FACTORS AFFECTING WATER USAGE FROM TEXAS' COLORADO RIVER

A Thesis

by

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ABSTRACT

Rapidly increasing population along with episodes of drought puts a substantial strain on water resources in parts of the state of Texas. Thus, sustainable and long-term management of the future of water supply has become the priority among the state agencies and water managers. With municipal water demand expected to increase in the future it is important to understand the drivers of residential water demand in Texas. This study focuses on the Colorado River basin, which represents one of the largest basins delivering water to 41 counties across the state. Importantly, in order to meet the future needs for water, counties that typically rely on the Colorado River will likely be forced to depend increasingly on limited groundwater reserves in the future. A greater rate of depletion of these ground water reserves and their disappearance due to drought in turn, may threaten the long-term availability of water from the Colorado River basin.

In this research we analyze the effects of climate patterns, socioeconomic factors, and land use patterns on per capita municipal water usage from the Colorado River across counties over the period from 1971 to 2014. Using fixed effects panel regression analysis methods, water usage from the Colorado River is found to be significantly determined by population density, home values, ethnicity, age, annual precipitation, and the number of hot days (temperature exceeding 29.44C) during summer months, along with urban structure. Results suggest that areas with greater annual precipitation and a higher housing price index tend to have a higher per capita municipal water usage. With regards to population demographics, results suggest that areas with a lower minority population and lower percentage of children (19 years old and younger) have a lower per capita municipal water usage. Results pertaining to urban structure

suggest that counties adjacent to a metropolitan county have the highest per capita municipal water usage, urban counties the next highest, followed by metropolitan counties, and rural counties which have the lowest per capita municipal water usage.

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Contributors

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Part of the data analyzed for Chapter 4 was provided by Dr. Meri Davlasheridze. This data consisted of climate data, age and race demographic data, and political data. Water usage data analyzed for Chapter 4 was provided by Nattie Gonzalez of the Texas Water Development Board.

All other work conducted for the thesis was completed by the student, under the advisement of Dr. Meri Davlasheridze of the Department of Marine Sciences.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 MOTIVATION

Water resource management is an increasingly important issue throughout the world. With ongoing climate change and rapid population growth adding new stressors to water resource availability it is important to be mindful of the ways we use this precious resource (Miller and Yates 2006; Breyer et al. 2012). Residential water demand is of particular concern to policymakers due to the fact that it constitutes a substantial proportion of total water demand (Worthington and Hoffman 2008).

In Texas increasing populations as well as changing climatic conditions are impacting the way the state views water. As Texas continues to grow concerns related to water availability and usage are becoming more pressing. From August 2010 to October 2014 Texas experienced the second-worst drought in recorded history with 2011 being the worst single-year drought (TWDB 2017). At the time LCRA was struggling to maintain the water levels of the Highland Lakes which provide water to over a million Texas residents (Hardball 2013).

Water scarcity also has the potential to put strain on the Texas economy and impede economic growth, particularly among water-intensive economic sectors such as agriculture and fisheries (Phillips et al. 2013). During the 2011 drought LCRA cut off a majority of rice farmers water supply reducing agricultural water use from 60% in 2011 to 21% in 2012 (Phillips et al. 2013). Also during the same time LCRA considered cutting off freshwater inflows to Matagorda Bay, which relies on the Colorado River for greater than 50% if its freshwater inflows required to meet peak productivity (Hardball 2013; LCRA et al. 2006). The State Water Plan (2017) estimates annual economic losses to amount to $73 billion in 2020 and more than double in 2070 as a result of water shortages if no strategy is implemented.

Texas receives 40% of its water supply from surface water in rivers and reservoirs (Phillips et al. 2013). In municipalities 62% of the water supply is comprised of surface water (Phillips et al. 2013). The remainder of the state's water supply comes from groundwater aquifers which are constantly at risk for being depleted (Kaiser and Skiller 2001). Aquifers recharge through precipitation runoff infiltrating sediments and moving downward toward the water table and becoming groundwater (Oden and Delin 2013). Aquifers can become depleted when the amount of water withdrawal exceeds the rate of replenishment (Phillips at al. 2013).

Regardless of where Texas residents get their water from and for what purpose the fact remains that it is becoming an increasingly scarce resource. Without better management through conservation and reservoir construction projects Texas is likely to face water shortages in the future. According to the State Water Plan (2017) the currently existing water supply is not sufficient to meet future water demand in times of drought. In the event if a drought similar to the 2011 drought it is estimated that in the year 2020 the state would need an additional 4.8 million acre-feet per year of water supply, 11 percent of which would be for municipal users (TWDB 2017).

1.2 PURPOSE AND RESEARCH QUESTIONS

Municipal water demands are expected to have the greatest total amount of increase from 5.2 million acre-feet per year in 2020 to 8.4 million in 2070 (TWDB 2017). This makes managing municipal water supplies critical to the future of Texas. In order to manage municipal water usage it is important to understand the drivers that influence the amount of water used by residents. This often includes socioeconomic and demographic characteristics (population, income, etc) as well as climatic conditions (e.g., weather), and land use patterns many of which have seldom been explored.

The purpose of this study is to determine the effects of climate, demographic and socioeconomic factors, as well as land use patterns and urbanization on municipal surface water usage from the Colorado River in order to assess the major environmental and anthropogenic stressors on this resource so that it can be better managed for the future. This thesis utilizes multiple panel regression models to evaluate the relative importance of weather variability, socioeconomic characteristics, and land use characteristics in explaining municipal water usage among 41 counties that use water from the Colorado River in Texas. Using these methods this thesis aims to answer the following research questions:

1. How does Colorado River water usage vary in response to weather patterns and what is the spatial variation of water usage across counties?
2. To what extent do certain socioeconomic variables explain variation in Colorado River water usage across the counties of Texas?
3. To what extent does urban spatial structure affect Colorado River water usage by counties in Texas?
4. To what extent do land use patterns explain Colorado River water usage?

CHAPTER II

BACKGROUND

2.1 THE COLORADO RIVER

The Colorado River is an important source of water in the state of Texas. At more than 900 miles long the Colorado River, shown in figure 1, is the longest river in the United States that is contained in one state (LCRA 2003). Its watershed totals greater than 39,000 square miles from Dawson County, Texas (near the New Mexico border) to Matagorda Bay in the Gulf of Mexico and includes many creeks, streams, lakes, springs, and aquifers (LCRA 2003; "Colorado River Watershed" n.d.). The Colorado River supplies water to a large region of Texas for a variety of purposes including: agriculture, public water supply, production of electricity, and recreation ("Colorado River Watershed" n.d.).

The Colorado River is also important as a major source of freshwater to the Matagorda Bay Estuary, which is the second largest in the State of Texas and known for its high degree of marine biodiversity and critical habitats (TWDB 2011; Brody et al. 2004). Freshwater inflows as well as the nutrients associated with them are an essential part of what makes estuaries like Matagorda Bay so productive and diverse (LCRA et al. 2006). Freshwater inflows mix with oceanic salt water to create brackish water. This mixing creates a variety of different habitats for marine organisms to thrive in such as wetlands, oyster reefs, and seagrass beds (LCRA et al. 2006). The Matagorda Bay estuary is economically important to the State of Texas as it is a vital part of the state's commercial and sport fishing industry (LCRA et al. 2006). It is estimated that 75-80% of the fishery species in the Gulf of Mexico depend on estuaries at some point in their life cycle (LCRA et al. 2006).

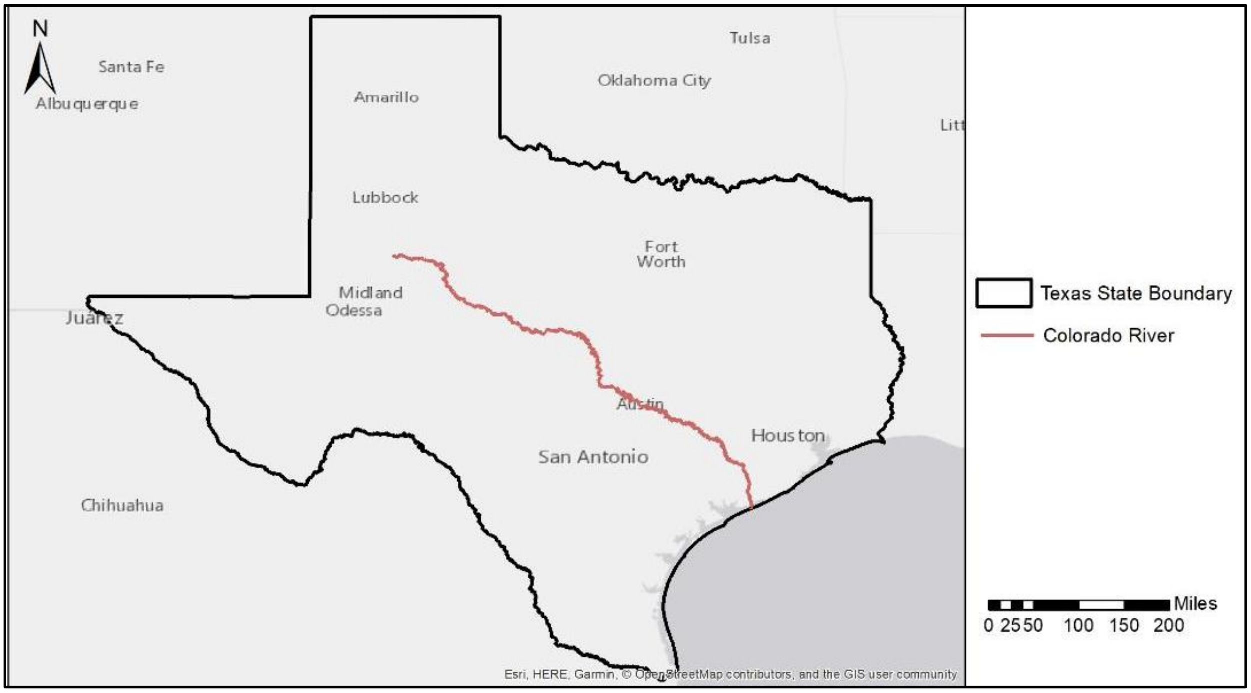

Figure 1. Map of the Colorado River as it runs through the state of Texas.

Because the Colorado River supplies water to not only Matagorda Bay but also to a large portion of the State of Texas, the proper and sustainable management of this important resource is of particular policy concert for multiple end-users and stakeholders. Multiple municipal and administrative authorities, shown in figure 2, manage the water supply and usage from the Colorado River. The Lower Colorado River Authority (LCRA) is one that was created in 1934 with the authority to store and sell water, generate electricity, help reduce flood damages, and implement reforestation and soil-conservation programs (LCRA n.d.). LCRA also manages the Highland Lakes, which act as storage reservoirs for water flowing from the Colorado River, and owns the rights to 2.1 million acre-feet per year of water from the Colorado River (LCRA 2017). The Colorado River Municipal Water District (CRMWD) owns and operates three major lakes and reservoirs at the upper portion of the Colorado River (CRMWD n.d.). The CRMWD is tasked with providing water from the Colorado River to regions of west Texas through its reservoirs (CRMWD n.d.). Other organizations with interests in the Colorado River include the Colorado River Alliance (CRA), the Colorado River Land Trust, and the Upper Colorado River Authority (UCRA). These organizations work in coordination with others to promote the conservation and protection of the Colorado River in order to ensure its place in the future as a vital source of water for Texas residents (CRA n.d.; Colorado River Land Trust n.d.; UCRA n.d.).

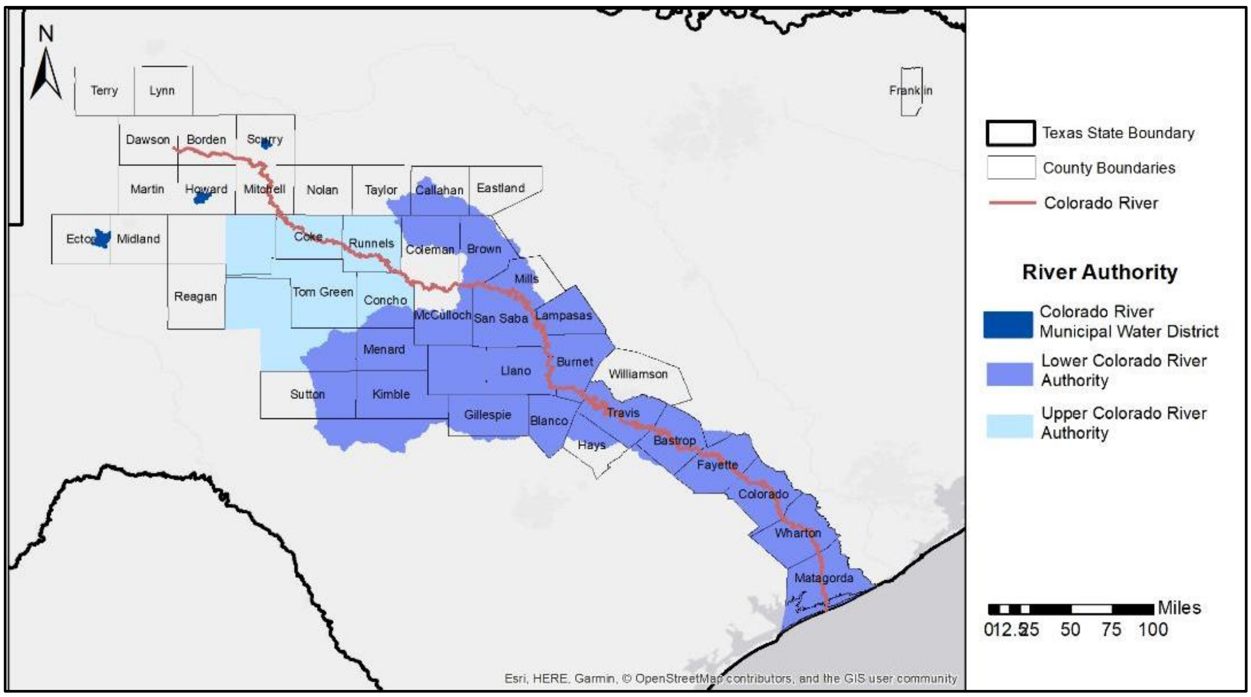

Figure 2. River authorities managing the Colorado River.

2.2 THE STUDY AREA: TEXAS

Texas is the second largest state in the nation, with regards to physical land size and population. Texas is also known to have one of the fastest growing populations in the U. S., with only 8 million residents in 1950 and nearly 25 million by 2010 (TWDB 2017). By 2070 the state’s population is expected to double with a projected population of around 51 million (TWDB 2017).

2.2.1 CLIMATE

The state of Texas experiences a wide variety of climatic conditions (TWDB 2012). Average annual temperature in the state ranges from approximately 12°C (53.6°F) in the northern Panhandle to about 24°C (75.2°F) in the Lower Rio Grande Valley. Figure 3 shows average annual temperatures across the state. Average annual precipitation in Texas ranges from about 200mm (7.87in) in the western part of the state to nearly 1500mm (59in) in the east. Figure 4 shows average annual precipitation as it varies across Texas.

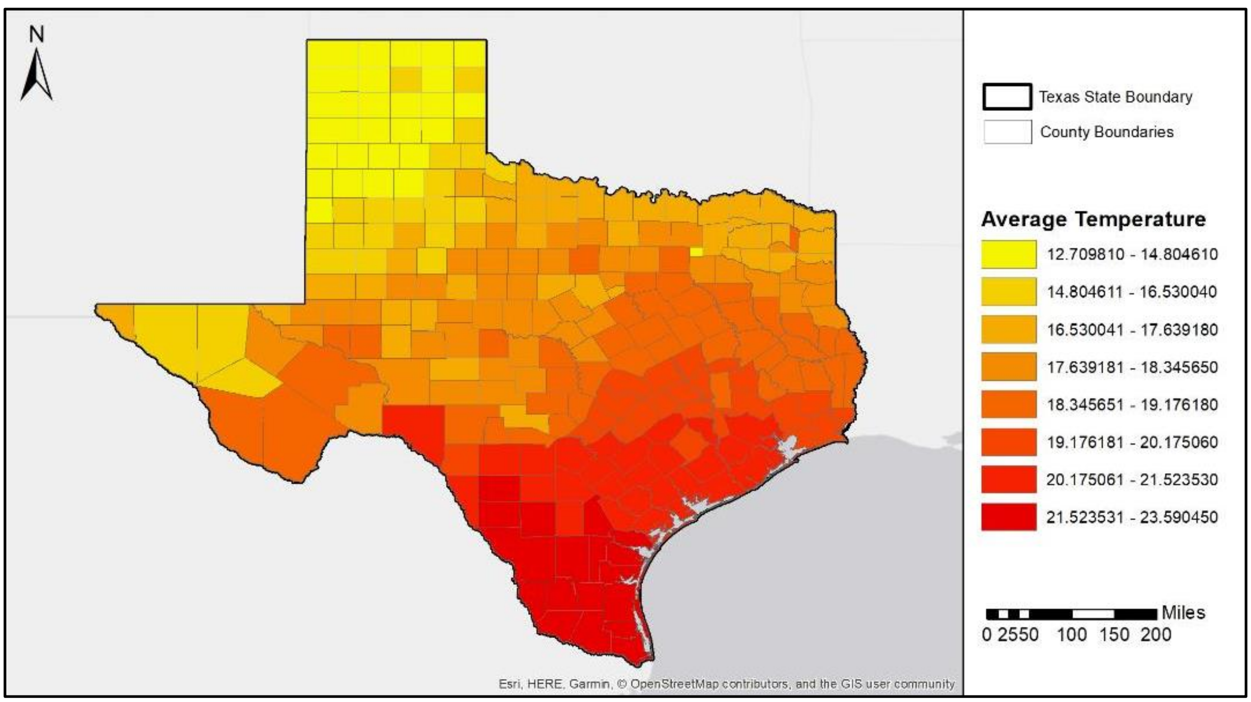

Figure 3. Average annual temperature from 1950 to 2014 (degrees Celsius) in counties across Texas (source data from NCDC).

The variability of both temperature and precipitation in Texas is not spatially exclusive. According to the 2012 State Water Plan climate in Texas is, has always been, and will always be variable. Historically climate in Texas has varied, as measured in the record as well as through scientific studies using environmental proxies (TWDB 2012). Texas has experienced several droughts throughout history. The current drought of record was during the 1950s and is the highest ranking in terms of intensity and duration (TWDB 2012). During this time TWDB (2012) reports that precipitation in the state was approximately 79 percent of the average. Scientists have estimated that between 1648 and 1995 Texas has experienced approximately 15 seven-year periods in which precipitation was lower than 90 percent of the average, which

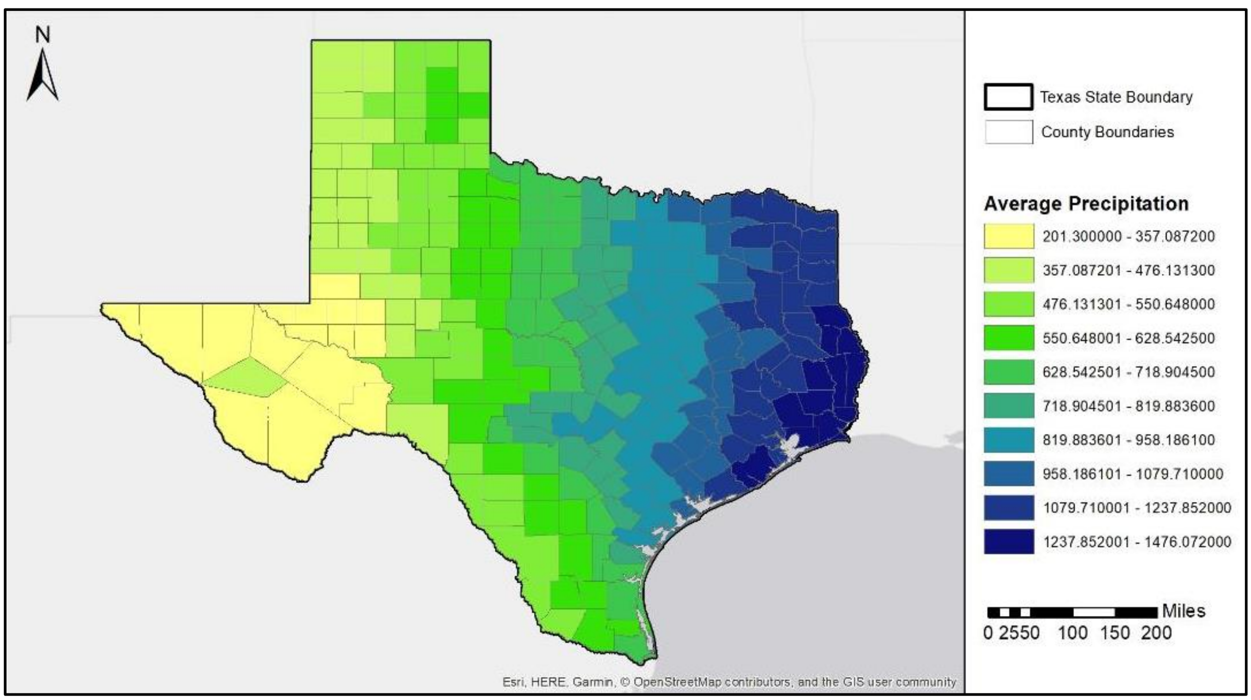

Figure 4. Average annual precipitation from 1950 to 2014 (millimeters) in Texas counties (source data from NCDC).

indicates extended drought (TWDB 2012). TWDB (2012) states that the variability of Texas climate has the potential to affect the states' available water resources, making the probability of drought a continuing concern.

2.2.2 WATER PLANNING

Water planning is not a new concept to the state of Texas, however changes made to Texas legislation in 2013 have led to a new era of water planning. This new approach to the state water plan has created the State Water Implementation Fund for Texas (SWIFT) to fund projects that aid in meeting the state's water need into the future (TWDB 2017).

The 2017 State Water Plan produced by the Texas Water Development Board (TWDB) estimates that between 2020 and 2070 state water demands will increase by approximately 17% and the states existing supplies will decrease by around 11%. The 2017 State Water plan is designed to assure adequate water supplies in times of drought, to which the state has succumbed to in the past. It warns that if no additional supplies are created approximately one-third of the state's municipal water users will have less than half of the water supply they require in 2070 (TWDB 2017).

Chapter 8 of the plan is dedicated to water management strategies. It recommends that conservation be included in all regional water plans and estimates that it could lead to a water savings of 2.3 million acre-feet per year (TWDB 2017). Some of the water conservation strategies recommended in the plan include landscape irrigation restrictions, low flow plumbing fixtures, water conservation pricing structures, and water system audits (TWDB 2017).

2.2.3 WATER LAW

Texas water law is slightly more complex than that of other states. This is because in Texas water is divided into two categories: groundwater and surface water (Lashmet 2018). According to Texas Water Code Section 36.001(5) groundwater is defined as "water percolating below the surface of the earth." Texas groundwater is composed of nine major aquifers and twenty-one minor aquifers (Ashworth and Hopkins 1995). Texas Water Code Section 11.021 defines surface water as all water "under ordinary flow, underflow and tides of every flowing river, stream, lake, bay, arm of the Gulf of Mexico, and stormwater, floodwater or rainwater of every river natural stream, canyon, ravine, depression, and watershed in the state." By these definitions the Colorado River is considered surface water and susceptible to the laws that regulate it.

In Texas surface water is owned by the state, held in a trust for its citizens, and regulated by the Texas Commission on Environmental Quality (TCEQ) (Lashmet 2018). In order to use surface water one must obtain a permit from TCEQ which designates the amount of water that may be used and the purpose that it may be used for (Lashmet 2018). Texas's groundwater however is much less regulated. Groundwater in Texas is treated as an unregulated private property right (Kaiser and Skiller 2001). That means that groundwater resources are owned by individual property and land owners (Lashmet 2018). Despite groundwater being privately owned, Texas has over 98 Groundwater Conservation Districts (GCD) that manage groundwater and regulate pumping from aquifers (Lashmet 2018). Each of these GCD has its own rules and permitting processes to regulate groundwater (Lashmet 2018). However even with these GCD in place the regulation of groundwater in Texas is still minimal, especially when compared to the state’s regulation of surface water (Kaiser and Skiller 2001). These differences in Texas groundwater and surface water regulations make water management a challenge.

CHAPTER III

LITERATURE REVIEW

3.1 FACTORS INFLUENCING WATER CONSUMPTION

Drivers of water consumption have been analyzed in many studies across the globe. Most commonly these studies are conducted using individual household water consumption data and take into account price and climate as well as other household specific characteristics to determine their individual effect on household water consumption. This study uses aggregate water consumption data at the county level and therefore individual household characteristics and consumer behaviors cannot be taken into account.

Many factors affect the amount of water that is used by a community including and not limited to wealth, housing features and value, employment status, weather and climate patterns (e.g., temperature and precipitation, drought), population density, demographic characteristics (e.g., age, race), affiliation with conservation groups and political preferences, along with land use patterns among others. Population growth is one of the main drives for demand, however water consumption patterns differ in areas with different urbanization patterns (Morote and Hernandez 2016). Morote and Hernandez (2016) suggest that while areas of low-density urbanization tend to have a lower population density, they also have a higher demand for and consumption of water for lawns, swimming pools and other water-intensive amenities. Whereas areas of high-density urbanization are composed of semi-detached homes and apartment buildings where green spaces and swimming pools are shared among the community and generally limited. Domene and Sauri (2006) found that low-density housing exhibited higher water consumption patterns than medium or high-density housing. A 2010 study by March and

Sauri found population density to be significant with water consumption decreasing as population density increases.

In terms of the natural process, Climate has been shown to have the largest impact on not only water usage but water supply (groundwater and surface water) as well. Changes in climate conditions are likely to have a profound impact on water supplies and create new challenges for water managers (McDonald et al. 2011). A study done on the Colorado River Basin in California showed that climate change would “lead to a situation where total system demand would exceed the reservoir inflows” (Christensen et al. 2004). Climatic conditions have been examined in many forms and their effects on water usage have been found to vary. For example, Tinker et al. (2006) study found both temperature and rainfalls to be significant factors in determining water use among households in Austin TX, with water usage increasing as temperatures and the amount of rainfall increase. A study conducted in Tulsa and Oklahoma City, OK found that precipitation was not significant in either city and temperature was significant only in Tulsa (Cochran and Cotton 1985). In Germany Schleich and Hillenbrand (2008) found that neither mean summer temperature nor total summer precipitation were significant. However this same study found that the average number of days with precipitation exceeding 1mm in a summer month was statistically significant ($p<0.1$) with water usage decreasing as the number of days with excess rainfall increased. Using drought conditions as the proxy for weather conditions House-Peters et al (2010) also found that it was not a significant factor in determining water use in Hillsboro, OR.

Wealth is an important economic driver of water usage. More wealth allows residents to have more lavish lifestyles which may include additional water intensive amenities such as additional bathrooms, larger yards/more outdoor landscaping/lawn irrigation systems, and personal swimming pools (USGS 1992). It is also noted that wealthier residents are likely to be less susceptible to higher water prices than lower income residents because water bills make up a lower proportion of their income (Arbues et al. 2003; USGS 1992). Wealth, measured using income, was found to be a significant influencing factor of water consumption in Barcelona but was not found significant in Oregon (Domene and Sauri 2006; March and Sauri 2010; House-Peters et al. 2010). Studies in Barcelona that found income to be significant also found that water usage increases as income increases (Domene and Sauri 2006; March and Sauri 2010).

A few studies have also suggested that water usage increases with an aging population (Schleich and Hillenbrand 2008). For example, House-Peters et al. (2010) explain that retired/older people use more water at home when compared to working adults who use water in their workplace or children who use water in schools, because they tend to stay at home more. Using the average age of the population, Schleich and Hillenbrand found age to be significant in determining water consumption with it increasing as average age increases. However using the median age of the population, House-Peters et al. (2010) did not find age to be a significant determining factor. Another important demographic variable, however seldom explored, that determines water usage is race. One study by Balling et al. (2008) explained that using race takes into account language barriers, when conservation messages may not be distributed in multiple languages, as well as the built environment of minority neighborhoods, where there may be lower quality infrastructure present. This study found that water usage in census tracts with a higher proportion of Hispanic residents were less sensitive to climate variation.

In addition to wealth and socio-demographic characteristics, Breyer et al (2012) suggests that municipal water use patterns should be examined through linkage of natural processes with culture, society and political institutions. Using culture and society to examine water consumption addresses attitudinal factors and beliefs that may impact the way societies use and manage water (House-Peters and Chang 2011). The consideration of political institutions can be said to be associated with one's attitude towards conservation practices. Also at the aggregate level the political views of decision makers may effect their perspective on conservation policies and demand management. Those with more conservative political ideologies tend to favor less government regulations over conservation practices while those with more liberal views favor more regulations regarding conservation.

CHAPTER IV

DATA

This thesis uses a panel dataset to examine the effects of various climate, socioeconomic, and spatial variables on municipal water usage from the Colorado River, Texas. Observations were taken from 41 counties which used water for municipal purposes from the Colorado River from 1971 to 2015. Some counties in the data set did not use water from the Colorado River every year, which makes the data an unbalanced panel data set. Table A-1 and figure 5 show the frequency at which counties utilized water from the Colorado River for municipal purposes. Table A-2 shows the number of counties which used water for municipal purposes from the Colorado River during any given year of the study period. The least amount of counties observed using water from the Colorado River in any given year was 27 with the most being 35.

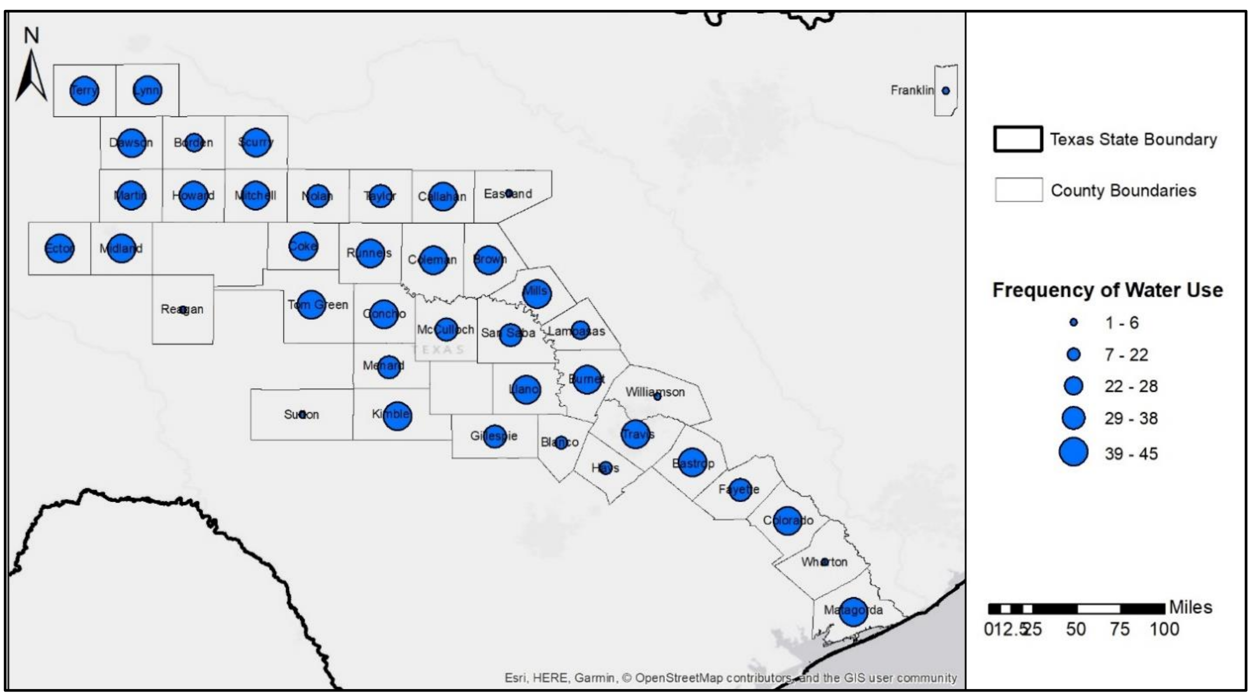

Figure 5. Map of Texas counties using water from the Colorado River and frequency of use.

4.1 THE DEPENDENT VARIABLE

The dependent variable represents per capita municipal water usage from the Colorado River. Per capita municipal water usage represents a time series of yearly municipal water use observations from 1971 to 2015 for 41 counties. This data were obtained from the Texas Water Development Board who collects information regarding water usage through their yearly water survey. Total municipal water usage from the Colorado River for each county for each year was divided by the population of that county for that year to obtain per capita municipal yearly water usage. Water usage data is reported in gallons.

Overall, per capita municipal water usage from the Colorado River has been decreasing over time as shown in figure 6. This is potentially due to the introduction of new water saving technologies as well as changing attitudes towards water conserving behaviors. Table A-3 shows the descriptive statistics of per capita municipal water use from the Colorado River. Average water usage over the entire study period was 292,068.8 gallons per person per year with a minimum corresponding to 2.68 gallons per person and a maximum to 25,900,000 gallons per person annually. Yearly per capita municipal water usage deviated from normal distribution which was indicated by the coefficients for skewness and kurtosis estimated at 10.19 and 108.02 respectively, this is shown in figure 7. The variable was log transformed to approximately a normal distribution, shown in figure 8.

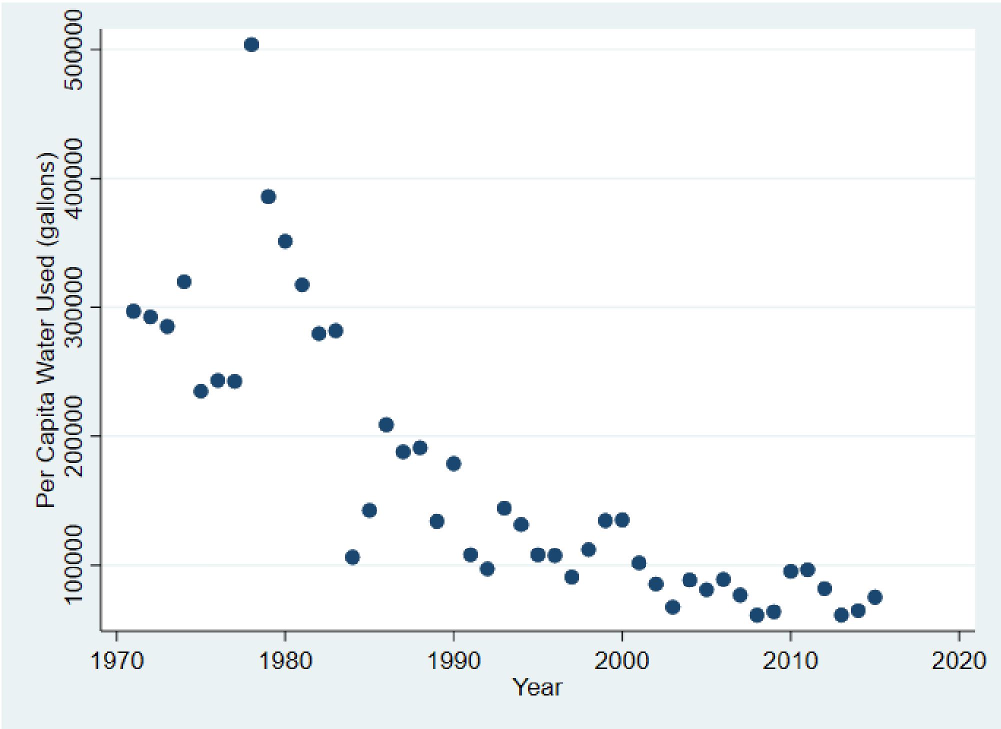

Figure 6. Graph showing the trend of per capita municipal water use from the Colorado River over time.

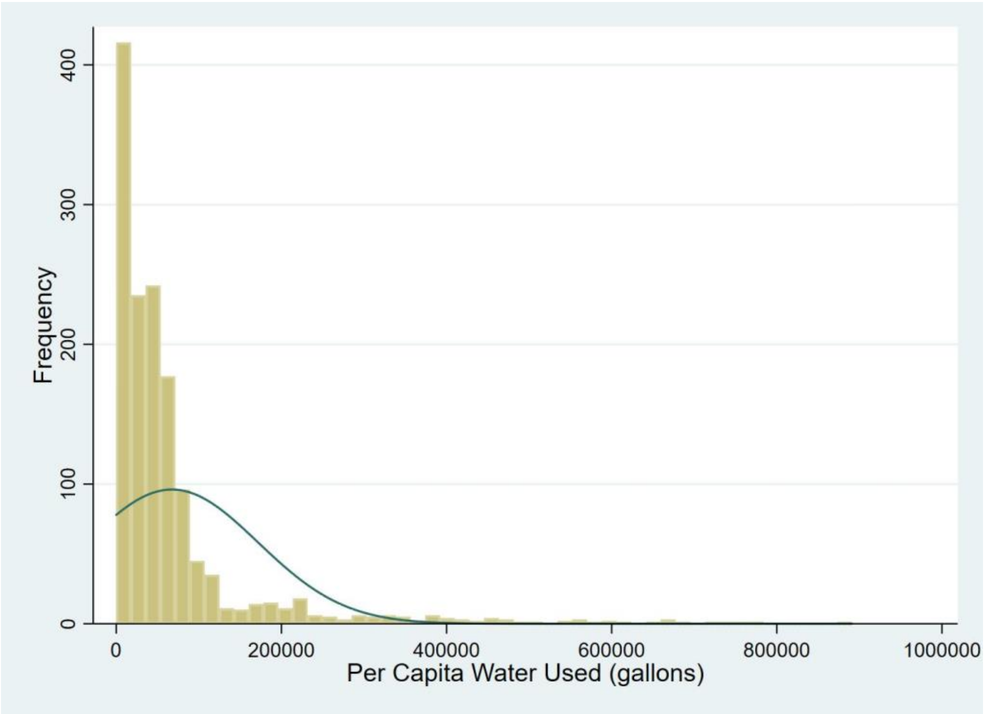

Figure 7. Histogram showing the distribution of per capita municipal water usage from the Colorado River. In order to show the distribution of observations only those with a value less than 1,000,000 gallons are shown. A total of 20 observations were excluded.

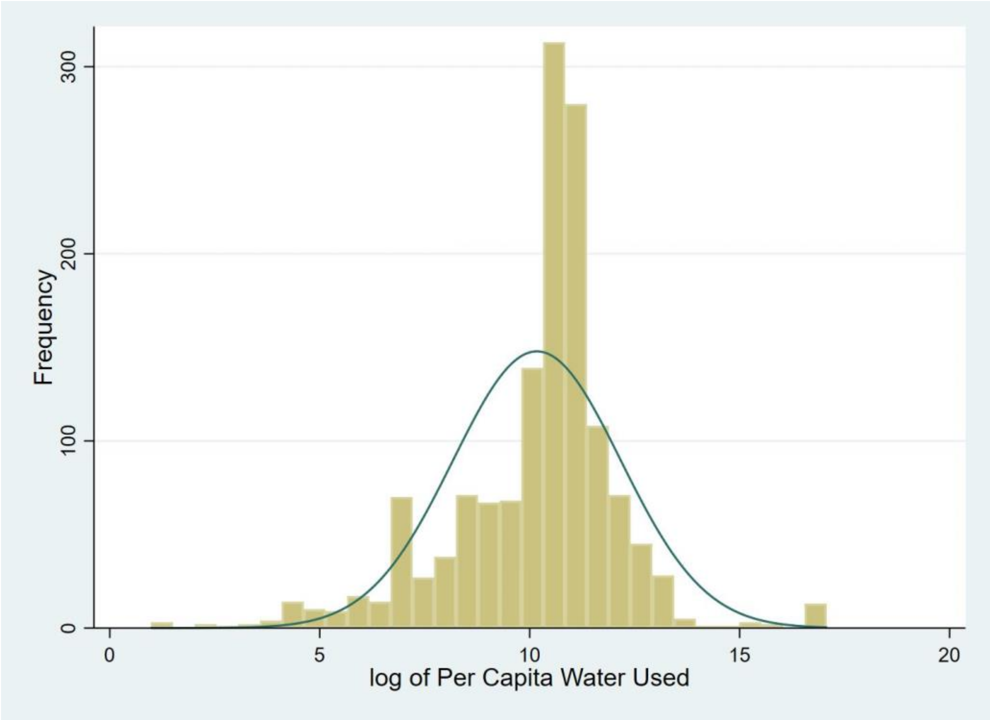

Figure 8. Histogram showing the distribution of log transformed per capita municipal water usage.

4.2 CLIMATE VARIABLES

Climatic effects of water usage were analyzed using a variety of climate variables. Temperature and precipitation data were obtained from the National Climatic Data Center (NCDC), which chronicles daily climate values by weather station. Weather stations are identified by latitude and longitude coordinates in the dataset where they were spatially matched to counties. If no weather station was present in a particular county, then the averages of neighboring counties were used to interpolate the missing data. In counties where more than one weather station was present the values were averaged across all weather stations in the county. Some errors in temperature observations were considered inaccurate and therefore eliminated, such observations were either abnormally high (greater than 60°C) or abnormally low (less than -80°C).

Daily precipitation values were totaled by county to obtain total yearly precipitation, which is reported in millimeters. Table A-3 summarizes the yearly precipitation variable. Annual total precipitation had a mean of 663.32 mm with a minimum of 89.3 mm and a maximum of 1950.825 mm.

Daily temperature, reported in degrees Celsius (°C), were used to determine the number of days per month where the temperature met or exceeded 29.44°C (85°F). The monthly totals for June, July, and August were then combined to create a variable representing the number of hot summer days in any given year. Table A-3 provides details on the number of hot summer days. The average number of hot summer days in a year was 21 with a minimum of zero and a maximum of 87 days.

Climate data were available for the years 1950 to 2015. However data for the year 2015 was only available for the first two months of the year and that year was excluded from the sample.

4.3 SOCIOECONOMIC VARIABLES

The socioeconomic effects of water usage were examined using a variety of variables. Data regarding the population and income of the counties were obtained from the Bureau of Economic Analysis (BEA) for all counties in the study area for the years 1971 to 2015. Population represents the number of people residing in each county and income represents per capita personal income in dollars. Population was used only to calculate per capita municipal water usage and not as an explanatory variable. Per capita income was converted into 2015 real prices using the Consumer Price Index (CPI). The income variable is described below as well as in Table A-3. Income per capita averaged $30,127.43 with a minimum of $12,176.66 and a maximum of $120,469.50. The log transformed income was used in the analysis.

Data on the unemployment rate were obtained from the Bureau of Labor Statistics (BLS) for each county in the study area. This data reports percent unemployed out of labor force and was only available for the years from 1990 to 2017. Table A-3 describes the unemployment rate throughout the study period. The average unemployment rate in the sample was 5.1% with the minimum corresponding to 1.6% and the maximum to 15.3%.

The housing price index (HPI) was used to measure the effects of housing price trends on water usage in each of the counties in the study area. HPI values are used at the 2000 base level. This data was obtained from the U.S. Department of Housing and Urban Development and was only available from 1986 to 2017. A summary of the HPI variable is given in Table A-3. HPI had an average of 110.38 with a minimum of 25.17 and a maximum of 260.66.

Data regarding the age and race distribution were obtained from the National Center for Health Statistics. Age was originally split into 13 age cohorts and given as the number of people in each category. Several of the categories were combined in an effort to condense the age variable into four categories. The number of people in each of the categories was then divided by the population in a county to obtain the percentage of the population in each age category. Age data was available from 1968 to 2016. Age variables are summarized in Table A-3. On average approximately 29% of the population was between the ages of zero and 19, 6% between 20 and 24 years of age, 48% between 25 and 64 years of age, and 17% was 65 years and older. Data on the distribution of race were available in two datasets. The first had data from 1968 to 2016 and two categories for race, the number of people in the population identifying as black and the number of people in the population identifying as white. The second data set had three categories for race: white non-Hispanic, black non-Hispanic, and Hispanic; but was only available from 1999 to 2016. In both datasets the number of people in each race/ethnicity was divided by the total population to obtain percentages of the population in each race category. Summaries of the race variables can be found in Table A-3. In the two race data set an average of 4.5% of the population identified as black while 94% of the population identified as white. In the three race data set an average of 4.5% of the population identified as black non-Hispanic, 65% as white non-Hispanic, and 29% as Hispanic.

Political affiliation was proxied by the percent of the voting population identifying as either Republican, Democrat, or Independent during presidential election years. Presidential voting data was obtained from Dave Leip's Atlas of U.S. Presidential Elections for every four years from 1980 to 2016 for each county in the study area. Because voting data was only available every four years the data from the most recent voting year was used for every following year until a new voting year occurred. Table A-3 summarizes the distribution of votes across major political parties. On average 32% of the population voted for the Democratic candidate, 63% for the Republican, and 4% for the Independent candidates during the sample period.

4.4 LAND USE AND URBAN SPATIAL STRUCTURE VARIABLES

Urban spatial structure was measured using two different variables, population density and rural-urban continuum codes (RUCC). Population density was calculated by dividing the number of people residing in each county each year by the area of the county and is given in people per square mile (mi^2). The population density variable is summarized in Table A-3. Population density averaged 51.9 people per square mile with a minimum of 0.79 people per square mile and a maximum of 1148.4 people per square mile.

RUCCs are a means of classifying counties by the population size of their metropolitan area (metropolitan counties) or by their degree of urbanization and adjacency to a metropolitan area (nonmetropolitan counties) (Parker 2016) and was obtained from the USDA for the years

1974, 1983, 1993, 2003, and 2013. The classification scheme for RUCC was updated between the release of the 1993 dataset and the 2003 dataset, for this reason it was necessary to make some minor adjustments in order to use the datasets comparably. Prior to 2003 metro counties had four levels of classification from zero to three. In 2003, the first time the new classes were used, metro counties had three levels of classification from one to three. In order to better utilize the RUCC datasets the first two class levels zero and one were combined to one for the 1974, 1983, and 1993 datasets. RUCC datasets are only updated every 10 years, therefore it was assumed RUCC classification did not change until a new update was released. Using the RUCC values four dummy variables representing metro, adjacent to metro, urban, and rural were created. A county was classified as metropolitan (metro) if the RUCC was 1[1], 2[2], or 3[3]. Adjacent to metro counties had an RUCC of 4[4], 6[5], or 8[6]; urban counties an RUCC of 5[7] or 7[8]; and rural counties an RUCC of 9[9]. Table A-4 shows the number of observations that appeared in each of the four categories of urban spatial structure. Urban spatial structure was reported for a total of 1,233 observations with 81 being rural, 447 urban, 451 adjacent to a metropolitan area, and 254

[1] An RUCC code of 1 corresponds to counties in metro areas with a population of 1 million or more.
[2] An RUCC of 2 corresponds to counties in metro areas with a population less than 1 million but greater than 250,000.
[3] An RUCC of 3 corresponds to counties in metro areas with a population less than 250,000.
[4] An RUCC of 4 corresponds to a county with an urban population greater than 20,000 that is also adjacent to a metro area.
[5] An RUCC of 6 corresponds to a county with an urban population less than 19,999 but greater than 2,500 that is also adjacent to a metro area.
[6] An RUCC of 8 corresponds to a county that is adjacent to a metro area and is either completely rural or has an urban population less than 2,500.
[7] An RUCC of 5 corresponds to a county with an urban population greater than 20,000 that is not adjacent to a metro area.
[8] An RUCC of 7 corresponds to a county with an urban population less than 19,999 but greater than 2,500 that is not adjacent to a metro area.
[9] An RUCC of 9 corresponds to a county that is not adjacent to a metro area and is either completely rural or has an urban population less than 2,500.

metropolitan. Figures 9 through 13 below demonstrate how the urban spatial structure of counties has changed over time.

Land use categories were obtained from the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Database (NLCD). The NLCD is a spatial data set that uses satellite imagery in combination with supplementary datasets to categorize land across the U.S. into usage categories. NLCD datasets are available for the years 1992, 2001, 2006, and 2011. Spatial analysis software, ArcMap 10.5.1, was used to calculate the area of each of the land use categories within each county of the study area. Development, more specifically development for residential purposes, was the land use category of interest in the study. Due to differences in the classification scheme of the 1992 NLCD it was not recommended that it be

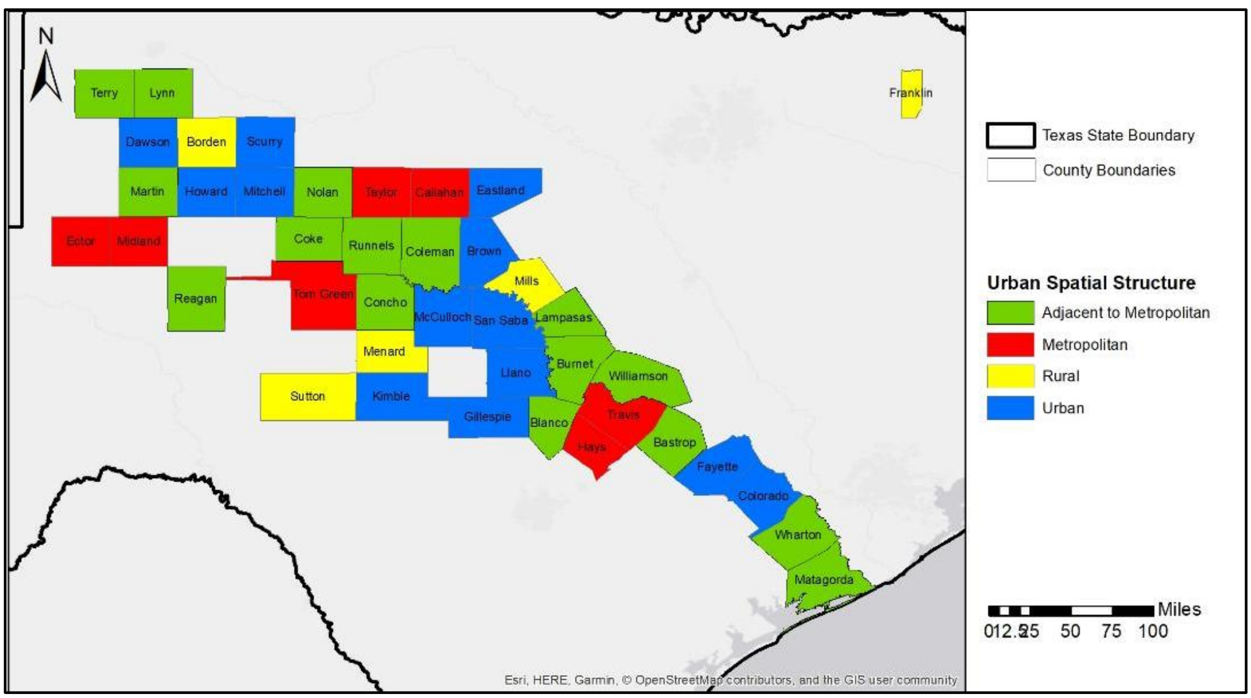

Figure 9. Urban spatial structure of counties based on the 1974 RUCC release.

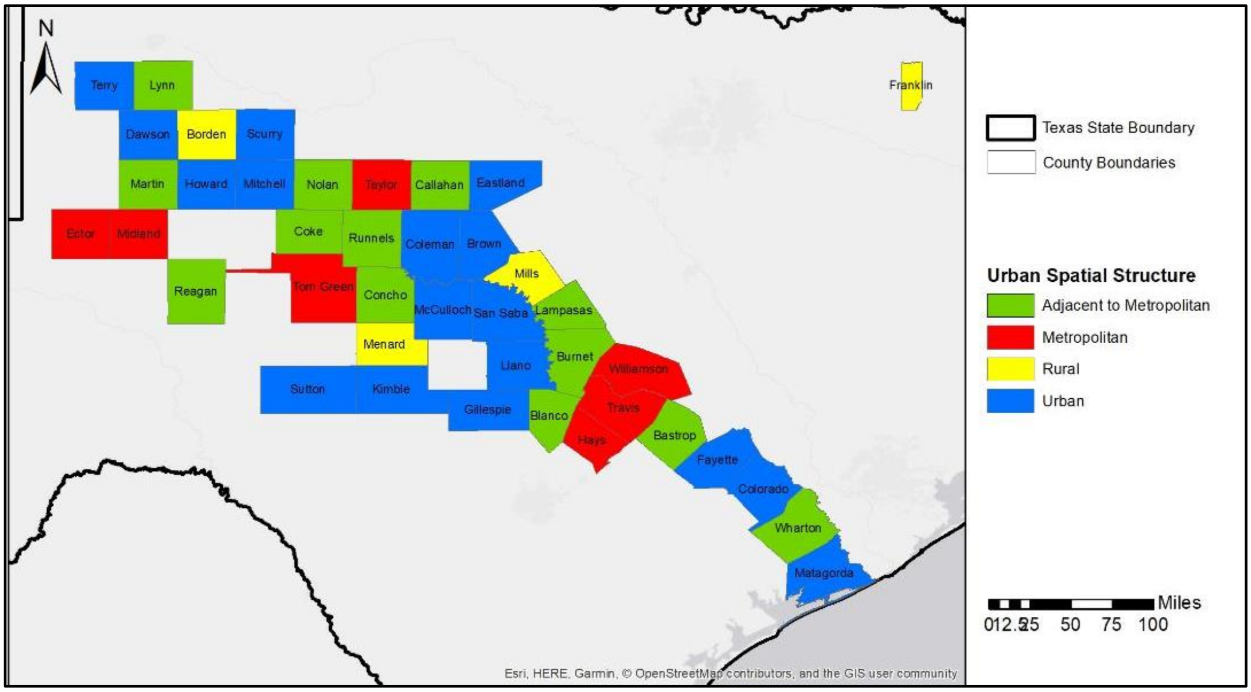

Figure 10. Urban spatial structure of counties based on the 1983 RUCC release.

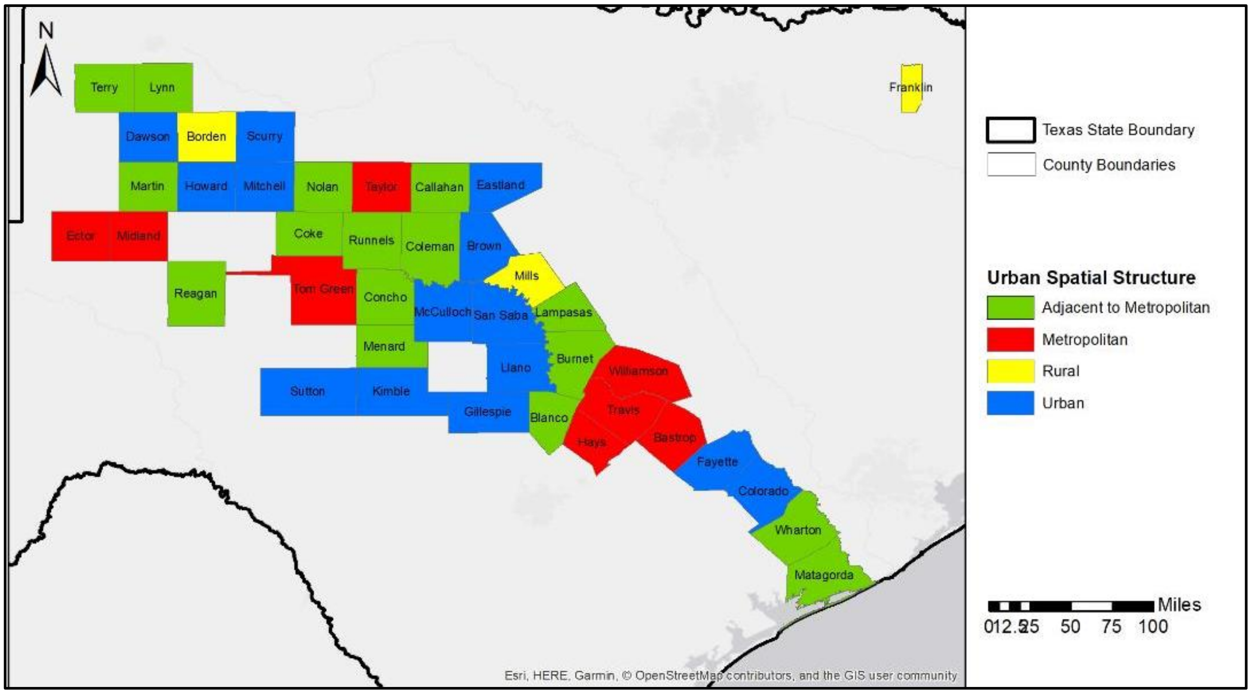

Figure 11. Urban spatial structure of counties based on the 1993 RUCC release.

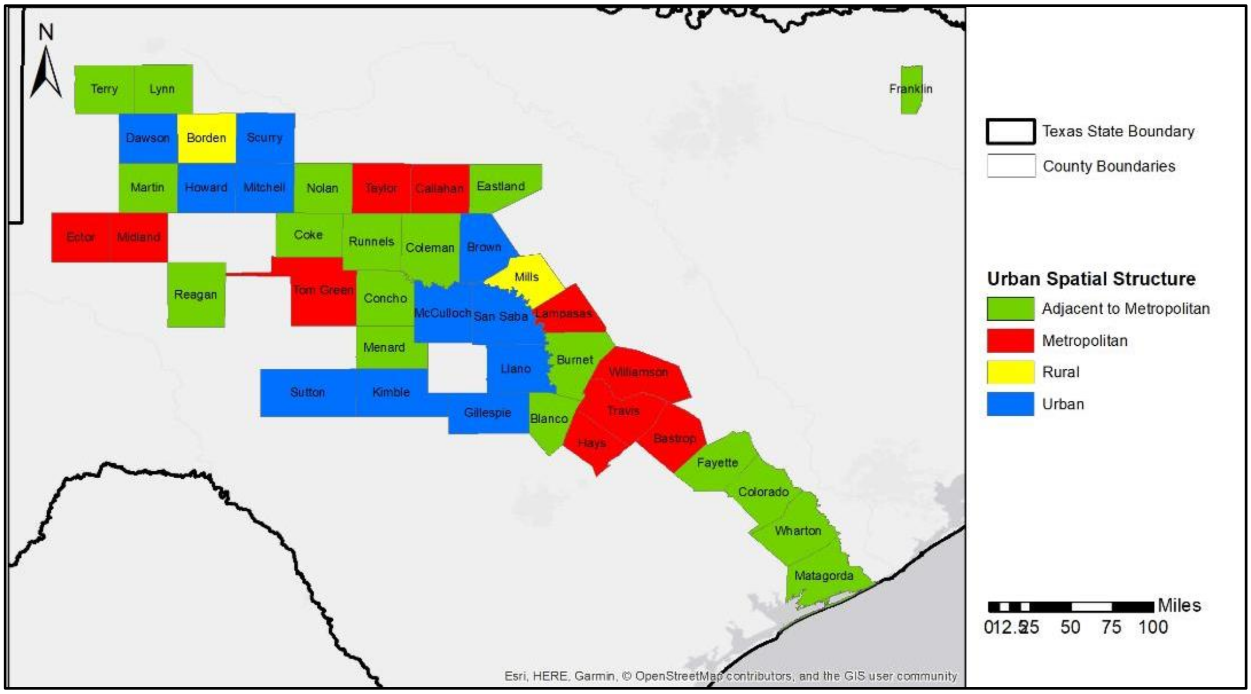

Figure 12. Urban spatial structure of counties based on the 2003 RUCC release.

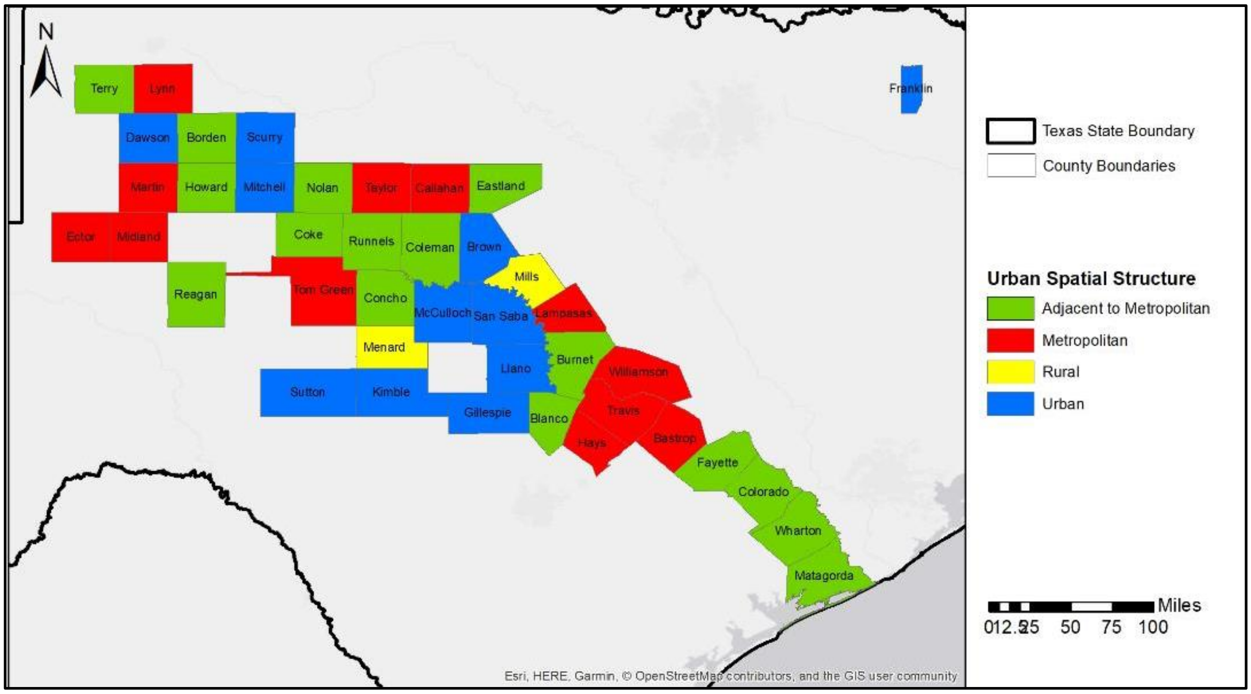

Figure 13. Urban spatial structure of counties based on the 2013 RUCC release.

compared directly with the others. In order to consistently calculate the percentage of land use, calculations for the 1992 NLCD were done differently than those for the 2001, 2006, and 2011 NLCDs. Using the 1992 release the percent of all development out of the total area of the county was calculated as follows:

$$(\text{Urban Recreational Grasses} + \text{Low Intensity Residential} + \text{High Intensity Residential} + \text{Commercial/Industrial/Transportation}) = \text{PCT\_Developed}$$

The percent of residential development out of total development for the 1992 release was calculated as follows:

$$(\text{Low Intensity Residential} + \text{High Intensity Residential})/\text{PCT\_Developed} = \text{PCT\_Resident}$$

Using the 2001, 2006, and 2011 NLCD the percent of all developed land out of the total county area was calculated as follows:

$$(\text{Developed Open Space} + \text{Developed Low Intensity} + \text{Developed Medium Intensity} + \text{Developed High Intensity}) = \text{PCT\_Developed}$$

The percent of residential development out of total development for the more recent releases was calculated as follows:

$$(\text{Developed Low Intensity} + \text{Developed Medium Intensity})/\text{PCT\_Developed} = \text{PCT\_Resident}$$

Because a new NLCD is not released every year linear interpolation was used to calculate the percentage of each category by county. Table A-3 summarizes the two land use variables. An average of 4.9% of the total county area was composed of developed land, of that 4.9% an average of 22.5% was for residential purposes.

CHAPTER V

CONCEPTUAL WATER DEMAND MODEL

Urban water demand is a complex process that deals with the relationship between humans and the natural environment at both a microscale (e.g., households) and a macroscale (e.g., municipal, regional) (House-Peters and Chang 2011). At the household level, the demand for water is primarily driven by water-consuming goods and services (e.g., laundry, bathroom use, lawn watering) and therefore demand models should take into account household characteristics (Olmstead et al. 2007). Municipal water use may also vary depending on water price and income. However, given that water is irreplaceable for most uses its consumption is considered to be price-inelastic (Corbella and Pujol 2009). In particular, lower income families do not respond to changing prices because water is only used to fulfill basic needs. While higher income families do not respond because water makes up only a small proportion of their budget (Arbues et al. 2003; USGS 1992; Corbella and Pujol 2009).

At the aggregate or municipal scale population is an in important driver of consumption and may vary by age, nationality, religious or cultural views, level of education, and race/ethnicity (Corbella and Pujol 2009). For example older people consume less water by exhibiting more saving attitudes while the younger may use more water by taking more showers or requiring more frequent laundering (Corbella and Pujol 2009). Moreover, nationality as well as religious and cultural views may affect the way people view and use water as a resource. For example, studies have found that immigrants are likely to use less water than the local population possibly due to the scarcity of the resource in their countries of origin (Smith and Ali 2006;

Corbella and Pujol 2009). Smith and Ali (2006) also found that religion affects not only how people use water but also how they think about water.

In addition to these important socioeconomic and demographic drives discussed above, it is believed that the climatic conditions such as drought and rain also ecplain domestic water consumption and in particular water use for outdoor activities (e.g., lawns and gardens, and the use of swimming pools) (House-Peters and Chang 2001).

Importantly, the presence of gardens and outdoor spaces as well as pools (e.g., urban structure) impacts water consumption (Corbella and Pujol 2009). Water consumption has been found to increase when these elements appear more frequently in communities with more disperse urban settlements than in more compact communities (Morote and Hernandez 2016; Domene and Sauri 2006; March and Sauri 2010).

CHAPTER VI

METHODS

To examine the effects of various weather, socioeconomic, and spatial factors on water usage from the Colorado River in Texas, several regression models were estimated using panel regression analysis methods in StataSE statistical software version 15. The first model estimated, referred to as the baseline model, is as follows:

$$\ln(w_{it}) = \beta_0 + \beta_1 (\ln Income_{it}) + \beta_2 (Pop\ Density_{it}) + \beta_3 (Race_{it}) + \beta_4 (Age_{it}) + \beta_5 (Rain_{it}) + \beta_6 (temp_{it}) + \lambda_i + \lambda_t + \varepsilon_{it}$$

The dependent variable, w_{it}, represents annual per capita municipal water usage from the Colorado River in county i for a given year t. Income represents the per capita annual income in real 2015 prices in county i in year t. Pop density represents the number of people per square mile in county i during year t. Race in this baseline model is represented using the two race dataset where the percent of the population identifying as black is the omitted variable. Age is the percent of the population in each of the age categories in county i in year t, where zero to 19 years of age is the omitted category. Rain is the total amount of precipitation in mm that county i received in year t. Temp represents the number of hot summer days in county i in year t. λ_i is the county specific fixed effects that represent any time invariant unobserved county characteristics such as topography and other water resources. λ_t represents the year fixed effects such as statewide policies, state conservation recommendations, and the introduction of water saving technologies. ε_{it} represents the error term.

6.1 INVESTIGATING SOCIOECONOMIC EFFECTS

Additional socioeconomic variables were added to the baseline model to better estimate the effects of socioeconomic factors on water usage. Model 1 refers to the model with these added variables which is estimated as follows:

$$\begin{aligned}\ln(w_{it}) = \ & \beta_0 + \beta_1 (\ln Income_{it}) + \beta_2 (Pop\ Density_{it}) + \beta_3 (Race_{it}) + \beta_4 (Age_{it}) \\ & + \beta_5 (Rain_{it}) + \beta_6 (Temp_{it}) + \beta_7 (Politics_{it}) + \beta_8 (Unemployment_{it}) \\ & + \beta_9 (HPI_{it}) + \lambda_i + \lambda_t + \varepsilon_{it}\end{aligned}$$

In this model race is represented using the three race dataset of white non-Hispanic, Hispanic, and with black non-Hispanic being the omitted category. Politics represents the percentage of the population in county i during year t voting for either the democratic candidate, the independent candidate, or the republican candidate with republican as the omitted category. Unemployment is the percentage of the labor force that is unemployed in county i in year t. Lastly HPI is the housing price index for county i during year t.

6.2 INVESTIGATING THE EFFECTS OF LAND USE

To examine the effects of land use on water consumption two models were estimated. Model 2 refers to the most basic land use model, a deviation from the baseline model, which is estimated as follows:

$$\begin{aligned}\ln(w_{it}) = \ & \beta_0 + \beta_1 (\ln Income_{it}) + \beta_2 (Pop\ Density_{it}) + \beta_3 (Race) + \beta_4 (Age_{it}) \\ & + \beta_5 (Rain_{it}) + \beta_6 (Temp_{it}) + \beta_7 (Residental\ Development_{it}) + \lambda_i + \lambda_t \\ & + \varepsilon_{it}\end{aligned}$$

Residential Development is the percentage of land developed for residential purposes out of the amount of total developed land in county i in year t.

To examine the effects of land use along with the full set of socioeconomic variables a deviation of Model 1 was created. This model is referred to as Model 3 and is estimated as follows:

$$\ln(w_{it}) = \beta_0 + \beta_1 (\ln Income_{it}) + \beta_2 (Pop\ Density_{it}) + \beta_3 (Race_{it}) + \beta_4 (Age_{it}) + \beta_5 (Rain_{it}) + \beta_6 (Temp_{it}) + \beta_7 (Politics_{it}) + \beta_8 (Unemployment_{it}) + \beta_9 (HPI_{it}) + \beta_{10} (Residental\ Development_{it}) + \lambda_i + \lambda_t + \varepsilon_{it}$$

6.3 INVESTIGATING THE EFFECTS OF URBAN SPATIAL STRUCTURE

To examine the effects of urban spatial structure on water use an additional two models were estimated. Model 4 is the most basic, deviating from the baseline model, and is estimated as follows:

$$\ln(w_{it}) = \beta_0 + \beta_1 (\ln Income_{it}) + \beta_2 (Race_{it}) + \beta_3 (Age_{it}) + \beta_4 (Rain_{it}) + \beta_5 (Temp_{it}) + \beta_6 (Urbanization_{it}) + \lambda_i + \lambda_t + \varepsilon_{it}$$

Urbanization represents the urban spatial structure of county i in year t. Urban spatial structure refers to either metro, adjacent to metro, urban, or rural with rural being the omitted category.

To examine the effects of urban spatial structure along with land use and the full set of socioeconomic variables, Model 5 was estimated as follows:

$$\ln(w_{it}) = \beta_0 + \beta_1 (\ln Income_{it}) + \beta_2 (Race_{it}) + \beta_3 (Age_{it}) + \beta_4 (Rain_{it}) + \beta_5 (Temp_{it}) + \beta_6 (Politics_{it}) + \beta_7 (Unemployment_{it}) + \beta_8 (HPI_{it}) + \beta_9 (Residental\ Development_{it}) + \beta_{10} (Urbanization_{it}) + \lambda_i + \lambda_t + \varepsilon_{it}$$

6.4 INVESTIGATING THE EFFECTS OF CLIMATE VARIABILITY

To examine how water usage is effected by varying climatic conditions lagged weather variables were added to the baseline model. This model is referred to as model 6 and is estimated as follows:

$$\ln(w_{it}) = \beta_0 + \beta_1 (\ln Income_{it}) + \beta_2 (Pop\ Density_{it}) + \beta_3 (Race_{it}) + \beta_4 (Age_{it}) + \sum_{j=0}^{5} \gamma_j Rain_{it-j} + \sum_{j=0}^{5} \gamma_j Temp_{it-j} + \lambda_i + \lambda_t + \varepsilon_{it}$$

To account for fluctuations in precipitation patterns (flooding versus drought) we include a lag of annual precipitation ($Rain_{it}$) in the current year as well as over the past five years. To account for fluctuations in temperature we include a lag of hot summer days ($Temp_{it}$) in the current year as well as over the past five years.

CHAPTER VII

RESULTS

A Hausman test was used to determine which method, either fixed effects or random effects, was the more appropriate panel regression analysis method for the data set. Under the Hausman test, the null hypothesis is that random effects regression is the appropriate method of analysis versus the alternative method of fixed effects regression. Using the p-value we can determine whether to reject the null hypothesis in favor of the alternative ($p<0.05$) or fail to reject the null hypothesis ($p>0.05$). The Hausman test produced a significant chi^2 of 165.91 (Prob<0.00001). Based on these results the Hausman test indicates that fixed effects panel regression analysis is the appropriate method of analysis for this dataset. Therefore only the results of fixed effects panel regression models will be presented from this point forward.

7.1 RESULTS OF BASELINE MODEL

The results of the initial baseline mode are reported in the first column of Table B-1. The baseline model had a sample size of $N = 1{,}267$ observations. The results indicate that per capita water significantly declines with population density ($p<0.01$) suggesting that more populous areas consume less water per capita. Specifically it was estimated that for every one person increase per square mile per capita municipal water usage decreases by 0.25%. We also find that the counties with a larger proportion of white population on average have higher per capita municipal water usage relative to other race and ethnicity. For every one percent increase in white population per capita water consumption increases by an estimated 8.9%, and the relationship is statistically significant at 1% significance level. In terms of age variables, estimated coefficients for two of the age cohorts considered in the analysis were estimated to have statistically significant effects on per capita municipal water use (p<0.01). We find that the younger population (age cohort 20-24 years) and senior citizens (65 years and older) on average consume less water relative to population 19 years and younger (the omitted category). The population in 25-64 age group was found to have statistically indistinguishable effects on per capita municipal water use relative to the omitted category. The regression results indicate that the counties with one percent higher in the percent of population in 20 to 24 year age cohort have 26.44% lower per capita municipal water usage, and a 1% higher population of senior citizens (65 and up) is associated with an 8.38% lower per capita municipal water usage.

In terms of climate variables, our baseline model indicates that per capita municipal water use increases with precipitation. We estimated for every millimeter increase in precipitation during the year was associated with a 0.05% increase in per capita municipal water usage. Other variables in this model such as income and the number of hot summer days were not found to have a statistically significant impact on per capita municipal water use.

7.2 RESULTS OF SOCIOECONOMIC MODEL

The results of Model 1 to examine the effects of additional socioeconomic variables are reported in the second column of Table B-1. Model 1 had a sample size of $N = 292$ observations. The results indicate that per capita water significantly increases with HPI (p<0.05) suggesting that areas with higher housing prices consume more water per capita. Specifically it was estimated that for every one unit increase in HPI per capita municipal water usage increases by 1.85%. We also find that the counties with a larger proportion of white non-Hispanic and Hispanic populations have lower per capita municipal water usage relative to other race and ethnicity. For every one percent increase in white non-Hispanic population per capita water consumption decreases by an estimated 38.41%, and for every 1% increase in Hispanic population per capita water consumption decreases by an estimated 32.74%. Both relationships were statistically significant at 5% significance level. In terms of age variables, the age cohorts which were found to be statistically significant in the baseline model are no longer significant. Instead we find that the 25-64 age group is now statistically significant ($p<0.05$) and on average consumes less water relative to population 19 years and younger (the omitted category). The regression results indicate that the counties with one percent higher in the percent of population in 25 to 64 year age cohort have 28.74% lower per capita municipal water usage. No other socioeconomic variables were found to be statistically significant in this model, nor were either of the weather related variables.

7.3 RESULTS OF LAND USE MODELS

The results of the land use models are reported in Table B-2. Model 2 had a sample size of $N = 581$ observations. The results indicate that the percent of residential development does not have a statistically significant impact on per capita water consumption. Variables in Model 2 experienced a loss of significance relative to the baseline model. The only variable in Model 2 that was found to have a statistically significant effect on per capita municipal water use was the age cohort 20 to 24 ($p<0.05$). The results indicate that the counties with one percent higher in the percent of population in 20 to 24 years of age have 19.91% lower per capita municipal water usage.

Model 3 had a sample size of $N = 235$ observations. Similarly to Model 2 the results indicate that the percent of residential development is not a statistically significant factor impacting per capita municipal water usage. Race variables in this model experienced a loss of significance relative to Model 1 while the variables 25 to 64 age group and HPI remained significant ($p<0.05$ and $p<0.01$ respectively) and increased their effect on per capita municipal water use. In this model the results indicate that the counties with one percent higher in the percent of population age 25 to 64 years of age have 42.92% lower per capita municipal water usage. In terms of HPI it was estimated that a one unit increase in HPI resulted in a 3.25% increase in per capita municipal water use.

7.4 RESULTS OF URBAN SPATIAL STRUCTURE MODELS

The results of the urban spatial structure models are reported in Table B-3. Model 4 had a sample size of $N = 1{,}267$ observations. The results indicate that different types of urban spatial structure do have a statistically significant impact on per capita municipal water use. The relationship between metro and per capita municipal water use was statistically significant at the 5% significance level while adjacent to metro and urban were statistically significant at the 1% significance level. We find that metro, adjacent to metro, and urban counties on average consume more water relative to rural counties (the omitted category). Specifically it was estimated that metro counties have 78.49% higher per capita municipal water usage, adjacent to metro counties have 111.21% higher per capita municipal water usage, and urban counties have 103.03% higher per capita municipal water usage. Variables which exhibited a statistically significant relationship to water usage in the baseline model were also found to be statistically significant in this model, with the exception of population density which was excluded.

Model 5 had a sample size of $N = 235$ observations. In contrast to Model 4, none of the urban spatial structures were found to have a statistically significant relationship with per capita municipal water use. The results of this model were similar to Model 3 with the same two variables exhibiting the same level of significance and similar effect on per capita municipal water usage.

7.5 RESULTS OF CLIMATE VARIABILITY MODEL

The results of the climate variability model are reported in Table B-4. Model 6 had a sample size of $N = 1{,}100$ observations. The results indicate that per capita municipal water usage is significantly affected by precipitation one and two years prior ($p<0.05$ and $p<0.01$ respectively). We estimate that the effect of a one year lag in precipitation was similar to the effect of precipitation at time t, approximately 0.06%, and the unit increase in precipitation two years before was associated with a 0.09% increase in per capita municipal water usage at time t. The number of hot days during summer months two years and four years before the year of observation was also found to have a significant relationship with per capita municipal water usage ($p<0.05$). A 1 day increase in hot days two years before was associated with a 1.13% increase in per capita municipal water usage, while a 1 day increase in hot days 4 years before was associated with a 0.92% increase in per capita municipal water usage. Other variables exhibiting a statistically significant relationship in Model 6 are the same as in the baseline model.

CHAPTER 8

DISCUSSION

This thesis utilized fixed effects panel regression models to determine the effects of multiple factors on municipal water usage from the Colorado River in Texas. Climatic factors were represented by total annual precipitation and the number of cumulative summer days that reached at least 29.44℃. The lagged effects of climate were also analyzed in this study by using climate from the previous five years. Socioeconomic factors analyzed in the various regression models included wealth, Housing Price Index, unemployment, political preferences, and demographic characteristics such as age and race. Land use patterns and degree of urbanization were also used as explanatory factors to determine their effects on water consumption.

8.1 VARIATION IN WEATHER PATTERNS

Response of per capita municipal water use to the number of hot summer days appears to be delayed. The number of hot summer days is only significant two years before the year of observation. This finding leads us to question the strain excessive high temperature days may have on resources and the ability of households to adapt. This relationship warrants future study. The finding of a positive relationship between water use and precipitation while unexpected, is not uncommon. Tinker et al. (2006) also found water use to increase with increased precipitation in Austin, Texas and expressed that the finding warranted further study.

There is a prolonged response of per capita municipal water use to precipitation as indicated by rainfall from the current year as well as prior years having a significant impact on water use. This prolonged effect could be the result of the states' fluctuations in precipitation patterns (drought versus flooding). Precipitation influences the amount of water flowing in the river and therefore the amount of water available for use, increasing precipitation increases the amount of water that can be used from the river. This prolonged effect could be the result of excess precipitation in previous years increasing the rivers available water supply thus allowing residents to use more water.

8.2 VARIATION IN SOCIOECONOMIC CONDITIONS

Socioeconomic factors were in many models found to exhibit a strong relationship with per capita municipal water use. The percentage of the population identifying as white was significant in 4 out of 7 models while the percentage of the population identifying as Hispanic was significant in 1 out of 3 models. The omitted race category was the percentage of the population identifying as black. Therefore a positive effect of other race categories means that more water is being used by that race than by blacks while a negative effect means that more water is being used by blacks than by other races. In the baseline model as well as in Models 4 and 6, which had the longest study period, the relationship between percent white and water use was positive. However in Models 1, which had a much shorter time frame, the relationship between percent white and water use was negative. The change of this relationship from positive to negative is likely due to time period differences such as the increasing popularity of water saving technologies which may be more costly and only affordable to a fraction of the population. The negative relationship between water use and the percentage of the population identifying as Hispanic, suggests that less water is being used by Hispanic communities than by black communities. However the magnitude of the relationship in Model 1 also indicates that white communities use even less water than Hispanic communities. These discrepancies in water use surrounding race lead us to question the relationship between water consumption and quality of water infrastructure in minority communities. Historically minority neighborhoods have been segregated from majority white neighborhoods. This segregation has led to an inequity of infrastructure across race and class lines (Rosales 2017). In the city of Houston, TX it has been reported that neighborhoods with an excess of low-income housing “lack the basic services and investment that majority white neighborhoods take for granted” (Julian et al. 2017). The inequality of infrastructure, especially water infrastructure, between minority neighborhoods and majority white neighborhoods could be the source of some of the discrepancies in water use seen across race lines in this study.

Age categories were also found to be significant in some models. The percentage of 20 to 24 years olds was significant in the baseline model as well as Models 2, 4 and 6, 25 to 64 year olds was significant in Models 1, 3, and 5, and the percentage of those 65 years and older was significant in the baseline model as well as Models 4 & 6 1. As the omitted age category was the percentage of the population age 19 years and younger, the negative effect of the other age categories is relative to the water usage of those between the ages of 0 and 19. Studies have suggested that an aging population uses more water at home and that children use less water (House-Peters et al. 2010). However the opposite applies to the baseline model and Models 4 and 6 where the significant relationship between water use and the percentage of those 65 years and older is negative. This finding agrees with Corbella and Pujol (2009) suggesting that less water is used by senior citizens and more water is used by children. The negative relationship of water use to the percent of population in the 20 to 24 year age cohort and the percent of population in the 25 to 64 year age cohort shows that less water is used by people of these age groups than by children or those 65 years and older. This effect could be because the 20 to 24 age range is likely to be composed of college students which would use less municipal water due to residing in a dormitory. For those 25 to 64 years of age, less water is likely to be used at home while more is likely to be used at the work place.

The housing price index (HPI) was the only other socioeconomic variable to exhibit a significant relationship with per capita municipal water usage. The positive relationship between the two suggests that as home values rise so does per capita municipal water use. A 2006 Austin, Texas study also found that increasing home values increased residential water consumption significantly (Tinker et al.). HPI was found to be significant in 3 out of 3 models.

8.3 VARIATION OF LAND USE

The single land use category representing the percent of residential development out of total development never experienced a significant relationship with per capita municipal water use. It is possible that this particular variable does not accurately depict where residents may require more water for lawn irrigation purposes or that the linearly interpolated values of land use are correlated with the county fixed effects thereby masking the direct effects of land use . Methods similar to those employed by Breyer et al. (2012) using aerial photography to classify land cover may produce a more accurate picture for determining where residential development effects water use.

8.4 VARIATION OF URBAN SPATIAL STRUCTURE

Urban Spatial Structure was examined using population density and by categorizing counties based on rural-urban continuum codes. Population density was found significant in 2 out of the 5 models it was used in. The negative relationship between population density and water use is consistent with the findings of other studies (Domene and Sauri 2006; March and Sauri 2010). Lower population densities are likely to indicate a greater number of single family homes and larger lot sizes which would increase the necessity for municipal water use. Higher population densities most likely illustrate fewer single family homes and more compact living quarters (apartment homes) which would require less municipal water usage as lawn areas and pools are shared spaces.

Categories of urban spatial structure included metropolitan, adjacent to metropolitan, urban, and rural. The omitted category for urban spatial structure was rural, therefore the relationship of other categories to water use is relative to the amount of water used in rural counties. All three included categories, metro, adjacent to metro, and urban, were significant in Model 4 which had the most observations and the longest study period. As the number of observations decreased in Model 5 none of the categories were significant. The category that appeared to exhibit the strongest relationship to water use was adjacent to a metropolitan county. These counties likely experience the effects of urban sprawl and consist of suburbs to major metropolitan areas where residents commute to their place of employment in another county. These areas likely consist of single family homes with larger lot sizes were residents are likely to require more water for lawn irrigation. The increase in water use of urban and metropolitan counties relative to rural counties is likely the result of increased population sizes.

CHAPTER IX

CONCLUSION

9.1 SUMMARY OF MAIN FINDINGS

This analysis used fixed effects panel regression to investigate the effects of various weather, socioeconomic, and land use patterns on municipal water usage from the Colorado River in Texas. Here evidence has been provided that Colorado River municipal water use is effected by a multitude of natural and social conditions at multiple spatial scales. The research questions posed in section 1.2 are best answered as follows.

1. The effects of climate on per capita municipal water use seem to have some time lagged effects. Weather patterns from as many as four years prior to the year of observation are effecting the amount of water used by residents. Despite the delayed response water usage variation due to weather patterns is likely the result of weather patterns affecting the available supply.
2. The most relevant socioeconomic factors explained by this study are race, age, and housing price index. When analyzing the effects of race and age on municipal water use patterns there are likely some underlying societal and cultural connections as expressed by Breyer et al. (2012). Housing markets also appear to have an influence on water usage possibly indicating the importance of individual household characteristics.
3. Urban spatial structure appears to have the strongest effect on water usage, particularly when categorized counties are analyzed.

4. Residential land use does not seem to aid in explaining water use, perhaps because all degrees of residential vegetation are lumped together and there is no distinguishing between large lots, small lots, or apartment homes.

The findings in this study further justify the inclusion of various social and natural system variables in determining large scale water demand. This research like many others before it confirms the complex relationship between human and natural systems in explaining water consumption. Here we can see the importance of not only using aggregate data but also of including a multitude of factors when analyzing consumption patterns. This study further shows us that the drivers of municipal water consumption are indeed very varied.

9.2 ADDRESSING RESEARCH LIMITATIONS

The current study takes into account many variables, some of which have been examined in previous studies and others which have not. However one very important explanatory variable missing from this analysis is price. Incorporating water prices to this analyses would be useful to obtain a better understanding of the influence of income on water consumption, despite the complicated structure of water prices. Water prices in urban areas can take on one of three forms: uniform marginal price, increasing block prices, or decreasing block prices (Olmstead et al. 2007). Under the uniform marginal price structure consumers pay the same price per unit regardless of the amount used. The block pricing structure is based on usage quantities where prices either increase as greater amounts are used (increasing block price) or prices decrease as greater amounts are used (decreasing block price) (Olmstead et al. 2007). Price data was not available for inclusion in this study.

Another important limitation of this study is the lack of available data. Some datasets used in this study were not available for the entire study period. This limited the number of observations that were able to be used in analyzing models with additional variables. It is possible that this limitation may have led to the inconsistency of variable significance between models.

9.3 FUTURE WORK

Future research should include further exploration of the effects of urban spatial structure. Perhaps looking at metropolitan, adjacent to metropolitan, urban, and rural counties separately to determine if other variables effect the types of counties at different levels. Land use should also be re-examined to apply more detailed classifications that would better reflect landscape irrigation requirements. Other considerations for future studies would expand the current dataset to analyze the water use patterns for the entire state of Texas.

9.4 POLICY IMPLICATIONS

The 2017 State Water Plan discusses management strategies for managing water for the future of Texas. In order for managers to effectively manage water resources it is necessary to understand the factors that affect water consumption. The demand for water will inevitably increase due to population growth and climate change. It is therefore necessary to take these matters into account now, before it is too late. By better understanding these factors it will be possible to implement better policies and water conservation strategies tailored to specific environmental and societal conditions.

The findings in this research can and should be utilized by water managers and policy makers to make better more informed decisions when it comes to managing water supplies. The results of climate’s effect on water consumption tells us there are some lagged effects of climate on municipal water consumption. We should take this finding as an indicator to monitor climate variability and better track water use. The findings regarding race should lead policy makers to assess water use in minority communities and better determine if the discrepancies in consumption are due to the quality of water infrastructure present. Lastly with regards to the findings of areas with low-density and those exhibiting urban sprawl, policy makers should examine and possibly adjust water conservation strategies in these areas where municipal water usage is highest.

REFERENCES

Arbues, F., Garcia-Valiñas, M. A., & Martinez-Espiñeira, R. (2003). Estimation of Residential Water Demand: A State-of-the-Art Review. *Journal of Socio-Economics* 32:81-102.

Ashworth, J.B., & Hopkins, J.H. (1995). Aquifers of Texas. Texas Water Development Board: Report 345. Retrieved from https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R345/R345Complete.pdf

Balling, R.C., & Gober, P. (2007). Climate Variability and Residential Water Use in the City of Phoenix, Arizona. *Journal of Applied Meteorology and Climatology* 46:1130-1137.

Balling, R. C., Gober, P., & Jones, N. (2008). Sensitivity of residential water consumption to variations in climate: An intraurban analysis of Phoenix, Arizona. *Water Resources Research* 44, W10401.

Breyer, B., Chang, H., & Parandvash, G.H. (2012). Land-use, temperature, and single-family residential water use patterns in Portland, Oregon and Phoenix, Arizona. *Applied Geography* 35(1-2): 142-151.

Brody, S.D., Highfield, W., Arlikatti, S., Bierling, D.H., Ismailova, R.M., Lee, L., & Butzler. M. (2004). Conflict On The Coast: Using Geographic Information Systems To Map Potential Environmental Disputes in Matagorda Bay, Texas. *Environmental Management* 34: 11-25.

Christensen, N.S., Wood, A.W., Voisin, N., Lettenmaier, D.P., & Palmer, R.N. (2004). The Effects Of Climate Change On The Hydrology And Water Resources Of The Colorado River Basin. *Climatic Change* 62: 337-363.

Cochran, R., & Cotton, A.W. (1985). Municipal Water Demand Study, Oklahoma City and Tulsa, Oklahoma. *Water Resources Research* 21(7): 941-943.

Colorado River Land Trust. (n.d.). Colorado River Land Trust. Retrieved from http://coloradoriverlandtrust.org/#page-top

Colorado River Watershed. (n.d.). Retrieved from https://www.traviscountytx.gov/tnr/environmental-quality/water-quality/colorado-river-watershed

Corbella, H.M., & Pujol, D.S. (2009). What Lies Behind Domestic Water Use? A Review Essay On The Drivers Of Domestic Water Consumption. *Boletín de la Asociación de Geógrafos Españoles* 50: 297-314.

CRA. (n.d.). About the Alliance. Retrieved from https://coloradoriver.org/about/

CRMWD. (n.d.). About CRMWD. Retrieved from https://www.crmwd.org/about/

Domene, E., & Saurí, D. (2006). Urbanisation and Water Consumption: Influencing Factors in the Metropolitan Region of Barcelona. *Urban Studies* 43(9): 1605–1623.

Harball, E. (2013). Drought: Texas Authority Votes To Cut Off Water To State's Second-Largest Estuary. Retrieved from http://www.eenews.net/climatewire/2013/09/30/stories/1059988021

House-Peters, L.A., & Chang, H. (2011). Urban Water Demand Modeling: Review Of Concepts, Methods, And Organizing Principles. *Water Resources Research* 47(5): 1-15.

House-Peters, L., Pratt, B., & Chang, H. (2010). Effects of Urban Spatial Structure, Sociodemographics, and Climate on Residential Water Consumption in Hillsboro, Oregon. *Journal of The American Water resources Association* 46(3): 461-472.

Julian, E.K., Lott, A., McCain, D., & Palay, C. (2017, February 16). Why Houston Remains Segregated. *The Houston Chronicle*. Retrieved from https://www.houstonchronicle.com/local/gray-matters/article/Why-Houston-remains-segregated-10935311.php

Kaiser, R. & Skiller. F.F. (2001). Deep Trouble: Options For Managing The Hidden Threat of Aquifer Depletion in Texas. *Texas Tech Law Review* 32: 249-304.

Lashmet, T.D. (2018). Basics of Texas Water Law. Retrieved from https://agrilife.org/texasaglaw/files/2018/01/Basics-of-Texas-Water-Law.pdf

LCRA. (2003). Colorado River Basin. Retrieved from https://maps.lcra.org/default.aspx?MapType=Watershed%20Posters

LCRA, TCEQ, TPWD, TWDB. (2006). Matagorda Bay Freshwater Inflow Needs Study. Retrieved from http://www.twdb.texas.gov/surfacewater/flows/freshwater/doc/Matagorda_Bay_Freshwater_Inflow_Needs_Study_2006.pdf

LCRA. (2017). How The Highland Lakes Work. Retrieved from https://www.lcra.org/water/water-supply/highland-lakes-overview/Documents/Fact-Sheet-Highland-Lakes.pdf

LCRA. (n.d.). LCRA: Providing power, water and transmission infrastructure to a growing Texas. Retrieved from https://www.lcra.org/about/overview/pages/default.aspx

March, H., & Sauri, D. (2010). The Suburbanization of Water Scarcity in the Barcelona Metropolitan Region: Sociodemographic and Urban Changes Influencing Domestic Water Consumption. *Professional Geographer 62* (1): 32–45.

McDonald, R., Green, P., Balk, D., Fekete, B., Revenga, C., Todd, M., & Montgomery, M. (2011). Urban Growth, Climate Change, And Freshwater Availability. *PNAS* 108(15): 6312-6317.

Miller, K., & Yates, D. (2006). Climate Change and Water Resources: A Primer for Municipal Water Providers. Denver, Colorado: American Water Works Association Research Foundation. Retrieved from https://www.niph.go.jp/soshiki/suido/pdf/h19JPUS/abstract/r11.pdf

Morote, A., & Hernandez, M. (2016). Urban Sprawl And Its Effects On Water Demand: A Case Study Of Alicante Spain. *Land Use Policy* 50: 352-362.

Oden, T.D., & Delin, G.N. (2013). Groundwater Recharge to the Gulf Coast Aquifer System in Montgomery and Adjacent Counties, Texas. Retrieved from https://pubs.usgs.gov/fs/2013/3043/pdf/fs2013-3043.pdf

Olmstead, S.M., Hanemann, W.M., & Stavins, R.N. (2007). Water Demand Under Alternative Price Structures. *Journal of Environmental Economics and Management, 54,* 181-198.

Parker, T. (2016). Rural-Urban Continuum Codes. Retrieved from https://www.ers.usda.gov/data-products/rural-urban-continuum-codes/

Phillips, K., Rodrigue, E., & Yücel, M. (2013). Water Scarcity a Potential Drain on the Texas Economy. Retrieved from https://www.dallasfed.org/~/media/documents/research/swe/2013/swe1304b.pdf

Rosales, C. (2017, August 31). Houston Knew Neighborhoods Of Color Were Inadequately Protected From Even Modest Storm Events. *Texas Housers*. Retrieved from https://texashousers.net/2017/08/31/houston-knew-neighborhoods-of-color-were-inadequately-protected-from-even-modest-storm-events/

Schleich, J., & Hillenbrand, T. (2008). Determinants of Residential Water Demand in Germany. *Ecological Economics* 68: 1756-1769.

Schoenbaechler C., & Guthrie, C.G. (2011). TxBLEND Model Calibration Validation For The Lavaca-Colorado Estuary And East Matagorda Bay. Retrieved from http://www.twdb.texas.gov/surfacewater/bays/major_estuaries/colorado_lavaca/doc/20110214clbbest_twdb_txblend.pdf

Smith, A., & Ali, M. (2006). Understanding The Impact Of Cultural And Religious Water Use. *Water and Environment Journal* 20: 203-209.

Texas Water Code Section 36.001(5)

Texas Water Code Section 11.021

Texas Water Development Board. (2012). Water for Texas: 2012 State Water Plan. Retrieved from http://www.twdb.texas.gov/publications/state_water_plan/2012/2012_SWP.pdf

Texas Water Development Board. (2017). Water for Texas: 2017 State Water Plan. Retrieved from http://www.twdb.texas.gov/waterplanning/swp/2017/doc/2017_swp_adopted.pdf

Tinker, A., Bame, S., Burt, R., & Speed, M. (2006). Impact of Non-Behavioral Fixed Effects on Water Use: Weather and Economic Construction Differences on Residential Water Use in Austin, Texas. *Electronic Green Journal* 1(22).

UCRA. (n.d.). About Us. Retrieved from http://ucratx.org/about_us.html

U.S. Geologic Survey. (1992). Factors That Affect Public Supply Water Use In Florida, With A Section On Projected Water Use To The Year 2020 (Water-Resources Investigations Report 91-4123). Tallahassee, FL: Marella. Retrieved from https://fl.water.usgs.gov/PDF_files/wri91_4123_marella.pdf

Worthington, A. C., and M. Hoffman. (2008). An Empirical Survey of Residential Water Demand Modelling. *Journal of Economic Surveys* 22(5): 842–71.

APPENDIX A

Table A-1. Summary of County variable showing how many years throughout the study period each county used water from the Colorado River.

County Used	Frequency
BASTROP	43
BLANCO	19
BORDEN	27
BROWN	45
BURNET	45
CALLAHAN	43
COKE	45
COLEMAN	45
COLORADO	45
CONCHO	41
DAWSON	43
EASTLAND	6
ECTOR	45
FAYETTE	38
FRANKLIN	3
GILLESPIE	38
HAYS	22
HOWARD	44
KIMBLE	45
LAMPASAS	28
LLANO	45
LYNN	43
MARTIN	44
MATAGORDA	45
MCCULLOCH	34
MENARD	33
MIDLAND	45
MILLS	44
MITCHELL	45
NOLAN	32
REAGAN	1
RUNNELS	45
SAN SABA	38
SCURRY	45
SUTTON	2
TAYLOR	33
TERRY	45
TOM GREEN	45
TRAVIS	45
WHARTON	1
WILLIAMSON	6
Total	1,426

Table A-2. Summary of Year variable showing how many counties used water from the Colorado River each year throughout the study period.

Year	Number of Counties
1971	27
1972	28
1973	28
1974	29
1975	30
1976	28
1977	31
1978	29
1979	30
1980	31
1981	32
1982	32
1983	32
1984	33
1985	33
1986	34
1987	34
1988	35
1989	34
1990	33
1991	34
1992	33
1993	33
1994	34
1995	34
1996	35
1997	34
1998	33
1999	33
2000	32
2001	32
2002	31
2003	30
2004	27
2005	27
2006	30
2007	28
2008	30
2009	29
2010	34
2011	34
2012	35
2013	34
2014	34
2015	33
Total	1,426

Table A-3. Summary explanatory variables. Per capita municipal water usage is measured in gallons. Precipitation is measured in millimeters (mm). Summer heat days refers to the total number of days during the months of June, July, and August where the temperature met or exceeded 29.44°C (85°F) Income was converted to real 2015 prices using the consumer price index. Unemployment rate is used as a proportion. The Housing Price Index (HPI) is used at the year 2000 base level. Age, race, and political variables are measured as proportions. Population density is measured in people per square mile (mi^2). Land use categories are measured in percentages.

Variable	Number of Observations	Mean	Standard Deviation	Min	Max
PC_CRtotal	1,426	292069	2157616	2.67629	2.59E+07
Year_Total_precip	1349	663.32	262.9985	89.3	1950.825
Summer_HeatDays	1284	21.7804	17.73798	0	87
real_Income	1426	30127.4	9334.136	12176.7	120469.5
unemploy	836	0.05143	0.018686	0.016	0.153
realHPI	581	110.385	36.33499	25.17	260.66
PCT0_19	1426	0.28881	0.044594	0.14492	0.419271
PCT20_24	1426	0.06339	0.023442	0.02599	0.176497
PCT25_64	1426	0.47702	0.035494	0.41077	0.655248
PCT65_up	1426	0.17079	0.05858	0.05175	0.344321
PCT_black	1426	0.04505	0.043612	0	0.223708
PCT_white	1426	0.94371	0.048502	0.77381	1
PCT_black_nonhispanic	533	0.04481	0.035608	0	0.149447
PCT_white_nonhispanic	533	0.64957	0.140429	0.35036	0.946154
PCT_hispanic	533	0.29349	0.126565	0.04815	0.609866
vote_dem_pct	1166	0.32298	0.105376	0.11469	0.638693
vote_rep_pct	1166	0.63008	0.138799	0.27721	0.881078
vote_ind_pct	1166	0.04143	0.076508	0	0.313837
Pop_Density	1426	51.9195	128.9242	0.79461	1148.405
PCT_Developed	633	4.91675	3.942652	0.05991	29.11765
PCT_Resident	633	22.4916	15.41115	2.72592	74.16504

Table A-4. Summary of urban spatial structure categories showing the number of observations throughout the study period that appeared in each category.

Urban Spatial Structure	Number of Observations
Metro	254
ADJ_Metro	451
Urban	447
Rural	81
Total	1233

APPENDIX B

Table B-1. Results of performing fixed effects regression analysis on the Baseline Model and Model 1 (standard errors are in parentheses)

	Baseline Model	Model 1
ln_Income	0.646279	-1.476255
	(0.333)	(1.121)
Pop_Density	-0.002544	-0.001822
	(0.001)**	(0.004)
PCT_white	8.526267	
	(2.980)**	
PCT20_24	-30.714627	-14.599051
	(5.801)**	(24.766)
PCT25_64	-4.402517	-33.887751
	(2.712)	(16.334)*
PCT65_up	-8.751569	17.432393
	(3.034)**	(16.380)
Year_Total_precip	0.000555	0.000898
	(0.000)*	(0.001)
Summer_HeatDays	0.001073	0.004839
	(0.004)	(0.007)
PCT_white_nonhispanic		-48.465198
		(19.035)*
PCT_hispanic		-39.665971
		(15.633)*
vote_dem_pct		-0.215033
		(2.979)
vote_ind_pct		0.500487
		(6.623)
unemploy		-4.750193
		(10.311)
realHPI		0.018358
		(0.008)*
Year Dummy	Y	Y
_cons	1.477061	81.393058
	(4.367)	(20.500)**
R^2	0.1	0.18
N	1,267	292

* Indicates significance at p<0.05, ** indicates significance at p<0.01

Table B-2. Results of performing fixed effects regression analysis on Models 2 and 3. (standard errors are in parentheses)

	Model 2	Model 3
ln_Income	0.56527	-2.023662
	(0.623)	(1.367)
Pop_Density	-0.002216	-0.004665
	(0.002)	(0.006)
PCT_white	-3.111227	
	(8.527)	
PCT20_24	-22.206568	-17.33455
	(9.851)*	(30.960)
PCT25_64	-3.938016	-56.06616
	(6.257)	(24.535)*
PCT65_up	-2.28296	22.609405
	(8.014)	(22.501)
Year_Total_precip	0.000657	0.001025
	(0.000)	(0.001)
Summer_HeatDays	0.002464	0.005731
	(0.005)	(0.008)
PCT_white_nonhispanic		-26.870423
		(25.358)
PCT_hispanic		-24.881651
		(19.949)
vote_dem_pct		2.182576
		(3.667)
vote_ind_pct		0.811344
		(7.181)
unemploy		-9.423585
		(11.447)
realHPI		0.032006
		(0.010)**
PCT_Resident	-0.003052	0.006881
	(0.008)	(0.043)
Year Dummy	Y	Y
_cons	10.97525	76.936842
	(10.095)	(27.855)**
R^2	0.06	0.2
N	581	235

* Indicates significance at p<0.05, ** indicates significance at p<0.01

Table B-3. Results of performing fixed effects regression analysis on Model 4 and Model 5. (standard errors are in parentheses)

	Model 4	Model 5
ln_Income	0.435813	-1.354678
	(0.318)	(1.423)
PCT_white	11.04298	
	(2.904)**	
PCT20_24	-21.774364	-11.455326
	(4.711)**	(29.248)
PCT25_64	-5.06617	-52.044716
	(2.706)	(24.505)*
PCT65_up	-6.511457	30.948858
	(3.037)*	(22.730)
Year_Total_precip	0.00065	0.001154
	(0.000)**	(0.001)
Summer_HeatDays	0.001836	0.004009
	(0.004)	(0.008)
PCT_white_nonhispanic		-39.235217
		(26.627)
PCT_hispanic		-37.287995
		(21.442)
vote_dem_pct		-0.254471
		(3.143)
vote_ind_pct		-0.179748
		(7.216)
unemploy		-8.053612
		(11.494)
realHPI		0.027838
		(0.011)**
PCT_Resident		0.014203
		(0.046)
Metro	0.579418	0.667585
	(0.226)*	(0.687)
ADJ_Metro	0.74769	1.101394
	(0.168)**	(0.809)
Urban	0.708202	0.787967
	(0.189)**	(1.016)
Year Dummy	Y	Y
_cons	0.027551	77.998413
	(4.435)	(27.992)**
R^2	0.11	0.21

N	1,267	235

* Indicates significance at p<0.05, ** indicates significance at p<0.01

Table B-4. Results of performing fixed effects regression analysis on Model 6. (standard errors are in parentheses)

	Model 6
ln_Income	0.229235
	(0.384)
Pop_Density	-0.002715
	(0.001)**
PCT_white	7.41917
	(3.466)*
PCT20_24	-31.498511
	(6.542)**
PCT25_64	-5.025002
	(3.088)
PCT65_up	-9.626196
	(3.513)**
Year_Total_precip	0.000623
	(0.000)*
Summer_HeatDays	0.003417
	(0.005)
lag1_precip	0.000645
	(0.000)*
lag2_precip	0.000914
	(0.000)**
lag3_precip	0.000373
	(0.000)
lag4_precip	0.000318
	(0.000)
lag5_precip	0.000081
	(0.000)
lag1_SummerHeat	-0.005619
	(0.005)
lag2_SummerHeat	0.011313
	(0.005)*
lag3_SummerHeat	0.008879
	(0.005)
lag4_SummerHeat	0.009177
	(0.005)*
lag5_SummerHeat	0.001832
	(0.005)

Year Dummy	Y
_cons	3.944567
	(4.999)
R^2	0.11
N	1,100

* Indicates significance at $p<0.05$, ** indicates significance at $p<0.01$