are from reducing outdoor use (averaging 25%), with indoor water savings between 5 and 16 percent (averaging 9%). Finally, because most indoor water savings are related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

Table 3.2: Averaged outdoor and indoor water and water-related energy use and conservation for various cities in California.

Utility	Total water (liters·hh/day)			Indoor water (liters·hh/day)			Energy (kWh·hh/day)		
	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%

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 Figure 3.6 and Figure 3.7.

For water use, Figure 3.6 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).



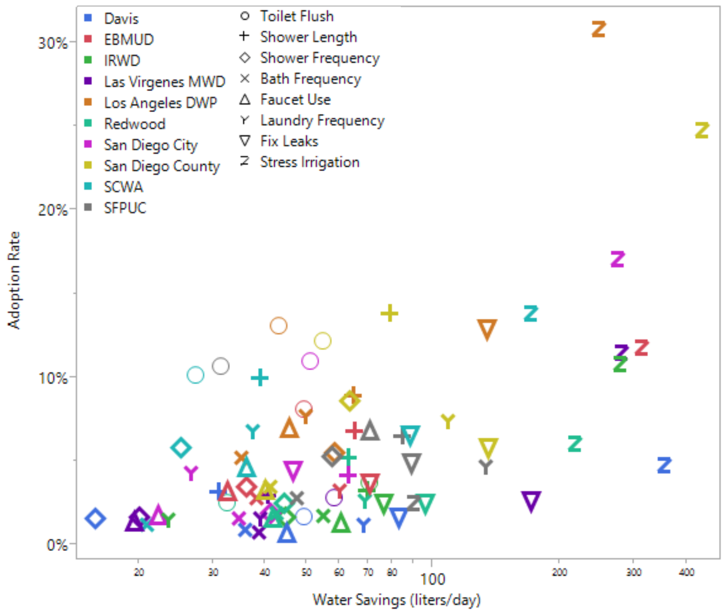


Figure 3.6: Optimized market penetration and average water savings for long-term or technological actions (up) and short-term or behavioral actions (down) presented in Table 3.1. Please, notice different *x* and *y* scales in both graphs.

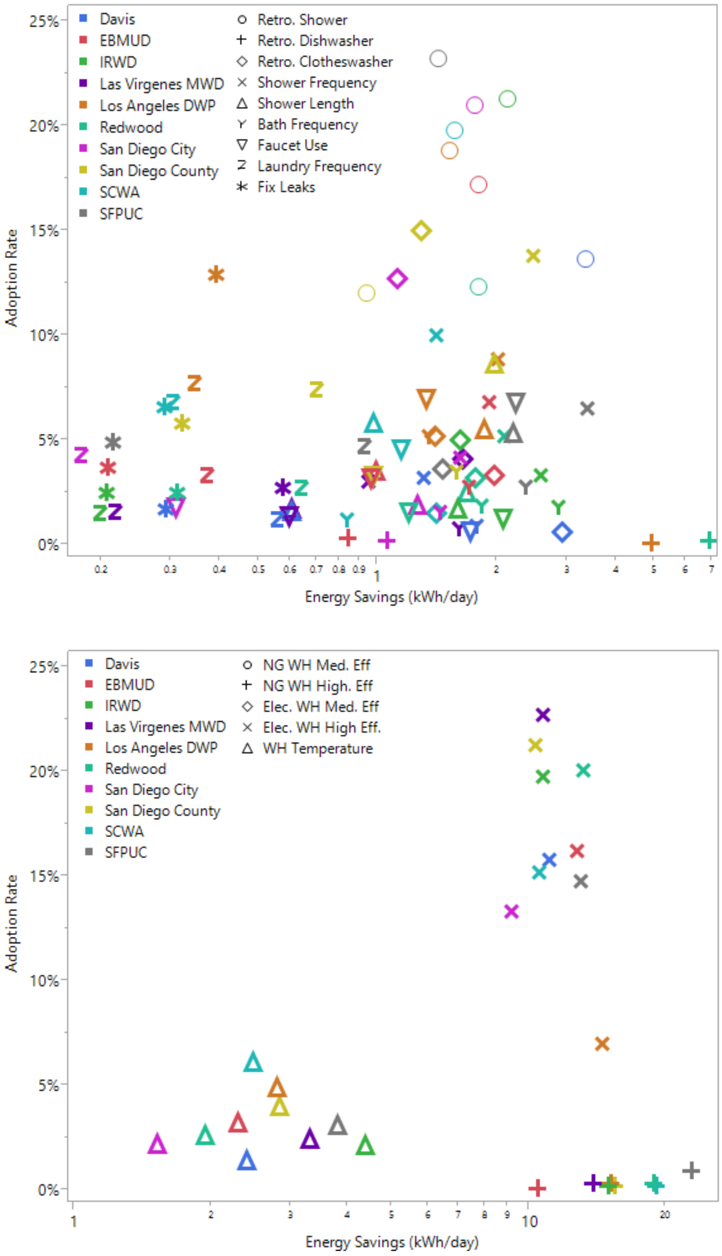
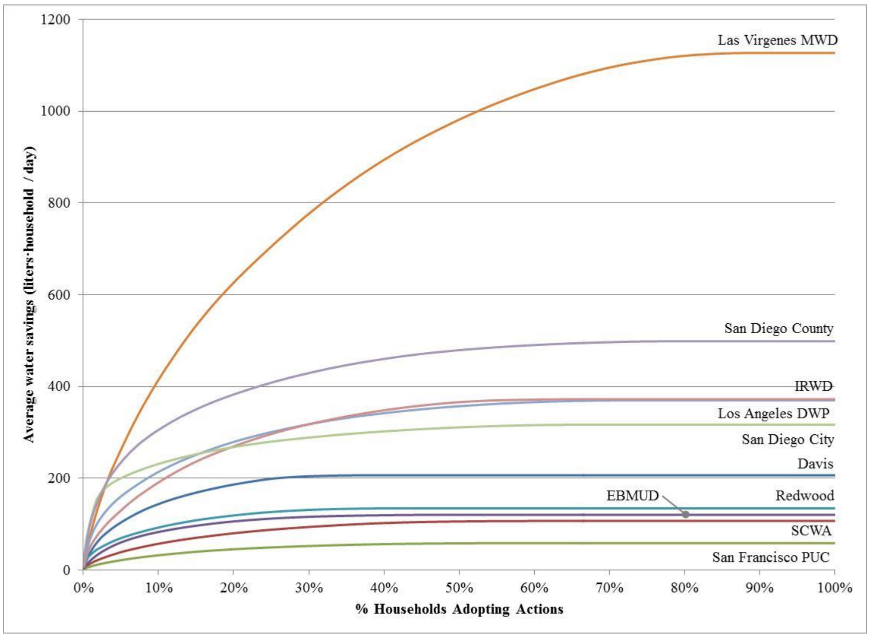


Figure 3.7: Market penetration and average energy savings for water (up) and energy actions (down) presented in Table 3.1.



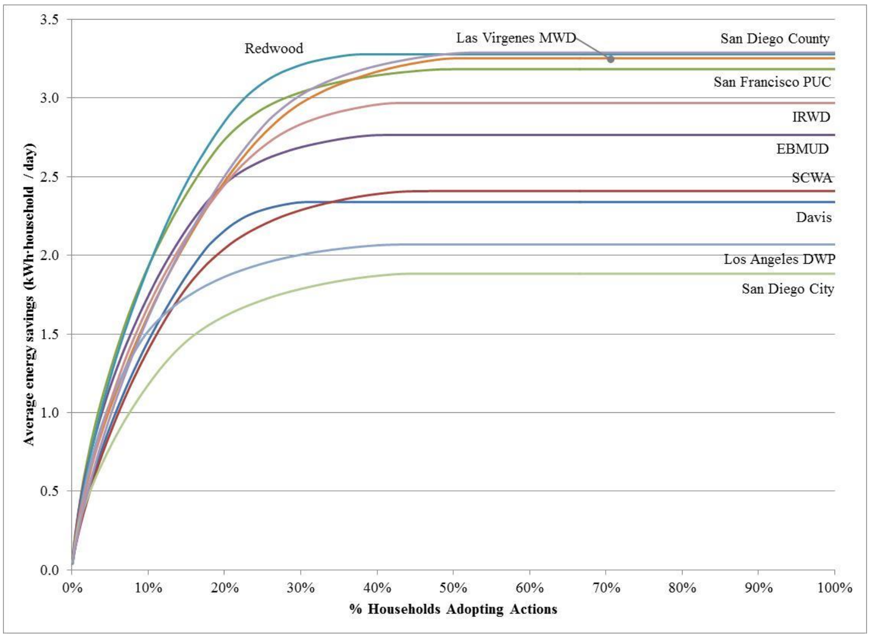


Figure 3.8: Total potential water (up) and water-related energy (down) conservation. *X* axis is ordered by customers from highest to lowest conservation potential.

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 non-negligible 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 120ºF (a 40% of them).

Figure 3.8 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.

3.4.2. *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 3.3. 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 GHG emissions savings from incorporating related energy costs are huge. As shown in Table 3.4, indoor water savings grow by 10 to 44 percent, averaging 24%, energy savings increase between 3 and 60 %, averaging 30%, whereas water-related GHG emissions fall by 21 to 98 %, averaging 53% —the huge difference between energy and GHG savings is because retrofitting the water heater reduces the effect of energy savings in the water-and-energy model, whereas in the GHG emission savings we 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.

Table 3.3: Increased willingness to adopt conservation actions if embedded energy is considered.

Utility	Long-Term Actions							Short-Term Actions								
	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%

Table 3.4: Optimized increased indoor water and water-related energy use and GHG emission reductions if embedded energy is considered for ten California cities.

Utility	Water reduction (liters·hh/day)			Energy reduction (kWh·hh/day)			CO_2 emissions reduction (kg·hh/day)		
	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%

3.4.3. *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 3.5. 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 (3rd column), whereas the energy price effect on water use is negligible (4th 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.

Table 3.5: Water and energy own- and cross-price elasticities.

Utility	ε_{WW}	ε_{EE}	ε_{EW}	ε_{WE}
Davis	-0.04	-0.01	-0.01	-0.001
SCWA	-0.08	-0.03	-0.04	-0.004
SFPUC	-0.04	-0.04	-0.03	-0.01
EBMUD	-0.09	-0.03	-0.02	-0.01
Redwood	-0.06	-0.03	-0.04	-0.005
Las Virgenes MWD	-0.04	-0.01	0.00	-0.001
Los Angeles DWP	-0.04	-0.03	-0.02	-0.003
IRWD	-0.05	-0.03	-0.04	-0.002
San Diego City	-0.06	-0.01	-0.01	-0.001
San Diego County	-0.03	-0.04	-0.02	-0.01

Another result from the model is the water demand function for each water utility given increases of 10 and 20 percent in marginal price. As expected from the results of the elasticities shown above, the water demand hardly decreases as marginal price increases (Figure 3.9).

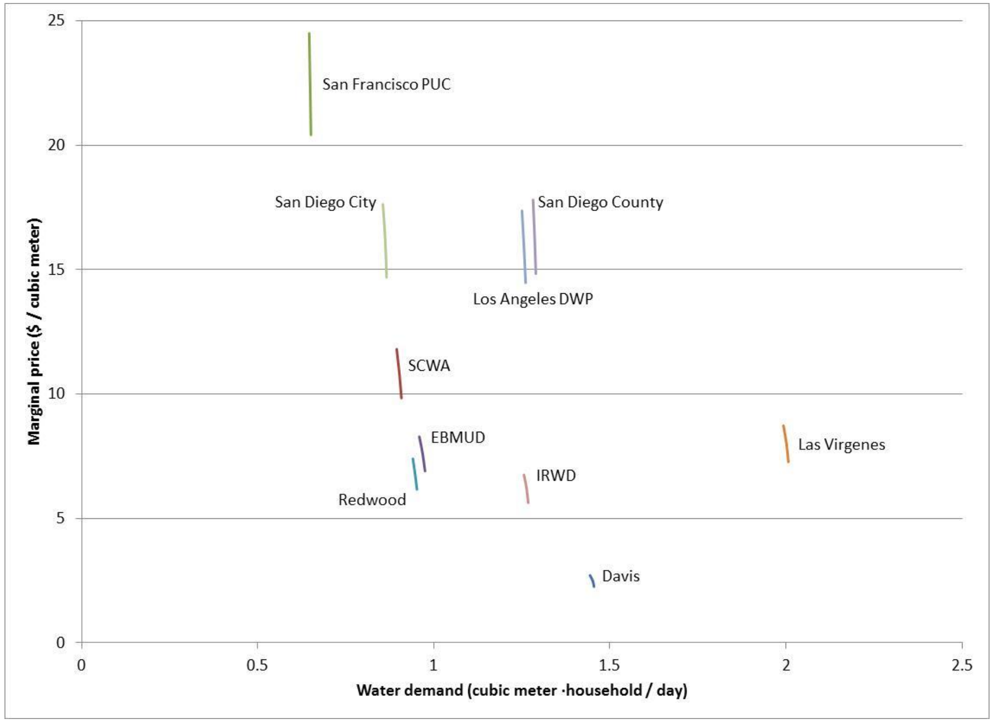


Figure 3.9: Average demand function given marginal water price increase for each utility.

3.5. 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.

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, Florax, de Groot, & Nijkamp, 2003; Espey, Espey, & Shaw, 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 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.

A natural extension of this study would be the economic assessment of potential use of economic incentives to promote water, energy and GHG emission conservation, following the approach developed by (Rosenberg et al., 2007). As a qualitative assessment, and following the results presented in Figure 3.6 and Figure 3.7, it seems logical that the utilities would be interested in promote either those strategies that are already economically feasible for customers (increasing potential adoption rates) or those strategies that could save more water, energy and/or GHG emissions. The results suggest that water utilities should be specially interested in promote outdoor use, but also clotheswasher, shower and toilet retrofitting, and also some behavioral reductions as stressing irrigation, fixing leaks or reducing shower and toilet uses. Energy utilities should be specially interested in reduce shower and faucet water use, but also for some utilities fixing leaks or retrofitting clotheswasher and dishwasher could result in increased rates of adoption and overall energy reductions. Therefore, water and energy utilities would be able to join efforts incentivizing economically shower, faucet and clotheswasher to reduce both water and energy use, reducing GHG emissions at the same time.

3.6. 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 customer objective. 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.

3.7. References

Abdallah, A., & Rosenberg, D. (2014). Heterogeneous Residential Water and Energy Linkages and Implications for Conservation and Management. *Journal of Water Resources Planning and Management, 140*(3), 288-297. doi: doi:10.1061/(ASCE)WR.1943-5452.0000340

Alcubilla, R. G., & Lund, J. R. (2006). Derived willingness-to-pay for household water use with price and probabilistic supply. *Journal of Water Resources Planning and Management-Asce, 132*(6), 424-433. doi: Doi 10.1061/(Asce)0733-9496(2006)132:6(424)

Arbués, F., García-Valiñas, M. a. Á., & Martínez-Espiñeira, R. (2003). Estimation of residential water demand: a state-of-the-art review. *The Journal of Socio-Economics, 32*(1), 81-102. doi: http://dx.doi.org/10.1016/S1053-5357(03)00005-2

Beal, C. D., Bertone, E., & Stewart, R. A. (2012). Evaluating the energy and carbon reductions resulting from resource-efficient household stock. *Energy and Buildings, 55*, 422-432. doi: DOI 10.1016/j.enbuild.2012.08.004

Cahill, R., Lund, J. R., DeOreo, B., & Medellin-Azuara, J. (2013). Household water use and conservation models using Monte Carlo techniques. *Hydrology and Earth System Sciences, 17*(10), 3957-3967. doi: DOI 10.5194/hess-17-3957-2013

Dalhuisen, J. M., Florax, R. J. G. M., de Groot, H. L. F., & Nijkamp, P. (2003). Price and income elasticities of residential water demand: A meta-analysis. *Land Economics, 79*(2), 292-308. doi: Doi 10.2307/3146872

DeOreo, W. B., Mayer, P. W., Martien, L., Hayden, M., Funk, A., Kramer-Duffield, M., & Davis, R. (2011). California single-family water use efficiency study. Aquacraft, Inc. Water Engineering and Management. July 20, 2011.

Dolnicar, S., & Hurlimann, A. (2010). Australians' Water Conservation Behaviours and Attitudes [online]. Australian Journal of Water Resources, Vol. 14, No. 1, 2010: 43-53. Availability: <http://search.informit.com.au/documentSummary;dn=242006012315522;res=IELENG> ISSN: 1324-1583.

EBMUD. (2011). Urban Water Management Plan 2010. Water Resources Planning Division. East Bay Municipal Utility District. June 2011. https://ebmud.com/water-and-wastewater/water-supply/urban-water-management-plan. Accessed 2/12/2015.

Escriva-Bou, A., Lund, J., & Pulido-Velazquez, M. (In press). Modeling residential water and related energy, carbon footprint and costs in California. *Environmental Science & Policy, DOI: 10.1016/j.envsci.2015.03.005*.

Escriva-Bou, A., Lund, J. R., & Pulido-Velazquez, M. (2015). Modeling residential water and related energy, carbon footprint and costs in California. *Environmental Science & Policy, 50*(0), 270-281. doi: http://dx.doi.org/10.1016/j.envsci.2015.03.005

Espey, M., Espey, J., & Shaw, W. D. (1997). Price elasticity of residential demand for water: A meta-analysis. *Water Resources Research, 33*(6), 1369-1374. doi: Doi 10.1029/97wr00571

Fidar, A., Memon, F. A., & Butler, D. (2010). Environmental implications of water efficient microcomponents in residential buildings. *Science of the Total Environment, 408*(23), 5828-5835. doi: DOI 10.1016/j.scitotenv.2010.08.006

Gilg, A., & Barr, S. (2006). Behavioural attitudes towards water saving? Evidence from a study of environmental actions. *Ecological Economics, 57*(3), 400-414. doi: DOI 10.1016/j.ecolecon.2005.04.010

Gregory, G. D., & Di Leo, M. (2003). Repeated behavior and environmental psychology: The role of personal involvement and habit formation in explaining water consumption. *Journal of Applied Social Psychology, 33*(6), 1261-1296. doi: DOI 10.1111/j.1559-1816.2003.tb01949.x

Hansen, L. G. (1996). Water and energy price impacts on residential water demand in Copenhagen. *Land Economics, 72*(1), 66-79. doi: Doi 10.2307/3147158

Jaffe, A. B., & Stavins, R. N. (1994). The Energy-Efficiency Gap - What Does It Mean. *Energy Policy, 22*(10), 804-810. doi: Doi 10.1016/0301-4215(94)90138-4

Kenway, S. J., Scheidegger, R., Larsen, T. A., Lant, P., & Bader, H. P. (2013). Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings, 58*, 378-389. doi: DOI 10.1016/j.enbuild.2012.08.035

LADWP. (2010). Urban Water Management Plan. Los Angeles Department of Water and Power. Los Angeles, California, 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 Resources Research, 31*(5), 1367-1372. doi: Doi 10.1029/95wr00481

Lutz, J., Whitehead, C. D., Lekov, A., Winiarski, D., & Rosenquist, G. (1998). WHAM: A Simplified Energy Consumption Equation for Water Heaters. (3AD). WHAM: A Simplified Energy Consumption Equation for Water Heaters. Proceeedings of the ACEEE 1998 Summer Study on Energy Efficiency in Buildings, 1. Washington, DC: ACEEE. .

Mayer, P. W., deOreo, B., Towler, E., & Lewis, D. M. (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. East Bay Municipal Utility District (EBMUD) and The United States Environmental Protection Agency (USEPA). July 2003.

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

Nicholson, W., & Snyder, C. (2012). *Microeconomic theory : basic principles and extensions* (11th ed.). Mason, Ohio: South-Western/Cengage Learning.

Olmstead, S. M., & Stavins, R. N. (2009). Comparing price and nonprice approaches to urban water conservation. *Water Resources Research, 45*. doi: Artn W04301 Doi 10.1029/2008wr007227

Pint, E. M. (1999). Household responses to increased water rates during the California drought. *Land Economics, 75*(2), 246-266. doi: Doi 10.2307/3147009

Reed, R. U., & Lund, J. R. (1990). Transferable Rations for Drought Management. *Optimizing the Resources for Water Management*, 726-730.

Renwick, M. E., & Archibald, S. O. (1998). Demand side management policies for residential water use: Who bears the conservation burden? *Land Economics, 74*(3), 343-359. doi: Doi 10.2307/3147117

Renwick, M. E., & Green, R. D. (2000). Do residential water demand side management policies measure up? An analysis of eight California water agencies. *Journal of Environmental Economics and Management, 40*(1), 37-55. doi: DOI 10.1006/jeem.1999.1102

Rosenberg, D. E., Tarawneh, T., Abdel-Khaleq, R., & Lund, J. R. (2007). Modeling integrated water user decisions in intermittent supply systems. *Water Resources Research, 43*(7). doi: Artn W07425 Doi 10.1029/2006wr005340

Rothausen, S. G. S. A., & Conway, D. (2011). Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change, 1*(4), 210-219. doi: Doi 10.1038/Nclimate1147

USDOE. (2009). Energy efficiency standards for Pool Heaters, Direct Heating Equipment and Water Heaters (EE-2006-STD-0129). Energy Efficiency and Renewable Energy Office (EERE). U.S. Department of Energy (DOE). Available at http://www.regulations.gov/#!documentDetail;D=EERE-2006-STD-0129-0170. Accessed 4/14/2014.

USEIA. (2009). *Residential Energy Consumption Survey 2009. U.S. Energy Information Administration. Available at http://www.eia.gov/consumption/residential/index.cfm. Accessed 4/14/2014.*

USEIA. (2015). *California price of natural gas delivered to residential customers. U.S. Energy Information Administration. Available at http://www.eia.gov/dnav/ng/hist/n3010ca3M.htm. Accesed 3/20/2015.*

USEPA. (2015). Energy Star. United States Environmental Protection Agency. Available at: http://www.energystar.gov/. Accesed March 23, 2015.

Valinas, M. D. A. G. (2006). Analysing rationing policies: drought and its effects on urban users' welfare (Analysing rationing policies during drought). *Applied Economics, 38*(8), 955-965. doi: Doi 10.1080/00036840600638925

Willis, R. M., Stewart, R. A., Panuwatwanich, K., Williams, P. R., & Hollingsworth, A. L. (2011). Quantifying the influence of environmental and water conservation attitudes on household end use water consumption. *Journal of Environmental Management, 92*(8), 1996-2009. doi: DOI 10.1016/j.jenvman.2011.03.023

Chapter 4

Managing the urban water-energy nexus

Abstract

Water use directly causes a significant amount of energy use in cities. In this paper we assess energy and greenhouse emissions related with each part of the urban water cycle and the consequences of several changes in residential water use for customers, water and energy utilities, and the environment.

First, we develop an hourly model of urban water uses by customer category including water-related energy consumption. Next, using real data from East Bay Municipal Utility District in California, we calibrate a model of the energy used in water supply, treatment, pumping and wastewater treatment by the utility. Then, using data from the California Independent System Operator, we obtain hourly costs of energy for the energy utility. Finally, and using emission factors reported by the energy utilities we estimate greenhouse gas emissions for the entire urban water cycle.

Results of the business-as-usual scenario show that water end-uses account for almost 95% of all water-related energy use, but the 5% managed by the utility is still worth over $12 million annually. Several simulations analyze the potential benefits for water demand management actions showing that moving some water end-uses from peak to off-peak hours such as outdoor use, dishwasher or clothes washer use have large benefits for water and energy utilities, especially for locations with a high proportion of electric water heaters. Other interesting result is that under the current energy rate

structures with low or no fixed charges, energy utilities burden most of the cost of the conservation actions.

4.1. Introduction

Water utilities face an increasing pressure to reduce their energy consumption and greenhouse gas (GHG) emissions for economic and environmental reasons. The urban water cycle is energy intensive, bringing attention of managers, policy-makers and researchers to describe and assess each process that relates water use and energy consumption.

Large-scale water-energy-GHG emission assessments have been conducted in recent years at the regional, national or even supranational level: Sanders and Webber (2012) found that 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 in the United States. In Spain Hardy, Garrido, and Juana (2012) found a value of 5.8% without including water end uses; Reffold, Leighton, Choufhoury, and Rayner (2008) found that 5.5% of GHG emissions in the UK are from water use; Tidwell, Moreland, and Zemlick (2014) obtained the geographic distribution of the electric footprint of water services for the western U.S. resulting in a variability from less than 2% to more than 34% of total electric uses. 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 use and GHG emissions.

More detailed urban water-energy studies have either focused on water utilities —i.e. supply, treatment, conveyance, wastewater collection and treatment—or on residential water use. For water utilities, among other studies, the California Public Utilities Commission identified patterns in the amount and timing of energy used by water and wastewater agencies, converting the results to a common metric, “energy intensity” (CPUC, 2010); Mo, Wang, and Zimmerman (2014) evaluated 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. Spang and Loge (2015) calculated energy use for urban water systems, providing insightful analysis of geographical and seasonal variability of water-related energy use. On the residential side, Fidar, Memon, and Butler (2010) analyzed energy consumption and carbon emissions changes from achieving water efficiency levels in the UK; Kenway, Scheidegger, Larsen, Lant, and Bader (2013) developed and applied a model for residential water and water-related energy use and GHG emissions in Australia. Finally Abdallah and Rosenberg (2014) identified heterogeneous water and energy uses and linkages for major indoor water end uses in the US.

Although end uses often have the highest energy use of all water-sector elements, it has not traditionally been seen as a direct part of the water sector and is often unaccounted for in water and energy management and policy (Rothausen & Conway, 2011). By coupling end-use and utility-scale detailed data we assess the energy and carbon footprint of the urban water cycle to assess demand side management policies to reduce GHG emissions, as seen from customer, water and energy utilities, and state or national perspectives.

In a regional context water and energy are managed in very different ways. Water utilities often obtain water resources for free and the price paid by customers depends on high infrastructure fixed costs and low variable operating costs. However, because electricity generation and demand are highly variable in time and its transportation much cheaper, auction-based energy markets have been developed in much of the world causing, high price variability in the wholesale market.

Despite these differences, water and energy rate structures are very similar, and traditionally uniform rates or increasing block rate structures to induce water conservation are used without customers seeing the variability in costs. This absence of price signal reduces the economic efficiency in the electricity market by avoiding changes in customers' patterns of consumption (Borenstein, 2005). The scarcity price signal is also absent in water pricing, inefficiently ignoring the resource opportunity cost (Pulido-Velazquez, Alvarez-Mendiola, & Andreu, 2013).

Because some elements of the water cycle are large energy consumers (mainly urban users), there is the potential collaboration for water customers and water utilities with energy utilities to reduce energy peaks, saving money and improving efficiency in the electricity market. Furthermore, reducing water peaks can deliver substantial savings in infrastructure capacity and operations (Cole, O'Halloran, & Stewart, 2012). We know of no study analyzing water and water-related energy use at an hourly time step capable of estimating the potential benefits of changes in intra-daily water use patterns for both water and energy utilities.

In this study, both final water end-use and related energy data and water-related energy use from urban services are used to develop a coupled end-use and utility-scale water-energy model with an hourly time step. This model can assess total water-related energy use and GHG gas emissions from each part of the urban water cycle including final end-uses, and to analyze how changes in water use patterns affect water and energy utilities. Using this model and by generating different scenarios we also estimate the potential benefits for water and energy utilities from demand-response policies applied to water use.

In the remainder of the paper we present first a case of East Bay Municipal Utility District (EBMUD). Section 3 presents the methods to assess water and water-related energy and GHG emissions from end-uses and water utility services. Section 4 presents the results from the models. Section 5 discusses the methods and results obtained and finally Section 6 presents the main conclusions.

4.2. Case study

Based on 2010 census data, approximately 1.34 million of people are served by EBMUD's water system within a 332-square-mile area including the major cities of Oakland, Berkeley, Walnut Creek and San Ramon. About 90 percent of the water delivered to EBMUD customers comes from the Mokelumne River watershed, including Pardee and Camanche Pardee Reservoirs. From Pardee Reservoir, the Mokelumne Aqueducts convey the 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 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 in the EBMUD's Main Wastewater Treatment Plant. Figure 4.1 presents a schematic of the elements included as a case study.

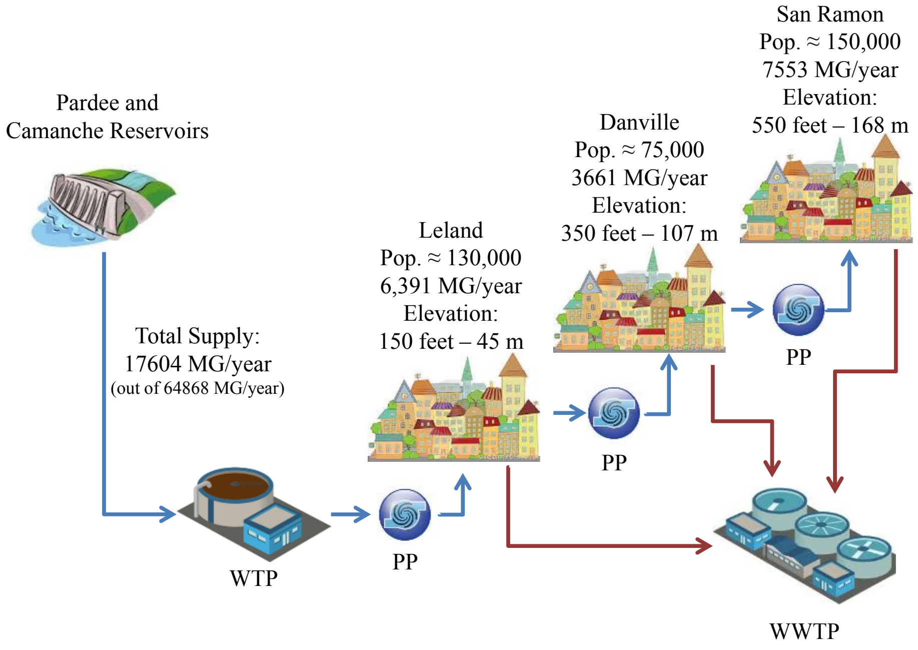


Figure 4.1: Schematic of EBMUD's subarea used as a case study

EBMUD has provided a complete dataset of water flows and water-related energy use for each of the main elements of the urban water cycle for years 2009 and 2010.

4.3. Methods

4.3.1. Overall description

The objective of this study is to obtain residential and utility-scale water and energy hourly uses from available data and compare them to real data in EBMUD, but with an approach that could be used in other locations. Once the model is implemented we run several simulations analyzing the benefits for water and energy utilities.

The first step was to obtain hourly water end uses. From total annual water use obtained from EBMUD data we broken down total annual consumption first into daily and then into hourly uses. After that we obtained water-related energy use for each the end-uses from energy-intensity values obtained from the literature.

The next step was to model hourly water and water-related energy of water utility elements. Data from EBMUD showed relationships between water and energy use and hourly patterns of water consumption with hourly water supply. Water utilities use capacity to modulate supply to minimize energy use in peak price hours

Once total hourly water-related energy is modeled, and accounting for the share of residential water-related energy that goes to gas-fired water heaters, we obtained total hourly water-related electric and natural gas demands. Using emission factors from the literature we obtain GHG emissions of both natural gas and electric water-related demands.

To obtain energy-related variable costs for the water and energy utilities we used hourly electricity prices from Pacific Gas and Electric[1] (PG&E) for the water utility and from the wholesale electricity market — the California Independent System Operator (CAISO)— for the energy utility.

Finally, we tested the model against real data and then we simulated several scenarios to analyze the consequences of changes in water use patterns for water and energy utilities.

A graphic description is presented in Figure 4.2.

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[1] PG&E supplies electricity and natural gas to both EBMUD and EBMUD water customers.

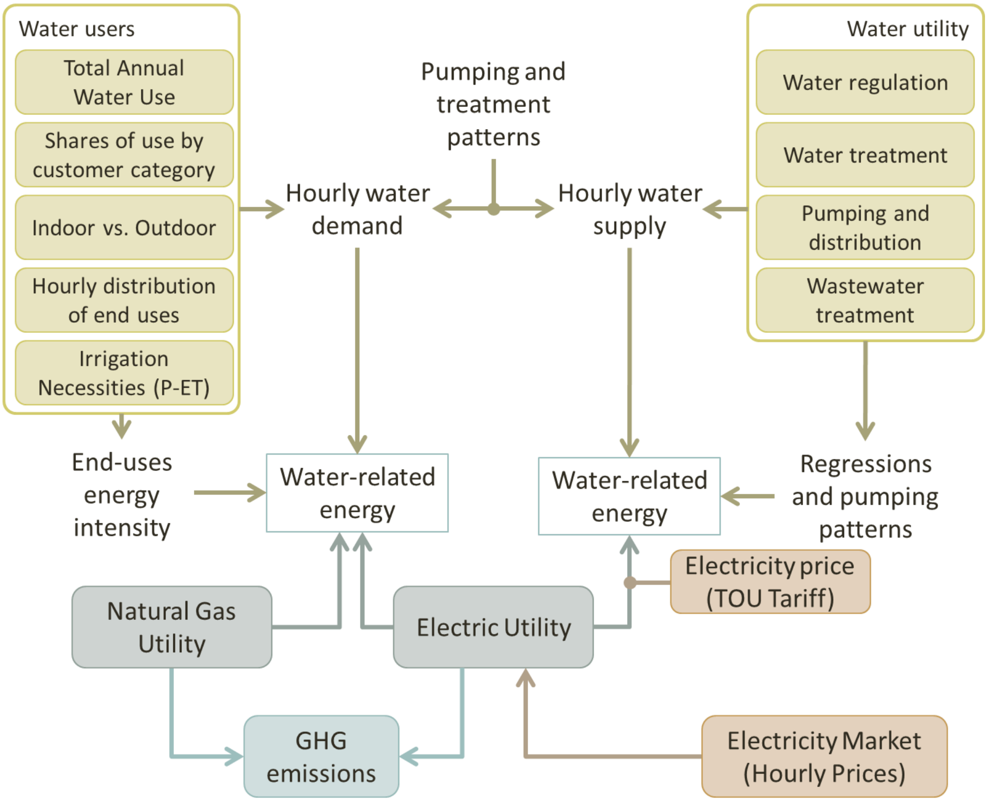

Figure 4.2: Flow diagram of coupled urban end-use and utility-scale water-energy model

4.3.2. Water use

For each city in the study area hourly water uses are based on available data. According to the Urban Water Management Plan (UWMP) (EBMUD, 2011), total annual water consumption is divided into different customers categories and then into indoor vs outdoor use[2] (Table 4.1).

From the annual use for each category, daily use is estimated using a simple model with few parameters. We assume that indoor use remains the same each day, but outdoor use varies with climatic conditions. Variability in outdoor use is included by using a daily share of the annual value obtained with the difference of average evapotranspi-

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[2] EBMUD's UWMP only shows indoor vs outdoor use for residential categories. The rest of values have been assumed.

ration and effective precipitation[3] in the last 28 days over the total annual necessities from the closest CIMIS station, in this case Moraga.

$$\boldsymbol{outdoor\_daily\_share(t)} = \frac{\boldsymbol{k_c \cdot avg(ET_0[t-28,t]) - avg(P[t-28,t])}}{\boldsymbol{\sum_{t=1}^{t=365} k_c \cdot avg(ET_0[t-28,t]) - avg(P[t-28,t])}} \qquad \textbf{Equation 1}$$

Where k_c is the crop coefficient for turf (assumed 0.7), ET_0 the daily reference evapotranspiration, and P the daily precipitation.

Table 4.1: Annual water use per customer category for the city of San Ramon

Total Water Consumption	7553.1	MG/year

Customer categories	Percentage	MG/year	% Indoor	% Outdoor	Indoor MG/year	Outdoor MG/year
Single-Family	46%	3474.4	53.1%	46.9%	1844.1	1630.3
Multi-Family	17%	1284.0	86%	14%	1104.3	179.8
Institutional	5%	377.7	30%	70%	113.3	264.4
Comercial	9%	679.8	50%	50%	339.9	339.9
Industrial & Petroleum	17%	1284.0	40%	60%	513.6	770.4
Irrigation	6%	453.2	0%	100%	0.0	453.2

Finally we obtain hourly use for each category assigning hourly percentages based on data from Funk and deOreo (2011) shown in Table 4.2. Accounting for the residential share of each end-use presented in the UWMP, and based on the hourly distribution also from Funk and deOreo (2011), we obtain hourly residential end-uses, what allow us later to obtain the benefits for water and energy utilities of residential demand-response by simulating changes in water use patterns.

4.3.3. Water-related energy use

Water-related energy use of the different end uses (Table 4.3) is obtained from different sources. Residential water-related energy is obtained from Escriva-Bou, Lund, and Pulido-Velazquez (2015a) accounting for the different energy intensities of each residential water end-use for EBMUD. Energy intensity of commercial and institutional uses were obtained for the sum of the end-uses accounted for each customer category in CEC (2005). Finally, because lack of data from other data sources, we assumed that 1 percent of institutional water use is used in faucets within public buildings.

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[3] To obtain effective precipitation we assume that all the daily rain above 0.2 inches become runoff. Then effective precipitation is only daily precipitation less or equal than 0.2 inches.

Table 4.2: Hourly distribution of water use per customer category

Hour	Single-Family		Multi-Family		Commercial	Institutional	Industrial & Petroleum	Irrigation
	Indoor	Outdoor	Indoor	Outdoor				
12:00 AM	1.8%	2.1%	2.4%	9.7%	2.9%	3.9%	4.5%	8.0%
1:00 AM	1.3%	2.4%	1.7%	9.7%	3.0%	3.7%	2.4%	5.2%
2:00 AM	1.1%	1.1%	1.2%	14.9%	2.4%	3.3%	2.4%	3.0%
3:00 AM	1.0%	2.2%	1.0%	10.3%	2.6%	3.5%	2.5%	4.1%
4:00 AM	1.3%	6.1%	0.9%	14.8%	2.4%	3.5%	4.0%	3.7%
5:00 AM	2.4%	9.3%	1.5%	7.5%	2.4%	3.0%	4.5%	1.0%
6:00 AM	4.9%	13.0%	3.3%	1.8%	2.4%	3.2%	4.8%	1.5%
7:00 AM	6.6%	12.2%	4.4%	1.0%	3.1%	3.9%	4.6%	1.9%
8:00 AM	6.5%	7.7%	5.3%	1.4%	4.4%	4.2%	4.7%	3.5%
9:00 AM	6.4%	5.9%	5.8%	1.4%	5.4%	4.4%	4.0%	4.9%
10:00 AM	5.8%	2.9%	6.1%	0.5%	5.9%	5.1%	4.5%	5.4%
11:00 AM	5.4%	2.5%	5.7%	1.0%	6.1%	4.6%	4.9%	6.0%
12:00 PM	4.9%	2.7%	6.2%	0.9%	6.2%	4.2%	4.8%	5.3%
1:00 PM	4.4%	2.2%	5.3%	2.3%	6.3%	5.2%	4.7%	6.0%
2:00 PM	4.0%	2.3%	4.9%	3.4%	6.3%	5.2%	4.5%	6.8%
3:00 PM	4.3%	2.0%	4.3%	0.5%	6.0%	4.9%	4.6%	7.2%
4:00 PM	4.6%	2.4%	4.4%	0.1%	5.2%	4.2%	4.4%	4.7%
5:00 PM	5.0%	3.3%	4.7%	0.2%	5.1%	4.1%	4.2%	2.7%
6:00 PM	5.4%	4.1%	5.9%	1.0%	4.3%	4.4%	4.4%	3.8%
7:00 PM	5.5%	5.6%	6.2%	1.0%	4.0%	4.8%	4.1%	2.1%
8:00 PM	5.3%	2.8%	5.6%	0.9%	3.8%	4.4%	3.8%	1.6%
9:00 PM	4.9%	2.7%	5.6%	3.6%	3.4%	4.5%	4.1%	2.0%
10:00 PM	4.2%	1.6%	4.2%	6.2%	2.9%	4.0%	4.2%	2.5%
11:00 PM	3.0%	0.8%	3.4%	5.9%	3.4%	3.8%	4.2%	7.1%

Table 4.3: Energy intensity of water use per customer category

Customer Category (and end-use)		Energy Intensity [MWh/MG]
Residential	Toilet	0.00
	Shower	159.63
	Bath	198.01
	Faucet	142.89
	DW	222.95
	CW	33.90
	L+O	12.43
	Outdoor	0.00
Institutional		1.43
Commercial		28.18
Industrial		85.60
Irrigation		0.00

4.3.4. Water-related energy use of urban water supply

At the urban scale, water-related energy use of water supply 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.

Using hourly data metered in EBMUD supply infrastructure, we fit linear regressions to model water-related energy from water supply. Figure 4.3 shows that linear models fit well the relationship of water supply and water-related energy for the infrastructure considered.

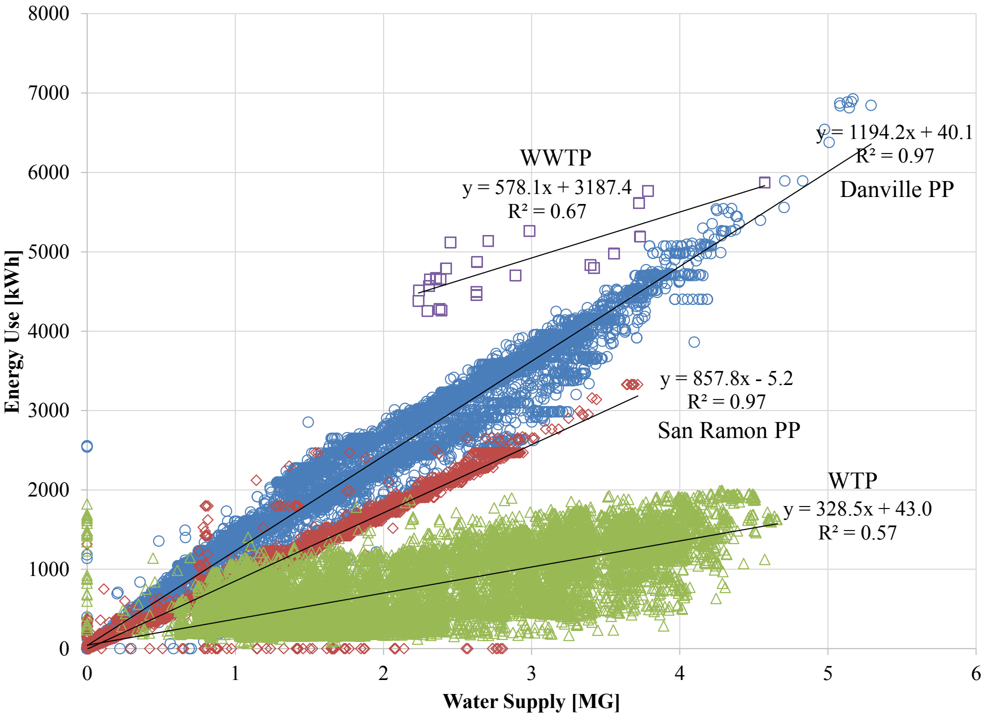

Figure 4.3: Linear fitting of water-related energy supply infrastructure

4.3.5. Adjusting hourly water demand and supply

Water demand is higher on day time, but metered data at EBMUD shows that water utility managers operate the system trying to minimize energy costs at peak energy price hours, especially in summer which has larger differences between peak and off-peak energy prices. Figure 4.4 shows how pump flow is almost zero during "on-peak hours" and minimized in "partial-peak hours". To meet higher daytime demand trying to minimize pumping on-peak hours, utility operators over pressurize the network before starting partial-peak hours, and they do it that again before starting on-peak hours.

To model that pattern, and as we lacked hourly water use data, we matched 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 shown in Figure 4.5. Following that approach, we obtained a simple rule: on winter days 45% of estimated total daily demand is pumped on peak hours, whereas in summer that proportion drops to 35%.

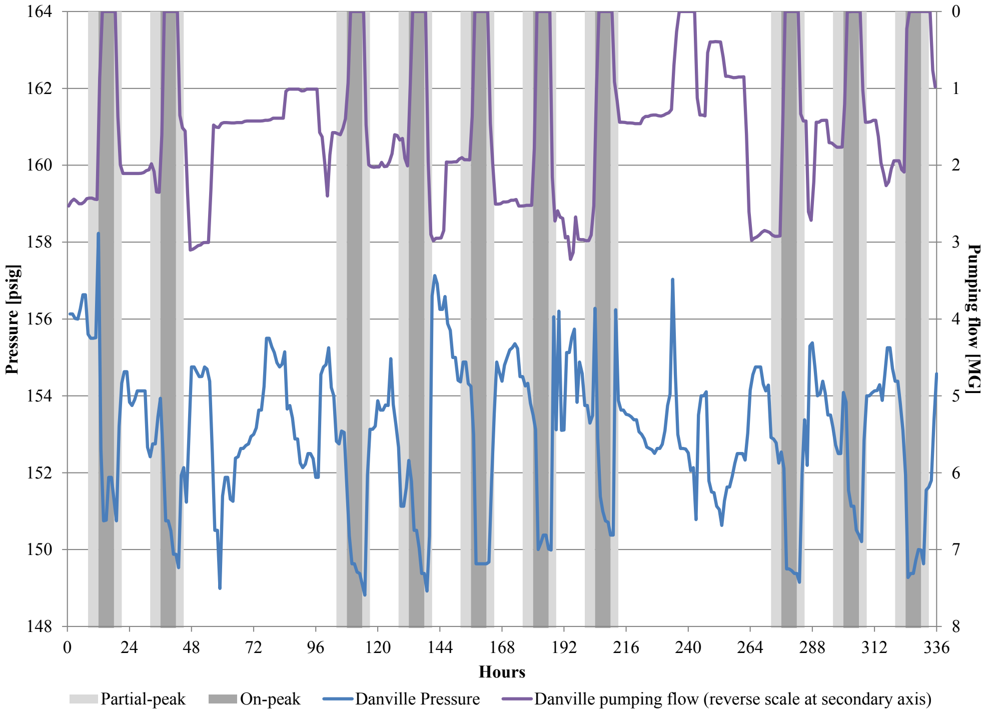

Figure 4.4: Pressure, pumping flow and time-of-use hours at Danville pumping station (July 1 to 14, 2010)

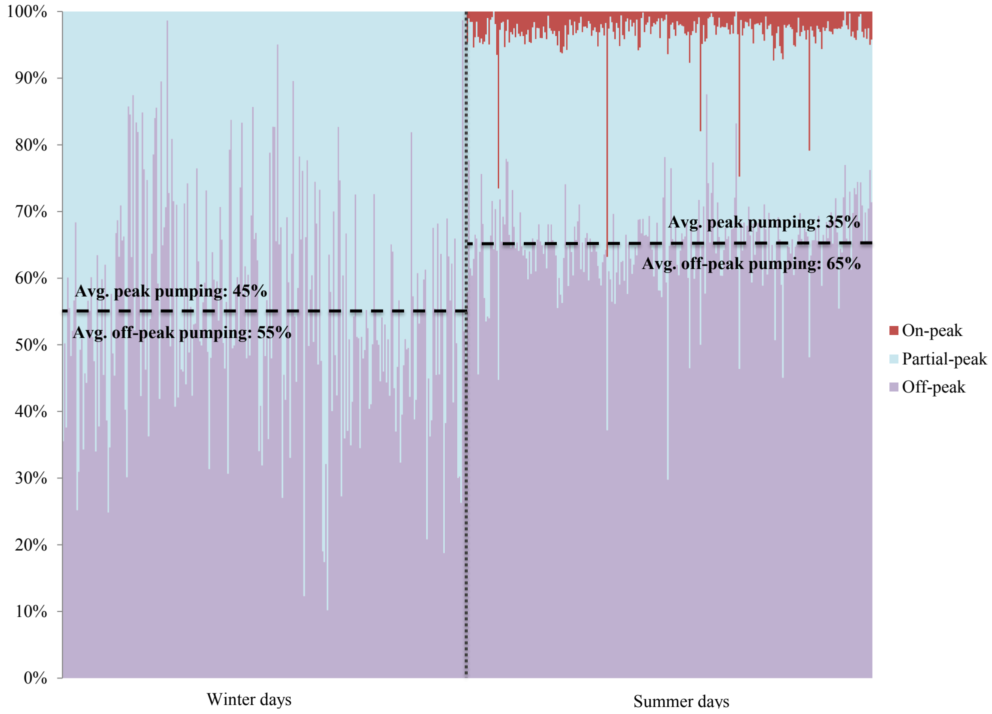

Figure 4.5: Pumping share over peak and off-peak hours on winter and summer days

4.3.6. GHG emissions

To account for GHG emissions we first obtained the source of energy for the different water-related energy uses. We assumed that 89% of the residential water heaters are gas-fired and 11% are electric, according to data from California of the Residential Energy Consumption Survey (USEIA, 2009). We assumed that the remaining water-related energy uses and energy for the water utility is supplied by the electricity grid.

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

Finally, we assessed the costs of the water-related GHG emissions assigning a value of $38/ton —assuming an average discount rate of 3% for the future— to obtain the economic savings of reducing emissions (USGovernment, 2013).

4.3.7. Energy costs

Energy costs are a small share of total costs for water and energy utilities, but they are still a significant cost. We accounted for energy costs by using current hourly prices.

The water utility buys electricity from PG&E, with prices varying by Time-of-Use (TOU). From November to April, the tariff has two steps (partial-peak from 8:30 am to 9:30 pm and off-peak the remaining of the hours) whereas in summer the tariff has an additional step from noon to 6 pm (On-peak). Prices in summer are higher than in winter due to higher demand. Table 4.4 shows TOU electricity tariff for EBMUD.

Table 4.4: PG&E Time-of-Use tariff for Industrial/General Service (E20) in $/kWh

	Off-peak	Partial-peak	On-peak
Winter	$ 0.0784	$ 0.0994	$ 0.0994
Summer	$ 0.0772	$ 0.1055	$ 0.1484

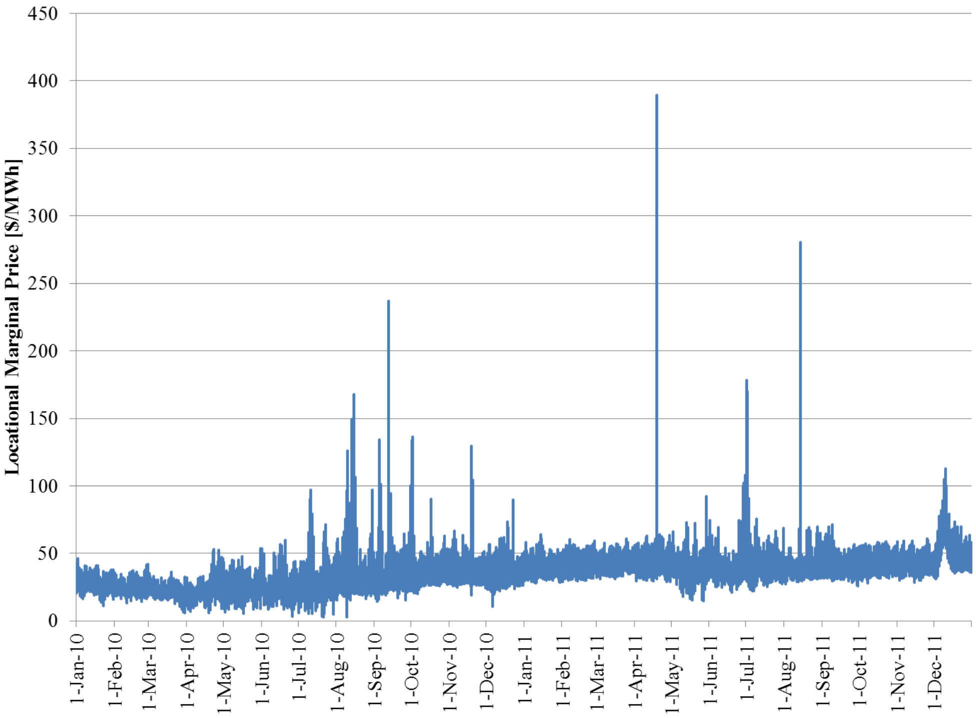

Figure 4.6: Hourly locational marginal prices for ValllyVW_1_N001 node

The energy utility works as a retailer buying its electricity from the wholesale market (CAISO) and then distributing this energy to customers with their own distribution infrastructure. We used the locational marginal price (LMP) for 2009 and 2010 for the ValleyVW_1_N001 node —that is in the EBMUD area— obtained from the CAISO Open Access Same-time Information System (OASIS). Figure 4.6 shows the large variability of hourly prices in the wholesale energy market what can provide benefits for the energy utility from changing current energy use patterns.

4.3.8. Simulations

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

- Business-as-usual scenario (BAU): To test the validity of our model we first compared the model results against actual data for EBMUD. The key values compared were the annual energy consumption and energy costs for each element of water utility operations.
- Residential optimal conservation (ROC): Escriva-Bou, Lund, and Pulido-Velazquez (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 the optimal solution for the EBMUD, average water use is reduced 11% in single-family homes (from 291 to 259 GPD per household) and 6% in multi-family homes (from 180 to 169 GPD per household). We had detailed water savings information for each residential end-use, therefore the hourly water and energy use was calculated.
- Demand response (DR): 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, energy utilities could reduce energy peaks by reducing embedded energy in water end-uses, and economic savings can arise from reduced needs in water infrastructure capacity. Our model can estimate some of the benefits from demand response programs. We simulated a simple hypothetical case where outdoor, dishwasher and clotheswasher uses occur in *off-peak* hours. With this case we did not simulated any reduction in water use, but only a change in timing 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. So a second set of simulations was exactly the same than before, but changing the share of electric water heaters to 90%, being the remaining 10% gas-fired. We called these simulated cases Business-as-usual 90% electric water heaters (BAU90%), Optimal Conservation 90% electric water heaters (ROC90%) and Demand response 90% electric water heaters (DR90%).

4.4. Methods

All the results presented below are obtained for the subset of the EBMUD utility (27% of the total EBMUD water consumption). Notice that the results for the entire EBMUD utility would be almost four times higher.

4.4.1. Validating the model

From annual water use, we calculated hourly use supplied by the water utility, minimizing energy use at peak hours. Results in Table 4.5 show that the annual energy consumption for each stage of the urban water cycle are very accurate, and the energy cost —an indicator of the accuracy of hourly supply— also is accurate.

Table 4.5: Modeled vs. observed data comparison of energy use for the urban water cycle in the EBMUD subset

Stage of the urban water cycle	Metered Data	Model	% respect total
Water Treatment [MWh/year]	6159	6160	16.3%
Pumping to Danville [MWh/year]	13743	13745	36.3%
Pumpint to Leland [MWh/year]	6433	6432	17.0%
Wastewater Treatment [MWh/year]	11493	11498	30.4%
Total Energy Consumption [MWh/year]	37828	37834	100.0%
Energy Cost for the Water Utility [$]	$ 3,312,595	$ 3,302,850	-

Behind these main results shown in Table 4.5, the hourly model is relying on the simplified daily model used to disaggregate annual water use based on climatic data. Figure 4.7 shows daily model results for the two years analyzed.

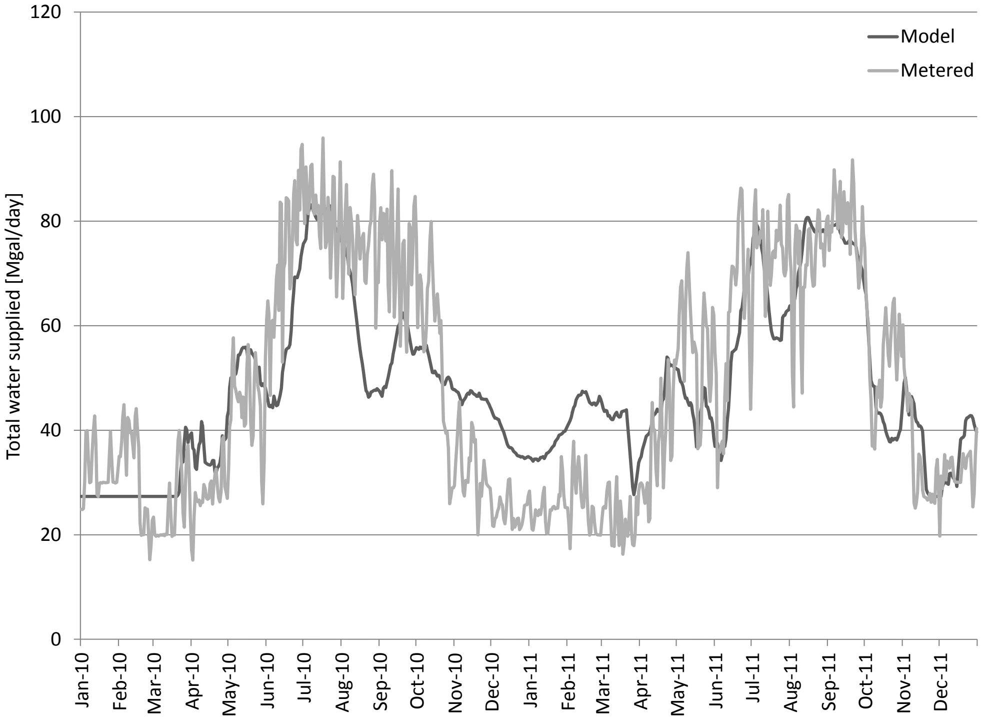

Figure 4.7: Modeled vs. metered daily annual water supply

4.4.2. Energy and GHG emissions of the urban water cycle

The complete model allows assessment of water-related energy use and GHG emissions. Figure 4.8 shows that almost 95% of the energy consumption in the urban water cycle for EBMUD is from end-uses, with residential end-uses responsible of more than 70% of allwater-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, this energy costs more than \$3.3 million per year (Table 4.5), for 27% of the EBMUD network. So total electricity cost for the water utility is more than \$12 million per year.

Because of the larger share of “cleaner” natural-gas used in residential end-uses, the share of GHG emissions from residential end-uses is a little lower (67%) than energy consumption (Figure 4.9), whereas the shares of the remaining sectors grow a little bit. Accounting for the total GHG emissions reported and the population in the area (355,000), the carbon footprint of the urban water cycle is 406 kg CO_2/person·year, representing 4.4% of total per capita GHG emission in California.

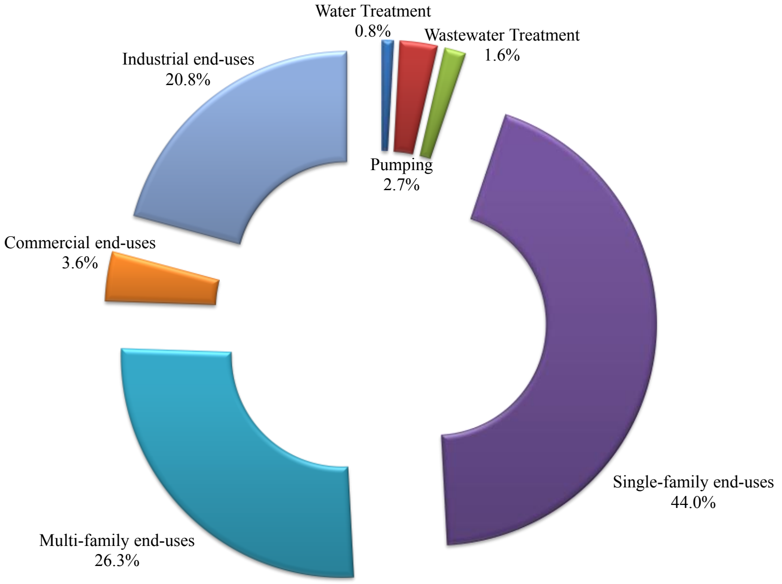

Figure 4.8: Annual water-related energy consumption in the urban water cycle for the subset of EBMUD

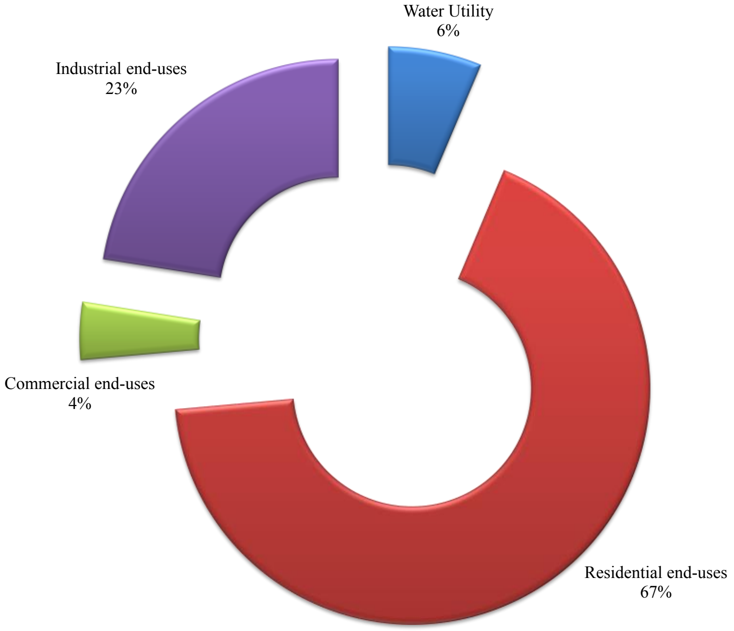

Figure 4.9: Annual water-related GHG emissions in the urban water cycle for the subset EBMUD

Hourly water-related energy profiles (Figure 4.10) show again 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 also illustrates the capacity of the water utility to modulate energy consumption from peak hours to off-peak hours driven by the lower cost of energy in off-peak hours.

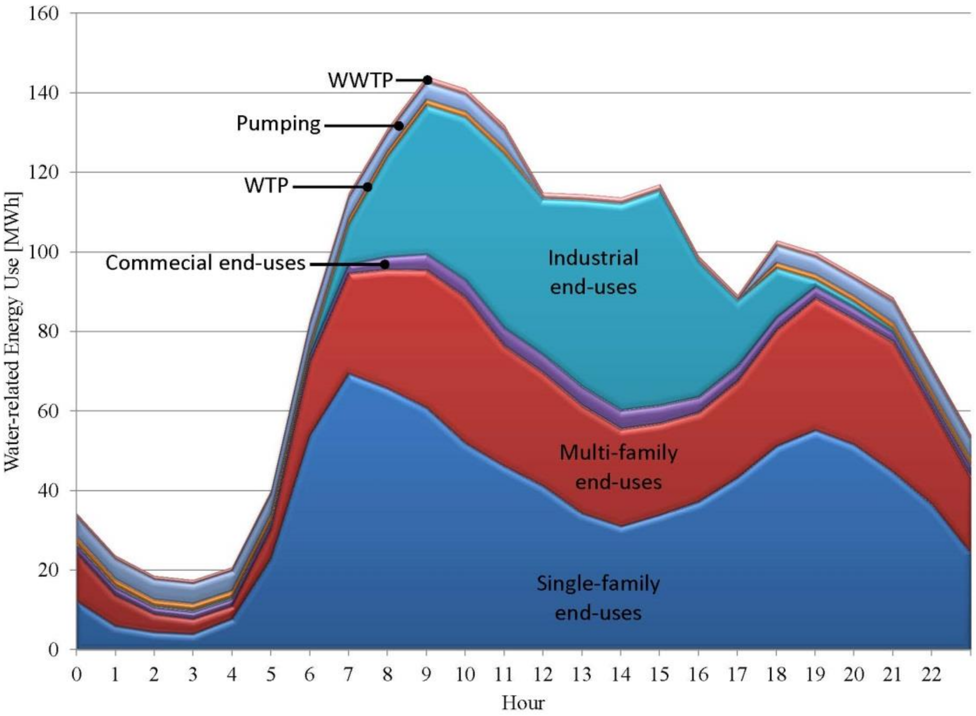

Figure 4.10: Hourly water-related energy profile for the different elements of the urban water cycle in a summer day for EBMUD

4.4.3. Residential water conservation effects

Reducing residential water use by 11% in single-family homes and 6% in multi-family homes results in 6% of annual water conservation for the entire utility, if other water uses remain constant. This reduction in residential water use reduces energy use of the water utility by 4.6% saving almost $150,000 per year (Table 4.6). The energy utility would save roughly $180,000 per year, representing 5.8% of total utility energy costs. Finally, GHG emissions would also be reduced in 4.8%, saving almost 7,000 tons of CO_2 per year ($264,300 accounting for the social cost of carbon emissions). Total benefits —the sum of energy cost savings for the water and energy utility and the social cost of carbon—, assuming stable revenues for the water and energy utilities, would be $591,500 per year for the residential optimal conservation.

Modifying the current share of electric vs. gas-fired water heaters, and assuming that 90% of the water heaters are electric, makes electric demand is much more important, so the benefits for the energy utility and the avoided costs of GHG emissions are much higher. The energy utility would save roughly $1,250,000 per year (6.6% for the BAU 90% scenario), and the emissions cost would be reduced almost $330,000. The total benefits of the residential optimal conservation assuming 90% of electric water heaters would be $1,726,467 per year (72% for the energy utility, 19% social benefits from GHG emissions abatement, and 9% for the water utility).

Table 4.6: Results of annual water, water-related energy and GHG emissions and energy costs for the water and energy utilities for the scenarios considered

			BAU	ROC	DR	BAU 90%	ROC 90%	DR 90%
Water use	Annual demand	(Mgal/year)	17,606	16,543	17,606	17,606	16,543	17,606
	Reduction	(%)	–	6.0%	0.0%	–	6.0%	0.0%
Energy	Water utility	(MWh/year)	37,834	36,098	37,833	37,834	36,098	37,833
	Reduction	(%)	–	4.6%	0.0%	–	4.6%	0.0%
	Residential demand	(MWh/year)	519,003	483,938	519,002	519,003	483,938	519,002
	Reduction	(%)	–	6.8%	0.0%	–	6.8%	0.0%
	Rest end-uses demand	(MWh/year)	180,999	180,999	180,999	180,999	180,999	180,999
	Reduction	(%)	–	0.0%	0.0%	–	0.0%	0.0%
	Total energy demand	(MWh/year)	737,835	701,035	737,834	737,835	701,035	737,834
	Reduction	(%)	–	5.0%	0.0%	–	5.0%	0.0%
	Electric demand	(MWh/year)	46,191	43,070	46,191	467,103	435,544	467,102
	Reduction	(%)	–	6.8%	0.0%	–	6.8%	0.0%
CO_2	Water utility	(tons/year)	9,080	8,664	9,080	9,080	8,664	9,080
	Reduction	(%)	–	4.6%	0.0%	–	4.6%	0.0%
	Residential end-uses	(tons/year)	96,773	90,235	96,773	121,510	113,301	121,510
	Reduction	(%)	–	6.8%	0.0%	–	6.8%	0.0%
	Remaining end-uses	(tons/year)	38,121	38,121	38,121	38,121	38,121	38,121
	Reduction	(%)	–	0.0%	0.0%	–	0.0%	0.0%
	Total emissions	(tons/year)	143,974	137,019	143,974	168,711	160,085	168,711
	Reduction	(%)	–	4.8%	0.0%	–	5.1%	0.0%
	Emissions cost	($/year)	$ 5,471,009	$ 5,206,730	$ 5,471,003	$ 6,411,035	$ 6,083,245	$ 6,411,028
	Reduction	(%)	–	4.8%	0.0%	–	5.1%	0.0%
Energy Cost	Water utility	($/year)	$ 3,302,850	$ 3,154,119	$ 3,200,597	$ 3,302,850	$ 3,154,119	$ 3,200,597
	Reduction	(%)	–	4.5%	3.1%	–	4.5%	3.1%
	Electric utility	($/year)	$ 3,090,572	$ 2,912,073	$ 2,992,665	$ 19,062,252	$ 17,812,305	$ 18,570,300
	Reduction	(%)	–	5.8%	3.2%	–	6.6%	2.6%

4.4.4. Demand response program effects

By switching outdoor, dishwasher and clotheswasher water use to off-peak hours, no water would be saved but water and water-related energy peaks are shaved to reduce energy costs. There is a reduction of 3.1% in water utility energy cost that represents more than $100,000 per year and a decrease of 3.2 in energy costs for the energy utility that would save almost $100,000 per year (Table 4.6). Total benefits of this case would be $200,165 that would be equally shared among both utilities.

Increasing the current share of electric water heaters to 90%, the water utility would keep saving the same amount, but the savings for the energy utility will increase in this case to almost $500,000 per year, representing a 2.6% decrease compared to business-as-usual case with 90% of electric water heaters. The total estimated benefits for the demand response programs with 90% of electric water heaters would be almost $600,000 per year.

4.5. Discussion

The water-related energy and greenhouse emissions calculated in this study agree with some previous studies. For example, Reffold et al. (2008) in a general study for south-east England assessed that 89 percent of carbon emissions in the water supply-use-disposal system is attributed to “water in the home” whereas the remaining 11 percent is related with public water supply and treatment. Our results show a lower share of water-related energy and GHG for the water utility side and, taking into account that the water supply system of EBMUD is conveyed by gravity from the mountains without using any additional source like groundwater, desalination or pumping from other surface systems, these results seem to agree. EBMUD has a “clean” water supply system mostly because of its water supply source. It would be interesting to replicate this study in other utilities, such as cities in southern California, where water sources have much more embedded energy because of long distances and elevations for pumped water transmission.

The results of the hourly model depend highly on model assumptions and the base data of hourly and seasonal variability. We highlight this point because the lack of hourly end-use data makes detailed model testing difficult. But, as shown in Table 4.5, the overall annual results appear good.

The cases selected focus on residential changes in consumptions because a) it is largest share of urban water use; b) it is the use where policy-oriented decisions have the largest impact; c) we assumed that industrial and commercial users are already minimizing their costs; and d) it is where better data exists about the water and energy interrelationships. There is a much room for research on non-residential water users, and as we show it is an important share of water-related energy use and GHG emission in the urban water cycle.

These cases show benefits for water and energy utilities to join efforts in saving and changing water use patterns of their customers. We calculated these benefits as the sum of the economic savings because energy cost reduction for the water and energy utilities plus the benefits from the social standpoint of reducing GHG emissions. This does not account for the reduction in revenues to water and energy utilities if customers reduce their water use and therefore their water-related energy consumption when conservation-oriented bills are in place. But because water and energy utilities have a high share of fixed costs, and they both work as natural monopolies, we assume that they will raise rates to stabilize their revenues and that energy cost savings are actually social benefits.

In this paper a very simplified demand response is used for residential water users that could benefit both water and energy utilities. Some studies have made these kinds of experiments in the energy field, but we know of none that have included water-related energy use both from the end-uses —direct energy heating water— and from the embedded energy in water supply and treatment. The case proposed here explores some of these programs for water users might work, by analyzing a shift of intra-daily variable residential water end-uses —outdoor, clotheswasher and dishwasher—. The results show that as larger the share of electric water heaters higher the benefits for the energy utility.

Other demand response programs could be analyzed, for example using hourly variable energy rates for residential customers, but much more detailed information about residential hourly elasticity would be needed. Such research seems likely to be developed soon.

Another related issue with the demand response programs is that if water hourly patterns reduce water peaks there are large potential economic impacts in terms of benefits by reducing water infrastructure capacity (Cole et al., 2012) that we did not accounted in this study, and that might be significant for new development, re-development or maintenance of existing infrastructures.

4.6. Conclusions

This paper develops a water-energy model at an hourly time step to estimate water-related energy and GHG emissions from the different water end-users and from different stages of the urban water cycle including water treatment, water pumping and wastewater treatment. As an overall result, in EBMUD 95% of water-related energy and 94% of the water-related GHG emissions are from end-uses of water (mainly residential water heating), whereas the rest are related with treating and pumping water and wastewater. These results show, compared with previous studies, that EBMUD is a less energy-intensive water utility, mostly because its water is from surface reservoirs conveyed by, but they still spend more than $12 million per year for electricity. The total carbon footprint per capita of the urban water cycle is 405 kg CO_2/year representing

4.4% of the total GHG emissions per capita in California, demonstrating that water-related energy uses is sizable for mitigating GHG emissions.

The model can also analyze the effects of changes in water use from any urban customer category on the water and energy utilities. We focused on residential water use, finding that water conservation can reduce GHG emissions, because of both direct energy consumption in households and energy savings in the urban water cycle, and also result in economic savings for the water and energy utilities because most residential water uses are within the day, when energy is more expensive.

The hourly model also allows examination of effects from changing patterns of consumption within the day. Given that the cost of energy is higher during the day, especially in summer, for the water utility —because TOU energy rates— and the energy utility —because hourly prices in the wholesale electric market— there is some profit for both utilities from having customers change their water use patterns, even without changing total water use. By shifting some residential end-uses —outdoor, clotheswasher and dishwasher— to off-peak hours we obtained that both water and energy utilities could reduce roughly 3% of their energy costs. As larger the share of electric water heaters higher the benefits for the energy utility.

A demand response program is analyzed to link water end-uses with the wholesale electric market. This could be a useful field to further explore, even more when there are other benefits are included, such as reduced water infrastructure capacity costs due to reduced water peaks. Other applications of demand response cases can be analyzed with the model proposed, including using variable hourly rates for water conservation on electricity peak hours or water use shifting from peak to off-peak hours, but much more data is needed on the intra-daily elasticity of water uses. This is an interesting and growing research field with the increasingly availability of data, and also with new technologies that are creating smarter cities and more informed natural resource customers.

4.7. References

Abdallah, A., & Rosenberg, D. (2014). Heterogeneous Residential Water and Energy Linkages and Implications for Conservation and Management. *Journal of Water Resources Planning and Management, 140*(3), 288-297. doi: doi:10.1061/(ASCE)WR.1943-5452.0000340

Borenstein, S. (2005). The long-run efficiency of real-time electricity pricing. *Energy Journal, 26*(3), 93-116.

CEC. (2005). California's Water - Energy Relationship. Prepared in Support of the 2005 Integrated Energy Policy Report Proceeding. California Energy Commission. November 2005. CEC-700-2005-011-SF.

Cole, G., O'Halloran, K., & Stewart, R. A. (2012). Time of use tariffs: implications for water efficiency. *Water Science and Technology-Water Supply, 12*(1), 90-100. doi: Doi 10.2166/Ws.2011.123

CPUC. (2010). Study 2: Water agency and function component study and embedded energy-water load profiles. San Francisco, CA, USA: California Public Utilities Commission.

CRPUW. (2009). Power/Utility Reporting Protocol (PUP). The California Registry Power/Utility Workgroup. Available at http://www.climateregistry.org/tools/protocols/industry-specific-protocols/power-utility.html. Accessed 4/14/2014.

EBMUD. (2011). Urban Water Management Plan 2010. Water Resources Planning Division. East Bay Municipal Utility District. June 2011. https://ebmud.com/water-and-wastewater/water-supply/urban-water-management-plan. Accessed 2/12/2015.

Escriva-Bou, A., Lund, J. R., & Pulido-Velazquez, M. (2015a). Modeling residential water and related energy, carbon footprint and costs in California. *Environmental Science & Policy, 50*(0), 270-281. doi: http://dx.doi.org/10.1016/j.envsci.2015.03.005

Escriva-Bou, A., Lund, J. R., & Pulido-Velazquez, M. (2015b). Optimal residential water conservation strategies considering related energy in California. *Water Resources Research*, n/a-n/a. doi: 10.1002/2014WR016821

Fidar, A., Memon, F. A., & Butler, D. (2010). Environmental implications of water efficient microcomponents in residential buildings. *Science of the Total Environment, 408*(23), 5828-5835. doi: DOI 10.1016/j.scitotenv.2010.08.006

Funk, A., & deOreo, W. B. (2011). Embedded Energy in Water Studies. Study 3: End-use Water demand Profiles. Prepared by Aquacraft, Inc. California public Utilities Commision. Energy Division. April 29, 2011.

Hardy, L., Garrido, A., & Juana, L. (2012). Evaluation of Spain's Water-Energy Nexus. *International Journal of Water Resources Development, 28*(1), 151-170. doi: Doi 10.1080/07900627.2012.642240

Kenway, S. J., Scheidegger, R., Larsen, T. A., Lant, P., & Bader, H. P. (2013). Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings, 58*, 378-389. doi: DOI 10.1016/j.enbuild.2012.08.035

Mo, W. W., Wang, R. R., & Zimmerman, J. B. (2014). Energy-Water Nexus Analysis of Enhanced Water Supply Scenarios: A Regional Comparison of Tampa Bay, Florida, and San Diego, California. *Environmental Science & Technology, 48*(10), 5883-5891. doi: Doi 10.1021/Es405648x

Pulido-Velazquez, M., Alvarez-Mendiola, E., & Andreu, J. (2013). Design of Efficient Water Pricing Policies Integrating Basinwide Resource Opportunity Costs. *Journal of Water Resources Planning and Management, 139*(5), 583-592. doi: Doi 10.1061/(Asce)Wr.1943-5452.0000262

Reffold, E., Leighton, F., Choufhoury, F., & Rayner, P. (2008). Greenhouse gas emissions of water supply and demand management. Science Report No SC070010. Environment Agency; 2008.

Rothausen, S. G. S. A., & Conway, D. (2011). Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change, 1*(4), 210-219. doi: Doi 10.1038/Nclimate1147

Sanders, K. T., & Webber, M. E. (2012). Evaluating the energy consumed for water use in the United States. *Environmental Research Letters, 7*(3). doi: Artn 034034

Doi 10.1088/1748-9326/7/3/034034

Spang, E. S., & Loge, F. J. (2015). A High-Resolution Approach to Mapping Energy Flows through Water Infrastructure Systems. *Journal of Industrial Ecology*, n/a-n/a. doi: 10.1111/jiec.12240

Tidwell, V. C., Moreland, B., & Zemlick, K. (2014). Geographic Footprint of Electricity Use for Water Services in the Western US. *Environmental Science & Technology, 48*(15), 8897-8904. doi: Doi 10.1021/Es5016845

USEIA. (2009). *Residential Energy Consumption Survey 2009. U.S. Energy Information Administration. Available at http://www.eia.gov/consumption/residential/index.cfm. Accessed 4/14/2014.*

USEIA. (2011). Voluntary reporting of greenhouse gases program (Voluntary reporting of greenhouse gases program fuel carbon dioxide emission coefficients). U.S. Energy Information Administration. Available at http://www.eia.gov/oiaf/1605/coefficients.html. Last updated January 31, 2011. Accesed 4/14/2014.

USGovernment. (2013). Interagency Working Group on Social Cost of Carbon. May 2013. Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866. United States Government. Available at: https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf. Accesed May 12, 2015.

Chapter 5

Modeling water resource systems accounting for water-related energy use, GHG emissions and water-dependent energy generation in California

Abstract

Most individual processes relating water and energy interdependence have been assessed in many different ways over the last decade. It is time to step up and include the results of these studies in management by proportionating a tool for integrating these processes in decision-making to effectively understand the tradeoffs between water and energy from management options and scenarios. A simple but powerful decision support system (DSS) for water management is described that includes water-related energy use and GHG emissions not solely from the water operations, but also from final water end uses, including demands from cities, agriculture, environment and the energy sector. Because one of the main drivers of energy use and GHG emissions is water pumping from aquifers, the DSS combines a surface water management model with a simple groundwater model, accounting for their interrelationships. The model also explicitly includes economic data to optimize water use across sectors during shortages and calculate return flows from different uses. Capabilities of the DSS are demonstrated on a case study over California's intertied water system. Results show that urban end uses account for most GHG emissions of the entire water cycle, but large water conveyance produces significant peaks over the summer season. Also the development of

more efficient water application on the agricultural sector has increased the total energy consumption and the net water use in the basins.

5.1. Introduction

Although some previous studies exist on the foundations of the water and energy literature, the California Energy Commission (CEC) Report on California's Water – Energy Relationship (CEC, 2005) focused the attention of researchers and decision-makers on the water-energy nexus. Ten years later, many studies with different approaches have defined and assessed most parts of this relationship, but there is still a need for a comprehensive tool for water and energy managers to deal with planning and management operations including the results of this consolidated field.

The literature on the water and energy interrelationship has been traditionally divided in three main subgroups: a) water end-uses; b) water supply, conveyance, treatment and distribution, and wastewater collection, treatment and discharge; c) water-dependent energy generation. Another subsequent field assesses on a regional scale one or some of these areas. We review these studies below to serve as a basis for a more integrated model.

Although most of the water-related energy is directly from end-uses of water (Reffold, Leighton, Choufhoury, & Rayner, 2008), this is the less studied field, probably because the potential effects of the water and energy utility management actions are finally determined by the water and energy customers. Assuming that environmental water use does not use energy directly, energy-related water end uses can be divided in urban, industrial and agricultural end-uses. Urban end-uses are the most energy-intensive water uses, but the heterogeneity of these uses makes their assessment difficult. Most of the urban studies focus on the residential water-energy relationship (Abdallah & Rosenberg, 2014; Escriva-Bou, Lund, & Pulido-Velazquez, 2015a, 2015b; Fidar, Memon, & Butler, 2010; Kenway, Scheidegger, Larsen, Lant, & Bader, 2013; Morales, Heaney, Friedman, & Martin, 2013), with a significant gap for commercial, industrial and rest of urban water end-uses. There are few references on energy consumption from agricultural water use, being the CEC report on California Agricultural Water Electrical Energy Requirements (CEC, 2003) the most comprehensive contribution. Jackson, Khan, and Hafeez (2010) have done a comparative analysis of water application and energy consumption of different irrigation technologies in Australia, which is also relevant for our purposes.

The most researched side of the water-energy relationship is the urban cycle of water. Different water supply options, treatment and distribution operations, and wastewater collection and treatment have different energy uses (CPUC, 2010b; Mo, Wang, & Zimmerman, 2014; Mo, Zhang, Mihelcic, & Hokanson, 2011; Nair, George, Malano, Arora, & Nawarathna, 2014; Plappally & Lienhard, 2012; Raluy, Serra, Uche, & Valero, 2004; Spang & Loge, 2015; Stokes & Horvath, 2009). In some water systems an important part of the embodied energy that is used in large conveyance infrastructure (CPUC, 2010a) or a tradeoff exists in different large-scale supply options (Munoz, Mila-i-Canals, & Fernandez-Alba, 2010).

As energy demand grows, water use for energy generation facilities is becoming more important, especially in water stressed regions. In the United States more than half of the water withdrawals are related to thermoelectric power generation (Healy, Alley, Engle, McMahon, & Bales, 2015) although almost all of these withdrawals are returned to the water system. Water-related use for power generation sources is highly variable, but it is possible to extract the water-intensity of the different power generation facilities using data from recent studies (Macknick, Newmark, Heath, & Hallett, 2012; Mielke, Diaz Anadon, & Narayanamurti, 2010; Tidwell, Kobos, Malczynski, Klise, & Castillo, 2012). Periods with high temperatures can concur with drought conditions, increasing energy demands for residential use and water demands for energy generation, at a time of reduced water availability (Scanlon, Duncan, & Reedy, 2013). If a life-cycle analysis is conducted, biofuel generation also might be included (de Fraiture, Giordano, & Liao, 2008; Elena & Esther, 2010), but in our approach this water use is included as part of the agricultural use.

Another topic in the literature of the water-energy nexus is to summarize and add up results in regional, national or supra-national scales. This was the goal of the California report (CEC, 2005), and there are many replications in different ways of this method that use available data to summarize water-related energy consumption and/or water necessities of energy generation (Hardy, Garrido, & Juana, 2012; Sanders & Webber, 2012; Siddiqi & Anadon, 2011; Tidwell, Moreland, & Zemlick, 2014; USDOE, 2006).

Most of these studies have been developed by using a static accounting of water and water-related energy interrelation, averaging historical series or assessing the values for a point in time. Although the results extracted are useful and have policy and management applications, they are not ready to be used in a dynamic, compatible with actual water resource systems planning and management.

This dynamic approach is the key characteristics in which DSS and models for water management have demonstrated their ability to ease the decision-making process by simplifying the many variables, processes, parameters and uncertainties included in a complex water resource system. AQUATOOL (Andreu, Capilla, & Sanchis, 1996), WEAP (Yates, Purkey, Sieber, Huber-Lee, & Galbraith, 2005), CALVIN (Draper, Jenkins, Kirby, Lund, & Howitt, 2003), MODSIM (Labadie, 2005) or MULINO (Giupponi, Mysiak, Fassio, & Cogan, 2004) are examples of models or DSS which represent complex water resource systems. Although some implicitly include energy-related issues —hydropower demand or energy costs— none explicitly includes and assesses energy use and GHG emission of different water uses.

This paper describes a basic DSS of water resource system management accounting for water-related energy and GHG emissions and water-dependent energy generation that includes an interrelation of surface and groundwater. The model is applied to a simplification of the California intertied water system using available data for the period 1984 to 2003, obtaining water and water-related energy and GHG emissions results for historical data and conditions. We then run several simulations of different scenarios.

The remainder of the paper is structured as follows: Section 2 presents the model motivations and objectives; Section 3 describes the method; Section 4 describes the California case study; Section 5 presents the results; Section 6 discusses the model and its results for the case study; and finally Section 7 presents conclusions.

5.2. Necessity of the model and modeling objectives

A new water resource system DSS is developed because previous models could not deal explicitly with our research objectives. Most of water-related energy of the water cycle is related directly with the end-uses of water, so an explicit module with water end uses and their water-related energy intensity was needed. When a shortage appears, water use across water sectors —and even between different end uses in the same sector, like residential indoor and outdoor use— is curtailed according to actual performance (that we modeled with economic demand curves) and therefore, non-consumptive water returns to the system follows the same pattern. Finally, groundwater pumping is also a key driver of energy consumption, so an explicit groundwater model that accounts for dynamic overdraft was needed to correctly account for energy use and GHG emissions.

Following these needs, the modeling objectives are:

- Assess historical energy use and GHG emissions from water use.
- Identify promising energy and GHG emission reductions from water conservation or management activities.
- Account for water and energy tradeoffs from different water supply strategies or different water demand scenarios.
- Investigate sensitivity of the energy sector to water availability shocks and the suitability of high water-dependent energy generating facilities for the system.
- Assess explicitly the economic value of GHG emissions abatement in the water sector.

5.3. Methods

The DSS developed has two main sub-models, the surface water management model —spatially represented as a flow network— and the groundwater model —spatially represented as a grid of cells—, and each is independently run but accounts for their interactions. The main inputs are time series of external inflows in the surface model, and spatially distributed precipitation and evapotranspiration for the groundwater model. Water demands (urban, agricultural, energy generation and environmental) are also external inputs related with a node in the surface network and a cell in the groundwater model. From demands, after the model run and accounting for potential curtailments, water from non-consumptive use is returned to the surface network and the aquifer. In the next subsections each sub-element is described in detail.

As a simulation model, the system decides monthly reservoir releases using a Standard Linear Operating Policy (SLOP) accounting for the water stored in reservoirs and the demands downstream, and the demands can complement the surface deliverieswith groundwater. When surface water is shorted more groundwater is pumped until a maximum capacity limit. We have run the period from October 1984 to September 2003 because data availability, with a monthly time step.

The model was programmed using Visual Basic for Applications (VBA) and the inputs and results are represented in a simple Microsoft Excel spreadsheet.

5.3.1. Inflows

Inflows are accounted in the model under two alternative ways. The first way is to include external surface inflow [Volume · $(\text{Time Step})^{-1}$] to a node of the surface network. The second is to include a spatially variable precipitation [Volume · $(\text{Area})^{-1}$ · $(\text{Time Step})^{-1}$] in each cell of the groundwater model. The surface inflow will be available for its use at the current time step in the model, whereas the precipitation will be processed in the groundwater model as storage in the next time step.

The present version of the model uses a simplification assuming that 10 percent of the precipitation goes to the saturated zone of the aquifer in the next time step whereas the remaining 90 percent is evaporated from the land and soil or evapotranspired by soil crops and native vegetation —as a simplification of Central Valley water data budget from DWR (2014).

5.3.2. Demands

The four main types of demands are explained below.

5.3.2.1. Urban demand

The main water demand input is total annual water use. The total annual demand is broken down into different end-uses using percentages —residential single-family, residential multi-family, institutional, commercial, industrial and irrigation—, and each end-use is divided for outdoor and indoor shares. A parameter represents consumptive water use differences between indoor and outdoor uses, assuming that indoor wastewater is returned to a wastewater treatment plant and then to the surface water network, while outdoor non-consumptive water use returns to the aquifer.

Indoor water use is equally distributed over the year. Outdoor water use varies monthly depending on precipitation and evapotranspiration patterns; monthly proportion of outdoor water use is an input parameter.

From indoor water end-uses and accounting from energy-intensity values from the literature (CEC, 2005; Escriva-Bou et al., 2015a), we obtain the water-related energy use from each water end-use, and we differentiate, including a parameter for each of the end-uses, if the energy fuel is natural gas or electricity.

Water utility energy consumption is accounted for using parameters for water supply, water treatment, water distribution, and wastewater collection and treatment. Water supply can come from different sources —surface water, groundwater, recycled water, brackish desalination, seawater desalination or water transfer— and each source has a capacity (maximum amount that can be supplied with this source), an unitary cost, an energy intensity[1] and a priority. Water treatment and distribution have different energy intensities depending on the quality of the water source —good, fair or bad quality— and the geographical characteristics of the city —flat, moderate or hilly—. Wastewater collection has an ad-hoc value for its energy intensity whereas wastewater treatment energy intensity will depend on which treatments do water needs —primary, secondary and/or tertiary—.

From energy use, and accounting for which fuel supplies for each energy use, we account for the GHG emissions by using GHG emission factors and we obtain GHG emission abatement price by including a price per ton of CO_2 displaced.

Finally economic values are included to obtain scarcity costs for unmet demands for each end-use. With that purpose we include the price of the water supplied —that will also depend on the different water sources— and different price elasticities for each end-use differentiating also between indoor and outdoor uses.

5.3.2.2. Agricultural demand

The agricultural demand can be either set as total annual water consumption or indirectly by including the acreage and annual water necessities for different crops. The latter is the preferred way because this approach differentiates between annual and perennial crops when water shortages appear.

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[1] Energy intensity of groundwater depends on the groundwater depth found by the groundwater model.

A second set of parameters includes the shares for different irrigation technologies that will determine application efficiencies and surface and/or groundwater returns. Accounting for the previous parameters and with the monthly distribution of water application —based on the monthly precipitation and crops' evapotranspiration— the model calculates the monthly demand and potential return flows.

Water-related energy consumption depends on water supply —different surface sources with different embedded energy, groundwater or water transfers— and energy needs of the irrigation technology if needed —booster pumps with different head requirements. From energy use, GHG emissions are estimated similarly as for urban uses.

Finally, economic values are included to calculate scarcity costs for unmet demands. Water price and different water price elasticities are included for perennial and annual crops.

5.3.2.3. Energy demand[2]

Two main inputs define the energy demands: the installed capacity and the type of generator, including its cooling process. With these inputs, and accounting for water withdrawal needs and consumptive use per MWh (Macknick et al., 2012; Mielke et al., 2010), freshwater demand and return flows are obtained. Including the percentage of working hours per year from CEC (2015) we obtain the energy generated. Including as an input the monthly shares of the total annual energy production monthly freshwater demand and returns are calculated for each facility.

Finally, similar to other demands, energy demands also have different availability and prices for each source, and water price elasticity is included to deal with potential shortages.

5.3.2.4. Environmental demand

We assume that environmental demand is not consumptive and it has no energy consumption. It is only a flow needed in a point or stream of the surface network. As inputs, the model needs an annual total demand, the monthly shares of this annual demand, and also economic values —water price and elasticity— to account for curtailments during shortages.

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[2] Hydropower is not included as energy demand directly because it depends on reservoir release decisions. Hydropower generation is included in the surface water infrastructure explained in section 5.3.3.1.

5.3.3. Surface water management model

The surface water model is represented as a network with nodes with storage (reservoirs) or without storage capacity (junction nodes, diversion nodes) and links (natural streams or artificial channels). The demands are also linked to certain nodes.

This network has to have an explicit connectivity given by the actual conditions, and a solution algorithm or how the demands are met by allocating and releasing water from reservoirs. Below we explain the main characteristics of the elements, connectivity, and the algorithm.

5.3.3.1. Reservoirs

Surface reservoirs are represented using a special type of node where water can be stored. Inputs for reservoir definition are maximum capacity, maximum depth, and initial storage. From these parameters the model can calculate automatically a storage-area-elevation curve —given by percentages— or if there is data available the storage-area-elevation curve can be explicitly set. Maximum monthly releases (or maximum capacity of the outlets) are also required as an input.

Besides these main inputs, average monthly evaporation and seepage rates per area (both in [Volume · Area^{-1} · (Time Step)$^{-1}$]) are needed to calculate monthly evaporation and infiltration as a function of actual storage.

If the reservoir has a powerhouse the model needs the height (if is a fixed height facility), the turbines efficiency and maximum capacity. With these data, the generated power is:

$$\boldsymbol{P = \mu \cdot \rho \cdot q \cdot g \cdot h} \qquad \textbf{Equation 1}$$

where P is the available power (W), μ is the turbine efficiency, ρ is the water density (1000 kg/m^3), q is the flow (m^3/s), g is the gravity acceleration (m^2/s) and h the available head (m)[3]. To obtain energy generation from available power we use the average monthly flow and the working hours per month.

5.3.3.2. Nodes

Nodes in the model are at junctions between links. Nodes can represent just the junction between two or more links, and in some cases these nodes will have water demands.

The nodes must meet the conservation of mass criteria, i.e. that all the water entering from the upstream link has to be either consumed or returned to the downstream link or aquifer.

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[3] In fixed height facilities, if current head is higher than the fixed head, the available power is calculated using the fixed head, and using the current head if current head lower than fixed head.

5.3.3.3. Natural streams

Natural streams are represented as links between two nodes where water flows downstream. Natural streams have a maximum monthly capacity and seepage rate. The current version of the model assumes that all the rivers can either lose water to the aquifer (if infiltration rate is positive) or just keep the water (infiltration is 0). Future developments will include gaining rivers as well.

5.3.3.4. Artificial channels

Artificial channels are represented as links between two nodes where water can either flow downstream or upstream. If it flows upstream, the link flow will have an energy intensity due to pumping.

5.3.3.5. Connectivity

Each link connects two nodes, but the network will be unidirectional, what means that each of the links only can have one node upstream and one downstream (in the flow direction). Although a node can have more than two links getting in and/or out, but only one link will be the preferred downstream outflow link representing the natural stream that receives return flows.

This connectivity is represented by the connectivity matrix, an $n \times n$ matrix (being n the number of nodes) where the row represent upstream nodes and the column represents downstream nodes. Although this matrix could be a weighted matrix (simulating the distance or losses between the nodes), for simplicity only 1 or 0 entries represent connectivity between nodes.

5.3.3.6. Water allocation algorithm

An algorithm determines monthly releases from reservoirs and allocations in each time step to meet current demands based on priorities, accounting for current reservoir storages, monthly inflows, evaporation and infiltration from reservoirs, outflows from already met demands, and available connectivity from upstream reservoirs. The main steps of the algorithm are:

i) In the beginning of each period reservoir storages are updated with new inflows.

ii) Each node has priority (1 means first), and according to their priority *for each node*:
   a. The node looks to meet their demand from water coming from upstream flows that can come either from outflows from other demands or from reservoirs.
   b. If the demand of the node can be met with upstream outflows it will take their water and return its outflows to its downstream link.

c. If node demand cannot be met with upstream outflows then: each node has a reservoir priority to get water. If the demand can be met from the first reservoir in its priority list, demand is met, return flows calculated and released downstream and release from this reservoir updated. If not, the demand looks for the second reservoir in its priority list and tries to meet the demand and so on. The loop finishes either if the total demand has been met or there is no more water in all the reservoirs upstream of the node.

d. If demand is met, surface and aquifer return flows are released.

e. If the demand of the node is not totally met, then an optimization module starts to minimize total scarcity costs according to water prices and elasticities for the demands included in that node. Usually urban outdoor demands are more elastic than indoor demands, annual agricultural cops more elastic than perennial crops, and energy more inelastic than anyone else. The minimization problem is defined with the following equations:

$$\mathit{Minimize}\ \boldsymbol{Total\ Scarcity\ Cost} = \sum_i \boldsymbol{SC_i} = \sum_i \frac{(\boldsymbol{Q_{0_i}} - \boldsymbol{Q_{s_i}})^2 \cdot \boldsymbol{P_{0_i}}}{2 \cdot |\boldsymbol{\varepsilon_i}| \cdot \boldsymbol{Q_{0_i}}} \qquad \textbf{Equation 2}$$

Subject to:

$$\sum_i \left(Q_{0_i} - Q_{s_i}\right) = \text{Total Shortage}$$

$$Q_{0_i} \geq Q_{s_i}$$

Where each *i* is a demand (even differentiating all the different sub-demands included in the urban and agricultural demands), SC_i is the scarcity cost for the demand *i*, Q_{0i} and Qs_i are the target demand and the demand actually supplied for the demand *i*, P_{0i} the price of the water for the demand *i*, and $\mathcal{E}_i$ the water price elasticity for the demand *i*.

The solution of this optimization is which demands are actually supplied and then return flows will be assessed.

iii) When all the nodes have tried to meet their demands, the releases from each reservoir will be the sum of the releases for each of the demands plus spills, and then the final month storage is calculated accounting for evaporation and infiltration (using the average area between the area for the initial storage and the area of the final storage that are obtained from the elevation-area curve).

5.3.4. Groundwater model

There are two options to model groundwater: a so-called *bucket* model and a two-dimensional model.

The bucket model is a simple groundwater reservoir that has only inputs from the percolation of precipitation and recharge from irrigation, and outflows from pumping. Each time step the groundwater depth will be calculated as:

$$\boldsymbol{h_{t+1} = h_t + \frac{(I_t - O_t)}{S \cdot A}} \qquad \textbf{Equation 3}$$

where h is the potentiometric head [L]; I_t the inflow and O_t the outflow [L^3]; S is the storage coefficient [dimensionless]; A the area of the cell or bucket [L^2]; and t the time step

As a more complex option a two-dimensional one-layer finite-difference groundwater model simulates non-steady flow for each time step based on a simplification of the MODFLOW model (Harbaugh, 2005). The groundwater flow equation is:

$$\boldsymbol{\frac{\partial}{\partial x}\left(K_{xx} \cdot \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy} \cdot \frac{\partial h}{\partial y}\right) - Q = S_s \cdot \frac{\partial h}{\partial t}} \qquad \textbf{Equation 4}$$

Where K_{xx} and K_{yy} are the hydraulic conductivities along the x and y coordinates [L/T], h is the potentiometric head [L], Q is the flux per unit of volume that represents sources and/or sinks [1/T], S_s is the specific storage [1/L] and t is the time step.

For each cell the *bucket model* needs only the storage coefficient as a parameter, whereas the *two-dimensional model* needs horizontal conductivities in each direction and specific storage. Both models need initial groundwater elevation and the sources and/or sinks for each cell and time step. The sources are the precipitation percentage that enters groundwater and return flows to the aquifer from agricultural and urban outdoor uses, and sinks are volumes pumped to meet demands.

5.3.5. Surface and groundwater model integration

Depending on supply source availability, demands can be supplied from surface water and/or groundwater (or other sources like desalination) and the return flows from non-consumptive use are returned to the surface water or the aquifer. Reservoirs and natural streams (rivers) are also connected with the aquifers via vertical infiltration rate.

This integration increases the capability of this model an approximate of how demands are met knowing that pumping is a main driver of energy use and greenhouse gas emissions, and also considering dynamic accounting for potential aquifer overdrafting.

5.4. Case study: California intertied water system

5.4.1. Assembling the model

We applied the model developed to the California intertied water system with many simplifications but that is capable to represent some of the major features of the system, and that has the ability to simulate different scenarios.

The first step was to make a very simplified schema of the California water resource system. Figure 5.1 presents the schemas used for the groundwater and surface water models and associated demand and source regions. The grid cells are 100x100 km^2 (62.14x62.14 $miles^2$), and only the green cells are demanding water. Each green cell has a population, agricultural acreage and water-dependent energy demand related with a node in the surface water model.

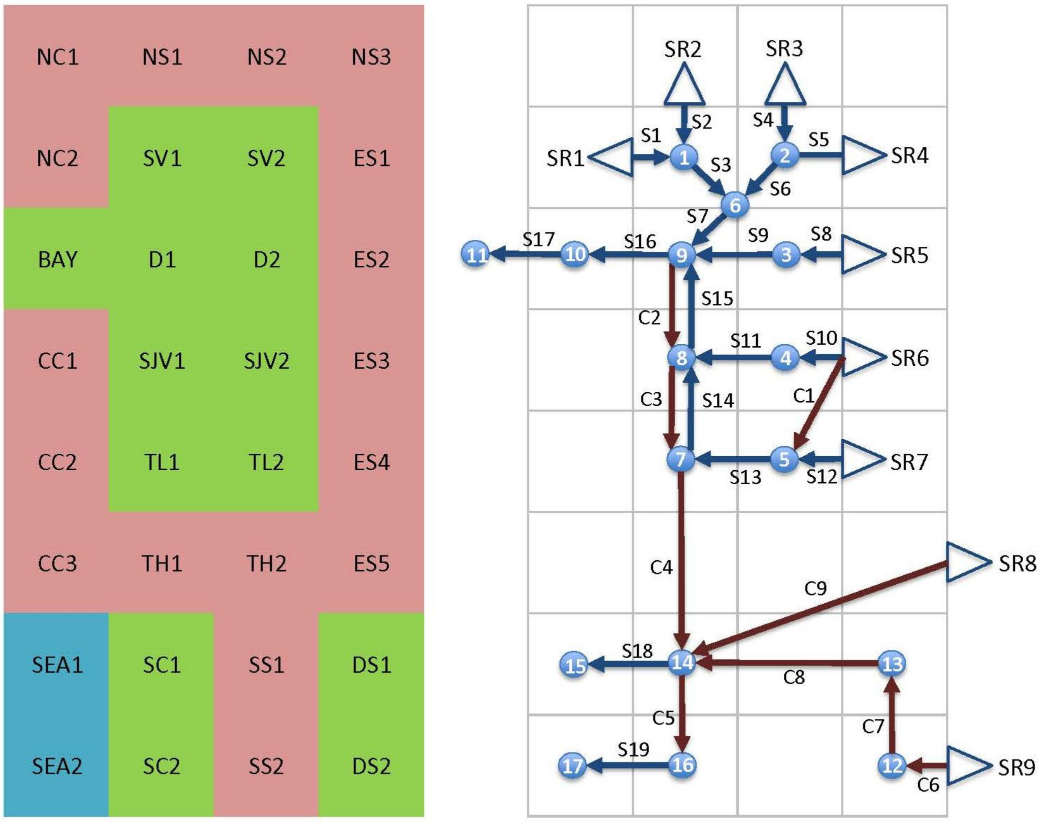

Figure 5.1: Grid cells of the different regions represented (left) and surface water network associated (right). [NC: north coast; NS: northern sierra; ES: eastern sierra; SV: Sacramento valley; D: delta; CC: central coast; SJV: San Joaquin Valley; TL: Tulare; TH: Tehachapi; SC: southern California; SS: southern sierra; DS: desert)

Table 5.1: Proportion of each county included in each cell (left) and total area of each cell accounting for the area of each county included (right)

County	Area (Sq. miles)	Area (Sq. km)	Cell 1	Cell 2	Cell 3	Cell 4	Share in Cell 1	Share in Cell 2	Share in Cell 3	Share in Cell 4
Alameda	739.02	1914.05	B1	–	–	–	100%	–	–	–
Alpine	738.33	1912.27	ES2	–	–	–	100%	–	–	–
Amador	594.58	1539.96	ES2	D2	–	–	50%	50%	–	–
Butte	1636.46	4238.42	SV2	–	–	–	100%	–	–	–
Calaveras	1020.01	2641.82	D2	–	–	–	100%	–	–	–
Colusa	1150.73	2980.38	SV1	–	–	–	100%	–	–	–
Contra Costa	715.94	1854.28	B1	–	–	–	100%	–	–	–
Del Norte	1006.37	2606.49	NC1	–	–	–	100%	–	–	–
El Dorado	1707.88	4423.39	D2	ES2	–	–	50%	50%	–	–
Fresno	5957.99	15431.13	TL1	TL2	CC2	ES4	25%	25%	10%	40%
Glenn	1313.95	3403.12	NC2	D2	–	–	75%	25%	–	–
Humboldt	3567.99	9241.06	NC1	NC2	–	–	50%	50%	–	–
Imperial	4176.60	10817.35	DS2	SS2	–	–	80%	20%	–	–
Inyo	10180.88	26368.38	ES4	ES5	–	–	50%	50%	–	–
Kern	8131.92	21061.59	TL1	TL2	TH1	TH2	10%	10%	20%	60%
Kings	1389.42	3598.58	TL1	–	–	–	100%	–	–	–
Lake	1256.46	3254.22	NC2	–	–	–	100%	–	–	–
Lassen	4541.18	11761.61	ES1	ES2	–	–	25%	75%	–	–
Los Angeles	4057.88	10509.87	SC1	TH1	–	–	75%	25%	–	–
Madera	2137.07	5534.99	SJV2	ES3	–	–	75%	25%	–	–
Marin	520.31	1347.60	B1	–	–	–	100%	–	–	–
Mariposa	1448.82	3752.43	SJV2	ES3	–	–	75%	25%	–	–
Mendocino	3506.34	9081.39	NC2	–	–	–	100%	–	–	–
Merced	1934.97	5011.55	SJV1	SJV2	–	–	75%	25%	–	–
Modoc	3917.77	10146.99	NS3	–	–	–	100%	–	–	–
Mono	3048.98	7896.83	ES3	–	–	–	100%	–	–	–
Monterey	3280.60	8496.72	CC1	CC2	–	–	80%	20%	–	–
Napa	748.36	1938.24	B1	NC2	–	–	50%	50%	–	–
Nevada	957.77	2480.61	SV2	ES1	–	–	25%	75%	–	–
Orange	790.57	2047.57	SC2	–	–	–	100%	–	–	–
Placer	1407.01	3644.14	SV2	ES1	–	–	50%	50%	–	–
Plumas	2553.04	6612.35	ES1	–	–	–	100%	–	–	–
Riverside	7206.48	18664.71	DS1	SS1	SC2	DS2	30%	50%	10%	10%
Sacramento	964.64	2498.41	D1	D2	–	–	80%	20%	–	–
San Benito	1388.71	3596.75	CC1	–	–	–	100%	–	–	–
San Bernardino	20056.94	51947.27	ES5	DS1	SS1		50%	25%	25%	–
San Diego	4206.63	10895.13	SC2	SS2	–	–	50%	50%	–	–
San Francisco	46.87	121.39	B1	–	–	–	100%	–	–	–
San Joaquin	1391.32	3603.50	D1	–	–	–	100%	–	–	–
San Luis Obispo	3298.57	8543.26	CC2	–	–	–	100%	–	–	–
San Mateo	448.41	1161.38	B1	–	–	–	100%	–	–	–
Santa Barbara	2735.09	7083.86	CC3	–	–	–	100%	–	–	–
Santa Clara	1290.10	3341.35	B1	CC1	–	–	50%	50%	–	–
Santa Cruz	445.17	1152.99	CC1	–	–	–	100%	–	–	–
Shasta	3775.40	9778.25	SJV1	NS2	–	–	25%	75%	–	–
Sierra	953.21	2468.80	ES1	–	–	–	100%	–	–	–
Siskiyou	6277.89	16259.67	NS1	NS2	–	–	50%	50%	–	–
Solano	821.77	2128.38	D1	B1	–	–	75%	25%	–	–
Sonoma	1575.85	4081.44	NC1	B1	–	–	75%	25%	–	–
Stanislaus	1494.83	3871.59	SJV1	–	–	–	100%	–	–	–
Sutter	602.41	1560.24	SV2	D2	–	–	50%	50%	–	–
Tehama	2949.71	7639.72	SV1	SV2	–	–	75%	25%	–	–
Trinity	3179.25	8234.23	NC1	NC2	–	–	20%	80%	–	–
Tulare	4824.22	12494.68	TL2	ES4	–	–	40%	60%	–	–
Tuolumne	2220.88	5752.06	D2	ES3	–	–	20%	80%	–	–
Ventura	1843.13	4773.69	SC1	TH1	–	–	70%	30%	–	–
Yolo	1014.69	2628.04	D1	–	–	–	100%	–	–	–
Yuba	631.84	1636.46	SJV2	–	–	–	100%	–	–	–

Cell	Area (Sq. Km)
NC1	11934.94
NS1	8129.84
NS2	15463.52
NS3	10146.99
NC2	27064.97
SV1	8710.17
SV2	9370.69
ES1	15704.09
B1	10590.95
D1	9826.55
D2	8904.48
ES2	13715.15
CC1	13217.78
SJV1	10074.82
SJV2	9854.91
ES3	14820.33
CC2	11785.72
TL1	9562.53
TL2	10961.82
ES4	26853.45
CC3	7083.86
TH1	8271.89
TH2	12636.95
ES5	39157.83
SC1	11223.98
SS1	22319.17
DS1	18586.23
SC2	9361.60
SS2	7611.04
DS2	10520.35

Most water use data has been obtained at the county level, so each cell is associated with the California counties trying to keep approximate the dimensions of the cells with the proportion of the counties included, especially those essential in the model (i.e. green cells). Table 5.1 shows how the counties have been assigned to each cell, and how the green cells (in the right side of the table) have an approximated area of 10,000 km^2.

Blue links in the surface network represent natural streams or rivers, whereas red lines represent the major water infrastructure in the California intertied system. C1 represents the Friant-Kern Canal; C2-C4 the California aqueduct; C5 the San Diego Aqueducts; C6-C8 the Colorado River Aqueduct, and C9 represents the Los Angeles Aqueduct.

Only 9 reservoirs (SR1 to SR9) aggregate major surface storage capacities statewide. SR1 represents Berryesa; SR2 includes Trinity Lake and Whiskeytown; SR3 is Shasta; SR4 includes the capacity of Oroville and Folsom; in SR5 we aggregate the capacity of New Don Pedro and New Melones reservoirs; SR6 includes New Exchequer and Millerton Lake; SR7 includes Pine Flat and Lake Isabella; SR8 represents the Haiwe reservoir in the Los Angeles Aqueduct; SR9 is the Lake Havasu in the Colorado River. Each reservoir receives the aggregated monthly inflow based on the more detailed Calvin model (Draper et al., 2003).

For groundwater we used a mix of the models described: a bucket model is used for each of the cells in southern California and the desert regions, whereas a two-dimensional model was used to model the Central Valley (cells SV1, SV2, Bay, D1, D2, SJ1, SJ2, T1 and T2). The rest of the cells —those represented in red— are not included in the model and have no interaction with the other cells.

5.4.2. Data

Total annual urban water use at the county level has been taken from the USGS Water Data for the Nation (Maupin et al., 2014) and from the estimated data for 1985, 1990, 1995, 2000 and 2005 we have built a monthly step data series from October 1984 to September 2003. Agricultural acreage at the county level has been taken from USDA (2015) and the monthly water necessities have been obtained following the method of the California Evapotranspiration Data for Irrigation District Water Balances (ITRC, 2015). Groundwater maximum capacity for urban and agricultural water uses have been obtained also from Maupin et al. (2014) assuming that groundwater extracted is the maximum amount that could be pumped. Energy facilities have been obtained from the California Energy Almanac (CEC, 2015) accounting only for those supplied with fresh water. Water use per MWh generated has been obtained from Macknick et al. (2012) and Mielke et al. (2010). For the environmental flows, based on daily data from delta outflow (DWR, 2015a), we assumed annual water demand for the node 11 of 9,900 kAF —that is roughly the median for the available years— and the monthly variability was assumed as the average monthly variability of the inflows.

Water-related energy use for residential urban end-uses was taken from Escriva-Bou et al. (2015a) and the remaining end-uses from CEC (2005), whereas the energy intensity used in urban, agricultural and energy water supply, treatment, and wastewater collection and treatment was obtained from CPUC (2010b). Water-related energy use for different irrigation technologies was obtained from CEC (2003). Energy intensity of the California Aqueduct and the Colorado River Aqueduct has been taken from Wilkinson (2007).

The groundwater model uses precipitation from Livneh et al. (2014), groundwater elevations from DWR (2015b)[4], and aquifer storage coefficients, conductivities, and specific storage from C2VSim (Brush, Dogrul, & Kadir, 2013). Inflows for the surface model were from the CALVIN model (Draper et al., 2003).

5.4.3. Scenario simulations

We have run several scenarios with the model:

- Business-As-Usual scenario (BAU): we used the historical 1985-2003 data to run the model. The main characteristics of this scenario are an increase in urban water demand (from roughly 6 to 7.5 MAF) and a decrease in agricultural water demand (from 40 to 35 MAF). It is also important to account for an increase in more efficient irrigation technologies (from flood irrigation to drip or sprinkle) that decreased in applied water use but increased energy use. Water-dependent energy facilities are only a very minor part of California water uses, because the largest energy facilities in California are cooled with seawater.
- Urban conservation: we simulate a decrease in 20% of total urban use to assess the decreased energy consumption and at the same time the agricultural benefits by reducing shortages with this scenario.
- Inefficient irrigation technologies: we simulate a constant share of irrigation technologies how they were in 1985. By comparing this case with the BAU scenario we try to capture the effects of the modernization of the irrigation technologies.
- Increased environmental flows: environmental concerns about the Sacramen-to-San Joaquin Delta health are likely to increase as environmental knowledge and consciousness rise. We run a case increasing environmental outflows from the delta by 50% to assess the effects on the whole system.

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[4] We only used a unique data of precipitation and groundwater elevation for each entire cell of 100x100 km^2. We know that is a huge simplification, but as we explain in the Discussion section, sufficient for our purposes.

5.5. Results

Figure 5.2 shows the inflows entering to the system plus the actual groundwater capacity cannot supply the current demands during the 1988-1992 drought. Environmental flows, Tulare basin demands, San Joaquin Valley demands and Delta demands —in this order— were curtailed severally according to the results of the model. Because the way that the model manages shortages —using economic criteria—, most unmet demands came from agriculture. Figure 5.3 shows that most water-related energy is urban-related (85.4%), especially from water end-uses. However, agricultural water-related energy uses (3.4%) and especially large infrastructure pumping —through the California Aqueduct and the Colorado River Aqueduct— (11.3%) are non-trivial energy consumptions in California, and totally concurrent with summer energy peaks. Accounting only for electricity demand from the entire water cycle modeled (40639 GWh/year on average) is roughly 14% of electricity use in California.

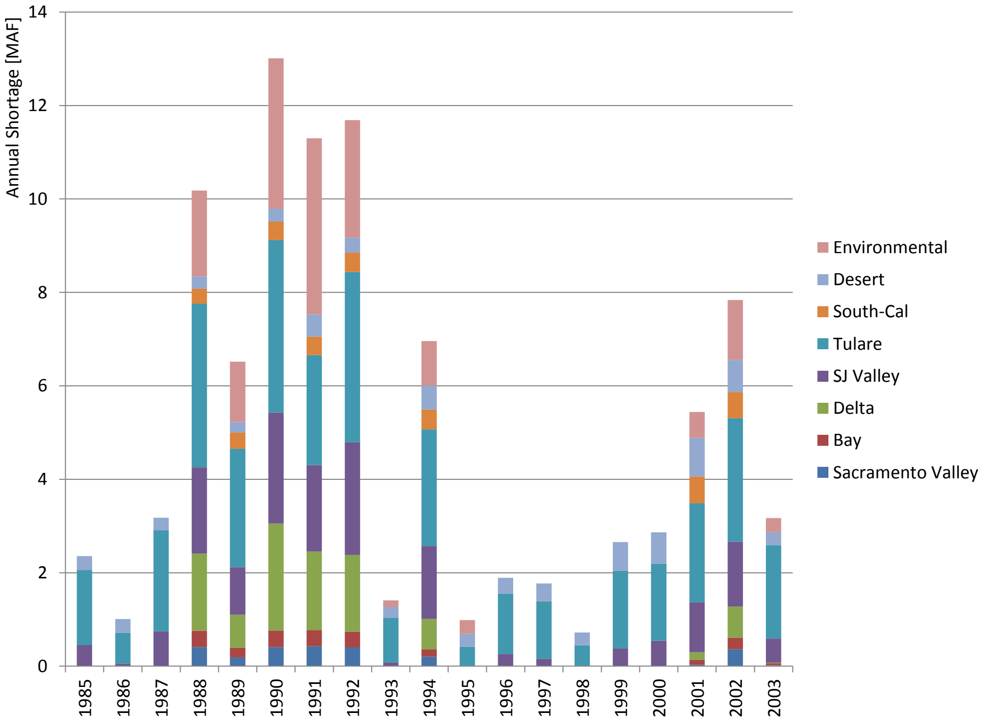


Figure 5.2: Annual shortage per region

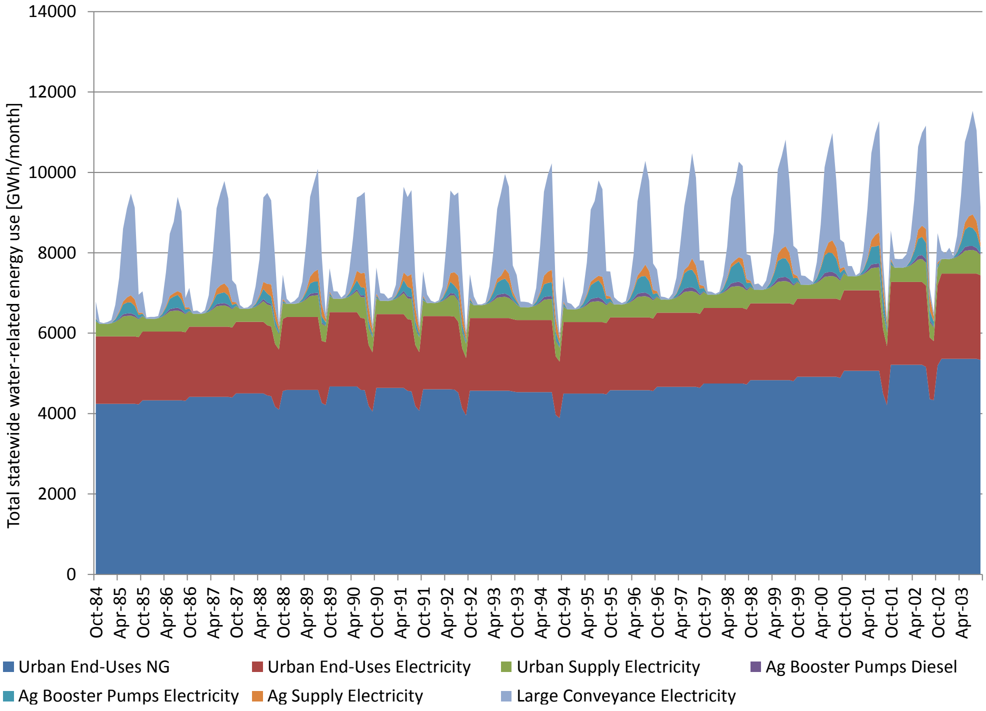
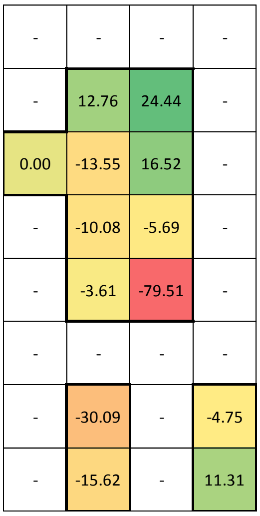


Figure 5.3: Statewide water-related energy use

Figure 5.4 shows changes in groundwater elevation from 1985 to 2003. Results show that the Sacramento Valley and the eastern Delta, because of higher precipitation and more surface water availability, increase the groundwater elevation whereas the southern part of the Central Valley and coastal Southern California regions are overdrafting the aquifers. Especially significant is the result of the eastern part of the Tulare Basin (depletion of roughly 80 feet) that is not under the scope of the California aqueduct and overdrafts the aquifer even in wet years. Only accounting for the Central Valley, Southern California and the Desert Regions (those with demands), total groundwater depletion after the 19 years would be 51.76 MAF, more than 2.7 MAF/year.

Figure 5.5 show that hydropower from reservoir releases is matching the actual behavior of California hydropower sector, but scaled down. The model included only 12 hydropower facilities —some of the largest in California— that account for roughly 20% of the installed capacity and according to the model results the hydropower generated was 18.4% of the actual generation.



-	-	-	-
-	12.76	24.44	-
0.00	-13.55	16.52	-
-	-10.08	-5.69	-
-	-3.61	-79.51	-
-	-	-	-
-	-30.09	-	-4.75
-	-15.62	-	11.31

Figure 5.4: Groundwater accretion/depletion in feet after 19 years

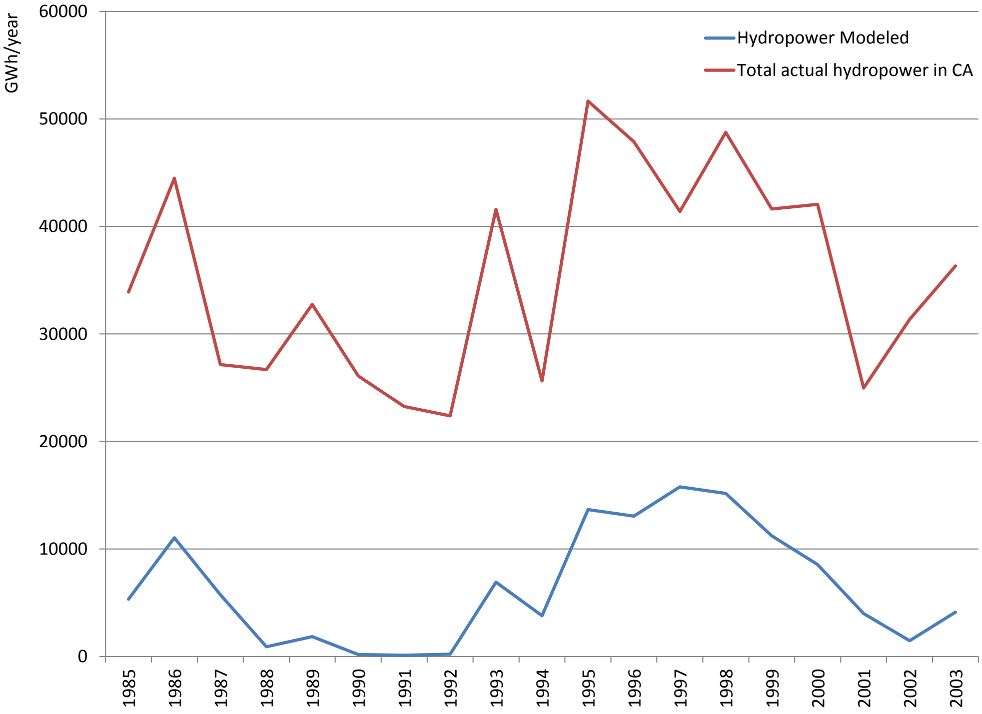


Figure 5.5: Comparison of hydropower modeled in the reservoirs included and total hydropower generated in California obtained from CEC (2015).

Results of the different scenario simulations (Table 5.2) show that urban conservation has a huge potential to save energy and also to benefit agriculture by reducing total water shortages and groundwater overdraft. The table also shows that improvements in irrigation technologies largely increased agricultural energy use, and reduce shortages because more efficiency in the application. Improvement in irrigation efficiency also increases total groundwater overdraft because there are less return flows with the new technologies. Finally, increasing environmental flows in the Sacramento-San Joaquin Delta by 50%, increases in shortages (although most of them would be environmental shortages) and groundwater overdraft because reduced surface availability. However this increase in water scarcity decreases energy use, because lower water use, and also lower exports from the Delta through the California Aqueduct.

5.6. Discussion

This is a first step to a further development for what we want to be a user-friendly decision support system that would be able to be applied in any water and energy system. Therefore, we know that the values that we stated by default in the current model based on literature research —agricultural water necessities, water-related energy intensity for all the water uses and processes, water-intensity of the energy generation, water prices and elasticities, etc.— do not have the generality to be used in the way that we did it, but this is the first time as far as we know that a model of these characteristics is released, so we hope that this model will leverage more research in this area.

Furthermore, both surface and groundwater models are quite preliminary. The surface model has to be improved with better algorithms to simulate and optimize the best options for the system —not only for releases from reservoirs—. Whereas the groundwater model will be in further developments of this DSS a spatially distributed conceptually-based hydrological model formed by different vertical tanks for each cell that will account for different fluxes —evapotranspiration from crops and native vegetation, infiltration, percolation as vertical fluxes and direct runoff, interflow, base flow and groundwater outflow as horizontal fluxes— and storages —root, non-saturated and aquifer storages— following the methodology of the Sacramento Soil Moisture Accounting (SAC-SMA) model (Sorooshian, Duan, & Gupta, 1993) or the TETIS model (Francés, Vélez, Vélez, & Puricelli, 2002). As far as we know there is not any previous model that has linked a spatially distributed hydrological model with a decision support model for California's water supply system. Another interesting development will be to couple the simulation model presented with an optimization model to analyze the set of optimal management options that could be taken under different scenarios.

We mentioned shallow optimization models, but we highlight that this model includes economic characteristics in every of the submodules. The main reason is to have the capabilities to work as a hydroeconomic optimization model, trying to obtain the most economically efficient management options from the different strategies that policy- and decision-maker have to deal with.

Table 5.2: Comparison of the main results for the different scenario simulations

	Water Shortages		Total Groundwater Overdraft		Hydropower Generation		Urban Energy Use		Ag Energy Use		Large-Conveyance Energy Use		GHG Emissions	
	MAF/Year	Change (%)	MAF	Change (%)	GWh/Year	Change (%)	GWh/year	Change (%)	GWh/year	Change (%)	GWh/year	Change (%)	Thousands Tons / year	Change (%)
Business-as-usual	4.99	-	51.76	-	6475.7	-	82560.9	-	3248.6	-	10877.4	-	21426.4	-
Urban Conservation	4.72	-5.4%	43.45	-16.1%	6489.2	0.2%	66217.2	-19.8%	3239.1	-0.3%	10639.4	-2.2%	17891.4	-16.5%
Non Irrigation Technology	5.19	3.9%	51.47	-0.6%	6419.8	-0.9%	82577.1	0.0%	2726.5	-16.1%	10900.1	0.2%	21294.6	-0.6%
Increased Environmental Flows	7.64	53.1%	60.12	16.2%	5696.6	-12.0%	82188.8	-0.5%	3222.9	-0.8%	10455.5	-3.9%	21218.7	-1.0%

Another key feature of our model is to obtain which water end-uses are curtailed in a shortage. Most of the models do not differentiate end-uses within a water demand, so when a shortage appears, all the end-uses are curtailed proportionately. But this is not the real performance of a water system. When water is shorted in a demand, low-value end water uses are curtailed first —outdoor uses in an urban demand or low-value crops in an agricultural demand—. This has many implications on the *downstream* uses. For example, if urban outdoor uses are curtailed first, urban water-related energy —that is mostly related with indoor uses— won't be affected until indoor water uses decrease. We account for this behavior, and not only differentiating within indoor and outdoor uses, but also accounting for all the different end-uses in a city and also differentiating between annual and perennial crops in agricultural demands.

For the California application, despite the huge simplifications, the main water management results agree with the many studies published. The period of 1988-1992 was one of the driest periods in California, and probably the results of the average annual shortage are too high because we are not including all the inflows and surface storages in California, but the results are representative of the reality. Groundwater depletion results are in agreement with Scanlon et al. (2012) in spite of the large size of our groundwater cells, and the regions with more depletion in the reality —Tulare Basin— are well represented. As seen in Figure 5.5, the hydropower generation results follow the actual performance of the system.

The results of the statewide total water-related energy consumption also agree with the results published by the California Energy Commission (CEC, 2005), only a little bit lower because some water demands and water infrastructure were omitted, and because we did not use the same method to account for the energy intensity of water uses.

Although the case study presented does not have many references to the water-dependent energy generation because the California energy sector is not very freshwater-dependent —many facilities are run with saltwater—, we built our model to deal with this water use, and it could serve in other regions where water stress is caused because water-dependent energy generation.

5.7. Conclusions

A first statewide decision support system was developed to deal with large-scale water management accounting for water-related energy use and GHG emissions, and water-dependent energy facilities. The model has been applied to the California intertied water resource system for the period comprised between 1985 and 2003. Throughout this period the California water system could not supply all the water demanded, with agricultural curtailments when shortages appeared.

California statewide water-related energy use modeled accounts for almost 100,000 GWh/year, with 85.3% used in cities, 3.4% in agricultural uses and 11.3% in large-conveyance infrastructure (the California aqueduct and the Colorado River Aqueduct).

Most of the water-related energy is used heating water in gas-fired water heaters, but the remaining 40.639 GWh/year that are electricity-supplied still represent 13.7% of total electricity consumption in California. The carbon footprint of the entire water cycle during this period, according to our model, was 21.43 millions of tons of CO_2/year, what was roughly 5% of California's total GHG emissions in 1990.

The results of the simulations explicitly account for tradeoffs between water and energy in the many management options. Improvements in irrigation efficiency save water but are much more energy-intensive, therefore already energy-stressed regions would avoid such policies. Increased environmental flows leave less surface water available for cities and farmers, so they would increase water pumping, if allowed by water regulations, and energy-intensive water transfers could increase energy use. Finally, urban water conservation could reduce shortages for farmers that would decrease aquifer overdrafting from reduced water pumping, and at the same time would save considerable water-related energy because urban users are the most energy-intensive water users.

We applied our model to the complex California intertied water resource system, but we developed the formulation in a way that it can be applied to other water and energy system. As demonstrated with a few simulations, the management options when using a model of these characteristics are almost countless, because it is not only a system, it is a system of systems concurrently operating. With the development of this research we tried to contribute to facilitate the decisions of policy and decision makers, although nothing but the art of modeling of the modeler will determine success.

5.8. References

Abdallah, A., & Rosenberg, D. (2014). Heterogeneous Residential Water and Energy Linkages and Implications for Conservation and Management. *Journal of Water Resources Planning and Management, 140*(3), 288-297. doi: doi:10.1061/(ASCE)WR.1943-5452.0000340

Andreu, J., Capilla, J., & Sanchis, E. (1996). AQUATOOL, a generalized decision-support system for water-resources planning and operational management. *Journal of Hydrology, 177*(3-4), 269-291. doi: Doi 10.1016/0022-1694(95)02963-X

Brush, C. F., Dogrul, E. C., & Kadir, T. N. (2013). Development and Calibration of the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), Version 3.02-CG: DWR Technical Memorandum.

CEC. (2003). California Agricultural Water Electrical Energy Requirements. ITRC Report No. R 03-006. California Energy Commission. Sacramento. December 2003.

CEC. (2005). California's Water - Energy Relationship. Prepared in Support of the 2005 Integrated Energy Policy Report Proceeding. California Energy Commission. November 2005. CEC-700-2005-011-SF.

CEC. (2015). Electric Generation Capacity & Energy. Energy Almanac. California Energy Commission. Online resource available at: http://www.energyalmanac.ca.gov/. Accessed on June 19, 2015.

CPUC. (2010a). Embedded Energy in Water Studies. Study 1: Statewide and Regional Water-Energy Relationship. Prepared by GEI Consultants/Navigant Consulting, Inc. California Public Utilities Commission. August 31, 2010.

CPUC. (2010b). Study 2: Water agency and function component study and embedded energy-water load profiles. San Francisco, CA, USA: California Public Utilities Commission.

de Fraiture, C., Giordano, M., & Liao, Y. S. (2008). Biofuels and implications for agricultural water use: blue impacts of green energy. *Water Policy, 10*, 67-81. doi: Doi 10.2166/Wp.2008.054

Draper, A. J., Jenkins, M. W., Kirby, K. W., Lund, J. R., & Howitt, R. E. (2003). Economic-engineering optimization for California water management. *Journal of Water Resources Planning and Management-Asce, 129*(3), 155-164. doi: Doi 10.1061/(Asce)0733-9496(2003)129:3(155)

DWR. (2014). California Water Plan Update 2013. Department of Water Resources. Online resource available at: http://www.waterplan.water.ca.gov/cwpu2013/final/index.cfm. Accessed July 8, 2015.

DWR. (2015a). Dayflow, an estimate of daily average delta outflow. California Department of Water Resources. Online resource available at: http://www.water.ca.gov/dayflow/. Accessed on June 20, 2015.

DWR. (2015b). Water Data Library. California Department of Water Resources. Online resource available at: http://www.water.ca.gov/waterdatalibrary/. Accesed June 21, 2015.

Elena, G.-d.-C., & Esther, V. (2010). From water to energy: The virtual water content and water footprint of biofuel consumption in Spain. *Energy Policy, 38*(3), 1345-1352. doi: http://dx.doi.org/10.1016/j.enpol.2009.11.015

Escriva-Bou, A., Lund, J. R., & Pulido-Velazquez, M. (2015a). Modeling residential water and related energy, carbon footprint and costs in California.

Environmental Science & Policy, 50(0), 270-281. doi: http://dx.doi.org/10.1016/j.envsci.2015.03.005

Escriva-Bou, A., Lund, J. R., & Pulido-Velazquez, M. (2015b). Optimal residential water conservation strategies considering related energy in California. *Water Resources Research*, n/a-n/a. doi: 10.1002/2014WR016821

Fidar, A., Memon, F. A., & Butler, D. (2010). Environmental implications of water efficient microcomponents in residential buildings. *Science of the Total Environment, 408*(23), 5828-5835. doi: DOI 10.1016/j.scitotenv.2010.08.006

Francés, F., Vélez, J. J., Vélez, J., & Puricelli, M. (2002). *Distributed modelling of large basins for a real time flood forecasting system in Spain.* Paper presented at the Second Federal Interagency Hydrologic Modeling Conference.

Giupponi, C., Mysiak, J., Fassio, A., & Cogan, V. (2004). MULINO-DSS: a computer tool for sustainable use of water resources at the catchment scale. *Mathematics and Computers in Simulation, 64*(1), 13-24. doi: DOI 10.1016/j.matcom.2003.07.003

Harbaugh, A. W. (2005). *MODFLOW-2005, the US Geological Survey modular ground-water model: The ground-water flow process*: US Department of the Interior, US Geological Survey Reston, VA, USA.

Hardy, L., Garrido, A., & Juana, L. (2012). Evaluation of Spain's Water-Energy Nexus. *International Journal of Water Resources Development, 28*(1), 151-170. doi: Doi 10.1080/07900627.2012.642240

Healy, R. W., Alley, W. M., Engle, M. A., McMahon, P. B., & Bales, J. D. (2015). The water-energy nexus—An earth science perspective: U.S. Geological Survey Circular 1407, 107 p., http://dx.doi.org/10.3133/cir1407.

ITRC. (2015). California Evapotranspiration Data for Irrigation District Water Balances. Irrigation Training & Research Center. CalPoly. San Luis Obispo. Online resource available at: http://www.itrc.org/etdata/waterbal.htm. Accessed on June 20, 2015.

Jackson, T. M., Khan, S., & Hafeez, M. (2010). A comparative analysis of water application and energy consumption at the irrigated field level. *Agricultural Water Management, 97*(10), 1477-1485. doi: DOI 10.1016/j.agwat.2010.04.013

Kenway, S. J., Scheidegger, R., Larsen, T. A., Lant, P., & Bader, H. P. (2013). Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings, 58*, 378-389. doi: DOI 10.1016/j.enbuild.2012.08.035

Labadie, J. (2005). MODSIM: River basin management decision support system. *Watershed Models. CRC Press, Boca Raton, Florida*.

Livneh, B., Rosenberg, E. A., Lin, C. Y., Nijssen, B., Mishra, V., Andreadis, K. M., . . . Lettenmaier, D. P. (2014). A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: Update and extensions (vol 26, pg 9384, 2013). *Journal of Climate, 27*(1), 477-486. doi: Doi 10.1175/Jcli-D-13-00697.1

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters, 7*(4). doi: Artn 045802 Doi 10.1088/1748-9326/7/4/045802

Maupin, M. A., Kenny, J. F., Hutson, S. S., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2014). Estimated use of water in the United States in 2010: US Geological Survey.

Mielke, E., Diaz Anadon, L., & Narayanamurti, V. (2010). Water consumption of energy resource extraction, processing, and conversion. Energy Technology Innovation Policy Research Group. Harvard Kennedy School. Belfer Center for Science and International Affairs. October 2010.

Mo, W. W., Wang, R. R., & Zimmerman, J. B. (2014). Energy-Water Nexus Analysis of Enhanced Water Supply Scenarios: A Regional Comparison of Tampa Bay, Florida, and San Diego, California. *Environmental Science & Technology, 48*(10), 5883-5891. doi: Doi 10.1021/Es405648x

Mo, W. W., Zhang, Q., Mihelcic, J. R., & Hokanson, D. R. (2011). Embodied energy comparison of surface water and groundwater supply options. *Water Res, 45*(17), 5577-5586. doi: DOI 10.1016/j.watres.2011.08.016

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

Munoz, I., Mila-i-Canals, L., & Fernandez-Alba, A. R. (2010). Life Cycle Assessment of Water Supply Plans in Mediterranean Spain. *Journal of Industrial Ecology, 14*(6), 902-918. doi: DOI 10.1111/j.1530-9290.2010.00271.x

Nair, S., George, B., Malano, H. M., Arora, M., & Nawarathna, B. (2014). Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resources Conservation and Recycling, 89*, 1-10. doi: DOI 10.1016/j.resconrec.2014.05.007

Plappally, A. K., & Lienhard, J. H. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable & Sustainable Energy Reviews, 16*(7), 4818-4848. doi: DOI 10.1016/j.rser.2012.05.022

Raluy, R. G., Serra, L., Uche, J., & Valero, A. (2004). Life-cycle assessment of desalination technologies integrated with energy production systems. *Desalination, 167*(1-3), 445-458. doi: DOI 10.1016/j.desal.2004.06.160

Reffold, E., Leighton, F., Choufhoury, F., & Rayner, P. (2008). Greenhouse gas emissions of water supply and demand management. Science Report No SC070010. Environment Agency; 2008.

Sanders, K. T., & Webber, M. E. (2012). Evaluating the energy consumed for water use in the United States. *Environmental Research Letters, 7*(3). doi: Artn 034034 Doi 10.1088/1748-9326/7/3/034034

Scanlon, B. R., Duncan, I., & Reedy, R. C. (2013). Drought and the water-energy nexus in Texas. *Environmental Research Letters, 8*(4). doi: Artn 045033 Doi 10.1088/1748-9326/8/4/045033

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., & McMahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences of the United States of America, 109*(24), 9320-9325. doi: DOI 10.1073/pnas.1200311109

Siddiqi, A., & Anadon, L. D. (2011). The water-energy nexus in Middle East and North Africa. *Energy Policy, 39*(8), 4529-4540. doi: DOI 10.1016/j.enpol.2011.04.023

Sorooshian, S., Duan, Q. Y., & Gupta, V. K. (1993). Calibration of Rainfall-Runoff Models - Application of Global Optimization to the Sacramento Soil-Moisture Accounting Model. *Water Resources Research, 29*(4), 1185-1194. doi: Doi 10.1029/92wr02617

Spang, E. S., & Loge, F. J. (2015). A High-Resolution Approach to Mapping Energy Flows through Water Infrastructure Systems. *Journal of Industrial Ecology*, n/a-n/a. doi: 10.1111/jiec.12240

Stokes, J. R., & Horvath, A. (2009). Energy and Air Emission Effects of Water Supply. *Environmental Science & Technology, 43*(8), 2680-2687. doi: Doi 10.1021/Es801802h

Tidwell, V. C., Kobos, P. H., Malczynski, L. A., Klise, G., & Castillo, C. R. (2012). Exploring the Water-Thermoelectric Power Nexus. *Journal of Water Resources Planning and Management-Asce, 138*(5), 491-501. doi: Doi 10.1061/(Asce)Wr.1943-5452.0000222

Tidwell, V. C., Moreland, B., & Zemlick, K. (2014). Geographic Footprint of Electricity Use for Water Services in the Western US. *Environmental Science & Technology, 48*(15), 8897-8904. doi: Doi 10.1021/Es5016845

USDA. (2015). Agricultural Statistics Annual. National Agricultural Statistics Service. United States Department of Agriculture. Online resource available at: http://www.nass.usda.gov/Publications/Ag_Statistics/index.asp. Accesed on June 20, 2015.

USDOE. (2006). Energy demands on water resources. Report to Congress on the Interdependency of Energy and Water. U.S. Department of Energy. December 2006.

Wilkinson, R. C. (2007). Analysis of the energy intensity of water supplies for West Basin Municipal Water District. *West Basin Municipal Water district Report March*.

Yates, D., Purkey, D., Sieber, J., Huber-Lee, A., & Galbraith, H. (2005). WEAP21 - A demand-, priority-, and preference-driven water planning model Part 2: Aiding freshwater ecosystem service evaluation. *Water International, 30*(4), 501-512.

PART III: GENERAL DISCUSSION AND CONCLUSIONS

Chapter 6

General discussion of the results

6.1. Summary of results’ discussions

Along the development of this dissertation we have been discussing the results obtained in each chapter. Next sections summarize the main discussions of the results as an introduction to the general discussion.

6.1.1. Residential water-energy nexus

i. The results of the water-energy-GHG emissions developed in Chapter 2 are consistent with previous studies: water-related energy used was slightly higher than results of Abdallah and Rosenberg (2014), probably because we are including losses with the Water Heater Analysis Model (WHAM) formulation, and slightly lower than those from Kenway, Scheidegger, Larsen, Lant, and Bader (2013) because we are not including energy used directly by appliances (although their results for total gas use, hot water + losses, are slightly lower than ours).

ii. Per capita total water-use variability is driven by variability in outdoor water-use. Cheaper water rates and inland climates imply a high outdoor use, meanwhile relatively small lots cause less total water-use, although indoor water-use is similar to other locations.

iii. Regression analysis results from households show that hot water-use and water heater characteristics are the main drivers of energy consumption, but outside and inlet temperatures also are important in energy consumption: even though the average indoor water-use in southern California households is larger, northern households use slightly more water-related energy due to lower winter temperatures.

iv. Interestingly although electric water heaters are more efficient heating water than gas-fired heaters, the overall performance[1] comparison depends on the main energy source of electricity generation. Electricity generation using natural gas in a combined plant could have a loss of two thirds of the main energy source including efficiency in generation and distribution losses when the electricity is used in a house. But most electric utilities have a diversified portfolio to generate electricity, so this variability in electric generation has to be considered in overall performance to pose smart policies to reduce GHG emissions.

v. Total water, water-related energy and greenhouse gas emissions savings for each utility depends on conditions of consumption given by technological, behavioral and external factors, whereas household economic benefits from savings rely on the water and energy rates of each utility. Water end-uses with a higher share of hot water receive more economic benefit by saving water because of the reduced energy cost. On the other side, technology or behavior improvements that only affect the energy side, i.e. retrofit water heaters or modify the setpoint temperature, lead to economic benefit only by energy savings.

vi. Including energy and CO_2 emissions and their costs in the conceptualization of water-use can improve people's knowledge about their actual expenses and environmental footprint, helping to incentivize potential conservation strategies. Moreover, throughout the analysis of spatial variability, we show that water and energy rates, energy sources available for customers and different energy portfolios of power companies can cause high variability in energy, cost and emission results with customers' water-use held constant. Customers' behavior, in reacting to bills and local, regional and national policies (like pricing carbon indirectly by the cap-and-trade market in California), can change outcomes depending on local conditions such as water and energy rates or temperature.

vii. The two-stage optimization model developed in Chapter 3 is a basic cost-minimizing problem that might be seen as myopic from an economic point of

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[1] Overall performance includes both final end-use energy consumption from different energy sources (electric vs. natural gas) and emission factors from the energy utility.

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.

viii. Our focus in that Chapter was to increase the information available to select the most efficient retrofit actions including the embedded energy of water appliances trying to reduce the efficiency gap, at the same time that we were modeling the economic behavior of people allowing reaction to short run prices changes.

ix. A difference exists between the way that long-term and short-term actions' assessment and costs in the optimization model that we developed: 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.

x. The price elasticity of water use obtained were much lower than those in the literature (Dalhuisen, Florax, de Groot, & Nijkamp, 2003; Espey, Espey, & Shaw, 1997) and that was directly related with assumptions made on the behavioral savings and costs, and probably because of the limited number of conservation actions accounted. 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 we noted, water and energy cross-price elasticities have been barely studied (see Hansen (1996)) probably 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.

xi. Although the residential end-use model based on Monte Carlo sampling allows for preserving the heterogeneity of water use, it does not allow for accurately predict high temporal resolution water consumption at the household scale. However, as smart metering is becoming common, the model could be used to analyze the potential success of a proposed conservation campaign given the current metrics and temporal trends of a sample of customers. This would not be applied as an individual household scale prediction, but as an overall utility performance, what would be really useful for water managers.

6.1.2. Urban water-energy nexus

i. The water-related energy and greenhouse emissions calculated in Chapter 4 agreed with some previous studies. For example, Reffold, Leighton, Choufhoury, and Rayner (2008) in a general study for south-east England assessed that 89 percent of carbon emissions in the water supply-use-disposal system is attributed to “water in the home” whereas the remaining 11 percent is related with public water supply and treatment.

ii. Our results showed a lower share of water-related energy and GHG for the water utility side and, taking into account that the water supply system of EBMUD is conveyed by gravity from the mountains without using any additional source like groundwater, desalination or pumping from other surface systems, these results seem to agree.

iii. The cases selected focused on residential changes in consumptions because a) it is largest share of urban water use; b) it is the use where policy-oriented decisions have the largest impact; c) we assumed that industrial and commercial users are already minimizing their costs; and d) it is where better data exists about the water and energy interrelationships. There is a much room for research on non-residential water users, and as we show it is an important share of water-related energy use and GHG emission in the urban water cycle.

iv. These cases show benefits for water and energy utilities to join efforts in saving and changing water use patterns of their customers. We calculated these benefits as the sum of the economic savings because energy cost reduction for the water and energy utilities plus the benefits from the social standpoint of reducing GHG emissions. This does not account for the reduction in revenues to water and energy utilities if customers reduce their water use and therefore their water-related energy consumption when conservation-oriented bills are in place. But because water and energy utilities have a high share of fixed costs, and they both work as natural monopolies, we assume that they will raise rates to stabilize their revenues and that energy cost savings are actually social benefits.

v. The case proposed in Chapter 4 explored some of these programs for water users might work, by analyzing a shift of intra-daily variable residential water end-uses. The results showed that as larger the share of electric water heaters higher the benefits for the energy utility.

vi. Other demand response programs could be analyzed, for example using hourly variable energy rates for residential customers, but much more detailed information about residential hourly elasticity would be needed. Such research seems likely to be developed soon.

vii. Another related issue with the demand response programs is that if water hourly patterns reduce water peaks there are large potential economic impacts in terms of benefits by reducing water infrastructure capacity (Cole, O'Halloran, & Stewart, 2012) that we did not accounted in our study, and that might be significant for new development, re-development or maintenance of existing infrastructures.

6.1.3. Basin-scale scale water-energy nexus

i. The model presented in Chapter 5 is a first step to a further development for what we want to be a user-friendly decision support system that would be able to be applied in any water and energy system. Therefore, we know that the values that we stated by default as assumptions in the current model based on literature research do not have the generality to be used in this way. However this is the first time, as far as we know, that a model of these characteristics is released, so we hope that this model will leverage more research in this area.

ii. Both surface and groundwater models were quite preliminary. The surface model has to be improved with better algorithms to simulate and optimize the best options for the system —not only for releases from reservoirs—. Whereas the groundwater model will be in further developments of this DSS a spatially distributed conceptually-based hydrological model formed by different vertical tanks for each cell that will account for different fluxes —evapotranspiration from crops and native vegetation, infiltration, percolation as vertical fluxes and direct runoff, interflow, base flow and groundwater outflow as horizontal fluxes— and storages —root, non-saturated and aquifer storages— following existing methodologies (Francés, Vélez, Vélez, & Puricelli, 2002; Sorooshian, Duan, & Gupta, 1993).

iii. Another key feature of the model developed was to obtain which water end-uses are curtailed in a shortage. Most of the models do not differentiate end-uses within a water demand, so when a shortage appears, all the end-uses are curtailed proportionately. But this is not the real performance of a water system. When water is shorted in a demand, low-value end water uses are curtailed first —outdoor uses in an urban demand or low-value crops in an agricultural demand—. This has many implications on the downstream uses.

iv. For the California application in Chapter 5, despite the huge simplifications, the main water management results agree with the many studies published. The period of 1988-1992 was one of the driest periods in California, and probably the results of the average annual shortages (Figure 5.2) are too high because we are not including all the inflows and surface storages in California, but the results are representative of the reality. Groundwater depletion results are in agreement with Scanlon et al. (2012) in spite of the large size of our groundwater cells, and the regions with more depletion in the reality —Tulare Basin— are well represented. Hydropower results follow the actual performance of the system.

v. Statewide total water-related energy consumption results agree with the results published by the California Energy Commission (CEC, 2005), only a little bit lower because some water demands and water infrastructure were omitted, and because we did not use the same method to account for the energy intensity of water uses.

vi. Although the case study presented does not have many references to the water-dependent energy generation because the California energy sector is not very freshwater-dependent —many facilities are run with saltwater—, we built our model to include water demands from energy generation, and it can be applied in other regions where water demands for energy are more important.

6.2. General discussion of the results

The carbon footprint of each step analyzed agrees with previous studies, but what it is more important from the development of this dissertation is that it shows a consistency from the bottom-up approach: residential water-related GHG emissions are 2 percent of total per capita emissions when only direct energy used in households is accounted, 4.4 percent when other urban uses and the urban water cycle is included, and 5 percent when agricultural uses and large-conveyance infrastructure is accounted.

This research has dealt with the scarcity of data, especially on the residential and urban sides of the water-energy nexus. 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.

As it has been also demonstrated by other authors we found a big gap on non-residential uses of water: industrial and commercial data are very difficult to find, so the assessment of the water-energy nexus of these significant end-uses of water relies on the very few studies found.

Although the agricultural water-energy relationship has been implicitly assessed in Chapter 5, we have focused most of our research on the urban side of the water-energy nexus. More research on the agricultural side of the nexus is needed to include all the tradeoffs between water use and energy consumption of different irrigation technologies that we only accounted with many simplifications. Other point that could be interesting to analyze is the economic productivity of different crops accounting for their total water and energy use at the basin or regional scale.

We have used several methodologies to account for the different sides of the management of the water-energy nexus. On the residential side, heterogeneity and spatial variability was accounted including technological and behavioral factors to understand which are the drivers of water and water-related energy use in households. And we did this assessment because only accounting for this variability the optimization used in

Chapter 3 makes sense to understand that different conditions make people to take different options. The optimization model permitted to obtain water and energy own- and cross-price elasticities in a way not used before, although the lack of data on behavioral modifications of consumption make impossible the calibration of the model. Probably with the new smart metering technologies that are being implemented in many water and energy utilities could ease this process and leverage more research on this topic.

Finally, chapters 4 and 5 used a system of systems approach to develop urban and basin-scale models of the water-energy interrelationship. These models were built using previous results developed in this dissertation, but also from the literature. The systems approach is very common in the water resource management literature, but our contribution was to include water-related energy consumption and water-dependent energy generation, and also economic assessments of this interrelationship to develop hydroeconomic models that could help policy and decision-makers to deal these very with complex systems.

6.3. References

Abdallah, A., & Rosenberg, D. (2014). Heterogeneous Residential Water and Energy Linkages and Implications for Conservation and Management. *Journal of Water Resources Planning and Management, 140*(3), 288-297. doi: doi:10.1061/(ASCE)WR.1943-5452.0000340

CEC. (2005). California's Water - Energy Relationship. Prepared in Support of the 2005 Integrated Energy Policy Report Proceeding. California Energy Commission. November 2005. CEC-700-2005-011-SF.

Cole, G., O'Halloran, K., & Stewart, R. A. (2012). Time of use tariffs: implications for water efficiency. *Water Science and Technology-Water Supply, 12*(1), 90-100. doi: Doi 10.2166/Ws.2011.123

Dalhuisen, J. M., Florax, R. J. G. M., de Groot, H. L. F., & Nijkamp, P. (2003). Price and income elasticities of residential water demand: A meta-analysis. *Land Economics, 79*(2), 292-308. doi: Doi 10.2307/3146872

DeOreo, W. B., Mayer, P. W., Martien, L., Hayden, M., Funk, A., Kramer-Duffield, M., & Davis, R. (2011). California single-family water use efficiency study. Aquacraft, Inc. Water Engineering and Management. July 20, 2011.

Espey, M., Espey, J., & Shaw, W. D. (1997). Price elasticity of residential demand for water: A meta-analysis. *Water Resources Research, 33*(6), 1369-1374. doi: Doi 10.1029/97wr00571

Francés, F., Vélez, J. J., Vélez, J., & Puricelli, M. (2002). *Distributed modelling of large basins for a real time flood forecasting system in Spain.* Paper presented at the Second Federal Interagency Hydrologic Modeling Conference.

Hansen, L. G. (1996). Water and energy price impacts on residential water demand in Copenhagen. *Land Economics, 72*(1), 66-79. doi: Doi 10.2307/3147158

Kenway, S. J., Scheidegger, R., Larsen, T. A., Lant, P., & Bader, H. P. (2013). Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings, 58*, 378-389. doi: DOI 10.1016/j.enbuild.2012.08.035

Reffold, E., Leighton, F., Choufhoury, F., & Rayner, P. (2008). Greenhouse gas emissions of water supply and demand management. Science Report No SC070010. Environment Agency; 2008.

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., & McMahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences of the United States of America, 109*(24), 9320-9325. doi: DOI 10.1073/pnas.1200311109

Sorooshian, S., Duan, Q. Y., & Gupta, V. K. (1993). Calibration of Rainfall-Runoff Models - Application of Global Optimization to the Sacramento Soil-Moisture Accounting Model. *Water Resources Research, 29*(4), 1185-1194. doi: Doi 10.1029/92wr02617

Chapter 7

Conclusions

7.1. Introduction

In the first chapter of this dissertation I set forth the objectives that I wanted to achieve and the research questions that motivated these objectives. In this chapter I present these goals again to compare them with the actual conclusions that I obtained along the development of the dissertation. Then an estimation of the degree of accomplishment of the objectives is done, and finally some research gaps and potential further developments are presented.

7.2. Initial objectives and research questions

The main objective of this research was *to develop a hydro-economic model of water management at the basin-scale including water balance (traditional models) and the water-related energy consumption and GHG emissions of the entire water cycle, including urban, agricultural, environmental and energy-related water demands.*

To accomplish this main goal, four objectives including several research questions were posed:

- **Objective 1**: Develop a residential water end-use model assessing related energy and GHG emissions in California. The model will explicitly account for heterogeneity in water and water-related energy use, geographic parameters affecting use, and variability in costs due to different water and energy rate structures.

  - How much energy and GHG emissions are associated with residential water end-uses?

    In Chapter 2 I obtained: "Direct residential water-related CO_2 emissions average about 730 kg/year per household, representing 2% of per capita greenhouse gas emissions in California. This result does not include other embedded energy in water supply, conveyance, treatment, pumping or wastewater collection and treatment."
  - How spatial variability and heterogeneity in consumption affects water and energy use?
  - How different water and energy rate structures can incentive/disincentive water and energy conservation?

- **Objective 2:** Develop an economic optimization model to obtain the optimal conservation strategies that Californian households can take to save water, and related energy and GHG emissions.
  - Based on variability of water and energy prices in different locations, what are the optimal strategies to save water and related energy in households?
  - How including energy costs in customer's perception of water use can increase water conservation attitudes?
  - How significant are water and energy own- and cross-price elasticities?
- **Objective 3:** Develop an urban-scale water and energy model that can assess heterogeneous water demand side management policies and the effects of these policies on households, water and energy utilities, and the environment.
  - How much energy and GHG emissions are embedded in the urban water cycle and who is the final responsible of them?
  - What are the economic effects of water conservation on water and energy utilities?
  - Are there synergies for water and energy utilities to work together?
- **Objective 4:** Develop a basin-scale water model including water-related energy and GHG emissions from water operations and from end-uses, including demands from cities, agriculture, environment and the energy sector.

  - How much energy and GHG emissions are embedded in the water cycle?
  - How increased demand is affecting energy and GHG emissions from water use?
  - What are the effects of large-scale water management options in energy consumption and greenhouse gas emissions?
  - Is the energy sector a real competitor for other water uses in California?

7.3. Summary of conclusions

The research identifies several important conclusions on residential, urban and large-scale water and energy interrelationship from the management perspective. Below I summarize some thematic and methodological contributions that arise from my research.

7.2.1. Thematic contributions

- Residential water-energy nexus:

i. Outdoor water-use accounts for more than 50 percent of water-use in California but most water-related energy and GHG emissions are from shower and faucet end-uses (roughly 80% of the total).

ii. Water-related energy cost represents a third of water cost in northern cities whereas in much less representative in the south. This is partially due to large water consumption and higher water prices in southern California, but also because outside and inlet temperatures play an important role in reducing energy consumption.

iii. As aforementioned, inlet temperature plays an important role in water-related energy consumption, what open the possibility for utilities to efficiently manage water supply from different sources to reduce energy consumption in households.

iv. Heterogeneity among households in water and water-related energy and GHG emissions is significant. So selective options targeting high-use households and effective conservation policies have high potential for cost-effective water, energy and CO_2 emission savings.

v. Direct residential water-related CO_2 emissions average about 730 kg/year per household, representing 2% of per capita greenhouse gas emissions in California. This result does not include other embedded energy in water supply, conveyance, treatment, pumping or wastewater collection and treatment.

vi. When energy costs are included in the customer objective function there is an increased willingness to adopt conservation actions and savings. 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.

vii. Outdoor conservation actions have the highest potential for water conservation, but when water-related energy costs are accounted, energy-intensive appliances, such as shower and dishwasher, have a significant increase in market penetration.

- Urban water-energy nexus:

i. Most of the water-related energy and GHG emissions in the urban water cycle are from water end-uses. In East Bay Municipal Utility District (EBMUD) I found that 95% of water-related energy and 94% of the water-related GHG emissions are from end-uses of water (mainly residential water heating), whereas the rest are related with treating and pumping water and wastewater.

ii. However, in big utilities —like EBMUD— this energy is still a large economic cost that is should be analyzed in detail to assess potential economic savings.

iii. The total carbon footprint per capita of the urban water cycle in EBMUD is 405 kg CO_2/year representing 4.4% of the total GHG emissions per capita in California, demonstrating that water-related energy uses is sizable for mitigating GHG emissions.

iv. Reducing residential water use by 11% in single-family homes and 6% in multi-family homes (reduction of 6% in total water use) would reduce energy use of the water utility by 4.6%, energy utility costs by 5.8%, and GHG in the entire urban water cycle by 4.8%,

v. Given that the cost of energy is higher during the day, especially in summer, for the water utility —because TOU energy rates— and the energy utility —because hourly prices in the wholesale electric market— there is some profit for water and energy utilities from having customers change their water use patterns, even without changing total water use. By shifting some residential end-uses to off-peak hours I obtained that both water and energy utilities in the EBMUD case could reduce roughly 3% of their energy costs, becoming higher with greater proportions of electric water heaters.

- Basin-scale water-energy nexus:

i. California statewide water-related energy use modeled accounts for almost 100,000 GWh/year, being 85.3% used in cities, 3.4% in agricultural uses and

11.3% in large-conveyance infrastructure (the California aqueduct and the Colorado River Aqueduct).

ii. Most of the water-related energy is used heating water in gas-fired water heaters, but the remaining 40,639 GWh/year that are electricity-supplied still represent 13.7% of total electricity consumption in California.

iii. The carbon footprint of the entire water cycle during this period, according to our model, was 21.43 millions of tons of CO_2/year, what is roughly 5% of total GHG emissions in California for the period considered.

iv. Improvements in irrigation efficiency, assuming that traditional irrigation is done flood irrigation, save water but are much more energy-intensive, therefore already energy-stressed regions would have to assess the real consequences of taking these types of policies.

v. Increased environmental flows would leave less water available for cities and farmers thus they would increase water pumping, if water regulations let them do it. Energy-intensive water transfers could increase energy use when water is available close to the final point of use.

vi. Urban water conservation could reduce shortages for farmers that would decrease aquifer overdrafting because reduced water pumping, and at the same time would save a lot of water-related energy because urban users are the most energy-intensive water users.

7.2.2. Methodological contributions

Along this dissertation I have developed several models and analysis approaches that provide methodological contributions to the literature on the water-energy nexus, but also on the traditional water resources systems management.

In Chapter 2, I developed a framework to model heterogeneous and geographically variable residential water end-uses, water-related energy consumption and greenhouse emissions while accounting for water and water-related costs to customers. The model was developed by using a deductive approach used before in the water arena (Cahill, Lund, DeOreo, & Medellin-Azuara, 2013; Rosenberg, Tarawneh, Abdel-Khaleq, & Lund, 2007), now accounting for energy consumption.

In Chapter 3 a stochastic optimization model with recourse that provides the minimum expected annual cost accounting for long- and short-term conservation actions and stochastic variability in water and energy prices and availability was developed. This model explores the behavior of customers analyzing the maximum potential of water and energy conservation accounting for current technology, behavior and location. A very interesting application of this model is that it is capable of obtaining water and energy own- and cross-price elasticities of customers facing variable water and energy prices. From there I was able to obtain water demand functions accounting for water price shocks.

Chapter 4 presented a water-energy model at an hourly time step to estimate water-related energy and GHG emissions from different water end-users and from different stages of the urban water cycle including water treatment, water pumping and wastewater treatment. I know from no other previous study that have developed a model to couple water end-uses, accounting especially for residential end-use, and water supply energy consumption, including electric cost variability of the energy utility. With this model I was able to simulate different scenarios for demand side management actions, being especially significant for its novelty the analysis of potential benefits for the water and energy utilities from demand response policies.

Finally in Chapter 6 I applied most of the results obtained previously to build a decision support system to deal with large-scale water resource management accounting for water-related energy use and GHG emissions, and water-dependent energy facilities. Besides the novelty in including water-related energy use for each of the water demands, I have included to features that are different from previous models. First is the linkage existent between the surface water network model with a two-dimensional groundwater model, that explicitly accounts for variability groundwater elevation —that is one of the main drivers of water-related energy consumption—. The second feature is the integrated economic optimization module that works when a shortage occurs: because the model includes all different water end-uses with their target demands and elasticities, the module minimizes the scarcity cost allocating the water with an economic argument, obtaining from there returning flows as well.

7.4. Accomplishment of objectives

As it has been stated, the objective of this dissertation was to develop a basin-scale hydroeconomic model for water management including the water balance and the water-related energy dependency in the entire water cycle, but using a bottom-up approach that let us deepen in the different research questions that arise in each of the levels of the water-energy interrelationship.

I have described and applied in California a basin-scale water-energy model, but at the same time, by following this type of approach, I have been able to explore in different scales —residential, urban, and basin or regional scale— different policy and management questions that go beyond the simple quantification of the water-energy relation. Some examples are: at the residential scale I have demonstrated that there is a potential increase in success for those water conservation campaigns that include energy savings from water use; at the urban scale managing water use to avoid energy use at peak hours could result in benefits for water and energy utilities; and at the basin-scale that the modernization of irrigation technologies have the downside of increasing water-related energy and GHG emissions.

Furthermore, the research questions that I posed in the Introduction have been answered along the development of the dissertation, and have been included in the summary of the conclusions presented above.

Therefore I think that I can positively say that I achieved the objectives that I stated in the introduction, although some other research questions have arisen from the research conducted.

7.5. Further research

Along the development of the dissertation I have answered several research questions that were research gaps before. At the same time I have opened new doors that had many other research gaps behind them and this is really exciting, because sometimes the success of a research can be measured by how many new questions are being asked rather that how many questions were answered.

In the residential water and energy use I realize that there is an important gap to understand how customers behave and which are the incentives needed to change people's behavior. To achieve that goal more data is needed, because usually water end-use data is scarce, but also more research about environmental psychology linked with basic concepts of microeconomics to understand personal involvement, habit formation or the role of social norms on water and energy consumption (Gregory & Di Leo, 2003).

The residential optimization model gave us the opportunity to develop an economic-based model that was capable to obtain water and energy own- and cross-price elasticities without use traditional econometric models. Our results were much lower than those in the literature, and I think that this discrepancy was related to the lack of data on the behavioral models that I used. Although this inconsistency I think that the development of this deductive approach to measure the price elasticity should be further explored.

Other research gap that I have identified during the development of this dissertation is the very few studies about the water and energy relationship on commercial, industrial and administrative end-uses. Clearly the focus started on urban and agricultural end-uses, but these other uses are also really important, even more when the water they use and the wastewater they produce, have a significant amount of energy embedded in it.

Besides the aforementioned point, in the urban water cycle, and after showing in Chapter 4 that there are potential benefits for water and energy utilities to work together, the focus would try to figure out how the policies have to be addressed to engage the utilities to do it. Furthermore a deep economic analysis on the consequences of water and energy conservation on the financial stability of the utilities is needed, to understand who will finally burden the costs of the environmental policies that are trying to reduce natural resource consumption and GHG emissions.

Although the agricultural water-energy relationship has been implicitly assessed in Chapter 5, I have focused most of our research on the urban side of the water-energy nexus. More research on the agricultural side of the nexus is needed to include all the tradeoffs between water use and energy consumption of different irrigation technologies that I only accounted with many simplifications. Other point that could be interesting to analyze is the economic productivity of different crops accounting for their total water and energy use at the basin or regional scale.

Finally, the water-energy model at the basin scale is nothing else than a first step to a further development for what I want to be a user-friendly decision support system that would be able to be applied in any water and energy system. Therefore, I know that the values that I stated by default in the model based on literature research does not have the generality to be used in the way that I did it, thus more research in each area is needed. Furthermore, the surface and groundwater models are first development versions. The surface model has to be improved with better algorithms to simulate and also optimize the best option for the system —not only for releases from reservoirs—, whereas what I called groundwater model will be in a further development part of a spatially distributed hydrological model that will include all the hydrological processes and that will be better linked to the surface model.

7.6. References

Cahill, R., Lund, J. R., DeOreo, B., & Medellin-Azuara, J. (2013). Household water use and conservation models using Monte Carlo techniques. *Hydrology and Earth System Sciences, 17*(10), 3957-3967. doi: DOI 10.5194/hess-17-3957-2013

Gregory, G. D., & Di Leo, M. (2003). Repeated behavior and environmental psychology: The role of personal involvement and habit formation in explaining water consumption. *Journal of Applied Social Psychology, 33*(6), 1261-1296. doi: DOI 10.1111/j.1559-1816.2003.tb01949.x

Rosenberg, D. E., Tarawneh, T., Abdel-Khaleq, R., & Lund, J. R. (2007). Modeling integrated water user decisions in intermittent supply systems. *Water Resources Research, 43*(7). doi: Artn W07425 Doi 10.1029/2006wr005340