Residential water use and landscape vegetation dynamics in Los Angeles

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Civil Engineering

by

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ABSTRACT OF THE DISSERTATION

Residential water use and landscape vegetation dynamics in Los Angeles

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Doctor of Philosophy in Civil Engineering

University of California, Los Angeles, 2013

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This research contributes to a better understanding of the dynamics of single-family water consumption associated with vegetation in semi-arid cities. The innovative research approach couples long-term water consumption data with remote-sensing based products, socio-demographic, land cover, landscaping and climate data analyzed with multidisciplinary techniques. Accurate water demand forecasting and long-term conservation planning are required to meet future urban water needs relying on a set of integrated sustainable resources. In the face of climate change and urbanization growth, quantifying and predicting ecosystems costs related to irrigation and benefits are important and challenging. To address these needs, the first
part of this study focuses on analyzing trends and determinants in single-family water use in Los Angeles indicating that the current water rate structure can be optimized to achieve higher water savings: Tier 2 water rates do not lead to more conservation behaviors, though they were implemented to do so. It also shows that residential landscape is primarily maintained by irrigation and is not correlated with the seasonal precipitation pattern. The analysis of the effectiveness of water restrictions during the last drought in Los Angeles confirms that there is still room for outdoor water conservation: there was no significant change in the landscape greenness during the implementation of the watering restrictions. Conservation programs focusing on efficient watering practices can lead to higher water savings while supporting healthy landscapes. Increased mandatory restrictions were more effective than voluntary restrictions during the drought period reaching a maximum of 23% water reduction in July-August 2009 in City-average single-family household water use. This suggests that outdoor water use savings may result from long-term conservation programs. This leads to the last part of this research work focusing on quantifying and predicting landscaping irrigation through the development of predictive models. The predictive regression model explores the relationship between single-family water use and vegetation greenness surplus estimated through remote-sensing vegetation indices that can be used as a predictive tool to target outdoor conservation measures. This project was integrated within a coupled socio-ecohydrological approach to address inter-disciplinary issues related to the urban landscape. It encourages the use of advanced models and remote-sensing products incorporated into policies that improve outdoor use modeling and predictions to guide future water demand management strategies under uncertain climate variability.
The dissertation of Caroline Mini is approved.

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DEDICATION PAGE

The dissertation is dedicated to my parents, Viviane and Philippe.
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Chapter 1. Introduction

1.1 Problem Statement

Population growth has led to expansive urban development that has had significant impacts on local, regional and global energy and water processes. Global population is estimated to increase by 50%, representing an additional three billion people by 2050 (NSF press release). Around 70% of the Earth’s population is expected to live in urban areas in 2050 compared to 50% today (U.N., 2008). This dramatic growth, combined with an urban-rural migration, introduces more difficulties in reaching Millenium Development Goals (World Health Organization, 2010) on water and sanitation access. This rapid increase, leading to unprecedented urbanization, has occurred mostly in semi-arid and arid regions (Jenerette and Larsen, 2006) that are more vulnerable to water stress and altered at a faster rate than previously experienced. Ecosystem services derived from water and vegetation support human well-being, including economic productivity, environmental air quality, stormwater mitigation (Millennium Assessment 2005; Costanza et al. 1998), pollution remediation, food production, recreation, aesthetic value, and sustaining wildlife living habitat. Urban forests also provide private benefits such as decreasing energy consumption through mitigation of the urban heat island (Jenerette et al. 2007, Gober et al. 2010). Ecosystem processes in complex urbanized systems are difficult to evaluate, and the magnitude, patterns, and processes of related services are poorly understood (Baker et al. 2009a). Their management may have costs and “disservices” that cause other environmental issues or unanticipated socioeconomic impacts (Lyytimäki et al 2008, Pincetl, 2010). Irrigation taps in scarce water resources and irrigation runoff may contribute to water pollution. The plantation of non-native vegetation in many arid and semi-arid cities results in water demand increases due to excess irrigation (Endter-Wada et al. 2008). Planting tree
programs are developed in cities to create more sustainable urban environment. However, making these decisions requires a thorough accounting of benefits and costs. Population growth coupled with climate change raises new issues relative to water management and water consumption associated with vegetation. This implies finding trade-offs between ecosystem services and disservices associated with water and vegetation. Understanding and quantifying the benefits and associated costs of the maintenance of urban forests is required to produce a comprehensive understanding of these interactions.

In urban areas, residential water consumption includes both domestic household needs and outdoor usage for landscaping irrigation, pools, yet accurate partitioning of each of these uses is rare in most environments (Wentz and Gober 2007, Xie 2009). Irrigation subsidies are associated with large costs, which are likely to be exacerbated due to global warming (Jenerette et al. 2006a) and they also depend on socio-economic, housing characteristics, climate variables and urbanization patterns. In semi-arid cities, residential outdoor water use can represent as much as 74% of total residential water consumption in Phoenix (Mayer and DeOreo, 1999). Los Angeles residential outdoor water use estimates vary between 40% to 70% (LADWP, 2010). Thus, a major part of urban water consumption is sensitive to variations in climate and outdoor usage constitutes a huge potential for water conservation and efficiency through targeted landscaping and irrigation practices (Gleick et al, 2003).

We hypothesize that a better understanding of urban water use dynamics and modelling of outdoor water use including remote-sensing will provide tools to identify targets for water conservation strategies in regions where these processes provide critical services to achieve higher water savings efficiently. Directly linking ecosystem services with the potential costs associated with irrigation and evaporative flux is also an integral step toward the promotion of more environmentally related
decision-making processes. Improved spatial and temporal landscaping irrigation estimates will also provide more accurate urban water budget estimates related to specific urban development patterns under climate variability. This research contributes significantly to improved regional hydrologic models for identifying outcomes of increasing population, future climate change and related water supply issues.

1.2 Research Objectives and Research Questions

The overarching goal of the current project is to understand residential water use dynamics, quantify landscaping irrigation use and develop outdoor water use models to better understand and predict water consumption behaviors associated with the urban forest in highly urbanized and semi-arid cities.

This research work provides an understanding of the trends and determinants in single-family water consumption in the City of Los Angeles over 10 years (from 2000 to 2010) to guide future targeted conservation measures. To this end, it compiles and analyzes a wide range of variables including socio-demographic, economic, housing, land cover, pricing and remote-sensing data explaining the variability in water use. It evaluates the impact of previous voluntary and mandatory restrictions on reducing water use to inform water managers of the effectiveness of these measures to reach the conservation goals and reduce reliability on imported water. This study also evaluates and compares landscaping irrigation using current existing methods and it includes the development of a predictive model based on remote-sensing vegetation products.
The primary science questions addressed in this research are:

• What are the patterns and key drivers in residential water use in Los Angeles over 10 years and how do they contribute to inform future water policies? What are the targeted neighborhoods for future conservation measures?
• What are the commonly-used methods to quantify outdoor water use and how do they perform in semi-arid cities such as Los Angeles?
• Does the use of remote-sensing of vegetation products provide improved estimates of landscaping irrigation over Los Angeles and can it be used as a predictive model?
• What are the impacts of water restrictions on residential water use during drought periods and are they effective?

1.3 Research approach and organization of dissertation

To address the science questions and understand the residential water use dynamics related to the residential landscape in semi-arid cities, the following research framework is proposed:

- Overview of Los Angeles water demand, water rates, policies and conservation programs implemented to identify future challenges and needs addressed by the current research work,
- Analysis of trends and determinants in single-family residential water use in Los Angeles,
- Quantification of outdoor water use and modeling landscaping irrigation through the use of remote-sensing data across Los Angeles,
- Evaluation of the effectiveness of water restrictions measures in response to drought conditions.

The dissertation covers background on residential water use in Los Angeles, water management and policies as well as conservation strategies. It includes the importance of understanding and modeling water use dynamics to face water supply challenges related to climate change and rapid urbanization growth. Results are also discussed to provide policy recommendations on future conservation programs and incentives. Finally, the last section presents the key contributions dedicated to water agency and possible continuation of work on investigating landscaping outdoor water use patterns and potential savings.
Chapter 2. Overview of Los Angeles water use system

This chapter introduces the water sources and water demand system managed by the Los Angeles Department of Water and Power (LADWP), which supplies water to the City of Los Angeles. It also describes the structure of the residential water rates, the various water conservation programs implemented since 1980s as well as the water demand forecast over Los Angeles. Most information and background are given for single-family residential customers as they are the focus of this dissertation.

2.1 Description of the study area

The City of Los Angeles benefits from a Mediterranean climate and has a population equal to approximately 3.8 million people with an expected 0.4% annual growth rate (U.S. Census Bureau, 2008, 2010). The City is subdivided in 114 neighborhoods that are relatively homogeneous in terms of demographic and socioeconomic factors (Los Angeles Times, Mapping L.A. website). The vegetation of the Los Angeles basin is composed of extensive coastal sage scrub and chaparral at low elevations, oak woodland and conifer forests at high elevations, and deserts. However, the urban landscape is strongly influenced by human activities resulting in significant modifications of ecosystem processes and services. The city receives around 15 inches (381 mm) of rainfall per year, with ENSO phenomenon driving seasonal climate variations (NOAA, 2008).

Residential water use was obtained from LADWP, a municipally-owned utility which is separated into a Water division and a Power division. LADWP is also a proprietary agency and its revenues come form the rate-payers. During the last 2007-2010 drought period, the agency implemented water conservation measures using higher tiered pricing, decreased first Tier block
water volume allotment and watering restrictions. The new rate structure proposed by LADWP consists of a reduced first Tier water allotment and increased second Tier rates to promote further conservation. The additional revenues will also serve to maintain the infrastructure and promote conservation programs such as recycled water (LADWP, 2013; Blanco et al., 2012). One of the opportunities of this research project is to demonstrate the feasible implementation of sustainable water saving strategies based not only on pricing, but integrating relevant variables that affect total and outdoor water consumption.

2.2 Water supply

Los Angeles depends primarily on three water sources:

- Water from the Owens Valley/Mono Lake through the Los Angeles Aqueduct managed by the Los Angeles Department of Water and Power (LADWP),
- Water from the Colorado River managed by the Metropolitan Water District (MWD), and
- Water from northern California delivered through the State Water Project managed by the State Department of Water Resources and MWD.

Over a five-year period (Fiscal Year 2005-2006 (FY 05/06) to FY 09/10), the distribution of the Los Angeles City water supply system shows that 52% of the water supply in the City was imported from the Metropolitan Water District (MWD), 36% was from the Los Angeles Aqueduct, 11% was from local groundwater sources, and less than 1% was from recycled water (LADWP, 2010). Around 90% of Los Angeles water supply is snowpack dependent and thus more vulnerable to climate change impacts. Three severe droughts impacted LA water supply sources: 1976-1977, 1987-1992, and 2007-2010. Thus, decreasing snowpack reduces fresh available water resources and during drought years, the water supply system is more dependent
on MWD imported water. Price of imported water is expected to rise as water resources are becoming scarce. During wet years, local water resources (recycling, groundwater) represent a higher percentage in water supply compared to drought years during which reliance on MWD imported water is exacerbated. Figure 1 shows the water supply sources from 1980 to 2010.

Figure 1: LADWP Historical water supply sources, with drought periods (in red) (2010 LADWP Urban Water Management Plan)

The main strategic goals stated by LADWP are:

- Increasing the use of alternative water sources (local groundwater, recycled water, etc.),
- Reducing water demand by implementing water conservation measures to improve water supply reliability,
- Decreasing reliance on imported water.
To become independent of increasingly unreliable imported water, LADWP has made a significant transition toward the development and remediation of local water resources (Hughes and Pincetl, 2011). It includes more investment in groundwater remediation and use of recycled water.

This research project contributes to these priority goals by providing a comprehensive assessment of residential water use patterns and determinants in the City of Los Angeles and through the development of a residential outdoor water use model to explain spatial and temporal variability. The results advance solutions to model City’s outdoor use patterns and it provides a basis to implement future targeted conservation incentives.

2.3 Water demand

LADWP water demand is divided into six categories: single-family residential, multifamily residential, commercial, industrial, government and non-revenue water. Total water use increased according to the annual population growth rate until 1990. LADWP began to implement mandatory restrictions and conservation programs from 1991 in response to the dramatic drought that occurred from 1987 to 1992. Economic recession and water supply shortage restrictions caused total water use to significantly drop in 1991 and 2009. Water conservation programs were also promoted through the installation of water-saving devices. All these efforts resulted in decreasing water use back to water demand level as it was in the 1980s despite an additional 1.1 million inhabitants in the City of Los Angeles in 2010 (Figure 2). Based on 25-year average calculations, single-family and multifamily residential water uses are the largest water-consuming billing categories compared to the other billing categories, representing respectively 36% and 29% of total water demand in LADWP’s service area and the residential
category contributes to 70% of the water agency revenues (LADWP, 2010; Blanco et al., 2012). Single-family residential housing area is 41% of the land uses in the City of Los Angeles and is expected to increase by 12% by 2035. Single-family accounts represent 70% of LADWP service area total number of accounts and makes up 38% of water deliveries, being the largest water delivery category (Blanco et al., 2012). Initial outdoor use calculations by LADWP show that 54% of single-family water use and 32% of multi-family water use is for outdoor purpose. These estimates are based on three methods: one method consists of using wastewater flows to estimate indoor use, the second method identifies the minimum month use to derive indoor use and outdoor use is calculated as the difference from total water use in both methods. The last method consists of calculating landscape irrigation needs based on the California Model Water Efficient Landscape Ordinance and local evapotranspiration estimates. This research work aims at evaluating and refining these estimates using remote-sensing model.

Figure 2: Los Angeles water use and demographics with drought periods (in red) (2010 LADWP Urban Water Management Plan)
2.4 Residential Water rates

In 1993, a Blue Ribbon Committee was appointed to implement a new water rate structure to encourage more responsible and efficient water use. An increasing block rate structure was applied with a lower first tier rate corresponding to a specified water allotment and a second higher tier rate for every additional billing unit (748 gallons) above the previous amount. For the single-family residential customer category, the first tier residential allotment was calculated based on lot size, climate zone or temperature zone and household size (6 persons or less). A household size with 7 persons or more is attributed a higher water allotment. The second tier rate represents the marginal cost of the additional amount of water required to meet the demand. Customers receive bimonthly bills. Water rates are proportional to the amount of water consumed and there are no fixed charges. Water charges are added to Tier 1 and Tier 2 base rates to account for water procurement adjustment, water quality, water revenue adjustment, water security, Owens Valley regulatory, and low-income subsidy charges. These additional charges are adjusted every quarter, except for the water revenue adjustment reviewed every year. As of May 2013, the Tier 1 rate is equal to $4.049/HCF and the Tier 2 rate to $5.823. This direct relationship promotes customer conservation practices to reduce the billing cost while decreasing revenues to the water agency to maintain water supply infrastructures. In June 2009, shortage year water rates were implemented: the first tier water allotment was reduced by 15% for all types of customers and Tier 2 rate was equal to the high season rate increased by 1.442 times to promote conservation and water use efficiency while providing the revenue to maintain the water use infrastructure (LADWP, 2010). Water rates are set differently for single-dwelling unit residential, multiple-dwelling unit residential and for commercial, industrial and governmental customers. Multiple-dwelling units are multiple units served by one meter.
The rate structure for the following fiscal years includes a higher Tier 2 rate and reduced Tier 1 water allotment to encourage conservation through pricing and providing revenues including maintaining and replacing the aging infrastructure and in recycled water, conservation and local water supply remediation programs (LADWP, 2013). LADWP claims its rate structure to be unique as it accounts for factors influencing residential water use such as the lot size in Tier water allotment for single-family customers. Customers having a larger lot size have a greater Tier 1 water allotment (Blanco et al., 2012). However, conservation could also be promoted by encouraging customers with larger lots to use water more efficiently by decreasing their water allotment.

2.5 Water conservation

Since the 1980s, conservation programs and measures have been undertaken by LADWP to decrease water demand and to improve water supply reliability. Customers saw the implementation of mandatory water rationing during the 1976-1977 drought and 1990-1991 period and more water-saving practices and devices were promoted during the 1987-1992 drought period. LADWP conservation strategy encompasses higher tiered pricing, mandatory outdoor watering restrictions, ordinances, public awareness programs and rebates/incentives on water-efficient devices. Voluntary conservation programs were developed to enable the installation of water-saving devices and the promotion of water-saving habits. To face the last water supply shortage from 2007 to 2009, mandatory outdoor watering restrictions were enacted as well as reduction in the Tier 1 water allotment by 15% and an increase in Tier 2 water rate. These conservation efforts led to a decrease in the amount of imported water purchased from
MWD, whose amount was 23% below the baseline allocations for the 2009/2010 fiscal year (LADWP, 2010).

Plumbing fixtures were first regulated to increase water efficiency through city ordinance. In 1988, the plumbing retrofit ordinance required the installation of water-efficient devices for residential and commercial customers and was amended in 1998 to implement more stringent regulations for ultra-low flow water-saving devices in residential properties prior to the close of escrow (LADWP, 2010). In addition, the Water Efficiency Requirements Ordinance was adopted in 2009 requiring the installation of high water-efficiency devices in new and renovated residential and commercial buildings (Table 1).

Reduction in outdoor usage was achieved through two main ordinances. The Emergency Water Conservation Plan Ordinance was enacted in 1990 and recently amended to include five conservation phases. During the recent water shortage period, Phase III of the restrictions was implemented in June 2009 (two-day watering per week) and Phase II in August 2010 (three-day watering per week). The main actions embedded in the outdoor restriction plan includes the use of spray head, bubblers, standard rotors and multi-stream rotary heads for a restricted time only, watering allowed only during designated days, landscaping irrigation prohibited between 9am and 4pm, no irrigation during rain, no excess irrigation flow on the streets, washing vehicles prohibited with a hose, obligation to fix leaks in a timely manner. The State Water Conservation in Landscaping Act of 2006 linked with the city landscape ordinance (1996) amended in 2009 promotes outdoor water use efficiency with the use of water budget for landscaping, decrease in runoff, increase in irrigation system efficiency and the use of low water-intensive plants.
Table 1: Conservation measures implemented

<table>
<thead>
<tr>
<th>LADWP Residential conservation measures/programs</th>
<th>Year in service</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULF Toilet Rebate program</td>
<td>1990</td>
</tr>
<tr>
<td>ULF Toilet Distribution program</td>
<td>1992</td>
</tr>
<tr>
<td>Addition of faucet aerators, showerheads</td>
<td></td>
</tr>
<tr>
<td>High Efficiency Washer Rebate program</td>
<td>1998</td>
</tr>
<tr>
<td>Partnership with CBOs for toilet installation</td>
<td>1993?-Until 2006</td>
</tr>
<tr>
<td>SoCal Water $mart program (rebates)* with MWD</td>
<td>2008</td>
</tr>
<tr>
<td>Rebates for high efficiency toilets</td>
<td>On-going</td>
</tr>
<tr>
<td>Sprinklerhead rotating nozzle retrofit rebates*</td>
<td>2008</td>
</tr>
<tr>
<td>Weather-based irrigation controller rebates*</td>
<td>2008</td>
</tr>
<tr>
<td>Turf removal program* (incentives)</td>
<td>2008</td>
</tr>
</tbody>
</table>

Water conservation goals were set to keep on-going conservation efforts and mitigate water demand as a result of population growth while increasing water supply reliability. LADWP set an additional 50,000 AFY of water saved by 2030 through the use of tiered water pricing structure, education programs, incentives/rebates and landscape irrigation efficiency programs (LADWP, 2010) (Figure 3). The State 20*2020 Act adopted in 2009 requires a 20% saving by 2020 on per capita water use from a calculated baseline. The baseline is a five-year average daily per capita water use equal to 145 gallons per capita per day (gpcd). The water use targets set by LADWP are 145 gpcd by 2015 and 138 gpcd by 2020.
Figure 3: Annual total water savings based on installation of water-saving devices and conservation behavior in homes and businesses

2.6 Water demand forecasts

Water demand forecast was developed by LADWP to project future water demand and target conservation programs. The baseline was calculated using 2005-2008 average water use divided by a demographic driver, which is the number of homes or employees, depending on the customer category. The 2005-2008 period was chosen as it corresponds to normal weather conditions without watering restrictions. Then, socioeconomic variables were taken into account and their influence on water use referred to as elasticity for price, income and family size. The benefits of conservation measures were also included due to mandatory restrictions, education awareness and mandated efficiencies related to the adoption of plumbing codes and ordinances.
Historical weather variability was investigated to analyze impacts of economy and drought conditions on water demand (LADWP, 2010). Annual weather adjustment factors were considered in the model to explain the range in forecasted water demand. The results show a 31% increase in single-family water use and a 33% increase in multi-family water use from 2010 to 2035 under passive water conservation. This percentage increase is lower under passive and active water conservation measures: 26% increase in single-family water use and 31% increase on multi-family water use over 2010-2035, showing a greater increase in multi-family water demand.

### 2.7 Summary of research needs

This first chapter provides an overview of LADWP water supply system and water demand in the City of Los Angeles. It highlights three main challenges and needs addressed in this research work:

Single-family customer category makes up the largest portion in terms of land use, revenues and water deliveries (38%) relative to the other customer categories. Hence, a better understanding of the trends and drivers of the single-family customers is needed to improve water demand forecast and find levers to trigger higher water savings.

To reduce dependency on imported water and achieve conservation goals, permanent water conservation measures are required. The 20% goal in water savings should not be difficult to reach in LADWP service area compared to the other agencies but strong water conservation policy is required to become water independent. The use of recycled water and local groundwater will not provide enough water supply to meet current water demand. Residential indoor use savings were the first programs implemented and more water savings can be achieved
in outdoor irrigation. Evaluating the effectiveness of past water restrictions and a better understanding of landscaping outdoor water budget are needed to plan further targeted water reductions.

LADWP proposed an increase in water rates and decrease in Tier water allotment for the next fiscal years as this pricing strategy was proven to be efficient in reducing water use during the last drought periods. A better understanding of the impact of the rate structure on customer water use is required. Rising water rates also brings equity issues that need to be investigated. For single-family customers, Tier 1 water allotment is determined based on several factors including lot size: a larger lot size corresponds to a larger water allotment (Blanco et al., 2012). Hence, reducing water allotment would allow water savings for targeted customers and alternative conservation measures can be implemented that are not based on pricing.
2.8 References


3.1 Introduction

The extent of water stress is increasing across large areas of the southwestern U.S. (Fawcett et al., 2011). California, the most populous state in the U.S., is expected to experience drier conditions and increasing periods of drought in the coming decades (NRDC, 2011; Seager et al., 2007; Seager and Vecchi, 2010; Overpeck and Udall, 2010; Cayan et al., 2010). Water supply shortages and shortfalls in water deliveries are also likely to occur from the Colorado River Basin, a system that supplies water to seven western states, due to predictions of a warmer and drier climate (Christensen et al., 2007; McCabe et al., 2007; Barnett et al., 2009). Municipal water use, including residential consumption, represents a lower percentage (15%) of water use in the Colorado Basin compared to agriculture, which consumes over 70% of Colorado water supplies (Reese, 2011). However, urban water consumption is growing at a faster rate than other uses in the Basin, increasing stress on overall water supplies for the region (Reese, 2011). Water management systems are divided into numerous separate entities, introducing significant challenges in understanding the complex management and flow of urban water budgets in the western U.S. (Pataki et al., 2011). In the face of climate change and increasing urbanization, quantifying and predicting urban water use is a critical step toward improved planning and management of water resources, especially in regions with significant dependency on remote water sources vulnerable to climate change impacts (Jenerette and Larsen, 2006; LADWP, 2010; Pataki et al., 2011).

Utilities such as the Los Angeles Department of Water and Power are implementing policies to reduce residential water demand through price increases, promoting indoor water-
saving devices and conservation behaviors by imposing residential irrigation restrictions (LADWP, 2010). As a result of the implemented conservation policies over the last decade, Los Angeles had the lowest water consumption per capita per day among cities over 1 million people in the U.S. in 2011 (LADWP, 2011). In the face of climate change and increasing urbanization growth, understanding and predicting urban residential water use dynamics is critical to improve future planning and management of water resources, especially in regions with significant dependency on remote water sources vulnerable to climate change impacts (Jenerette and Larsen, 2006; LADWP, 2010; Pataki et al., 2011). Further conservation strategies in Los Angeles, as in many other large cities, are including sustainable “local” supplies to cope with climate extremes and reduce acute water loss (LADWP, 2012). These efforts can be improved and better targeted with rigorous and comprehensive investigation of residential water consumption patterns and key determinants driving water use at the neighborhood scale.

Residential water consumption has been related to a range of socio-economic, structural housing, climate, and water pricing variables, typically integrated with statistical regression techniques at the household or neighborhood scale (Worthington and Hoffman, 2008). Income is generally shown to have a positive and significant impact on residential water consumption (Arbués et al., 2003; Harlan et al., 2009; Guhathakurta and Gober, 2007). Household size is also significant in explaining variability in water use particularly indoor use and is generally negatively correlated with water use per capita (Domene and Sauri, 2006; Schleich and Hillebrand, 2009; Wentz and Gober, 2007). Studies have also shown the importance of housing structural characteristics on water consumption; lot size, garden size, building size, building age contribute significantly to variability in total water use (Domene and Sauri, 2006; Wentz and
Gober, 2007; Balling et al., 2008), with higher-density urban complexes associated with lower water demand (Balling et al., 2008). Climate variables have been coupled with socio-economic and structural variables to explain residential water demand. Balling et al. (2008) investigated the climate sensitivity of residential water use per census tract in Phoenix and demonstrated that tracts with large lots, higher percentages of pools, large areas of irrigated, non-native landscaping and higher income levels showed the greatest sensitivity to climate. When only climate variables were evaluated, higher temperatures, lower precipitation and drought conditions were statistically significant and positively correlated with annual residential water use in Phoenix and Tucson, Arizona (Balling and Gober, 2007). Finally, water pricing is generally incorporated in water demand models to evaluate the impact of factors controlled by utilities on water consumption (Worthington and Hoffman, 2008; Arbués et al., 2003; Schleich and Hillenbrand, 2009; Hoffmann et al., 2006; Kenney et al., 2008). Water pricing can be represented as the marginal price or average price and studies show that the choice of what price actually influences consumer behavior is still controversial (Arbués et al., 2003).

Importantly, factors related to landscape type and land use should also be integrated in water demand models as they exert significant influence on outdoor use. Garden characteristics and irrigated landscape areas have been included in some models at the household level when surveys and observations were conducted to provide the necessary data (Harlan et al., 2009; Domene et al., 2005). At the neighborhood or block level, studies have used available property lot and building size information (House-Peters et al., 2010). However, very few studies have utilized remote-sensing vegetation and landcover products to evaluate landscape type and irrigated areas in urban regions. Wentz and Gober (2007) retrieved the percentage of land area in residential mesic landscaping over Phoenix using an existing 1998 Landsat TM land cover
classification database. Guhathakurta and Gober (2007) used Landsat Normalized Differential Vegetation Index (NDVI) and other remote sensing information to estimate vegetation type, land cover and residential irrigated landscape areas.

The goal of the current study is to understand residential water use trends and the roles of socio-economic, climate, tree/grass cover, vegetation greenness and pricing variables on single-family residential (SFR) water consumption in a large, semi-arid metropolis that is heavily dependent on imported water. Our work is unique in that we combine a range of previously studied variables into a single integrated model, covering ten years of residential water consumption data at the census tract level for the entire city of Los Angeles over 1000 km$^2$. We also integrate satellite-based land cover and greenness indices in our assessment and models. Los Angeles is the second largest city in the United States and has been characterized as profligate in its water use, relying heavily on external sources, including the Colorado River, northern California and the eastern Sierra Nevada. Studying water use patterns in this unique and diverse system may yield important insights for other southwest cities potentially facing water stress and evaluating current water conservation policies. Our approach is based on an interdisciplinary and collaborative research team consisting of ecologists, geographers, social scientists and hydrologists to analyze determinants of single-family indoor and outdoor water use.

3.2 Study Area

The City of Los Angeles has a population of approximately 3.8 million (U.S. Census Bureau, 2010) and an areal extent of 1300 km$^2$. The City contains 114 neighborhoods with
distinct demographic and socioeconomic characteristics (Los Angeles Times, 2010) (Figure 4). Los Angeles has a Mediterranean climate, receiving an average 381 mm of rainfall per year (downtown) and having an annual average temperature of 19°C (NOAA, National Weather Service Forecast Office, 2012). There are significant gradients in temperature and precipitation from the coast to inland valleys. Native vegetation is composed of coastal sage scrub and chaparral shrublands, at low elevations, and oak woodland and conifer forests at high elevations (Miller, 2008). However, the urban landscape has been significantly altered by human activity and urbanization, resulting in extensive non-native species and landscapes (Pouyat et al., 2007).

Figure 4: Map of study domain with zip codes, boundary of the City of Los Angeles (thick grey line) and park areas (dotted areas). The selected study neighborhoods are also outlined on the map (black lines).
Los Angeles depends primarily on three water sources: 1) Owens Valley/Mono Lake Los Angeles aqueduct managed by the Los Angeles Department of Water and Power (LADWP), 2) Colorado River, and 3) Northern California water delivered through the State Water Project managed by the State Department of Water Resources. Water delivery across the City is managed by LADWP, a municipally-owned utility that is divided into separate water and power divisions, with revenues generated from the rate-payers. Over a five-year period (Fiscal Year 2005-2006 (FY2006) to FY2010), 52% of the water supply in the City was imported from the Metropolitan Water District (MWD), 36% was from the Los Angeles Aqueduct (its own independent source from the Owens Valley in California), 11% was from local groundwater sources, and less than 1% was from recycled water (LADWP, 2010). Approximately 90% of the City’s water supply is snowpack dependent. During wet years, local water resources (local groundwater and recycled water) and the Los Angeles aqueduct (eastern Sierra) represent a higher percentage of the water supply, compared to drought years when reliance on imported water from the Colorado River (MWD) is increased (LADWP, 2010). In recent years, LADWP has implemented water conservation measures during drought periods (most recent drought period is 2007-2009), which include a higher tiered pricing structure and watering restrictions.

Residential water rates for LADWP were restructured in 1993 and consist of a unique and complex system to reflect the climate differences across the region and variability in lot size. This initial 1993 rate structure came about as a result of the LADWP and the City Council realizing that water rates needed revision to ensure better water conservation, as a result of previous drought periods. The decision makers at the time were acutely concerned with income
impacts, as well as impacts on the ability to maintain landscaping even in the warmer parts of the region leading to highly nuanced and complex pricing structure approach.

There is an increasing block rate structure starting with a lower first tier rate (Tier 1) corresponding to a specified water allotment, and a second higher tier rate (Tier 2) for every additional billing unit (1 Hundred Cubic Feet (HCF) or 2831.5 Liters or 748 gallons) above the previous amount for the billing cycle (LADWP, 2010). Customers receive their water billing bimonthly. The Tier 1 residential water allotment for single-family customers is calculated based on lot size and a temperature zone identified for each ZIP code. Additional volumes to the Tier 1 usage block are allocated for households with more than six persons. For example, in Pacific Palisades (lower temperature zone) the Tier 1 usage block allocation for the high season ranges from 16 HCF (45 307 L) to 55 HCF (155 743 L) per month based on residential lot size. Lot size values are divided into five categories from 0 to 43 560 square feet (4 047 m2) and above. In Downtown (medium temperature zone) the allocated Tier 1 is from 18 HCF (50 970 L) to 62 HCF (175 564 L) per month during the high season, also depending on lot size. Pacoima, in the higher temperature zone, has a Tier 1 allotment varying from 19 HCF (53 802 L) to 65 HCF (184 060 L) per month during the high season, again depending on lot size. The Tier 2 rate is said to represent the “marginal cost” of the additional amount of water required to meet the demand above Tier 1 usage block (LADWP, 2010).

Water rates are directly proportional to the amount of water consumed within each block or Tier and there are no fixed charges (generally used to maintain infrastructure). LADWP (2010) notes that this structure promotes water conservation while reducing consumption and customer bill cost. Tier 2 water base rates are defined for a low season (November through May) and high season (June through October). The Tier 1 allocated volume is also larger for single-
family customers during the high season across temperature zones and lot size groups.

Adjustments are added to the base water rates per hundred cubic foot to account for water procurement, water quality expenditures, water revenue, water supply security, the low-income subsidy and Owens Valley regulatory expenditures (LADWP, 2012). Water charges are reviewed every quarter.

3.3 Data

3.3.1 Water Consumption Data

Single-family residential (SFR) water data was provided by LADWP for the period January 1, 2000 to December 31, 2010. The initial database contained around 480,000 individual residential customers identified by census tract numbers. Less than 1% of the records (500 to 600 single-family customers) did not match the U.S. Postal Service ZIP code database and were removed. The LADWP reading period is bi-monthly (every 60 days) and the agency pro-rated the data to calculate monthly water consumption. However, some reading intervals were >60 days. In these cases, the readings were pro-rated monthly over the given period.

Monthly individual customer records were aggregated to the census tract level to protect customer privacy. The current LADWP service area includes customers residing in the City of Los Angeles and on the edge of the City boundary. However, only the census tracts contained within the City boundary were analyzed and the LADWP customer data were matched with the census residential population data in the City of Los Angeles. The final aggregated list includes 857 census tracts with monthly water data for a ten year period. Monthly water consumption data was also aggregated by fiscal year (FY) (a fiscal year is defined as the period from July 1st of the preceding year to June 30th of the current year, for example FY2010 corresponds to the fiscal
year July 1\textsuperscript{st} 2009 to June 30\textsuperscript{th} 2010) and normalized per SFR account/SFR customer for each census tract. The GIS census tract boundary layer comes from the 2000 US Census.

3.3.2 Independent Study Variables

The study was designed around variables that are available across the City and also relevant to the study area (the City of Los Angeles). We included income, household size, grass cover and Enhanced Vegetation Index (EVI) (both from satellite imagery and remote sensing platforms), total precipitation and average daily maximum temperature in our analysis. Lot size data was available but was strongly correlated to income (Pearson’s correlation equal to 0.7; significant at p<0.05) and hence not included in our study. We also evaluated marginal block rates and quantity allowance to assess the impact of pricing and tier block structures (Table 2).

\textit{Price}

Water pricing follows an increasing block rate structure with the first block width determined for each single-family customer based on lot size and temperature zone. The first block rate ranged from $1.731/HCF in January 2000 to $3.694/HCF in January 2010. The Tier 2 rate evolved from $2.330/HCF in January 2000 (low season) to $5.590/HCF in January 2010 due to the implementation of shortage year increased Tier 2 rates. We include the two block rates lagged by one billing period with the first Tier usage block allowance. Water rates were inflation-adjusted to 2000 dollars per HCF, averaged by bimonthly period and lagged by one bimonthly period as customers are billed bimonthly. Aggregating data at the census tract level did not allow us to consider individual discrete changes in marginal price. However, as census tracts have homogenous characteristics related to single-family lot size and temperature, we
assumed the first tier usage block allocation was homogenous per census tract. In addition, using
the two rates allowed the analysis of the effect of both block prices on consumption. The choice
of using Tier block price in our regression model is supported by the fact that marginal rate
information is provided on customer water bills and that there are no fixed charges, which
theoretically should improve customer response to marginal price.

Socio-demographic Variables

Socio-demographic and economic data were collected from the 2000/2010 U.S. Census
and American Community Survey (ACS) 5-year estimates (2006-2010) at the census tract level
(U.S. Census Bureau, 2010). We considered average household size (average number of persons
per household) and median household income (in 2000 dollars-inflation adjusted using the All
Items Consumer Price Index CPI-U-RS (research series) from the Bureau of Labor Statistics
(Bureau of Labor Statistics, 2012). Linear interpolation was applied to estimate average
household size and median household income between 2000 and 2010 at the census tract level
per fiscal year. Median household income was also scaled by 1000 dollars and calculated by
bimonthly period.

Landscape Area

The percentage of grass land-cover area was computed for each census tract using a land
cover database derived from high resolution satellite imagery (McPherson et al., 2011). This
database was created using Quickbird imagery and aerial photography from 2002 to 2005 at very
high spatial resolution (< 2 m pixel resolution) and identifies four primary landcover types: tree
(tree and shrub), grass (green grass and ground cover), dry grass/bare soil (dry grass and bare
soil), and impervious surface (includes pervious pavement) (McPherson et al., 2011). The percentage of grass land-cover area is the portion of grass surface within the total census tract area. We assumed that land cover was static and generally well-developed over the 10-year study period for the City.

*Vegetation*

Urban vegetation greenness was estimated using the Enhanced Vegetation Index (EVI) from NASA’s Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Product (MOD13Q1), 16-day composite data with 250-m resolution (Huete et al., 2002). The EVI is a measure of photosynthetic activity or greenness using the reflectivity and absorption by plants for specific bands (values range from 0 to 1 with higher value indicating more biomass or photosynthetic activity). The EVI data was averaged spatially for each census tract from 2000 to 2010. Cumulative EVI was computed as the sum of 16-day EVI values within each fiscal year for each census tract, providing an index of the total greenness over each period (Archibald and Scholes, 2007; Ponce Campos et al., 2013).

*Climate Data*

Precipitation and temperature climate data were collected from a network of regional stations for the study period. Daily precipitation data were collected from the Los Angeles Department of Public Works (LADPW) ALERT gauges; 47 stations with complete precipitation records were used. Daily maximum temperature data were retrieved from National Climatic Data Center (NCDC) stations from 2000 to 2010. Four stations with complete temperature records were used and four additional stations with more than nine years of data were included in the
Inverse-distance weighting was used to estimate bimonthly precipitation totals from daily precipitation values and the average daily maximum temperature values by bimonthly period at the centroid of each census tract (Table 2).

Table 2: Description of the dependent and independent variables used in the regression models to analyze determinants of residential water consumption. Variables are calculated at the census tract level for each bimonthly period within the 2000-2007 fiscal year period.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Definition</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Each variable is calculated bi-monthly for FY00-07 and for each census tract.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFR Water use</td>
<td>Single-family water use per household per bi-monthly period</td>
<td>HCF/hsl/d/bi-monthly period</td>
<td>LADWP</td>
</tr>
<tr>
<td>Average household size</td>
<td>Average number of persons per household</td>
<td>Persons /household</td>
<td>U.S. Census 2000/2010</td>
</tr>
<tr>
<td>Median household income</td>
<td>Median household income scaled by 1000 (bi-monthly)</td>
<td>Inflation-adjusted 2000-dollars/hsl</td>
<td>U.S. Census 2000 ACS 2006-2010</td>
</tr>
<tr>
<td>Grass area percentage</td>
<td>Percentage of grass landcover area (constant)</td>
<td>%</td>
<td>McPherson et al. 2011 landcover database (2002-2005)</td>
</tr>
<tr>
<td>Bi-monthly total precipitation</td>
<td>Cumulative daily precipitation</td>
<td>mm</td>
<td>LADPW gage stations</td>
</tr>
<tr>
<td>Average daily maximum temperature</td>
<td>Bi-monthly average of the daily maximum temperatures</td>
<td>°C</td>
<td>NCDC gage stations</td>
</tr>
<tr>
<td>Cumulative EVI (Enhanced Vegetation Index)</td>
<td>Sum of 16-day EVI values per bi-monthly period</td>
<td>[0-1]</td>
<td>MODIS Terra (250m, 16 days)</td>
</tr>
<tr>
<td>Marginal block prices</td>
<td>Tier 1 and Tier 2 rates per bi-monthly period (lagged by one bi-monthly period)</td>
<td>2000-dollars/HCF</td>
<td>LADWP</td>
</tr>
<tr>
<td>First tier usage block</td>
<td>Bi-monthly quantity of water allocated for the first tier averaged per household</td>
<td>HCF/hsl/d/bi-monthly period</td>
<td>LADWP</td>
</tr>
</tbody>
</table>
3.4 Methods

3.4.1 Descriptive Analysis

A descriptive analysis of the dependent variable (water consumption per SFR customers) was undertaken for twelve representative neighborhoods from July 2000 to June 2010. The twelve selected neighborhoods are generally representative of the City’s characteristics and were selected based on population, density, ethnicity, median household income, average household size, housing tenure, education level, immigration status and microclimate criteria (Figure 4; Table 3). Census tracts within each neighborhood boundary were identified and median single-family water use and average EVI were estimated for each unit.
Table 3: Key characteristics of the twelve neighborhoods used in the study from the U.S. Census (2000 & 2010).

<table>
<thead>
<tr>
<th>Neighborhood</th>
<th>Zip code</th>
<th>Population 2010</th>
<th>Percentage of white people 2010 (%)</th>
<th>Percentage of hispanic or latino origin (of any race) 2010 (%)</th>
<th>Average household size 2010</th>
<th>Number of people with a high school degree or less 2000</th>
<th>Percentage of residents foreign born 2000</th>
<th>Median household income in 1999-dollars</th>
<th>Income per capita 2000, in 1999-dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Florence (FL)</td>
<td>90003</td>
<td>66266</td>
<td>30</td>
<td>74.5</td>
<td>4.22</td>
<td>17779</td>
<td>41.3%</td>
<td>29447</td>
<td>7804</td>
</tr>
<tr>
<td>Koreatown (KR)</td>
<td>90005</td>
<td>37681</td>
<td>29.1</td>
<td>52</td>
<td>2.5</td>
<td>43861</td>
<td>68.0%</td>
<td>30558</td>
<td>12015</td>
</tr>
<tr>
<td>Leimert Park (LMP)</td>
<td>90008</td>
<td>32327</td>
<td>8.5</td>
<td>23.4</td>
<td>2.33</td>
<td>3063</td>
<td>10.7%</td>
<td>45865</td>
<td>20672</td>
</tr>
<tr>
<td>Mid-Wilshire (MDW)</td>
<td>90019</td>
<td>64458</td>
<td>30</td>
<td>46.1</td>
<td>2.7</td>
<td>8548</td>
<td>33.9%</td>
<td>58483</td>
<td>16987</td>
</tr>
<tr>
<td>Downtown (DW)</td>
<td>90021</td>
<td>3951</td>
<td>41</td>
<td>41.3</td>
<td>1.57</td>
<td>13454</td>
<td>41.8%</td>
<td>15003</td>
<td>11126</td>
</tr>
<tr>
<td>Silver Lake (SLL)</td>
<td>90039</td>
<td>28514</td>
<td>56.5</td>
<td>40.9</td>
<td>2.47</td>
<td>8869</td>
<td>41.1%</td>
<td>54339</td>
<td>25069</td>
</tr>
<tr>
<td>Playa Vista (PV)</td>
<td>90045</td>
<td>39480</td>
<td>61.1</td>
<td>18.2</td>
<td>2.37</td>
<td>752</td>
<td>31.1%</td>
<td>68597</td>
<td>28635</td>
</tr>
<tr>
<td>Pacific Palisades (PCP)</td>
<td>90272</td>
<td>22986</td>
<td>90</td>
<td>4.5</td>
<td>2.49</td>
<td>1545</td>
<td>15.5%</td>
<td>168008</td>
<td>81609</td>
</tr>
<tr>
<td>Venice (VN)</td>
<td>90291</td>
<td>28341</td>
<td>77</td>
<td>20</td>
<td>1.95</td>
<td>7215</td>
<td>22.3%</td>
<td>67647</td>
<td>34455</td>
</tr>
<tr>
<td>Pacoima (PC)</td>
<td>91331</td>
<td>103689</td>
<td>44.4</td>
<td>87.8</td>
<td>4.6</td>
<td>31699</td>
<td>47.1%</td>
<td>49066</td>
<td>10806</td>
</tr>
<tr>
<td>Reseda (RS)</td>
<td>91335</td>
<td>74363</td>
<td>53.8</td>
<td>50.6</td>
<td>3.21</td>
<td>21087</td>
<td>43.1%</td>
<td>54771</td>
<td>16899</td>
</tr>
<tr>
<td>Sherman Oaks (SHO)</td>
<td>91423</td>
<td>30991</td>
<td>80</td>
<td>12</td>
<td>2.07</td>
<td>10790</td>
<td>26.2%</td>
<td>69651</td>
<td>40797</td>
</tr>
<tr>
<td>North Hollywood (NRH)</td>
<td>91601</td>
<td>37180</td>
<td>59.2</td>
<td>43.8</td>
<td>2.32</td>
<td>27591</td>
<td>46.4%</td>
<td>42791</td>
<td>16817</td>
</tr>
</tbody>
</table>

3.4.2 Spatial Statistics

Moran’s I index and the Anselin Local Moran’s I index were calculated to evaluate spatial autocorrelation of single-family water use and average EVI across the City. The Moran’s I index indicates the degree of spatial autocorrelation for each variable and it ranges from -1 (dispersed pattern) to 1 (clustered pattern) (O’Sullivan and Unwin, 2003). The Anselin Local
Moran’s I index shows the degree of significant spatial clustering with its surrounding values for each census tract (Anselin, 1995).

3.4.3 Statistical Model

The developed regression model includes price, climate, socio-economic and landscaping variables over seven years from 2000 to 2007, prior to the implementation of residential irrigation restrictions. The model is developed to assess water use trends and the role of key explanatory variables on single-family water use before the drought period and prior to water conservation measures undertaken by LADWP from FY2008 to 2010. Hence, the impact of these restrictions is not investigated in this modeling framework. Single-family census tracts are selected to be included in the model if the ratio of aggregated single-family lot size over census tract area was above 0.5, resulting in a subset of around 160 census tracts for which single-family land use area represents more than half of census tract. The dependent variable is single-family water consumption per household and by bimonthly period (corresponding to the length of the billing period). All independent variables are computed by bimonthly period and at the census tract level (Table 2).

The model used presents a linear form with a natural logarithm on the dependent variable and on the price variables for census tract $i$ and bimonthly period $t$:

$$\ln(wateruse_{i,t}) = \beta_0 + \beta_1 \text{avghsldsize}_{i,t} + \beta_2 \text{medianhslldincome}_{i,t} + \beta_3 \text{cumEVI}_{i,t} + \beta_4 \text{percentgrass}_i + \sum_{t=1}^{T} \ln(1) \ln(2) \text{totprecip}_{i,t} + \beta_5 \text{avg max temp}_{i,t} + \beta_6 \text{usageblock}_i + \beta_7 \ln(rate1_{i,t-1}) + \beta_8 \ln(rate2_{i,t-1}) + \varepsilon_{i,t}$$  \hspace{1cm} eqn. 1

$$\varepsilon_{i,t} = a_i + u_{i,t}$$
The error term \((e_{i,t})\) is composed of the idiosyncratic error \(u_{it}\) and the unobserved effects \(a_i\) specific to each census tract and are considered time invariant (Wooldridge, 2009). Several studies previously cited use the Ordinary-Least-Squares (OLS) estimation technique to estimate the parameters in the water demand model (Agthe and Billings, 1980; Hoffmann et al., 2006). However, due to the presence of unobserved effects at the census tract level, the OLS parameter estimates are likely to be biased. Thus, a random effects approach is developed to address this issue. This is also the preferred method considering that one independent variable is assumed to remain constant over time and other variables such as income experience minimal change over time. However, factors such as income do show large variability across the census tracts that can be accounted for in the random effects approach. Omitted factors specific to each census tract included demographic characteristics (age of householder), irrigable land area, and other structural (building age) and demographic variables. The expression of the error term into two components allows us to consider the unobserved census tract-level effects.

3.4.4 Disaggregation of Water Use Customers

Two categorical scenarios were developed to allow for a detailed analysis of the key explanatory variables, including price, on a range of water users across the City. Disaggregating the SFR water use dataset by water use and income level helps to better evaluate the impact that parameters, such as water pricing, have on different customer categories. *Scenario One* disaggregates data into low, medium and high water use tracts based on the annual average single-family water use for each census tract for the study period (similar to Kenney et al. (2008)). The 25\(^{th}\) quartile, 75\(^{th}\) quartile values were determined in order to divide the users into the three groups.
Scenario Two disaggregates data into two groups based on the annual average median household income from 2000 to 2007: above the median value (high income) and below the median value (low income). We also tested the interaction of parameter coefficients by introducing dummy variables (to test if the estimated coefficients were significantly different) between low, medium and high water users, and between low and high income customers.

3.5 Results

3.5.1 Sociodemographics

As expected, there is extensive variability in sociodemographic characteristics across Los Angeles. Downtown neighborhoods have denser population characteristics (average household size varies from 2 to 4 persons per household) and a relatively higher percentage of Hispanic or Latino residents. Income per capita ranges from around $8,000 to around $20,000 (available from the U.S. Census Bureau 2000 at http://factfinder2.census.gov/, in 1999-dollars). Downtown neighborhoods also have less (irrigated) residential green space. Alternatively, coastal neighborhoods generally have higher education levels correlated to higher income levels, reaching around $80,000 per capita (available from the U.S. Census Bureau 2000 at http://factfinder2.census.gov/, in 1999-dollars) and have a higher percentage of White residents. Average household size for these more affluent neighborhoods is around 2-2.5 persons per household. Neighborhoods in the northern part of the City, including Reseda, Pacoima and North Hollywood, have similar median household incomes to one another and much warmer climates. However, Sherman Oaks has higher income levels (~$40,000) when compared to Reseda, Pacoima and North Hollywood (~$15,000) (1999-dollars). Average household size varies from 2 to 4.6 persons per household across the four neighborhoods. Sherman Oaks has a higher
percentage of White residents; Reseda, Pacoima and North Hollywood are mainly populated by Hispanic or Latino residents.

3.5.2 Water Use

Total water use across the City increased slightly relative to the annual growth rate of population from 1980 to 1990 (Figure 5). City population and water consumption increased by 1.7% annually during that period (LADWP, 2010). In 1991 LADWP began to implement temporary mandatory restrictions and conservation programs in response to a significant drought that occurred from 1987 to 1992. Water conservation programs were promoted primarily through the installation of indoor water-saving devices. The economic recession and water supply shortage restrictions contributed to a drop in total water use in 1992 and in 2010 (LADWP, 2010). More recent efforts resulted in water use levels in FY2010 being similar to water demand in FY1994, despite an additional 1.1 million inhabitants in the City of Los Angeles (Figure 5) (LADWP, 2010). To address the most recent drought (2007 to 2009), voluntary (June 2007), mandatory water waste provisions (August 2008) and increased mandatory (June 2009) outdoor irrigation restrictions of two days per week were enacted across the City. A mandatory 15% reduction in the Tier 1 block allocation as well as an increase in Tier 2 rates for all customers were also enacted in June 2009 (LADWP, 2010). These conservation efforts led to a decrease in the amount of imported water purchased from MWD in 2009, whose own amount was 23% below the baseline allocations for the FY2010 (LADWP, 2010).
SFR water use per household shows nearly a three-order magnitude variation across the same climate zone for the 2000-2010 period, ranging on average from about 25 485L/SFR customer/month (9 HCF/SFR customer/month) (Venice) to about 67 960L/SFR customer/month (24 HCF/SFR customer/month) (Pacific Palisades) (Figure 6). Neighborhoods with high water use are also associated with high seasonal variability (inland areas and wealthy neighborhoods near the coast). The decrease in water use during the winter is correlated with an increase in precipitation (negative correlation statistically significant at p<0.05), as would be expected. Neighborhoods located in downtown Los Angeles (i.e. Florence) have higher population density, less greenspace, and lower water use with average difference between monthly summer and winter consumption equal to about 10.7 m$^3$/SFR customer/month (3.78 HCF/SFR customer/month); in contrast to about 39.6 m$^3$/SFR customer/month (14 HCF/SFR customer/month) between monthly summer and winter use for Pacific Palisades. An overall decrease in water use is observed from 2007 due to the implementation of voluntary water use.
reductions (in June 2007), mandatory water waste provisions (in August 2008) and the implementation of increased mandatory outdoor watering restrictions (in June 2009). The amount of decrease in annual single-family water use between FY2008 and FY2010 is about 17% for Pacific Palisades and about 11% for Florence relative to water use level in FY2008. In addition, LADWP also imposed a 15% reduction in the first tier allotments for all customers in June 2009 corresponding to shortage year rates (LADWP, 2010).

Figure 6: Monthly single-family water consumption (in cubic meters/single-family customer) for the selected neighborhoods (median water use) (bottom plot). Monthly precipitation totals for downtown LA are also shown as an inverse bar plot (mm).

There is also significant spatial variation in single-family water use per census tract from 2000 to 2010 (Figure 7). In general, higher water use occurs across the warmer northern parts of the City and along the (wealthier) coast, while lower water use generally occurs in the downtown
region. This reflects income (correlated with lot size), land use density and climate effects. Average single-family water use ranges from 106 m$^3$/SFR customer/year (37.4 HCF/SFR customer/year) in Downtown area to 3 438 m$^3$/SFR customer/year (1 214 HCF/SFR customer/year) for the census tracts located next to the Santa Monica mountain. The Moran’s I index for spatial autocorrelation of SFR water use is 0.2388 (significant at $p<0.05$), showing a moderate clustering across the City. High and low water use clustered areas are also identified with Anselin Local Moran’s I index. High water use clusters are located around the Santa Monica Mountains and in the warmer northern sections of the City. Low water use clusters are situated north of the Downtown area as well as next to the less affluent Florence and Leimert Park neighborhoods.
3.5.3 Vegetation

Higher 16-day EVI values (raw composite data) and high seasonal variability are observed in neighborhoods with higher water use (Figure 8). Downtown neighborhoods have lower EVI values (less vegetation) with relatively smaller seasonal variation, with values
generally ranging from 0.05 to 0.15. Observed maximum EVI values are around 0.4 during the summer period or spring and are noted in the Pacific Palisades. EVI values remained at the same greenness level over the 2007-2010 watering restrictions period (Figure 8). The Mann-Kendall trend test applied on the EVI time-series shows no statistically significant trend at the 0.05 level over the 2007-2010 period for eight of the evaluated neighborhoods. However, four neighborhoods show a statistically significant, but only slight downward trend (at p<0.05) with a slope near zero (between -0.005 and -0.002).

![Figure 8: Select 16-day EVI time-series for five select neighborhoods for the period February 2000 to June 2010.](image)

The spatial EVI (10-year average) pattern confirms the temporal patterns noted above, with lower values in the downtown area and higher values in the northern part of the City and the coastal neighborhoods (Figure 9). The Moran’s I index is 0.5949 (significant at p<0.05),
indicating a significant clustering pattern for EVI. The Anselin Local Moran’s I index also provides information on the spatial clustering of high/low EVI values for census tracts across the City, revealing a cluster of high average EVI values in census tracts close to and north of the Santa Monica Mountains. Lower average EVI clustering is located among the Koreatown, Downtown and Florence neighborhoods, all denser and less affluent neighborhoods.

Figure 9: Ten-year average of the MODIS cumulative Enhanced Vegetation Index (EVI) per census tract over the study area.

The observed spatial patterns of average EVI mimic single-family water use spatial patterns. Correlation between annual single-family water use and average EVI across the census
tracts is positive (Pearson’s correlation equal to 0.66) and significant at \( p<0.05 \) over 2000-2007. The correlation between average EVI in single-family census tracts and annual total precipitation is relatively low at 0.135 (significant at \( p<0.05 \)), indicating that variations in single-family residential average EVI is not primarily a function of precipitation but due to other factors, including household water use.

3.5.4 Regression Model

The following section discusses regression model results, starting with the general random effects model and then analyzing model parameter coefficients by water use and income level groups (Table 4).

Table 4: Regression coefficients from the random effects model for key determinants.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>By water use level</th>
<th>By income level</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(SFR water use per household per bimonthly period)</td>
<td>All</td>
<td>Low</td>
</tr>
<tr>
<td>Average household size</td>
<td>0.0032</td>
<td>0.0696*</td>
</tr>
<tr>
<td>Median household income</td>
<td>0.0197*</td>
<td>0.0195*</td>
</tr>
<tr>
<td>Cumulative EVI</td>
<td>0.1431*</td>
<td>0.1684*</td>
</tr>
<tr>
<td>Percent grass cover</td>
<td>-0.4163</td>
<td>0.3668*</td>
</tr>
<tr>
<td>Total precipitation</td>
<td>-0.000552*</td>
<td>-0.000498*</td>
</tr>
<tr>
<td></td>
<td>0.02865*</td>
<td>0.0207*</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>----------</td>
<td>---------</td>
</tr>
<tr>
<td>Average daily maximum temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First tier usage block allocation per household</td>
<td>0.0088*</td>
<td>0.0166*</td>
</tr>
<tr>
<td>ln(First Tier block rate)</td>
<td>-0.1878*</td>
<td>-0.1118*</td>
</tr>
<tr>
<td>ln(Second Tier block rate)</td>
<td>-0.0697*</td>
<td>-0.0800*</td>
</tr>
<tr>
<td>R²</td>
<td>0.895</td>
<td>0.845</td>
</tr>
</tbody>
</table>

*Denotes significance at the 5% level

*Price*

The developed random effects model utilizes the natural logarithm of both water use and Tier block rates variables. Model coefficients show the price elasticity coefficient significant and negative (-0.19) for the first tier block and -0.07 for the second Tier block, indicating that a 10% increase in the first Tier block rate decreases water demand by around 2% and by 0.7% for the second Tier. This result shows that Tier 2 price elasticity is lower than Tier 1 price elasticity and suggests that the second Tier pricing may not reach its conservation target. The price elasticity values are consistent with previous studies using marginal price, including Arbués et al. (2003), who report price elasticity ranging from -1.57 to -0.003. In California, Renwick and Archibald (1998) developed a panel data model including marginal price and found price elasticity ranging from -0.53 to -0.11, similar to our first tier marginal rate elasticity estimate. Other panel data studies found price elasticity ranging from -0.55 to -0.12 across Arizona and Texas close to our estimates (Agthe and Billings, 1980, 1987; Agthe et al., 1986; Nieswiadomy and Molina, 1989; Gaudin et al., 2001).
Scenario One. The random effects model disaggregated by water use level reveals different and significant (p<0.05) price elasticity for the first Tier block rate: from -0.1118 for low water use customers to -0.2459 for high water use customers, indicating high water users are more sensitive to price changes than lower water users. Results also suggest that a 10% increase in the first Tier block rate will decrease water demand by over 2% for high water users. These price elasticity values are also within price elasticity estimates found in previous work (Arbués et al., 2003; Worthington and Hoffman, 2008). We note that differences between the three estimated coefficients for the second Tier block rate are not statistically significant, indicating that low, medium and high water users have similar responses to changes in the second Tier block rate. Tier 2 price elasticity is lower than Tier 1 price elasticity and this holds across the tested water use groups.

Scenario Two. Response to price changes also varies across the two tested income-level groups, with lower income groups appearing to be less responsive to increased water price than higher income level customers at the first Tier rate. Price elasticity for the first Tier block rate is equal to -0.133 for the lower income group and to -0.239 for the higher income group (significant at p<0.05), indicating that lower income level customers may have less potential or margin for water conservation than customers in the higher income group, likely because lower income customers have lower outdoor usage. However, lower income customers are more sensitive to an increase in the second Tier block rate than higher income customers, with a price elasticity equal to -0.103, similar to Tier 1 price elasticity. Higher income customers have a price elasticity equal to -0.027 in the second Tier block rate (statistically different at p<0.05). These results also demonstrate that Tier 2 price elasticity is lower than Tier 1 price elasticity and this is true across the income level groups.
First Tier block allocation

The model coefficient for the first Tier block water allocation per single-family customer is positive and significant (0.0088), indicating that an increase in water quantity allocated in the first Tier block of 10 HCF per single-family customer (equivalent to a 30% increase in the first Tier block water volume on average over the selected census tracts) results in an increase in single-family water consumption by around 9%.

Scenario One. The first Tier block water allocation also impacts single-family water consumption across the tested water use groups - low, medium and high water users - with statistically significant differences between the three groups (respective coefficients). There is a greater sensitivity to changes in the first Tier block water usage for low water users, with a higher model coefficient (0.0166) in this group compared to high water users (coefficient of 0.0074).

Scenario Two. High income customers are less responsive than low income customers to changes in the first Tier block water allocation. The estimated coefficient is positive and statistically significant for low and high income single-family customers, equal to 0.0096 and 0.0082, respectively. The difference between these two coefficients is also statistically significant (p< 0.05).

Socio-demographics

Our general model indicates that income is significantly related to SFR consumption and household size is not. A 1000 dollar increase in median household income increases single-family water use by about 2% (coefficient of 0.0197). The income coefficient is also statistically
significant and positive for low water users (equal to 0.0195) and for high income customers (equal to 0.0139). Increasing household size increases total single-family household water consumption for low water use customers (0.0696) and lower income-level customers (0.0693) (both coefficients are statistically significant) across the City. This result suggests that water consumption for lower income and low water users is largely indoor, and related to household size, when compared to the other groups. However, household size is not a key predictor for high water users and higher income customers. We note that average household size for single-family household does not vary significantly over our study period and this may be influencing our model’s sensitivity to this variable.

Cumulative EVI

The regression analysis shows that an increase in cumulative EVI by 0.2 over a bimonthly period (about 25% of the average cumulative EVI across the selected tracts) leads to an increase in SFR water use by 2.9% (model coefficient of 0.1431). The coefficient for cumulative EVI ranges from 0.1684, 0.1581, and 0.1252 for low, medium and high water users respectively (significant at p<0.05). However, the three coefficients are not statistically significantly different from each other, indicating that response to possible changes in greenness is similar between the three water user groups. These results also hold true across low and high income groups (0.1305 and 0.1540, respectively).

Grass cover

Overall model results show that the percentage of grass cover generally does not have a statistically significant impact on SFR water users. Only low water use customers showed a
relationship between water consumption and grass cover, with variations in grass cover resulting in statistically significant changes in water consumption in this group (a 10% increase on average in percentage of grass cover leads to an increase in water use of 3.7%; coefficient of 0.3668 statistically significant at p<0.05 in low water use group). We hypothesize that lower water users likely have smaller landscaping area but a significant portion may be irrigated grass, increasing their sensitivity to this variable. The coefficient estimate for the other customer groups is not statistically significant in our model, indicating that their water consumption may be independent of the presence of grass in this model.

*Climate*

*Precipitation.* The random effects model showed a negative and significant relationship between precipitation and water use. Each additional 10 mm of precipitation over the bimonthly period leads to a decrease in water use of 0.6%. This holds true across all single-family customer water groups - low, medium and high water users - with the estimated coefficients ranging from -0.000498 to -0.00071. High water users also tend to be more sensitive to variations in precipitation than low water users who are likely to be using water largely for indoor purposes. The coefficients for high and low water users are statistically different. Results also hold across income groups (coefficients of -0.000458 and -0.00064 for low and high income groups, respectively and statistically significant), with higher income customers seeming to respond slightly more to changes in precipitation than lower income customers.

*Temperature.* Our study model also shows a positive and significant relationship between temperature and water use, with a coefficient estimate of average daily maximum temperature equal to 0.02865. For each degree Celsius increase in the average daily maximum temperature
over the bimonthly period, an increase in water use of 2.9% is observed. This holds across water use groups, with coefficients ranging from 0.0207 to 0.0302, and high water users showing more sensitivity to changes in temperature than low water users less likely to have large outdoor water consumption. Low and high income users also show increasing water use with increasing temperature. Model coefficients are similar between the two types of customers, (0.02831 for low income users and 0.02952 for high income users; both statistically significant) with no statistically significant difference between the two groups, indicating that low and high income customers have similar response to variations in temperature.

3.6 Conclusions

This study is one of the first to evaluate water consumption patterns in a semi-arid, highly altered hydrologic system across an extensive urban area (1300 km²) and extended time period (ten years) using a wide range of explanatory variables. Our analysis provides key information on SFR water consumption across Los Angeles and allows us to develop a rigorous statistical model to understand urban residential water consumption patterns. Results shows that SFR water demand across Los Angeles is primarily related to household income, landscape greenness (proxied by cumulative EVI), tier pricing and volume allocations. However, the impact of these factors varies across water users and income levels. Low water users are more sensitive to changes in the volume of water allocated to them in the Tier 1 block than higher water users. Lower income customers are also more sensitive to changes in Tier 2 rates than higher income customers. However, low, medium and high water users respond similarly to changes in the second Tier block price (increasing Tier 2 price decreases water consumption across all groups). Overall, Tier 1 price elasticity is higher than Tier 2 price elasticity, indicating that the current
Tier 2 price is less effective at reducing water use across all groups and does not reach its conservation goal. Average household size is a significant predictor for water consumption in the lower income customer group, indicating that indoor use may represent a larger portion of their water budget compared to the other higher income groups. Low water users appear less sensitive to climate variability than high water users, likely since lower water use customers have lower outdoor water use. Water use of lower income customers is also less sensitive to changes in climate conditions than higher income customers as lower income customers likely have smaller irrigated landscape.

The first Tier block water usage allocation and water rates have been used by the Los Angeles Department of Water and Power to reduce water consumption during severe drought. In June 2009, LADWP decreased the first Tier water volume allocation by 15% due to severe shortage to reduce water consumption (LADWP, 2010). Based on our model, a 15% decrease in the first Tier water volume allocation corresponds to a decrease in water consumption per single-family customer by around 5% on average for the selected census tracts. It should be noted that this conservation measure was part of other restrictions such as an increase in block rates and a reduction in residential outdoor irrigation.

Finally, SFR water use and vegetation greenness patterns are strongly and positively related, while regional variations in precipitation explain a smaller portion ($R^2=0.018$) of the observed variance in vegetation greenness. This suggests that residential outdoor irrigation drives much of the temporal and spatial greenness across the City. We note that even during drought periods and mandatory restrictions, Los Angeles generally maintained the same level of greenness, with EVI values remaining stable. This suggests that vegetation may be overwatered or that water use for outdoor landscapes is not efficiently managed.
Our analysis contributes to improved understanding of residential water demand for the City of Los Angeles and we advocate that similar methods could be applied to other semi-arid, highly irrigated cities. Investigation of the key predictors across different customer groups provides insight on consumer behavior and also provides information for targeted conservation efforts at the neighborhood scale and for different customer groups. This information could be used by the City and LADWP to refine incentives for water use reduction to improve efficient use of water while paying careful attention to equity concerns. Neighborhoods with high residential water use levels tend to be wealthier and be spatially clustered. This suggests that revising rates in Tier 2, or adding a third tier may help with conservation efforts and bring additional revenues for the water utilities. While previous phases targeted indoor water consumption, the next phase of conservation will likely need to target outdoor water use through alternative landscape planting and irrigation system efficiency. However, changes in outdoor landscaping are costly to residents. The additional revenues derived from revised tier structuring could help subsidize a systematic shift toward more climate appropriate landscapes and practices.

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Chapter 4. Estimation of Residential Outdoor Water Use in Los Angeles

4.1 Introduction

Residential water use is the largest urban water use category, with single-family water use noted to represent half of urban water consumption in California (DeOreo et al., 2011; Gleick et al., 2003; CDWR, 2005). A recent study by DeOreo et al. (2011) notes that residential outdoor use in Southern California is twice as high as in Northern California and represents a significant portion of household water budget (65% of average daily water use in Southern California study sites based on household logged water records and flow trace analysis) (DeOreo et al., 2011). This study of single-family water use includes several water agencies across California from Sonoma County Water Agency to San Diego Water Authority including the Los Angeles Department of Water and Power. It is important to note that most cities in California’s Central Valley do not yet have residential water meters, thus studying residential water use in California is generally restricted to the major coastal metropolitan areas. It is evident that outdoor water use has the largest potential for water conservation. Studies highlight that residential outdoor use in California can be reduced by 25% to 40% with improved management practices and increased use of available irrigation technology (Gleick et al., 2003). The difficulty resides in quantifying and predicting outdoor water use for which current approaches entail significant uncertainties related to heterogeneous land cover characteristics, water consumption metering, climate, and availability of data (Gleick et al., 2003).

A range of methods have been developed to estimate residential outdoor use. Early methods developed by Costello et al. (1994; 2000) focused on landscape coefficients and estimated irrigation requirements based on the landscape characteristics and reference
evapotranspiration (ET\textsubscript{O}). The landscape coefficient (K\textsubscript{L}) is the product of three factors evaluating species, density and microclimate conditions based on field observations (Costello et al., 1994; 2000). The landscape method is difficult to apply at regional and longer temporal scales as it requires data for each plant species within heterogeneous urban landscapes. Previous studies implemented this method at the household level, producing reasonable estimates of landscaping irrigation requirements that account for effective precipitation and irrigation system efficiency (DeOreo et al., 2011; Salvador et al., 2011; Haley et al., 2007; Domene et al., 2005). This method is particularly challenging to apply to Southern California as the region has high floral biodiversity, perhaps some of the highest in the nation due to is benign climate (Pincetl et al., 2012 and forthcoming).

A second category of methods relies on the formulation of urban water balance models. Grimmond et al. (1986a; 1986b; 1996) estimates urban water budget coupled with an energy balance approach to evaluate human impacts in urbanized areas. The model relies on the partition of the urban domain into three surfaces: impervious, pervious irrigated and pervious non-irrigated. The developed model can be run from daily to annual time scales but requires climate data, land cover characteristics, surface retention capacities, soil storage capacity, field capacity, water use data (for the imported water supply component), water storage conditions and surface aerodynamic characteristics for evapotranspiration, many of which are difficult to obtain in highly urbanized areas (Grimmond et al. 1986a, 1986b).

Urban irrigation is also not routinely incorporated in urban hydrologic models including Land Surface models (LSMs) which are commonly used for longer term climate and ecosystem impact studies. Micro-scale urban water models have been employed to better understand runoff and landscape irrigation processes (Xiao et al., 2007). Xiao et al. (2007) developed an urban
water model at the residential parcel scale based on physical parameters to evaluate the impact of best management practices on landscaping irrigation. Vahmani and Hogue (2013) developed an irrigation module within the coupled Noah-SLUCM (single layer urban canopy model) to assess residential irrigation and the impact on urban meteorological processes at the block level in Los Angeles.

Several studies have also used total and indoor water use to derive outdoor use estimate as a residual (Endter-Wada et al., 2008; Syme et al., 2004; DeOreo et al., 2011; Grimmond et al., 1996). There are different models used to estimate indoor use, including water billing data and direct measurement through household logged water data and flow trace analysis (DeOreo et al., 2011; Mayer et al., 1999). Total water use is generally obtained from water billing data or logged water records from these same studies.

The Pacific Institute (Gleick et al., 2003) developed minimum use month and average minimum use methods for regions of California, which can be applied using monthly water use billing data. The assumption underlying both aforementioned methods is that indoor use remains consistent throughout the year (non-seasonally dependent). This hypothesis was tested in the Mayer et al. (1999) study which showed there were no statistically significant differences in indoor use between different seasons in the cities selected in warmer and cooler climates (except for Tampa, FL). For the minimum use month method, the month with the minimum water use is identified for each year as indoor use and the difference between the minimum value and each monthly water use value represents outdoor use. The same approach is used for the average minimum use method: the average of the three lowest water consumptions is selected to be equal to indoor use and outdoor use is calculated as the residual. The estimation of indoor use using the minimum use month in semi-arid climates generally includes some residential irrigation and
overestimates indoor use (Mayer et al., 1999; Gleick et al., 2003). Several studies have shown that the minimum and average minimum use methods underestimate outdoor use in warmer and more arid climates in cities such as San Diego, CA, Scottsdale, AZ, Phoenix, AZ, Tempe, AZ and Las Virgenes, CA (Gleick et al., 2003; Mayer et al., 1999; DeOreo et al., 2011). Thus, the advancement of these types of methods needs to be designed with specific consideration of climate zones. Data loggers installed on household water meter provide records used in flow trace analysis in studies at the household level, allowing more accurate estimates of indoor and outdoor use (DeOreo et al., 2011; Mayer et al., 1999). This approach is limited by the duration of the logging period as annual and outdoor consumption totals are difficult to estimate for data collected over small logging periods. However, logged water use data are often combined with billing records to obtain more accurate total and residential outdoor use estimates (Mayer et al., 1999).

More recent approaches involve the use of remote-sensing vegetation indices to estimate urban irrigation which is a significant part of the outdoor water budget in many semi-arid cities. The Normalized Difference Vegetation Index (NDVI) is a measure of the photosynthesis activity of plants and has been shown to be strongly related to evapotranspiration (Li et al., 2012; Keith et al., 2002; Szilagyi, 2002). Results from Keith et al. (2002) demonstrate the relationship between maintained high NDVI values and increased water use during moderate and severe drought conditions in domestic and agricultural water use categories. In addition, Szilagyi et al. (1998) found strong correlation between monthly mean NDVI and one month-lagged evaporation in a prairie water-limited environment. Szilagyi (2002) confirmed the existence of a strong correlation between monthly NDVI and areal evapotranspiration in a prairie domain with areal evapotranspiration being lagged by one month. Kondoh and Higuchi (2001) also found a
strong relationship between NDVI and daily evapotranspiration rate during the growing season in a grassland area. Finally, Johnson and Belitz (2012) estimated urban irrigation rate from the relationship between evapotranspiration and NDVI surplus calculated as the difference between irrigated landscaping NDVI and non-irrigated landscaping NDVI values. They also found a strong exponential relationship between water delivery and NDVI surplus ($R^2=0.94$) over a 2-year period (Johnson and Belitz, 2012).

The primary goal of the current study is to quantify outdoor and irrigation water use using several previously-published methods and to investigate the relationship between residential water use and urban vegetation greenness surplus across a semi-arid highly developed urban metropolis. Our work is one of the first to quantify outdoor and landscaping irrigation use during drought periods with voluntary and mandatory utility restrictions on outdoor watering. We compare two methods from the Pacific Institute (Gleick et al., 2003) that quantify outdoor use using LADWP water billing data and we utilize a remote-sensing approach inspired from Johnson and Belitz (2012) that provides landscaping irrigation estimates. We developed the remote-sensing model based on NDVI, land use and land cover products. The developed model is then utilized to compare the efficacy of two outdoor watering restrictions periods implemented during 2007-2010 on landscaping irrigation application. Ultimately, the developed model can be used by regional utilities as a predictive tool for landscaping irrigation budgets and to help target conservation efforts across the City.


4.2 Data

4.2.1 Water consumption data

Monthly single-family residential (SFR) water billing and lot size data were provided by LADWP for the period from January 1, 2000 to December 31, 2010. The initial database contained around 480,000 individual residential customers identified by census tract numbers. Less than 1% of the records (500 to 600 single-family customers) did not match the U.S. Postal Service ZIP code database and were removed. The LADWP reading period is bi-monthly (every 60 days) and the utilities pro-rated the data to calculate monthly water consumption. The 2000-2010 data includes the following restriction periods: voluntary outdoor watering restrictions were implemented throughout fiscal year (FY) 2008 with additional enforced water waste provisions implemented in August 2008 (a fiscal year is defined as the period from July 1<sup>st</sup> of the preceding year to June 30<sup>th</sup> of the current year) while increased mandatory two-day per week outdoor watering restrictions and water rates increase (coupled with a 15% decrease in Tier 1 water allotment) were implemented in June 2009 for FY2010 (LADWP, 2010).

The current LADWP service area includes customers residing in the City of Los Angeles and on the edge of the city boundary. However, only the census tracts contained within the City boundary were analysed and the LADWP customer data was matched with the census residential population data in the City of Los Angeles. The final set of monthly individual customer records was aggregated to the census tract level to protect customer privacy. The aggregated list includes 857 census tracts with monthly water data for a ten year period. The average customer lot size was calculated for each census tract. Monthly water consumption data was normalized per the number of SFR accounts or SFR customers and per average lot size area. The GIS census tract boundary layer comes from the 2000 U.S. Census Bureau.
4.2.2 Land cover data

Irrigated, non-irrigated and impervious areas across the city were selected using a land cover database derived from high-resolution satellite imagery (McPherson et al., 2011). The database was created using Quickbird imagery and aerial photography from 2002 to 2005 at high spatial resolution (< 2 m pixel resolution) and identifies four primary land cover types: tree (tree and shrub), grass (green grass and ground cover), dry grass/bare soil (dry grass and bare soil), and impervious surface (includes pervious pavement) (McPherson et al., 2011). Eight golf courses and irrigated urban parks were delineated to represent irrigated areas in the city. Non-irrigated surfaces were identified in the Northern part of the city using the dry grass land cover areas and the non-irrigated fields next to airports. Impervious areas were selected in the downtown neighborhood and at airports runways. We assumed that land cover was generally static over the 10-year study period for the delineated endmembers in the City.

4.2.3 Land use data

The land use database was acquired from the NOAA C-CAP 2006 (30m) classification database. We selected the pixels in the low density development category within each census tract boundary as it primarily includes single-family residential areas. The land cover was assumed to remain static over the 10-year study period.

4.2.4 Vegetation Indices

Urban vegetation greenness was estimated using the NASA Landsat Thematic Mapper 5 (Landsat TM 5) satellite that provides remote-sensing products at 30-m resolution every 16 days.
This higher resolution data compared to NASA’s Terra Moderate Resolution Imaging Spectroradiometer (MODIS) 250-m product is more appropriate to extract and map vegetation characteristics in the delineated land cover areas and census tracts. We used spectral band 3 (wavelength is from 0.626μm to 0.693μm, red band) and band 4 (wavelength is from 0.776μm to 0.904μm, near-infrared band) to calculate NDVI (Rouse, 1974). Landsat images were downloaded over the 2000-2010 period using a cloud cover threshold below 10%, resulting in 111 images for the study period. The raw digital numbers (DNs) values for bands 3 and 4 were processed using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) developed by Masek et al. (2006). The LEDAPS provides processed Landsat data including atmospherically-corrected surface reflectances for bands 3 and 4. The LEDAPS software was originally developed by Vermote et al. (1997) for the Terra MODIS platform using the atmospheric correction 6S radiative transfer model. Atmospheric correction minimizes the impacts of scattering and absorption by atmospheric gas and particles on measured reflectance. The NDVI values range from -1 to 1, with values close to 1 for healthy plants and around 0 for impervious, non-vegetation surfaces. The NDVI pixel values were averaged spatially in single-family areas for each census tract and for the delineated irrigated, non-irrigated and impervious surfaces.

4.3 Methods

4.3.1 Descriptive Analysis

A descriptive analysis was undertaken for twelve representative neighborhoods using monthly time-series plots from 2000 to 2010 for single-family customer water consumption and NDVI data. The twelve selected neighborhoods are generally representative of the city’s
characteristics and were selected based on population, density, ethnicity, median household income, average household size, housing tenure, education level, immigration status and microclimate criteria. Census tracts within each neighborhood boundary were identified and median single-family water use and average NDVI were estimated for each tract. Trend analysis in monthly single-family water consumption and NDVI were conducted using a Seasonal Mann-Kendall trend test. The linear trend slope was estimated using the Sen’s slope or Seasonal Kendall slope estimator. The Seasonal Mann-Kendall test accounts for seasonality: the test is derived for each monthly “season” (Hirsch et al., 1982). The resulting slope is the median of all slopes computed from pair observations (Helsel and Hirsch, 2002).

4.3.2 Outdoor Use: Minimum use month and average minimum use month models

Two existing methods described by the Pacific Institute (2003) use monthly water-billing data to estimate residential outdoor use as the residual of monthly total water use minus indoor use per single-family customer (Gleick et al., 2003). The underlying assumptions of the two methods are that indoor use is consistent throughout the year and that the minimum use month is the best estimate of indoor water use. **Minimum use month**: A monthly minimum water use is identified for each fiscal year and for each tract and is assumed to represent monthly indoor use. **Average minimum use**: The average of the three lowest monthly water use records is calculated and is assumed to represent monthly indoor use. The monthly outdoor use values were obtained from the minimum and average use methods for each fiscal year and for each tract. Finally, the ratio of outdoor use to total single-family water use was calculated.
4.3.3 Landscaping irrigation estimates: Remote sensing model

Our approach is based on Johnson and Belitz (2012) that estimates the rate of urban irrigation in residential neighborhoods in the San Fernando Valley in Southern California using Landsat NDVI products. We build upon this approach to estimate landscaping irrigation patterns over 10 years at the census tract scale across Los Angeles and include differing climate conditions, including “dry” and “wet” years relative to the 30-year average precipitation in Los Angeles. We analyze the impact of the restrictions periods (voluntary and mandatory) on landscaping irrigation. We also account for individual tract-specific effects. We first describe the NDVI surplus calculations at the census tract level and then apply the model to estimate the amount of landscaping irrigation per census tract.

Calculation of NDVI surplus

Each pixel in a Landsat image may be modeled as a linear mixture of image endmembers (Adams et al., 1995). Each image endmember is composed of a “pure” land cover type that participates in the mixed pixels in the image. Johnson and Belitz (2012) selected two endmembers to represent single-family residential land-use class targeted in this study: irrigated landscaping and impervious surfaces. In addition, this land use class is not likely to include extensive natural native vegetation that has high NDVI values and no landscaping irrigation. Previous studies have shown that Los Angeles urban vegetation, as in many semi-arid cities, is more likely to be non-native and well-watered (Bijoor et al., 2012). In Los Angeles, 12% of urban land cover area is estimated to be irrigated grass and 21% is estimated to be tree canopy cover; the remaining percentage represents mostly impervious and dry grass/bare soil areas (McPherson et al., 2011).
To compute the amount of irrigation, three endmembers are needed that each represents one land cover type: irrigated landscaping, non-irrigated landscaping and impervious areas (Johnson and Belitz, 2012). The endmembers were delineated using a high resolution land cover database developed by McPherson et al. (2011) that classifies land cover types as tree, grass (green grass), dry grass/bare soil and impervious surfaces. Google Earth imagery was an additional resource used to visually check the endmembers. The irrigated landscaping endmember includes eight golf courses and irrigated urban parks identified in the tree/grass land cover type and visually checked on Google Earth. For the non-irrigated endmembers, dry grass surfaces were delineated in the Northern part of the city and in non-irrigated fields next to the Los Angeles International airport. Impervious surfaces were delineated in the Downtown area and at the Los Angeles International airport runways to constitute the impervious endmember. These endmembers were kept the same for all images and are assumed to remain invariant over time. The 30-m NDVI pixel centroids were extracted within each endmember boundary. The resulting NDVI values were averaged for each endmember land cover type (irrigated landscaping, non-irrigated and impervious) and for each Landsat image.

To compute the NDVI values in the targeted single-family land use areas within each census tract, we utilized the NOAA C-CAP 30-m land cover database. The single-family land-use pixels classified in the low intensity development category were selected in each census tract. The 30-m NDVI pixel centroids were extracted from the single-family areas in each census tract and each Landsat image. The resulting NDVI values were spatially averaged for each census tract. Similar to Johnson and Belitz (2012), NDVI in single-family areas is represented as a two-endmember model (Eq. 2):

\[
NDVI_{tract}(t) = F_{irr,tract}(t) \times NDVI_{irr}(t) + (1 - F_{irr,tract}(t)) \times NDVI_{imp}(t) \quad \text{(eq. 2)}
\]
where NDVI_{tract}(t) is the average NDVI value for single-family areas within each tract and each Landsat image, F_{irr,tract}(t) is the portion or “fraction of irrigated landscaping” in each single-family tract area and for each image, NDVI_{irr}(t) is the irrigated landscaping endmember and NDVI_{imp}(t) is the impervious endmember. F_{irr,tract}(t) is computed from Eq. 2 in single-family areas within each tract and for each image using the averaged NDVI values per endmember and tract.

The NDVI from irrigated landscaping areas is expected to remain constant over time as it is maintained by residential irrigation. The NDVI values from non-irrigated landscaping areas follow precipitation patterns. The difference in NDVI between the two endmembers called “NDVI surplus” is related to the amount of irrigation and defined as (Johnson and Belitz, 2012) (Eq. 3):

\[
NDVI_{\text{surplus}}(t) = NDVI_{\text{irr}}(t) - NDVI_{\text{nonirr}}(t) \quad (\text{eq. 3})
\]

where NDVI_{surplus}(t) is the NDVI surplus between the irrigated landscaping endmember and the non-irrigated landscaping endmember for each Landsat image.

The last step involves multiplying the NDVI surplus by F_{irr,tract} representing the portion of irrigated landscaping in single-family areas within each tract and for each image (Eq. 4):

\[
NDVI_{\text{surplus}}_{\text{tract}}(t) = NDVI_{\text{surplus}}(t) \times F_{\text{irr,tract}}(t) \quad (\text{eq. 4})
\]

where NDVI_{surplus}_{tract} is the NDVI surplus calculated in single-family areas for each census tract and each image.

Finally, NDVI surplus was interpolated monthly between 2000 and 2010 using a piecewise cubic Hermite algorithm and is used as an input in the relationship with monthly single-family water use normalized per customer and lot size.
Development of the relationship between NDVI surplus and single-family water use

A non-linear mixed effects exponential model was developed to predict the relationship between NDVI surplus in single-family areas and single-family water use (in mm/SFR customer/month) at the census tract level. Single-family water use was lagged by one month as a one-month lag was observed between NDVI and water inputs (Szylagyi et al., 1998). The final model equation is (Eq. 5):

\[
SFR_{wateruse,tract}(t - 1) = b_{tract} \exp(k_{tract} \times NDVI_{surplus,tract}(t)) + m \times restriction \times NDVI_{surplus,tract}(t)
\]

(eq. 5)

where \( SFR_{wateruse,tract}(t-1) \) is monthly single-family water use in mm/household/month lagged by one month, \( b_{tract} \) is the constant tract-specific intercept, \( NDVI_{surplus,tract} \) is monthly NDVI surplus in single-family areas within each tract, “restriction” is a dummy variable interacting with NDVI surplus for the fiscal years FY2008, FY2009 and FY2010 during which residential irrigation restrictions were implemented. The model dummy variable controls for the overall impact of restrictions on residential irrigation.

The non-linear mixed effects model was selected in order to account for omitted variables specific at the census tract level. Other models were tested (such as simple linear regression) that produced lower \( R^2 \) values. Outlier tracts with very low water consumption and under 10 customers per tract were removed to reduce uncertainty. The final model was run for 710 tracts across the city at the monthly time scale over a ten-year period (FY2001 to FY2010). We also controlled for heteroskedasticity and serial correlation of the residuals. The serial correlation issue was solved by de-trending the monthly water use and NDVI data for each tract: the
difference term between the monthly mean and the annual mean per tract was computed and subtracted from the monthly values for each tract.

The b constant in the exponential model represents water used for purposes other than landscaping irrigation, including household indoor use and outdoor usage such as pool and dry-weather runoff (it is the intercept estimated when NDVI surplus is equal to zero). The exponential term contributes to water used for landscaping irrigation in single-family households, which is related to the NDVI surplus variable. This equation form is different from the initial model equation found by Johnson and Belitz (2012). In their study, the water use component excluding landscaping irrigation is a separate constant added to the exponential term. This original model was tested and not selected as it did not represent a good fit over the ten year study period.

4.4 Results and Discussion

The following section presents results from the minimum use month and average minimum use methods and compares our results with previously-published values (including DeOreo et al. (2011) and Mayer et al. (1999)). It also describes the landscaping irrigation results from the developed remote-sensing model, including water use and NDVI surplus analysis.

4.4.1 Outdoor use estimates: Minimum month and average minimum month models

The 10-year average outdoor use rate for the minimum use month model has a mean of 213 mm/year (27.3% of total single-family water use) and ranges from 19 to 635 mm/year (Figure 10). Higher outdoor use values are located in the Northern part of the City and Coastal
tract neighborhoods while lower values are observed for census tracts located in the Downtown area.

Figure 10: Average outdoor use rate (in mm/year) over 10 years using the minimum month use method

The average minimum month model provides similar results: the 10-year average outdoor use rate has a mean of 211 mm/year (27% of total single-family water use) and ranges from 18 to 630 mm/year. For both methods, high outdoor water use values are positively related with high vegetation indices in the Northern arid part of the City and in the coastal tract neighborhoods (correlation (r) between average annual outdoor use and NDVI in single-family areas equal to 0.47 significant at p<0.05). The outdoor use values calculated using the minimum use and
average minimum use methods in Los Angeles are similar to CDWR (2005) estimates (232 mm/year in 2004) but are generally lower than estimates found in previous studies which range from 384 to 980 mm/year (Table 5). DeOreo et al. (2011)’s outdoor use estimate averages 384 mm/year representing 56.8% of total single-family water use in Los Angeles. LADWP estimates that 54% of total single-family water use is for outdoor purposes, combining data from wastewater flow, minimum month and landscape ET requirements. Previous studies support that these methods likely underestimate actual outdoor use and have relatively high uncertainties (Gleick et al. 2003, DeOreo et al. 2011, Mayer et al. 1999). This uncertainty primarily comes from the fact that many single-family customers still irrigate during winter months. Johnson and Belitz (2012) calculated that landscaping irrigation accounted for 1/3 of total water delivery during winter months in the San Fernando Valley in Southern California.

Table 5: Comparison of outdoor use estimates from Los Angeles water billing data with estimates of outdoor use including a CDWR estimate of outdoor use, DeOreo et al. (2011), Mayer et al. (1999) and Grimmond et al. (1996). Outdoor use rate: depth of water applied over entire lot size area (mm/year), except for Mayer et al. (1999) study for which outdoor use estimates are over irrigable area. Outdoor use estimates from billing data are averages over 10 years. Salvador et al. (2011) study provides applied irrigation water use in the Zaragoza region in Spain, which has a semi-arid climate with similar annual average precipitation (average precipitation of 337mm in Zaragoza compared to 396mm in Los Angeles).

<table>
<thead>
<tr>
<th>Method</th>
<th>Outdoor use rate (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outdoor use estimates from billing data</td>
</tr>
<tr>
<td>Minimum use</td>
<td>213 (standard deviation=69.7)</td>
</tr>
<tr>
<td>Average minimum use</td>
<td>211 (standard deviation=68.9)</td>
</tr>
</tbody>
</table>
### 4.4.2 Irrigation Use: Remote-sensing NDVI model

**Descriptive time-series analysis**

Monthly time-series of single-family water use and NDVI were first analyzed to identify trends and correlations in the selected study neighborhoods. Single-family water use time-series normalized per household and lot size reveals seasonal variability correlated with the precipitation patterns over the 10 years (correlation r between -0.49 and -0.61 significant at p<0.05) (Figure 11).

<table>
<thead>
<tr>
<th></th>
<th>Outdoor use estimates for comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDWR (estimate WY 2004)</td>
<td>232</td>
</tr>
<tr>
<td>DeOreo et al. (2011) (Los Angeles, 2005-2008 estimates)</td>
<td>384</td>
</tr>
<tr>
<td>Mayer et al. (1999) (San Diego, CA)</td>
<td>841</td>
</tr>
<tr>
<td>Mayer et al. (1999) (Phoenix, AZ)</td>
<td>980</td>
</tr>
<tr>
<td>Mayer et al. (1999) (Las Virgenes, CA)</td>
<td>914</td>
</tr>
<tr>
<td>Salvador et al. (2011) (Spain)</td>
<td>1276-1378</td>
</tr>
<tr>
<td>Hunt et al. (2001) (Irvine, CA)</td>
<td>1764</td>
</tr>
<tr>
<td>Grimmond et al. (1996) (Los Angeles)</td>
<td>482-500</td>
</tr>
</tbody>
</table>
Figure 11: Time-series plot of median single-family water use in mm per single-family customer per month over 2000-2010 for the selected neighborhoods with precipitation (mm) on the inverse bar plot.

A decrease in single-family water use is observed during the winter months followed by an increase during the summer months. On average, monthly single-family water use ranges from 54.8 mm/hsl/mo to 72.9 mm/hsl/mo across the selected neighborhoods over 10 years. After the voluntary, enforced water waste provisions and increased mandatory water restrictions went into place (in June 2007, August 2008 and June 2009 respectively), single-family water use was observed to decrease (from FY2008 to FY2010). The Seasonal Mann-Kendall trend test performed on monthly single-family water use per neighborhood confirms the presence of a
downward and statistically significant trend for all selected neighborhoods for FY2008-2010 (significant at p<0.05) with average slope equal to a decrease of 5 mm/year (or 7.5% of average single-family water use) over a year for the selected neighborhoods).

Non-irrigated areas identified in Los Angeles also follow seasonal precipitation patterns (Figure 12). Higher NDVI values are observed in the winter months and lower NDVI values in the summer months. NDVI for non-irrigated endmember ranges from 0.130 to 0.523. NDVI for irrigated landscaping endmember remains relatively stable over 10 years with an average NDVI equal to 0.507. Impervious surfaces have smaller NDVI values that are relatively constant over 10 years. The average NDVI value for the impervious endmember is equal to 0.057.

Figure 12: NDVI time-series for the three endmembers: irrigated landscaping, impervious and non-irrigated landscaping areas from 2000 to 2010 with precipitation (mm) on the inverse bar plot (Precipitation data is from the Downtown LA station)
The NDVI surplus time-series reveals a seasonal pattern over 10 years for single-family land use areas in the selected neighborhoods (Figure 13). High NDVI surplus values are observed during summer months and lower values during winter months. It is also correlated with seasonal precipitation patterns (correlation r between -0.27 and -0.54 significant at p<0.05). High positive NDVI surplus values indicate that residential vegetation maintained by irrigation is greener than non-irrigated vegetation that follows precipitation pattern. Average monthly NDVI surplus ranges from 0.071 to 0.174 across the selected neighborhoods over 10 years. The Seasonal Mann-Kendall trend test performed on monthly NDVI surplus per neighborhood revealed a statistically significant downward trend over FY2008-2010 for the neighborhoods (significant at p<0.05) except for two neighborhoods: Silver Lake (SLL) does not have a statistically significant trend and Playa Vista (PLV) has a positive trend. The average slope across the selected neighborhoods is equal to a decrease of 0.0072 (or 3% of average NDVI surplus) over a year.
Figure 13: Time-series plot of average NDVI surplus for the selected neighborhoods from 2000 to 2010 with precipitation (mm) on the inverse bar plot.

NDVI surplus vs single-family water use

The non-linear exponential model was first applied to each individual tract in the City over the 10 year period to assess the distribution of the b and k coefficients in Eq. (5). The b coefficient (intercept) follows two distinct distributions: the first normal distribution is centered on 26.5 mm/hsld/month (with a standard deviation equal to 6.41 mm/hsld/month) and includes 61% of the tracts. For the second group, 39% of the tracts also follow a normal distribution with a mean equal to 41.3 mm/hsld/month (with a standard deviation equal 15.38 mm/hsld/month).
Two non-linear mixed effects models were implemented to reflect these two different coefficient distributions. The final equations for the two models are:

\[
SFR_{\text{wateruse}}(t-1) = 25.872 \exp(5.963 \cdot \text{NDVIsurplus}_{\text{tract}}(t)) + 0.050 \cdot \text{restriction} \cdot \text{NDVIsurplus}_{\text{tract}}(t) \quad \text{(eq. 6)}
\]

\[
SFR_{\text{wateruse}}(t-1) = 39.136 \exp(5.086 \cdot \text{NDVIsurplus}_{\text{tract}}(t)) - 0.110 \cdot \text{restriction} \cdot \text{NDVIsurplus}_{\text{tract}}(t) \quad \text{(eq. 7)}
\]

The mean value for the b intercept is 25.872 mm/hsl/d/month (with a standard deviation equal to 4.245 mm/hsl/d/month) for the first group (61% of the tracts) (eq. 6) and 39.136 mm/hsl/d/month (with a standard deviation equal to 15.951 mm/hsl/d/month) for the second group (39% of the tracts) (eq. 7). The value for the mean k coefficient is 5.963 with a standard deviation of 1.388 for the first group and mean of 5.086 with a standard deviation of 2.413 for the second group. All the estimated coefficients are statistically significant at p<0.05. Note that the estimated coefficient for the interaction variable with NDVI surplus is positive for the first group and negative for the second group, indicating that the 3-year watering restrictions may have different impacts on the tracts. However, this does not reflect the response at the individual tract level. Results from both equations (eqs. 6 and 7) are highlighted (Figures 14 through 17) to analyze the overall performance of the model and landscaping irrigation estimates across the City.

**Performance of the NDVI model**

The R² value indicating the performance of the model was calculated for each tract to compare the actual and simulated water use values (Figure 14). The mean R² value is equal to 0.721 and it ranges from 0.0017 to 0.913 with a standard deviation equal to 0.169 (Figure 14). Higher values are observed in the Northern arid part of the City as well as in tracts surrounding...
the Santa Monica Mountains and Griffith Park area (Figure 14). The correlation between the $R^2$ values and household income is equal to 0.43 (significant at $p<0.05$), showing a moderate correlation between model $R^2$ and income patterns. The model $R^2$ appears to coincide with vegetation greenness patterns: the correlation between $R^2$ values and average annual NDVI in single-family areas for each tract is equal to 0.58 and significant at $p<0.05$. Hence, the NDVI model performs better in greener landscape areas.

Figure 14: R-square results from single-family water vs. NDVI surplus exponential regression at the Census tract level
According to the derived model, single-family water use can be divided into two terms: a constant value b (intercept) and the exponential term related to NDVI surplus, which represents landscaping irrigation. Hence, the intercept b is the volume of water used for purposes other than landscaping irrigation and we assume that it remains constant for the study period. The value of the b constant was multiplied by the average lot size per tract to obtain the volume of water for household indoor uses and other consumption not related to the landscape and to compare with other previously-found values. The mean b estimate is equal to 667 L/hsl/day, which matches relatively well (583 L/hsl/day) with the volume of water used for purposes other than irrigation in Johnson and Belitz (2012). To some extent we can also compare this value to indoor use values found by Mayer et al. (1999) and DeOreo et al. (2011). The resulting value of 667 L/hsl/day is comparable with indoor use of 589 L/hsl/day found in San Diego, CA and 771 L/hsl/day in Las Virgenes, CA (Mayer et al., 1999). The DeOreo et al. (2011) study showed indoor use for the LADWP area equal to 685 L/hsl/day, which is also relatively close to our estimate.

**NDVI model irrigation estimates**

Finally, landscaping irrigation is estimated by subtracting the b value from total single-family water use for each individual tract. We assume that the value of the b intercept is water consumption for purpose other than landscaping irrigation and is constant over the study period. The landscaping irrigation rate was expressed for three periods: FY2001-2007, FY2008-2009 (voluntary outdoor watering restrictions and beginning of mandatory water waste provisions) and FY2010 (mandatory two day-per week irrigation restrictions coupled with water rates increase and decrease in water allotment). Table 6 provides a comparison of irrigation rates between the
three periods and with other studies. For 57 tracts, the model produced negative values for FY 2010 due to low $R^2$ values (below 0.4) relative to all the other tracts; these values were not accounted for in Table 6.

Table 6: Comparison of landscaping irrigation rate (in mm/year) from NDVI model with other irrigation rate and evapotranspiration (ET) estimates including Moering (2011), Johnson and Belitz (2012), Mayer et al. (1999).

Net ET requirement estimates for Mayer et al. (1999) study are for turf grass areas. Moering (2011)’s ET estimate is for irrigated park in Los Angeles. Vahmani and Hogue (2013) ET estimate is simulated grass ET. Irrigation estimates from NDVI model are averages over the given period assuming volume of water used for other purposes than irrigation is kept constant. Salvador et al. (2011) study provides irrigation requirements in the Zaragoza region in Spain, which has a semi-arid climate with similar annual average precipitation (average precipitation of 337mm in Zaragoza compared to 396mm in Los Angeles).

<table>
<thead>
<tr>
<th>Method</th>
<th>Irrigation rate (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Remote-sensing model</strong></td>
<td></td>
</tr>
<tr>
<td>FY2001-2007</td>
<td>439 (standard deviation=132)</td>
</tr>
<tr>
<td>FY2008-2009 (voluntary restrictions and beginning of mandatory restrictions)</td>
<td>412 (6% decrease) (standard deviation=140)</td>
</tr>
<tr>
<td>FY2010 (increased mandatory restrictions)</td>
<td>285 (35% decrease) (standard deviation=98)</td>
</tr>
<tr>
<td><strong>Irrigation estimates from NDVI model</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Irrigation estimates for comparison</strong></td>
<td></td>
</tr>
<tr>
<td>Moering (2011)</td>
<td>1200</td>
</tr>
<tr>
<td>Salvador et al. (2011) (Spain)</td>
<td>502-599</td>
</tr>
<tr>
<td>Vahmani and Hogue (2013)</td>
<td>759</td>
</tr>
<tr>
<td>Mayer et al. (1999) (San Diego, CA)</td>
<td>1118</td>
</tr>
</tbody>
</table>
For the FY2001-2007 period, the average landscaping irrigation estimate of 439 mm/year is well within the range of values published by Johnson and Belitz (2012) (between 114 and 541 mm/year) and comparable to irrigation values from Salvador et al. (2011). Our values are lower than evapotranspiration (ET) estimates found in an irrigated park in Los Angeles or for turf grass areas (from 759 mm/year to 1864 mm/year) (Moering, 2011; Mayer et al., 1999). The average landscaping irrigation estimates for the restrictions periods considered are equal to 412 and 285 mm/year, for FY2008-2009 and FY2010 respectively. This shows a large decrease in landscaping irrigation due to increased mandatory restrictions in FY2010 (35% decrease relative to the FY2001-2007 period) compared to 6% decrease due to restrictions in FY2008-2009, highlighting the effectiveness of mandatory restrictions (including two-day irrigation per week, water rates increase and decrease in water allotment), rather than voluntary regulations in FY2008-2009, in reducing landscaping irrigation.

Figures 15 through 17 highlight landscaping irrigation per tract for the three periods. Landscaping irrigation during FY2001-2007 ranges from 142 to 1182 mm/year per tract with an average of 439 mm/year and a standard deviation of 132 mm/year. Higher landscaping irrigation is located in the Northern and warmer parts of the City and in the tracts bordering the Santa Monica Mountains (Figure 15). Lower values are observed in the Downtown area. This pattern relates with previously-identified spatial trends in total water use and greenness level (Mini et al., 2013). Landscaping irrigation is also strongly correlated with income across the City (correlation (r) with income equal to 0.753 significant at p<0.05). During the restrictions period in FY2008-2009, the percent change in irrigation relative to the FY2001-2007 period ranges from -74% to
+109% with an average of -7%. During the increased mandatory restrictions period in FY2010, the percent change in landscaping irrigation varies from -92% to +38% with an average of 35% decrease relative to the FY2001-2007 period. These results indicate a large spatial variation in landscaping irrigation change per tract over the City. Overall, a higher decrease in irrigation is observed during the FY2010 period. We hypothesize that the increase in irrigation observed in some tracts for these two water restrictions periods may be due to uncertainties in the model or restrictions not being efficient in these tracts.

Figure 15: Average landscaping irrigation rate (in mm/year) for the FY2001-2007 period from single-family customers at the Census tract level
Figure 16: Percentage change relative to the FY2001-2007 period in landscaping irrigation rate (in mm/year) for the FY2008-2009 period during voluntary outdoor watering restrictions from single-family customers at the Census tract level.
Figure 17: Percentage change relative to the FY2001-2007 period in landscaping irrigation rate (in mm/year) for the FY2010 period during mandatory outdoor watering restrictions from single-family customers at the Census tract level.
4.5 Conclusion

The current study evaluates outdoor use and landscaping irrigation methods in Los Angeles using water billing data and remote-sensing products. Two methods described by the Pacific Institute in California and a developed remote-sensing NDVI model are applied at the census tract level using aggregated water use data and high-resolution vegetation, land cover and land use products. Quantifying outdoor use in the City is critical to facilitate outdoor water conservation measures and implement revised water pricing/water allowances targeted toward high water-intensive non-native landscaping practices.

Minimum use month and average minimum use methods result in outdoor use estimates that are below outdoor use values compared to other studies including the analysis of data logging measurements in California (Mayer et al., 1999; DeOreo et al., 2011). We note that the two methods underestimate outdoor use due to the existence of landscaping irrigation during the lowest water consumption months in Los Angeles. Landscaping irrigation results from the NDVI model compare reasonably well with irrigation requirement estimates from other studies (Johnson and Belitz, 2012; Salvador et al., 2011). However, when compared with ET estimates from turf grass and irrigated turf grass parks, our model produces lower landscaping irrigation estimates. This is likely due to the fact that residential landscape in Los Angeles is often composed of trees, turf grass and tree-covered turf grass which are likely to produce variable surface evapotranspiration (Pincetl et al., 2012).

Based on the NDVI model, landscaping irrigation use represents, on average, 54% of total single-family water use. This use decreased by 6% and 35% on average across the City during voluntary and enforced water waste provisions (FY2008 and FY2009) and increased mandatory (FY2010) restrictions periods, respectively. Modeling results show large variability in
landscaping irrigation estimates (large standard deviation found in our results) across the City: the standard deviation is equal to one-third of the average estimate during FY2001-2007 and it remains consistent over the three periods (FY2001-2007, FY2008-2009, FY2010). This might be explained by differences in climate zones and in the proportion of trees and turf grass cover in residential landscaping between the tracts. In addition, our results show that income is strongly correlated with landscaping irrigation patterns in the City.

The current work is one of the first to show where and how residential outdoor water is used across a large, semi-arid metropolis. Key results include that outdoor use is strongly related to income and that stringent mandatory restrictions are more efficient at reducing residential irrigation. We advocate that introducing a new threshold in water pricing and/or water allotments specifically targeting customers with higher landscaping irrigation may be effective. Partitioning indoor and outdoor use is important to identify true landscaping irrigation needs for specific vegetated cover and the potential savings (for both money and water) from reducing over-watering. We advocate that the use of dual-metering data is critical to further improve landscape water budgets and models.
4.6 References


http://landsat.usgs.gov/PLSRP.php
http://ledaps.nascom.nasa.gov/


Chapter 5. Effectiveness of drought water restriction policies on single-family water use in Los Angeles

5.1 Introduction

In February 2009, a state of emergency for statewide water shortage in California was declared. The 2007-2009 period represents the 12th driest three-year period in the state (CDWR, 2009). Warmer conditions have been observed in California over the past decade (2000-2010): five of the warmest three-year averages were experienced after 2000 and annual precipitation totals were below average in 2007, 2008 and 2009 for eleven cities in California (including Los Angeles) (CDWR, 2009). In addition, snowpack in Sierra Nevada was at 85% average for water year 2009 and statewide reservoir storage was at 65% average (CDWR, 2009). This decline in available water resources had severe impacts across California. The drought impacts that occurred in 2007-2009 were considered more severe relative to the 1987-1992 drought impacts due to additional court-mandated restrictions that reduced water imported from the Sacramento-San Joaquin River Delta and a population increase by 9 million in California since 1990 (CDWR, 2009). The River Delta water conveyed through the State Water Project is one of the water supply sources managed by the Metropolitan Water District (MWD) that delivers water to Southern California cities including Los Angeles. Regulatory pumping restrictions to protect the fish species were enacted resulting in a decrease by 24% of water delivery from the Delta (City of Los Angeles, Department of City Planning, 2012). MWD receives 46% of the total water delivery capacity of the Delta through the State Water Project and also conveys water from the Colorado River. The Colorado River Basin also experienced water supply shortages: the 2000-2010 period represents the driest eleven-year period on record with average annual runoff being 69% below normal during that period (City of Los Angeles, Department of City Planning, 2012).
These constraints on available water resources triggered water agencies in Southern California to implement various water conservation programs from voluntary conservation measures to more stringent conservation plans including water rate increase (CDWR, 2009). McKee et al. (1993) developed the Standardized Precipitation Index (SPI) as a drought planning tool to identify “dry”, “normal” and “wet” years. The SPI calculation is based on 30 years of precipitation data and is estimated from the probability of precipitation and the standard deviation from the mean. A “wet year” is defined by a SPI value above 1, a “normal year” by a SPI value between -1 and 1 and a “dry year” by a SPI value below -1. Liu et al. (2011) estimated the annual standardized precipitation index for Los Angeles over 1939-2010 and found that the 2000-2010 period had one “wet” year and two “dry years with the lowest SPI value over the 71-year period (Liu et al., 2011) (Figure 18). This result highlights the relatively drier conditions experienced in the City over the 10-year period studied in this paper.

Figure 18: Annual Standardized Precipitation Index (SPI) for water year (October to September) 1939-2010 in Los Angeles (Liu et al., 2011)
The Los Angeles Department of Water and Power provides water to the City: 52% of water supply is purchased from MWD (average over 2006-2010), with the remaining water being supplied by the City-owned Los Angeles Aqueduct and local groundwater (LADWP, 2010). Since 1990, the Los Angeles population has increased by 9% while developed open space areas (including large-lot single-family housing units, parks and golf courses) have increased by 1.54% between 1996 and 2006 in the City (NOAA, C-CAP, 1996-2006; U.S. Census, 1990 and 2010). The 1986-1990 average total water demand in the City was equal to 846*10^6 m^3 (685 594 AFY) and decreased after the implementation of long-term conservation measures in 1990 (LADWP, 2010). The 2001-2005 average total water demand was 3.4% lower than the 1986-1990 water demand level (LADWP, 2010). Single-family water demand represents around 36% of total water demand in the City (LADWP, 2010). Five-year average single-family water demand decreased in 1991-1995 due to the implementation of mandatory watering restrictions, conservation programs and rebates/distribution of indoor water-saving devices. Average single-family water demand in 2001-2005 was equal to 296*10^6 m^3 (239 754 AFY) (around 487 m^3 per household) similar to the 1990 water demand level (LADWP, 2010).

In response to the hydrologic drought conditions and additional stress due to population increase and regulatory water restrictions on the Delta, LADWP implemented an emergency water conservation plan and outdoor watering restrictions to reduce water consumption in 2007-2010. After calling for voluntary restrictions in 2007, mandatory restrictions started being implemented in August 2008 to limit landscape watering and prohibit water-waste usage. In response to regulatory restrictions and increased water shortage conditions, MWD announced a 10% reduction in water supply deliveries to its member agencies starting in July 2009 (City of Los Angeles, Department of City Planning, 2012). Before this announcement by MWD,
LADWP decided to increase the level of its water use restrictions. More stringent mandatory restrictions were implemented in June 2009 to limit outdoor watering to two days per week, combined with an increase in water rates. In addition, the economic recession in 2008/2009 might have also contributed to a decrease in overall total water consumption in the City (LADWP, 2010).

Previous studies have evaluated the effectiveness of water conservation measures in response to drought using a range of approaches. Previous research work (Shaw et al., 1992; Maidment et al., 1985; Shaw and Maidment, 1988) decomposed water use into base use and seasonal use with seasonal use being represented as a stochastic function of temperature and precipitation. This statistic model was used for municipal daily and weekly water use data and it was applied in Los Angeles to measure the drought response in 1990-1991 on municipal weekly water use, with overall good model performance ($R^2=0.95$). Another approach is to compare water use between the same month of two periods prior to and during water restrictions. This method can be easily used by water agencies as it only requires water use data. However, Kenney et al. (2004) demonstrated that this method could underestimate water savings as drought conditions generally contribute to an increase in water demand. Kenney et al. (2004) and Lee and Warren (1981) developed a predictive regression model based on municipal water use data in Colorado and in Iowa, respectively, from pre-restrictions years and used the model to predict water use during restrictions years while accounting for climate variations. The regression models resulted in accurate water savings values across the cities ($R^2$ ranging from 0.62 to 0.77 in Colorado and 0.93 in Iowa). However, in these two studies, the models were built based on one or two years of water use data prior to the restrictions and they evaluated the
impact of the restrictions over short periods of time (few months). The last approach consists of
the development of a multiple linear regression model including multiple independent variables
determining water use and dummy variables to identify the impact of water conservation
policies. This type of regression model was used for total residential and single-family residential
customers at different spatial scales (City, community or household level data) in California
(Renwick and Archibald, (1998)), in Utah (Narayanan et al., (1985)), in Colorado (Kenney et al.,
(2008)) and for cities in the Southwestern United States (Michelsen et al., (1999)). This method
allows one to understand the impact of water restrictions measures while controlling for the
effects of individual household characteristics. However, this model also requires a significant
amount of data available at the appropriate spatial scale and may be more difficult for water
utilities to implement.

The overarching goal of the current study is to analyze the effectiveness of water
restrictions measures successively implemented between 2007 and 2010 to reduce single-family
water use across Los Angeles. We evaluate the change in water use due to voluntary, mandatory
and more stringent restrictions implemented on single-family water use while accounting for the
effect of the economic recession and drier climate conditions. The objectives of our work are to
(1) develop a simple model that provides reasonably accurate results compared to other more
complex regression models and can be transferred to water utilities, (2) quantify the change in
water consumption and identify water use savings during the spring and summer periods in
2007-2010 at the Public Use Microdata Area (PUMA) level in the City of Los Angeles due to
water restrictions, (3) evaluate the change in water use by temperature zone, income range and
lot size category at the same regional spatial scale, and (4) evaluate the relative effectiveness of
the three restrictions measures.

In the current work, a predictive model similar to the third approach described in Kenney et al. (2004) and Lee and Warren (1981) studies, was developed to assess the effectiveness of water restrictions on bimonthly single-family water use over spring (May-June) and summer (July-August and September–October) during three years with gradually increasing water restrictions measures. This model significantly differs from previous modeling work as it is built over seven years prior to restrictions and focuses on single-family housing units in a semi-arid environment. The model easily integrates accessible variables and can be applied by water utilities to assess water savings. The current study is the first to evaluate the effectiveness of water restrictions on single-family water use in Los Angeles under unique circumstances that include water shortages conditions, price and non-price conservation measures, as well as an economic recession. Understanding the effectiveness of conservation measures is critical to develop more accurate water demand forecasting models that account for water conservation programs as a solution to reduce the impact of water shortage conditions.

5.2 Data

5.2.1 Temporal and spatial scales

The City of Los Angeles is composed of 24 Public Use Microdata Areas (PUMA) defined by the U.S. Census that each contains around 100 000 inhabitants (characteristics and number of households in each PUMA are presented in Table 7). The PUMA spatial scale was selected (1) to provide water savings results at a regional scale relevant for LADWP and (2) to collect annual unemployment rate values from the American Community Survey within our study period. The
PUMA is the smallest spatial scale available to collect annual unemployment rate values from the American Community Survey website. The GIS PUMA boundary layer comes from the American Community Survey (2007) (Figure 19).

Table 7: Description of PUMAs

<table>
<thead>
<tr>
<th>PUMA</th>
<th>Average annual water use (m³/hslld) (10-year annual average)</th>
<th>Number of SFR customers</th>
<th>Climate zone</th>
<th>Average lot size (m²)</th>
<th>Median household income (ACS 2006-2010 estimates in 2010 dollars)</th>
<th>Unemployment rate (%) (Min-Max range over 2000-2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05414</td>
<td>470.89</td>
<td>1032</td>
<td>Medium</td>
<td>671.6²</td>
<td>32289¹</td>
<td>5.7, 16.3</td>
</tr>
<tr>
<td>05403</td>
<td>574.85</td>
<td>17644</td>
<td>High</td>
<td>732.53²</td>
<td>52305²</td>
<td>5.8, 12.1</td>
</tr>
<tr>
<td>05424</td>
<td>417.61</td>
<td>21832</td>
<td>Low/Medium</td>
<td>578.92²</td>
<td>50494²</td>
<td>5.9, 15.7</td>
</tr>
<tr>
<td>05409</td>
<td>719.3</td>
<td>31649</td>
<td>High</td>
<td>926.48²</td>
<td>66604³</td>
<td>3.9, 11.8</td>
</tr>
<tr>
<td>05420</td>
<td>402.04</td>
<td>18899</td>
<td>Low</td>
<td>543.73¹</td>
<td>77628³</td>
<td>4.5, 11.6</td>
</tr>
<tr>
<td>05419</td>
<td>369.1</td>
<td>19699</td>
<td>Medium</td>
<td>569.75²</td>
<td>37415²</td>
<td>8.2, 14.9</td>
</tr>
<tr>
<td>05411</td>
<td>528.97</td>
<td>20368</td>
<td>Low/Medium</td>
<td>655.12²</td>
<td>64602³</td>
<td>5.7, 9.4</td>
</tr>
<tr>
<td>05413</td>
<td>676.37</td>
<td>16662</td>
<td>Medium</td>
<td>1018³</td>
<td>43594²</td>
<td>7, 12.9</td>
</tr>
<tr>
<td>05418</td>
<td>419.99</td>
<td>5065</td>
<td>Medium</td>
<td>562.03¹</td>
<td>26692¹</td>
<td>8.6, 15.2</td>
</tr>
<tr>
<td>05417</td>
<td>390.66</td>
<td>5363</td>
<td>Medium</td>
<td>498.99¹</td>
<td>26078¹</td>
<td>7.1, 14.2</td>
</tr>
<tr>
<td>05401</td>
<td>859.97</td>
<td>38173</td>
<td>High</td>
<td>1050.5²</td>
<td>73281³</td>
<td>3.7, 12.6</td>
</tr>
<tr>
<td>05405</td>
<td>589.63</td>
<td>13956</td>
<td>High</td>
<td>795.14²</td>
<td>47023²</td>
<td>4.2, 13.2</td>
</tr>
<tr>
<td>05422</td>
<td>425.36</td>
<td>6119</td>
<td>Medium</td>
<td>490.46¹</td>
<td>29431¹</td>
<td>6.3, 14.3</td>
</tr>
<tr>
<td>05416</td>
<td>381.8</td>
<td>30984</td>
<td>Medium</td>
<td>615.87²</td>
<td>50791²</td>
<td>6.4, 13.9</td>
</tr>
<tr>
<td>05407</td>
<td>590.99</td>
<td>17658</td>
<td>Medium/High</td>
<td>731.11²</td>
<td>45045²</td>
<td>4.8, 13.5</td>
</tr>
<tr>
<td>05406</td>
<td>588.49</td>
<td>13903</td>
<td>Medium</td>
<td>681.73²</td>
<td>47363²</td>
<td>6.6, 16.1</td>
</tr>
<tr>
<td>05421</td>
<td>375.89</td>
<td>20936</td>
<td>Medium</td>
<td>522.09¹</td>
<td>33502¹</td>
<td>10.8, 16.8</td>
</tr>
<tr>
<td>05404</td>
<td>586.19</td>
<td>24856</td>
<td>High</td>
<td>969.63³</td>
<td>52238²</td>
<td>5.6, 14</td>
</tr>
<tr>
<td>05412</td>
<td>625.21</td>
<td>14804</td>
<td>Medium</td>
<td>720.55²</td>
<td>57321²</td>
<td>5.3, 12.5</td>
</tr>
<tr>
<td>05423</td>
<td>401.64</td>
<td>14607</td>
<td>Medium</td>
<td>488.44¹</td>
<td>31063¹</td>
<td>7, 14.3</td>
</tr>
<tr>
<td>05415</td>
<td>374.68</td>
<td>9793</td>
<td>Medium</td>
<td>655.92²</td>
<td>34974²</td>
<td>6.1, 15.8</td>
</tr>
<tr>
<td>05410</td>
<td>1008.3</td>
<td>39889</td>
<td>Low/Medium</td>
<td>1464.4³</td>
<td>97302³</td>
<td>4.6, 11</td>
</tr>
<tr>
<td>05408</td>
<td>785.37</td>
<td>33169</td>
<td>High</td>
<td>1016.7³</td>
<td>60054²</td>
<td>4.7, 12.6</td>
</tr>
<tr>
<td>05402</td>
<td>708.16</td>
<td>26662</td>
<td>High</td>
<td>1021.2³</td>
<td>64180³</td>
<td>4.5, 13.7</td>
</tr>
</tbody>
</table>

¹Values below the 25th percentile (lower quartile) in the set of values
²Values between the 25th and 75th percentiles in the set of values
³Values above the 75th percentile (upper quartile) in the set of values
5.2.2 Water consumption data

Single-family residential (SFR) water billing and lot size data were provided by LADWP for the period from January 1, 2000 to December 31, 2010. The initial database contained approximately 480,000 individual single-family residential customers identified by census tract numbers. Less than 1% of the records (500 to 600 single-family customers) did not match the U.S. Postal Service database and were removed. The LADWP reading period is bi-monthly.
(every 60 days) and the utilities pro-rated the data to calculate monthly water consumption.

We aggregated single-family water use data at the Public Use Microdata Area (PUMA) spatial scale. The average customer lot size was calculated for each PUMA unit. Monthly water consumption data was normalized by the number of SFR accounts or SFR customers and calculated per bimonthly period in cubic meter per SFR customer (or household) (for July-August, September-October and May-June) for each fiscal year. A fiscal year is defined as the period from July 1st to June 30th of the current year and the notation FY2001 (for example) reflects the current year.

5.2.3 Climate data

Daily precipitation data were collected from the Los Angeles Department of Public Works (LADPW) ALERT gauges; 47 stations with complete precipitation records were used. Daily maximum temperature data were retrieved from National Climatic Data Center (NCDC) stations from 2000 to 2010. Four stations with complete temperature records were used and four additional stations with more than nine years of data were included in the analysis. Inverse-distance weighting was used to estimate bimonthly precipitation totals from daily precipitation values and average daily maximum temperature values for each bimonthly period at the centroid of each PUMA for 2000-2010.

5.2.4 Unemployment data

The recent economic recession started in December 2007 until June 2009 and triggered an increase in the unemployment rate from 5% to 9.5% across the U.S. (U.S. Bureau of Labor Statistics, 2012). Even after the recession, the unemployment rate kept increasing to reach its
highest value of 10% in October 2009. California experienced one of the highest unemployment rates among the 50 States: the unemployment rate increased from 5.4% in July 2007 to 12.4% July 2010. Available annual data was collected from the American Community Survey from 2005-2010 at the PUMA level. The Public Use Microdata Areas are statistical geographic areas with a population threshold of 100,000 and built from counties and census tract boundaries (U.S. Census, 2010). City-level annual unemployment rate values were collected from 2000 to 2010. A linear regression was developed between City-level unemployment rate values and each PUMA unemployment rate values from 2005 to 2010. The 2000-2004 PUMA missing values were predicted based on the regression coefficients and the 2000-2004 City-level annual unemployment rate values.

5.3 Methods
5.3.1 Water pricing structure

In the early 1990s, LADWP adopted an emergency water conservation plan Ordinance and revised its water rate structure (LADWP, 2010). The current pricing structure is an increasing block rate structure starting with a lower first tier rate (Tier 1) corresponding to a specified water allocation, and a second higher tier rate (Tier 2) for every additional billing unit (1 Hundred Cubic Feet (HCF) or 2831.5 Liters or 748 gallons) above the previous amount for the billing cycle (LADWP, 2010). Customers receive their water billing bimonthly. The Tier 1 residential water allocation for single-family customers is calculated based on lot size and a temperature zone identified for each ZIP code by LADWP. There are three temperature zones (low, medium, high) in the City based on reference evapotranspiration measured by the California Irrigation Management Information System stations (CIMIS). Households located in a
higher temperature zone receive a higher water allocation under Tier 1. Additional volumes to the Tier 1 usage block can be allocated for households with more than six persons. Water rates are directly proportional to the amount of water consumed within each block or Tier and there are no fixed charges (generally used to maintain infrastructure). LADWP (2010) advocates that this structure promotes water conservation while reducing consumption and customer bill cost. The water conservation plan was updated in response to the drought conditions in 2007-2010 to include phases with higher penalties, increasingly more stringent restrictions and prohibited uses to reach higher reductions by phase (LADWP, 2010).

5.3.2 Restrictions

In response to the drought conditions, voluntary water restrictions were first implemented in June 2007 throughout fiscal year (FY) 2008 (a fiscal year is defined as the period from July 1st of the preceding year to June 30th of the current year). In August 2008, mandatory water restrictions were enacted (corresponding to Phase I of the plan) to prohibit water-waste practices, irrigation between 9am and 4pm and limit landscape watering when using sprinklers or similar non-conserving techniques. In June 2009, mandatory water conservation requirements were increased (corresponding to Phase III) with more stringent water restrictions including a two-day landscaping irrigation per week, increased restrictions on the time and frequency of landscaping irrigation for the use of sprinklers (spray head, bubblers, standard rotors and rotary heads) and additional prohibited water-waste usage such as car washing. Price conservation measures were also enacted in June 2009 throughout FY2010 corresponding to a reduction in Tier 1 water allocation by 15% and an increase in Tier 2 rates in order to trigger higher reductions and provide revenue to LADWP to face water shortage conditions. Specifically, Tier 2 rate for
single-family customers was increased by 44% in June 2009 under the shortage year water rates.

Table 8 summarizes the conservation measures implemented in 2007-2010. It is worth noting that these measures aimed at reducing the duration and frequency of landscaping irrigation with penalties for non-compliance but they do not set volume conservation targets that might be logistically more difficult to implement.

Table 8: Summary of drought water conservation measures implemented in 2007-2010

<table>
<thead>
<tr>
<th>Water conservation measures implemented between June 2007 and June 2009 in response to water shortage conditions</th>
<th>June 2007 Voluntary conservation</th>
<th>August 2008 Mandatory restrictions (Phase I)</th>
<th>June 2009 Increased mandatory restrictions and price conservation incentive (Phase III+Price)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Voluntary conservation measures called by the Mayor</td>
<td>• Voluntary conservation • No irrigation between 9am and 4pm • Limitation in frequency and duration of landscape irrigation depending on the irrigation technique (for spray head, bubblers, standard rotors and multi-stream rotary heads) • Limitation of water waste practices (no washing vehicles with a hose, no use of a water hose to wash paved surfaces, no irrigation during rain, no watering with excess water flow)</td>
<td>All previous prohibited uses + • Two-day watering allowed per week only • No washing of vehicles in streets • No filling of residential pools and spas with potable water • Increased reductions in watering times and frequency for all types of irrigation nozzles</td>
<td>• Implementation of water shortage year rate: Decrease in single-family household water allocation by 15% Increase in second Tier rate by 44% for single-family customers</td>
</tr>
</tbody>
</table>
5.3.3 Model development

The impact of water restrictions on single-family water use was assessed using a linear mixed-effects regression model developed using panel data at the PUMA spatial scale for the pre-restriction period from FY2001 to FY2007. The model was then used to calculate predicted single-family water use during the restriction period from FY2008 to FY2010. Our predictive model was built upon findings from previous research studies and also significantly differs from these studies in several ways: the model was developed over a longer time period (7 years) prior to restrictions and analyzes the impact of successively increasing water restrictions measures over 3 years. It focuses on single-family customers to evaluate potential water savings per bimonthly period in spring and summer.

The dependent variable is bimonthly single-family water use at the PUMA level (in m$^3$ per SFR customer). The independent variables are bimonthly precipitation totals (mm), average maximum daily temperature (°C) and percent unemployment rate. Only the spring and summer bimonthly periods (May-June, July-August and September-October) were included in the model development and for predictions to control for seasonal variations. The spring and summer months are also periods of high water demand and when larger water savings need to be achieved. The developed linear mixed-effects model based on the pre-restriction (FY2001-2007) data is:

$$\ln(y_{i,t}) = \beta_0 + \beta_1 x_{1,i,t} + \beta_2 x_{2,i,t} + \beta_3 x_{3,i,t} + dummy_{Jul-Aug} + dummy_{Sep-Oct} + e_{i,t}$$

$$e_{i,t} = a_i + u_{i,t}$$

(eq. 8)

where $y_{i,t}$ is single-family water use in m$^3$ per household per bimonthly period (t in May-June, July-August and September-October), $\beta_1$ is bimonthly precipitation total in mm, $\beta_2$ is the average...
maximum daily temperature in degree Celsius for the bimonthly period and \( \beta_3 \) is the unemployment rate in percentage, dummy_{Jul-Aug} is a dummy variable equal to 1 for July-August and 0 for the other bimonthly periods and dummy_{Sep-Oct} is a dummy variable equal to 1 for September-October and 0 for the other bimonthly periods. The error term is composed of the idiosyncratic error \( (u_{i,t}) \) and unobserved effects \( a_i \) that are estimated at the PUMA level and are time-invariant, accounting for PUMA-level characteristics. First, the dependent variable and predictors for May-June, July-August and September-October from FY2001 to FY2006 were used from the original dataset to develop the regression coefficients (pre-restriction calibration period). The model R\(^2\) value was high equal to 0.98. Then, the model was tested for FY2007 (also pre-restriction validation period) to assess model performance on an independent data set and make accurate predictions. The R\(^2\) value for the validation period was equal to 0.98.

Single-family water use was predicted for each PUMA for May-June, July-August and September-October periods in FY2008, FY2009, and FY2010 based on the resultant regression coefficients, precipitation, temperature and unemployment rate values. These predicted values represent water use that would have been consumed during the same period without the implementation of water restrictions. Predicted water use was then compared to actual water use in FY2008, FY2009 and FY2010 for the same bimonthly periods to calculate the difference in water volume due to the restrictions for each PUMA and each bimonthly period. The predicted and observed water use values were tested using a one-tail t-test that was significant for the prediction period (FY2008-FY2010).
5.3.4 Analysis

The following metrics were used to analyze model results and evaluate the difference in water use for each bimonthly period (May-June, July-August and September-October) during the water conservation measures from FY2008 to FY2010:

- Predicted and observed average household water use at the PUMA and City levels (in m$^3$ per household),

- Percent water use change by PUMA: ratio of the difference between predicted and actual water use to predicted water use, multiplied by 100, for each spring/summer bimonthly period between FY2008 and FY2010,

- Mean percent water use change and standard deviation by temperature zone: average percent water use change for the PUMAs in each temperature zone. Temperature zones were defined by LADWP based on reference evapotranspiration and categorized as low, medium, high temperature zones. Each PUMA was identified in one or two temperature zones if overlaying one or two temperature zones (Table 7). In addition to the average, the standard deviation was calculated for each category,

- Mean percent water use change and standard deviation by income range: average percent water use change for 25% of PUMAs with the lowest median household income (below the 25th quantile), average percent water use change for 25% of PUMAs with the highest median household income (above the 75th quantile) and average percent water use change for PUMAs between the 25th and 75th quantiles in median household income (Table 7). The standard deviation was also calculated for each income range.
Mean percent water use change and standard deviation by lot size category: average percent water use change for 25% of PUMAs with the lowest average lot size (below the 25\textsuperscript{th} quantile), average percent water use change for 25% of PUMAs with the highest average lot size (above the 75\textsuperscript{th} quantile) and average percent water use change for PUMAs between the 25\textsuperscript{th} and 75\textsuperscript{th} quantiles in average lot size (Table 7). The standard deviation was also calculated for each lot size category.

5.4 Results

5.4.1 Impact of water restrictions on City average single-family water use

Positive differences between predicted and observed city average water use were observed in spring and summer of FY2009 and FY2010 (Figure 20). Observed city-average household water use was the highest in July-August 2007 equal to 140 m\textsuperscript{3}/household, which was higher than the City 2000-2010 average water use of 102 m\textsuperscript{3}/household. Observed water use decreased over the spring and summer periods during the water restrictions to reach the lowest value of the period equal to 94 m\textsuperscript{3}/household in May-June 2010. Predicted city average household water use was similar to observed water use in FY2008 with a water use difference smaller than 2m\textsuperscript{3}/household. The difference between predicted and observed water use increased in FY2009 and FY2010 after mandatory restrictions on the time and frequency of irrigation were implemented. Higher differences in water use were achieved in FY2010: water savings ranged from 32m\textsuperscript{3}/household in July-August 2009, to 23 m\textsuperscript{3}/household in September-October 2009 and 25 m\textsuperscript{3}/household in May-June 2010.
Voluntary restrictions that started in June 2007 did not trigger average household water use savings at the City level during the spring and summer periods of FY2008. Mandatory restrictions in FY2009 and FY2010 were found to be more effective. Significant savings were achieved during the spring and summer periods of FY2009 with the implementation of mandatory restrictions and greater savings were realized after June 2009 when outdoor watering was limited to two days per week and Tier 2 rate was increased. The highest water use savings
correspond to a reduction of 23% in average single-family water use in July-August 2009. Reductions in water use were smaller in the spring and summer periods of FY2009 ranging from 4% to 15%, compared to reductions of 19% to 23% during the spring and summer periods of FY2010.

5.4.2 Effectiveness of water restriction policies at the PUMA spatial scale and influence of climate zone, lot size and income on water savings

From July-August 2007 to May-June 2008, there was no decrease in water use compared to predicted use across the temperature zones except for the PUMAs in the low temperature zone that exhibited very low reductions (Figure 21). Significant water savings were observed after the implementation of mandatory restrictions on the frequency and duration of outdoor watering in July-August 2008. The highest water savings were achieved for all zones in July-August 2009 after implementing a two-day per week watering restriction, an increase in Tier 2 rate and a decrease in household allocation. Water savings in July-August 2009 ranged from 19% to 25% of predicted use, with the highest savings for the PUMAs in the higher temperature zone. The combination of a price increase with more stringent watering restrictions had a larger impact on reducing water use across the temperature zones. PUMAs in the high temperature zone (corresponding to higher water users since their Tier 1 water allocation is larger) were showing higher reductions in water use from May-June 2009 to May-June 2010 compared to the other zones. It was not possible in our study to differentiate the impact of a price increase and non-price watering restrictions programs on single-family water use, both implemented in June 2009.
Figure 21: Percent mean water use change (%) and standard deviation from predicted water use per temperature zone during restrictions by summer bimonthly period. Three temperature zones were defined by LADWP based on reference evapotranspiration (low, medium, high). The PUMAs regions were identified in one or two zones if they were overlaying one or two temperature zones: N=1 PUMA in low temperature zone, N=3 in low/medium temperature zone, N=12 in medium temperature zone, N=1 in medium/high temperature zone and N=7 in high temperature zone.
Higher water use savings were achieved across income range and lot size categories in spring and summer of FY2010 (Figures 22 and 23). There is a high significant correlation (correlation equal to 0.7 at p<0.05) between median household income and average lot size. From July-August 2007 to May-June 2008, there were no significant water savings except for the PUMAs in the lower income and lower lot size category. Positive water use savings were estimated in July-August 2008 and greater savings were observed after the implementation of more stringent watering restrictions and price increase in June 2009. In both figures, mandatory restrictions had the largest impact on PUMAs in the 75th quantile (higher income and higher lot size). This is similar to Renwick and Archibald (1998) study on the impact of irrigation restrictions on single-family water use in Santa Barbara (CA): they found that reduction in water use of low density households (lot size above 0.55 acre) was higher than higher density households, likely due to higher margin for water conservation.
Figure 22: PUMA percent mean water use change (%) and standard deviation per income range during restrictions by summer bimonthly period (water use change is expressed as the ratio of the difference in water use between predicted and actual values to predicted values).
Figure 23: PUMA percent mean water use change (%) and standard deviation per average lot size range during restrictions by summer bimonthly period (water use change is expressed as the ratio of the difference in water use between predicted and actual values to predicted values).

5.5 Discussion

Our findings support previous studies in California, Colorado, Texas and Iowa analyzing the impact of water restrictions in response to drought (Shaw et al. (1992), Kenney et al. (2004), Shaw and Maidment (1988), Lee and Warren (1981)). However, it is somewhat difficult to make direct comparisons to these findings as they investigated municipal water use that includes not only single-family residential water consumption but also all municipal water consumptions. Shaw et al. (1992) in their study of the effectiveness of the voluntary and mandatory restrictions
in San Diego and Los Angeles in 1991 (during the 1987-1992 drought period) found an average 25% reduction in municipal water use in 1991 in Los Angeles and a 36% reduction in summer 1991 due to mandatory restrictions. In the early 1990s, total municipal water consumption in Los Angeles was higher than 2010 municipal water consumption level. In addition, the 2000-2010 period experienced drier conditions and additional regulations were applied on water supply in California. Our results showed that it was still possible to reduce single-family water consumption with water use savings in FY2010 similar to average water use reduction in 1991.

These studies also confirm the effectiveness of mandatory water restrictions. During the 1976-1977 drought, water use savings of 16% and 30% were estimated in Los Angeles and San Francisco respectively following the implementation of mandatory water restriction measures (CDWR, 2008). Another study by Kenney et al. (2004) analyzed the effectiveness of water restrictions of eight water providers in Colorado in response to the 2002 drought. Mandatory water restrictions provided a reduction in water use by 18-56%, higher than the 4-12% reductions in water use due to voluntary restrictions observed in the selected cities (Kenney et al., 2004). Shaw and Maidment (1988) analyzed the impact of combined water conservation policies on municipal use that included mandatory restrictions (reduced frequency of lawn watering, maximum monthly water use limit), prohibited water-wasting practices and price increase, and found a 33% decrease in water use compared to forecasted use.

Voluntary restrictions did not lead to reduction in water use in our study and were found to be less effective than mandatory restrictions. Findings on voluntary restrictions are still debated in the literature. In Shaw et al. (1992) study comparing Los Angeles mandatory restrictions and San Diego voluntary restrictions during the 1987-1992 drought, results showed a
maximum reduction of 27% achieved during the summer 1991. It indicates that the voluntary restrictions were effective with savings comparable to the mandatory restrictions in Los Angeles in 1991. Lee and Warren (1981)’s study also demonstrated the higher effectiveness of mandatory restrictions but they also concluded that the credibility of the local government relative to water shortage information could play a key role in achieving effective reductions through voluntary conservation measures. Communities’ rules may also have a negative impact on the effectiveness of mandatory watering restrictions as shown by Ozan and Alsharif (2013). In this study, Ozan and Alsharif (2013) looked at the transition from twice-a-week to once a-week irrigation mandatory restrictions in several communities in Florida and found an increase of 7% in water use after implementing the more stringent restrictions due to contradictory policies between the City and homeowners associations.

Some of these previous studies also provide some insights on water savings per level of water consumption: mandatory outdoor watering restrictions (on time and frequency of watering) were showed to have a larger impact on residential water use of high water users (Kenney et al., (2008), Narayanan et al., (1985)). The same study by Kenney et al. (2008) in Aurora (CO) also showed that a price increase led to higher reduction in single-family water use of low water users. They also noted that low water users are also more likely to have less margin to reduce their water consumptions.

5.6 Limitations

The limitations in our study reside in the spatial scale and the lack of information to differentiate the impact of price and non-price conservation measures. The PUMA spatial scale was selected to be able to collect available annual census data on unemployment rate between
2000 and 2010, being a key indicator of economic recession. However, results based on water savings per lot size and income range at the PUMA level may be less significant at this spatial scale than household-level studies.

We could not distinguish in our model between the impact of price and non-price restrictions programs on single-family water demand, implemented at the same time in June 2009. We still observed that mandatory restrictions based on limiting time and frequency of lawn watering had a smaller impact on water use than the combination of price increase and restricting irrigation to only two days per week (on top of the previous restrictions). There is a lack of information to understand what would be the impact of these individual restrictions. A previous study by Kenney et al. (2008) showed that there were no additive effects between pricing and watering restrictions measures and that water users were less sensitive to price when drought restrictions were in place. They also found that higher water users achieved higher reductions in water use due to watering restrictions compared to pricing measures and that lower water users were more sensitive to an increase in price than high water users under restrictions (Kenney et al., 2008). Another study by Michelsen et al. (1999) showed that increasing the number of conservation programs implemented decreased the effectiveness of each individual program. Hence, it may not be necessary to combine price increase, quantity restrictions and watering restrictions if efficient reductions in water use can be achieved by targeting higher water users with only mandatory watering restrictions.

This relatively simple model was developed based on a limited number of independent variables and easily accessible data. We had to assume that some social characteristics impacting water use would remain almost the same over the study period. The linear mixed-effects model already accounts for PUMA-level specific characteristics constant over time. Some of the key
social characteristics included in multiple regression water demand models that are used to analyze water restrictions (in particular in Renwick and Archibald (1998), Michelsen et al. (1999) and Kenney et al. (2008) studies) include income and household size. In Los Angeles, the median change in median household income at the PUMA level was 8.8% between 2005 and 2010 relative to 2005 and the median change in household size at the PUMA level was 3% between 2005 and 2010 relative to 2005 (ACS, 2005-2010). High variability in these variables would require to include them in future prediction models.

5.7 Conclusions

Our study demonstrates that the more stringent mandatory watering restrictions combined with a price increase led to higher water use savings than the two preceding restriction periods for PUMA-average single-family water use. The highest water savings ranging from 19% to 23% were achieved in spring and summer of FY2010 due to a combination of stringent mandatory restrictions that included limiting irrigation to two days per week, limiting the time and frequency of irrigation, water rate increase and a decrease in the household allocation quantity. The City average household water use was reduced by a maximum of 23% in July-August 2009. Voluntary watering restrictions implemented during FY2008 were less effective and did not lead to a decrease in water use at the City level. After identifying PUMAs by temperature zone according to LADWP classification, we found that PUMAs in the high temperature zone (corresponding to higher water users) achieved higher reductions in water use during FY2010 and had higher reductions compared to the other temperature zones in FY2010.

The relatively simple model developed in this study, based solely on climate and unemployment data, provides can accurately predict single-family water use at the PUMA level
under successive water conservation restrictions implemented over three years. It provided reasonable estimates of water savings at the PUMA level and can be used as a tool by water utilities to incorporate into water demand projections at a large community scale. The model can be transferred to water utilities to better evaluate the potential water reductions of future targeted conservation measures and reduce the adverse impacts of drought. This first study of the 2007-2010 drought restriction period was developed under unique climate and regulation circumstances, focusing on single-family customers to help implement highly effective conservation measures. Based on the City-level average water savings in FY2009 and FY2010, the restriction of outdoor watering to two days per week with a price increase is a more effective approach than limiting the time and frequency of irrigation during the day. These conservation measures also seemed logistically easier to implement, enforce and deliver a clear message to customers. How these measures interact with each other and the individual effectiveness of these programs should be further investigated with additional detailed information.

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5.8 References


Chapter 6. Conclusion and key contributions

The overarching goal of this research work is to provide a better understanding of single-family residential water use dynamics and develop models using remote-sensing vegetation products to evaluate landscaping irrigation and potential outdoor use savings. Such landscaping irrigation models can be ultimately utilized as tools to predict water use and target efficient conservation measures. This research work contributes to advance understanding on landscaping and irrigation practices and can help inform the implementation of permanent outdoor conservation programs. Conservation programs are a key component of water management strategies in semi-arid cities such as Los Angeles and can help meet conservation targets and reduce reliance on imported water. Conserved water represents a sustainable alternative resource in the local water supply portfolio that also includes recycled water and groundwater. This work shows that the availability of individual water use data for detailed research and the deployment of dual metering throughout cities are two critical elements for further investigation of the dynamics of urban water use and the development of more accurate small-scale landscaping models.

The main results and contributions from this research work address the initial science questions:

*What are the patterns and key drivers in residential water use in Los Angeles over 10 years and how does their analysis contribute to inform future water policies? Which neighborhoods should be targeted for future conservation measures?*

Single-family water use across the City of Los Angeles is primarily influenced by household income, landscape greenness, tier water rates and Tier 1 water allotment. Single-family water use
and vegetation patterns are positively related, indicating that greener neighborhoods (located in the Northern part and coastal regions of the City) have higher water use and tend to be spatially clustered. Further, precipitation only accounts for a small portion of the observed variance in vegetation greenness suggesting that residential landscaping irrigation primarily supports temporal and spatial vegetation greenness across the City. This study contributes to estimate the impact of the current water rate structure on single-family water use and proposes alternative incentives for conservation. Results show that low, medium and high water users respond similarly to changes in Tier 2 rate and that Tier 2 price elasticity is lower than Tier 1 price elasticity. Tier 2 price seems less effective in reducing water use and does not represent an incentive for conservation for the targeted customers. Investigation of the key predictors across different customer groups provides insights on consumer behavior that could be used by the City and LADWP to refine incentives for water use reduction and to improve efficient use of water while paying careful attention to equity concerns. Neighborhoods with high residential water use levels tend to be wealthier and be spatially clustered. This suggests that revising rates in Tier 2, or adding a third tier may help with conservation efforts and bring additional revenues for the water utilities. While previous phases targeted indoor water consumption, the next phase of conservation will likely need to target outdoor water use through alternative landscape planting and irrigation system efficiency.

What are the commonly-used methods to quantify outdoor water use and how do they perform in semi-arid cities such as Los Angeles?

Two methods to estimate outdoor water use in California described by the Pacific Institute, include estimating the minimum month use and the average minimum water use. These models
result in lower outdoor use estimates than previously-published values in California and in other semi-arid regions. It is likely that outdoor water use is underestimated by these models due to the occurrence of landscaping irrigation during the lowest water consumption months in semi-arid cities such as in Los Angeles. This suggests that traditional methods based solely on water billing data do not suffice to estimate residential outdoor use across the City.

**Does the use of remote-sensing vegetation products provide improved estimates of landscaping irrigation over Los Angeles and can it be used as a predictive model?**

A remote-sensing model based on remotely-sensed vegetation products and water billing data was developed to predict landscaping irrigation at the census tract level. Our results show that landscaping irrigation represents on average 54% of total single-family water consumption and decreased by 35% on average during the mandatory restriction period (FY2010) across the census tracts. The model seemed to perform better in the tracts that have a higher greenness level and it showed large variability in landscaping irrigation over the City. Household income and landscaping irrigation patterns were also found to be strongly correlated. This modeling work contributes to a better understanding of the partition between indoor and outdoor use and suggests that advanced approaches may be needed for utilities in the absence of detailed household water use metering and lack of dual metering of indoor and outdoor water use. In addition, it evaluates and compares models for predicting landscaping irrigation and encourages the development of advanced transferable models integrating remote-sensing vegetation products.
What are the impacts of water restrictions in Los Angeles on residential water use during drought period and are they effective?

During the last 2007-2009 drought period in Los Angeles, mandatory restrictions resulted in higher reduction in single-family water use and were more effective than voluntary conservation. Stringent mandatory watering restrictions combined with a price increase and a decrease in Tier 1 water allotment led to higher water use savings in FY2010 than the two preceding restriction periods for PUMA-average single-family water use. Water savings ranged from 19% to 23% in spring and summer of FY2010. These stringent mandatory restrictions more specifically included limiting irrigation to two days per week, limiting the time and frequency of irrigation, prohibiting water waste usage, a water rate increase and a decrease in the household allocation quantity. The City average household water use was reduced by a maximum of 23% in July-August 2009. Voluntary watering restrictions implemented during FY2008 were less effective and did not lead to a decrease in water use at the City level. The relatively simple model developed in this study based on climate and unemployment data was used to predict water use during restrictions to provide reasonable estimates of water savings at the PUMA level. It can be used as a tool by water utilities to incorporate into water demand projections at a large community scale.

The modeling tools developed to estimate landscaping irrigation as well as to evaluate the effectiveness of water restrictions provide critical information for water conservation and sustainable water demand management in semi-arid cities in the context of climate change uncertainty. Further research built on this work can help evaluate the impacts of climate and land cover change scenarios on landscaping irrigation using the developed models. It is critical to better understand the costs, benefits and challenges related to a drier climate or growing urban
forest (Pincetl et al., 2012). Several scenarios focusing on increasing temperature or growing tree canopy cover or turf grass areas can be tested in the remote-sensing model to estimate the costs related to landscaping irrigation. These costs added to maintenance and planting costs can be included in a cost-benefit analysis to evaluate the potential net benefits of urban forest and guide the urban planning decisions. Urban forest has been shown to have environmental, economic and health benefits: Pincetl et al. (2012) demonstrated decreasing air temperature with higher tree canopy cover in Los Angeles. This approach will provide the necessary tools to better inform urban planning decisions related to urban landscape in the City.