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FORECASTING THE EFFECTS OF CLIMATE, POPULATION, PRICE, AND CONSERVATION BEHAVIOR ON WATER USE IN LOS ANGELES, CALIFORNIA

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ABSTRACT

In 2015 California entered its fourth year of record-breaking drought which led many to question the sustainability of future water supply in the state, especially in Southern California. With over 90% of its water imported from outside the city, Los Angeles has been greatly impacted by this instability. Due to climate change, population growth, groundwater contamination, and competing demands, Los Angeles' water sources (Los Angeles Aqueduct, Colorado River Aqueduct, California Aqueduct, local groundwater, and reclaimed water) are subject to various stressors, which make projections of water supply and planning for system sustainability challenging. Reductions in availability from each water source will influence the price and availability of residential water and inevitably lead to greater need for conservation, and for the development of new sources of water supply. Understanding the future Los Angeles water system in the context of a growing population and climate change thus merits careful investigation.

The overall objective of this work was to evaluate the factors that impact water demand in Los Angeles as well as apply and compare various modeling techniques to forecast water demand. This was accomplished by (1) assessing the sustainability of each of the water sources that supply Los Angeles under present and future conditions using a system characterization and analysis. (2) Analyzing the importance of various factors influencing water demand in Los Angeles using multiple linear regression and artificial neural network models. (3) Projecting water demand in Los Angeles until 2050 under various scenarios of price, precipitation, temperature, conservation and population. (4) Developing an agent based model of Los Angeles

water demand that provides insight into interactions among consumers and the Los Angeles Department of Water and Power (LADWP) water management system.

First, the sustainability of each of the water sources that supply Los Angeles under present and future conditions was analyzed using a system characterization and analysis. The results of the study showed that of the five main water sources that supply Los Angeles, a majority will be impacted by climate change, water quality, energy, and cost stressors. While the expansion of water demand management and agricultural water transfers can help address the challenge of increasing demand, the impacts of climate variability and competing demands are likely to limit their potential.

Next, multiple linear regression (MLR) and artificial neural network (ANN) models were used to evaluate historical (1970-2012) water demand data for Los Angeles to assess the importance of water price, population, conservation methods, temperature, and precipitation on influencing water demand. Results indicated that the multiple linear regression models were comparable to the artificial neural network models in ability to describe historical water demand data. Models developed for and fitted to monthly data were more accurate in estimating water demand compared to models based on yearly data. Temperature, precipitation, conservation, population, and water price were all significant in impacting monthly water use in Los Angeles. Additionally, fitting of the data with the MLR models revealed that price and conservation impacts have significantly counteracted the impact of population growth on water demand.

After the variables significant in impacting water demand were identified through the modeling of the historical water demand data, MLR modeling with the same variables, water price, population, temperature, precipitation, and conservation, were used to project Los Angeles water demand until 2050. The model used projections of four global climate models with two CO_2 emission scenarios, as well as high, medium, and low scenarios of population, water pricing, and conservation to generate an envelope of forecasts of water demand in Los Angeles from 2013 to 2050. Results of the forecasting with the MLR models under the various scenarios indicated that the effects of climate change on water demand (not supply) are projected to be modest. Without the introduction of increased water pricing and conservation methods, water demand in Los Angeles has the potential to nearly double from 130 billion gallons per year in 2013 to 250 billion gallons in 2050. However, more likely scenarios of population growth, conservation implementation, climate change, and pricing structures yielded predicted increases in water demand of approximately 30 percent, to a level of 170 billion gallons per year by 2050.

Finally, an agent based model for water demand was developed to understand the interactions between Los Angeles water consumers and management actions by the LADWP. The model was calibrated with historical (1970-2012) data for water demand. In the model, consumers react to changes in water supply variability and adjust their conservation levels. These changes in conservation help reduce the dependability of imported water in Los Angeles. Projections of various water variability scenarios showed that consumers respond to advertisement intensity and shifts in contact rates with other consumers, which allows for more system resiliency. This is evident in the present day drought in Los Angeles in which water demand is being reduced. Results of the agent based model also demonstrated that high variability in water supply can increase water demand by up to 2.67 times from 2013 to 2050. Validation of the model indicates the agent based model can adequately project water demand in the future under changes in population, climate, and water supply reliability.

Water management in Los Angeles needs to be understood as a highly integrated social, engineered infrastructure, economic, and ecological system. Previously, research efforts in Los Angeles have been focused on understanding the hydrological components of the problem without the consideration of social impacts and human behavior. Consideration of the human decision making and adaptive responses involved is important because it affects water resources management and planning. Adaptive agent modeling can provide insights into how consumer-manager-supplier interactions impact overall water system performance and evolution.

The projection models proposed in this research offer a means of assessing potential impacts of water conservation initiatives, restrictions on water demand, pricing incentives, and other water system management options. They also provide insight into the relative importance of environmental conditions that affect water supply on water demand. By viewing the Los Angeles water supply system as a complex system, identification of areas in which there are problems as well as possible solutions can be evident. The city of Los Angeles is still growing and dependency on transferred water is inevitable, so understanding the complexity of the system is imperative to develop sustainable solutions to water scarcity and reliability.

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Chapter 1 : Introduction

1.1 Introduction

The City of Los Angeles, with a 2015 population of approximately 3.9 million people and a combined statistical area population of 17.8 million, was founded in a semi-arid region of the United States (Schroeder 2011). The area is prone to drought with very limited local water sources to accommodate the growing population. Although the population growth of Los Angeles has slowed since the late 20th century, it is expected to expand in the future (LADWP 2010; US Census Bureau 2010). This increase in population will place a greater pressure on the already limited amount of water in the region.

With an arid environment and limited local water sources, Los Angeles imports over 90% of its water supply (LADWP 2010). Los Angeles obtains water from five major sources. The main source is the Eastern Sierra Nevada watershed, from which snowmelt water is transported to Los Angeles through the Los Angeles Aqueduct (LAA). The next two sources, in order of annual volume, are the Colorado River and the California State Water Project (SWP). Water from both sources is purchased from the Metropolitan Water District of Southern California (MWD). The last additional sources, which contribute a small amount of the total Los Angeles water supply system, are local groundwater and recycled water (Villaraigosa 2008). Each source is needed to meet Los Angeles' increasing water demand due to population and economic growth.

The overall objective of this work was to evaluate the factors that impact water demand in Los Angeles as well as apply and compare various modeling techniques to forecast water demand. The importance of this research lies in the uncertainty around the potential impact of future water stressors, especially climate change and population growth. Performing scenario analyses for Los Angeles water resources management and planning will help identify steps needed to establish a sustainable future for the Los Angeles water supply system. Additionally, this research applies various user interactive software, such as Anylogic and Tableau, to allow users to choose from numerous scenarios of population, price, climate, and conservation. In doing so, a larger envelope of scenarios could be observed allowing for better analysis of the data.

1.2 Problem Identification

Currently, California is experiencing one of the worst droughts in its history with record high temperatures and record low precipitation. The continuous four years of drought is impacting all water sectors from urban to agriculture. Drought conditions in California are especially a great concern in Los Angeles, due to the fact that a majority of the water supply is from snowmelt runoff in Sierra Nevada, where warming climate and changes in precipitation patterns have decreased its reliability (Jeton et.al. 1996; Roy et al. 2012). Additionally, the population served by LADWP has increased by an annual growth rate of approximately 1.3 percent from 1980 to 2010. The population of Los Angeles is expected to grow by 0.4 percent annually in the next 25 years and reach 4.5 million in 2035 (U.S. Census Bureau 2010). Increases in population will exacerbate the effects of limited water supply reliability in Los Angeles.

Understanding each source of water in Los Angeles and how it will be affected by changes in precipitation and temperature, coupled with analysis of increases in demand and water quality challenges, will be vital for system sustainability. There have been numerous studies conducted on climate change and water resources in California (Pierce et. al. 2013; Miller et. al. 2003; Kiparsky and Gleick 2005; Freeman et. al. 2008; Dettinger et. al. 2004), but none have addressed the combined water sources of Los Angeles and projected water demand in Los Angeles until 2050.

This dissertation examines the strengths and challenges of the Los Angeles water supply system with respect to its sustainability in the future. A number of factors, such as population growth and climate change, affect the sustainability of water supplies in cities (Roy et al. 2012). Since Los Angeles depends heavily on imported water and with increasing growth in future population it's imperative to understand the complexity of the water system so that more sustainable solutions can be identified and adopted.

1.3 Research Objectives

The overall goal of this research was addressed through four specific objectives.

(1) evaluate the sustainability of each of the water sources that supply Los Angeles under present and future conditions using a system characterization and analysis

(2) analyze the importance of various factors influencing water demand in Los Angeles using multiple linear regression and artificial neural network models

(3) project water demand in Los Angeles until 2050 under various scenarios of price, precipitation, temperature, conservation and population

(4) develop an agent based model of Los Angeles water demand that provides insight into interactions among consumers and the LADWP water management system.

The four objectives pursued in this dissertation were established to identify factors that impact water demand, and to enable development of forecasts for water demand that will allow formation of approaches to make the water supply system more robust. Projections of the interactions between water supply and demand within the Los Angeles water supply system determine system resiliency and bound the options for sustainable solutions to meet both a growing demand and climate change adaptation. Los Angeles' water supply is a dynamic, integrated system and new approaches that focus on recognizing and modeling changes in its system are necessary in order to preserve California ecosystems and to meet the demand for water in Los Angeles in the context of continuing economic and population growth.

1.4 Structure of Dissertation

The dissertation consists of six chapters, of which the four main chapters have been or will be submitted for publication in peer-reviewed journals. Following this introductory chapter, the second chapter of the dissertation analyzes the characteristics and sustainability prospects of the water supply system in Los Angeles. Historical information on the water sources and stressors are identified. Climate change, competing demands, water quality, energy and cost stressors on each water source are addressed. The third chapter focuses on the factors influencing water demand. Temperature, precipitation, price, conservation methods, and population data were incorporated in multiple linear regression and artificial neural network models in order to evaluate which independent variables are significant in influencing total water demand in Los Angeles and which model is better in modeling the system. The fourth chapter uses the models and results from the third chapter to project water demand in Los Angeles until 2050 under various scenarios of population, climate change, conservation efforts, and water prices. The fifth chapter gathers information, data, and insights from previous chapters to build an agent based model of the Los Angeles water demand. Interactions between consumers and LADWP are modeled under various drought stages to understand the underlying factors that influence conservation. Finally, the last chapter of the dissertation summarizes the study and presents overall implications of the results, limitations, and recommendations for future research.

Comprehensive and effective analytical modeling tools to project water supply and demand are needed to achieve sustainable water supply acquisition and distribution in Los Angeles, and in other cities. This research makes the following contributions towards this goal: evaluates the characteristics and sustainability prospects of the water supply in Los Angeles, identifies the various factors impacting water demand in Los Angeles, projects water demand in Los Angeles, and models the interactions driving the complex water demand system in Los Angeles under various scenarios of climate change and population growth using agent based modeling.

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Chapter 2 : CHARACTERIZING THE LOS ANGELES WATER SUPPLY SYSTEM: A BASIS FOR SUSTAINABILITY ASSESSMENT

This chapter, written by Negin Ashoori and co-authored by David A. Dzombak, and Mitchell J. Small, has been published in ASCE *Journal of Water Resources Planning and Management*, 2015, doi: 10.1061/(ASCE)WR.1943-5452.0000541

ABSTRACT

The City of Los Angeles, with a population reaching 4 million people in 2013, imports nearly 90% of its water from sources outside the city. However, climate change, population growth, competing demands, water quality concerns, and environmental restoration projects all have a large impact on Los Angeles' dependency on future water importation. In this study, a system characterization was performed to assess each of the water sources that supply Los Angeles and the factors affecting them under present and potential future conditions. Additionally, water demand and conservation methods in Los Angeles were examined to understand their impact on the overall water supply system. Of the five main water sources that supply Los Angeles – Los Angeles Aqueduct, Colorado River, California Aqueduct, local groundwater, and reclaimed water – a majority will be impacted by climate change, water quality, energy, and cost stressors. While the expansion of water demand management and agricultural water transfers can help address the challenge of increasing demand, the impacts of climate variability and competing demands are likely to constrain their potential. The characteristics of the Los Angeles water supply system provide the basis for a system sustainability assessment that bounds the options for solutions to meet both a growing demand and the need for climate change adaptation.

2.1 INTRODUCTION

The Los Angeles Aqueduct is Los Angeles' main water source which comes from the Eastern Sierra Nevada watershed. In years where LADWP cannot acquire adequate amounts of water from the Los Angeles Aqueduct to meet demand, it purchases water from the Metropolitan

Water District of Southern California (MWD). MWD obtains water from the Colorado River and the California State Water Project (SWP). A small quantity of water that contributes to the total Los Angeles water supply comes from local groundwater and recycled water (Villaraigosa 2008). The Los Angeles region is already prone to drought with limited amounts of local water sources to rely upon to sustain itself (Schroeder 2011). Although the population growth of Los Angeles has slowed since the late 20th century, it is expected to expand in the future (US Census Bureau 2010). This increase in population will place a higher pressure on the already limited amount of water in the region. Due to population and economic growth, each source is important in meeting Los Angeles' increasing water demand.

The purpose of this chapter was to provide insight into strengths and challenges of the Los Angeles water supply system with respect to its sustainability. Water sustainability is defined in this chapter as the ability to reliably meet present and future demands using water sources that are already in use (Roy et al. 2012). A current water supply system is sustainable if it is affordable, is energy efficient, minimizes environmental impact, and is resilient to threats from changing or variable conditions, including drought, competing demands, and climate change. Resiliency is the capacity of a system to be robust under various changes and disturbances (Walker et al. 2004; Sandoval-Solis et al. 2011).

In this chapter the characteristics of each water source for Los Angeles and factors affecting them are inventoried and analyzed to provide a basis for sustainability assessment. A number of factors, including population growth, competing demands, water quality, cost, and climate change, pose significant challenges for the sustainability of water supplies (Roy et al. 2005).

There have been various studies conducted on climate change and water resources in California (e.g., Cayan et al. 2001; Costa-Cabral et al. 2013b; Hanak et al. 2011; Jeton et al. 1996; Kiparsky and Gleick 2005; Medellin-Azuara et al. 2008; Miller et al. 2003; Vanrheenen et al. 2004), but none have addressed the combined water sources of Los Angeles. The contribution of this study is in the systematic, comparative review of the sources and stressors that impact the sustainability of the Los Angeles water supply system. Improved understanding of these challenges can help inform future decisions on water management in Los Angeles.

2.2 Los Angeles Water Sources and Stressors

Los Angeles imports a majority of its water from external sources, including the Los Angeles Aqueduct, the State Water Project, and the Colorado River Aqueduct. The precipitation that falls on Los Angeles on average can only sustain the lives of an estimated 500,000 people (Fulton et al. 2001). It is the use of inter-basin water transfers from locations outside of Los Angeles that has allowed for population growth within the city. As seen in Table 2-1, current water supply in Los Angeles comes from five separate sources, each of which operates under various stressors.

Table 2-1: Characteristics of the Water Sources Supplying Los Angeles[1]

Water Supply Source	Year Developed	Principal Source	Percent contribution 2000-2012 (min, max)	Major Availability Factor	Ownership and Control	Water Quality Concerns	Susceptibility to Climate Change
Los Angeles Aqueduct	1st Aqueduct-1913 2nd Aqueduct-1970	Sierra Nevada Mountains	38% (18, 59)	Snowpack	LADWP	Arsenic	High
Colorado River Aqueduct	1928	Colorado River	49% (31, 71)	Demand	MWD	Salinity, nutrients, Perchlorate, uranium, chromium VI levels	High
California Aqueduct	1960	Sierra Nevada Mountains, valleys of Northern and Central California		Environmental Restoration	DWR	Salinity, nutrients	High
Groundwater	Late 1800s	San Fernando, Sylmar, Eagle Rock, Central and West Coast Basins	12% (8, 14)	Water Quality	LADWP	Salinity, nutrients, pesticides, volatile organic compounds	Medium
Recycled Water	1979	Los Angeles wastewater	1% (0.23, 1.48)	Water Quality	LADWP	Salinity, nutrients, trace organics and contaminants	Low

[1]Information from sources discussed and cited in paper
LADWP - Los Angeles Department of Water and Power
MWD – Metropolitan Water District of Southern California
DWR – Department Water Resources

2.2.1 Los Angeles Aqueduct

The Los Angeles Aqueduct transports snowmelt water from the Eastern Sierra Nevada to the city of Los Angeles. The Los Angeles Department of Water and Power (LADWP) owns and operates the aqueduct, which has the capacity to supply Los Angeles with over 550,000 acre feet of water each water year (Costa-Cabral et al. 2013b). The routes of the LAA, as well as the other water sources that supply Los Angeles, are shown in Figure 2-1.

Figure 2-1: Map of the Major Water Supply Systems for California (Source: MWD 2010)

Residents of Los Angeles used local water supply from the groundwater basin and the Los Angeles River extensively until 1913, when the first Los Angeles aqueduct was built (Hanak et al. 2011). The aqueduct brought water from the Owens Valley, located 240 miles north of Los

Angeles (LADWP 2010). It took only eleven years before the rate of water being used depleted Owens Lake and transformed it into dry salt flats. The dry lakebed developed into a source of dust storms with high levels of PM10, i.e., particulate matter that is smaller than 10 microns, easily diffused in the lower respiratory tract, and known to increase bronchitis, chronic cough, and morbidity (Libecap 2007; Fuller and Harhay 2010; Reheis 2006).

As the city of Los Angeles continued to grow in the decades following 1913, a second aqueduct was built in 1970, which diverted Mono Lake's tributary streams to Los Angeles. Los Angeles was granted permission to divert over 100,000 acre feet of water per water year that otherwise would flow into Mono Lake, located 325 miles north of Los Angeles.

2.2.2 Stressors Affecting the Los Angeles Aqueduct

The Los Angeles Aqueduct is under various stressors relating to climate change, competing demands, and water quality. Intermittent drought in the Eastern Sierra Nevada region has decreased its reliability as a sustainable water source for the city of Los Angeles. For example, drought in the 1980s created ecological stress in Mono Lake and Owens Valley. This resulted in judicial and regulatory actions requiring Los Angeles to restore the environment in the two locations (Costa-Cabral et al. 2013a). Environmental restoration and mitigation plans implemented in 1989 decreased the permitted amount of water to the Los Angeles Aqueduct by two-thirds of the original limit and created competing demands between Los Angeles residents and environmental restoration and mitigation plans (Costa-Cabral et al. 2013a). In 2010 alone, the City of Los Angeles used approximately 206,000 acre feet of water to restore and prevent further harm to both the Owens Valley and Mono Basin (LADWP 2010).

Projections of future water supply from the Sierra Nevada Mountains are dependent on temperature, precipitation, and snowpack changes. Various investigators have shown the effect of climate change on decreasing snowpack (Bales et al. 2014; McCabe and Wolock 2007; Cayan et al. 2008; Gleick 2010; Kiparsky and Gleick 2005). Increased temperatures are impacting both the timing and amount of runoff, as has been elucidated in hydrologic modeling (Jeton et al. 1996; Nash and Gleick 1993). Snowpack in the Sierra Nevada historically has melted in early April of each year (Cayan et al. 2001), but predicted increases in temperatures of 2-4^0 C are expected to lead to snowpack melting prior to April and create a disturbance in the flow of water throughout the year (Young 2007; Maurer et al. 2007; Kim et al. 2002). During the last 50 years, stream flow data from several Sierra Nevada watersheds have shown a trend of progressively earlier occurrence of runoff (Dettinger et al. 2004; Stewart et al. 2005). Further effects can also be seen in the increased snow to rain shifts, which have increased the short-term runoff ratio and decreased the water available for seasonal storage and utilization during dry summer months (Hunsaker et al. 2012; Miller et al. 2003).

Although the LAA is under stress due to climate change and competing demands, it experiences minimal energy, cost, and water quality stress. Arsenic, which is found naturally near volcanic formations around Hot Creek in Long Valley, California, is present at levels as high as 200 parts per billion (ppb), but concentrations decrease when mixed with snowmelt from the Sierra Nevada. Arsenic levels of untreated LAA water range between 10 to 74 ppb, which is higher than the Federal and State drinking standard of 10 ppb. However, that level of contamination is reduced to an average 3.3 ppb after remediation efforts (LADWP 2010). The water conveyance in the LAA to Los Angeles is also entirely gravity driven, which is why the energy and cost required for pumping is lower than that of other Los Angeles water sources (LADWP 2010).

2.2.3 Colorado River Aqueduct

The Colorado River is one of the most heavily utilized river systems in the world since it supplies water to over 27 million people in seven states and two countries, as well as three million acres of farmland (Barnett and Pierce 2009; Lord et al. 1995). MWD operates the Colorado River Aqueduct, which traverses 240 miles from Lake Havasu to Lake Mathews (see Figure 2-1) and has a transport capacity of approximately 1.25 million acre feet per water year (MWD 2010).

MWD, which was first established in 1927, is the leading water district in the state. Nineteen million people in San Diego, Orange, Riverside, San Bernardino, and Los Angeles Counties depend on MWD for 60 percent of their water (MWD 2010). MWD brings water to Southern California via the Colorado River Aqueduct, the California State Water Project (see Figure 2-1), and transfers with other agencies (Groves et al. 2014; O’Connor 1998). LADWP is the largest of MWD’s 26 member agencies.

2.2.4 Stressors Affecting the Colorado River Aqueduct

The Colorado River Aqueduct is subject to water quality, climate change, competing demands with growing cities in the area, cost and energy stress. As seen in Figure 2-2, in calendar years when supplies from the LAA are low, LADWP purchases water from MWD to fill in the gap between supply and demand (MWD 2010).

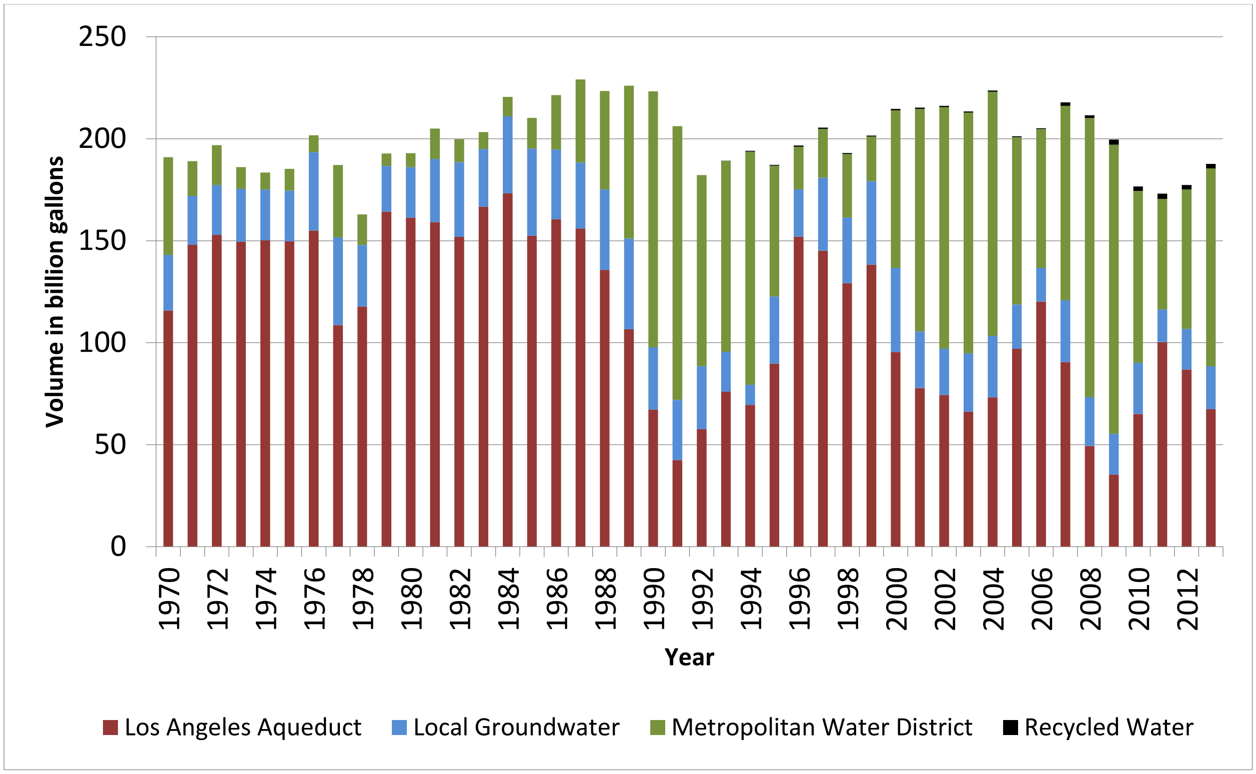

Figure 2-2: LADWP Historical Water Supply Sources, 1969-2011 Calendar Years (Source: Los Angeles Department of Water & Power)

Approximately 70 percent of the annual runoff in the Colorado River Basin originates from the snowpack in the Rocky Mountains (Christensen et al. 2004). Much of the basin area is dry and there is high variability in the amount of runoff from the Rocky Mountains to the Colorado River. Between 1906 and 2000, the minimum amount of annual flow from the river was 6.54

billion m^3 while the maximum was 24 million acre feet (Christensen et al. 2004). Due to drought, the last decade has seen a decrease in the amount of water available in the Colorado River Basin, which has reduced the upper river basin water storage levels in Lake Mead and Lake Powell (Christensen et al. 2010; Barnett and Pierce 2009; MWD 2010). In 1922, an agreement was made among the seven states drawing water from the Colorado River, which gave California the right to use 4.4 million acre feet per water year. In December 2007, after eight consecutive years of drought and with reservoir levels at 50 percent less than capacity (MWD 2010), the U.S. Secretary of the Interior signed an agreement to adjust guidelines pertaining to Colorado River water allocation until 2026. The guideline indicates that under extreme shortages California would obtain 4 million acre feet instead of 4.4 million acre feet (U.S. Bureau of Reclamation 2007). Historically, unused water in Arizona and Nevada was given to California when demands exceeded the 4.4 million acre feet limit (MWD 2010). The ability of Arizona and Nevada to provide excess water to California has been constrained, however, due to the increased population and water demands in those states (NRC 2007). Arizona alone is expected to increase by 5 million people by 2030 and to become one of the 10 most populated states in the U.S. (MacDonald 2010). Competing demands with other growing areas will therefore place stress on the already limited amount of water given to Los Angeles via the Colorado River Aqueduct.

Variability in climate is another stressor in the sustainability of the Colorado River Basin. Nash and Gleick (1993) examined the effects of both temperature and precipitation changes on the runoff in the Colorado River Basin. They showed that an increase in annual average temperature of 2-4^0C, which is projected for the Colorado River Basin for 2050, would decrease the average annual runoff in the Colorado River by 4 to 21 percent. An increase in temperature in the

Colorado River Basin would not only decrease snowfall, but would increase rainfall in the winter months, further modifying runoff schedule (Christensen et al. 2004). Other climate modeling for the region has shown that climate change could reduce runoff in the Colorado River Basin by 10-30 percent by 2050 (Barnett and Pierce 2009). Even with a 10% decrease in runoff, the current delivery of water from the Colorado River would not be sufficient and sustainable for the growing areas that utilize its water, especially Los Angeles (Barnett and Pierce 2009).

The Colorado River Aqueduct is also under stressors relating to water quality, mainly due to high salinity levels, which average around 630 mg/L (LADWP 2010). The source of the salinity is from sediments that are deposited around the Colorado River Basin. Rainfall in this region dissolves salt in the sediment and transports it to intake points for water supply systems. In addition, high nutrient levels have been detected in the water supply, mainly consisting of phosphorus and nitrogen, which originates from upstream urbanization (MWD 2010). Central treatment of MWD water before distribution is costly and increases its selling price. Both the energy and cost restraints related to obtaining water from the Colorado River affect the price and allocation of water in Los Angeles.

2.2.5 California Aqueduct

The second source of water from MWD is the California State Water Project (SWP), or California Aqueduct, which is owned by the state of California and operated by the California Department of Water Resources (DWR). It is the largest state-built water conveyance system in the United States (MWD 2010). The system contains over 700 miles of aqueduct, 34 storage areas, capacity for 5.8 million acre feet of storage, five hydroelectric power plants, 17 pumping plants, and three pump stations (MWD 2010). The Sacramento and San Joaquin River basins, which supply SWP with its water, together provide 80 percent of the runoff in California (Ejeta 2014). The rivers converge to form the Sacramento-San Joaquin delta (also referred to as the Bay Delta) and water is brought to Southern California with the assistance of large pumps (Gleick and Chalecki 1999). The distribution of SWP water to MWD began in 1960 when MWD became one of 29 water agencies to establish a long-term contract with DWR. Since MWD distributes water to such a large number of people, it is allocated approximately 46 percent of SWP water (MWD, 2010).

2.2.6 Stressors Affecting the California Aqueduct

Environmental stressors on the sustainability of the Bay Delta, which supplies water to the California Aqueduct, have driven legal actions resulting in reduction of the amount of water allocated to MWD (MWD 2010). The State Water Project is a crucial water source since it provides more than 30 percent of Southern California's water supply (MWD 2010). The SWP has various water quality stresses, including fluctuating salinity levels and high levels of nutrients introduced by wastewater discharges and agricultural runoff in the Bay Delta (MWD 2010). One of the environmental concerns of climate change on the Bay Delta is future sea level rise that would increase salinity intrusion and further disrupt the SWP diversion. Restrictions on the SWP have been implemented to increase the quantity of smelt and salmon in the waters of the Bay Delta region and have further decreased the amount of water allocated to MWD (MWD 2010).

Changes in climate have the potential to become a major driver in the allocation of water from the California Aqueduct to MWD (Knowles and Cayan 2002). Drought years, such as the ones experienced between 2007-2009, saw decreases in allocation by up to 40 percent (LADWP 2010). Studies done by Gleick (1999) on the effects of temperature on annual and monthly runoff in the Sacramento-San Joaquin River basin showed that higher temperatures decrease water flows in the summer and increase them in the winter. Another study by Vanrheenen et al. (2004) examined climate change impacts on the Sacramento-San Joaquin River basin using various climate simulations. Results indicated a 10 to 25 percent decrease in winter and spring precipitation, as well as decreased snowpack and earlier snowmelt.

2.2.7 Regional Groundwater

A significant source of local water supply in the city of Los Angeles is groundwater. In the last decade, an average of 11 percent of the total Los Angeles water supply was obtained from regional groundwater. Historically, however, the groundwater source has contributed almost 30 percent of total supply (LADWP 2010). Due to contamination issues, LADWP has been unable to utilize the full capacity of its groundwater resources. The degradation of regional groundwater is the result of runoff of fertilizers and pesticides used for agricultural purposes, as well as nitrogen, pathogenic bacteria, and hazardous substances from leaks and underground storage tanks in the area (Karimi 1998). San Fernando Basin provides 80% of Los Angeles' groundwater, but analysis of well water in the San Fernando Valley has indicated the presence of solvent-related contaminants including trichloroethylene (TCE), perchloroethylene (PCE), and other volatile organic compounds (VOCs). One survey of well water contamination revealed that out of 115 wells in the San Fernando Valley, 57 couldn't be used due to high levels of chemical contamination (LADWP 2010).

Another limitation on the use of regional groundwater is that pumping of coastal groundwater in the Los Angeles region has increased the level of saltwater intrusion (Nishikawa et al. 2009). More freshwater is being pumped than the rates of natural recharge, resulting in drawdown and saltwater intrusion. Water from coastal aquifers cannot be used without treatment or blending since it does not comply with agricultural and drinking water standards (Edwards and Evans 2002). Treatment of groundwater to reach drinking water standards increases both its energy and cost stresses. In order to reduce the amount of groundwater contamination and saltwater intrusion a number of steps have been taken since the 1950s. The Water Replenishment District of Southern California (WRDSC) was established to oversee the protection of groundwater in Los Angeles and is responsible for reducing pumping and increasing recharge through artificial means (Nishikawa et al. 2009). LADWP is also working on a $19 million Groundwater System Improvement Study in the San Fernando Valley to begin both short and long term projects to utilize more groundwater in the region (LADWP 2010). LADWP is projecting groundwater contribution to increase in the future from 10 percent to 37 percent by the year 2035. This would decrease imported water supply by up to 87,000 acre feet a year (LADWP 2010). The current costs related to use of groundwater are due to pumping and maintenance, but additional treatment facilities need to be built to make more use of groundwater resources. This will increase costs associated with groundwater use in Los Angeles. The additional costs and energy associated with the treatment systems would be a stressor to the sustainability of the Los Angeles water supply system.

Climate change is impacting groundwater supplies through modification of the recharge rates of groundwater which is indirectly impacting water quality. Higher temperatures, which lead to higher evaporation rates and decreased precipitation, can lower recharge rates in many areas (Leonard et al. 1999). On average, the annual evapotranspiration rate for Los Angeles is 50 inches per year, but that number increases with temperature (LADWP 2010). Currently, the average precipitation in Los Angeles is 15.6 inches annually and 90 percent occurs between November and April (LADWP 2010). Evapotranspiration is the sum of evaporation from soil and plant surfaces and transpiration from plants. Rates of evapotranspiration greater than that of precipitation indicates that water is being imported from surface water outside of Los Angeles and/or that groundwater supplies in Los Angeles are being depleted (Sanford and Selnick 2013). Projections of precipitation in southwestern United States in 2050 show a decrease in precipitation in a majority of the 16 global climate models testing water withdrawal and supply sustainability (Roy et al. 2012). Fluctuations in precipitation will alter the amount of groundwater available for the Los Angeles water supply system due to groundwater recharge.

2.2.8 Reclaimed Water

There are four wastewater reclamation plants in Los Angeles, which employ tertiary treatment including reverse osmosis, microfiltration, and advanced oxidation to treat municipal wastewater to meet regulatory water reuse standards and produce reclaimed water. Tertiary treatment of municipal wastewater for reclamation places both an energy and cost stress on the system due to the amount of resources necessary to reach water quality standards for drinking water. However, it has limited competing demands and is relatively robust to projected climate change. The Los Angeles Water Supply Action Plan of 2010 by LADWP has set goals of increasing reclaimed water use to 50,000 acre feet per year. This will decrease Los Angeles' dependence on outside water sources.

Currently, LADWP reclaims wastewater for non-potable use in addition to groundwater recharge. Since 1979, Los Angeles has used reclaimed water for both irrigation and industrial purposes at Griffith Park, Mount Sinai and Forest Lawn Memorial Parks (LADWP 2010). The non-potable water reuse is regulated by the California Department of Public Health, State Water Resources Control Board, Los Angeles Regional Water Quality Control Board, and the Los Angeles County Department of Public Health. Tertiary treated wastewater is injected into aquifers for storage and retention prior to use.

Regulatory agencies have allowed for the recharge of groundwater under strict requirements, but have found it a safe and effective way of recycling water. One requirement by the regulatory agencies is to ensure retention time of the reclaimed water in the storage aquifers for a minimum of six months before being extracted for use (Johnson 2009). A two-year pilot study done by Karimi et al. (1998) was performed to assess the impacts of reclaimed water on the quality of groundwater in the San Fernando Valley. Water was extracted from the basin 1000 feet down gradient from the point of injection and was found to comply with both federal and state drinking water quality standards, proving that it can be an effective way to recycle water.

2.2.9 Desalination

Desalination is another potential source of water to supply Los Angeles, but its use is constrained by cost and energy requirements. Seawater desalination is a method of removing salts and other dissolved impurities in seawater to reach a drinking water standard. Currently, the LADWP is not focusing on this water source because of the high capital and operating costs. The energy and cost of desalinated water in Los Angeles would be higher than obtaining water from current sources. Still, continued research is being done on the feasibility of desalination for Los Angeles (LADWP 2010).

2.2.10 Rainwater Harvesting

Rainwater harvesting has also been analyzed to help meet increasing demand for water in Los Angeles. Many residential and commercial properties in Los Angeles have intercepted rainwater from their roofs or other surfaces to water their landscape. Although rainwater harvesting is a sustainable water source, it only fulfills a small portion of the demand for water in Los Angeles (LADWP 2010).

2.2.11 Water Transfers

Another potential water source is the transfer of water from the agricultural to urban sector. Due to climate change, population growth, and reduced reliability of out-of-state water supplies, California started implementing a statewide policy in 1982 that allowed for the transfer of water within the state between individual organizations (Rosegrant 1995). In times of drought, urban sector water users have a greater willingness to pay for water compared to the agricultural sector (Newlin et al. 2002; Draper et al. 2003; Harou et al. 2010). There have been several studies analyzing the benefits of water transfers in California (Medellin-Azuara et al. 2008; Lund and Israel 1995a,b). In order for water transfers to be financially beneficial to urban users, water transactions would have to be less than or equal to other sources (Hansen et al. 2008). However, during periods of drought, water transfers alleviate some of the stress related to obtaining sufficient amounts of water to meet demands. The agricultural sector in California itself uses 80% of the state's water, while it uses over 50% more to irrigate crops compared to the national average (Hanak et al. 2011). Implementing more efficient water systems for agriculture will not only reduce water demand, it will also make available more water for transfer to the urban sector.

MWD already receives agricultural water transfers when sufficient water is not obtained from either the California Aqueduct or the Colorado River (Israel and Lund 1995). Storage and transfer programs from the Central Valley are expected to alleviate some of the pressure during droughts in the future (MWD 2010). Currently in Los Angeles, water transfers have been developed to reduce the burden created by the decrease in reliability of water from the Los Angeles Aqueduct (LADWP 2010). To address circumstances when the amount of water from LAA is not sufficient to fulfill demand, LADWP has developed the Neenach Project which interconnects the Los Angeles Aqueduct and the California Aqueduct. This will allow for flexibility of water transfers in times of drought. The project is expected to add an additional

40,000 acre-feet of water to Los Angeles per year (LADWP 2010). Water transfers allow for short-term solutions to California droughts (Johns 2003).

There are, however, issues related to the increased use of water transfers to supply Los Angeles. Storage, treatment, and conveyance costs are often more than the implementation of conservation methods that yield the same amount of available water. During times of severe drought, the use of water in urban areas in California reaches levels that stress available supplies – much of it for unessential applications, with up to 40-70% of it being used for outdoor purposes (Loaiciga 2014). Therefore, it may be economically more desirable to implement conservation methods to reduce the use of water than to increase reliance on water transfers (Freeman et al. 2008). Other issues include potential economic and environmental harm to agricultural areas due to farmers idling their land and selling the unused portions of their allocated water to other agencies (Howitt 2014, Hanak et al. 2011, Johns 2003). Even with these concerns, water transfers will continue to allow for increased reliability of future water supply in Los Angeles.

2.3 Water Demand and Conservation

Los Angeles is the largest city in California and the second largest in the U.S., after New York City, with a population of 3.9 million as of 2010 (U.S. Census Bureau 2010). The LADWP service area, which extends beyond the boundary of the City of Los Angeles, has been increasing over the years. As seen in Table 2-2, the population served by LADWP has increased from 2.97 million in 1980 to 4.1 million in 2010 indicating an annual growth rate of approximately 1.3

percent. In addition, the population of Los Angeles is expected to grow by 0.4 percent annually in the next 25 years (U.S. Census Bureau 2010).

Table 2-2: Population Growth in the City of Los Angeles and the Los Angeles Department of Water and Power Service Area, 1910-2010

Year	Population of the City of Los Angeles	Population of LADWP Service Area	Ranked Most Populous City in the U.S.
1910	319,000	345,000	17
1920	577,000	603,000	10
1930	1,238,000	1,264,000	5
1940	1,504,000	1,530,000	5
1950	1,970,000	1,996,000	4
1960	2,479,000	2,505,000	3
1970	2,816,000	2,842,000	3
1980	2,967,000	2,970,000	3
1990	3,485,000	3,502,000	2
2000	3,695,000	3,733,000	2
2010	3,793,000	4,100,000	2

(Sources: LADWP 2010; US Census Bureau 2010)

Most of the water sold in Los Angeles is for residential customers, accounting for approximately 68 percent of the water demand (Villaraigosa 2008). The second largest group is commercial customers, which provide 17 percent of the demand. Of the other users, government accounts for seven percent of the demand; industrial four percent; and non-revenue generating uses for four percent (Villaraigosa 2008). Residential indoor use of water in a single-family home is between 65-80 gallons per capita per day. Outdoor use, including watering the lawn, filling swimming pools, and cooling, is highly variable from 25-100 gallons per capita per day (Hanemann 1993). Mayor Antonio Villaraigosa wrote in his City of Los Angeles Water Supply Action Plan in 2008 that approximately 30% of total water is used outdoors, equivalent to about 190,000 acre feet per year. In times of drought, however, the residents of Los Angeles are pressured to reduce their water use. During the drought years of 2008-2009, the City of Los Angeles was able to reduce total water usage by 17% (MacDonald 2010).

Previous investigators have analyzed the effectiveness of demand management in order to decrease stress placed on water supplies from climate change, population growth, and other factors. Wood et al. (1997) and Lettenmaier et al. (1999) showed that water demand alone had more of an impact on the water supply system than climate change effects. Reducing demands created from increased population in arid locations, like Los Angeles, can play a major role in the sustainability of the water supply system in the future (Kiparsky and Gleick 2005). It is projected that water withdrawals will exceed 100% of the available precipitation in California placing an even higher stress on the water supply system in Los Angeles (Roy et al. 2012).

There are three main strategies to increase water conservation: price increases, regulations, and rebates (Freeman et al. 2008). Since the early 1980s, LADWP has financially incentivized customers to undertake water conservation efforts, mainly through the installation of low-flow toilets and showerheads (LADWP 2010). These efforts, in addition to increases in water prices, have kept down the growth in water demand over the past 25 years, although there has been a population increase of 1 million people during that time frame (Villaraigosa 2008). This can also be seen in Figure A-1 in the appendix. It is estimated that an additional total of 60,000 acre feet per year will be saved between 2010 and 2035 through conservation (LADWP 2010).

Tiered water pricing structures that implement higher prices on water above certain levels of use encourage efficient use of water (Freeman et al. 2008). Following a drought in the 1980s, Los Angeles implemented voluntary conservation measures in 1990 and mandatory measures in 1991 that significantly lowered per capita consumption (Ngo and Pataki 2008). In 1993, Los Angeles also revised its water prices to incorporate a tiered rate structure. The tiered structure remains in use and has assisted in conserving water over the years. As seen in Figure 2-3, water prices have increased steadily after the tiered water structure was implemented.

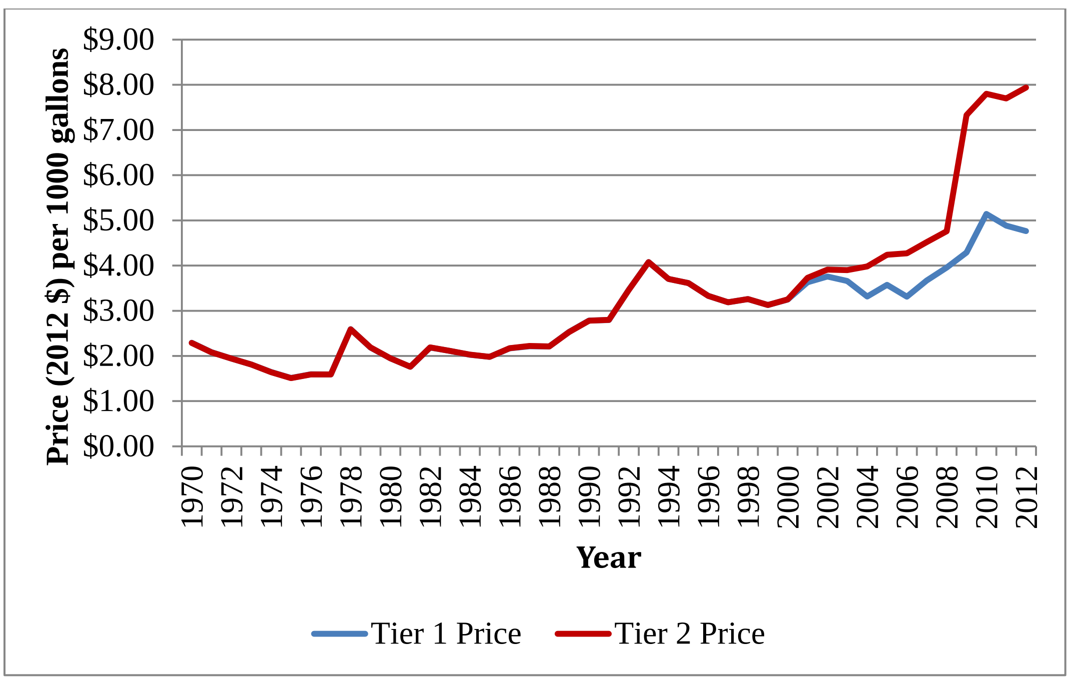

Figure 2-3: Inflation Adjusted Price of Los Angeles Residential Tier 1 & Tier 2 Water per 1000 gallons from 1970-2012 (Source: Los Angeles Department of Water & Power)

Significant reductions are possible with conservation-oriented rate structures (Cuthbert and Lemoine 1996). After continuous years of drought from 2007-2009, LADWP implemented a more stringent tier system for water prices as of June 1, 2009. Customers were charged more if they used an excess of the allocated Tier 1 water level, which was 15% less than prior years. Tier 1 allocation depends on location, lot size, and number of household members (LADWP 2009). When acceptable price increases are not sufficient to achieve needed use reductions, LADWP bans use of water for non-essential uses, such as for outdoor purposes. This decreases the stress placed upon the water supply system during periods of drought.

Conserving water is also beneficial in reducing the demand for energy because energy is needed to transport water and for water end use. LADWP conserves water through the use of tiered water pricing, education, financial incentives for installation of water efficient devices, and landscape irrigation efficiency programs (LADWP 2010). The overall goal for conservation in Los Angeles is to reduce water demand by 20% by 2020, which costs between $75 to $900 per acre-foot of water saved due to the cost of conservation initiatives (LADWP 2010).

2.4 Key Factors Impacting Sustainability

The sustainability of Los Angeles water supply system is defined as the ability to meet future water demands under various environmental, economic, and demographic changes. As seen in Figure 2-4 and previous sections, the water sources that supply Los Angeles are under various stresses relating to demand, climate change, water quality, energy, and cost. System wide demand is impacted by factors such as behavior, population, economic activity, and technological change. Through gathering data on each water source and analyzing the stressors placed upon them, it is clear that two large-scale factors impact significantly the characteristics and sustainability of the Los Angeles water supply system: climate change and increasing demand caused by population growth. Additionally, issues with water quality are present for all the current and potential water sources for the Los Angeles water supply system. These stem mostly from contamination related to salinity and nutrient levels. Cost and energy stresses are evident in all sources except the Los Angeles Aqueduct, which has lower operational and maintenance costs compared to other water sources. Cost and energy stresses are especially high for potentially new water sources, such as seawater desalination, treatment of contaminated regional groundwater, and environmental mitigation and restoration of water supplies. A large amount of energy is needed to transport, treat, and distribute water from each of the water sources to Los Angeles. Both the Colorado River Aqueduct and the California Aqueduct are energy intensive water sources since they require energy to pump and transport water to Los Angeles. The Los Angeles Aqueduct however is entirely driven by gravity, which gives it significantly lower energy and cost stress.

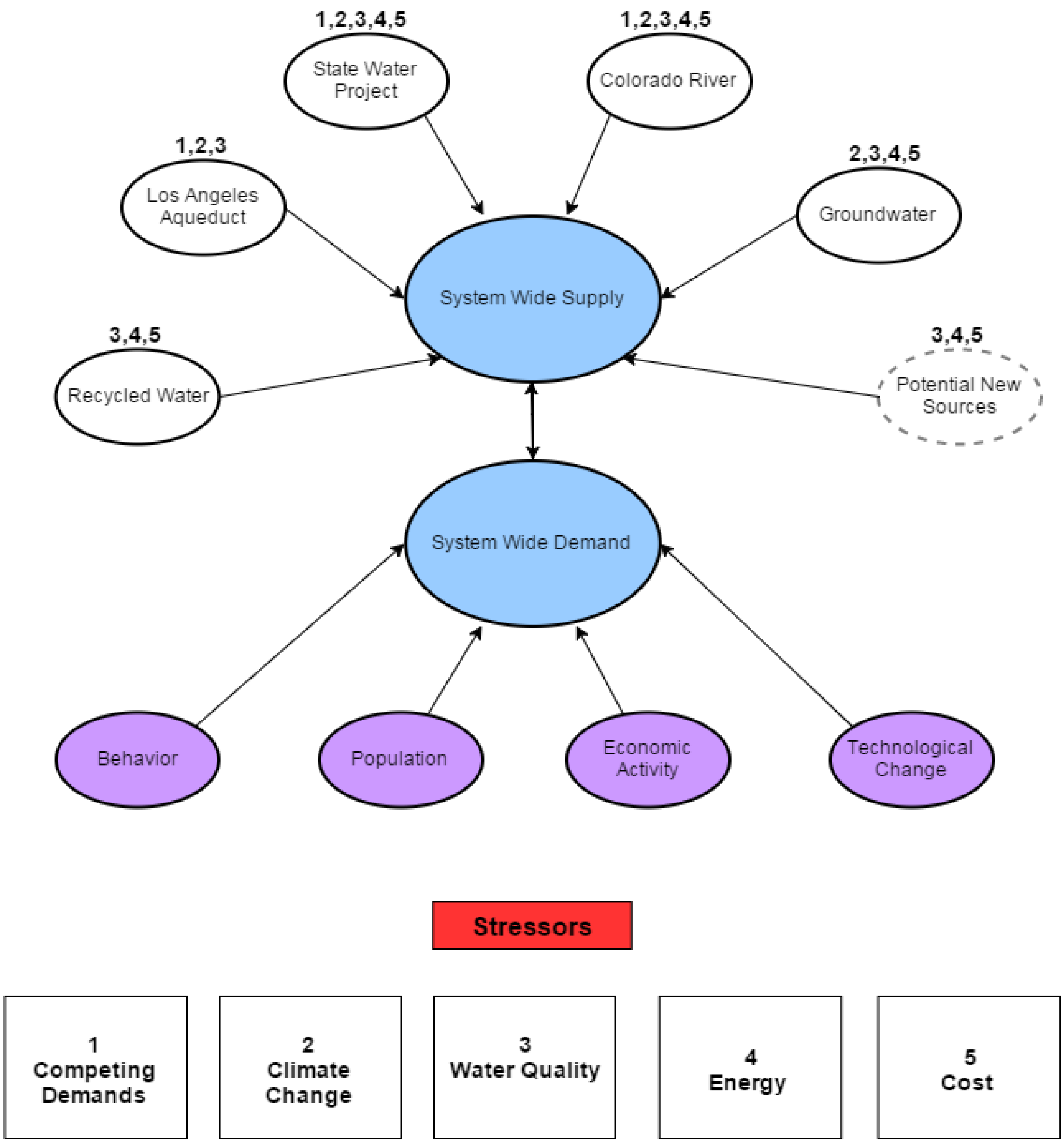

Figure 2-4: Conceptual Model of the Social-Ecological Interactions of the Los Angeles Water Supply System

Climate change is negatively impacting all the water sources, especially the Los Angeles Aqueduct. Changes in snowpack, timing of snowmelt, and precipitation levels are major issues affecting the Los Angeles water supply system due to possible ongoing and future climate change. The Colorado River and California SWP supplies are also affected by climate change, but the LAA is greatly impacted by changes in snowmelt timing and snowpack (Kiparsky and Gleick 2005; Dettinger et al. 2004).

A comprehensive analysis of the stressors to the water sources supplying Los Angeles is imperative for its future sustainability. Water supply in Los Angeles needs to be resilient to the stressors placed upon it from changes in temperature, precipitation, and urbanization. The southwestern United States water resources are scarce and susceptible to climate change effects, which are impacting water availability, quality and demand (Leonard 1999; Costa-Cabral et al. 2013b; Miller et al. 2003; Kiparsky and Gleick 2005). Therefore, new approaches to reduce the use of water in these areas are vital. Especially important in this regard are water conservation and water use efficiency programs. Currently, water conservation is dependent on higher water prices and voluntary actions taken on by customers. Utilization of local water sources in Los Angeles is important in order to decrease dependence on inter basin water transfers. The sustainability of the future water supply in Los Angeles will depend on a combination of increases in water conservation, usage of reclaimed water, treatment of local groundwater, and introduction of potential water transfers from agriculture to urban sector.

2.5 Summary and Conclusions

The goals of this study were to inventory and examine the water sources for Los Angeles and to identify factors impacting the sustainability of the water supply in Los Angeles. The characteristics of each water source supplying Los Angeles were identified to provide a basis for assessing the strengths and limitations of the sources. Understanding the stressors of present and future water sources is valuable in developing and evaluating the future sustainability of the Los Angeles water supply system. Current and future limitations of each of the water sources supplying Los Angeles were identified and compared.

When water supplying the Los Angeles Aqueduct is reduced due to decreased snowmelt from the Sierra Nevada, LADWP purchases extra water from MWD to meet water demands in Los Angeles. Potential new sources of water include desalination and rainwater harvesting, both of which have not been utilized significantly to date because of cost, energy requirements in the case of desalination, and limited potential to meet growing demand. Water transfers from the agricultural sector to Los Angeles can provide relief when traditional sources cannot fully meet water demand, but such transfers involve storage, treatment, and conveyance costs that may not be sustainable in the long term, especially with potential yields from conservation at much lower cost.

Climate change effects are a great concern for Los Angeles water supply, due to the fact that a majority of the water supply is from snowmelt runoff in Sierra Nevada, where warming climate and changes in precipitation patterns are decreasing snowmelt flows. Understanding each source of water for Los Angeles and how it will be affected by changes in precipitation, snowpack, temperature, as well as increases in demand, and water quality concerns is imperative to future sustainability of water supplies.

Future sustainability of the main five water sources and developing sustainable new water sources is of critical importance to Los Angeles. Issues with water supply management and water demand can further exacerbate the already threatened Los Angeles water sources. Therefore, various modeling techniques should be applied to understand the factors impacting water demand and projecting them under shifting economic and population scenarios.

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Chapter 3 : MODELING URBAN WATER DEMAND IN LOS ANGELES, CALIFORNIA: APPLICATIONS OF ARTIFICIAL NEURAL NETWORKS AND MULTIPLE LINEAR REGRESSION

This chapter, written by Negin Ashoori and co-authored by David A. Dzombak, and Mitchell J. Small, is being reviewed by the *Journal of American Water Works Association.*

Abstract

With a service area population exceeding 4 million people and with close to 90% of the water supply being imported from sources outside the city, the Los Angeles water system is subject to various stressors, including climate change and population growth. These factors and others were considered in developing and comparing six multiple linear regression (MLR) and six artificial neural network (ANN) models for monthly and yearly residential water demand. The key variables used to develop and validate the models were total precipitation, average temperature, price, population, conservation methods, and water demand data from 1970 to 2012 in the service area of the Los Angeles Department of Water and Power. Performance of the models was compared using the coefficient of determination, root mean square error, and average absolute relative error. Results of the comparison indicate that the multiple linear regression models were comparable to the artificial neural network models in describing water demand data. Models developed for and fitted to monthly data were more accurate in estimating water demand compared to models based on yearly data. Fitting of the data with the MLR models revealed that price and conservation impacts have significantly counteracted the impact of population growth on water demand. The results of this study can be applied to support forecasting of water demand under changing scenarios of population growth, climate change, policies for water pricing, and conservation.

3.1 Introduction

A key aspect in planning, design, operation, and management of a water system is the accurate prediction of water demand. Analyzing water demand is complex, as the factors impacting demand are numerous and dynamic. Some of these factors, such as population growth and climate change, pose significant challenges to the sustainability of water supplies in cities. The Los Angeles area is especially prone to drought with very limited local water sources (Ashoori et al. 2015). Although the population growth of Los Angeles has slowed since the late 20th century, it is expected to expand in the future (LADWP 2010; Fuller and Harhay 2010). This increase in population and susceptibility to drought will place an even greater pressure on the already limited amount of water in the region, and on the external sources of water that supply Los Angeles. Therefore, it is imperative to compare various models for sustainable management of the supply system and understand the underlying factors influencing water demand in Los Angeles.

Reducing water demand in order to decrease stress placed on water supplies from climate change, population growth, and other factors has been investigated in previous studies. For example, Wood et al. (1997) and Lettenmaier et al. (1999) showed that water demand had a greater impact on a water supply system compared to the effects of climate change on source water. Because water withdrawals in southern California will exceed 100% of the precipitation that is available (Roy et al. 2012), a comparison of models is necessary to understand the factors that impact water demand in order to improve forecasts.

Los Angeles obtains its water from the Los Angeles Aqueduct, Colorado River Aqueduct, California State Water Project, local groundwater, and reclaimed water (Ashoori et al. 2015).

Each source is needed to meet Los Angeles' increasing water demand. Sixty eight percent of the total water demand in Los Angeles is for residential customers with the remaining thirty two percent coming from commercial customers, government, industrial, and non-revenue accounts (Villaraigosa 2008).

In this thesis, the focus was on modeling residential water demand and not water used for commercial, governmental, and agricultural purposes. Over 30% of the total residential water demand is for outdoor use, which is an approximately 190,000 acre feet a calendar year (Villaraigosa 2008). However, in times of drought both outdoor water use and overall water use are reduced.

The US Census Bureau projects that the population of Los Angeles will increase to 4.5 million by the year 2035. This will impact the demand for water, the supply of which is already under stress due to climate change and environmental restoration programs (Ashoori et al. 2015). Despite the increase in water demand that comes with growing population, as population in Los Angeles has increased over the past two decades the total demand for water has stayed approximately the same (LADWP 2010). There could be many factors impacting the drop in per capita water use, including water price, conservation efforts, and fluctuations in climate (Babel et al. 2007).

Previous studies have shown that people conserve water when it is priced at a higher level (Nieswiadomy 1992; Gaudin 2006; and Grafton et al. 2011). Residents are responsive to price and it is important to know the impact of price elasticity, i.e., the change in demand related to a change in price (Young 1973; Piper 2003). During periods of drought, increases in water prices in Los Angeles have lowered the demand for water mainly through voluntary measures (Frederick 1997). Los Angeles restructured its water pricing in 1993 in order to integrate a tiered rate structure. After the drought years of 2007-2009, the tiered water price structure became stricter. Customers were charged an increased fee if they used more than the allocated Tier 1 water level. The Tier 1 level was set at 15% lower than prior years and is dependent on numerous factors, such as location, lot size and number of individuals in a household (LADWP 2009). This rate structure is still in use in Los Angeles. The tiered water pricing structure gives customers monetary incentives to reduce water use and be more efficient with the water they use (Freeman et al. 2008).

Southern California's water conservation methods can be categorized into voluntary, mandatory, and market-based strategies (Maggioni 2015). Conservation methods, such as ordinances, rebate programs, tiered pricing rates, and education of customers regarding water stresses, have been implemented in Los Angeles since the 1990s. Voluntary conservation was introduced in 1990 whereas mandatory conservation started in 1991 after several years of drought in the 1980s (Ngo and Pataki 2008). These available tools have helped reduce per capita water use in Los Angeles. The importance of conservation and its relationship to water demand must be considered in modeling water demand.

Climatic variables, such as temperature and precipitation, have an effect on short-term seasonal changes in water demand, especially in arid areas such as Los Angeles. Residents use more than 30% of their water outdoors in Los Angeles, and that percentage fluctuates depending on the amount of precipitation and temperature of the region (LADWP 2010). Increases in precipitation drive down water demand and increased temperatures raise overall water demand, e.g., in relation to water use for outdoor landscaping (Villaraigosa 2008). Climate variables thus were included in the analysis of water demand in Los Angeles.

The overall objective of this study was to develop and compare and evaluate different models to understand the factors that impact water demand in Los Angeles. Various techniques are available for modeling water demand (Peters and Chang 2011; Kostas and Chrysostomos 2006). In this study, multiple linear regression (MLR) and artificial neural network (ANN) models of monthly and yearly water demand were developed and compared to evaluate their effectiveness. Other studies have used ANNs to model and estimate water supply (Cigizoglu 2005; Adamowski and Karapataki 2010). The present study applied both MLR and ANN models to residential monthly and yearly water demand in Los Angeles. The time period considered was from 1970 to 2012, using actual data on water demand for this period. In order to evaluate the performance of the models, coefficients of determination, average absolute relative errors, and root mean square errors were calculated. The novelty of this study lies in the application of actual case study data used to compare model performances for a large system. Comparing the MLR and ANN techniques in modeling water demand provided insights into the relative importance of factors affecting water demand and the sustainability of the future water supply in Los Angeles. Implementing these different models for evaluation of historical water demand data can also inform the selection of a model for use in future studies predicting water demand in Los Angeles under various scenarios of climate and population.

3.2 METHODOLOGY

3.2.1 DATA COLLECTION

In order to identify the factors that most significantly impact water demand in Los Angeles, various combinations of variables from Table 3-1 were selected. In total there were twelve models (four yearly ANN, four yearly MLR, two monthly ANN, two monthly MLR).

Table 3-1: Candidate Explanatory Variables in the MLR and ANN Models of Los Angeles, California Water Demand

Variables in the Models	Units	Abbreviation
Total monthly precipitation	Inches	R_M
Total yearly precipitation	Inches	R_Y
Average monthly temperature	^oF	T_M
Average yearly temperature	^oF	T_Y
Tier 2 price	$	WP
Total estimated monthly population	# people	P_M
Total estimated yearly population	# people	P_Y
Estimation of conservation	10^3 gallons water	C

These variables were chosen as candidates for inclusion in the model based on previous research on water demand modeling (Adamowski and Karapataki 2010; Babel et al. 2007; Bougadis et al. 2005; Ghiassi et al. 2008; Liu et al. 2003; Adamowski et. al. 2012; Peters and Change 2011; and Cochran and Cotton 1985). The dependent variable in the modeling was monthly water demand (M_t) or yearly water demand (Y_t) in m^3 of water. MLR and ANN models with per capita water demand as the dependent variable were also developed. However, overall relationships between water demand and population were identified with greater clarity in the total water demand models for Los Angeles. Therefore, per capita water use was not considered as a dependent variable in this analysis. The water demand data were available for a period from 1970 to 2012 from the Los Angeles Department of Water and Power (LADWP).

Independent variables considered in the analysis include climatic data, population, price of water, and conservation effort. Climatic data, consisting of precipitation and temperature in Los Angeles, were obtained from the National Oceanic and Atmospheric Administration (NOAA). Data on conservation, water price, and service area population were obtained from LADWP. Prior to 1993, Los Angeles had no tiered water rates and there was one set price for water use. Therefore, the water prices used in the models were the Tier 2 price for water use above the Tier 1 allocation after 1993, and set water prices prior to 1993.

A distinguishing feature of the present study is that conservation was considered as an explanatory variable in water demand modeling. The conservation values were estimated by LADWP by subtracting the actual water use from projections of water use made with statistical models based on historical water use, and considering population, weather, and the economy in the given year without the implementation of conservation (LADWP 2010). Estimates of water conservation were from hardware conservation programs, such as low flow toilets, high efficiency appliances, and various other measures, as well as non-hardware programs that are estimates from water customer behavior. Non-hardware conservation is a result of public education and programs. Data on conservation prior to 1990 were not available as conservation efforts were not formally implemented by the LADWP until that decade. The model accuracy for conservation was evaluated by using it to project water use from 1980 to 1990 when conservation was not implemented. The results of the back casting model showed similar water consumption amounts to the actual water consumption levels (as seen in Figure B-7 in the appendix). The amount of water demand in Los Angeles is influenced by consumer investment in conservation and modeling that relationship is imperative to future water planning management. Therefore, conservation was used as an explanatory variable in several of the models in the paper in order to understand how effective it is in impacting water demand. Further details regarding the LADWP water demand model were not available for the public domain.

As indicated in Figure 3-1, the population of Los Angeles increased steadily throughout most of the study period from 1970-2012. However, the residential water demand exhibited yearly and decadal variations that differed from tis strictly upward temporal trend. In particular, following a predominantly increasing trend in the first half of the study period (until 1990), the residential water demand exhibited both periods of increase and decrease, with very little net change over the period 1990-2012. To what extent can this variable response of water use to population be explained by weather/climate variations and the demand influences of changing price and conservation efforts? Visual inspection of the dataset cannot provide a clear answer to this question. Instead formal methods are needed to identify and isolate the contributions of each factor. The multiple linear regression and artificial neural network models described in the following sections were designed to accomplish this objective.

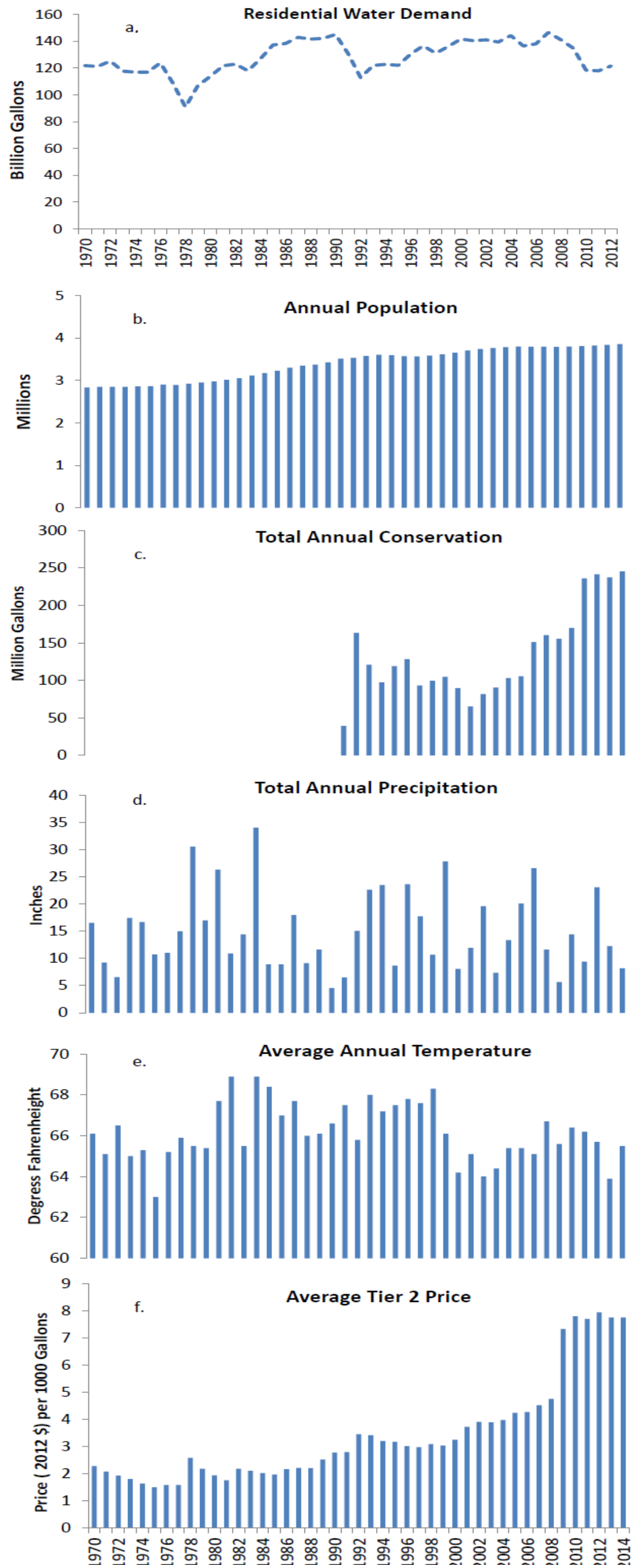


Figure 3-1: Values of the Dependent Residential Water Demand and Explanatory Variables in the MLR and ANN Models from 1970-2012 Calendar Years

3.2.2 Multiple Linear Regression

Simple and multiple linear regression have previously been applied in water demand modeling (Babel et al. 2007; Bougadis et al. 2005; Cochran and Cotton 1985; Nieswiadomy 1992). Multiple linear regression models are used to describe the relationship between explanatory variables, such as conservation, population, price, temperature, and precipitation, and a dependent variable. MLR involves fitting a linear equation constructed with explanatory variables to the observed data presented to the model. Hence, every observation consists of the full set of explanatory variables and the corresponding dependent variable, with multiple linear regression coefficients chosen for the former to estimate the latter with least square errors. Multiple linear regression models are limited in their ability to model datasets exhibiting nonlinear relationships and high levels of data noise.

In this study, six multiple linear regression models were developed, four yearly models and two monthly models (Table 3-2). An initial multiple linear regression was performed to understand the significance of relationships between total yearly or monthly water use and the five explanatory variables: temperature, precipitation, water price, population, and conservation.

$$\mathrm{Y_t} = \beta_0 + \beta_1(price) + \beta_2(population) + \beta_3(precipitation) + \beta_4(temperature) + \beta_5(conservation) \quad (1)$$

Equation (1) shows the hypothesized dependence of water demand $\mathrm{Y_t}$ on the explanatory variables. The regression models were fitted using all monthly and yearly data from 1970 to 2012 for water demand and the explanatory variables. A cross validation was done using 80% of the data points for fitting followed by predictive testing on the remaining 20%. The results of the cross validation are provided in Table B1 in the appendix. After running the initial regression, all significant variables (i.e. p-value< 0.05) were retained. The non-significant variables in each case, such as median household income, were omitted from the regression equation. Explanatory variables were additionally tested for collinearity.

In order to understand the proportion of the total variance explained by each variable, stepwise regressions were performed. In stepwise regression, explanatory variables were presented to the model one at a time and variables that contributed the most to increasing the coefficient of determination (R^2) were added sequentially. Results of stepwise regression were used to rank explanatory variables by how strongly they increased the goodness of fit.

3.2.3 Artificial Neural Network

Several studies have used artificial neural networks to model water resource data (Liu et al. 2003; Bougadis et al. 2005; Cigizoglu 2005; Razavi et al. 2012; Tiwari et al. 2013). In the present study, a backpropagation, multilayer perceptron ANN procedure was undertaken in SPSS 22.0 to produce a predictive model of the Los Angeles water demand. Six models were developed considering the same averaging time and explanatory variables addressed by the MLR models, with two monthly and four yearly models (Table 3-2). Additional models were developed (see Table B3, B4, B7 and B8 in the appendix), but were not included in this study.

Table 3-2: Models used for Modeling Water Demand in Los Angeles, California

Models for Water Demand in Los Angeles, CA*	Multiple Linear Regression Model	Artificial Neural Network Model
Monthly model with R_M, T_M, WP, and P_M as explanatory variables	MLRM1	ANNM1
Monthly model with R_M, T_M, WP, $P_{M,}$ and C as explanatory variables	MLRM2	ANNM2
Yearly model with R_Y, T_Y, and WP as explanatory variables	MLRY1	ANNY1
Yearly model with R_Y, WP, P_Y, and C as explanatory variables	MLRY2	ANNY2
Yearly model with R_Y, T_Y, WP, and P_Y as explanatory variables	MLRY3	ANNY3
Yearly model with R_Y, T_Y, WP, P_Y, and C as explanatory variables	MLRY4	ANNY4

*See Table 3-1 for definitions of variables

The multilayer perceptron used in ANN, which is a supervised learning technique, pertains to layers of nodes. Every node is a receptor, through the ANN algorithm, of a particular weight related to every other node within its layer (Adamowski 2008). ANNs are mathematical models that describe a highly interconnected network used to map input data for a system to output response data. The neural network algorithm learns and reconstructs the nonlinear complexities in the input and output relationships within its hidden layer(s) through numerous iterations, illustrated in Figure 3-2. The input layer contains the predictors, the hidden layer contains unobservable nodes, and the output layer contains the responses. In the present study, the output layer was the annual or monthly water demand in Los Angeles and the input layers were the three to five predictor variables used also in the multiple linear regression models (Tables 3-1 and 3-2).

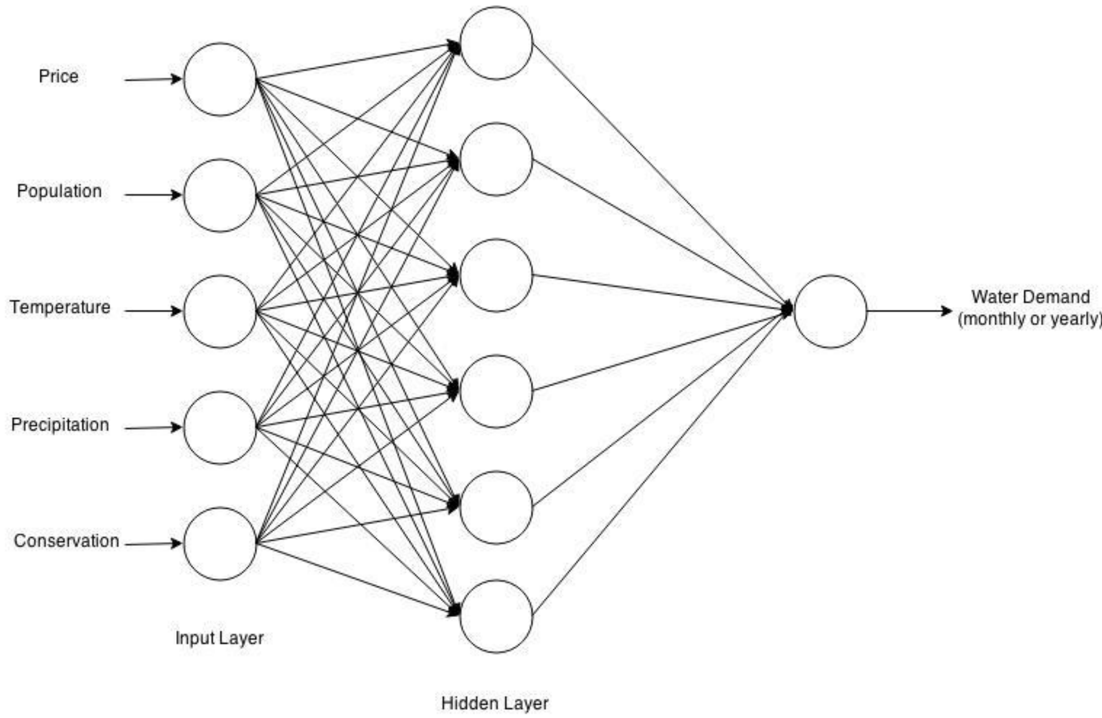


Figure 3-2: Artificial Neural Network Architecture for Modeling Water Demand in Los Angeles, CA

The nodes in the hidden layer are responsible for mapping the relationship between the input and output variables, and the number of nodes was determined using trial and error to obtain the best model fit. In this study, SPSS was used to optimize the number of nodes, between 1-50, in the hidden layer in order to generate the best results. Additionally, the learning coefficient, which defines the magnitude of the weight changes relative to random allocation, was optimized for each of the six ANN models.

In a back propagation ANN, the predictors in the input layer are initially propagated forward and the output variable is calculated with the use of a non-linear activation function. The errors in the output are then computed and back propagated through the model using a training procedure. The back and forth propagation through the model is continued until a certain level of output prediction accuracy is reached. The principal objective of the modeling procedure is to be able to describe and replicate the relationship between the input and output variables.

In the ANN modeling of historical water demand data, the synaptic weights (connection strengths between nodes) and importance analysis of each variable were determined. The independent variable importance analysis performs a sensitivity analysis. This analysis is done by observing both the training and testing samples. The importance analysis was done in order to rank variables in terms of their influence on water demand in Los Angeles. These percentages were compared to the percentages of variance explained by the explanatory variables in the MLR models.

The 43-year dataset was divided into two parts: a training set consisting of 34 years of data, and a testing set consisting of the remaining nine years of data. The 516 month dataset was also divided into two parts: a training set consisting of 413 months and a testing set of 103 months. ANN models rely on the training dataset to estimate relationships between the dependent and independent variables. The testing set is used in order to prevent overtraining the data. In addition, ANN models using all data points for training were developed and are provided in Table B2 in the appendix.

3.2.4 Goodness of Fit Metrics

The relative performance of the MLR and ANN models was evaluated using three different parameters: coefficient of determination (R^2), average absolute relative error (AARE), and root mean square error (RMSE). In order to compare monthly and yearly models, monthly values for AARE and RMSE were accumulated for each year and compared with the yearly models.

3.2.4.1 Average Absolute Relative Error

Average absolute relative error (AARE) reflects the average error on a fractional basis. It is computed using Equation (2):

$$\text{AARE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\hat{y}_i - y_i}{y_i}\right| \qquad (2)$$

where y_i is the actual water demand, $\hat{y}_i$ is the predicted water demand obtained from the model, and n is the number of observations. Water demand models with lower AARE values perform better than those with larger values for AARE.

3.2.4.2 Coefficient of Determination (R^2)

The coefficient of determination is an indicator of the relationship between the observed and predicted results in a model. This goodness of fit parameter shows what amount of the total variation in the model is due to the explanatory variables and the strength between the linear association of water demand and the explanatory variables. Therefore, the higher the R^2 the better the goodness of fit. The coefficient of determination can be calculated using Equation (3):

$$R^2 = \frac{SS_{regression}}{SS_{Total}} = \frac{\sum_{i=1}^{n}(\hat{y}_i - \bar{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \quad \text{and} \quad \bar{y}_i = \frac{1}{n}\sum_{i}^{n} y_i \qquad (3)$$

where $\bar{y}_i$ is the mean water demand, and SS is the sum of squares of residuals. The coefficient of determination varies over the range of 0 and 1 and is calculated for each of the alternative models developed in this study.

3.2.4.3 Root Mean Square Error

The root mean square error (RMSE) describes the average prediction error, with larger errors given greater weight in the calculation. The equation used to calculate RMSE is given by

$$RMSE = \sqrt{\frac{(\sum_{i=1}^{n}(y\mathrm{i} - \hat{y}\mathrm{i})^2\ )}{n}} \qquad (4)$$

The numerator in the expression inside the square root is equivalent to the total sum of squares for the model.

3.3 Results and Discussion

3.3.1 Performance analysis metrics of monthly and yearly water demand models

Table 3-3 displays the performance analysis metrics for the monthly MLR and ANN models. The results show that the ANN and MLR models yielded similar water demand modeling performance. Since the results of the ANN and MLR were similar, the relationships between the explanatory variables and the output variables are well described by a linear expression. The monthly MLR with all five variables (MLRM2) had the highest R^2, lowest AARE, and lowest RMSE compared to the monthly ANN models. The R^2 for MLRM2 was 0.72 indicating that 72% of the variability of monthly water demand was explained by the independent variables: price, precipitation, and population, conservation, and temperature.

Table 3-3: Performance Analysis Metrics for Monthly Water Demand Models for Los Angeles, California

Monthly Water Demand Models	R^2	AARE$^+$	RMSE (gallons)$^{++}$
MLRM1	0.67	5.65	8.53E6
MLRM2	0.72	4.01	6.01E6
ANNM1	0.68	5.16	8.28E6
ANNM2	0.71	4.91	6.92E6

$^+$ AARE- Average Absolute Relative Error

$^{++}$RMSE- Root Mean Square Error

When comparing the monthly and yearly performance results shown in Tables 3-3 and 3-4, it can be seen that the yearly models had higher coefficients of determination, meaning that their explanatory variable values were better at modeling water demand compared to the monthly models. However, the monthly models had lower average absolute relative errors and root mean square errors. The higher coefficient of determination indicates it follows a linear relationship, but that does not mean the model is better. The observed vs. predicted scatterplots exemplifying the goodness-of-fit of each of the models can be seen in Figures B1-B3 in the appendix. Additionally, comparison of actual data and predicted water demand values for the drought years 2013-2015 using the MLRM1 model can be seen in Figure B-6 in the appendix. The model does not take into consideration the impact of conservation on water demand since estimates of conservation were not available. Implementing these conservation values is predicted to yield more accurate projections of water demand in Los Angeles using model MLRM2.

Table 3-4: Performance Analysis for Yearly Water Demand Models for Los Angeles, California

Yearly Water Demand Models	R^2	AARE[+]	RMSE (gallons)[++]
MLRY1	0.71	7.77	1.23E7
MLRY2	0.77	7.08	1.11E7
MLRY3	0.71	7.85	1.24E7
MLRY4	0.77	7.16	1.13E7
ANNY1	0.65	7.74	1.17E7
ANNY2	0.70	7.35	1.14E7
ANNY3	0.74	7.58	1.24E7
ANNY4	0.79	6.43	1.05E7

[+] AARE- Average Absolute Relative Error

[++] RMSE- Root Mean Square Error

By comparing models MLRM2, MLRY4, ANNM2, and ANNY4, it can be seen that the monthly models have lower AARE and RMSE values, with MLRM2 being the best model (Figure 3-3).

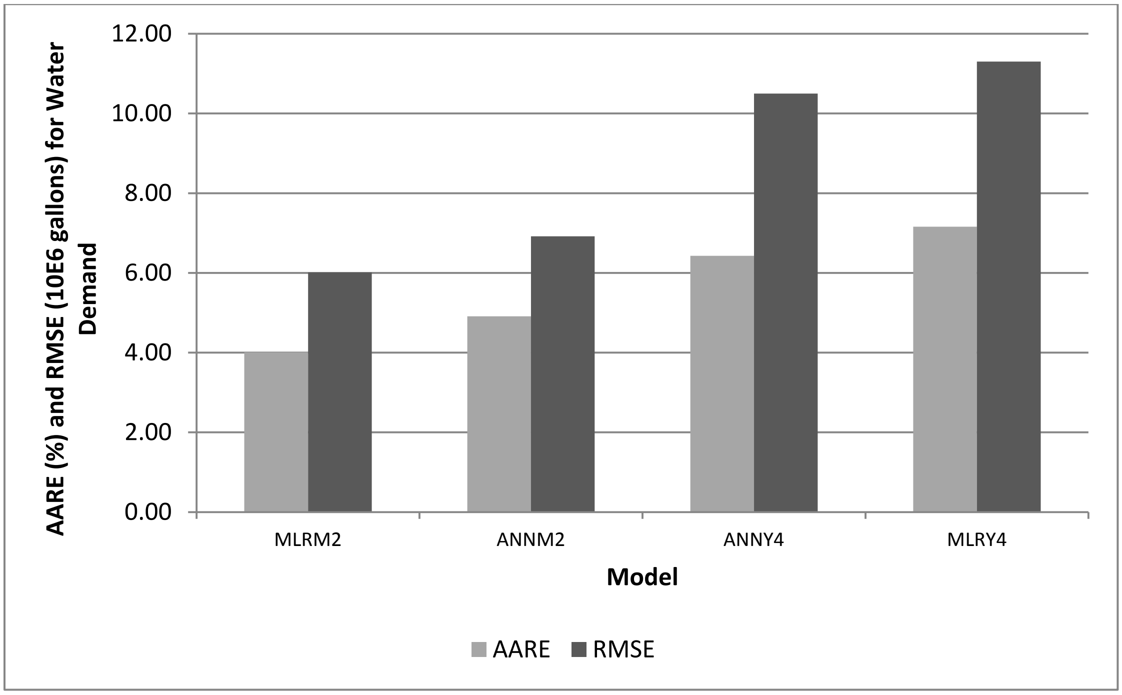


Figure 3-3: Comparing Model Performances for MLRM2, MLRY4, ANNM2, and ANNY4 in Modeling Water Demand in Los Angeles, California

3.3.2 Significance of each variable in the model

Overall, the results of the study indicated that the ANN and MLR models had similar coefficients of determination, average absolute relative errors, and root mean square errors, demonstrating that the two modeling techniques were comparable in modeling water demand. Analysis of the performance criteria, however, reveals that the best model for describing the historical data was the monthly multiple linear regression model with all five explanatory variables (MLRM2). With R^2 of 0.72, AARE of 4.01 and RMSE of 6.01E6 gallons, the model was able to predict water demand better than the other eleven models.

Additionally, the five variables selected were all statistically significant in explaining monthly water demand in the MLR model (Table 3-5). Table 3-5 displays the MLR modeling results, including coefficients and their standard errors. The best model, with all significant variables, was the monthly MLR model with five explanatory variables (MLRM2):

$$M_t \text{ (1000 gallons)} = -2.38E7 + 2.12E5(T_M) - 5.85E4(R_M) - 2.45E5(WP) + 6.46E0(P_M) - 4.49E0(C) \quad (5)$$

As shown in Equation (5), a one person increase in population in the model yields a 6.46E3 gallon increase in water demand per month. As for climate variables, an inch increase in precipitation would decrease water demand by 5.85E7 gallons per month. This is reasonable, as increased rain would discourage people from using water for outdoor landscaping, which is responsible for over 30% of total residential water demand as noted earlier. For temperature, a 1.0 degree Fahrenheit increase would increase water demand by 2.12E8 gallons each month. This could be explained by the fact that rises in temperature increase water demand for outdoor purposes. Finally, a one-dollar per 1000 gallons increase in water price would decrease water demand by 2.45E8 gallons, and conservation methods would decrease water demand by 4.49E3 gallons per month. Each of the five variables is significant, as indicated by p-values below the p=0.05 level. The yearly MLR models indicated that population, precipitation, and conservation were always statistically significant. However, temperature was not significant in any of the yearly models.

Table 3-5: Unstandardized Coefficients+ for Explanatory Variables of the Monthly and Yearly MLR Water Demand Models for Los Angeles, California

MONTHLY						
Monthly water demand MLR models(see Table 3-2)	β_0 =Constant [1000 gallons]	β_1 =WP [1000 gallons/$]	β_2 =P_M [1000 gallons/person]	β_3 =R_M [1000 gallons/in]	β_4 =T_M [1000 gallons/^{o}F]	β_5 =C [ ]
MLRM1	-1.97E7* (1.09E6)	-5.28E5* (5.02E4)	5.61E0* (2.86E-1)	-3.94E4 (3.09E4)	1.96E5* (1.04E4)	-
MLRM2	-2.38E7* (1.07E6)	-2.45E5* (5.42E4)	6.46E0* (2.73E-1)	-5.85E4* (2.82E4)	2.12E5* (9.58E3)	-4.49E0* (4.49E-1)
YEARLY						
Yearly water demand MLR models (see Table 3-2)	β_0 =Constant [1000 gallons]	β_1 =WP [1000 gallons/$]	β_2 =P_M [1000 gallons/person]	β_3 =R_M [1000 gallons/in]	β_4 =T_M [1000 gallons/^{o}F]	β_5 =C [ ]
MLRY1	3.41E7* (1.33E7)	-4.92E6* (9.75E5)	3.55E1* (4.46E0)	-7.09E5* (1.49E5)	-	-
MLRY2	6.28E6 (1.68E7)	-1.92E6 (1.52E6)	4.26E1* (5.08E0)	-6.57E5* (1.42E5)	-	-9.58E1* (3.85E1)
MLRY3	5.17E7 (5.46E7)	-5.01E6* (1.02E6)	3.58E1* (4.58E0)	-7.00E5* (1.53E5)	-2.77E5 (8.33E5)	-
MLRY4	1.83E7 (5.31E7)	-1.99E6 (1.57E6)	4.28E1* (5.18E0)	-6.51E5* (1.46E5)	-1.87E5 (7.84E5)	-9.5E1* (3.90E1)

+ Units for all coefficients are in 1000 gallons of water per indicated variable unit (see Table 3-1)
**Indicates the coefficient is significant at the p= 0.01 level
*Indicates the coefficient is significant at the p= 0.05 level
( ) Standard error of the coefficient

3.3.3 Importance analysis of ANN and MLR monthly and yearly models

Artificial neural network models can assess the importance of the explanatory variables in impacting water demand (Adamowski 2010). This is done through network node weights. Nodes are connected to one another and their connection is assigned a value, which indicates the strength of the connection. There are three different types of nodes: input nodes, hidden layer nodes, and output nodes. Activation values are assigned to the input nodes and go through the network until it gets to the output nodes. Through backpropagation the input values are modified to reduce error. By performing a sensitivity analysis, the importance of each explanatory variable (input node) was calculated in determining water demand.

For the multiple linear regression models, the relative importance of explanatory variables was examined through the use of stepwise regression for each significant variable. Each variable's proportion of the total variance for the MLR model was compared to the other explanatory variables. By using stepwise regression, individual explanatory variable impacts on the variance could be analyzed instead of observing all the variables in the multiple linear regression.

In order to examine the relative importance of each explanatory variable in the MLR and ANN models, the fractions of variance in models MLRM2 and MLRY4 were compared against the relative weights of models ANNM2 and ANNY4 shown in Table 3-6 and illustrated in Figure B5 in the appendix. These models were selected because they had the largest coefficients of determination (Table 3-3 and 3-4). Table 3-6 shows that most of the variables were similar in importance between the MLR and ANN models for the same averaging time. However, the model results differed between the monthly and yearly models.

Population exhibited the largest impact on water demand for all six ANN and MLR models, except for model MLRM2 for which temperature had the strongest impact on water demand. Price, on the other hand, exhibited the lowest percentage impact for the ANN and MLR models. However, an increase of one dollar in Tier 2 price would still decrease water demand by 2.45E8 gallons per month.

Table 3-6: Independent Variable Importance Analysis of ANN and MLR Monthly and Yearly Water Demand Models for Los Angeles, California

Monthly and yearly water demand models (see Table 3-2)	Price	Population	Precipitation	Temperature	Conservation
MLRM2	1.3%*	36.0%	0.3%*	46.8%	16.3%*
ANNM2	3.7%	32.9%	14.6%	32.6%	16.2%
MLRY4	5.2%*	43.2%*	17.7%*	0%	33.9%*
ANNY4	7.7%	46.6%	25.3%	8.3%	12.1%

*Indicates the coefficient is significant at the p= 0.05 level

% indicates the relative weights of each explanatory variable in the ANN models and the fraction of the variance explained by each explanatory variable in the MLR models

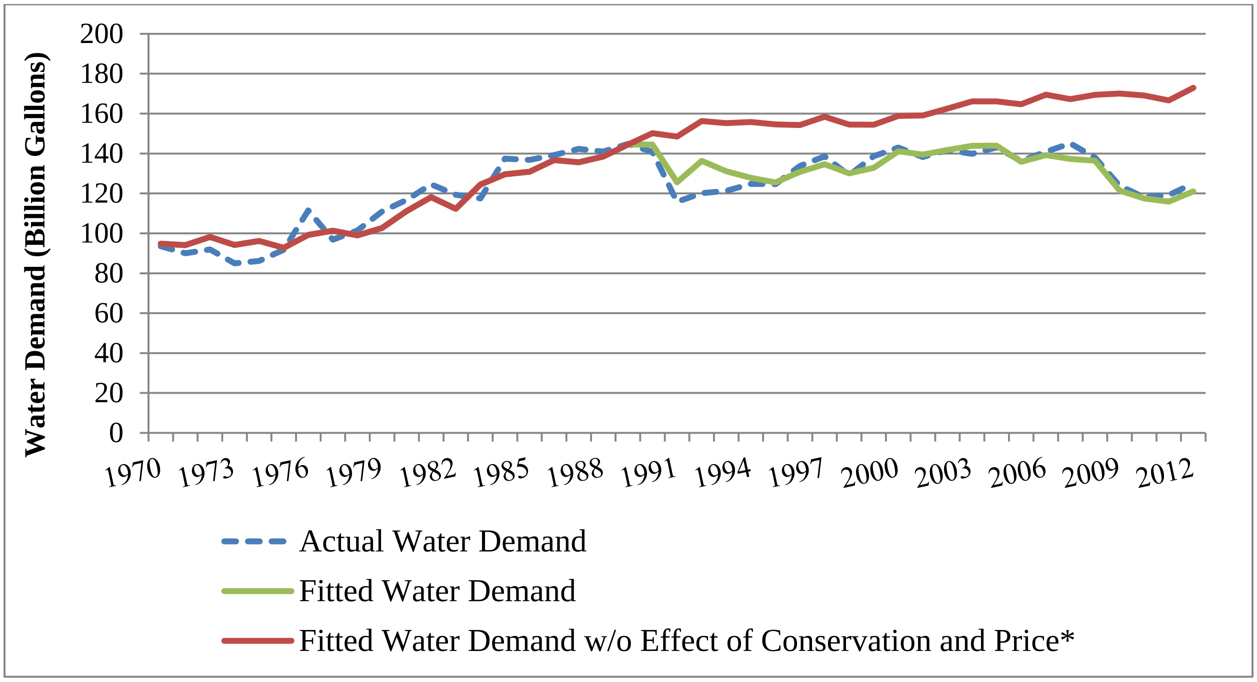
What can also be seen in Table 3-6 is that the impact of average temperature becomes greater for the monthly models compared to the yearly models (46.8% and 32.6% instead of 0% and 8.3%). This could be because fluctuations of average temperature are greater between months than between years. Overall averages of temperature between years do not fluctuate as much as monthly temperature averages, which could explain the importance of temperature in impacting water demand in monthly models, but not in yearly models. However, the opposite is true for precipitation. Precipitation is seen to impact water demand strongly in yearly models for both ANN and MLR.

For conservation, there is a distinct difference in importance between the ANN and MLR models. The relative contribution of conservation as a component in MLRM2 and ANNM2 is similar with the percent importance being 32.9% for ANNM2 and 36% of the total variance explained by the coefficient of determination in MLRM2. As for the yearly models, MLRY4 and ANNY4, conservation is 12.1% for ANNY4 and 33.9% for MLRY4. The importance analyses for the remaining ANN and MLR models are provided in Tables B5 and B6 in the appendix.

3.3.4 Counterfactual effects of price and conservation on predicted annual LA water demand

To understand better the influence of demand management policies on residential water use, consider how the demand in the top panel of Figure 3-1 might have differed over recent decades had the conservation efforts and price increases implemented by LADWP not taken place. To illustrate such a counterfactual analysis we used the best fitted monthly model (MLRM2) to predict water demand with and without the conservation and pricing changes implemented in 1991. For the prediction without these changes the price was fixed at 1990 levels and the total annual conservation was kept at zero. The results are shown in Figure 3-4 using aggregated monthly data points to show the yearly variation in water demand. Individual monthly variations between the MLR model and actual data can be observed in the next chapter under Figure 4-2.

As indicated, the fit of the full model (green line) to the observed water demand (blue dashed line) with conservation and pricing inputs properly considered throughout the 1972-2012 study period was very good throughout. However, when price was fixed and conservation set to zero, the model prediction (red line) continued along the upward trend exhibited during the first half of the study period, influenced predominantly by population growth. The growing difference between the red and green lines in Figure 3-4 thus provides an estimate of the influence of the LADWP pricing and conservation policies in offsetting the effects of population growth.



*Monthly multiple linear regression model, MLRM2, fit to observations 1970-2012, estimated demand with constant price and no conservation shown for 1991-2012

Figure 3-4: Effects of Price and Conservation on Predicted Annual Los Angeles Water Demand

Conservation, using values obtained from LADWP from 1990-2012, was used directly as an explanatory variable in order to analyze the overall water demand in Los Angeles with and without its effects. As seen in Figure 3-4, conservation effort, along with price play a large role in reducing water demand even with increases in population. Additional research is needed, however, to improve understanding of the impact of specific conservation, technology, and communication programs and price policies in Los Angeles. Identifying these impacts will allow for better water demand management and planning of future water supply in Los Angeles.

3.4 Conclusions

Predicting water demand plays a pivotal role in planning and decision making for sustainable water supply, assisting in the design, and management of urban water supply systems. The purpose of this study was to develop and compare two water demand modeling techniques with application to water demand data for Los Angeles, California in order to identify important factors impacting the system. Artificial neural network and multiple linear regression models were developed and used to fit historical (1970-2012) water demand data for Los Angeles. The models yielded similar results in modeling water demand when considering population, residential water price, accumulated precipitation, average temperature, and conservation as independent variables. Models based on monthly data were more accurate for modeling water demand compared to yearly models when analyzing their coefficients of determination, average absolute relative errors, and root mean square errors. In the monthly MLR models, all five variables were significant in impacting water demand. Taken together, the results of the ANN and MLR models indicate that population has the strongest influence on water demand, but the impacts of conservation and price since the early 1990s have counteracted the increase in water demand from population growth. The variables affecting water demand vary both spatially and temporally and are subject to numerous stressors, including climate change. Understanding the underlying drivers of urban water demand can help inform planning for the sustainability of water supply systems, such as that of Los Angeles, in the future. Further, development of such models will enable for better forecasting of water demand under changing conditions of climate, population, and economy.

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Chapter 4 : FORECASTING RESIDENTIAL WATER DEMAND IN LOS ANGELES, CALIFORNIA UNDER CLIMATE CHANGE

This chapter, written by Negin Ashoori and co-authored by David A. Dzombak, and Mitchell J. Small, will be submitted for publication.

ABSTRACT

With frequent drought conditions in California and steady increases in population, Los Angeles' water supply is under pressure. Changes in climate not only impact water supply, but alter the behavior of water consumers, affecting water demand. In order to understand this relationship, a multiple linear regression model calibrated with historical water demand data was employed to forecast future water demand in Los Angeles. The model uses projections of four global climate models with two CO_2 emission scenarios, as well as future scenarios of population, water pricing, and conservation to generate an envelope of forecasts of water demand in Los Angeles from 2013 to 2050. Improving water demand forecasts for Los Angeles will help planners better understand and optimize future investments in system infrastructure. Results of the study show that population and price are predicted to have the strongest impact on future water demand in Los Angeles. Effects of climate change on water demand (not supply) are projected to be modest at 6 percent increase in water demand in 2050. Without increases in water pricing and conservation, water demand in Los Angeles has the potential to nearly double from 130 billion gallons per year in 2013 to 250 billion gallons in 2050. However, more likely scenarios of population growth, conservation implementation, climate change, and pricing structures yield predicted increases in water demand of approximately 30 percent, to a level of about 170 billion gallons per year by 2050. Demand side water management is imperative to the future sustainability of the Los Angeles water supply system, which will depend on new conservation methods, modified water pricing structures, and new water infrastructure to reach the demand set by a growing population.

4.1 Introduction

Long-term forecasting of water demand is critical to the planning and management of a water supply system. Effective demand forecasting requires an understanding of the influence of population and climate on water use, as well as how water consumers react to changes in water prices and conservation efforts. Better informed water management decisions can be achieved through this process (Bougadis et al. 2005).

With over 90% of its water being imported (Ashoori et al. 2015a), recurring periods of extended drought (NOAA 2015), and growing population (Fuller and Harhay 2010), Los Angeles' water supply is under increasing pressure (Ashoori et al. 2015a). Water demand forecasting is necessary to evaluate and plan for the future ability of supply to meet demand. By understanding the underlying factors influencing water demand in Los Angeles and forecasting them, approaches for sustainable management of the supply system can be identified.

Variations in climate have an impact on both the sources of water to Los Angeles and water demand by consumers. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment (IPCC 2014) estimates that temperatures throughout the world are to increase by 0.3°-0.7°C from 2016-2035 and will reduce the potential yield of surface and groundwater resources. With anticipated increase in demand, water withdrawals in California are projected to exceed 100% of the precipitation that is available in the state by 2050 (Roy et al. 2012). Since over 30% of the total residential water demand in Los Angeles is for outdoor purposes (LADWP 2010), changes in regional precipitation and temperature that alter water demand for these applications, including residential and commercial landscaping, swimming pools, and other outdoor uses, may have a significant impact on total water demand. Prior studies on climate change and its effect on water demand have shown that increases in temperature and decreases in precipitation lead to increases in water demand (Balling and Gober 2006).

There are various methods currently used to reduce the water demand in Los Angeles. One of these methods is water pricing (Gaudin, 2006). A tiered water price structure began in Los Angeles in 1993, which involves an increased fee for water use above a certain allocated Tier 1 level. The tiered water price structure in Los Angeles has been shown to exert downward pressure on water demand (Ashoori et al 2015a). Tiered water pricing provides a monetary incentive to customers to reduce their water use. In addition to water pricing structures, conservation methods have been implemented in Los Angeles since 1990 to reduce urban water demand (LADWP 2010). During previous drought years in Los Angeles, consumers lowered demand through voluntary measures (Villaraigosa 2008). Through investing in progressive programs and measures, LADWP has been able to keep water demand at a constant level despite a 1.3% annual growth in population since 1980 (LADWP 2010).

The objective of this study was to apply a previously developed multiple linear regression model for water demand in Los Angeles (Ashoori et al. 2015b), which considers important factors that impact monthly urban water demand, to project water demand until 2050 under various scenarios for the governing factors - climate change, population growth, pricing structures, and conservation methods. The multiple linear regression model for Los Angeles water demand was calibrated previously with historical data (Ashoori et al. 2015b). Previous studies have focused on understanding factors that impact water demand (Babel et al. 2007, Gaudin 2006), but none have projected future water demand under various future scenarios in Los Angeles. Contributing factors to urban water demand, such as climate change, population growth, pricing and conservation are difficult to project accurately. Therefore, a systematic set of scenarios was developed to determine an envelope of water demand possibilities for the future.

4.2 Methodology

4.2.1 Multiple Linear Regression Equation

The projections of urban water demand in this paper build on our previous work on analysis of the main factors influencing water demand in Los Angeles (Ashoori et al. 2015b). A multiple linear regression (MLR) model for Los Angeles water demand was developed which includes conservation, population, price, temperature and precipitation as the explanatory variables and total monthly water demand as the dependent variable. Data on monthly water demand, Tier 2 pricing, and conservation estimates from 1970 to 2012 were obtained from the Los Angeles Department of Water and Power (LADWP). The MLR model was calibrated with these data. For forecasting purposes, the MLR model was used to project water demand under alternative future scenarios. The MLR model for monthly water demand in Los Angeles, with Tier 2 price, population, conservation, temperature, and precipitation as explanatory variables, is as follows (Ashoori et al. 2015b):

$$M_t = \beta_0 + \beta_1 price + \beta_2 population + \beta_3 precipitation + \beta_4 temperature + \beta_5 conservation \quad (1)$$

where M_t, the monthly water demand in Los Angeles (in 1000 gallons) is the dependent variable, and the other coefficients and variables are as given in Table 4-1. Other candidate variables, such as median household income, were investigated by Ashoori et al. (2015b), but their influence was not statistically significant (Figure B7-B8 and Figure E1). As seen in Table 4-1, five variables were ultimately used in the MLR model and to project water demand from 2013-2050.

Table 4-1: Descriptions of the Explanatory Variables in the MLR Model of Los Angeles, California Water Demand

Variables in the Model	Description	Units	Abbreviation	Fitted β values[+]	P-values	Units of β values
Precipitation	Total monthly precipitation	inches	R_M	$-5.85E4$	0.03*	1,000 gallons/in
Temperature	Average monthly temperature	$^{\circ}F$	T_M	$2.12E5$	0.00**	1,000 gallons/ ^{o}F
Price	Tier 2 price	$/1000 gallons	WP	$-2.45E5$	0.00**	1,000 gallons/$
Population	Total estimated monthly population	# people	P_M	$6.46E0$	0.00**	1,000 gallons/person
Conservation	Estimation of monthly conservation	1000 gallons	C	$-4.49E0$	0.00**	[ ]

+ fitted beta values determined from historical data (1970-2012) from Ashoori et al. 2015b
** Indicates the coefficient is significant at the p=0.01 level
*Indicates the coefficient is significant at the p= 0.05 level

Substitution of the fitted β values of Table 4-1 into Equation 1 yields:

$$M_t \text{ (1000 gallons)} =$$

$$-2.38E7 + 2.12E5 * T_M - 5.85E4 * R_M - 2.45E5 * WP + 6.46 * P_M - 4.49 * C \qquad (2)$$

The coefficients in the model are all statistically significant at the 0.05 level or lower (Ashoori et al. 2015b), and can be interpreted as follows. For population, each additional person contributes 6460 gallons to the Los Angeles monthly water demand. For the climate variables, a one-inch increase in precipitation decreases Los Angeles water demand by 58×10^6 gallons per month. For temperature, a 1 degree Fahrenheit warmer month leads to an increase in water demand of 212×10^6 gallons each month. A $1 increase in Tier 2 water price would decrease water demand by 245×10^6 gallons, while conservation efforts have yielded an additional decrease in water demand of 4490 gallons per month from the value otherwise expected by LADWP. Interpreting conservation indicates that for every 1000 gallons which is estimated by LADWP to be saved, an additional 4490 gallons is conserved.

To put the fitted coefficients into perspective, their values combined with the 2012 population of 3.9 million in Los Angeles, lead to the following equivalent changes in population-related water demand for each variable:

- A 1-inch increase in precipitation reduces demand equivalent to a population decrease of 9,100 people

- A 1^{o}F increase in average temperature increases demand equivalent to a population increase of 32,800 people
- A $1 increase in Tier 2 water price reduces demand equivalent to a population decrease of 37,900 people
- Current conservation efforts have reduced water demand equivalent to a population decrease of 103,000 people (when taking into consideration estimates of conservation from LADWP as well as the MLR model)

4.2.2 Scenario Development

The model of Equation (2) was used to estimate water demand for different scenarios of climate change, population growth, pricing structures, and conservation methods from 2013-2050. A summary of the scenarios developed is presented in Table 4-2. In this study, three scenarios were developed for each of the five factors in the MLR model for Los Angeles water demand: population, Tier 2 water price, precipitation, temperature, and conservation. As the climate-related variables precipitation and temperature co-vary, more combined scenarios were developed for these two variables. In total, 81 scenarios were generated for the model inputs and water demand forecasting in Los Angeles.

As seen in Table 4-2, three bounding scenarios (low-bound, baseline, high -bound) were selected considering combinations of the explanatory variables. The low-bound scenario estimates water demand if population and climate were to remain constant while price and conservation efforts were maximized. The low-bound scenario projects water demand under the best case scenario for minimization of water demand. For the baseline scenario, projections for the variables are estimated to be in line with what has been previously predicted for Los Angeles (LADWP 2010). Finally, a high-bound scenario for water demand was developed to analyze water demand increases given maximum population growth and climate change, while keeping Tier 2 price and conservation at a minimum. Although the high-bound scenario shows the upper level of water demand under conditions of population, tier 2 price, climate, and conservation, water availability limitations in the future will enforce additional mandatory water conservation methods.

Table 4-2: Summary of Bounding Scenarios for Projecting Urban Water Demand in Los Angeles, California from 2013-2050

Water Demand Scenario	Population	Tier 2 Price	Climate	Conservation
Low-bound Scenario	*Constant baseline* (2012 level)	*High increase* (200% growth)	*Constant baseline* (2012 level)	*High increase* (40% growth)
Baseline Scenario	*Medium growth* (20% growth)[1]	*Medium increase* (50% growth)	*B1 for precipitation and temperature*[2]	*Medium increase* (20% growth)
High-bound Scenario	*High growth* (40% growth)	*Constant baseline* (2012 level)	*A2 for precipitation and temperature*[3]	*Constant baseline* (2012 level)

[1] Data for projections of baseline population were obtained from the Los Angeles Department of Water and Power (2010)
[2,3] Data for projections of climate variables were obtained from the California Energy Commission, Cal-Adapt data source and explained in section 4.2.2.3
All other scenarios were chosen to reflect historic and potential future bounds

It is acknowledged that the influence of the explanatory variables on water demand in the future could be altered by structural changes in water supply or housing infrastructure, evolving perceptions and behavior, or other factors. However, the projections that follow are based on our best current understanding of these relationships and provide a baseline against which other modeling assumptions can be compared.

4.2.2.1 Population

Los Angeles is the second largest city in the United States, with the LADWP service population being 3.9 million in 2015 (LADWP 2015). With a projected population of 4.5 million by 2035 (US Census Bureau 2010), it is imperative to estimate quantitatively the increase in water demand due to population growth. However, other factors, such as conservation efforts and pricing strategies, can alleviate the impacts of population and climate on water demand (Babel et al. 2007). The three scenarios selected for population projections result from varying assumptions of growth in Los Angeles. The low-bound scenario population projection assumes that population stays constant at 3.9 million after 2012. The baseline scenario provides for an increase of 20% in population by 2050, meaning the population would reach roughly 4.7 million by 2050. The high-bound population scenario assumes population will increase by 40% during the projection period, giving a population of 5.4 million by 2050. These three scenarios encompass a broad range in the spectrum of potential population growth influencing Los Angeles water demand.

4.2.2.2 Tier 2 Price

With the likelihood of future increases in water prices in Los Angeles, it is useful to investigate how consumers will react and how pricing will affect total water demand. Various price scenarios were developed in order to represent possible changes in Los Angeles water price in the future. Three scenarios were established using 2012 Tier 2 LADWP prices as the starting reference price. The 2012 Tier 2 water price was $8.02 per 1000 gallons (LADWP 2013). Therefore, in the high-bound scenario the Tier 2 rate was maintained at this constant value from 2013 to 2050. The baseline scenario for price provides for a 50% increase in price from 2013 to 2050, whereas the low-bound scenario increases the Tier 2 water price by 200% from 2013 to 2050 (i.e., by a factor of 3). All values for water prices were readjusted for inflation for the year 2012. Values for both Tier 1 and Tier 2 prices from 1970-2012 can be seen on page 30 of the thesis.

4.2.2.3 Climate

The climatic variables, temperature and precipitation, have an effect on short-term seasonal changes in water demand. Los Angeles residents use 30% of their water outdoors, and that use fluctuates depending on the temperature and amount of precipitation in the region (LADWP 2010). Projections of precipitation in the southwestern United States in 2050, made from an ensemble of 16 global climate models, indicated decreases in precipitation with most of the models (Roy et al. 2012). As parametrized in the MLR model, this leads to an increase in water demand, most likely for outdoor uses such as landscaping, as noted above. Climate change effects on water supply are also likely to be crucial to the sustainability of the Los Angeles water system (Ashoori et al. 2015a), but this study focuses solely on the impacts of climate change on water demand.

In order to develop three scenarios for climate encompassing both temperature and precipitation, two different methods were employed. A bootstrap technique was initially used to generate temperature and precipitation inputs for a climate scenario in which there is no change in the current climate (a low change scenario). The bootstrap procedure involved re-sampling the joint monthly temperature and precipitation dataset with replacement. The dataset used included the 1970-2012 monthly values for temperature and precipitation in Los Angeles. For the two additional scenarios, four different climate models were used (California Energy Commission 2015):

- Parallel Climate Model (PCM1)
- Community Climate System Model (CCSM3)
- Geophysical Fluid Dynamics Laboratory (GFDL)
- National Centre for Meteorological Research (CNRM)

Data for these scenarios were obtained from the California Energy Commission, Cal-Adapt data source. The climate models were analyzed using two different climate scenarios (A2, B1) for temperature and precipitation in Los Angeles. The A2 scenario assumes continuously increasing global population and economic growth whereas the B1 scenario assumes the introduction of resource-efficient technologies accompanying the increase in global population (Nakicenovic et al. 2000). For each climate scenario the average of the four different models was calculated and used in the projection. Together, the three scenarios provide a broad range of estimates for the effect of climate on water demand.

4.2.2.4 Conservation

Los Angeles' water conservation methods can be categorized into voluntary, mandatory, and market-based strategies (Maggioni 2015). Since the 1990s, LADWP has implemented various conservation methods and analyzed their impact on water demand. These available tools have helped reduce per capita water use in Los Angeles. The amount of water demand in Los Angeles is influenced by consumer investment in conservation, and modeling that relationship is critical to future water planning management. LADWP is expected to increase conservation in the coming decades (LADWP 2010). In order to show its impact on the overall water demand, three scenarios were established. The initial scenario estimated water conservation to stay constant after 2012. This scenario assumes nothing additional is done to conserve residential water. The baseline scenario assumes water conservation would increase by 20% while the high scenario for conservation assumes it would increase by 40% from 2013 to 2050.

4.2.3 MLR Variables for 2013 to 2050

Figure 4-1 depicts each of the explanatory variables in the MLR model and its assumed or calculated value from 2013 to 2050.

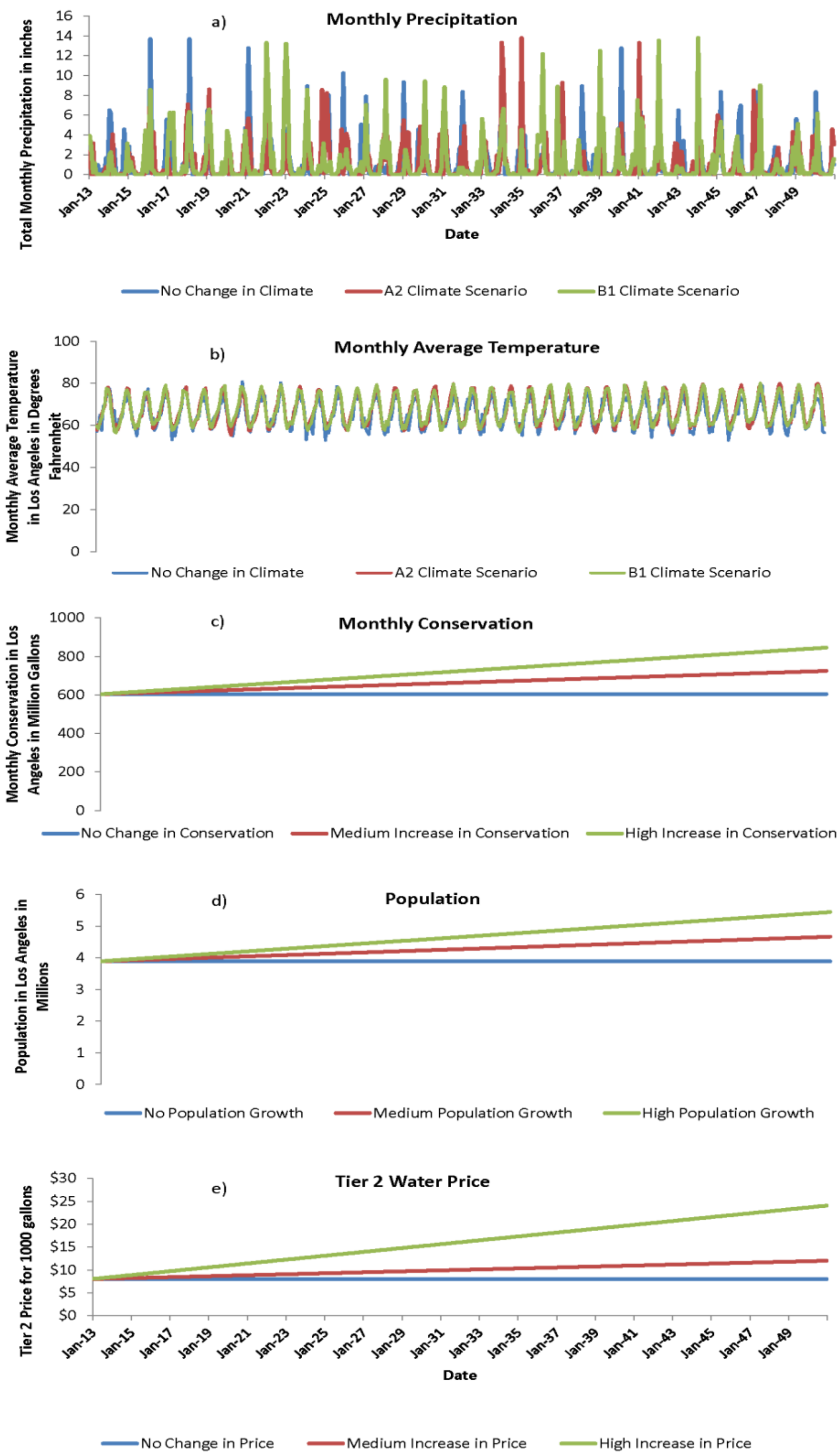

Figure 4-1: Scenario values for the five variables in the MLR model used to project water demand in Los Angeles from 2013-2050 (see Table 4-2 for sources and scenario descriptions)

4.3 Results and Discussion

In this study, projections of total monthly urban water demand in Los Angeles for 2013-2050 were developed using the various scenarios for population, water pricing, conservation methods, and climate. The MLR model forecasting results indicate that price, population, temperature, precipitation, and conservation methods all were significant in impacting projected water demand. As shown in Figure 4-2, the monthly MLR model, used to project water demand from 2013 to 2050 (Figures 4-3 to 4-5), closely follows the actual monthly water demand in Los Angeles during the period for which the model was fit, 1970-2012. The R^2 for the model was 0.72 indicating that 72% of the variability of monthly water demand is explained by the explanatory variables. The figure also shows the marked seasonal variation in water demand. High demands are seen in hot, dry summer months, whereas low demands are typical for cooler, wetter winter months. This high and consistent degree of seasonal variation is one reason why a strong weather-climate signal can be identified in the historical water demand record for Los Angeles, allowing relatively confident prediction of the effect of possible future changes in temperature and rainfall on its water demand.

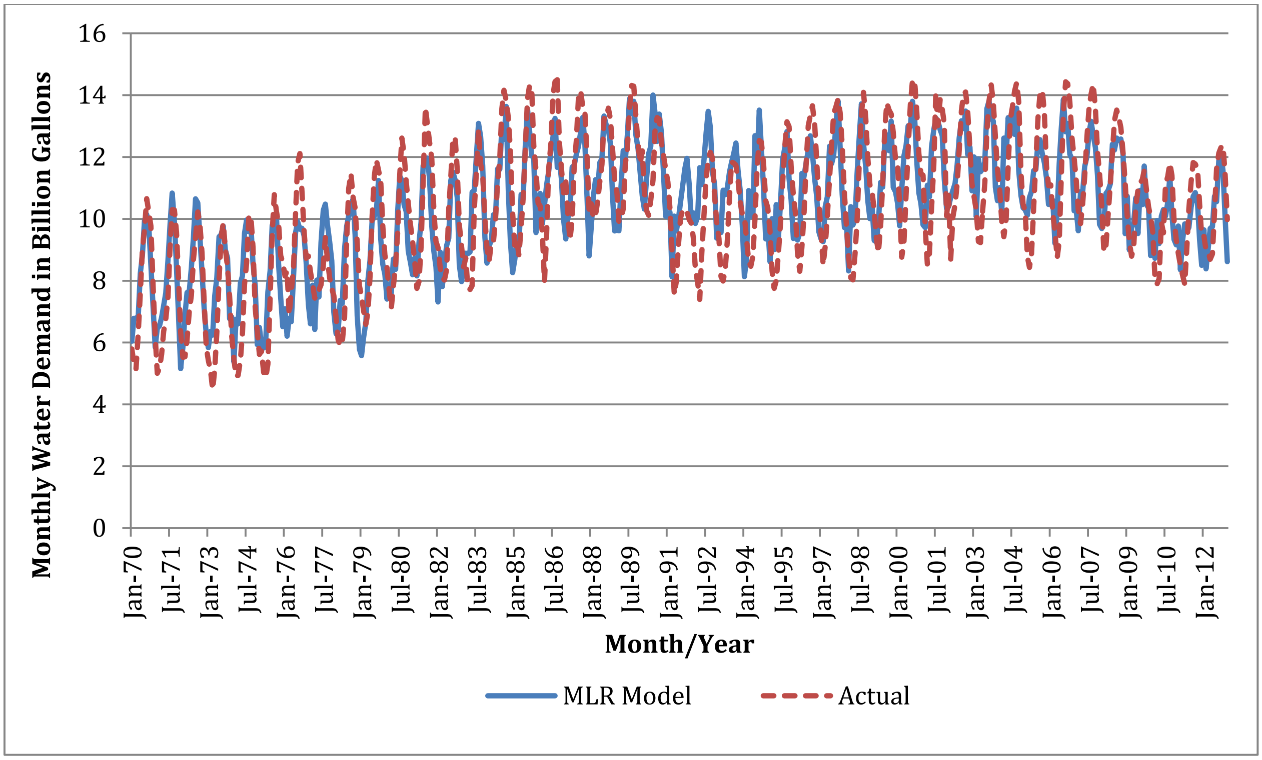

Figure 4-2: Comparing actual versus fitted MLR model of monthly water demand in Los Angeles, 1970-2012

Figure 4-3 shows projections of water demand from 2013-2050 with a focus on the effects of different population scenarios. All projections were modeled in Tableau, which is computer software used for interactive data visualization. Users are able to choose from the various model scenarios for price, population, climate models, climate scenarios, and conservation in order to visualize individual scenarios of water demand. As seen in Figure 4-3, the effects of various scenarios of population are more pronounced than the effects of the different scenarios of price, climate, and conservation. The water demand under high population growth was estimated to vary from 190-250 billion gallons in 2050 while the medium population growth yielded an estimate of 130-190 billion gallons in 2050. For the case of no population growth the range of values for 2050 water demand in Los Angeles is estimated at 70-130 billion gallons, representing a 0-46% decrease in the water demand reported in 2012.

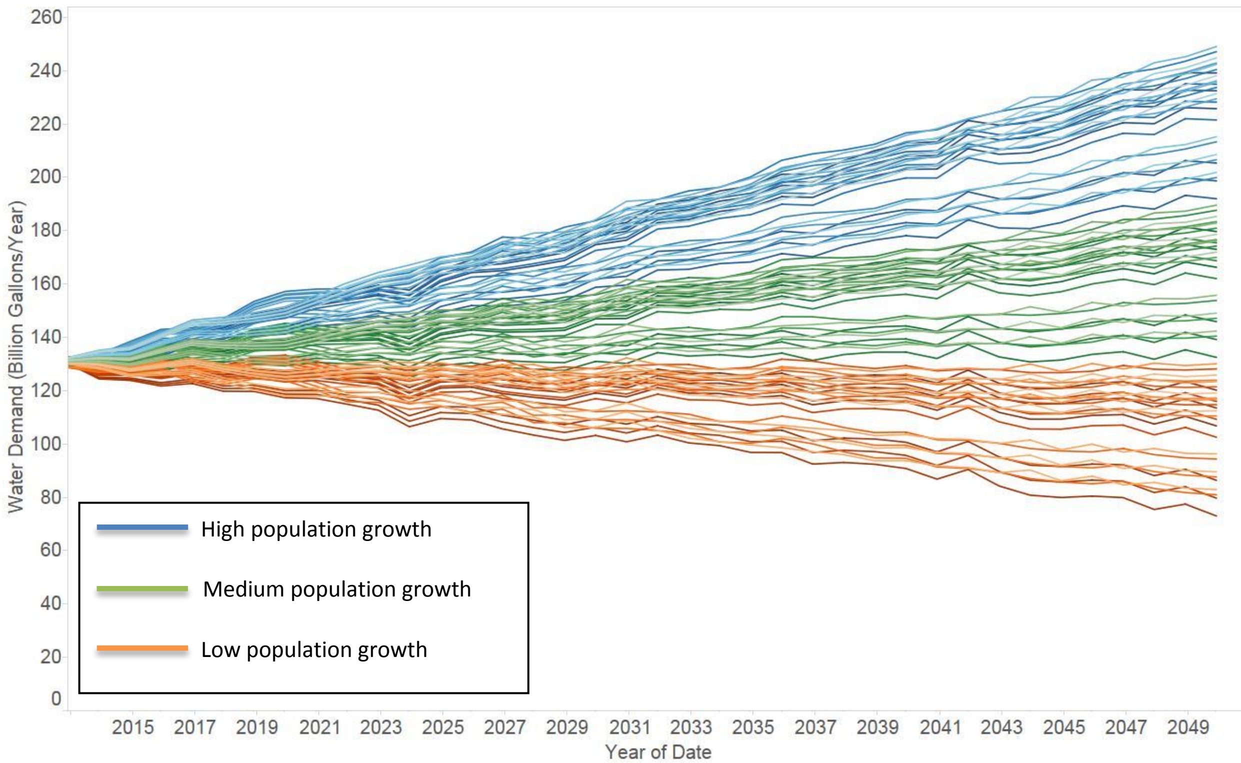

Figure 4-3: Projections of water demand from 2013-2050 under high, medium, and no population growth scenarios

Similar to population, price is predicted to have a very significant influence on future water demand. Figure 4-4 shows the varying scenarios of water demand in Los Angeles under changes in Tier 2 water pricing. Each of the indicated colors that signify the water price scenario is separated into three distinct groups. This grouping is caused by the somewhat larger impact of population in the model. The model results indicate that population stability and increases in price can drastically reduce water demand, by as much as 60 billion gallons a year in the future (nearly half of current use). Without the input of Tier 2 price, the potential range of water demand shifts upward from 70-215 billion gallons per year to 107-250 billion gallons in 2050.

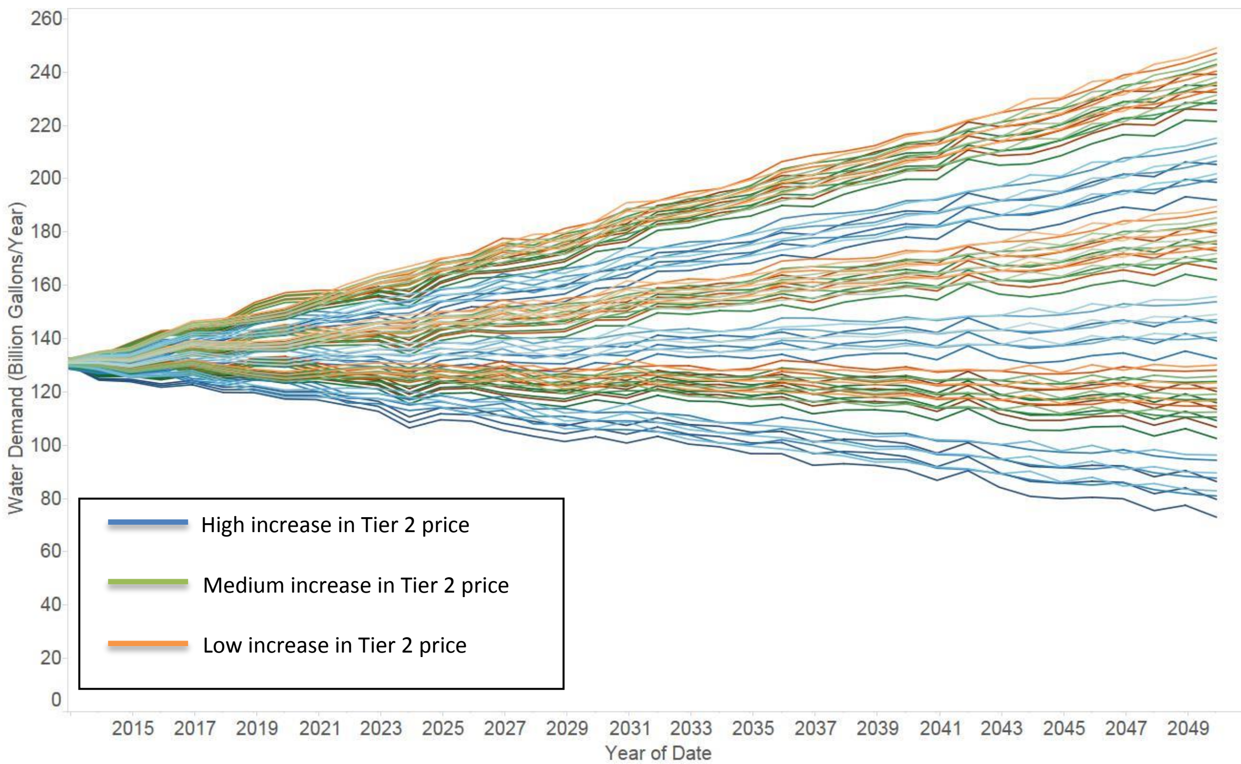

Figure 4-4: Projections of water demand from 2013-2050 under high, medium and no tier 2 price increase scenarios (Los Angeles)

The effect of climate on water demand in the projections is not as significant as that of population and price. As seen in Figure 4-5, water demand for three scenarios of climate change is shown with consideration of baseline scenarios of population, price, and conservation. What can be observed is a small increase in water demand under the A2 climate scenario compared to the B1 and no change scenarios. The difference between no change in climate and the A2 climate scenario in 2050 is 10 billion gallons per year. Therefore, a 6% increase in water demand could be attributed to climate change by 2050, under baseline scenarios of population, price, and conservation. Although it appears that changes in climate will not have a major effect on future water demand in Los Angeles, climate changes is likely to have a strong influence on the overall water supply system which relies primarily on water from the Los Angeles Aqueduct, Colorado River Aqueduct, and the California Aqueduct (Ashoori et al., 2015a). Another study done by the Pacific Institute (Christian-Smith et al. 2012) observed the changes in urban water demand under climate change. Results of their study demonstrated that climate change could increase water demand in 2100 by 8% in California when observing medium-high greenhouse gas emission scenarios.

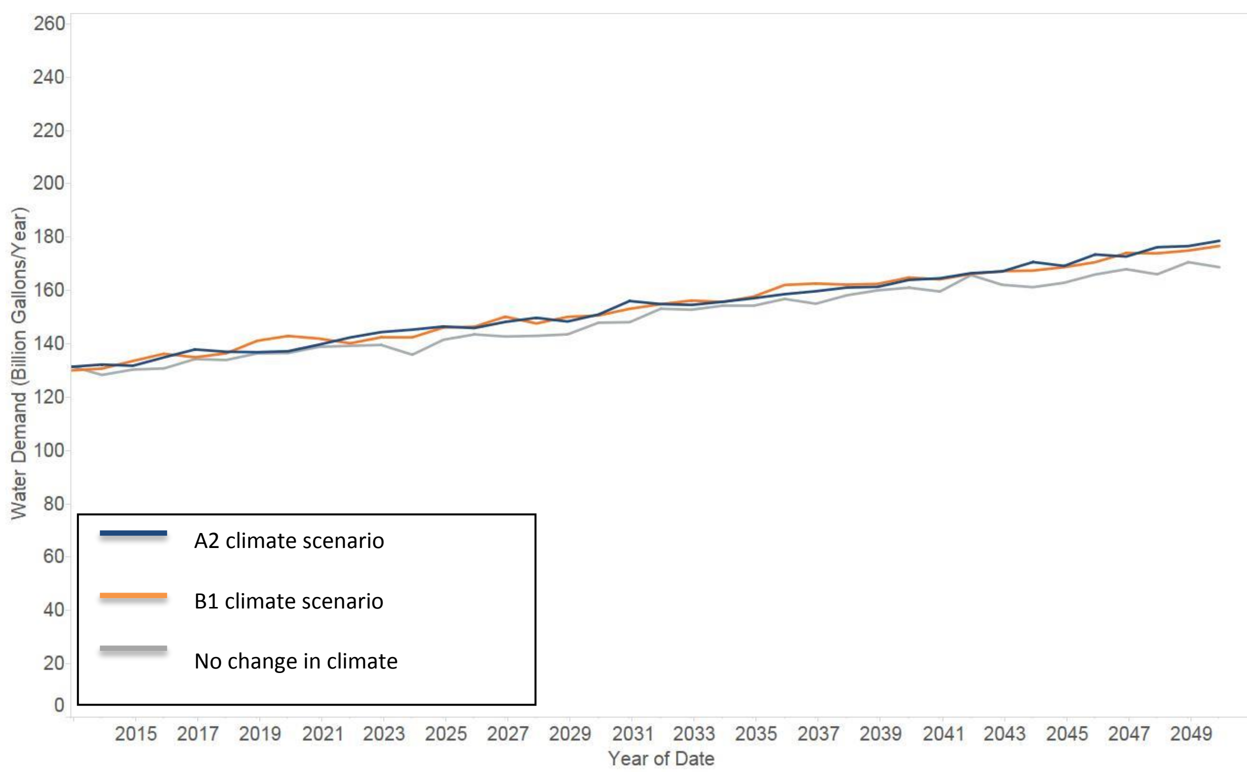

Figure 4-5: Projections of water demand from 2013-2050 under the baseline scenario with different climate models (assuming 20% increase in population, 50% increase in price, and 20% increase in conservation) indicating a very small impact of alternative climate scenarios on water demand

To visualize the relative magnitude of the potential impact of each factor (population, climate, price, and conservation) on water demand, given the uncertainties in each of the other factors, cumulative distribution functions for projected water demand in 2050 were generated for the three subsets of scenarios defined by each input factor (Figure 4-6). If the CDF's are highly displaced from each other, exhibiting little overlap, then the input factor is clearly important in the prediction of water demand in 2050, and its uncertainty. Figure 4-6 indicates that population is most important, yielding distinct separation of CDF's, with price yielding moderate separation and climate and conservation exhibiting nearly complete overlap and little discrimination for predicting water demand in 2050.

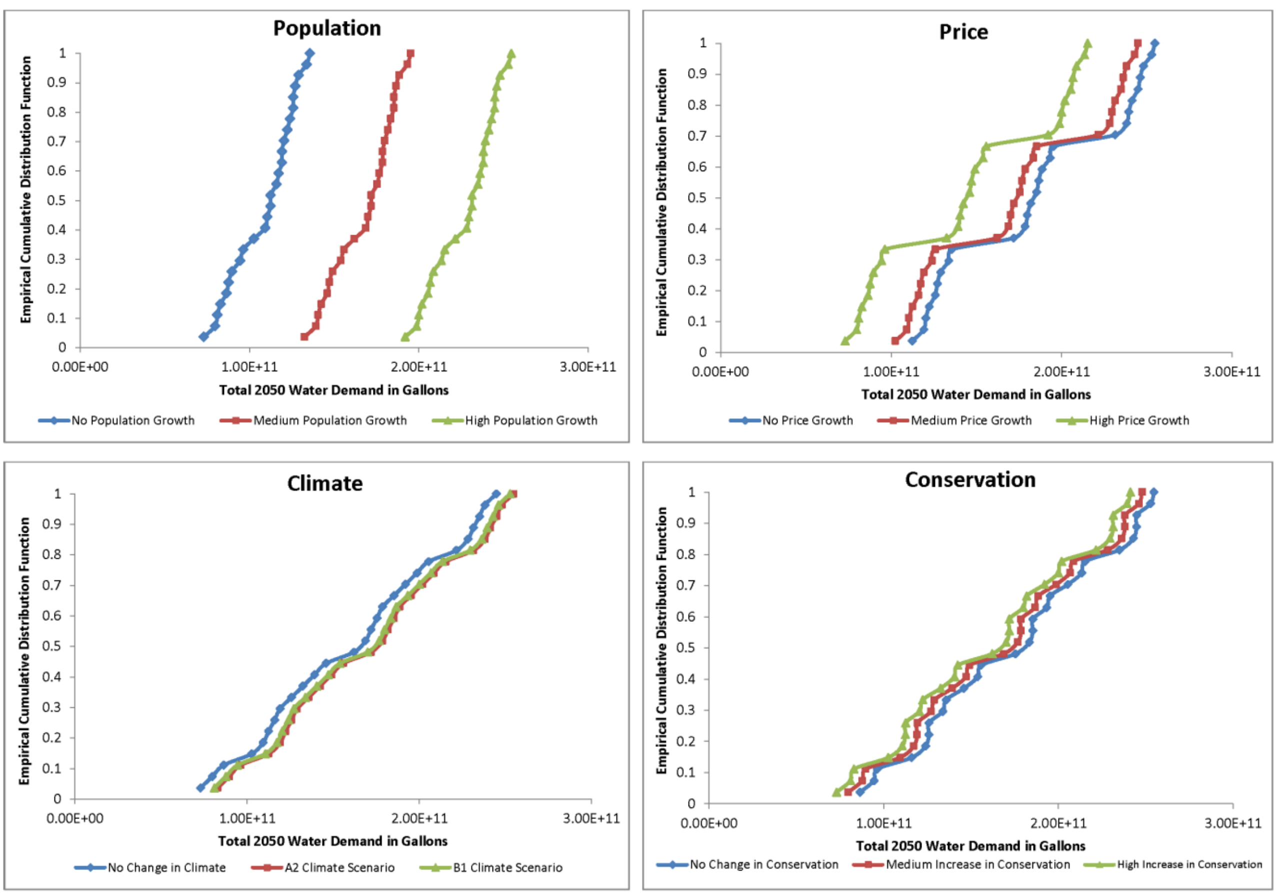

Figure 4-6: Empirical Cumulative Distribution Function based on indicated subsets of the four input factors of projected water demand in Los Angeles in 2050

Shown in Table 4-3 are the projected values for water demand in Los Angeles between 2015-2050 for bounding scenarios representing the extreme low and extreme high outcomes, with a middle (baseline) scenario included for comparison. The total monthly water demand in Los Angeles for 2015 was in the range of 124-137 billion gallons. However, the plausible range of forecasted water demand expands considerably, extending from 73 to 250 billion gallons for 2050 under changing scenario values of population, price, climate, and conservation.

Table 4-3: Total projected water demand* for the period 2015-2050

Year	Low-Bound Scenario	Baseline Scenario	High-Bound Scenario
2015	1.24	1.34	1.37
2020	1.17	1.43	1.51
2025	1.10	1.46	1.70
2030	1.03	1.51	1.84
2035	0.97	1.58	2.00
2040	0.91	1.65	2.16
2045	0.80	1.69	2.30
2050	0.73	1.77	2.50

*In one hundred billion gallons per year

Low Bound Scenario: projected water demand with no population growth, high increases in water pricing and conservation efforts, and no climate change.

Baseline Scenario: 20% increase in population growth from 2013-2050, medium increase in water pricing and conservation efforts, and B1 climate change scenario.

High Bound Scenario: Highest increase in population, no increase in price and no conservation with A2 climate change scenario.

The baseline scenario, which is perhaps the most likely scenario, will see an increase in water demand from 130 to 177 billion gallons per year by 2050. This is equivalent to an increase of 36%. From this analysis, it is seen that future water demand is expected to be largely driven by price and population rather than climate change. Conservation can decrease water demand and climate change can cause modest increases, but their long-term effects are small compared to the large potential impacts of population growth and pricing policies in the LADWP service region. However, during periods of extreme drought consumers are capable of conserving an increased amount of water due to mandatory restrictions. As seen in Figure B-6 in the appendix, water demand in Los Angeles has decreased even further during the drought years of 2013-2015. Exploring the long-term and short-term changes in behavior to drought and water demand changes is important to investigate. Such information will lead to better solutions to future water demand management concerns.

4.4 Conclusions

Management of water demand is important to the future sustainability of the Los Angeles water supply system. Since uncertainty is present in future climate forecasts, population estimates, pricing structures, and conservation methods, water planners must direct their attention to long-term strategies that are robust under a range of scenarios. In this study, the total monthly residential water demand in Los Angeles during the period of 2013-2050 was projected across various scenarios of population, water pricing, climate, and conservation levels. Three future scenarios for each input factor were developed based on historical trends and predictions from other sources. The maximum total water demand is projected to occur when population increases, climate becomes drier and hotter, and price and conservation efforts remain stagnant. The projected maximum residential water demand in 2050 is estimated to be 250 billion gallons, a 92% increase from the 2012 water demand of 130 billion gallons. However, in the more likely baseline scenario, water demand is estimated to be 177 billion gallons per year in 2050 indicating that water demand will increase by 36% from 2012. The study results indicate that changes in population and price in Los Angeles are expected to play a bigger part in influencing future water demand than climate change and conservation programs. Understanding the importance and future pathways of the factors affecting water demand will be a key step in ongoing planning for a reliable and resilient water supply for Los Angeles.

Acknowledgements

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Chapter 5 : Agent-Based Modeling of Residential Water Demand in Los Angeles, California: Insights into Water Conservation Behavior

This chapter, written by Negin Ashoori and co-authored by Emily Z. Berglund, David A. Dzombak, and Mitchell J. Small, will be submitted for publication.

Abstract

Residential water demand in Los Angeles is dynamic and influenced by numerous factors relating to hydrology, climate, and population dynamics. This paper presents an agent-based model (ABM) developed to investigate how residential consumers and Los Angeles Department of Water and Power (LADWP) interact with one another under various scenarios of drought, population growth, and supply variability. Projections of water demand and planning for system sustainability is challenging, since there are many underlying social factors influencing the system. Currently, LADWP relies mostly on imported water to supply the over 4 million people who depend on them. With increasing stress on the sources of water supply for Los Angeles, as well as growing population, conservation will be increasingly important. It is therefore important to understand how consumers react to various conservation programs in periods of drought. In order to make accurate projections and assess sustainability of water supply and demand in Los Angeles, an evaluation of conservation strategies was conducted using Anylogic, an agent-based computational model, to investigate the dynamic behavioral characteristics of water demand and to simulate social decision making and system evolution. The model was calibrated using actual water demand, population, and conservation data obtained from LADWP for the period 1970 to 2012. Forecast simulations were then performed with the model for 2013 to 2050 on a monthly time step. Results of the modeling indicate that water supply availability and variability greatly impact the amount of conservation. Conservation ranges from 300,000 – 1,750,500,000 gallons per month depending on drought level. When drought levels are high and supply is variable, consumers are responsive to conservation efforts, social pressures from their surroundings, as well as increases in water price. Under such conditions, water demand levels can remain constant

even when population growth occurs. However, high variability in water supply in the study will increase water demand by 4 billion gallons per month compared to low variability in 2050 which will place additional stress on the already limited water supply. The agent based model provides insight into the societal and environmental responses of water consumers to various water supply, climate change, and population growth scenarios. In doing so, water management decisions regarding conservation methods and water efficiency programs can be analyzed.

5.1 Introduction

As Los Angeles imports more than 90% of its water supply (LADWP 2010), and as its population of more than 4 million is growing, understanding how water demand will evolve in the future is important to water supply planning. Water demand in Los Angeles, as in other urban areas, is influenced by numerous factors relating to hydrology, climate, population, and economy. Projections for future water demand require knowledge of the inter-relationships among these factors, and social interactions that affect them.

In this work an agent-based model was developed to investigate how residential consumers and Los Angeles Department of Water and Power (LADWP) interact with one another under various scenarios of drought, population growth, and supply variability. The overall objective of the agent-based modeling was to simulate and evaluate the societal and environmental responses to varying climate change, population growth, and hydrological scenarios. A good understanding of the drivers of residential water demand is essential to implement effective management policies and infrastructure planning strategies (Athanasiadis et al. 2005). An agent-based model can evaluate these interactions and assess the state of natural water resources, water supply infrastructure, and water demand (Ali et. al. 2014, Galan et al. 2009). It can allow for future plans and actions to be implemented under different scenarios and can optimize the system according to costs, capacity requirements, and human opinions.

Agent-based modeling (ABM) is a type of computational modeling that simulates the actions and interactions of individual agents in order to analyze their impacts on the system as a whole (Barthel 2010). It allows for learning and adaptation of the model using evolutionary algorithms, and other learning techniques (Brian 2002). In regard to water resources, ABM has been used to simulate supply-and-demand of urban water systems under different climatic, demographic, and infrastructure scenarios (Giacomoni et. al. 2013; Abrami 2012; Zhao 2003, 2009; Berglund 2015). Multi-agent modeling can analyze the interactions of multiple agents to explain the complexity of water uses and users within regions (Berger et. al. 2007; Moss 2000). Other studies have used agent-based modeling to evaluate the effect of climate change on the sustainability of future water resources (Barthel 2008; Mikulecky 2009; Chu 2009, Kanta and Zechman 2014), but none have focused on Los Angeles water demand and the range of factors affecting it.

An agent in an agent-based model is a discrete entity with its own goals and behaviors. Examples of agents are people, groups, organizations, and robots and can be defined as anything that is capable of making individual decisions (Borshchev and Filippov 2004). Each agent assesses a situation and makes decisions based on a set of defined rules and ABM analyzes these agents and their relationships between one another. Additionally, agents can also evolve to take into account behavior changes.

For water resources, sustainability and long-term management goals are important to identify, but agents, such as residents in urban areas, and water suppliers, all have different priorities when it comes to water. These relations and dependencies on water supply will also vary under the influence of climate change and population growth. An advantage of agent-based modeling in application to water resources is that it captures emergent phenomena, when a complex system develops from numerous and diverse interactions (Macal and North 2010, Barreteau 2003). The water supply system in Los Angeles and the consumers exerting demand through individual actions is an inherently complex system characterized by phenomena that emerge in response to multiple stimulating factors. The agent-based modeling described herein yielded insights into this system.

5.2 Methodology

Agent based modeling simulates the behaviors of various agents, all of which have their own interests, which can be dependent on economic benefits, social status, and other factors. Agent based models are structured with four features: environment, decision making, interactions, and adaptation. Simulation is conducted with a bottem-up modeling approach (Borshchev and Filippov 2004). Possible actions are defined, and every action has behavioral options from which an agent can choose. Both quantitative and qualitative states of water resource processes can be evaluated by ABM.

The key steps in developing an agent-based model are (Akhbari and Grigg 2013):

1. Choose agents in the model
2. Indicate their behaviors and goals
3. Develop the environment in which agents interact
4. Specify agent interactions
5. Aggregate agent-related data
6. Validate the agent-based model

In this study, LADWP and Los Angeles consumers were chosen as agents with each consumer being a separate agent individually acting on the system. Their behaviors were identified and their overall goals were selected. For LADWP, their main goal is to have enough water to meet demand without having to increase water transfers, which are obtained at a much higher price than the main five water sources supplying Los Angeles. As for consumers, their main goal is to pay less money for water and to be socially accepted in their community. By identifying these goals, the agents behaviors are modeled. The environment of the agents is developed, which states the parameters and other factors playing into the system in order for agent interactions to occur. Data regarding those interactions and decision making is aggregated, such as monthly water demand, number of residential water conservers, drought level, and water supply. These projected values are compared to actual values to calibrate the agent-based model.

A community of individual water consumer agents was defined and their behavior simulated with a water demand model based on the models from Chapters 3 and 4. Social interactions related to water conservation methods were defined and considered explicitly to simulate the impact of individual water conservation decisions within Los Angeles under various drought level scenarios. The complex interactions between consumers and LADWP, as well as between individual consumers themselves, were represented in the model.

5.2.1 Agent Based Modeling Framework

The agent-based model was developed in Anylogic 7.2 and implemented in Java. Two major agents in the Los Angeles water supply were considered: Los Angeles consumers and the Los Angeles Department of Water & Power (LADWP). These agents and the parameters affecting the water system are depicted in Figure 5-1. The model includes the water supply system of LADWP, which supplies water to over 4 million people. For water resources, sustainability and long-term management goals are important to identify, but agents all have different priorities when it comes to water demand and supply.

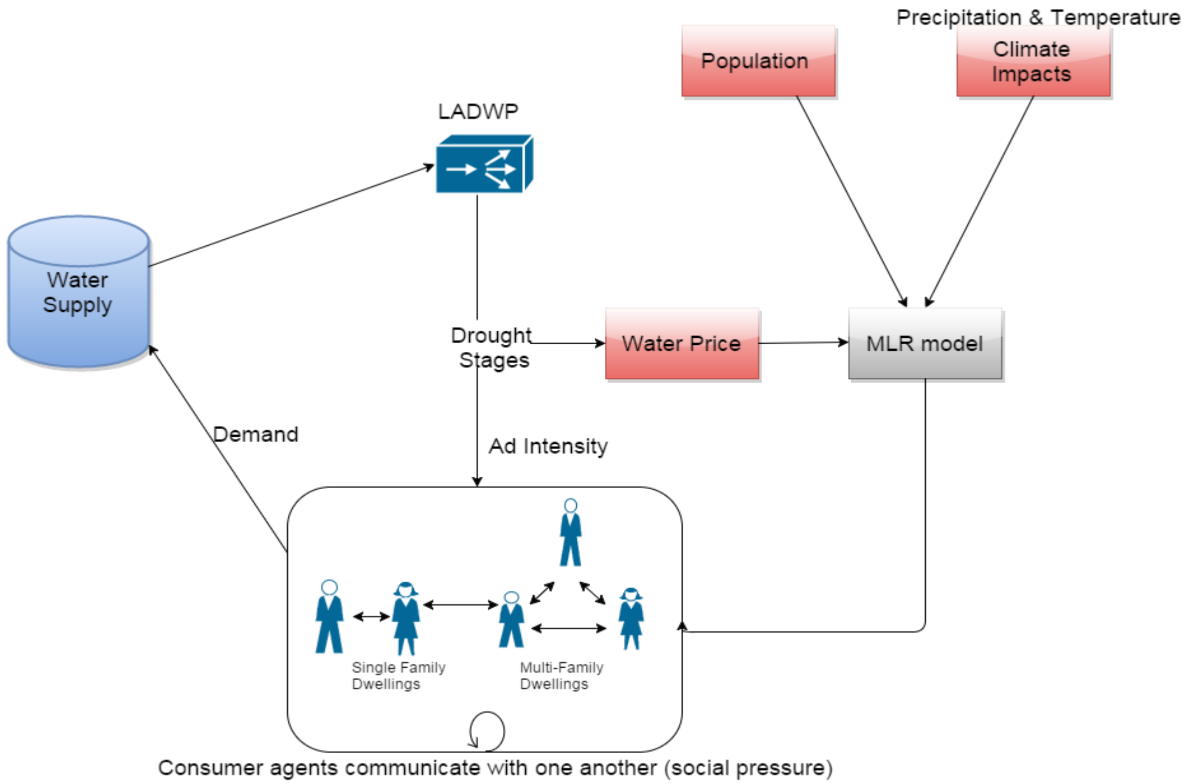

Figure 5-1: Agent-based modeling framework for simulating water demand in Los Angeles, CA with LADWP and consumers being the agents and water price, population, and climate being parameters impacting the water demand system

5.2.2 Los Angeles Department of Water and Power

LADWP is simulated as an agent who first observes the amount of water supply and sets what criteria distinguish each drought level. The drought level then defines water prices, advertisement intensity, contact rates between consumers, and adoption fraction. During periods of drought, at the threat of water shortage, the LADWP agent may campaign for water conservation measures. After rainfall events, as water supply returns to normal levels, conservation campaigns may recede in priority and consumers may neglect their water-saving habits. To avoid similar water shortages in the future, water prices can be adjusted to incentivize consumers for efficient water use. Thus, the LADWP agent offers incentive-based conservation programs, imposes water-use restrictions, and allocates water supply. At the beginning of each month, the LADWP agent evaluates the level of water which is in their storage tanks. The storage amounts model the total amount of water LADWP receives from Metropolitan Water District of Southern California, Los Angeles Aqueduct, recycled water, and groundwater. Depending on those levels, the LADWP agent defines the stage of drought. Description of drought levels can be seen in Table 5-1. LADWP uses various water conservation strategies to deter residents from consuming water. Some of these strategies include:

- Water conservation education
- New water efficiency technology
- Increasing water price
- Restrictions or bans to limit water use

The first three conservation strategies are considered voluntary, whereas the last strategy is mandatory. Water conservation education includes sending advertisements to consumers to let them know about drought levels as well as ways to conserve water. During periods of drought, increases in water prices in Los Angeles have lowered the demand for water mainly through voluntary measures (Ngo and Pataki 2008, Frederick 1997). Tiered water pricing structures that implement higher prices on water above certain levels of use encourage efficient use of water (Freeman et al. 2008). In this model, tier 2 water rates are set by LADWP depending on water supply levels. Other ways of conserving water, such as mandatory restrictions and increasing water efficient technology can reduce water demand, but are outside the scope of this research.

5.2.3 Consumers

Residential consumers in the LADWP service area are also simulated as agents. Each agent makes behavioral decisions dependent on conservation levels set by LADWP. All residential agents belong to a social network, which represents the interactions and word-of-mouth communication among agents. Based on the behavior and rules of the residential agents' interactions, a residential agent can adopt water conservation measures. Each residential agent's water consumption is affected by water conservation policies and interaction within social network. Consumers also respond to changes in water prices. The proportion of agents influenced by society, authority, or not at all is defined. As seen in Figure 5-2, there are five parameters in the consumer state-chart. Based on drought levels, a consumer's decision to conserve is impacted by advertisement intensity, contact rate, adoption fraction, and willingness to reuse. Descriptions of the five parameters and how they can effect conservation are shown in Table 5-1 and Table 5-2.

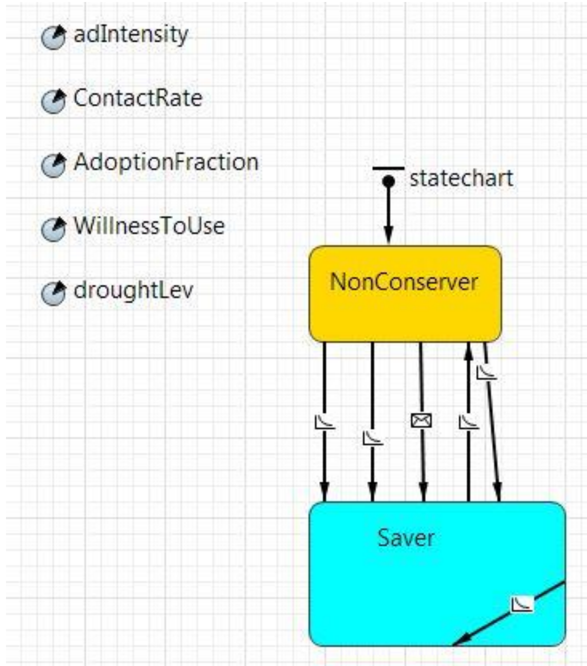

Figure 5-2: ABM state-chart of consumer agents and the parameters impacting their decision-making

Conservation in the model is influenced by the amount of water in the storage system. Climate change will increase variability in water supply to Los Angeles (Freeman et al. 2008), which is considered in this model using water supply variability buttons in the user interface (Figure 5-3). After the LADWP agent defines the drought level, which is dependent on water storage, conservation is generated through water price changes, advertisement intensity, contact rate, and adoption fraction. Advertisement intensity is the amount of contact made from LADWP to consumers asking them to reduce water use. As drought levels increase, so also do the number of advertisements distributed to consumers. Contact rate is the rate consumers communicate with one another. During each contact the consumer agent will tell another agent to conserve water. Communication increases when there is a higher level of drought. Finally, the adoption fraction is the willingness of the consumer to become a conserver. This fraction increases depending on the level of drought as well. Values for contact rate, adoption rate, and amount conserved dependent on drought level can be observed in Table 5-2.

Table 5-1: Description of drought levels in the agent based model of Los Angeles water demand

Drought Level	Water Supply Condition	Trigger (% Storage)*	Reverse Trigger
Permanent Conservation Measures	No Shortage	--	--
Level 1	Low Shortage	<85%	>= 85%
Level 2	Moderate Shortage	<80%	>= 80%
Level 3	Severe Shortage	<65%	>= 65%
Level 4	Critical Shortage	<50%	>= 50%

*information on drought stage conditions was obtained by the LADWP Urban Water Management Plan 2010

As seen in Table 5-2, the increased drought levels lead to an increase in advertisement intensity, contact rate, and adoption fraction, as well as increase the average amount of water conserved per person. For example, if the drought level was 4 for any given month, advertisement intensity would be 5 advertisements from LADWP for the month, 25 contacts from other consumers pressuring the agent to conserve, a conservation adoption percentage of 40%, and average amount conserved per consumer of 35 gallons per day. With each time step the drought level gets adjusted based on available water supply and the system begins again at changing these parameters. In addition, the state-chart specifies an additional parameter named *Willingness to Use*. This parameter reverses conservers back into users once drought levels have decreased. In doing so, a more realistic approach to modeling water demand in Los Angeles is undertaken since people are willing to use more water when prices are low and water supply is high. The reverse trigger values can be seen in Table 5-1.

Table 5-2: Description of parameters influencing consumer agents to conserve water under various drought levels in Los Angeles

Drought Level	Ad Intensity	Contact Rate	Adoption Fraction	Average amount conserved (per conserver) in gallons per day
Permanent Conservation Measures	0	1	0.2	10
Level 1	2	10	0.23	20
Level 2	2.5	15	0.26	25
Level 3	3	20	0.30	30
Level 4	5	25	0.40	35

In the user interface (Figure 5-3), users are able to adjust the climate scenario, population growth, and level of water supply variability in the system. In doing so, the user can see various changes in the system which are dependent on the initial parameters.

Figure 5-3: Agent based model interface allowing users to choose climate scenario, population growth rate, and degree of water supply variability**.**

5.2.4 MLR MODEL FOR CONSUMER WATER DEMAND

A multiple linear regression model (MLR) for water demand in Los Angeles, which was formulated and discussed in Chapter 3, is included within the agent based model to simulate the effects of climate, population, and water price on consumer water demand. In separating those factors, there is a better understanding of conservation and how in which it affects the system.

The total water demand for each month is calculated as

$$D_t\ (1000\ gallons) = -2.38E7 + 2.12E5 * T_t - 5.85E4 * R_t - 2.45E5 * WP + 6.46E0 * P_t - C \quad (1)$$

where:

D_t = Monthly total water demand in Los Angeles in 1000 gallons

T_t = Average monthly temperature (°F)

R_t = Total monthly precipitation (in)

WP = Water price per 1000 gallons

P_t = Total estimated monthly population

C = Estimation of monthly conservation (1000 gallons)

Conservation in the system is modeled by the agent-based model and not the MLR model. After the MLR model is run to calculate monthly water demand, the estimated monthly conservation calculated from advertisement intensity, contact rate, and adoption fraction, is subtracted to yield the total water demand for the month.

5.2.5 Water Pricing

Since water prices are influenced by drought levels, a linear relationship was developed between price and water volume using SPSS 22.0. Prior to 2012 actual data for water prices were implemented in the system. However, after 2012, water prices were calculated depending on the monthly inflow of water:

$$WP = 16.26 - S_t * 5.98E\text{-}8 \quad (2)$$

where *WP* indicates water price per 1000 gallons and S_t represents monthly inflow of water into the system in 1000 gallons. The linear model indicates that a gallon increase in water supply decreases price per 1000 gallons by 5.98E-8. After the water price is calculated, the value is inputted into the MLR water demand model.

5.2.6 Climate Scenarios

Data for the climate scenarios were the same used in Chapter 4. Three climate scenarios were developed, one of which used bootstrapping of actual monthly average temperature and total precipitation values in Los Angeles from 1970 to 2012.

For the other two scenarios, the average of four different IPCC climate models were undertaken (Parallel Climate Model, Community Climate System Model, Geophysical Fluid Dynamics Laboratory, National Centre for Meteorological Research) and analyzed using two IPCC climate scenarios (A2, B1) (California Energy Commission 2015). The A2 scenario indicates continual population increase and economic growth and the B1 scenario indicates the introduction of efficiency technologies with increases in population (Nakicenovic et al. 2000). Prior to 2012, actual climate data were used in the model.

5.2.7 Population Scenario

Much like the climate scenarios, users are able to choose which population growth scenario to analyze in the model, as seen in Figure 5-3. The three scenarios selected for population projections result from varying assumptions of growth in Los Angeles. The low-bound scenario population projection assumes that population stays constant at 3.9 million after 2012. The baseline scenario provides for an increase of 20% in population by 2050, meaning the population would reach roughly 4.7 million by 2050. The high-bound population scenario assumes population will increase by 40% during the projection period, giving a population of 5.4 million by 2050. These three scenarios encompass a broad range in the spectrum of potential population growth influencing Los Angeles water demand (LADWP 2010).

5.2.8 Water Storage Model

In order to simulate how much water is in the system at any given time point, water storage is calculated monthly using this equation:

$$W_t = W_{t-1} + S_t - D_t \tag{3}$$

where W_t is the volume of water (1000 gallons) which is given to LADWP in the beginning of the month and W_{t-1} is the volume of water (1000 gallons) from the previous month. The initial water volume for January 1970 is set as 2.2E11 gallons, which is the total water capacity for LADWP (LADWP 2010). S_t is the supply of water (1000 gallons) into the system. Supply is randomly generated from bootstrapping previous water supply data obtained from the Los Angeles Department of Water and Power from 1970 to 2012 and multiplying it by various stages of variability, which the user chooses. Variability ranges from high, which can be up to 50% different from the bootstrapped water supply data, to low variability, which gets up to 10%. The variability levels were chosen by subtracting the highest water amount given to LADWP through the actual data with the lowest amount recorded between 1970-2012. LADWP observes the amount of water in the storage and defines drought levels set in Table 5-1.

5.2.9 Agent Architecture

In the user interface (as shown in Figure 5-3), users specify the initial water supply variability, population growth, and climate change (temperature and precipitation), which can be adjusted on the agent based model interface. The LADWP agent analyzes the amount of water in the system and adjusts the drought level according to the amount of water stored and begins the initial simulation procedure. By choosing drought levels, LADWP sets water prices, contact rate communication between consumer agents, and advertisement intensity, which persuades people to conserve water. The simulation procedure then evolves in an iterative manner.

The model was calibrated using actual data for the period of 1970-2012. The calibration model was used to adjust conservation parameters in the system. This was done by using actual data for precipitation, temperature, price, population, water supply, and water demand to adjust values impacting conservation, such as ad intensity, contact rate and adoption fraction. Actual drought level stages were obtained from LADWP and incorporated into the final model. Conservation programs implemented from 1990 were analyzed in order to explain changes in ad intensity. However, ad intensity, contact rate, and adoption fraction values for each drought level are uncertain and calibrated using data available. In order to address this uncertainty, data needs to be obtained from LADWP on how often they contact consumers to conserve water, as well as analyze observations on how often consumers interact with one another. In understanding these relationships, a better calibration of the model can be reached.

5.3 Results

Having specified initial values of population, climate change, and water supply variability, the model was used to evaluate 45 different scenarios of water demand. One of the scenarios is simulated and shown in Figure 5-4. Figure 5-4a shows the monthly changes in the multiple linear regression model, which takes into consideration climate, population, and price, as well as the overall total water demand, which incorporates conservation into the model. Fluctuations in the monthly model reflect the seasonal variation in water demand. The output also yielded the total number of water savers vs. non-conservers (Figure 5-4c) and the estimated amount of water they conserved (Figure 5-4b), dependent on drought level. Water savers are consumer agents who conserve water during the specific month shown, whereas non-conservers are consumer agents who use an average amount of water per month and do not conserve. Drought level fluctuations per time step can be seen in Figure 5-4f which is dependent on water supply (Figure 5-4e). Users initially choose the water supply variability impacts the robustness of the system. Water storage amounts, seen in Figure 5-4d, display the effects of water demand from the previous month in addition to water supply values. As water storage values increase, drought levels decrease.

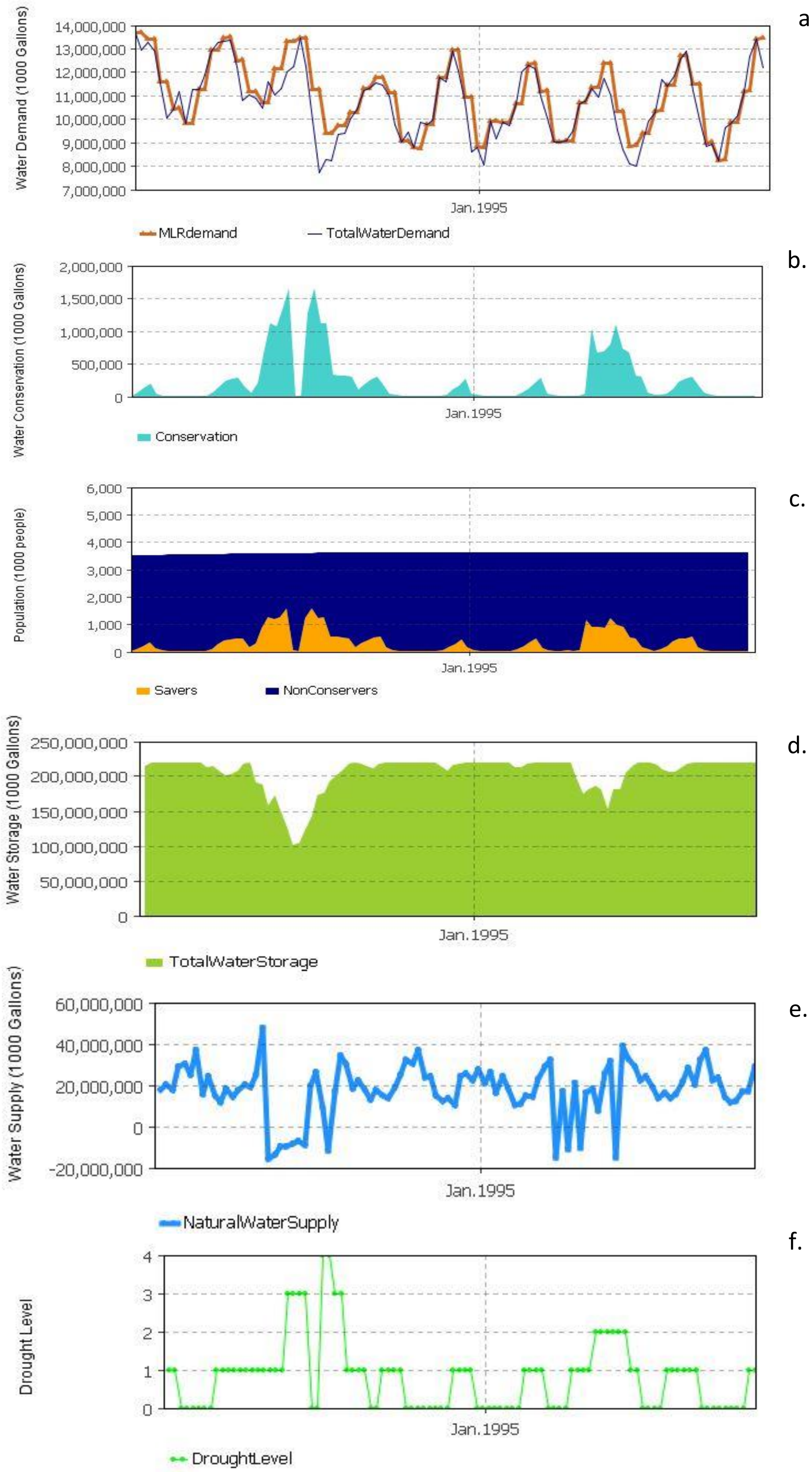

Figure 5-4: Screenshot of graphical model results in Anylogic

Results of the study indicate that the agent based model can be accurate in estimating conservation and monthly water demand (Figure 5-5). Figure 5-5 shows the difference between the ABM model, the MLR model, and actual water demand values obtained from the Los Angeles Department of Water and Power. Values of the projection of water demand using agent-based modeling can be seen in Figure 5-5. The mean absolute percentage error between the agent based model and actual water demand for 1970-2012 was 9.76%.

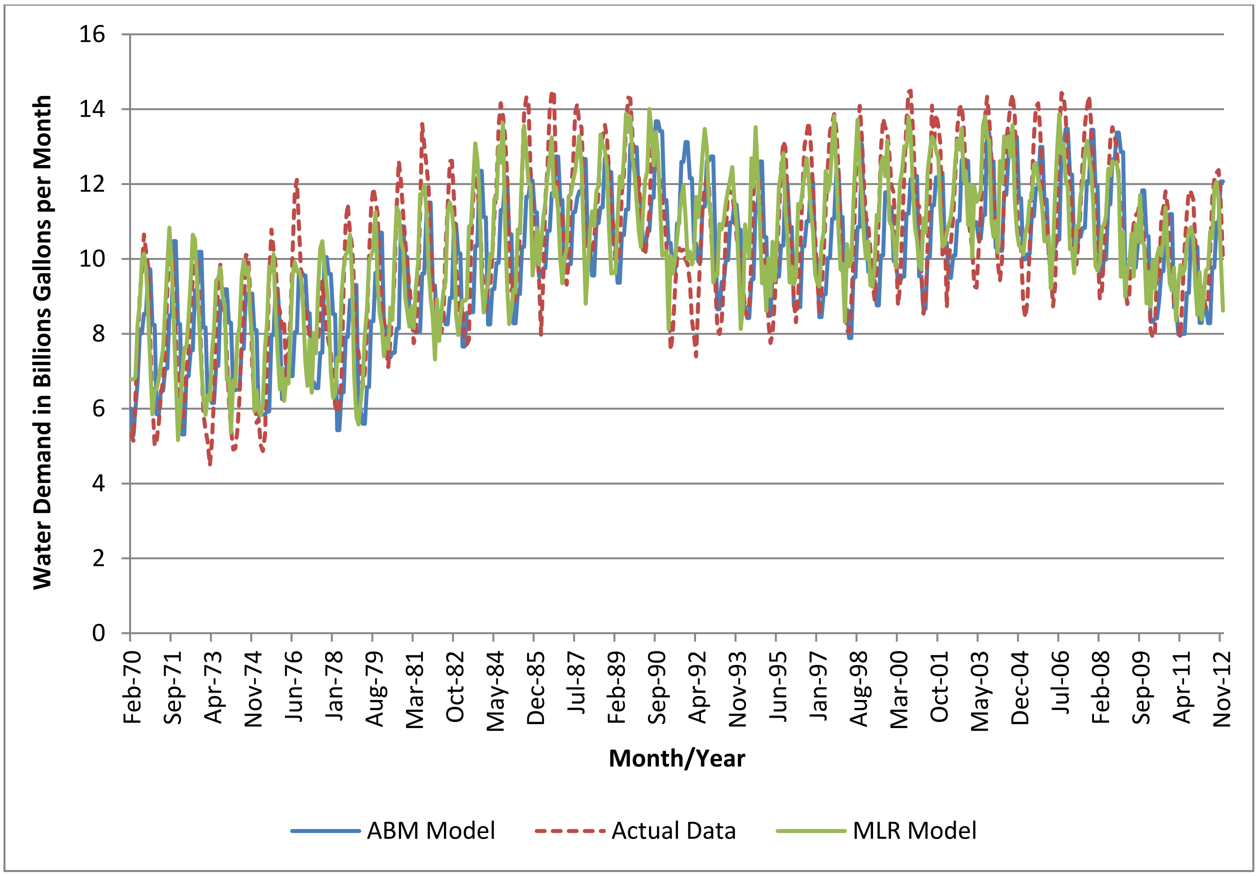

Figure 5-5: Comparison of agent-based model, multiple linear regression model, and actual yearly water demand in Los Angeles from 1970 to 2012 using scenario 2 for climate, 20% increase in population from 2013 to 2050 and medium variability in water supply

The results also show that consumers respond greatly to drought levels and therefore are influenced by ads and social pressure. Conservation values were calibrated from data available from 1970-2012 and used to model the relationship between drought conditions and conservation levels. Variability in the water supply system which determines drought levels is demonstrated in Figure 5-6. The figure analyzes water storage amounts for the baseline scenario (B1 scenario for climate and 20% increase in population from 2013 to 2050). High variability in the system dropped water supply values significantly lower. Various months even had storage values below zero, indicating severe water drought and changes in the allocation of water to environmental restoration and mitigation.

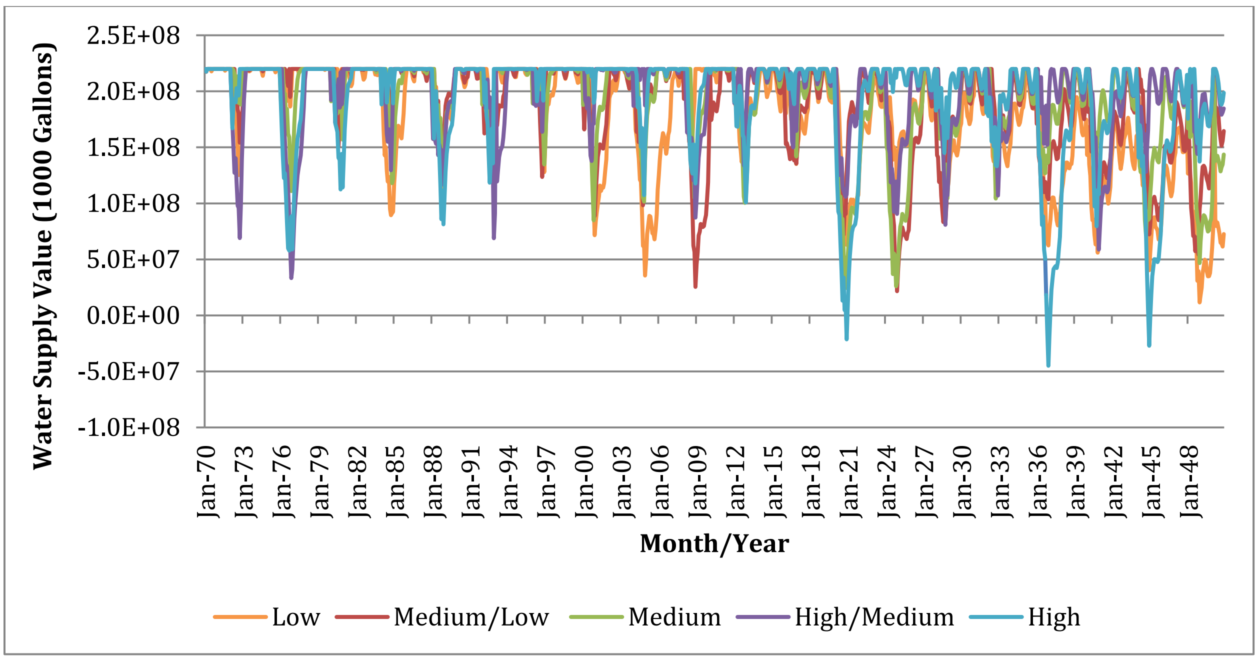

Figure 5-6: Effect of different water supply variabilities on the monthly water storage amounts in Los Angeles, CA from 1970 to 2050 assuming scenario 2 climate and 20% increase in population from 2013 to 2050

High variability in water supply additionally increased monthly water demand (Figure 5-7). For example, the 2050 monthly average for water demand was 1.6E10 gallons while the average for low variability was 1.2E10. The total amount of water capacity in Los Angeles is 2.2E11 gallons (LADWP 2010). Additionally, water demand increased from 2013 to 2050 for low variability by a factor of 2.07, whereas water demand increased by a factor of 2.67 from 2013 to 2050 for the high variability scenario. This is assuming a baseline scenario for climate and population (B1 climate change, 20% increase in population).

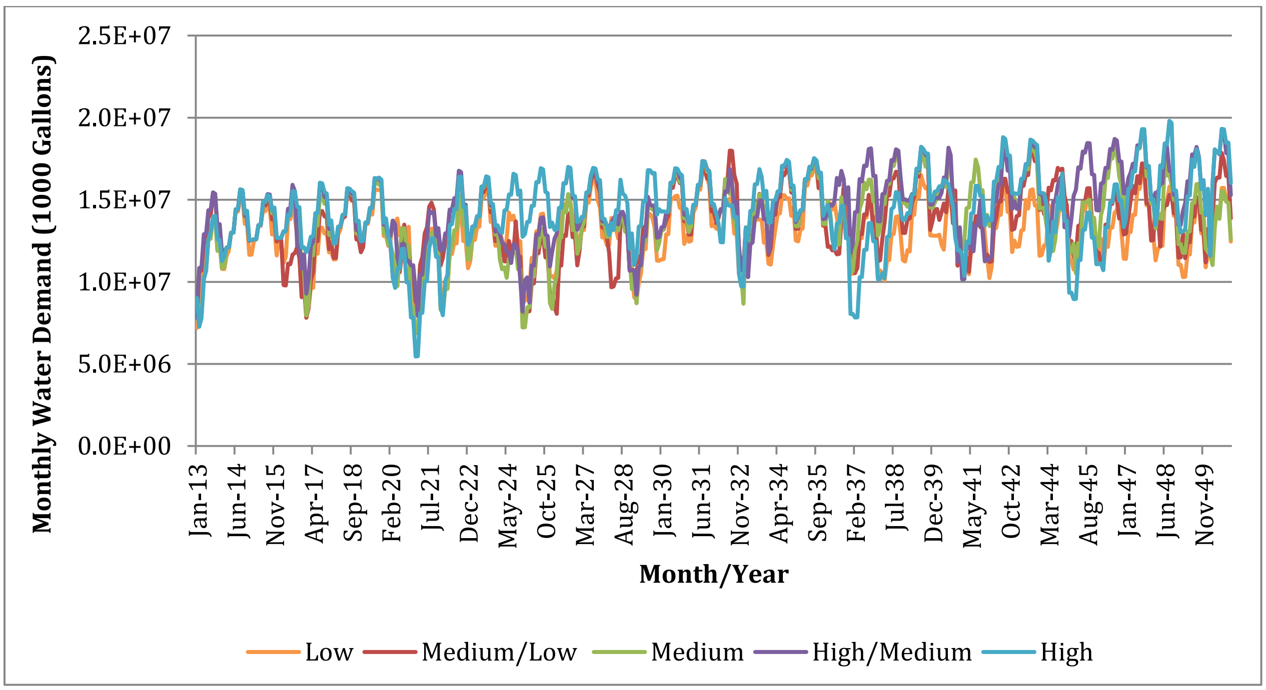

Figure 5-7: Fluctuations of monthly Los Angeles water demand dependent on water supply variability from 2013-2050 assuming baseline scenarios of population and climate

5.4 Discussion

In this study, a methodology of water demand modeling was presented. What can be learned from the simulations of the complex social system associated with the Los Angeles water demand model is that consumers can be responsive to social pressures and water prices during periods of drought. Throughout the duration of the simulation, higher drought levels yielded higher numbers of conservers and increased amounts of conservation which eventually reduced the level of drought. These values were obtained by calibrating estimated conservation amounts to the values indicated for ad intensity, adoption rate, and contact rate.

The water system in Los Angeles is complex because there are various changing interconnected factors that will only get more complex with time and climate change. As seen in Figure 5-4, when drought levels increase, the number of conservers as well increases. Large fluctuations in climate and increases in population can reduce the robustness of the system. In years of drought, LADWP is responsible for finding water to meet the demand of all those living in Los Angeles. This form of adaptation will be more difficult when the sources that LADWP relies on are less reliable.

However, the Los Angeles water supply system does have a feedback system that regulates the amount of water used. As water supply becomes less reliable, water prices increase and consumers are incentivized to conserve more water. The model used in the study tried to analyze this feedback mechanism. Water demand is receptive to water supply variability which is impacted by drought levels. Without the reliability of water supply, it is up to consumers to conserve water under increased prices or social pressure from their surroundings. The advantages of agent-based modeling in this application are to show the non-linear behavior of consumers and their decision making on conservation strategies. Modeling human decisions is challenging using MLR and ANN. ABM allows for each agent in the model to be represented under shifting projections of climate, population, and water pricing strategies and provides insight into consumer decision-making. Social dimensions related to water demand can therefore be observed using ABM to understand the emergence of drought conditions and their impact on water-efficient behavior.

Changing one part of the Los Angeles water supply system can have a large effect on other agents. As seen in this research, slightly increasing water prices can decrease water demand. However, the city of Los Angeles is still growing and dependence on transferred water remains high. Understanding the complexity of the system is important to develop sustainable solutions to future water scarcity in Los Angeles.

5.5 Conclusions

The multi-agent approach used in this model helps represent real-world decision making for consumers and water utility companies. The Agent-based model focuses on the social impacts to water demand as well as the environmental, and economic factors that occur due to climate change and population growth. Simulating how consumers react to drought and adjust their water demand is important for the sustainability of the Los Angeles water supply system. This study applies an agent-based model to simulate social decision making and system evolution. Using an integrated approach to model each agent in the water supply system in Los Angeles will assist in comprehending what will happen in the future under various scenarios of climate change and population growth in the region. Results of the study demonstrate that consumers respond to drought levels and are influenced by advertisements, social pressure, and water pricing. Conservation ranges from 300,000 – 1,750,500,000 gallons per month depending on drought level. In addition, water supply variability significantly impacted water demand in the system. High variability water supply in the study increased water demand by 4 billion gallons per month compared to low variability in 2050. Comparing the model to actual water demand in Los Angeles proved the agent-based model to be a suitable tool to model the complex water demand system.

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Chapter 6 : Conclusions, Research Implications, and Future Work

The overall objective of this work was to evaluate the factors that impact water demand in Los Angeles as well as apply and compare various modeling techniques to forecast water demand. This was accomplished by (1) assessing the sustainability of each of the water sources that supply Los Angeles under present and future conditions using a system characterization and analysis. (2) Analyzing the importance of various factors influencing water demand in Los Angeles using multiple linear regression and artificial neural network models. (3) Projecting water demand in Los Angeles until 2050 under various scenarios of price, precipitation, temperature, conservation and population. (4) Developing an agent based model of Los Angeles water demand that provides insight into interactions among consumers and the LADWP water management system.

6.1 Conclusions

Chapter 2 of the dissertation focused on the sustainability of each of the water sources that supply Los Angeles. The sources were analyzed under present and future conditions. Out of the five main water sources that supply Los Angeles, Los Angeles Aqueduct, Colorado River Aqueduct, California Aqueduct, groundwater, and recycled water, most are highly impacted by climate change, energy, and cost stressors. Additionally, all the sources are impacted by water quality concerns. Even though agricultural water transfers and water demand management strategies have been implemented to offset these stressors and concerns, climate variability and competing demands in the future are likely to hinder their potential.

Chapter 3 evaluated the importance of monthly and yearly water price, population, conservation methods, temperature, and precipitation on influencing water demand using numerous multiple linear regression and artificial neural networks. Historical (1970-2012) water demand data were fitted with each of the model types. Results showed that the multiple linear regression and artificial neural network models were comparable in modeling water demand in Los Angeles. Population, price, conservation, temperature, and precipitation were all highly significant in impacting water demand. Additionally, fitting monthly data yielded more accurate data fits compared to fitting yearly data. Results also showed that while population growth has had a substantial impact on water demand, price and conservation impacts have significantly counteracted increased water demand from population growth.

Chapter 4 used the multiple linear regression model from Chapter 3, calibrated based on historical monthly water demand data, to project water demand in Los Angeles until 2050. Using various scenarios of climate, population growth, water pricing, and conservation efforts, the results of the projects demonstrated that the effects of climate change on water demand (not supply) are projected to be relatively small. In the envelope of scenarios, water demand is projected to be within the range of 70-250 billion gallons in 2050. The maximum total water demand is projected to occur when population increases, climate becomes drier and hotter, and price and conservation efforts remain stagnant. The projected maximum residential water demand in 2050 sees a 92% increase from the 2012 water demand of 130 billion gallons. However, in the more likely baseline scenario, water demand is estimated to be 177 billion gallons per year in 2050 indicating that water demand will increase by 36% from 2012. This increase in demand will elevate the stress on the water supply system in Los Angeles.

Finally, in Chapter 5, an agent based model was developed to understand the interactions between Los Angeles consumers and the Los Angeles Department of Water and Power that govern water demand in the context of water management decisions. Projections of various water variability scenarios showed that consumers respond greatly to advertisement intensity and shifts in contact rates with other consumers. This is evident in the present day drought in Los Angeles where in which water demand is being reduced due to limited precipitation in California. High water variability additionally increased monthly water demand. For example, the 2050 monthly average for water demand was 1.6E10 gallons, increasing by a factor of 2.67 from 2013, while the average for low variability was 1.2E10, which saw a factor of 2.07 increase in water demand from 2013.

6.2 Research Implications

The original contributions of this research to the environmental engineering and science knowledge base are as follows: (1) evaluated the sustainability of each of the water sources that supply Los Angeles under present and future conditions using a system characterization and analysis; (2) determined the various significant factors influencing water demand in Los Angeles using multiple linear regression and artificial neural network models; (3) projected water demand in Los Angeles until 2050 under various scenarios of precipitation, price, and population; (4)

developed an agent based model of water demand under various scenarios of climate change to provide insights into interactions between water consumers and water management actions.

This research yielded a tractable approach for forecasting the interactions of water supply and demand under scenarios of climate change and population growth. The results will help inform decision making about water pricing and water conservation and their potential impacts on water demand in Los Angeles. The results of this work can be applied to help water demand forecasting efforts and decision making on conservation methods and pricing strategies in Los Angeles during periods of drought. Los Angeles relies heavily on conservation and pricing structures to reduce water demand during periods of limited access to imported water. Reliability of water from imported sources is uncertain and will likely increase dependability on these conservation methods. However, limits to the amount of water able to be conserved will determine the sustainability of the future water supply system in Los Angeles under future population growth. This research therefore applies various user interactive software, such as Anylogic and Tableau, to allow users to pick from scenarios of population, price, climate, and conservation. In doing so, a larger envelope of scenarios could be observed and makes it easier for users to analyze the data.

The models developed and applied in this dissertation can be used to gain insights into the impacts of water conservation initiatives and restrictions on water demand, and also to project their effects under shifting futures of climate and population growth. The Los Angeles water supply system is diverse and complex, requiring modeling approaches that capture at least the main drivers of system behavior. The main contribution of this study to forecasting is therefore to compare and contrast various methods of modeling water demand in Los Angeles in order to better understand the water system. Los Angeles depends heavily on imported water and with increasing growth in future population it's imperative to understand the complexity of the water system so that more sustainable solutions can be identified and adopted.

6.3 Future Work

Although this study advances the understanding of the impacts of water demand in Los Angeles, this research could be further improved by additional work not addressed in this study. Some advancements include the addition of variables in the multiple linear regression and artificial neural networks, direct measurements of conservation in Los Angeles, and expanding the agent-based model to include all the water sources that supply Los Angeles and various consumer groups.

Although annual median household income was not significant in the multiple linear regression or the artificial neural network models, the socioeconomic levels of households could play a part in impacting water demand. LADWP has shown that people who live in single-family houses rather than multi-family residences, which are people residing in apartments, use more water due to outdoor water demand. Future work should focus on showing that relationship and its impact on water demand. Socioeconomic levels can also be analyzed by observing annual median household income for each zip code in Los Angeles and comparing it to the amount of water used in that area. This information can be used to better understand the relationship between water use and income.

Socioeconomic factors were also not included in the agent based model. This study modeled consumers as one type of agent, but further work should focus on separating multi and single family households since they make decisions regarding conservation differently. For example, a person using water for outdoor purposes has more potential to conserve water than a person who only uses water for indoor purposes (laundry, bathing, washing dishes, etc.). However, people with higher incomes are less impacted by increases in water prices as compared to lower income households. These social differences can help build a better agent-based model that represents water demand in Los Angeles.

The values for conservation used in Chapters 3-5 were obtained from the Los Angeles Department of Water and Power. The estimates of conservation were calculated using a model that projected monthly water demand depending on climate and population. The projections for water demand were subtracted by the actual amount of water used in Los Angeles and the difference between the two numbers was estimated to be the amount of water conserved by month. Although these estimates are useful, further research can be done to better model conservation. Currently, there are very limited studies focusing on estimating conservation. Using direct measurements of conservation instead of estimations would strengthen projections of water demand made in this research. Additionally, the study did not have a cap to how much water can be conserved. Realistically, there is a limit to the amount of water available to consumers as well as a limit on how much water can be conserved. Human beings need water for sanitation and survival. Therefore, limits of water allocation and water conservation should be incorporated in the model. Higher levels of imported water to Los Angeles will likely not be available in the future and conservation and increased water pricing can only reduce water demand to a certain level. The city must then rely on other water sources, such as recycled water and local groundwater, to counteract the impacts of population growth. Understanding the potentials and limitations of conservation is imperative to the future sustainability of the water system.

Future work on water demand modeling in Los Angeles should also focus on adding a scenario where water availability is constrained to current levels of supply. Water demand for future increases in population would have to be met through conservation, recycling, or additional sources. In modeling the system under present supply availability, impacts of population growth and climate change on the robustness of the water system can be observed.

Currently, variability in supply is limited to LADWP, who obtains water from five main sources, Los Angeles Aqueduct, California Aqueduct, Colorado River Aqueduct, local groundwater, and reclaimed water. Each of the sources is impacted by various factors and becoming less reliable.
Modeling these changes is important to be able to adjust and integrate other water system solutions. The agent based model developed in this dissertation is focused only on water demand, but the model should be expanded to include variability in not only the demand side, but also on the water supply sources that Los Angeles relies on. Figure 6-1 shows the entire model of the water supply and demand in Los Angeles which can be modeled using agent based modeling. Future work should therefore focus on modeling these individual factors on the entire system as a whole. Modeling of the water supply should also analyze scenarios in which water availability

is capped at lower amounts in order to observe what occurs in the overall system. In doing so, a more in-depth analysis of the interactions within the system will be achieved.

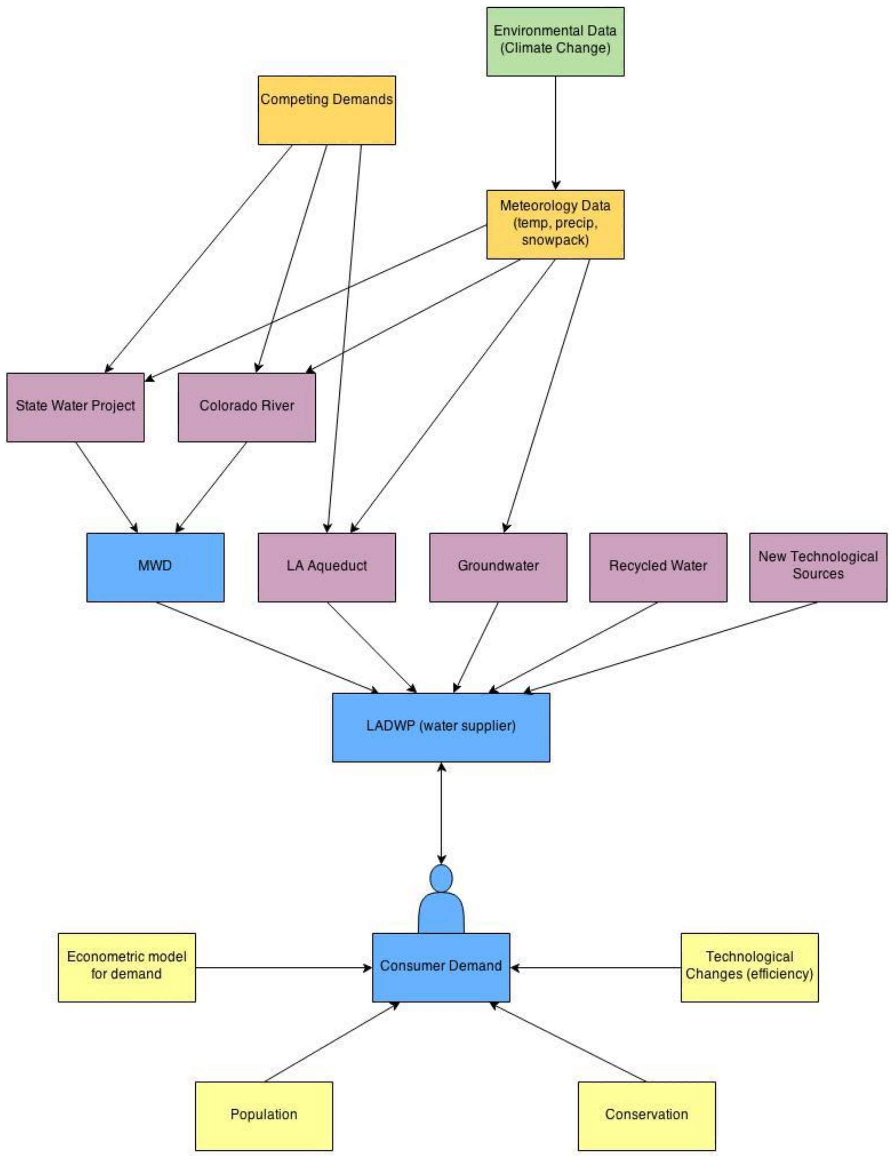

Figure 6-1: Agent based model of the Los Angeles water supply and demand system

APPENDIX A: SUPPORTING INFORMATION FOR CHAPTER 2: SUSTAINABILITY REVIEW OF WATER SUPPLY OPTIONS IN THE LOS ANGELES REGION

Population growth in Los Angeles has been steadily occurring during the last several decades. Although population has increased, water demand has stayed relatively stagnant. People are therefore consuming less water in 2007 than they did in 1970 (Figure A-1). This could be due to introductions of conservation methods and pricing structures which were implemented in 1990.

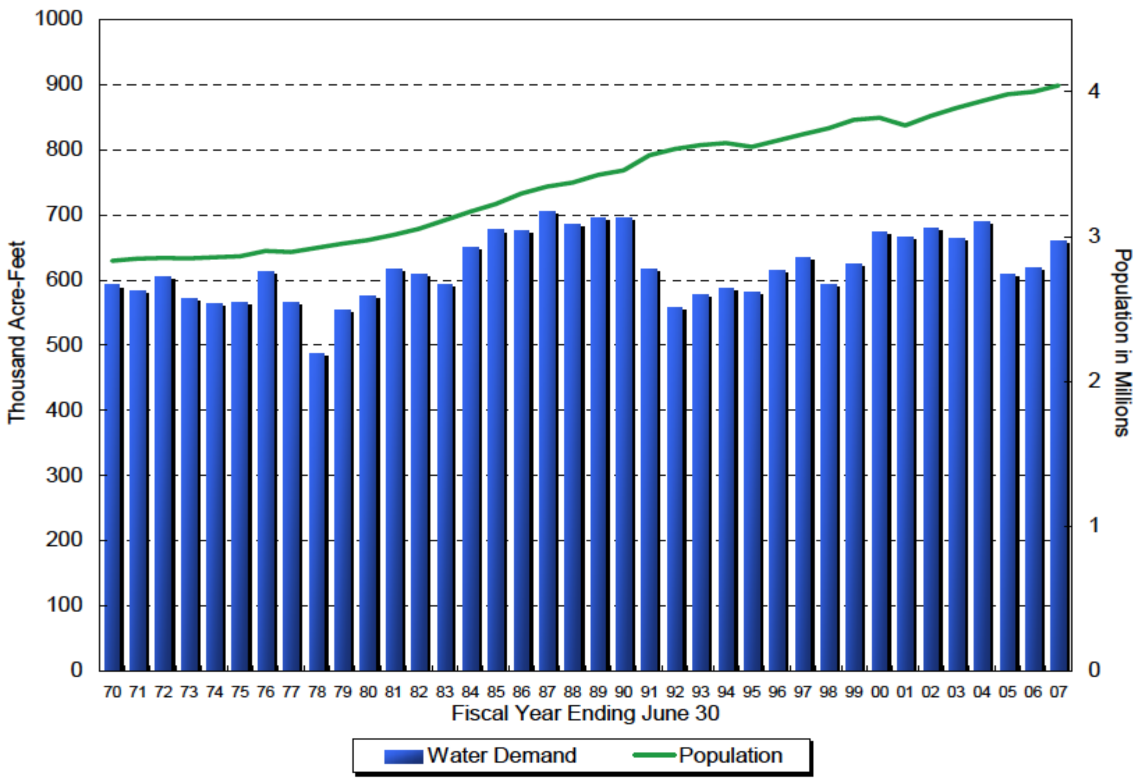

Figure A-1: Change in total population in comparison to total water demand in Los Angeles from 1970 to 2007 (Source: LADWP 2010)

Appendix B: Supporting Information for Chapter 3: Modeling Urban Water Demand in Los Angeles, California: Applications of Artificial Neural Networks and Multiple Linear Regression

Table B-1: Performance Analysis for MLR Monthly and Yearly Water Demand Cross Validation Models for Los Angeles, California Using 80% Data Points for Training and 20% for Testing

Model	R^2 Training	R^2 Testing	AARE	RMSE (gallons)
MLRM1	0.66	0.63	5.84	8.72E6
MLRM2	0.73	0.63	4.56	7.05E6
MLRY1	0.73	0.84	10.23	1.55E7
MLRY2	0.80	0.84	9.31	1.47E7
MLRY3	0.74	0.83	10.53	1.62E7
MLRY4	0.80	0.83	9.58	1.53E7

Table B-2: Performance Analysis for ANN Monthly and Yearly Water Demand Models Using All Data Points for Los Angeles, California

Model	R^2	AARE	RMSE (gallons)
ANNM1	0.73	4.45	7.08E6
ANNM2	0.79	2.93	4.59E6
ANNY1	0.70	7.73	1.21E7
ANNY2	0.75	6.99	1.12E7
ANNY3	0.81	7.12	1.20E7
ANNY4	0.80	7.00	1.14E7

Table B-3: Multiple Linear Regression Models for Individual Months without conservation as an explanatory variable

Month		R square	Constant (1000 gallons)	Water Price (1000 gallons/$)	Temperature (F)	Precipitation (in)	Population (1000 gallons/person)
January	Coef.	**0.76**	-1.57E7	-6.01E5	6.6E0	8.34E4	-1.07E4
	Sig.		0.00**	0.00**	0.00**	0.19	0.82
February	Coef.	**0.70**	-1.28E7	-5.71E5	5.8E0	6.58E4	-3.89E4
	Sig.		0.02**	0.00**	0.00**	0.24	0.36
March	Coef.	**0.79**	-1.15E7	-5.10E5	5.3E0	6.59E4	-1.24E4
	Sig.		0.00**	0.00**	0.00**	0.12	0.02**
April	Coef.	**0.64**	-1.35E7	-4.72E5	4.8E0	1.15E5	4.17E4
	Sig.		0.00**	0.00**	0.00**	0.05**	0.78
May	Coef.	**0.68**	-1.94E7	-5.56E5	5.6E0	1.80E5	-9.06E4
	Sig.		0.00**	0.00**	0.00**	0.01**	0.71
June	Coef.	**0.63**	-1.70E7	-5.89E5	5.7E0	1.52E5	4.38E5
	Sig.		0.00**	0.00**	0.00**	0.00**	0.57
July	Coef.	**0.56**	-1.03E7	-6.86E5	6.0E0	6.10E4	-7.13E6
	Sig.		0.12	0.00**	0.00**	0.46	0.17
August	Coef.	**0.55**	-9.68E6	-6.51E5	5.1E0	9.93E4	-8.43E5
	Sig.		0.09*	0.00**	0.00**	0.13	0.07*
September	Coef.	**0.59**	-9.62E6	-5.88E5	5.9E0	5.54E4	3.29E5
	Sig.		0.10*	0.00**	0.00**	0.39	0.28
October	Coef.	**0.63**	-3.63E6	-4.20E5	5.3E0	-1.26E4	2.33E4
	Sig.		0.52	0.00**	0.00**	0.88	0.91
November	Coef.	**0.70**	-7.58E6	-4.96E5	6.0E0	-2.91E3	1.04E5
	Sig.		0.08*	0.00**	0.00**	0.96	0.43
December	Coef.	**0.82**	-1.66E7	-4.44E5	5.8E0	1.47E5	-1.21E5
	Sig.		0.00**	0.00**	0.00**	0.00**	0.03**

**Indicates the coefficient is significant at the p= 0.01 level
*Indicates the coefficient is significant at the p= 0.05 level

Table B-4: Multiple Linear Regression Models for Individual Months without conservation as an explanatory variable

Month		R square	Constant (1000 gallons)	Water Price (1000 gallons/$)	Temperature (F)	Precipitation (in)	Population (1000 gallons/person)	Conservation ( )
Jan	Coef.	**0.45**	1.17E7	-1.43E5	-5.13E4	-1.06E5	9.20E-1	-2.60E-1
	Sig.		0.26	0.26	0.56	0.04**	0.62	0.07*
Feb	Coef.	**0.25**	8.18E6	-2.51E5	-5.49E4	-7.94E4	1.73E0	-1.20E-1
	Sig.		0.59	0.13	0.63	0.21	0.51	0.51
Mar	Coef.	**0.62**	1.00E7	-2.17E5	-7.35E4	-2.01E5	1.37E0	-5.00E-2
	Sig.		0.11	0.02**	0.11	0.00**	0.27	0.55
Apr	Coef.	**0.47**	-1.33E7	-5.62E4	-4.46E3	-3.43E5	6.55E0	-3.60E-1
	Sig.		0.27	0.68	0.96	0.19	0.01**	0.02**
May	Coef.	**0.69**	-1.90E7	-6.19E4	1.13E5	-2.82E5	6.3E0	-3.80E-1
	Sig.		0.01**	0.61	0.09*	0.20	0.00**	0.00**
Jun	Coef.	**0.48**	-1.60E7	-2.13E5	4.73E4	2.91E5	7.12E0	-3.30E-1
	Sig.		0.23	0.25	0.67	0.72	0.01**	0.03**
Jul	Coef.	**0.87**	-3.51E6	-3.72E5	-2.62E4	-1.88E7	5.86E0	-3.20E-1
	Sig.		0.54	0.00**	0.59	0.00**	0.00**	0.00**
Aug	Coef.	**0.61**	-2.37E7	-2.68E5	1.16E5	8.48E6	8.44E0	-4.00E-1
	Sig.		0.06*	0.08*	0.15	0.5	0.00**	0.00**
Sep	Coef.	**0.57**	-1.13E7	-1.23E5	2.51E4	1.59E6	6.85E0	-5.60E-1
	Sig.		0.43	0.46	0.79	0.24	0.02**	0.00**
Oct	Coef.	**0.53**	-9.87E6	-3.89E4	6.52E4	1.36E5	5.41E0	-5.20E-1
	Sig.		0.46	0.78	0.56	0.55	0.02**	0.00**
Nov	Coef.	**0.56**	-1.12E7	-7.41E4	6.85E4	1.60E5	5.53E0	-5.70E-1
	Sig.		-0.25	0.57	0.33	0.51	0.01**	0.00**
Dec	Coef.	**0.54**	-1.08E7	-1.96E5	1.32E5	-1.36E5	4.30E0	-2.80E-1
	Sig.		0.34	0.06*	0.20	0.01**	0.03**	0.03**

**Indicates the coefficient is significant at the p= 0.01 level
*Indicates the coefficient is significant at the p= 0.05

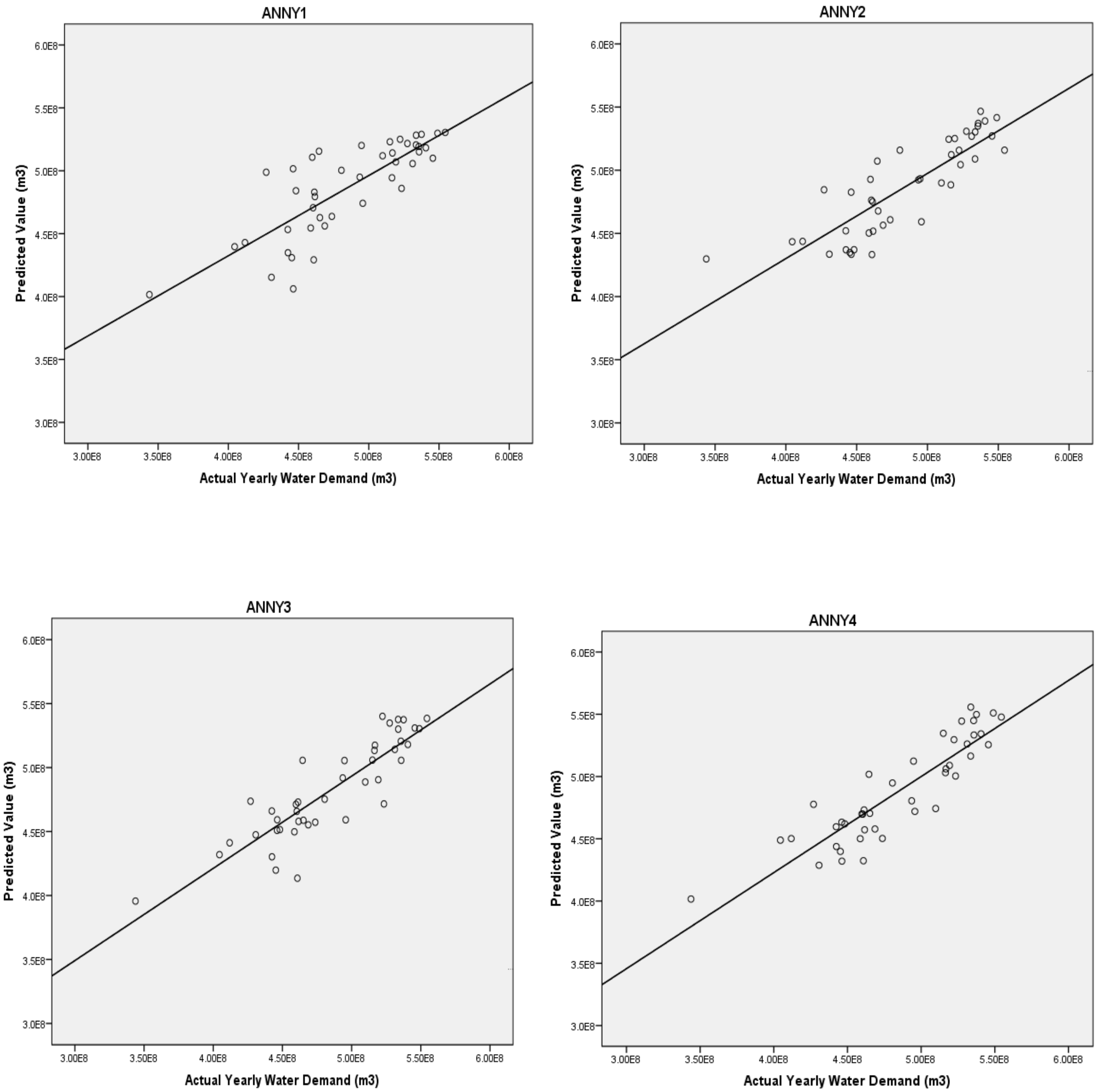

Figure B-1: Performance Analysis for ANN Monthly and Yearly Water Demand Models Using All Data Points and Best Fit Line for Los Angeles, California

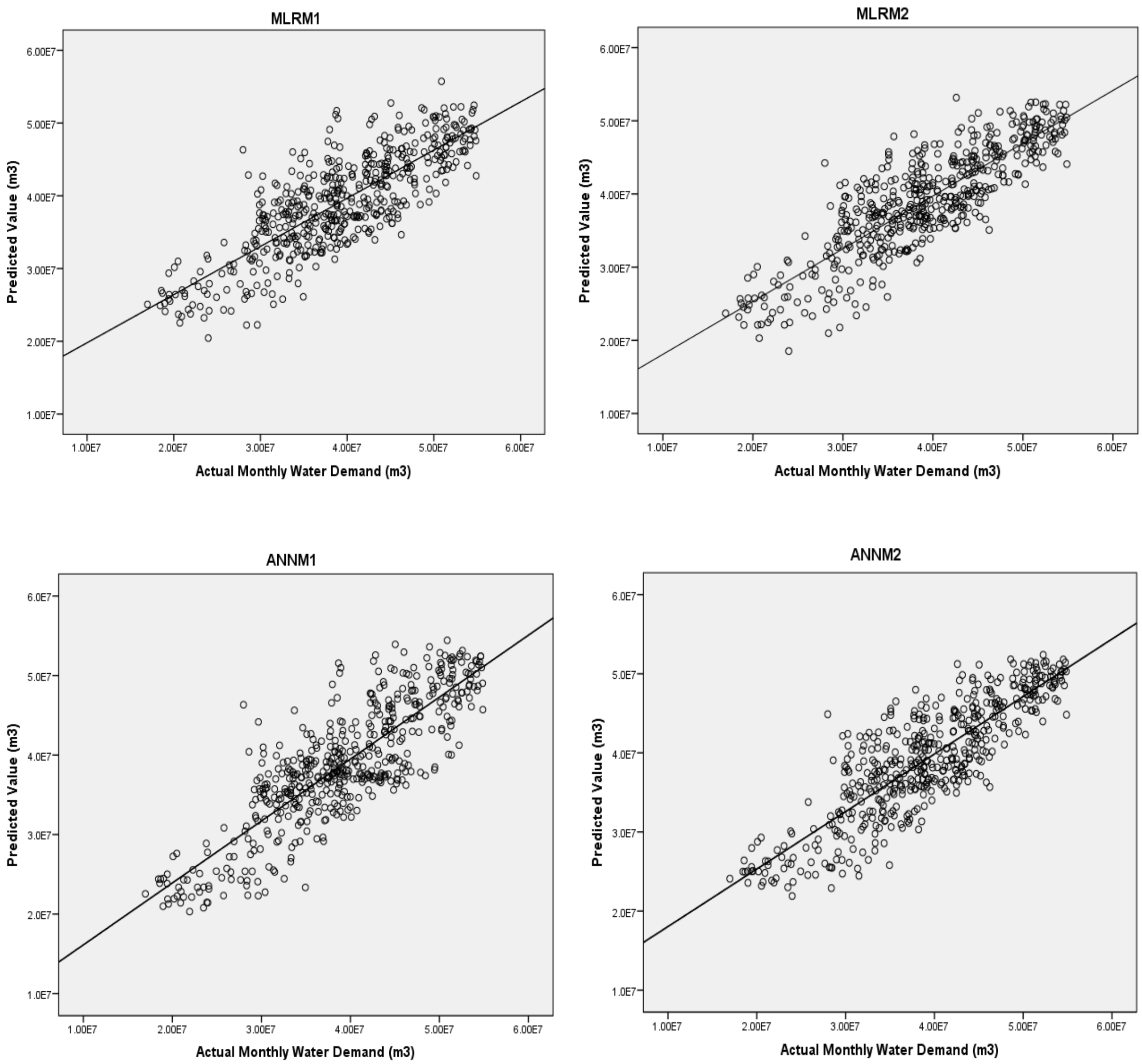

Figure B-2: Performance Analysis for ANN Monthly and Yearly Water Demand Models Using All Data Points and Best Fit Line for Los Angeles, California

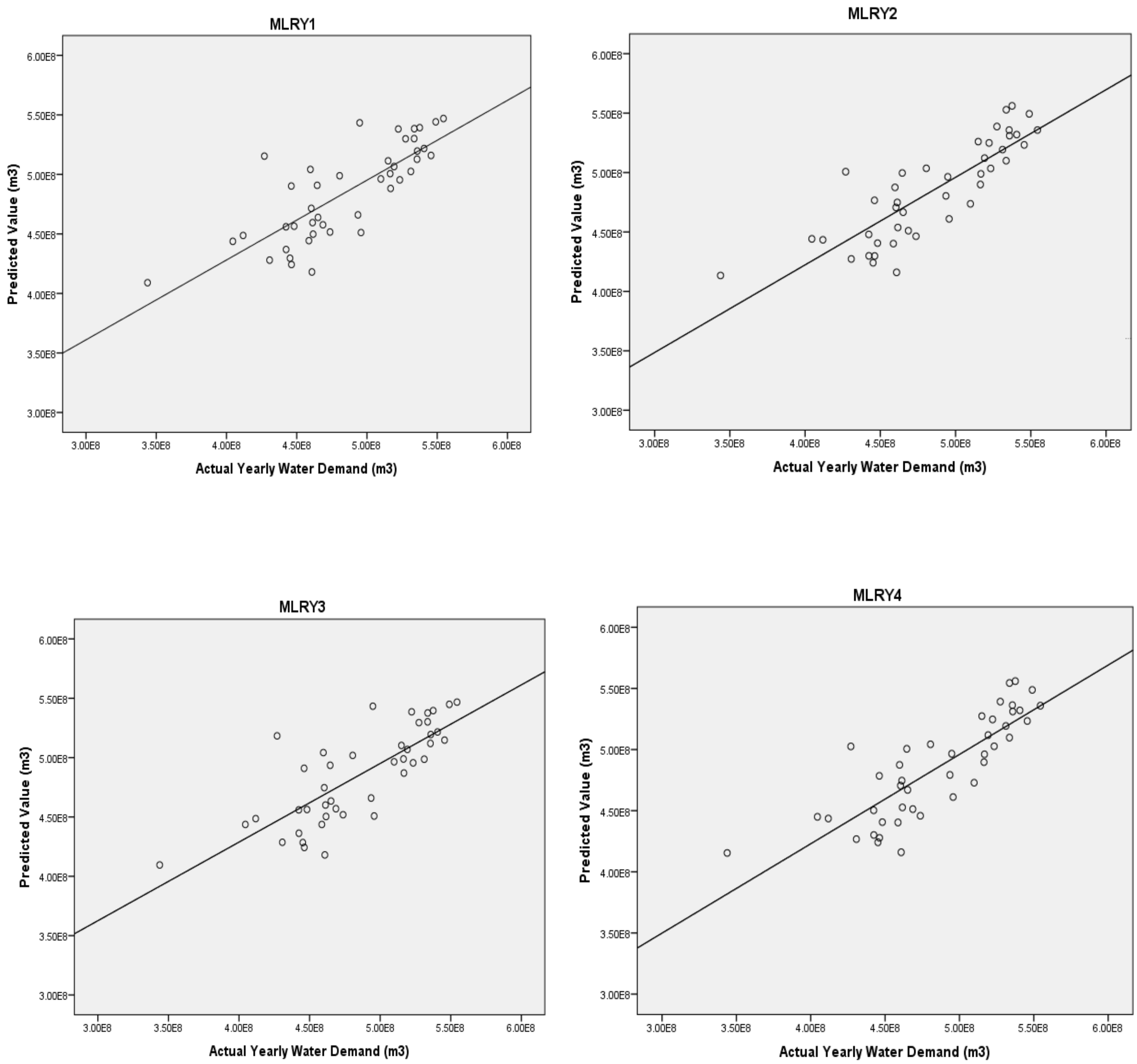

Figure B-3: Performance Analysis for ANN Monthly and Yearly Water Demand Models Using All Data Points and Best Fit Line for Los Angeles, California

Table B-5: Independent Variable Importance Analysis of ANN Monthly and Yearly Water Demand Models for Los Angeles, California

ANN Models	Price	Population	Precipitation	Temperature	Conservation
ANNM1	15.2%	36.3%	12.5%	36.0%	-
ANNM2	3.7%	32.9%	14.6%	32.6%	16.2%
ANNY1	9.8%	52.1%	38.1%	-	-
ANNY2	4.0%	43.6%	30.4%	-	22.0%
ANNY3	15.0%	42.5%	36.0%	6.5%	-
ANNY4	7.7%	46.6%	25.3%	8.3%	12.1%

% indicates the relative weights of each explanatory variable in the ANN prediction

Table B-6: Independent Variable Importance Analysis of MLR Monthly and Yearly Water Demand Models for Los Angeles, California

MLR Models	Price	Population	Precipitation	Temperature	Conservation
MLRM1	10.2%	39.0%	0%	50.8%	-
MLRM2	1.2%	35.8%	0.3%	46.5%	16.2%
MLRY1	35.1%	47.2%	17.7%	-	-
MLRY2	5.2%	43.2%	17.7%	-	33.9%
MLRY3	35.1%	47.2%	17.7%	0%	-
MLRY4	5.2%	43.2%	17.7%	0%	33.9%

% indicates the fraction of variance of each explanatory variable in the MLR prediction

Table B-7: Multiple Linear Regression model of Los Angeles water demand system using adjusted annual median household income as an explanatory variable, as well as Tier 2 price, population, yearly total precipitation, and average yearly temperature

Dependent Variable	B coefficient	Std. Error of Coefficient	Significance	Lower Bound 95% CI	Upper Bound 95% CI
Constant	-1.23E7	8.8E7	0.89	-1.92E8	1.67E8
LA Adjusted Annual Median Household Income	5.36E2	4.48E2	0.24	-3.71E2	1.44E3
Tier 2 water price	-7.26E6	1.31E6	0.00**	-9.92E6	-4.59E6
Population	4.13E1	5.78E0	0.00**	2.96E1	5.30E1
Precipitation	-9.22E5	1.92E5	0.00**	-1.31E6	-5.33E5
Temperature	9.87E5	1.13E6	0.39	-1.30E6	3.27E6

**Indicates the coefficient is significant at the p= 0.01 level
*Indicates the coefficient is significant at the p= 0.05

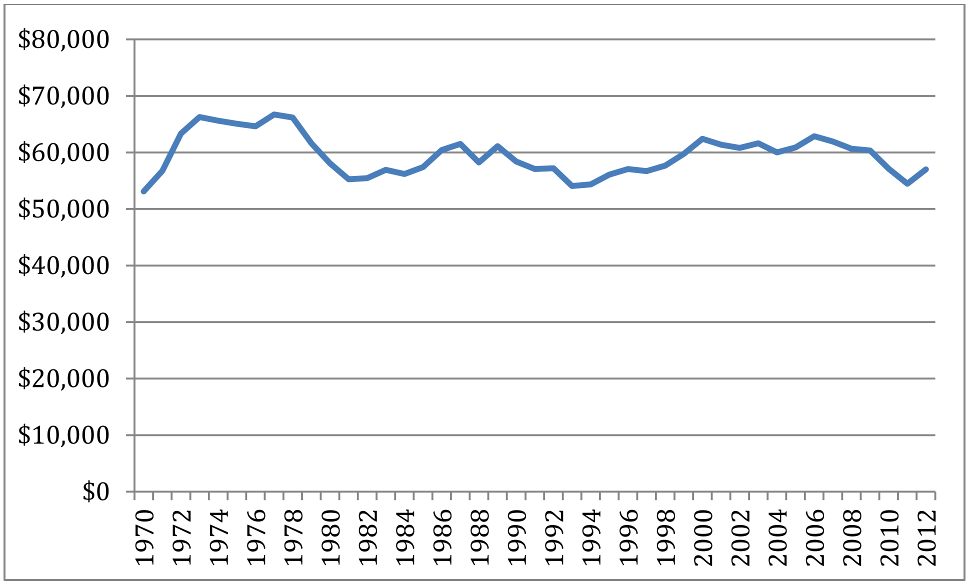

Figure B-4: Change in monthly median household income adjusted for 2012 $ from 1970 to 2012

Table B-8: Multiple Linear Regression model of Los Angeles water demand system using conservation as a binary explanatory variable, as well as adjusted annual median household income, Tier 2 price, population, yearly total precipitation, and average yearly temperature

Dependent Variable	B coefficient	Std. Error of Coefficient	Significance	Lower Bound 95% CI	Upper Bound 95% CI
Constant	5.27E6	6.60E7	0.94	-1.29E8	1.39E8
LA Adjusted Annual Median Household Income	8.43E1	3.39E2	0.81	-6.03E2	7.72E2
Tier 2 water price	-5.19E6	9.55E5	0.00**	-7.13E6	-3.25E6
Population	5.32E1	7.47E0	0.00**	3.80E1	6.83E1
Precipitation	-6.21E5	1.45E5	0.00**	-9.16E5	-3.27E5
Temperature	-4.38E5	8.44E5	0.61	-2.15E6	1.27E6
Conservation (binary)	-1.34E7	4.85E6	0.01**	-2.33E7	-3.61E6

**Indicates the coefficient is significant at the p= 0.01 level
*Indicates the coefficient is significant at the p= 0.05

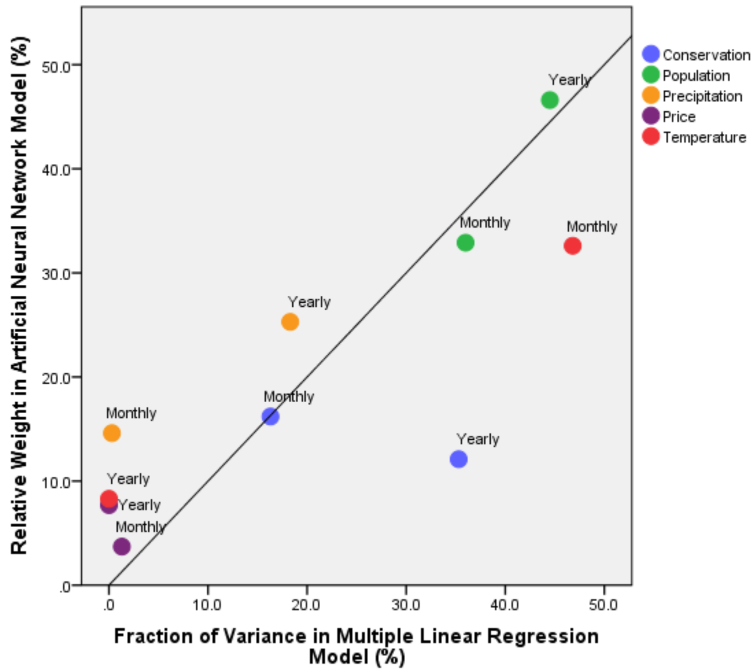

Figure B-5: Comparing Importance Analyses of MLRM2, MLRY4, ANNM2, and ANNY4 Explanatory Variables in Modeling Water Demand in Los Angeles, California

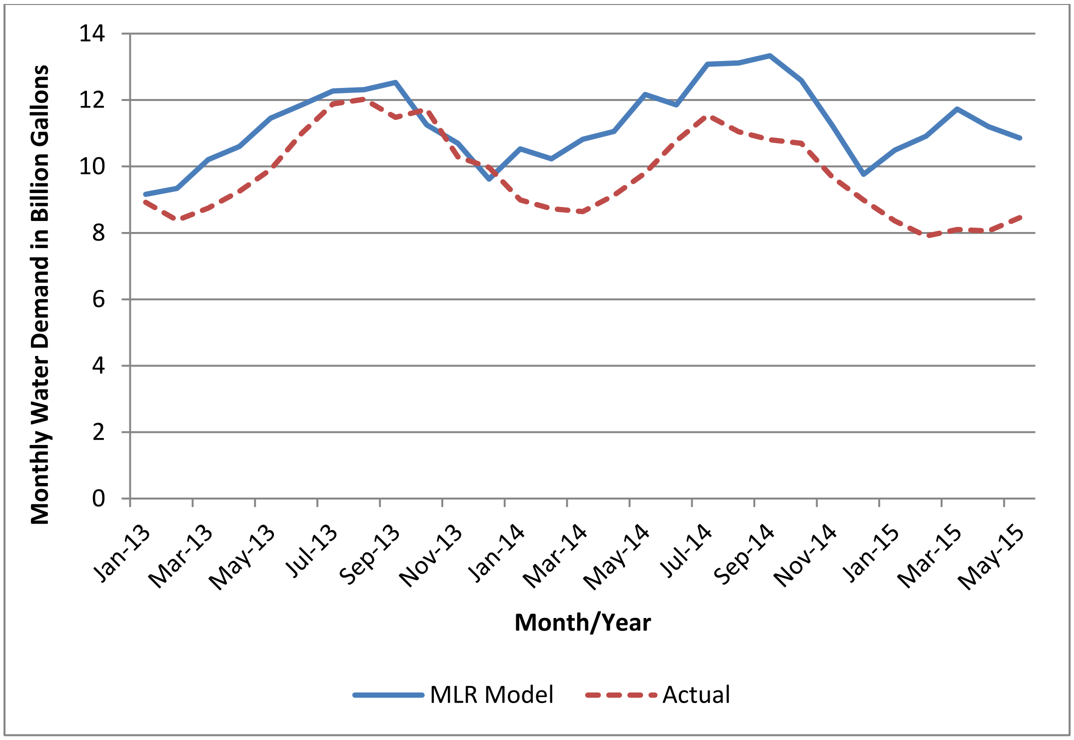

Figure B-6: Comparing MLR model with price, population, temperature, and precipitation as explanatory variables, with actual monthly water demand values for Jan 2013-May 2015

Data for price, population, and water demand were obtained from Los Angeles Department of Water and Power. Temperature and precipitation values were obtained from the National Oceanic and Atmospheric Administration (NOAA). Estimated conservation amounts were not available for this time period. Therefore, the model, MLRM1 with price, population, temperature, and price was used to compare with actual data for this drought period. The model does not take into consideration the impact of conservation on water demand. Implementing these conservation values is predicted to yield more accurate projections of water demand in Los Angeles.

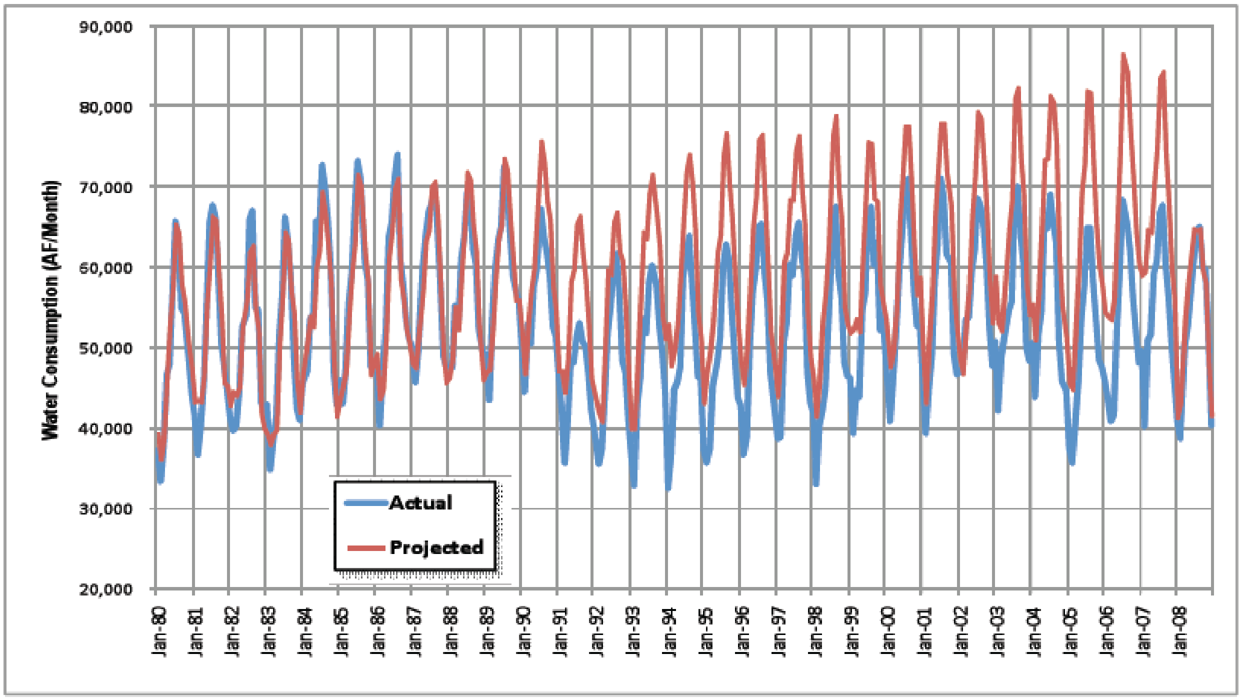

Figure B-7: Fitting of LADWP water demand model using climate, population, economic recession, and conservation as explanatory variables with actual water demand in Los Angeles from 1980-2008

APPENDIX C: SUPPORTING INFORMATION FOR CHAPTER 4: FORECASTING RESIDENTIAL WATER DEMAND IN LOS ANGELES, CALIFORNIA UNDER CLIMATE CHANGE

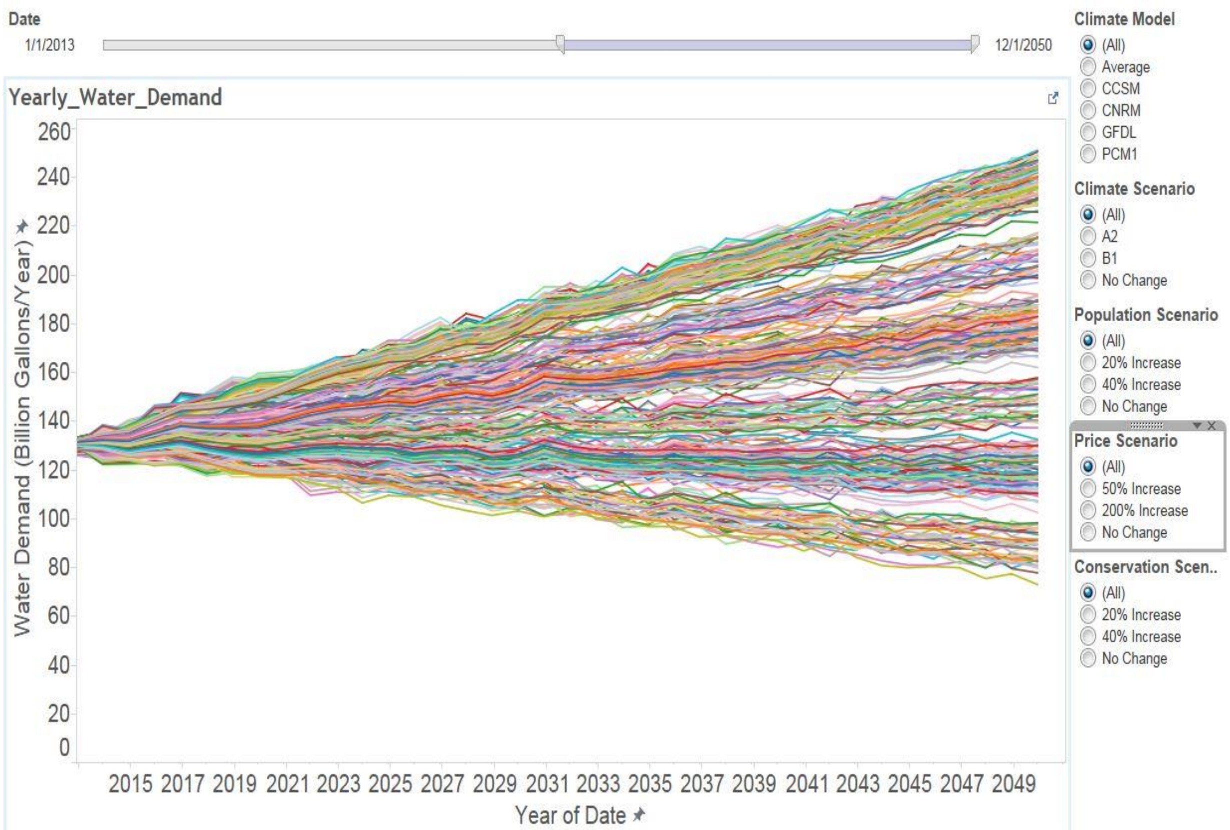

Figure C-1: Tableau interface of all 405 scenarios where users choose scenarios for climate model, climate, population, price, and conservation.

Table C-1 : Yearly water demand projections of multiple linear regression model and validation of data

Yearly models of multiple linear regression were initially developed using projections of LADWP population and increases in price (Table C-1).

Scenario 1.1 – LADWP projection of population, constant price of price
Scenario 1.2 – LADWP projection of population, low increase in price
Scenario 1.3 – LADWP projection of population, high increase in price
Scenario 2.1 – Linear increase in population, constant price of price
Scenario 2.2 – Linear increase in population, low increase in price
Scenario 2.3 – Linear increase in population, high increase in price

Year	Actual amount (1000 gallons)	Scenario 1.1	% Error	Scenario 1.2	% Error	Scenario 1.3	% Error	Scenario 2.1	% Error	Scenario 2.2	% Error	Scenario 2.3	% Error
1970	1.22E+08	1.14E+08	6.75E-02	1.20E+08	1.57E-02	1.19E+08	2.01E-02	1.20E+08	1.39E-02	1.25E+08	2.60E-02	1.20E+08	1.27E-02
1971	1.21E+08	1.15E+08	4.74E-02	1.20E+08	8.50E-03	1.18E+08	2.40E-02	1.19E+08	1.86E-02	1.16E+08	4.13E-02	1.20E+08	8.20E-03
1972	1.25E+08	1.19E+08	5.06E-02	1.22E+08	2.59E-02	1.24E+08	7.30E-03	1.24E+08	6.20E-03	1.22E+08	2.13E-02	1.17E+08	6.46E-02
1973	1.18E+08	1.13E+08	4.14E-02	1.12E+08	4.68E-02	1.13E+08	3.99E-02	1.13E+08	3.89E-02	1.13E+08	3.74E-02	1.17E+08	2.30E-03
1974	1.17E+08	1.14E+08	2.11E-02	1.13E+08	3.07E-02	1.14E+08	2.22E-02	1.14E+08	2.03E-02	1.15E+08	1.64E-02	1.17E+08	3.50E-03
1975	1.17E+08	1.20E+08	2.76E-02	1.20E+08	2.69E-02	1.19E+08	2.14E-02	1.20E+08	2.51E-02	1.20E+08	2.59E-02	1.19E+08	1.86E-02
1976	1.24E+08	1.21E+08	2.52E-02	1.21E+08	2.53E-02	1.21E+08	1.88E-02	1.22E+08	1.32E-02	1.21E+08	2.05E-02	1.19E+08	3.87E-02
1977	1.09E+08	1.18E+08	8.75E-02	1.18E+08	8.52E-02	1.15E+08	5.58E-02	1.15E+08	5.63E-02	1.16E+08	7.03E-02	1.19E+08	9.03E-02
1978	9.08E+07	1.05E+08	1.59E-01	9.93E+07	9.29E-02	9.37E+07	3.20E-02	9.51E+07	4.76E-02	9.46E+07	4.17E-02	9.18E+07	1.05E-02
1979	1.07E+08	1.14E+08	6.42E-02	1.14E+08	6.38E-02	1.11E+08	3.78E-02	1.11E+08	4.20E-02	1.09E+08	2.14E-02	1.05E+08	1.40E-02
1980	1.14E+08	1.11E+08	2.01E-02	1.11E+08	2.78E-02	1.12E+08	1.98E-02	1.13E+08	6.60E-03	1.11E+08	2.24E-02	1.16E+08	1.57E-02
1981	1.22E+08	1.21E+08	5.90E-03	1.23E+08	1.13E-02	1.21E+08	7.00E-03	1.21E+08	4.60E-03	1.27E+08	4.10E-02	1.26E+08	3.29E-02

1982	1.23E+08	1.18E+08	3.90E-02	1.21E+08	1.21E-02	1.20E+08	2.30E-02	1.21E+08	1.73E-02	1.23E+08	2.40E-03	1.21E+08	1.51E-02
1983	1.18E+08	1.11E+08	5.83E-02	1.11E+08	5.53E-02	1.14E+08	3.00E-02	1.16E+08	1.66E-02	1.16E+08	1.91E-02	1.18E+08	2.20E-03
1984	1.27E+08	1.28E+08	1.03E-02	1.28E+08	1.04E-02	1.26E+08	7.60E-03	1.23E+08	3.16E-02	1.31E+08	3.18E-02	1.27E+08	3.10E-03
1985	1.37E+08	1.32E+08	3.88E-02	1.33E+08	3.00E-02	1.36E+08	9.00E-03	1.32E+08	3.52E-02	1.37E+08	7.00E-04	1.34E+08	2.12E-02
1986	1.38E+08	1.28E+08	7.38E-02	1.30E+08	6.27E-02	1.37E+08	6.40E-03	1.39E+08	1.90E-03	1.34E+08	2.93E-02	1.37E+08	1.26E-02
1987	1.43E+08	1.36E+08	4.94E-02	1.41E+08	1.26E-02	1.42E+08	3.80E-03	1.42E+08	5.90E-03	1.41E+08	1.35E-02	1.46E+08	2.21E-02
1988	1.42E+08	1.35E+08	4.54E-02	1.37E+08	3.52E-02	1.40E+08	8.40E-03	1.40E+08	1.11E-02	1.40E+08	8.90E-03	1.39E+08	2.05E-02
1989	1.42E+08	1.38E+08	3.03E-02	1.44E+08	1.37E-02	1.42E+08	1.70E-03	1.42E+08	1.00E-04	1.42E+08	2.70E-03	1.43E+08	5.90E-03
1990	1.45E+08	1.39E+08	3.94E-02	1.42E+08	2.11E-02	1.43E+08	1.49E-02	1.42E+08	1.84E-02	1.42E+08	1.89E-02	1.45E+08	1.00E-03
1991	1.31E+08	1.35E+08	3.45E-02	1.33E+08	1.59E-02	1.33E+08	1.82E-02	1.33E+08	1.63E-02	1.35E+08	3.06E-02	1.31E+08	3.50E-03
1992	1.13E+08	1.27E+08	1.25E-01	1.25E+08	1.07E-01	1.22E+08	7.84E-02	1.22E+08	8.29E-02	1.21E+08	7.25E-02	1.22E+08	8.02E-02
1993	1.22E+08	1.26E+08	3.06E-02	1.23E+08	7.00E-03	1.21E+08	9.50E-03	1.21E+08	3.80E-03	1.20E+08	1.14E-02	1.18E+08	2.83E-02
1994	1.23E+08	1.39E+08	1.32E-01	1.33E+08	8.64E-02	1.32E+08	7.41E-02	1.29E+08	5.20E-02	1.34E+08	9.02E-02	1.28E+08	4.02E-02
1995	1.22E+08	1.27E+08	4.22E-02	1.24E+08	2.04E-02	1.21E+08	5.70E-03	1.22E+08	1.40E-03	1.22E+08	1.90E-03	1.20E+08	1.52E-02
1996	1.30E+08	1.33E+08	2.31E-02	1.30E+08	5.00E-04	1.28E+08	1.48E-02	1.29E+08	1.39E-02	1.31E+08	4.20E-03	1.29E+08	1.36E-02
1997	1.37E+08	1.39E+08	1.56E-02	1.38E+08	7.60E-03	1.40E+08	2.43E-02	1.40E+08	2.35E-02	1.39E+08	1.94E-02	1.37E+08	6.70E-03
1998	1.31E+08	1.27E+08	2.66E-02	1.25E+08	4.35E-02	1.23E+08	6.00E-02	1.25E+08	4.48E-02	1.25E+08	4.62E-02	1.28E+08	2.34E-02
1999	1.36E+08	1.41E+08	3.40E-02	1.44E+08	5.58E-02	1.43E+08	5.25E-02	1.43E+08	4.85E-02	1.43E+08	4.75E-02	1.42E+08	4.20E-02
2000	1.41E+08	1.39E+08	2.08E-02	1.45E+08	2.36E-02	1.43E+08	1.18E-02	1.43E+08	7.90E-03	1.42E+08	4.80E-03	1.41E+08	2.80E-03
2001	1.40E+08	1.35E+08	3.83E-02	1.35E+08	3.79E-02	1.38E+08	1.58E-02	1.40E+08	5.00E-04	1.37E+08	2.41E-02	1.39E+08	1.09E-02
2002	1.41E+08	1.40E+08	6.80E-03	1.42E+08	1.01E-02	1.43E+08	1.36E-02	1.43E+08	1.08E-02	1.42E+08	5.50E-03	1.41E+08	6.00E-04
2003	1.39E+08	1.39E+08	5.70E-03	1.36E+08	2.70E-02	1.37E+08	1.95E-02	1.38E+08	1.12E-02	1.37E+08	1.91E-02	1.37E+08	1.62E-02
2004	1.44E+08	1.37E+08	4.94E-02	1.36E+08	5.99E-02	1.38E+08	4.57E-02	1.40E+08	2.76E-02	1.37E+08	5.13E-02	1.38E+08	3.92E-02
2005	1.36E+08	1.32E+08	3.52E-02	1.33E+08	2.52E-02	1.39E+08	1.58E-02	1.41E+08	3.44E-02	1.37E+08	7.60E-03	1.39E+08	2.22E-02
2006	1.38E+08	1.37E+08	5.60E-03	1.45E+08	5.27E-02	1.43E+08	3.32E-02	1.42E+08	3.15E-02	1.42E+08	3.17E-02	1.41E+08	2.06E-02
2007	1.46E+08	1.37E+08	6.27E-02	1.46E+08	1.90E-03	1.42E+08	2.99E-02	1.42E+08	2.98E-02	1.43E+08	2.20E-02	1.44E+08	1.63E-02
2008	1.41E+08	1.34E+08	4.79E-02	1.42E+08	9.90E-03	1.40E+08	5.30E-03	1.41E+08	1.40E-03	1.42E+08	8.50E-03	1.38E+08	1.84E-02
2009	1.35E+08	1.27E+08	5.79E-02	1.30E+08	3.25E-02	1.28E+08	4.93E-02	1.34E+08	7.20E-03	1.42E+08	5.64E-02	1.34E+08	4.60E-03

2010	1.18E+08	1.12E+08	5.53E-02	1.21E+08	2.22E-02	1.12E+08	5.40E-02	1.17E+08	1.31E-02	1.12E+08	5.16E-02	1.19E+08	8.40E-03
2011	1.18E+08	1.19E+08	7.80E-03	1.22E+08	3.59E-02	1.20E+08	1.50E-02	1.21E+08	2.59E-02	1.17E+08	4.40E-03	1.19E+08	1.38E-02
2012	1.21E+08	1.21E+08	2.90E-03	1.22E+08	7.00E-03	1.20E+08	1.10E-02	1.21E+08	2.60E-03	1.20E+08	1.02E-02	1.20E+08	1.29E-02
2013	1.26E+08	1.24E+08	1.52E-02	1.23E+08	2.32E-02	1.20E+08	5.18E-02	1.21E+08	3.92E-02	1.29E+08	2.20E-02	1.23E+08	2.77E-02
2014		1.25E+08		1.23E+08		1.19E+08		1.22E+08		1.34E+08		1.26E+08	
2015		1.22E+08		1.22E+08		1.18E+08		1.21E+08		1.25E+08		1.20E+08	
2016		1.27E+08		1.23E+08		1.19E+08		1.22E+08		1.31E+08		1.21E+08	
2017		1.33E+08		1.25E+08		1.20E+08		1.26E+08		1.38E+08		1.22E+08	
2018		1.29E+08		1.23E+08		1.18E+08		1.22E+08		1.28E+08		1.19E+08	
2019		1.35E+08		1.27E+08		1.20E+08		1.31E+08		1.39E+08		1.20E+08	
2020		1.29E+08		1.22E+08		1.16E+08		1.22E+08		1.19E+08		1.18E+08	
2021		1.27E+08		1.22E+08		1.13E+08		1.21E+08		1.14E+08		1.18E+08	
2022		1.37E+08		1.28E+08		1.19E+08		1.38E+08		1.41E+08		1.19E+08	
2023		1.30E+08		1.22E+08		1.13E+08		1.22E+08		1.20E+08		1.18E+08	
2024		1.35E+08		1.24E+08		1.17E+08		1.34E+08		1.36E+08		1.18E+08	
2025		1.35E+08		1.24E+08		1.16E+08		1.34E+08		1.35E+08		1.18E+08	
2026		1.37E+08		1.25E+08		1.17E+08		1.41E+08		1.40E+08		1.18E+08	
2027		1.29E+08		1.21E+08		1.01E+08		1.22E+08		1.13E+08		1.18E+08	
2028		1.28E+08		1.21E+08		9.89E+07		1.22E+08		1.13E+08		1.18E+08	
2029		1.31E+08		1.22E+08		1.01E+08		1.25E+08		1.20E+08		1.18E+08	
2030		1.35E+08		1.23E+08		1.08E+08		1.40E+08		1.36E+08		1.18E+08	
2031		1.37E+08		1.24E+08		1.10E+08		1.42E+08		1.40E+08		1.18E+08	
2032		1.33E+08		1.22E+08		9.81E+07		1.34E+08		1.25E+08		1.18E+08	
2033		1.37E+08		1.24E+08		1.06E+08		1.43E+08		1.40E+08		1.18E+08	
2034		1.38E+08		1.26E+08		1.09E+08		1.43E+08		1.43E+08		1.18E+08	
2035		1.38E+08		1.24E+08		1.06E+08		1.43E+08		1.42E+08		1.18E+08	
2036		1.37E+08		1.24E+08		1.02E+08		1.43E+08		1.41E+08		1.18E+08	
2037		1.37E+08		1.23E+08		1.00E+08		1.43E+08		1.42E+08		1.18E+08	

2038		1.39E+08		1.25E+08		1.03E+08		1.43E+08		1.44E+08		1.18E+08	
2039		1.38E+08		1.24E+08		9.89E+07		1.43E+08		1.43E+08		1.18E+08	
2040		1.36E+08		1.22E+08		9.27E+07		1.43E+08		1.38E+08		1.18E+08	
2041		1.39E+08		1.24E+08		9.79E+07		1.43E+08		1.44E+08		1.18E+08	
2042		1.38E+08		1.24E+08		9.57E+07		1.43E+08		1.43E+08		1.18E+08	
2043		1.36E+08		1.22E+08		9.04E+07		1.43E+08		1.36E+08		1.18E+08	
2044		1.37E+08		1.22E+08		9.13E+07		1.43E+08		1.41E+08		1.18E+08	
2045		1.38E+08		1.22E+08		9.10E+07		1.43E+08		1.42E+08		1.18E+08	
2046		1.38E+08		1.23E+08		9.12E+07		1.43E+08		1.43E+08		1.18E+08	
2047		1.38E+08		1.23E+08		9.10E+07		1.43E+08		1.43E+08		1.18E+08	
2048		1.38E+08		1.23E+08		9.06E+07		1.43E+08		1.43E+08		1.18E+08	
2049		1.37E+08		1.22E+08		8.96E+07		1.43E+08		1.41E+08		1.18E+08	
2050		1.39E+08		1.24E+08		9.08E+07		1.43E+08		1.44E+08		1.18E+08	

APPENDIX D: SUPPORTING INFORMATION FOR CHAPTER 5: AGENT-BASED RESIDENTIAL WATER USE IN LOS ANGELES, CALIFORNIA: IMPLICATIONS ON WATER CONSERVATION BEHAVIOR

The program used to generate the agent-based mode was Anylogic 7.2. The programming language Java was used to program the agents and parameters in the system. Specific parts of the codes, which outline the various stages of drought, conservation, water supply variability, and water demand are shown as follows. In order to obtain all the Java code, please contact the author.

D.1 JAVA CODE FOR IDENTIFYING DROUGHT STAGES IN LOS ANGELES AND DEFINING AD INTENSITY, CONTACT RATE AND ADOPTION FRACTION USING ANYLOGIC 7.2

```
 // Functions

  public
int
 getDroughtLev( double MaxWaterStorage, double WaterVolume ) {

double storageRate;
int droughtLev = 0;
storageRate = WaterVolume / MaxWaterStorage;
if (storageRate >= 1){
            droughtLev = 0;
} else if (storageRate > 0.85 && storageRate < 1){
            droughtLev = 1;
} else if (storageRate >= 0.8 && storageRate <= 0.85){
            droughtLev = 2;
```

```
} else if (storageRate > 0.65 && storageRate < 0.8){
        droughtLev = 3;
} else if (storageRate > 0.5 && storageRate < 0.65){
        droughtLev = 4;
}
return droughtLev;
  }



double
 adjustAdIntensity( int DroughtLev ) {



double AdIntensity = 0;
switch(DroughtLev){
        case 0:
                break;
        case 1:
                AdIntensity = 2;
                break;
        case 2:
                AdIntensity = 2.5;
                break;
        case 3:
                AdIntensity = 3;
                break;
        case 4:
                AdIntensity = 5;
                break;
}
return AdIntensity;
```

```
  }


double
 getAdoptionFrac( int DroughtLev ) {

double adoptionFrac = 0.2;
switch(DroughtLev){
	case 0:
		break;
	case 1:
		adoptionFrac = 0.23;
		break;
	case 2:
		adoptionFrac = 0.26;
		break;
	case 3:
		adoptionFrac = 0.3;
		break;
	case 4:
		adoptionFrac = 0.4;
		break;
}
return adoptionFrac;
  }


double
 getContactRate( int DroughtLev ) {

double contactRate = 1;
```

```
switch(DroughtLev){

        case 0:
                break;
        case 1:
                contactRate = 10;
                break;
        case 2:
                contactRate = 15;
                break;
        case 3:
                contactRate = 20;
                break;
        case 4:
                contactRate = 25;
                break;
}
return contactRate;
  }



double
 getWillingUse( int DroughtLev ) {

double Willingness = 7;
switch(DroughtLev){
        case 0:
                break;
        case 1:
                Willingness = 8;
                break;
```

```
        case 2:
                Willingness = 9;
                break;
        case 3:
                Willingness = 10;
                break;
        case 4:
                Willingness = 11;
                break;
}
return Willingness;
  }
```

D.2 Java code for calculating water conservation, demand, and supply per month in Los Angeles using Anylogic 7.2

```
function
   */
  public Conserver( double adIntensity, double ContactRate, double AdoptionFraction, double

WillnessToUse, int droughtLev ) {
    markParametersAreSet();
    this.adIntensity = adIntensity;
    this.ContactRate = ContactRate;
    this.AdoptionFraction = AdoptionFraction;
    this.WillnessToUse = WillnessToUse;
    this.droughtLev = droughtLev;
  }

    // Port connections
```

```
  }

  /**
   * <i>This method should not be called by user</i>
   */
  private int _conservers_NumNonCon_xjal() {
    int _value = 0;
    for ( Conserver item : conservers ) {
      boolean _t = 
item.inState(Conserver.NonConserver)
;
      if ( _t ) {
        _value++;
      }
    }
    return _value;
  }
  /**
   * <i>This method should not be called by user</i>
   */
  private int _conservers_NSaver_xjal() {
    int _value = 0;
    for ( Conserver item : conservers ) {
      boolean _t = 
item.inState(Conserver.Saver)
;
      if ( _t ) {
        _value++;
      }
    }
    return _value;
```

```
  }
  // Functions



double
 MLRdemand( double Price, double Temperature, double Precipitation, int Population ) {

double currentPop = getCurrPop();
double result = -19570903-512405 * Price + 195433 * Temperature - 42250 * Precipitation +
5.58 *

currentPop;
//System.out.println("MLR Demand is: " + result);
return result;
  }



int
 getCurrPop(  ) {

int currentMonth = getCurrMonth();

int columnNum = 8;
PreviousPop = conservers.size();
switch(popChoice){
	case 0:
		columnNum = 8;
		break;
	case 1:
		columnNum = 9;
		break;
```

```
        case 2:
                columnNum = 10;
                break;
}

double PopulationData = ClimateData.getCellNumericValue("sheet1", 3 + currentMonth,
columnNum);
int currentPop = (int) Math.round(PopulationData);
WaterPrice = getWaterPrice();
Temperature = getTemp();
Precipitation = getPrecip();
Population = currentPop;
return currentPop;
  }



double
 ConservationCalc(  ) {

int num_conserver = conservers.NSaver();
double personSaving = 10;
switch(lADWP.DroughtLev){
        case 0:
                break;
        case 1:
                personSaving = 20;
                break;
        case 2:
                personSaving = 25;
                break;
        case 3:
```

```
        personSaving = 30;
            break;
    case 4:
            personSaving = 35;
            break;
}
double result = num_conserver * personSaving * 30;
return result;
  }


double
 WaterVolumeCalc(  ) {

double MLRdemand = MLRdemand(WaterPrice, Temperature, Precipitation, Population);
double Conservation = ConservationCalc();
double totalDemand = MLRdemand - Conservation;
double NatureSupply = getWaterSupply();
lADWP.WaterVolume = lADWP.WaterVolume - totalDemand / 0.708 + NatureSupply;
//totalDemand is for residential so we need to time a factor
if (lADWP.WaterVolume > lADWP.MaxWaterStorage){
    lADWP.WaterVolume = lADWP.MaxWaterStorage;
}
int currentMonth = getCurrMonth();
System.out.println("Scenario:" + ScenarioNum);
System.out.println("Current drought Level is: " + lADWP.DroughtLev);
System.out.println("Current Month is: " + currentMonth);
//System.out.println("Previous Population is: " + PreviousPop);
//System.out.println("Current Population is: " + Population);
//System.out.println("Current WaterPrice is: "+ WaterPrice);
//System.out.println("Current Temperature is:" + Temperature);
```

```
//System.out.println("Current Precipitation is:" + Precipitation);
double popGrowth = Population / 1000 - PreviousPop;
//System.out.println("Pop Growth is:" + popGrowth);
for(int i=1; i < popGrowth; i++){
        add_conservers();
}
updateLADWP();
updateConserv();
writeOutFile(currentMonth, totalDemand, MLRdemand, Conservation, NatureSupply);
return lADWP.WaterVolume;
  }



int
 getCurrMonth(  ) {

int currentMonth = getYear() * 12 + getMonth()-23640;
return currentMonth;
  }



double
 getWaterPrice(  ) {

int currentMonth = getCurrMonth();
int Year = getYear();
int columnNum = 13;
switch(ScenarioNum){
        case 0:
                columnNum = 13;
                break;
```

```
        case 1:
                columnNum = 12;
                break;
        case 2:
                columnNum = 11;
                break;
}
double WaterPrice = 0;
if (Year <= 2012){
        WaterPrice = ClimateData.getCellNumericValue("sheet1", 3 + currentMonth,
columnNum);
        } else {
        WaterPrice = 16.257 - (lADWP.WaterVolume * 5.982E-8);
        }
return WaterPrice;
  }


double
 getTemp( ) {

int currentMonth = getCurrMonth();
int columnNum = 2;
switch(ScenarioNum){
        case 0:
                columnNum = 5;
                break;
        case 1:
                columnNum = 7;
                break;
        case 2:
```

```
                        columnNum = 6;
                        break;
}
double Temperature = ClimateData.getCellNumericValue("sheet1", 3 + currentMonth,
columnNum);
return Temperature;
  }

double
 getPrecip( ) {

int currentMonth = getCurrMonth();
int columnNum = 2;
switch(ScenarioNum){
            case 0:
                        columnNum = 2;
                        break;
            case 1:
                        columnNum = 4;
                        break;
            case 2:
                        columnNum = 3;
                        break;
}
double Precipitation = ClimateData.getCellNumericValue("sheet1", 3 + currentMonth,
columnNum);
return Precipitation;
  }

  void updateLADWP( ) {
```

```
lADWP.DroughtLev = lADWP.getDroughtLev(lADWP.MaxWaterStorage,
lADWP.WaterVolume);
lADWP.AdIntensity = lADWP.adjustAdIntensity(lADWP.DroughtLev);
//lADWP.WaterPrice = lADWP.WaterPrice + lADWP.adjustWaterPrice(lADWP.DroughtLev);
lADWP.ContactRate = lADWP.getContactRate(lADWP.DroughtLev);
lADWP.AdoptionFraction = lADWP.getAdoptionFrac(lADWP.DroughtLev);
lADWP.WillingToUse = lADWP.getWillingUse(lADWP.DroughtLev);
  }

  void updateConserv(  ) {

for( Conserver c : conservers ){
   c.adIntensity = lADWP.AdIntensity;
         c.AdoptionFraction = lADWP.AdoptionFraction;
         c.droughtLev = lADWP.DroughtLev;
         c.WillnessToUse = lADWP.WillingToUse;
         c.ContactRate = lADWP.ContactRate;
}
  }

  void writeOutFile( int currentMonth, double totalDemand, double MLRdemand, double
Conservation, double

NatureSupply ) {

//Output.setCellValue(currentMonth, 1, currentMonth, 1);
Output.setCellValue(lADWP.DroughtLev, 1, currentMonth+2, 2);
Output.setCellValue(Conservation, 1, currentMonth+2, 3);
Output.setCellValue(MLRdemand, 1, currentMonth+2, 4);
Output.setCellValue(totalDemand, 1, currentMonth+2, 5);
Output.setCellValue(lADWP.WaterVolume, 1, currentMonth+2, 6);
```

```
Output.setCellValue(WaterPrice, 1, currentMonth+2, 7);
Output.setCellValue(NatureSupply, 1, currentMonth+2, 8);
Output.setCellValue(conservers.NSaver()*1000, 1, currentMonth+2, 9);
Output.setCellValue(conservers.NumNonCon()*1000, 1, currentMonth+2, 10);
Output.setCellValue(Population, 1, currentMonth+2, 11);
Output.writeFile();
  }
double
 getWaterSupply(  ) {

int currMonth =  getMonth();
int currYear = getYear();
System.out.println("Varibility: " + variability);
Random randomGenerator = new Random();
int randomInt = 0;
switch(variability){
        case 0:
            randomInt = randomGenerator.nextInt(50);
                break;
        case 1:
                randomInt = randomGenerator.nextInt(40);
                break;
        case 2:
                randomInt = randomGenerator.nextInt(30);
                break;
        case 3:
                randomInt = randomGenerator.nextInt(20);
                break;
        case 4:
                randomInt = randomGenerator.nextInt(10);
                break;
```

```
}
double WaterSupply = 0;
if (currMonth == 0 || currMonth == 1 || currMonth == 11){
	WaterSupply = InitialWaterVolume * 0.2*(100 - randomInt)/100;
} else if (currMonth == 9 || currMonth == 10 || currMonth == 2){
	WaterSupply = InitialWaterVolume * 0.16 * (100 - randomInt)/100;
} else if (currMonth == 3 || currMonth == 4 || currMonth == 8){
	WaterSupply = InitialWaterVolume * 0.13 * (100 - randomInt)/100;
} else if (currMonth >= 5 && currMonth <= 7){
	WaterSupply = InitialWaterVolume * 0.1 * (100 - randomInt)/100;
}
int randomYear = 4;
double randomFactor=(randomGenerator.nextInt(3)-0.5);
if (currYear % randomYear == 0){
	WaterSupply = randomFactor * WaterSupply;
}
return WaterSupply;
  }
```

APPENDIX E: ADDITIONAL SUPPORTING INFORMATION

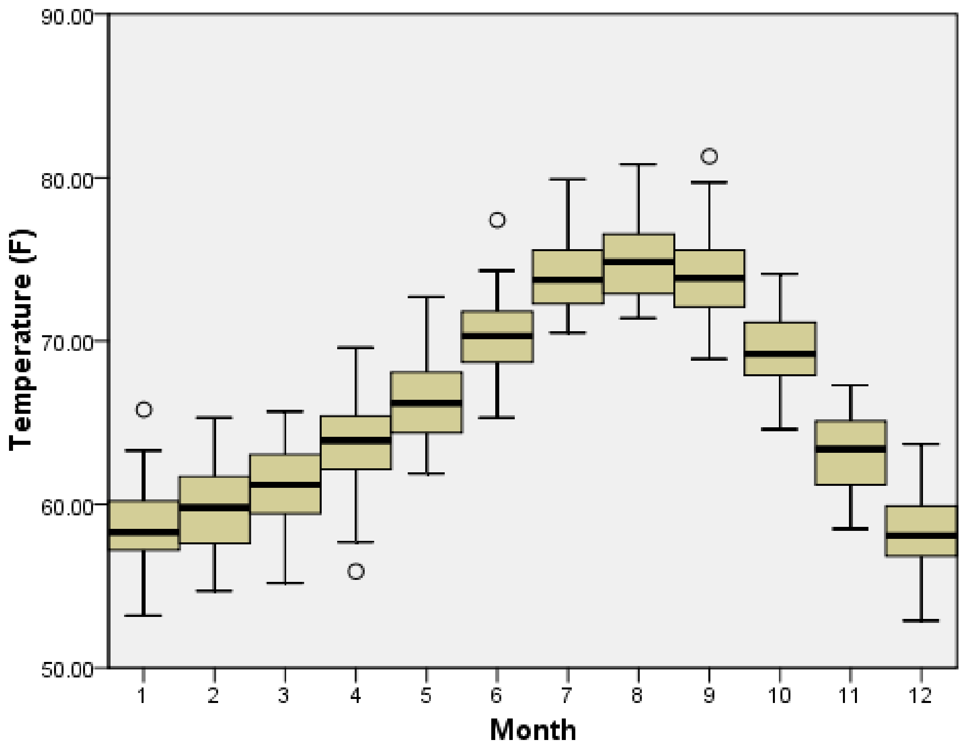

Figure E-1: Boxplot distributions of monthly average temperature observed throughout the year from 1970-2012 in Los Angeles, California

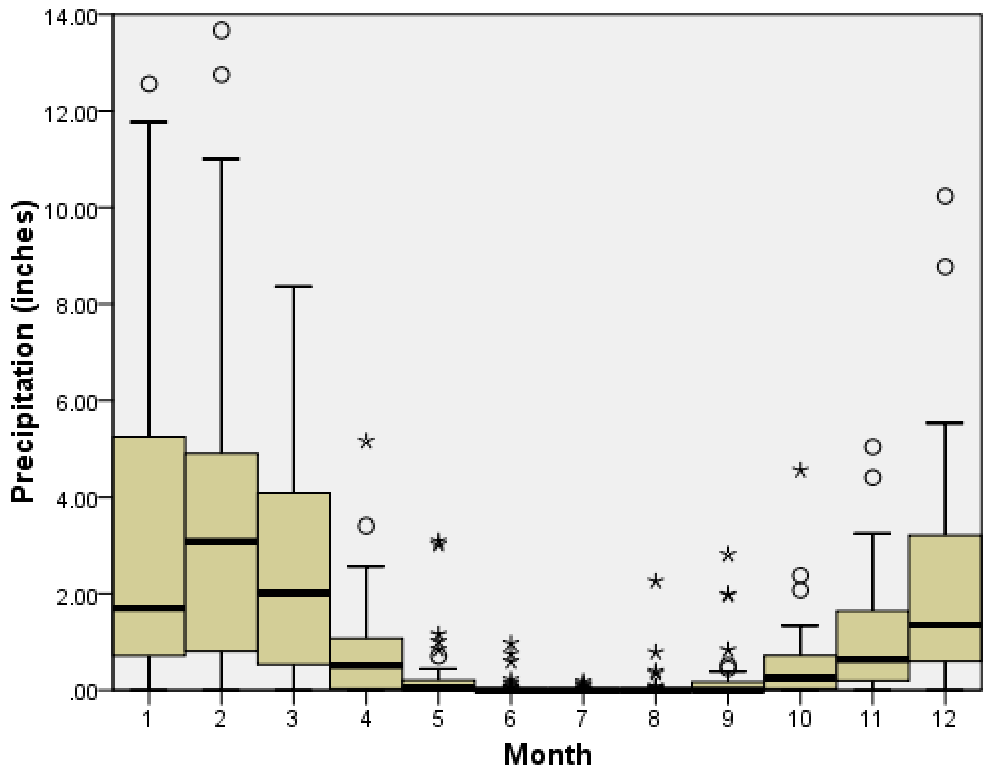

Figure E-2: Boxplot distribution of accumulated precipitation in inches throughout the year from 1970-2012 in Los Angeles, California

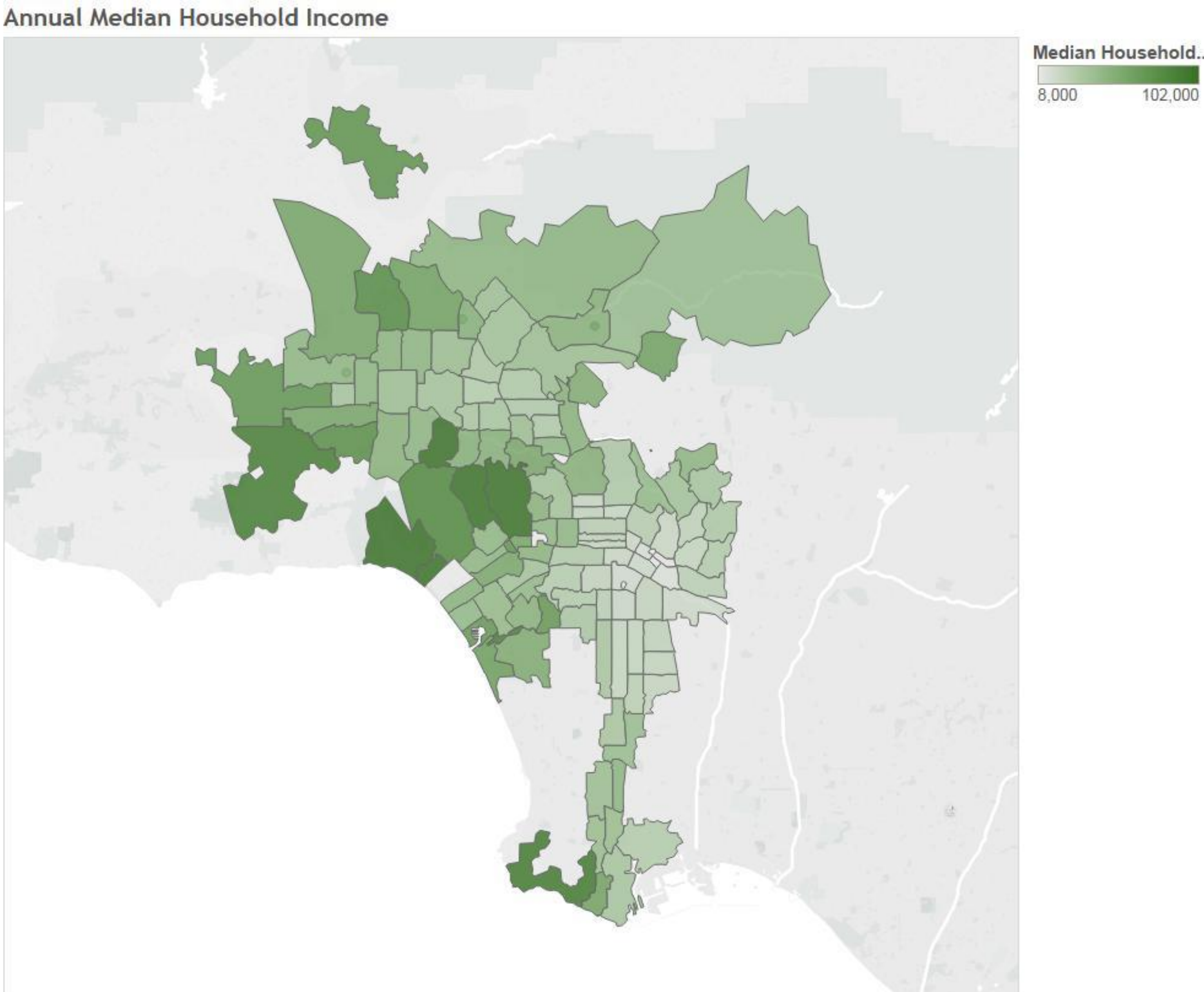

Figure E-3: Annual median household income in Los Angeles from 1970-2012 adjusting for 2012 price of inflation and divided by zip code

*Darker green indicating higher annual median household income and lighter green representing lower annual median household income

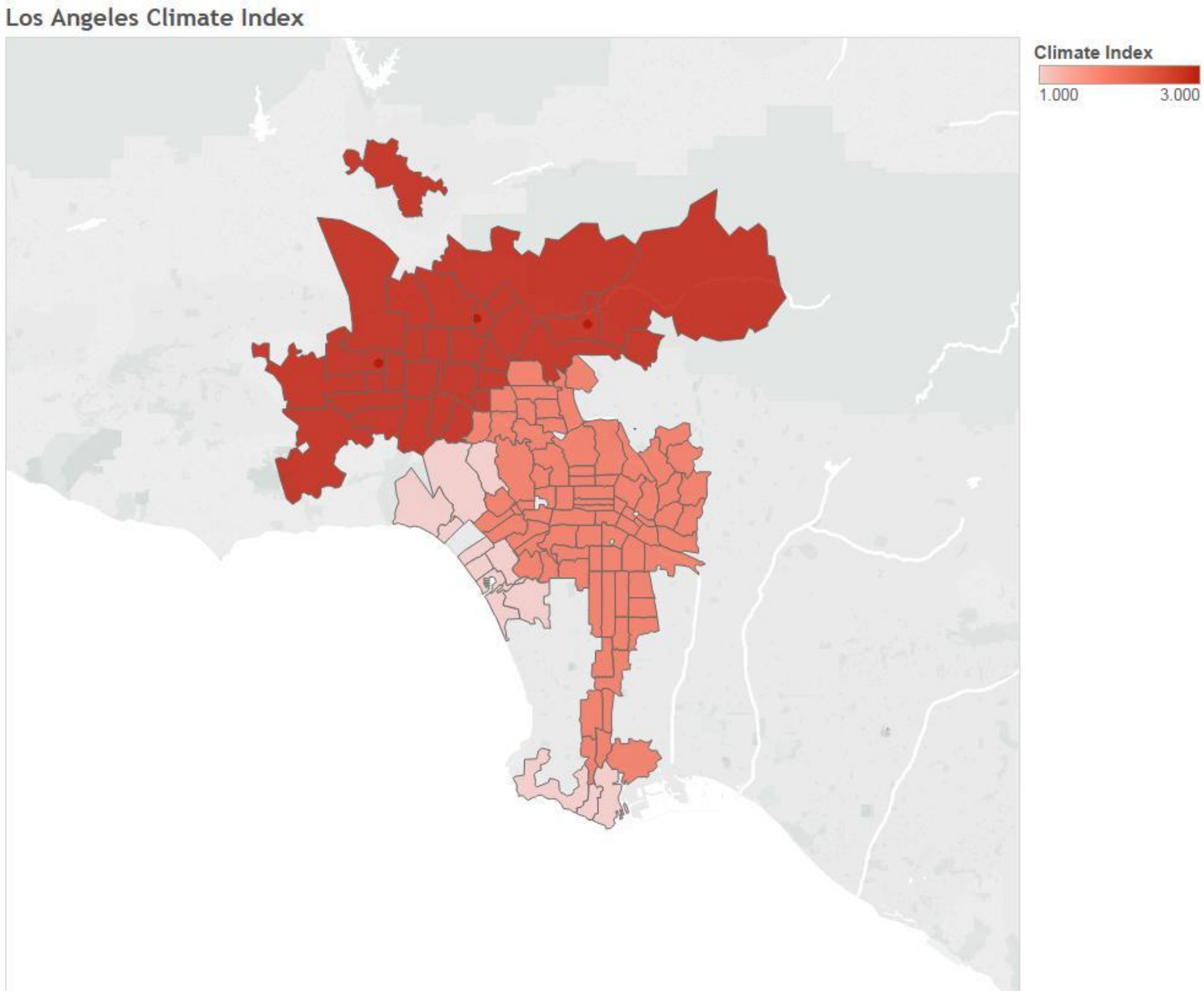

Figure E-4: Climate index of temperature in Los Angeles from 1970-2012

*Dark red represents high temperatures, light red indicates medium temperatures, and the lightest pink indicates coastal low temperatures

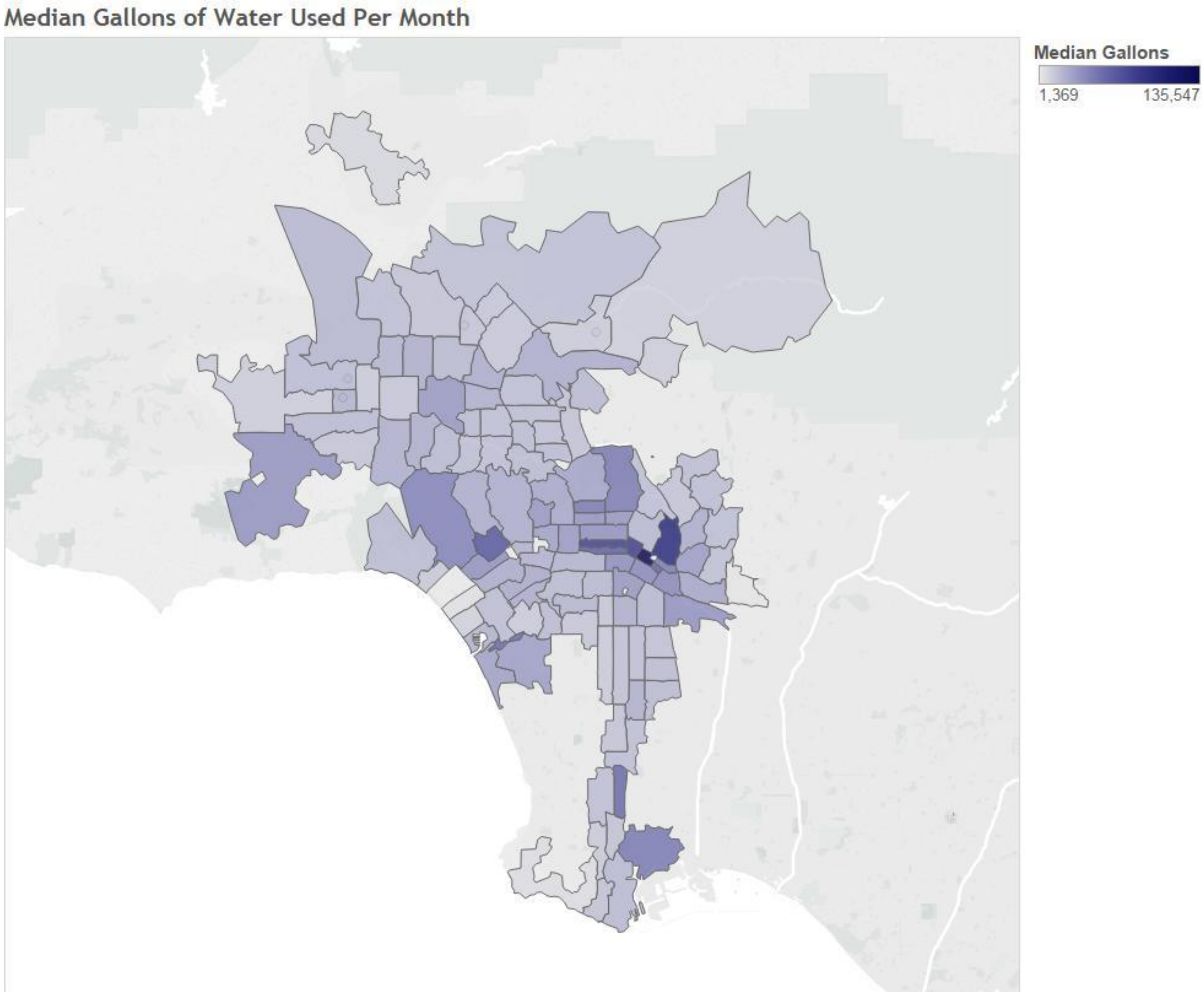

Figure E-5: Monthly water use in each household in Los Angeles and divided by zip code

*Darker shades of blue indicating larger amounts of water usage as compared to light blue shades which demonstrates lower uses of median monthly household water