URBAN WATER SUPPLY RELIABILITY AND CLIMATE CHANGE

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DEDICATION

To my family, and to Allen

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Abstract

Severe drought, climate change, population growth, and economic factors are all issues which can affect water supply reliability. In this thesis I examine aspects of urban water supply reliability through an econometric analysis of water rights prices, and a case study discussion on several factors influencing urban water supply reliability, vulnerability, and resiliency. The econometric analysis involves sale and lease prices of water rights for several urban areas in the western United States. Sales models include urban areas in Colorado, New Mexico, Nevada, and Texas, while lease models include urban areas in Texas. In discussing urban water supply reliability I use the cities of Tucson, Arizona, Las Vegas, Nevada, and Portland, Oregon as case studies.

Chapter 1 Introduction

1.1 Overview of Water in the Western United States

Water use in the western United States occurs in many sectors including agricultural, industrial, municipal, and environmental. Rights to use water are typically can be sold or leased subject to federal and state policies. The majority of water in the western U.S. is governed by the prior appropriation doctrine, where those who first put the water to beneficial use have the highest priority to use the water. The term beneficial use can vary from state to state in what is considered by law to be a beneficial use of water. Under this system those who have the highest priority uses for water are able to use their share before lower priority users. This is important during times of drought when there may not be enough water to satisfy the rights of all users. Prior appropriation developed due to the arid climate and scarceness of water in the West, where water often needs to be diverted from the original source in order to be put to beneficial use (BLM 2010).

In the past century many major water infrastructure projects, such as dams, reservoirs, and water transport canals, were completed in the western U.S. to increase water supplies and water reliability. However, claims to water are fully allocated in many regions, leading to competition for water use between and within sectors. For example, agricultural water users may be competing with each other and with municipalities to secure additional water supplies. Competition for water supplies has led to the development of water markets, with market transactions providing a mechanism for efficient reallocation of water. Water transfers are voluntary agreements between two entities, and enable water to move from lower value uses to higher value uses since those who place a higher value on the water are willing to pay more to acquire it. Often, lower value uses are agricultural and higher value uses are municipal. (Brewer et al 2007). Driven largely by population growth, municipal water uses are increasing and municipalities are willing to invest in order to secure water sources to meet projected water use.

1.2 Urban Water Transactions

The first objective of this research is to investigate water transactions involving water moving to urban areas. Using data on water sales from 1987-2009 in Colorado, Nevada, New Mexico, and Texas, and also data on water leases in Texas, I develop an econometric analysis of prices for urban water transfers. These transfers do not reflect consumers purchasing retail water from a utility, but rather transactions where a utility or a municipality purchases or leases water to augment their municipal supplies. The geographic scale for the analysis is at the Metropolitan Statistical Area (MSA) level. Water transactions occurred with enough frequency in most MSAs included in the research to have a separate model for the individual MSA. However, a few models include more than one MSA in the regression. Findings suggest that water sales prices for water moving to urban areas are influenced by characteristics of the sale, such as quantity, and demographic data such as housing prices and population. The influence of drought on sales price is mixed.

1.3 Urban Water Supply Reliability

Along with water use growth, municipalities are also faced with emerging climatic threats to water supply reliability. Recent research investigating drought severity using tree ring reconstructions of streamflow in several western locations is revealing that droughts more extreme that those experienced in the recent past are possible. Since observed data on streamflow dates back 100 years or so, using reconstructed data on streamflow that extends back several hundred years provides a more comprehensive picture of potential drought severity. In the case of the Colorado River, tree ring reconstruction research suggests that current water allocations on the river are greater than the mean average flow of the River.

Along with the realization that more severe droughts are possible given what we have learned from investigating the past, is uncertainty of how future water supply conditions may be affected by climate change. Anticipated climate change impacts in the Mountain West are: “warmer and shorter winter seasons; warmer and potentially drier summer seasons; and more frequent and intense rainfall events,” (AMWA 2007 p4) while impacts to the Southwest region are, “warmer and probably drier overall with more extreme droughts and heat waves; and more intense rainfall events,” (AMWA 2007 p5). In the past, municipalities planned for water supply reliability with the assumption that climate was not changing, in the sense that they would not experience extremes beyond what had already been experienced in the recent past. In planning for climate change impacts, municipalities and utilities now need to account for climatic baselines that are no longer stationary (EPA 2010). Utilities throughout the country are preparing reports to assess their vulnerability to potential climate change impacts. The approaches for the assessments range from the expensive and complex using climate change computer modeling, to those using the inside knowledge of the utility and generally more qualitative in nature. The two approaches can be equally important and are not mutually exclusive (EPA 2010).

The second objective of this research is to explore the components of municipal water systems that influence the reliability, vulnerability, and resiliency of the water supply. Using Tucson, Arizona, Las Vegas, Nevada, and Portland, Oregon as case studies, I discuss each city's water supply and supply system. To enhance the discussion I also calculate several indicators which help provide a more complete picture of water supply reliability, vulnerability, and resiliency.

With water use increasing and water supply impacts looming, municipalities face challenges to meet increasing water use, while also planning for potential future supply shortages and increased supply variability. Water markets are more developed in certain states and regions than in others. Table 1.1 illustrates the number of water sales in each Urban area from 1987-2009 (Water Strategist).

Table 1.1 Urban Water Sales by MSA

MSA	Colorado Front Range	Reno, Nevada	Albuquerque, New Mexico
Urban Water Sales	965	213	35

However, if drought and climate change lead to an increasingly arid west, and water use continue to grow, water markets may begin to mature and transactions will become more routine as water is reallocated to higher value uses. Water transactions provide an alternative to building costly new infrastructure and engaging in litigation to enhance supplies.

CHAPTER 2 LITERATURE REVIEW

Literature reviewed for this research is separated into four categories: Water Supply Reliability; Climate Change and Water Supply; Current Water Supply Issues in Tucson, Arizona, Las Vegas, Nevada, and Portland, Oregon; and Water Transactions. The first section on Water Supply Reliability discusses concepts, definitions, and analysis on water supply reliability, while the second section looks at the relationship between climate change research and how climate change may affect water supplies. The third section discusses prepared documents by the municipal water providers to examine water supply issues in the three case study cities. Finally, the last section of this chapter discusses previous literature on transactions of water sales and leases.

2.1 WATER SUPPLY RELIABILITY – DEFINITIONS, VALUES AND PERCEPTIONS

Hashimoto et al (1982) produced foundational work in the area of looking at performance criteria for water resource systems. Branching out from traditional performance measures of mean and variance, (used to measure performance ranging from water pollution concentrations to system operations) the authors develop qualitative as well as quantitative measures of reliability, resiliency, and vulnerability of water resource systems. Reliability describes the frequency with which a water resource system "fails," where the authors define a failure as simply "unsatisfactory performance." Climate factors which can lead to unsatisfactory system performance or water system stress can be as mild as a moderate drought or flood. Resiliency relates to the quickness of the system to recover from a failure, and vulnerability relates to the significance or magnitude of the system failure. “By adding these performance measures to those already used to describe the expected costs and benefits of projects, individuals and groups should be better able to understand how a project might perform in the uncertain future,” (Hashimoto et al, 1982, p14).

In Chapter 5, I define more precisely the concepts of reliability, resiliency, and vulnerability and use them to examine the components of urban water supply systems in Tucson, Las Vegas, and Portland.. Also in Chapter 5, I provide indicator measures related to water supply system performance. Each component of an urban water system, from a reservoir, to a water right is integral to the performance of the system as a whole. Looking at each component individually helps to clarify which components are more or less reliable, resilient, and vulnerable. Water planners and managers can use this information to determine the best reliability and vulnerability tradeoff for their region and asses any shortcomings in their system wide components.

The challenges of balancing supply reliability, vulnerability, and resiliency are specific to each municipal location and climate, but often water supply reliability is the factor most important and tangible for urban water consumers. Municipalities and city water managers must juggle the challenges of long versus short term water supply augmentation techniques and costs, along with various water use management strategies and pricing options. Therefore, understanding the consumers view of their water supply reliability becomes increasingly important not only for ease in implementing of new strategies, but also, according to Griffin and Mjelde (2000), to understand the value water consumers place on supply reliability. The authors contend that, "perfect water supply reliability, meaning no chance of future shortfall, is not optimal when water development costs are high." The study suggests that while consumers do value water supply reliability and are willing to pay for reliability increases, they are also willing to accept some probability of shortfall in exchange for lower water rates.

Howe and Smith (1994) examine willingness to pay and willingness to accept values (for increased or decreased supply reliability) for consumers in the cities of Boulder, Aurora, and Longmont Colorado. They also assess whether, if employed, if any of several supply reliability scenarios would result in an actual net annual gain for the city. Four scenarios for each city were analyzed and consisted of two willing to pay and two willing to accept scenarios with different degrees of increasing or decreasing supply reliability. Important to note is the baseline of reliability, with Boulder having an inherently more reliable supply than both Aurora and Longmont. Of the latter two, Aurora's supply is more reliable than Longmont's. Reliabilities are based on probabilities of standard annual shortage events as mathematically described in the paper.

To analyze the WTP and WTA responses from these contingent valuation surveys in the context of net annual gains and losses, the authors compared average WTP and WTA values from each scenario and each city with actual costs of increasing supply reliability. Actual costs were gauged by what the city would spend purchasing additional water rights, or save selling currently held water rights. For all three cities the WTP values were not high enough to justify an increase in supply reliability. For Aurora and Longmont the WTA amounts indicated compensation values which were too high to justify any savings from selling currently held water rights. For Boulder, however, both WTA scenarios illustrated an amount that would justify decreasing water supply reliability by selling water rights, and the City did take that action by selling water rights worth $32 million (Howe and Smith 1994).

Building off the research by Howe and Smith (1993), Griffin and Mjelde (2000) also look water reliability values in both current and future contexts. To examine how consumers value water supply reliability the authors conducted two different contingent valuation surveys in the same questionnaire. The questionnaire was mailed to just under 5,000 households in seven cities in Texas. The design of the first survey was to capture reliability values for current water shortfalls by asking consumers if they would be willing to pay $X to avoid a water shortfall of X% for X number of days. The X's were pre-filled by the authors and survey responses were in the dichotomous choice format. The second survey question attempted to capture future values for shortfalls by asking consumers the maximum increase in their average water bill they would be willing to pay to decrease the occurrence of future supply shortfalls. Each customer's actual average water bill was printed on the questionnaire and the amount one would be willing to pay was filled in by the consumer. For the second survey question, the analog of willingness to accept was also used.

For the first survey question a logistic model was used with statistically significant variables indicating that respondents are less willing to pay a fee to avoid water use restrictions if the fee amount is too high or if their water bill is already high, but they are more willing to pay a fee if their income is high, the water shortfall is a more pronounced decrease from the normal supply, or the duration of the water shortfall is longer (Griffin and Mjelde 2000).

Using mean dollar values calculated from this model, the authors use expected utility theory models to generate values of willingness to pay to avoid future water shortfalls. The generated results using expected utility theory do not correspond to the results calculated using the second survey question on willingness to pay to avoid future water shortfalls. Given this outcome, the authors indicate future research should be in the area of exploring values related to current water shortfalls, which can then serve to generate values for future losses. They warn against using contingent valuation surveys to analyze values of future water shortfalls since the probabilistic nature and design of the question could come across as confusing and alter responses.

Another point of interest on the concept of water supply reliability is to examine how different utilities and municipalities interpret water supply reliability for their own water supply. California is an ideal state to use for this review since they enacted the Urban Water Management Planning Act in 1983 which requires municipalities serving over 3,000 acre feet of water per year, or serving over 3,00 customers to prepare an Urban Water Management Plan and update the Plan every 5 years.

A component of the plan is to report on water reliability issues, and a review of several documents from different cities revealed that, in general, cities view their own water supply reliability as being affected by climatic factors, such as drought, or disasters caused by earthquakes, chemical spills, power outages, etc. Legal and environmental factors were also listed as issues that can affect supply reliability and often reliability was looked at in short run and long run terms. Consistent with findings of Griffin and Mjelde, discussed above, one municipality cited the rising costs of demand management and supply augmentation as reasons to look at the costs of “unreliability,” (City of Santa Cruz 2006; El Dorado Irrigation District 2006; City of Gilroy 2005; City of Ceres 2005; Goleta Water District 2005).

The concepts and perceptions of water supply reliability discussed in the literature reviewed above provide the basis for my discussions on water supply reliability and vulnerability in Tucson, Las Vegas, and Portland in Chapter 5. Applying supply reliability concepts to components of urban water supply systems that contribute to the overall water supply reliability of a municipality allows for an examination of water system strengths and weaknesses.

2.2 Climate Change and Water Supply

Lane et al (1999) and Hurd et al (1999) both address the issue of climate change and the potential effect on water resources in the U.S. Although exact climate change impacts are not currently known, identifying regions and watersheds that are already “water stressed” or vulnerable to hydrologic changes can help identify where more water resource attention and planning is necessary to mitigate or adapt to impeding climate changes. To help identify critical regions and watersheds that may be more susceptible to climate change, both sets of authors present and develop a number of indicators to identify several types of water stress in different areas of the country.

Lane et al begin with a set of eight socioeconomic indicators and eight environmental indicators. The socioeconomic indicators are to assess a region's ability to cope, both financially and socially, with water stress. For example, regions with higher per capita incomes may be more able to finance major supply augmentation projects. The environmental indicators assess both regional water quality and water quantity. The authors' state that, "an indicator must be measurable, accessible, not redundant, and practical to be useful," (Lane et all 1999). Based on this statement, three indicators are dropped from each category, leaving five socioeconomic and five environmental indicators.

All ten indicators are then calculated for each of the 18 U.S. Water Resources Council regions using 1990 as the base year. Following the base year calculations, the authors then use Global Circulation Models (for environmental indicators) and "business as usual" water use scenarios (for socioeconomic indicators) to project indicator values for the year 2100. When comparing current climate and projected future climate indicator scenarios the results indicate that the western U.S. will experience the greatest climate change impacts due to, "(1) less stress on hydroelectric systems because of the increase in electricity production from other sources, and (2) more stresses on available water due to increases in total withdrawals and, in some cases, decreases in stream flow," (Lane et al 1999 p204). The authors were not just concerned about results, however, and also discussed several methods for comparing and displaying indicator values.

Hurd et al begin with two categories of indicators, the first being water supply, distribution, and consumptive use indicators (water quantity), and the second being instream use, water quality and ecosystem support indicators (water quality). Each category has six indicators. The spatial scale used by the authors to calculate each indicator is greater than that used by Lane, and includes 204 watersheds in the continental U.S. The authors also aggregate the indicators in each category to form a single index for water quality and a single index for water quantity for each watershed, and then merge the final two indicators to form a single water vulnerability index. Although a single index is a simplified number, a significant amount of detail is lost in the aggregation. Two regions could have the same vulnerability index, but for very different reasons.

Building on the research by Lane et al and Hurd, I adapt several pertinent indicators to assess water supply reliability, resiliency, and vulnerability, for the cities of Tucson, Las Vegas, and Phoenix. Calculating these indicators for an urban area adds to the research of the two preceding authors by decreasing the spatial scale from the regional or watershed level to a city level. Given the unique water supply make up between cities within the same region or even the same watershed, calculating these indicators on a city level provides a detailed look at where water supplies could be the most impacted by climate change.

Two recent studies addressing water supply vulnerability and climate change focus on Colorado River flows, and management and impacts the two main reservoirs, Lakes Mead and Powell. The Colorado River serves as a primary water source for two of my case study cities, Tucson and Las Vegas. The most recent study (Kenney, et al 2010) compares a study on projected impacts of Colorado River drought made in 1995 with actual observed impacts of sustained drought around the years 2001-2008. The 1995 study used the paleo record of Colorado River flows from reconstructed tree rings and developed what was considered at the time a worst case scenario: mean flows of just 9.57 million acre feet over a 16 year period. The estimated long run mean of the river is 15 million acre feet. The outcome of the study projected sharp declines in Lake Powell resulting in only 59% of the Upper Colorado Basin water demands met, while only 3% of the Lower Basin water demands were unmet. Lake Mead remained about two-thirds full, or 20 million acre feet of storage, until Lake Powell was empty, but still never dropped below 7.5 million acre feet of storage. Therefore, the findings suggested that the reliability of the water supply system favored Lower Basin water users (Kenney, et al 2010).

The outcome of actual drought impacts on the Colorado River resulted in sharp declines in both reservoirs, and the authors suggest this was due to a combination of sustained drought accompanied by increased lower basin water use. Inflow into Lake Mead from Lake Powell remained steady at 8.23 million acre feet per year during the all drought years, but the completion of the Central Arizona Project canal allowed water use to increase, and this increase was, “sufficient to pass the threshold that determines whether or not Lake Mead is stable or declining,” (Kenney et al 2010, p8).

Sustained droughts and potential climate change impacts play a crucial role in water system vulnerability. However, other factors, such as water use growth, reservoir management, and long term average flows are just as important to evaluate when determining how much water and who will be affected. Taking these issues into account, another Colorado River water supply study (Rajagopalan et al 2009) simulates decreased river flows as a result of climate change, coupled with several management scenarios to gain an understanding of the role of water management in climate change mitigation and adaptation.

Several climate change studies suggest that average annual Colorado River flows will decline. The magnitude of the decline is unknown, but several model results point towards reductions of between 6-20%. Rajagopalan et al use a time period of 50 years, 2008-2057 and for each year they randomly generate streamflows based on the historical paleo record and the historical observed record. To include climate change impacts, scenarios of linear reductions in annual streamflow of 10% and 20% are considered.

Results of the Rajagopalan et al study find less than a 9% chance, under any climate or management scenario, of both reservoirs, Lake Mead and Lake Powell, drying before the year 2026. However, after the year 2026, the risk of drying increases up to 26% for the 10% climate change scenario and up to 51% for the 20% climate change scenario. Although these percentages are alarming, a major finding of the study is that the risk of reservoir drying can be greatly decreased with appropriate and timely management strategies.

Rajagopalan et al conclude that the use of climate change scenarios with linear reductions in 10% and 20% of Colorado River average annual streamflow is not meant to simulate reality, but rather to provide insight on the importance of diligent water management on the Colorado to mitigate the real potential challenges of increasing water use and decreasing average annual flows (Rajagopalan et al 2009).

Although the application of Global Circulation Models is beyond the scope of this research, the literature includes analyses of city-level water supplies illustrating the unknowns of climate change and the need to develop various techniques to examine water supply on a city by city basis. Using global warming temperature projections from the Intergovernmental Panel on Climate Change (IPCC) and eight Global Circulation Models (GCM), Maheepala and Perera develop a framework to analyze water supply changes for the year 2030 in Benalla, Australia. The authors use the lower and upper bounds of the 2030 temperature increases provided by the IPCC (0.55 and 1.27 degrees Celsius), as well as two midpoint temperature projections (0.80 and 1.04 degrees Celsius). Using each of these four temperature scenarios with each of the eight Global Circulation Models allows the authors to generate 32 regional future climate scenarios for rainfall and evaporation.

These 32 scenarios make up the Climate Change Module, which is the first of six proposed modules used for the model. The next module is the Climate Variability Module which takes these 32 scenarios as input to generate stochastic climate data sequences. The authors, however, were unable to generate stochastic climate data sequences, and instead used historical data from the years 1969-1999, which may not have the same variability as future climate. The generated sequences are then input for the Runoff/Streamflow Module, the Consumption Module and the Water Planning Simulation Module, which simulate impacts on streamflow, consumption, and water supply security. Finally, the Impact and Adaptation Assessment Module simulates the magnitude future climate changes will have on the water supply system (Maheepala and Perera 2003).

After analyzing the usable generated data on the changes in streamflow and system yield, the authors determined both variables could be looked at using a log-normal distribution. Using this distribution, probabilities of system yield and streamflow decreases could be projected. For example, using the 70% level of probability, there is a 70% chance of a reduction in mean annual streamflow of 12% in the year 2030. For system yield there is a 70% chance in the year 2030 that system yield with decrease by 8% (Maheepala and Perera 2003).

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Through their unique framework, the authors were able to generate 32 different climate scenarios for the City of Benalla, Australia. Using these scenarios, projections of streamflow and system yield decreases in the year 2030 were examined for Benalla. This analysis is useful as a tool in helping cities project future water supply changes due to climate change and prepare for appropriate mitigation and adaptation strategies.

Although studies like the one conducted for Benalla Australia hold promise, the Water Utility Climate Alliance White Paper titled, “Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change,” highlights areas of climate science that are still lacking in providing utilities the cooperation and detail desired for water supply planning. Utilities are examining the impacts of climate change in their watersheds and many have used GCMs in conjunction with a few emissions scenarios. The resolution of GCMs is still quite large, so utilities also need to employ downscaling techniques to capture smaller, regional changes.

GCM technology and climate science are advancing rapidly, but areas where either the technology or the research fall short and utilities would like to see greater improvements are: 1) "Model agreement on change in key parameters," (Water Utility Climate Alliance 2009, pS-5) which applies to scientific research and agreement on certain inputs into GCMs such as circulation patterns: 2) "Narrowing of the range of model output," (Water Utility Climate Alliance 2009, pS-5) which states that a wide range of climate projections are given due to the many emissions scenarios. Narrower ranges of climate projections could aid utilities in their planning, but due to future emissions uncertainties, utilities are realistic about how much improvement can be made in this area; 3) "Climate model resolution at a special and temporal scale that matches water utilities' current system models," (Water Utility Climate Alliance 2009, pS-5). Currently the resolution of GCMs is 100-400 km, but utilities would ideally be able to match GCM resolution with their watersheds size, or around 50-200 km. Increased resolution does not equate better projections, however, so just improving resolution is not sufficient; 4) "Improved projections within water utility planning horizons," (Water Utility Climate Alliance 2009, pS-5) as utilities are interested in projections of the next few decades and not only longer term projections. Decadal projections are often more dependent on natural climate variability than on human induced climate changes, so utilities would benefit from improved research and modeling of natural decadal climate variations.

Even with rapid technological and scientific advances, many of the improvements utilities need are at least a decade from being realized. Also important to note is that GCMs are only one tool of many that utilities currently use and will use in the future to aid them in water supply planning. In the meantime, continuing to understand the relationship between climate and water planning as well as developing new tools utilities can put into practice now will help utilities plan for and adapt to climate change. Development of an urban water supply reliability framework may provide utilities with an alternative blueprint with which to build their own assessment of their city's water supply reliability.

2.3 Current Water Supply Issues in Tucson, Arizona, Las Vegas, Nevada, and Portland, Oregon

To develop a firm understanding of the current and future water supply issues facing the cites of Tucson, Arizona, Las Vegas, Nevada, and Portland, Oregon I reviewed the principal water planning documents prepared by each city's water utility. Water supply in each city consists of a different makeup of surface water, groundwater, and reclaimed water or effluent. Projections of future population growth coupled with recent droughts and future uncertainties of climate change are creating more challenges for each city to create reliable and diverse water supply portfolios. In this chapter I provide an overview of each city by highlighting current water supply sources for each city, their projected planning horizon, and how they are planning to meet projected water use increases within said planning horizon. A water supply reliability framework for each city is developed in Chapter 5.

2.3.1 Tucson, Arizona

Water supply sources in Tucson are groundwater, reclaimed water, and Colorado River surface water brought to the city through the Central Arizona Project (CAP) canal. The two main planning documents used to for information on Tucson's water are: Tucson Water's "Water Plan: 2000-2050," which was updated in 2008 to reflect the progress and decisions made since the first installment; and Arizona Department of Water Resources (ADRW) Draft Demand and Supply Assessment for the Tucson Active Management Area (AMA). Due to the information content and larger geographic area used for ADWRs Demand and Supply Assessment, it is used as a primary source and Tucson Water's "Water Plan" as a supplemental source.

The goal of ADWR is to halt groundwater overdraft and attain a "safe yield" use of groundwater for each AMA in Arizona by the year 2025. A safe yield or sustainable use of groundwater would mean that the use of groundwater would not exceed the amounts of natural or artificial groundwater recharge. To assess the ability of Tucson area in attaining this goal, ADWR completed the Supply and Demand Assessment, which takes a detailed look at past water use by source and by sector and projects several future water use scenarios out to the year 2025.

ADWRs three Baseline Scenarios 1-3 look at three levels of future water use, and then the scenarios are calculated again to reflect the effect of a shortage on the Colorado River. One additional scenario is calculated to reflect maximizing the use of reclaimed water. In total, seven scenarios are calculated with the only scenario coming close to achieving ADWRs goal of "safe yield" being the maximized reclaimed water use scenario. In calculating each scenario, the shifts in water supply sources and water use by sector, help provide an overall picture of water supply reliability and vulnerability.

2.3.2 Las Vegas, Nevada

Southern Nevada Water Authority (SNWA) is the umbrella water supply and management organization in the Las Vegas metropolitan area charged with overseeing and augmenting the area's water supplies. Currently Las Vegas is dependent on the Colorado River for 90% of its consumptive use and groundwater for 10%. Although Las Vegas' allocation of Colorado River water is 300,000 acre feet per year, the city is allowed to intake a significantly higher amount through its return flow credit program. The return flow credit program treats and returns water to the Colorado River via the Las Vegas Wash, so as long as total net consumption does not exceed 300,000 acre feet, the city is in compliance.

As the population of Las Vegas continues to grow SNWA has long been searching for viable water supplies to add to its overall water portfolio. The primary source of augmentation will be the development of additional groundwater sources outside of the Las Vegas area. Exact amounts are unknown at this time due to pending permits and approvals by the State Engineer, but resource scenarios include 134,000 acre feet per year from the Clark, Lincoln and White Pine Counties Groundwater Development Project. Along with groundwater, other sources include utilization of intentionally created surplus and banked water sources, along with increased demand management efforts. The conservation goal for Las Vegas is to decrease gallons per capita day (GPCD) from 250 to 199 by the year 2035. The full planning horizon for Las Vegas extends through the year 2060.

2.3.3 Portland, Oregon

Portland's main water source is the Bull Run Watershed. Supply infrastructure in the watershed consists of two reservoirs which are dependent on winter snowfall as well as fall and spring rains for refill. Water use in Portland is less during the fall, winter, and spring wet seasons and increases during the summer months, which is also when the reservoirs receive less rain and begin to draw down. To supplement reservoir draw down in the summer months and emergencies, or when the Bull Run supply is disrupted, Portland also relies on groundwater drawn from the Columbia South Shore Well Field (CSSWF). The well field consists of 26 wells which draw on three different aquifers. Drawing groundwater, however, is not without challenges. The main issues with the well field include, "the pumping capacities of the aquifers that the wells draw from over extended periods of time, the mechanical reliability of the system and the need for continuing maintenance of the facilities, as well as the presence of manganese in some of the CSSWF wells."

Portland's planning horizon extends to 2028 and after looking into a number of supply augmentation alternatives, the most economically and environmentally sound alternative was to develop four currently held groundwater rights to increase supply from the CSSWF. Developing the supply was scheduled to begin in 2009 and be completed by 2028. Increased use of groundwater and continued conservation, are the preferred methods of supply augmentation for Portland at this time. As the city's needs change in the future and as population growth brings in greater financial capacities, the city may again explore additional supply augmentation alternatives.

This research offers additional methods for cities and utilities to examine their water supply sources and to identify deficiencies in reliability and vulnerability. Indicators relating to groundwater use, imported water, storage capacity, etc. will add to the way we look at and analyze water resources.

2.4 Water Transactions

In this section I review relevant literature relating to water sale and lease transactions which provide a foundation for my econometric models. The models analyze the determinants of water prices for water purchased several urban areas in Nevada, Colorado, New Mexico, and water leased by several urban areas in Texas. The literature in this section includes both descriptive and quantitative research on water transactions, both of which are important to a thorough understanding of water markets. I first review descriptive research followed by quantitative research.

Brewer et al (2007) examine water allocation in 12 western states to see if water is transferred from lower value uses of water to higher uses. Their analysis focuses on the movement of water from lower value agriculture to higher value demands of urban and environmental users. They provide an outline and history of the legal system which defines how water is transferred in the West and point out how the development of the legal system serves to encourage inefficient uses of water. Their logic is to suggest that western water markets serve to remedy some of these water use inefficiencies.

The authors' findings suggest that water is shifting from agriculture to urban and environmental uses with increasing urban population growth and heightened awareness of environmental protection. The article is formative for this research as it lays the descriptive groundwork for western water transaction trends from 1987-2005, though it does not develop an econometric model.

Colby et al (2007) provide a history of water transfer development in Arizona and how transactions have been used and continue to be a pivotal water supply planning tool. The four categories of water discussed are surface water transfers, CAP transfers, effluent transfers, and tribal water transfers. Each category is subject to different sets of laws and regulations governing transfers which may serve to hinder or enhance the ease of a transfer. Over the period of 1987-2004 the highest number of transactions and the highest volume of water transferred were through CAP transfers.

The use of these transfers to enhance supply reliability is seen through two vehicles, the Arizona Water Banking Authority (AWBA), and transfers based on irrigation forbearance. The AWBA is not only banking unused CAP entitlements for future use in Arizona, but is also "banking" water for future Nevada use. The agreement allows Nevada to accrue storage credits in Arizona and when the time comes to use the stored water, Arizona will use the stored water in lieu of Colorado River water, and Nevada will in turn increase its Colorado River use, by the amount in storage.

Transfers involving irrigation forbearance generally move water from agricultural to urban uses, while temporarily taking low value crops out of rotation and compensating farmers for their lost profits. The amount of water used for agriculture coupled with targeted temporary agriculture to urban transfers can achieve huge cost savings across the board. An irrigation forbearance rate of 4-11% of Colorado River water used in the lower basin would generate 200,000 to 600,000 acre feet with costs ranging from $20-$100 per acre foot.

The following articles developed econometric models related to water markets. Established water markets are found around the globe and understanding water markets in other countries can provide valuable insight into our own markets. The first article in this section is on Australian water markets, while the rest present research on western U.S. water markets. All of the research in this section on U.S. markets is based, at least partially, on data from *Water Strategist*, which I also use for my econometric models.

Bjornlund and O'Callaghan address implicit and explicit water irrigation prices in northern Victoria, Australia. Implicit prices reflect transactions where farmland and water are sold together, while explicit prices are simply water sold on its own for agricultural purposes. To extract implicit prices, the authors apply hedonic pricing techniques and suggest hypothesized convergence of the two prices in mature markets.

When water sales first began many farmers were selling unused water at low prices, as selling the water did not compromise their current production levels. Explicit prices were therefore lower than implicit prices. Over time, the authors found that the two types of prices did converge around 2001, but subsequent years of prolonged drought drove explicit prices higher than implicit prices. Evidence is seen through sales of farmland where the attached irrigation water is transferred to the buyer's location and the purchased land is left dry and unproductive. The article highlights irrigation water price sensitivity and variability to climate. Although the research is in Australia using agriculture to agriculture transfers, it suggests that the similar arid climates of the western U.S. may also experience water price sensitivities due to climate. This research builds on the ideas of Bjornlund and O'Callaghan by seeking to identify climatic sensitivities of water transfers which move water into urban areas.

Brookshire et al (2004) examine the major water markets in Arizona, New Mexico, and Colorado which are the Central Arizona Project, the Middle Rio Grande Conservancy, and the Colorado Big Thompson Project. The authors provide a thorough background on each project including important historical points and unique features which are central to understanding how these water markets currently operate. The authors acknowledge that water markets are not perfectly competitive, but markets in some states and/or basins are more efficient and competitive than others. In Colorado the Colorado Big Thompson project rights are traded as shares, which makes these water rights more of a homogeneous commodity, and therefore more conducive to competitive market trading.

Differences across the three states in transaction costs, including monetary, legal, and time costs also play a role in market efficiency. Arizona's transaction costs include an extensive written application, $500 fee, and an approval time of up to 420 days. In New Mexico an extensive application must be submitted along with a modest fee of $25-

$50. Once the application is received, a 30 day public notification period is required followed by a hearing. The whole process can take around 18 months. Colorado's CBT project clearly has the lowest transaction costs which entail filling out a brief form, a fee of $70, and approval by the Northern Colorado Water Conservancy District which takes up to 45 days.

Although these water markets are not perfectly competitive, the authors are able to gain valuable insight into water price variation using econometric analysis. The model used is a two stage least squares with the included exogenous variables being: type of buyer (government, irrigation district, or municipal), annual population change, annual per capita income, and the PDSI drought index. With most variables statistically significant at the 1% level and an R2 of 0.734, the model performs well. Model results indicate higher prices in Colorado than in Arizona and New Mexico, while government buyers pay a lower price than agricultural or municipal buyers. Water use increases as populations become wealthier, and prices are higher in drier years. To determine the relationship between price and quantity the authors use the same price model described above to serve as an instrumental variables for price in separate model with quantity as the dependent variable. The results indicate an inverse relationship between quantity and price.

The article provides a strong basis for understanding water market maturity and water market price variation, with the type of buyer being a significant determinant of price. Building off this foundation and some of the variables used in the Brookshire et al econometric analysis, my research examines water transactions in which the buyer is always municipal in order to further identify urban water price determinants.

Brown (2006) discusses water market trends over time while also looking at the categories of buyers and sellers for sales and leases. He incorporates an econometric analysis looking at sale and lease prices separately, but including in both models only transactions where the purpose of the water was for municipal, urban, or environmental use. Brown does not break down his models geographically, but instead includes all relevant transactions from a total of 14 states. To analyze the variation in water prices he includes seven explanatory variables: transaction year, the Palmer's Drought Severity Index (PDSI), quantity (in mega liters) transferred, the population in the year 2000 of the county of the buyer, a dummy variable for groundwater (otherwise surface water), and dummy variables for municipal water use and environmental water use (otherwise irrigation use.)

For leases, the adjusted R^2 was 0.24 and the statistically significant findings suggest higher prices occur in drier climates, larger county population, municipal and environmental uses. For sales, the adjusted R^2 was 0.21 with statistically significant findings suggesting that higher sales prices are in line with smaller county populations, municipal use, surface water, and smaller volumes of water traded. Brown's "big picture approach" looks at western water markets as a whole and touches on a wide range of issues. However he does not test for potential problems with his models, such as endogeneity between price and quantity or heteroskedasticity. His results may be biased without thorough testing and correcting of these problems.

On a much smaller scale than Brown's western U.S. analysis, Pullen and Colby (2008) analyze water sales transactions in just one area of New Mexico, the Gila-San Francisco basin. Creating an econometric model of derived demand for sales prices, the authors model price variation by including variables relating to the characteristic of the water right such as: the size of the transaction, location of the transaction, and the year the transaction occurred. Other exogenous variables included were: the Standard Precipitation Index (SPI), the change in population, the price of copper (due to the mining industry in the area during the study period), and calf prices (due to the ranching industry). The SPI drought index measures drought conditions for varying lengths of time, and in the article the authors use both 12 month and 24 month SPI. Due to lag time between when the sale actually occurs versus when the sale is published, the authors not only test both the 12 and 24 month SPI values, but also test models using a 6 month lag of each. Therefore, holding all other variables in the model constant, the authors test four models with varying values of SPI to more accurately assess impact of drought on water sales in the regions.

Using a Hausman Wu test, the authors test for and confirm the endogeneity of price and quantity in the model. To control for this problem, a two stage least squares model is employed using instrumental variables as a proxy for quantity. Although the instrumental variables used are not great predictors for quantity, quantity is found to be significant in all of the models. All of the other variables used in each model are significant as well, at the 1% level, except SPI. SPI 12 and 24 are not statistically significant, however, the SPI 12 with a 6 month lag is significant at the 1% level and the

SPI 24 with a 6 month lag is significant at the 10% level. R^2 values for the models are in the 0.73-0.74 range indicating that the variables explain close to 75% of the variation in price.

As part of her Master's Thesis, Pullen (2006) also analyzed urban water transactions by including water sales occurring in major urban areas in Arizona, Nevada, New Mexico, Colorado, and Utah within a single model. Significant findings in the results suggested that urban water prices were influenced by location, quantity, population change, and a trend variable indicating the year in which the transaction occurred. Although population change was significant, the sign was negative, which was not expected. The model was run twice with two different climate variables, SPI24 and SPI24 lagged six months. Although the latter was significant at the 5% level, the sign was positive, which was not expected.

Jones and Colby (2010) look at water leases, as contrasted with sales, and their econometric models provide further insight into determinates of water lease prices. The two models used in their research serve to point out similarities and differences between water leased for environmental purposes and water leased for other purposes, such agriculture, municipal, or industrial uses. To account for these differences, one model is set up for environmental water lease prices, while the other is set up to model water lease prices for other uses. Most variables remain constant in both models and include: quantity, temperature (mean temperature three months before the reported date of the lease), SPI drought index, income, land (variable measures, the value of agricultural land compared to the value of its products), population (by climate division), transaction number (number of leases by climate division), years (length of the lease), pub (dummy variable that indicates if the water is administered by a government entity), location dummy variables, and in the non-environmental lease model, dummy variables for the different water uses (agricultural, municipal, etc.).

Significant results from the environmental lease model suggest that determinants of environmental lease prices include temperature, per capita income, location, whether the water was leased for a mandated or a voluntary environmental purpose, and whether the water leased was administered by a government entity. The R^2 value for the model was 0.32. Looking at the non-environmental lease model significant determinants of price include quantity, SPI, income, population, transaction number, location, land, different water uses, and whether the water leased was administered by a government entity. The R^2 value for the model was 0.45.

O'Donnell (2010) for his Master's thesis estimated lease models for California, Colorado, and New Mexico. His models were at the state level and included all leases, paired with state level demographic data. O'Donnell did include a housing price variable, but the variable did not perform well due to the large spatial scale of the data. Modeling water transactions at the state level was done to assess any efficiency gains by doing so, but since water markets are localized, smaller spatial scales generally produce stronger models. Lake Mead elevation data was included as a variable and performed well. Reservoir data was explored for this research, but my search to obtain data for the principal reservoirs for each MSA, for the timeline needed was not successful. Climate variables used included the Pacific Decadal Oscillation (PDO), temperature, and precipitation.

Econometric research on water sales and leases by Brookshire, Brown, Pullen and Colby, and Jones and Colby uses various climate and economic indicators, as well as variables inherent to the characteristics of the water right or lease contract to explain price variation. Based on the econometric modeling foundation built by these authors, this research also includes climate, economic, and water characteristic variables, as well as use a two stage least squares econometric model, where endogeneity tests reject exogeneity. However, my exploration of a new subset of water transactions in the urban market allows for the inclusion of other economic indicators such a housing price index, and urban area population growth, as well as a new approach in including climate variables. Where possible, I included a drought index for the climate division where the water supply for the urban area originates, as opposed to previous research which included a drought index for the area where the transaction occurred. Table 2.1 provides a summary of recent econometric analysis on water transactions to identify differences in approach.

Table 2.1 Summary of Recent Water Transaction Research

Author	**Time & Spatial Scale**	**Transaction Types & Location**	**Independent Climate Variables**	**Independent Demographic Variables**	**Description**
Pullen 2006	1987-2004, County	Sales AZ, NM, CO, NV, UT	SPI 24 & SPI 24 lag 6	Population change; per capita income	One single, price dependent regression of sales combining several urban areas in the states listed.
Jones	1987-	Sales and	Sales: SPI 12 lag	Population and	One single, price

2010	2007 County,	Leases AZ, CA, NV, NM, UT, WY	6 & temperature lag6; leases: SPI 6 lag 3 & temperature lag 3	State level per capita income	dependent regression for sales, and one for leases combining all transactions in the listed states, but excluding environmental water uses.
O'Donnell 2010	1987-2009, State	Leases CA, CO, NM	PDO lag 6 & temperature lag 3 & precipitation lag 3	Median home prices, population, income	Three, price dependent regressions of leases, one for each state
Basta 2010	1987-2009, MSA	Sales and Leases CO, NM, NV, TX	Sales: SPI 12 lag 6; leases SPI 12 lag 3. Using 2 different climate divisions.	Housing price index; population	5 price dependent regressions of sales for individual MSA's, 1 price depended regression of lease for individual MSA, and 2 price dependent regressions, one for sales, one for leases combining 3-4 MSA's.

CHAPTER 3 DATA AND METHODOLOGY

This chapter provides a description of the data, data sample selection, and any necessary data cleaning. I present my reasoning for choosing the models used for the analysis as well as any tests used to detect problems with the regressions. Also, all variables used in the regressions are described and the expected signs are discussed.

3.1 DATA DESCRIPTION

Data on water sale and lease transactions comes from the *Water Strategist*. The *Water Strategist* is a monthly publication compiling information on water sales and leases in the western United States. All transactions are reported in text form in the *Water Strategist.* From this text, University of Arizona Researchers create a data format. Reported transactions generally contain the following information about the water sale or lease: price per acre foot of water, total quantity, the buyer, the seller, previous use of the water, new use of the water, and for leases, the terms of the lease. Water Strategist is the most comprehensive source for western U.S. water transactions, and although the publication may not have information to report on all transactions, any reporting bias is assumed to be the same for all states. Therefore, any comparisons made across states would not be influenced by a reporting bias (Howitt and Hansen 2005).

Transactions are listed by state and by month. However, transactions within any given state occur at irregular intervals. So, several months may pass in which no transaction is reported in a specific state. Alternatively, several transactions may be reported a state in a single month. Also, the month the transaction is reported in the

Water Strategist typically does not correspond with the month when the transaction actually was negotiated or implemented. There is usually a time lag between when parties involved in the transaction reach an agreement on price and other terms, and when the transaction is reported (Colby 1990). The duration of the reporting lag is unknown and likely varies between states and transactions. Since this analysis is examining relationships between a set of independent variables and the negotiated price, I use time lags for certain independent variables, such as the Standard Precipitation Index (SPI). These variables can vary significantly in shorter periods of time, so the time lags attempt to correct for the reporting lag. Shorter time lags are used for leases than for sales, as sales generally take longer to finalize.

Due to the varying nature of the transactions, different amounts of written information are included with each transaction. Some transactions are listed as a single transfer of water from one party to another, while other transactions are a summary of several transactions grouped into one entry. As Jones found in her research, if the transactions are disaggregated to fullest extent possible, including multiple entries with exactly the same price and quantity, then the error variance may be artificially reduced, and the R^2 artificially inflated (Jones 2008). Another issue is that disaggregated entries may not reflect the true individual market prices and quantities if they represent averages. Consequently, in this analysis, if enough information is included with grouped transactions to separate out the different prices and corresponding quantities of each separate transaction, then the entries are split and recorded as multiple transactions. If, however, the information included is only enough to extrapolate averages of either prices or quantities, then these entries are treated as a single entry. Therefore, each included transaction may be a single transaction or may also be a transaction involving multiple parties.

Each transaction (as defined above) is one observation and transaction data included the quantity in acre feet sold or leased and the price per acre foot. Data from the transactions are paired with demographic and economic data at the Metropolitan Statistical Area (MSA) level, and climate data at the climate division level. The climate data used in this research is the SPI. Often in the West, water supply originates as snow pack in a different climate division from where the water is being used. For the models where the climate division that represents the origin of a primary source of water supply is known, the SPI from that climate division is used. In the remaining models, the SPI representing the climate division of the urban area where the water is used is included in the models.

For the models which incorporate the SPI from the climate division representing the origin of a primary source of water supply, I also ran the models using the same variables, but changing the SPI variable to the SPI from the climate division where the water is used and they can be found in Appendix E. The SPI variable in those models is not significant, so I do not include the models in this chapter. Figure 3.1 uses Colorado to illustrate climate division boundaries (NOAA 2010b). Municipal water use in the Denver and Boulder MSAs is within climate division 4. However, a significant portion of the water supply for these metro areas falls as snow and rain within climate division 2.

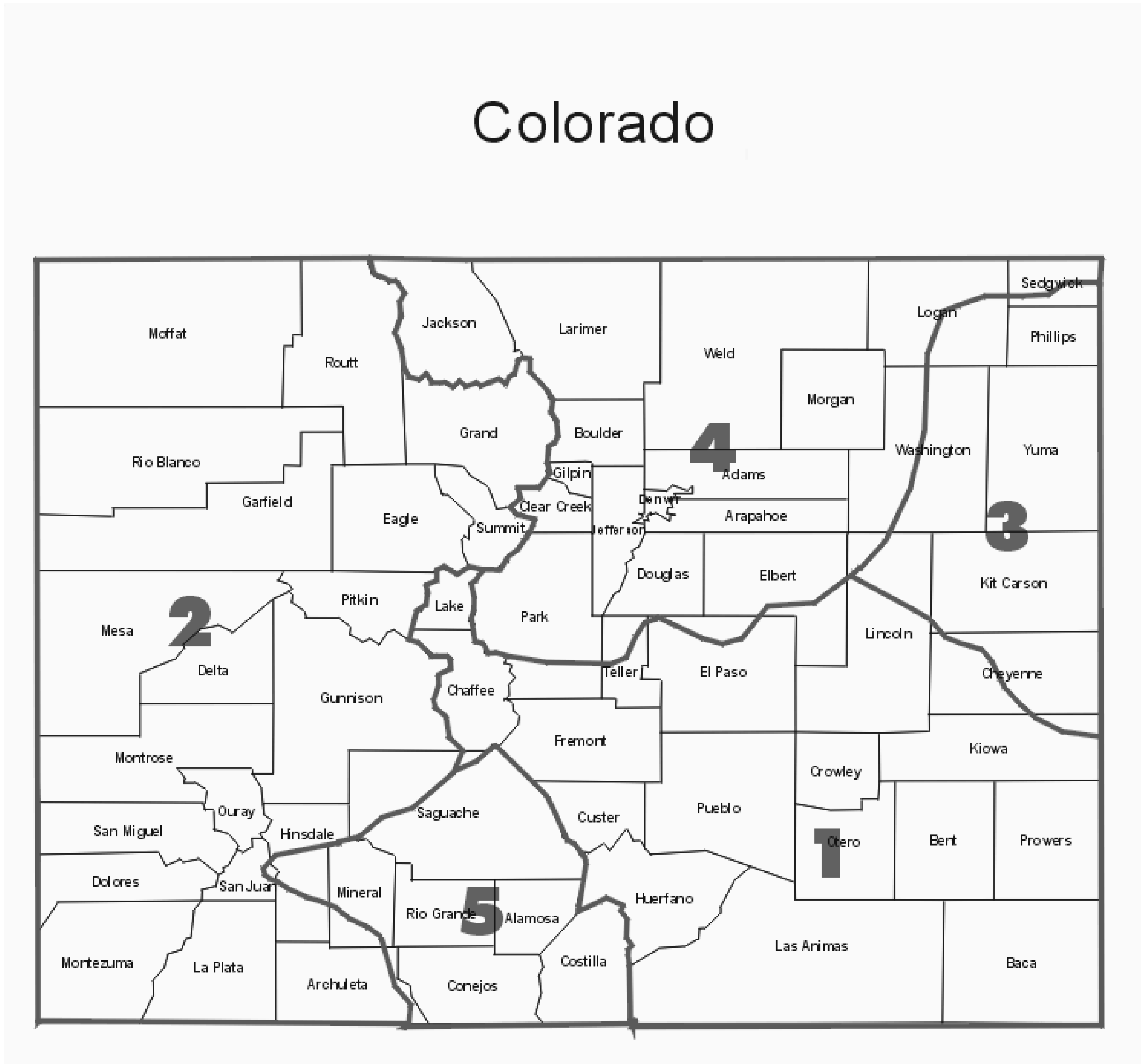

Figure 3.1 Colorado Climate Division Map

3.1.1 DATA CLEANING

Observations are deleted from the data for several reasons. If water is sold or leased with land and the price for the water alone is not reported and cannot be determined, then the observation is deleted. Observations with sales prices of less than $5.00 per acre foot were not included since prices below market reflect non-market transactions, such as sales between family members. Any transactions listed as exchanges or donations where a price was not listed were not included. As stated above, any transactions containing several prices or quantities which could not be split into separate transactions were averaged, but this applies to only a small number of transactions. Since usable transactions for this research are based on water moving to specific urban areas, transactions listed for municipal use, but for which the location or geographic region cannot be determined are not included in the data. A breakdown of how data was selected for each model is discussed in the following section.

3.1.2 Data Selection by State

In identifying urban water transactions for this analysis from the entire water transactions data set, I examined several states and urban areas within states to determine where urban water transactions occurred with enough frequency to model. I made several decisions within each state about what transactions to include and how to classify them by MSA.

Colorado

Colorado has the most active transactions market, in terms of the number of transactions, of all the states in this research. Transactions to supply urban areas in Colorado are concentrated on the northern Front Range in the Denver, Boulder, Greeley, and Fort Collins areas. I analyze three separate urban water markets in Colorado. A full model of all Colorado urban water sales is provided in Appendix B.

Front Range: The Front Range model includes the urban areas of Denver, Fort Collins, and Greeley. These areas are grouped together in one model due to their similar demographics, and also the fact that many of the water supply entities operate across these cities.

Boulder: Boulder demographics are different from other areas in the Colorado Front Range in that the costs of living, and, in particular, housing prices are much higher (City-Data, 2010). Those water sales which could be determined as moving to the Boulder MSA were categorized as Boulder transactions.

CBT: The Colorado Big Thompson (CBT) model. The CBT project is the largest trans-mountain water diversion project in the state (NCWCD 2010a), so this model represents sales of CBT project water to any urban area along the northern Front Range.

Nevada

Reno: Reno and Las Vegas are the largest urban areas in Nevada. However only handful of the transactions occur in Las Vegas, so the only Nevada urban area included in this research is Reno. A full Nevada state model of all transactions, Reno and Las Vegas, is in Appendix B.

New Mexico

Albuquerque: Only sales involving water moving to the Albuquerque MSA are included in the model. Urban water transactions occurring outside of this MSA are sparse.

Texas

Texas is the only state where enough urban water transactions of both sales and leases occur with enough frequency to analyze. The majority of urban transactions are concentrated in the areas of El Paso, Laredo, McAllen, and San Antonio. Figure 3.2 is a map of southwestern Texas showing all the above cities (jrb-ble.org 2010).

Texas Sales: Sales transactions involving all four MSAs are included in the Texas sales model.

Texas Leases: Only El Paso, McAllen, and San Antonio are included in the Texas lease model. Several leases in the Lower Rio Grande region only specify that the water is for municipal use, but do not list the exact municipalities where the water will be used. For these cases, they are classified in the McAllen MSA since McAllen has the highest population and population growth rates in the Lower Rio Grande basin area.

McAllen Leases: Since there are adequate numbers of Lower Rio Grande surface water leases, I run a separate lease model for the McAllen, Texas area.

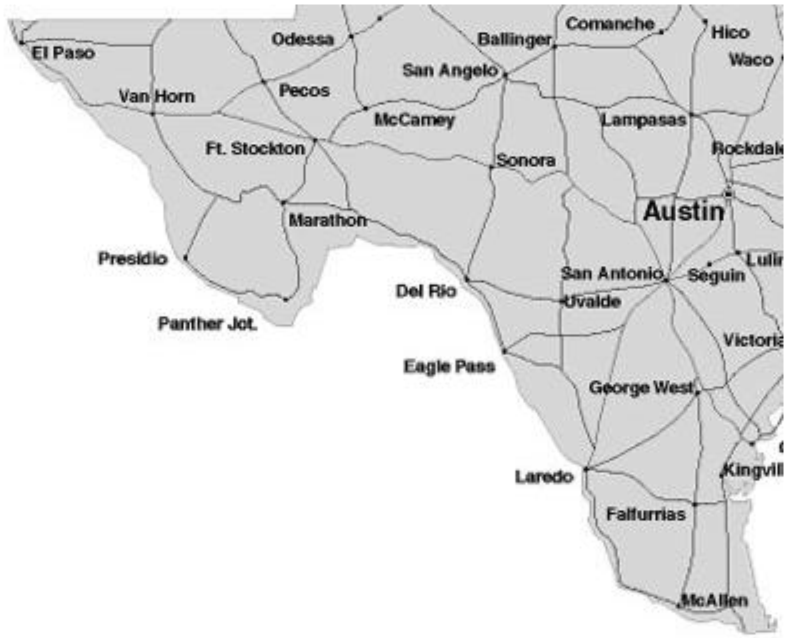

Figure 3.2 Map of Southwestern Texas

3.2 Methodology and Variable Description

3.2.1 Methodology

Previous research indicates that smaller geographic scales, either at the climate division or county level provide stronger models. For this reason I use the MSA geographic scale for all models. I also explore using SPI values from the climate divisions representing the water supply origin, where previously SPI values were used only for the location representing the water transfer or the water use. Lastly, I incorporate a housing price index as a new economic variable which has not been used in previous research on water transactions.

Each model is set up with lnprice, the natural log of price, as the dependent variable. A semi-log functional form is used for all models. Box cox transformation results for each model indicate that the natural log of price improves model fit over a linear form. Double log models were explored as well and displayed a similar model fit when compared to semi-log models for most cases, but a weaker fit in a couple of cases.

I conduct endogeneity and heteroskedasticity tests on each model. Endogeneity between price and quantity is a potential problem. If quantity is not independent from the disturbance term, then OLS estimators are biased and inconsistent (Johnston and DiNardo 1996). I use a Hausman Wu test to test for endogeneity between price and quantity, with the null hypothesis assuming the variables are exogenous. If I reject that quantity is exogenous, then a Two Stage Least Squares (2SLS) model is used. However, if I fail to reject exogeneity, then I use an OLS model since 2SLS estimators not as efficient as OLS estimators if all independent variables are exogenous (Wooldridge 2000). In estimating the 2SLS models I regress all exogenous variables, plus additional instrumental variables, on quantity in the first stage. Then, I use the predicted values of quantity in place of the actual values of quantity in the second stage. In generating the correct standard errors for the 2SLS models, sigma squared is calculated using the parameter estimates in the second stage regression, but the actual values of all the variables. In testing for heteroskedasticity, I use White's test. If homoskedasticity is rejected then robust standard errors are generated using the ACOV option in SAS. None of the 2SLS models had heteroskedasticity. The following tables display the test statistics for endogeneity and heteroskedasticity.

Table 3.1 Endogeneity Test Results

	Hausman Wu Test Results	H_o: Quantity is Exogenous
Front Range	P-value: <.0001	Reject H_o
Boulder	P-value: 0.4896	Fail to Reject H_o
CBT	P-value: <.0001	Reject H_o
Albuquerque	P-value: 0.6641	Fail to Reject H_o
Reno	P-value: 0.1318	Fail to Reject H_o
Texas Sales	P-value: 0.1255	Fail to Reject H_o
Texas Leases	P-value: 0.107	Fail to Reject H_o
McAllen Leases	P-value: 0.9989	Fail to Reject H_o

Table 3.2 Heteroskedasticity Test Results

	White's Heteroskedasticity Test Results	H_o: Homoskedasticity
Front Range	Chi-Square (20): 70.06 Pr > ChiSq: <.0001	Fail to Reject H_o
Boulder	Chi-Square (19): 18.89 Pr > ChiSq: 0.4637	Reject H_o
CBT	Chi-Square (27): 151.42 Pr > ChiSq: <.0001	Fail to Reject H_o
Albuquerque	Chi-Square (26): 26.68 Pr > ChiSq: 0.4264	Reject H_o
Reno	Chi-Square (23): 45.11 Pr > ChiSq: 0.0039	Fail to Reject H_o

Texas Sales	Chi-Square (26): 22.65 Pr > ChiSq: 0.6526	Reject H_o
Texas Leases	Chi-Square (34): 52.78 Pr > ChiSq: 0.0209	Fail to Reject H_o
McAllen Leases	Chi-Square (26): 19.19 Pr > ChiSq: 0.8282	Reject H_o

For each regression I also investigate multicollinearity. Using the collinearity diagnostics of the Variance Inflation Factor (VIF) tolerance levels, I examine what variables may be causing collinearity in the model and adjust the model accordingly. For the VIF, the recommendation is that the value be below 10 for each variable and for tolerance, the value should be greater than 0.10 (Ho Yu 2010 and Ayyangar 2007). For all regressions, variables which had a VIF greater than 10, also had a tolerance level of less than 0.10, so for simplicity I only mention VIF values. All regressions had multicollinearity as evidenced by several variables having VIF values greater than 10. Examining each model, I discovered that the income variable had a high VIF value in every regression. I suspected that income and population were similar measures, so I explored running each regression without income to see if multicollinearity issues subsided. In almost every model, eliminating income reduced the VIF values under 10 for all variables.

Even after eliminating income, a few regressions still exhibited some collinearity issues, which necessitated eliminating another variable in some cases. For these regressions I discuss further steps to reduce collinearity in the individual results section. For all other regressions, collinearity problems were sufficiently reduced by removing income as a variable. All regessions with income and a total quantity variable are in Appendix D.

3.2.2 Description of Variables and Expected Signs

The following variables are used in all models:

Lnprice: The natural log of price per acre foot of water for either sales or leases for each transaction. All prices are adjusted for inflation using the Consumer Price Index and are in 2009 real prices. Lnprice is the dependent variable in all regressions.

Quantity/Qhat: Quantity in acre feet per transaction, or the predicted value of quantity in acre feet for each transaction from stage one IV regressions. I expect Quantity/Qhat to have a negative sign indicating a downward sloping demand curve and the inverse relationship between price and quantity for normal goods. However, if the sign on quantity is positive, this could indicate increasing transaction costs stemming from higher levels of objections to a larger transfer (Colby 1990). Graphs of the total quantity sold or leased each year for each model are in Appendix C.

Adj_cmhpi: Conventional Mortgage Home Price Index (CMHPI) (Freddie Mac 2010a) adjusted for inflation using the Consumer Price Index to reflect 2009 prices. The CMHPI is released quarterly, so quarterly values were expanded using PROC EXPAND in SAS to monthly values. The CMHPI is compiled by Freddie Mac and, “is based on mortgages that were purchased or securitized by Freddie Mac or Fannie Mae since January 1975. These mortgages are "conventional" in their financing: they are not insured or guaranteed by any federal government agency… the index is based on mortgages for single unit residential houses only," (Freddie Mac 2010b). The CMHPI is used as a variable over other accessible housing market data, such as median home values from the National Association of Realtors, since the data is available for both the number of years needed (1987-2009) desired spatial scale of Metropolitan Statistical Area (MSA). I expect the sign of adj_cmhpi to be positive since housing prices are a strong indicator of the status of the local economy.

Trans_freq: This variable represents the frequency of urban water transactions occurring in each year, for each model. Years with high numbers of transactions represent years with high market activity, while years with fewer transactions represent less market activity. I expect trans_freq to be positive since higher market activity may indicate more competition for water, therefore increasing prices. Graphs of annual transaction frequency are in Appendix C.

Variables used in certain models:

SPI12_L6 or SPI12_L3: A six month lag of the 12 month Standardized Precipitation Index (SPI) for sales and a 3 month lag of SPI12 for leases. The SPI is a drought measurement index based on precipitation. The SPI is calculated for different time scales, from one month to 24 months, to measure short term and long term climate conditions. (NCDC 2010a) SPI12 picks up drought conditions over the past year, and the time lags attempt to capture any reporting lags from when the transfer occurred to when the transfer was reported in the *Water Strategist*. Lease arrangements generally take less time than sales transfers, which is why I chose to lag leases three months and sales 12 months. This SPI variable represents the climate division which encompasses the MSA where water is used (as opposed to the climate division representing the origin of water supply). Since the origin of a primary source of water supply for the areas modeled in Texas was not identified, all Texas models use the SPI variable representing the climate division for the urban area where the water is used.

The range of the SPI is continuous between -3 to +3 with negative values corresponding to drier than normal conditions and positive values to wetter than normal conditions (NCDC 2010b). Several combinations of SPI time scales with varying lags were tried in the models to examine how the SPI performed in the models. I use the same time scale and lag for sales to compare the effect of SPI on urban water prices across states and municipalities.

COSPI12_DIV2_L6: An SPI climate variable used in all Colorado models which represents the climate division where the primary water supply sources originate. In Colorado this climate division, division 2, includes the northern Rocky Mountains., where this primary water supply for the front-range area originates as snowpack.

COSPI12_DIV2_L6: An SPI climate variable used in the Albuquerque model which represents the climate division where a primary water supply sources originate. In Albuquerque, this climate division, which is Colorado climate division 5, This includes the southern Rocky Mountains which are the headwaters of a main water supply, the Rio Grande, for the Albuquerque region. The Albuquerque area does have other primary water supplies which originate in other areas, such as in Southwest Colorado where water from the San Juan Chama Project originates. However, not all regions where water supplies originate for the Albuquerque region could be included.

CASPI12_DIV3_L6: An SPI climate variable used in the Reno model and represents the climate division where primary water supply sources originate. For Reno, this climate division is the Northern Sierras, where a main source of water for the Reno area originates as snowpack.

I expect all SPI variables to be negative since drier conditions and water scarcity in the area in which supplies originate, or where water is used, can lead to water price increases.

Pop_exp: Total population by MSA (Real Estate Center 2010). Annual data was available, so the values were expanded to monthly values using PROC EXPAND in SAS. I expect the sign on pop_exp to be positive since water use increases with population and higher water use leads to increasing prices. Pop_exp is not used in all models due to collinearity issues.

Sup_dummy: A dummy variable with a value of 1 if the original water use was for agricultural uses, 0 otherwise. I expect the sign to be negative since agricultural water is a lower value use than other uses such as industrial, environmental, or municipal uses. Therefore, a municipality purchasing or leasing water is likely to pay less if the water was previously used in the agricultural sector, than if the water was used in another sector .

CBT_dummy: A dummy variable in the Boulder model taking a value of 1 if the transfer was Colorado Big Thompson (CBT) Project water, and 0 otherwise. I expect this variable to be positive, as CBT prices are generally on the higher end of water sales prices in Colorado. The CBT market is highly developed and competitive, so buyers may be willing to pay more for CBT water if transaction costs are lower, and there is an ease of entry into the market.

Lease_yrs: Only applicable for the Texas lease model, this variable indicates the number of years of the water lease under the terms of the lease. The minimum lease term in the data is one year, and lease terms of over 50 years are classified as sales. I expect this variable to be positive since leasers of water may be willing to pay a higher price to secure water for a longer period of time.

Instrumental Variables used in all stage one regressions:

frminc_lag12: Annual total farm income at the state level lagged 12 months. I lag the variable 12 months since farm income from the previous year is more likely to have an effect on the quantity of water sold out of agriculture in the current year. Also, at the time of this research, data was not available for the most current year (USDA 2010).

Groundwater OR sup_dummy: I use the sup_dummy variable for several models in the second stage regression, so for those models where sup_dummy is a variable used in the second stage, I use groundwater as an instrumental variable in the first stage. For models which do not include a sup_dummy variable in the second stage regression, I use the sup_dummy variable as an instrumental variable. Groundwater is a dummy variable taking a value of 1 if the water transferred is groundwater, 0 otherwise. The sign on groundwater could vary between locations depending on the quality and infrastructure of groundwater in the area. This variable is only used in certain models where groundwater use is prevalent. As stated above sup_dummy is a dummy variable with a value of 1 if the original water use was for agricultural uses, 0 otherwise.

Instrumental SPI climate variables used in stage on regressions for specific models:

SPI24_L6 OR SPI24_L3: I use another SPI variable, which reflects longer term drought conditions, to account for any long term drought conditions which may affect decisions on selling or leasing water. This variable is a 24 month drought variable and measures drought conditions over a two year period. The SPI drought variables listed previously are all SPI 12 variables and capture drought conditions over a one year period. This SPI variable, used in Texas stage one regressions, is from the climate division that incorporates the MSA where the water is used. I lag this variable six months for sales and three months for leases.

COSPI24_DIV2_L6: SPI 24 variable lagged 6 months. The variable is from the climate division representing much of the water supply origin in all Colorado models.

COSPI24_DIV5_L6: SPI 24 variable lagged 6 months. The variable is from the Colorado climate division representing much of the water supply origin for the Albuquerque MSA.

CASPI24_DIV3_L6: SPI 24 variable lagged 6 months. The variable is from the California climate division representing much of the water supply origin for the Reno MSA.

CHAPTER 4 RESULTS

4.1 INTRODUCTION

For each model I provide a brief background on the water right laws and policies governing each water market, as well as a discussion on make-up of unique buyers and sellers in each model. Markets with several unique buyers and sellers are more representative of a competitive market than those with just one or a few unique buyers or sellers.

Since a few of the variables in each model vary, I include a table of variables with a brief description for each model, along with a table of summary statistics. Regression results of each model are discussed, and tables with parameter estimates and marginal effects are included. In calculating the marginal effects, since all models are in semi-log functional form, all non dummy variable parameter estimates represent the percent change in water price per acre foot given a unit change in the corresponding variable. If the variable is a dummy variable, then the percent change in water price is calculated as $e^{B}-1$, where B is the dummy variable parameter estimate. The marginal effects for all models are in tables 4.25 and 4.26.

4.2 COLORADO

Water sales in Colorado are governed by the prior appropriation doctrine. Although the State Engineer in Colorado administers the State's waters, there is not a single point agency in charge of issuing water rights (BLM 2010). Water rights are issued by water courts and there are seven water courts in the state, one to represent each major river basin. The case load of each water court determines the length of time needed to obtain a water right (BLM 2010).

4.2.1 Front Range Sales

Investigating the number of unique buyers and sellers included in the Front Range model reveals an active market with numerous unique buyers and sellers. The sellers are more difficult to determine as many are often just listed as an irrigator, or a farmer, without any additional information. Nonetheless, buyers and sellers in the Front Range include multiple cities, ditch companies, brokers, investors, banks, water districts, and private companies.

The variables pop_exp and CBT_dummy are not included in the Front Range regression due to collinearity. After removing income, the VIF of several variables was still well above 10. Removing pop_exp and CBT_dummy from the model reduced the VIF on all remaining variables below 10. The Hausman Wu regression test rejects quantity as exogenous, so a 2SLS model is used for the Front Range. Results from the first stage regression are in Appendix A. Tests for heteroskedasticity fail to reject homoskedasticity, so the standard errors need no correction.

Table 4.1 Front Range Sales List of Variables

Variable	Description
adj_cmhpi	housing price index by MSA adjusted for inflation

trans_Freq	the number of sales in each year
COSPI12_DIV2_L6	SPI 12 lag six for CO climate division 2 where water supply is located for front range
Qhat	predicted quantity per transaction in acre feet

Table 4.2 Front Range Sales Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	10273.4	7369.19	105.22	28476.78
Quantity	111.5	698.4	0.5	13000
adj_cmhpi	237.68	47.38	158.97	302.85
trans_Freq	52.8	22.8	10	90
COSPI12_DIV2_L6	-0.05	0.86	-2.89	1.54

Table 4.3 Front Range Sales 2SLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.64662	0.17319	32.6	<.0001
adj_cmhpi	1.388%	0.01388	0.00054	25.59	<.0001
trans_Freq	0.084%	0.00084	0.00105	0.8	0.4246
COSPI12_DIV2_L6	-7.445%	-0.07445	0.02319	-3.21	0.0014
Qhat	-0.064%	-0.00064	0.00020	-3.2	0.0014
n = 965					
adj R^2=0.596					

All variables in the Front Range model have the expected sign and are all statistically significant except for transaction frequency. Housing prices positively affect urban water prices, and quantity has a negative influence on water prices. Since the range of the SPI drought variable is negative when conditions are dry, the negative sign suggests that drought conditions in the climate division when water supply originates have a positive effect on urban water prices. That is to say that drier conditions increase prices.

4.2.2 Boulder, Colorado Sales

Boulder is a much smaller model than the Front Range, with just 87 observations. Nonetheless, the urban water market in the Boulder MSA remains active and competitive with several unique buyers and sellers represented in the data. Collinearity diagnostics revealed that collinearity was still prevalent in the model even after income was removed, so pop_exp was also removed. After removing pop_exp, all VIF values of the variables were less than 10. I use an OLS model for Boulder since the Hausman Wu test fails to reject exogeneity. Heteroskedasticity results reject homoskedasticity, so standard errors are corrected to reflect robust standard errors.

Table 4.4 Boulder Sales List of Variables

Variable	Description
CBT_dummy	dummy variable equal to 1 if the sale is CBT water, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
trans_Freq	the number of sales in each year
COSPI12_DIV2_L6	SPI 12 lag six for CO climate division 2 where water supply is located for front range
quantity	quantity per transaction in acre feet

Table 4.5 Boulder Sales Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	9764.24	7774.89	697.40	23137.39
CBT_dummy	0.74	0.44	0	1
adj_cmhpi	281.7	66.4	174.9	363.7
trans_freq	6.29	3.66	1	13

COSPI12_DIV2_L6	-0.11	0.95	-2.26	1.54
Quantity	132.34	462.78	0.7	3500

Table 4.6 Boulder Sales OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.2538	0.3345	15.71	<.0001
CBT_dummy	150.07%	0.9166	0.1693	5.41	<.0001
adj_cmhpi	1.05%	0.0105	0.0007	15.48	<.0001
trans_freq	-3.43%	-0.0343	0.0147	-2.33	0.0223
COSPI12_DIV2_L6	-8.28%	-0.0828	0.0491	-1.69	0.0958
Quantity	0.04%	0.0004	0.0001	5.30	<.0001
n = 87					
adj R^2=0.819					

All variables in the Boulder model are statistically significant. CBT_dummy and adj_cmphi both have the expected positive signs with CBT project water and housing prices positively influencing urban water prices in Boulder. The SPI variable is negative as expected, so urban water prices increase during periods of drought in the climate division affecting water supplies. Trans_freq and quantity both display unexpected signs. A negative sign on trans_freq could indicate that if markets are inactive then perhaps less water is available and prices are higher than in years where water supply is abundant. A positive sign on quantity is not in line with economic theory, but the sign could be indicative of water transaction with higher transaction costs.

4.2.3 Colorado Big Thompson (CBT) Sales

The Colorado Big Thompson (CBT) Project is the largest trans-mountain water diversion project in Colorado (NCWCD 2010a). Through a system of dams, reservoirs, tunnels, canals, and pipes, the project moves water from the western to the eastern slope of the Rocky Mountains. Completed in 1957, the CBT Project delivers about 213,000 acre feet of water annually for irrigation, municipal, and industrial uses in Northeastern Colorado. Around 30 cities and town receive supplemental municipal water from the Project (NCWCD 2010a). The importance of the CBT project to urban water users is seen in the number of observations in the model. Of the total 1052 Colorado observations, 940 are CBT Project sales. Figure 4.1 provides an illustration of the Project's eastern slope distribution system (NCWCD 2010b).

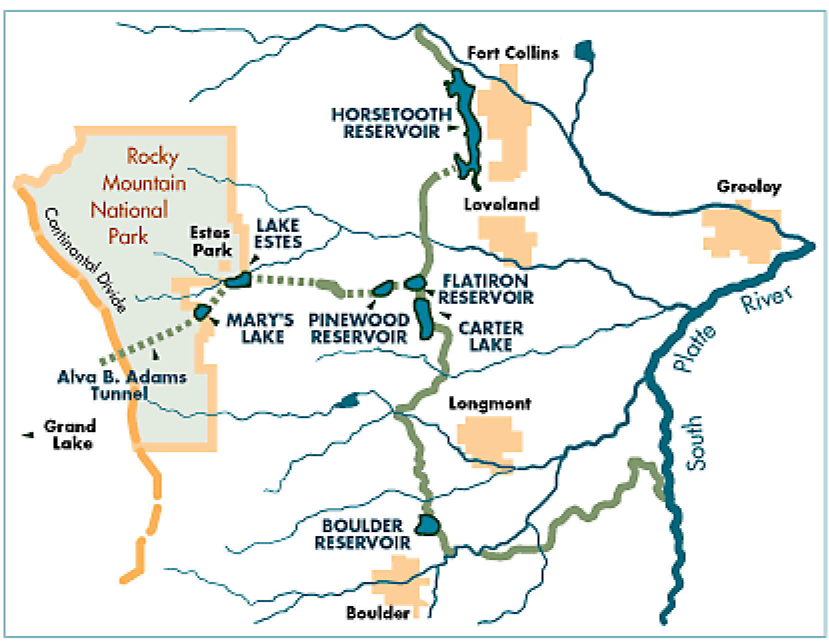

Figure 4.1 CBT Eastern Slope Distribution

Since the model only contains CBT sales, it is not surprising that the heteroskedasticity test fails to reject homoskedasticity, so no standard error correction is necessary. In testing for endogeneity, however, the Hausman Wu results reject that quantity is exogenous, so a 2SLS model is used for the CBT regression. Results from the first stage regression are in Appendix A. Without the income variable in the equation, all the VIF values for the variables are less than 10.

Table 4.7 CBT Sales List of Variables

Variable	Description
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
COSPI12_DIV2_L6	SPI 12 lag six for CO climate division 2 where water supply is located for front range
Qhat	predicted quantity per transaction in acre feet

Table 4.8 CBT Sales Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	10894.8	7441.35	1100	28476.78
adj_cmhpi	243.89	50.04	158.97	361.18
pop_exp	1944974	499920	220489	2496205
trans_freq	53.9	23.3	2	91
COSPI12_DIV2_L6	-0.087	0.854	-2.89	1.54
Quantity	40.29	98.32	0.5	1246

Table 4.9 CBT Sales 2SLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.7111	0.2840	20.11	<.0001
adj_cmhpi	1.276%	0.0128	0.0005	23.31	<.0001
pop_exp	0.00002%	0.0000002	0.0000001	3.33	0.0009

trans_freq	0.115%	0.0011	0.0012	0.96	0.3361
COSPI12_DIV2_L6	-11.581%	-0.1158	0.0289	-4	<.0001
Qhat	-0.705%	-0.0071	0.0019	-3.62	0.0003
n = 940					
adj R^2=0.5206					

The variables included in the CBT regression all have the expected sign, and with the exception of trans_freq, they are all statistically significant. Positive influences on urban water prices for CBT project water include housing prices, population, and drought, while quantity is a negative influence. The impact of the SPI variable in all the Colorado models is consistent and significant, so drought in the climate division where water supply originates for the area as a whole increases the prices paid for urban water.

4.3 NEW MEXICO

4.3.1 ALBUQUERQUE, NEW MEXICO SALES

Water rights in New Mexico are based on the prior appropriation doctrine. All distribution and appropriation of water in the state is managed by the office of the State Engineer. The length of time to complete a water right sale in New Mexico can vary. The minimum is around three months if the transaction is not complex and there are no protests. However, for more complex transfers and for those involving protests and litigation, the process can take years (BLM 2010). Varying transaction and reporting times can create difficulties when using time specific variables in a model, such as climate variables.

The urban water sales model for New Mexico involves only transactions in the Albuquerque area, and the city of Albuquerque is the predominant buyer of water for the included transactions. Although, the city of Albuquerque is a major buyer of urban water in the area, urban water transactions are only a subset of the general water market in the area and several other industrial and agricultural users are also active water buyers. The number of observations in the regression is small at just 35, but interesting insights into the urban water market in the Albuquerque area are still attained. To represent the water supply origins of Albuquerque's water, I use Colorado's climate division 5, which represents the lower Colorado Rockies.

Table 4.10 Albuquerque Sales List of Variables

Variable	Description
sup_dummy	dummy variable equal to 1 if the supply comes from agriculture, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
COSPI12_DIV5_L6	SPI 12 lag six for CO climate division 2 where water supply is located for New Mexico
Quantity	quantity per transaction in acre feet

Table 4.11 Albuquerque Sales Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	3402.6	2032.1	1154.6	8000
sup_dummy	0.8	0.4	0.0	1
adj_cmhpi	188.80	21.26	162.31	245.82
pop_exp	671116	90525.9	562268	847485.4
trans_freq	2.6	1.35473	1	5

COSPI12_DIV5_L6	0.492	0.980	-1.920	2.150
Quantity	147.6	156.8	2.2	680.4

Table 4.12 Albuquerque Sales OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		3.3048	0.4019	8.22	<.0001
sup_dummy	-19.7850%	-0.2205	0.1070	-2.06	0.0487
adj_cmhpi	0.6050%	0.0061	0.0024	2.51	0.0182
pop_exp	0.0005%	0.000005	0.000001	6.34	<.0001
trans_freq	3.4840%	0.0348	0.0279	1.25	0.2215
COSPI12_DIV5_L6	-0.1680%	-0.0017	0.0509	-0.03	0.9738
quantity	0.0016%	0.00002	0.0003	0.05	0.9622
n=35					
adj R^2=0.8592					

For the Albuquerque test results, I fail to reject exogeneity and homoskedasticity, so an OLS model is used for the regression with corrected standard errors. Collinearity diagnostics after removing income from the model display VIF values of all variables under 10.

Although only three variables are significant in the Albuquerque regression, they all have the expected sign. Population and housing prices both positively influence urban water prices in the Albuquerque MSA, while water sold out of agriculture to the urban area is lower than water sold from other uses.

4.4 NEVADA

4.4.1 Reno, Nevada Sales

Urban water sales in Nevada occur primarily in Reno. The market is characterized by numerous sales for new development in Reno due to the Truckee Meadows Water Authority's (TMWA) Rule 7. Rule 7 requires new development that will require new water service to dedicate water rights to TMWA in the amount needed for service (TMWA 2010). Water supply in the Reno area originates as snowpack in the Sierra Mountains, which straddle western Nevada and eastern California. To account for climatic changes in water supply, the SPI from California's climate division (DIV 3) is included in the model.

Table 4.13 Reno Sales List of Variables

Variable	Description
sup_dummy	dummy variable equal to 1 if the supply comes from agriculture, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
CASPI12_DIV3_L6	SPI 12 lag six for CO climate division 2 where water supply is located for Reno
Qhat	predicted quantity per transaction in acre feet

Table 4.14 Reno Sales Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	14108.3	11966.8	797.0	47887.7
sup_dummy	0.00469	0.06852	0	1
adj_cmhpi	260.43	65.30	175.16	363.29
pop_exp	362938	51511.9	233036	418792.8
trans_freq	17.3	6.7	1	27
CASPI12_DIV3_L6	-0.15	1.07	-2.01	1.91
Quantity	231.6	458.9	0.15	3487

Table 4.15 Reno Sales OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.7027	0.3174	17.97	<.0001
sup_dummy	-20.7434%	-0.2325	0.5945	-0.39	0.6961
adj_cmhpi	0.6230%	0.0062	0.0012	5.3	<.0001
pop_exp	0.0005%	0.000005	0.000001	4.38	<.0001
trans_freq	-0.3280%	-0.0033	0.0104	-0.32	0.7529
CASPI12_DIV3_L6	7.5440%	0.0754	0.0420	1.8	0.0738
quantity	-0.0244%	-0.0002	0.0001	-2.77	0.0062
n=213					
adj R^2=0.5608					

Reno regression tests fail to reject exogenetiy, so an OLS model is used. White's heteroskedasticity test fails to reject homoskedasticity, so the standard errors are robust and do not need correcting. Removing the income variable from the regression reduced the VIF values of all variables to under 10.

The variables included in the regression explain a moderate amount of the variation in urban water sales with an R^2 of .5608. Most significant variables in the model also have the expected signs. Adj_cmhpi and pop_exp are both positive and significant, while quantity is negative and significant. The SPI variable is unexpectedly positive. Perhaps if drought is affecting the quantity of the water supply, there are few or no transactions to register an increase in prices.

4.5 TEXAS

4.5.1 TEXAS SALES

Surface water rights in Texas adopted both the riparian and prior appropriation doctrines, with both systems merging into one permit system in the 1960s. Surface water belongs to the State and anyone wishing to appropriate water must receive a permit for use from the Texas Commission on Environmental Quality. Groundwater rights, on the other hand, belong to the owner of land above where the water is located (Texas A&M 2010).

Urban water sales in this data set are composed of sales in El Paso, Laredo, McAllen, and San Antonio. Sales in El Paso are mostly 75 year leases (reclassified as sales due to the extended lease length) and El Paso Water Utilities is the primary acquirer of urban water. The City of Laredo is the most active purchaser of urban water in the Laredo area, with most sales being Lower Rio Grande surface water rights. Sales in the McAllen area are also primarily Lower Rio Grande surface rights with several municipalities involved in the purchases. Groundwater from the Edwards Aquifer is the main water source purchased in the San Antonio area, with San Antonio Water System being the primary buyer. There are 58 observations in the Texas Sales regression.

Table 4.16 Texas Sales List of Variables

Variable	Description
sup_dummy	dummy variable equal to 1 if the supply comes from agriculture, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
SPI12_L6	SPI 12 lag six for the climate division where the water use is located
Qhat	predicted quantity per transaction in acre feet

Table 4.17 Texas Sales Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	1370.2	1324.4	72.7	6500
sup_dummy	0.6	0.49	0	1
adj_cmhpi	174.2	19.85	141.35	214.28
pop_exp	920046	616919	153324	2065502
trans_freq	3.3396	1.2395	1	5
SPI12_L6	0.07	1.01	-1.82	2.32
Quantity	4354.7	10705	2.5	70000

Table 4.18 Texas Sales OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		5.42530	1.3495	4.02	0.0002
sup_dummy	-30.862%	-0.36907	0.2959	-1.25	0.2186
adj_cmhpi	1.021%	0.01021	0.0071	1.44	0.1579
pop_exp	0.00006%	0.0000006	0.0000002	3.22	0.0024
trans_freq	-13.3090%	-0.13309	0.0816	-1.63	0.1099
SPI12_L6	-9.5380%	-0.09538	0.0904	-1.06	0.2969
Quantity	-0.0041%	-0.00004	0.000009	-4.4	<.0001
n=53					
adj R^2=0.4673					

In testing the model, I fail to reject exogeneity and homoskedasticity, so an OLS model is used for Texas Sales and no correction is needed for the standard errors. Compared to other models in this analysis, the variables in the Texas Sales regression explain the least amount of the variation in urban water prices. However, in terms of the variable's signs, most are as expected, with the only exception being trans_freq, which is negative, but was expected to be positive. However, several different MSAs are combined in this regression, so evaluating the effects of market activity on price is challenging if market activity is different between MSAs. Population is a positive and significant influence on water prices, while quantity is a negative and significant influence. Potential future improvements to the model could be made with when enough observations are available to analyze each individual MSA separately.

4.5.2 Texas Leases

Texas urban water leases in this regression include the El Paso, San Antonio, and McAllen MSAs. El Paso and McAllen leases are largely for Rio Grande surface water while San Antonio lease are primarily Edwards Aquifer groundwater leases. The length of the leases in the model range from 1 year to 40 years, but the majority are one year leases.

Table 4.19 Texas Leases List of Variables

Variable	Description
sup_dummy	dummy variable equal to 1 if the supply comes from agriculture, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
lease_yrs	the terms of the lease in years
SPI12_L6	SPI 12 lag six for the climate division where the water use is located
Qhat	predicted quantity per transaction in acre feet

Table 4.20 Texas Leases Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	76.58	88.69	14.48	789.71
sup_dummy	0.73	0.45	0	1
adj_cmhpi	167.8	14.2	143.8	201.4
pop_exp	1019276	599438	399819	2044795

trans_freq	6.3	2.1	1	9
lease_yrs	4.13	6.40	1	40
SPI12_L3	0.07	1.04	-1.96	1.7
Quantity	3132.97	4626.07	3	28116

Table 4.21 Texas Leases OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		4.2784	0.8238	5.19	<.0001
sup_dummy	-11.123%	-0.1179	0.1327	-0.89	0.3766
adj_cmhpi	-0.775%	-0.0078	0.0049	-1.59	0.1147
pop_exp	0.00005%	0.0000005	0.0000001	3.8	0.0003
trans_freq	8.801%	0.0880	0.0247	3.56	0.0006
lease_yrs	3.221%	0.0322	0.0096	3.37	0.0011
SPI12_L3	-2.977%	-0.0298	0.0433	-0.69	0.4934
Quantity	0.00143%	0.00001	0.00001	1.26	0.2114
n=92 adj R^2=0.5683					

Test results for the model fail to reject exogeneity, so I use an OLS model for the Texas leases regression. I also fail to reject homoskedasticity, so corrected standard errors are calculated. Without the income in the model, the VIF collinearity diagnostic values are under 10 for all variables. Although several variables in the model are not significant, Pop_exp, trans_freq, and lease_yrs are all significant and have an expected positive sign.

4.5.3 McAllen, Texas Leases

The McAllen, Texas lease model is a sub set of the Texas lease model, with 58 observations. All of the leases in the McAllen area are one year leases for Lower Rio Grande surface water. Although several entities lease water for municipal use in the area, further information about the leases, such as the exact entities and their locations is not always provided. For this reason, some leases included in the data set may fall outside of the McAllen MSA. McAllen is the largest MSA in the region, so its demographics are likely to influence the greater area even if they are not entirely representative of exact location of the water lease.

Table 4.22 McAllen Leases List of Variables

Variable	Description
sup_dummy	dummy variable equal to 1 if the supply comes from agriculture, 0 otherwise
adj_cmhpi	housing price index by MSA adjusted for inflation
pop_exp	population by MSA
trans_Freq	the number of sales in each year
SPI12_L6	SPI 12 lag six for the climate division where the water use is located
Quantity	quantity per transaction in acre feet

Table 4.23 McAllen Leases Summary Statistics

Variable	Mean	Std Dev	Minimum	Maximum
adj_price	44.93	14.55	14.48	95.40
sup_dummy	0.91	0.28	0	1
adj_cmhpi	163.0	6.8	152.3	175.6
pop_exp	598071.4	89608.6	399819	739483.5
trans_freq	3.7	1.1	1	5
SPI12_L3	-0.03	0.95924	-1.82	1.54
Quantity	2494.85	2510.63	3	9062.1

Table 4.24 McAllen Leases OLS Regression Results

Variable	Marginal Effects	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		4.2000	1.0245	4.1	0.0001
sup_dummy	3.9126%	0.0384	0.0596	0.64	0.5225
adj_cmhpi	-1.6750%	-0.0168	0.0083	-2.03	0.0479
pop_exp	0.0003%	0.000003	0.000001	3.99	0.0002
trans_freq	5.0210%	0.0502	0.0391	1.28	0.2048
SPI12_L3	-4.4060%	-0.0441	0.0317	-1.39	0.17
quantity	0.0006%	0.00001	0.00001	0.46	0.6508
n=92 adj R^2=0.5683					

Hausman Wu regression test results fail to reject exogeneity, so an OLS model is used for the McAllen lease regression. As for heteroskedasticity, the test results reject homoskedasticity, so the standard errors are corrected. No collinearity issues exist after removing income from the model.

The only positive, significant variable is pop_exp, which is positive as expected, so population appears to have a strong influence on one year water leases of urban water in the McAllen, Texas MSA. The housing price index, adj_cmhpi, is significant, but the sign is negative, which is unexpected. Competition for water leases in the area could keep lease prices from declining, even as housing prices in recent years have decreased.

4.6 Concluding Remarks

Different spatial scales have been used in previous research on water transactions, such as the state level and the county level, and often several states or regions were included in a single regression. In this research, I run several models with data from a single MSA, and also models combining several MSA's. In examining previous results, as well as my own, smaller spatial scales with data on an individual market generally perform better than those at higher spatial scales or those including more than one area. Econometric research on water transactions is often limited by the number of transactions occurring on a smaller spatial scale. However, as more transactions occur over time, many models could be improved as more data becomes available.

Although each water market is unique and the factors influencing water prices can differ across regions and be quite localized, some consistent patterns can still be observed after examining all regression results. For all sales regressions the housing price index variable, adj_cmhpi is statistically significant with the exception of Texas sales. The importance of including adj_cmhpi in the regressions is that it may be a more appropriate demographic variable to incorporate that those included in the past such as income. Since houses and water are both legally considered property, fluctuations in the urban housing market may have a stronger relationship with fluctuations in the urban water market.

Population is also a strong variable across models. The population variable was removed from the Front Range and Boulder models, due to collinearity with the housing index variable. However population is positive and significant in every other model. Since the per capita income variable was removed from all models due to collinearity with either the population or the housing index variable, I am not able to discuss how per capita income influences urban water prices. The following tables compile the marginal effects of each model. The calculation of marginal effects is discussed in section 4.1.

Table 4.25 Marginal Effects and Significance for CO, NM, and NV Models

State:	**Colorado**			**New Mexico**	**Nevada**
Model:	**Front Range**	**Boulder**	**CBT**	**Albuquerque**	**Reno**
Variables					
CBT_dummy	N/A	1.5007***	N/A	N/A	N/A
sup_dummy	N/A	NA	N/A	-0.19785**	-0.2074
adj_cmhpi	0.01388***	0.0105***	0.0128***	0.0061**	0.0062***
pop_exp	N/A	N/A	0.0000002***	0.000005***	0.000005***
trans_freq	0.00084	-0.0343**	0.0011	0.0348	-0.0033
##SPI12_DIV#_L6	-0.07445***	-0.0828*	-0.1158***	-0.0017	0.0754*
Qhat/quantity	-0.00064***	0.0004***	-0.0071***	0.00002	-0.0002***
**** significant at 1% ** significant at 5% * significant at 10%*					

Table 4.26 Marginal Effects and Significance Levels for TX Models

State:	**Texas**		
Model:	**Texas Sales**	**Texas Leases**	**McAllen Leases**
Variables			
sup_dummy	-0.30862	-0.11123	0.0384
adj_cmhpi	0.01021	-0.0078	-0.0168**
pop_exp	0.0000006***	0.0000005***	0.000003***
trans_freq	-0.13309*	0.0880***	0.0502
Lease_yrs	N/A	0.0322***	N/A
SPI12_L6	-0.09538	-0.0298	-0.0441
Qhat/quantity	-0.00004***	0.00001	0.00001
**** significant at 1% ** significant at 5% * significant at 10%*			

In the Front Range, Boulder, CBT, Albuquerque, and Reno models I use the SPI variable which corresponds to the climate division where much of the water supply for the urban area originates, and in the Texas models I use the SPI variable which corresponds to the climate division where the water is used. For Texas, identifying a single climate division to use which would represent where much of the water supply originates, is challenging, so I did not attempt it. In the other models, a primary supply source region easier to identify. However, in either case, including an SPI variable from more than one climate division in a regression could potentially provide more information on the effects of drought on urban water prices. The main problem in doing so is that an interaction term would need to be included in the regression as well. The scaling of the SPI from -3 to +3 does not permit creating a multiplicative interaction term, so, at this point I am not able to include more than one SPI variable in a regression.

Identifying which climate division SPI variable has an effect on urban water prices is clearer in some models than in others. In the Colorado models, the SPI variable from the climate division representing where much of their water supply originates is negative, and significant in all three models. In Appendix E, I show the results of running the Colorado models with a different SPI variable, that which represents the climate division where the water is used. The SPI variable in the latter case is not significant in any of the three models. Both SPI variables are a 12 month SPI lagged 6 months. So, for Colorado, drought the climate division representing where significant portions of their water supply originate increases urban water prices, while drought in the climate division representing where the water is used has an insignificant effect.

CHAPTER 5 URBAN WATER SUPPLY RELIABILITY CASE STUDIES

5.1 INTRODUCTION

This chapter is an in-depth look at urban water supply reliability using the cities of Tucson, Arizona, Las Vegas, Nevada, and Portland, Oregon, as case studies. Assessing urban water supply reliability is approached with a discussion on each city as well as calculating indicators for a quantitative perspective. In discussing each city, I look not only at water supply reliability, but also supply vulnerability and resiliency, adopting the following definitions, "System performance can be described from three different viewpoints: (1) how often the system fails (reliability), (2) how quickly the system returns to a satisfactory state once a failure has occurred (resiliency), and (3) how significant the likely consequences of failure may be (vulnerability)" (Hashimoto, et al 1982 p15). Several different aspects of a city's water supply contribute to its reliability, vulnerability, and resiliency such as: diversity and governance of supply sources, water storage and back-up supplies, rate of water use growth, ability to secure new water sources, and vulnerability to climate impacts (Lang 2003). Each of these aspects will be discussed in detail for each city.

Numerous methods exist in the literature for approaching water supply reliability, vulnerability, and/or resiliency in a quantitative way, spanning multiple disciplines and levels of complexity. The intention of this research is to explore quantitative measures which can be useful to municipalities for their own internal use, and which could also be useful as a means to compare across municipalities. For this reason I explored several uses of water supply reliability and vulnerability indicators in the literature, looking for examples of indicators with relatively straightforward definitions and calculations, and which can be computed with available data.

5.1.1 Indicators from the Literature

The indicators chosen for this research are adopted from two articles (Lane, et al 1999 and Hurd, et al 1999), both of which applied the indicators to water supply systems on larger geographic scales, one at the regional level, and one at the watershed level. Here these indicators are applied to a smaller geographic scale to provide insights about a municipal level water supply system. Some adaptations of the indicators are necessary to make them relevant on this smaller scale and to suit the different geographic regions. In an effort to compare indicator values across each city, all indicators are set up so that the higher the value of the indicator, the more stress water system for that component of the system the indicator is evaluating. The indicators as they appear in the literature are as follows:

1. **Storage Vulnerability** – "Measure of region's ability to cope with extreme water events; by reservoir yield, which is approximated by consumptive demand divided by regional reservoir storage capacity (internal and upstream)." (Lane, et al 1999, p195)
2. **Withdrawal ratio** – "Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable

ground waters, plus water imports from both transfers and natural upstream systems." (Lane, et al 1999, p196)

3. **Natural Variability** "Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of unregulated annual streamflow to the unregulated mean annual streamflow. Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes." (Hurd, et al 1999, p1401)
4. **Groundwater Depletion** "Ratio of average groundwater withdrawals in year [i] to annual average baseflow, reflecting the extent that groundwater use rates may be exceeding recharge. Regions with high depletion rates are vulnerable to long-run changes in hydrology," (Hurd, et al 1999, p1401).

Since the indicators discussed above in the literature do not include any indicators to evaluate resiliency, I developed an indicator based on the resiliency definition, "how quickly the system returns to a satisfactory state once a failure has occurred," (Hashimoto et al 1982 p15). The exact speed of recovery would be impossible to know with exact knowledge of future climate and water use. However we can get a strong idea of which systems are more resilient than others. In the context of a reservoir system, the speed of recovery from drought depends on the size of the system, average streamflows, and the intensity of water use from the system. One measure could calculate total reservoir capacity divided by average annual inflow, but this would not take into account how much of the water is released from the system for consumption. A way to integrate the intensity of use into a resiliency is to also calculate annual water consumption from the system divided by average annual inflows. Multiplying these two values we arrive at a figure that increases as a reservoir becomes less resilient. The proposed indicator is as follows:

Reservoir System Resiliency – A measure of a reservoir system's ability to recover from drought; 1) Reservoir capacity divided by average annual inflows; 2) Annual water use or system outflows divided by average annual inflows; 3) multiply both values together.

The limitation of this indicator is that it is only applicable to surface water reservoir systems and does not measure resilience of other water sources, such as groundwater. The indicator, along with the other indicators introduced above are not meant to be complete indicators of a water supply system, but rather partial indicators that measure particular aspects of water supply reliability, vulnerability, and resiliency. Although the definitions and calculations of the indicators are straightforward, one of the challenges is in finding useful data and a proper geographic scale to actually calculate indicators. Another challenge is the context of the indicator, what is the number telling us and can it be used to compare one city to another?

These indicators are often referred to as sustainability indicators (Roy, et al 2005). Since several definitions of sustainability exist, I adopt the following, which is from a set of defined rules regarding sustainability, "Renewable resources such as fish, soil, and groundwater must be used no faster than the rate at which they regenerate," (ACWI 2010). While I do not directly refer to the indicators in this discussion as sustainability indicators, using the above definition, the Withdrawal Ratio and Groundwater Depletion

Indicators can be seen as measuring aspects of water use sustainability for each municipality. The other indicators, Storage Vulnerability, Natural Variability, and Reservoir Resiliency, are not considered measures of sustainability using the above definition. However, in measuring aspects of reliability, vulnerability, and resiliency, these indicators measure features of water supply system which can influence sustainable use of water resources.

The indicators presented in the literature and discussed above can aid in developing a quantitative picture of municipal reliability, vulnerability, and resiliency to drought and climate change. In the following sections, I address these issues of calculating and using indicators, and whether the particular indicators selected are useful for the purpose of assessing actual municipal water supply systems. The benefit of employing a quantitative approach is to provide another method of evaluation beyond just a discussion of the issues. Each method can give different angles on the subject and lead to a more thorough understanding of urban water supply reliability, vulnerability, and resiliency.

5.2 Tucson, Arizona

Tucson’s arid climate and growing population are pressing factors in the area’s quest towards sustainable long term water sources. Along with sustainable water sources, however, Tucson must also continually evaluate the reliability, resiliency, and vulnerability of its entire water source system. Tucson’s population is expected to continue growing and the effects of severe drought or climate change could significantly alter future water supplies. These factors could all lead to previously sustainable water supplies becoming unsustainable, or non-renewable, in the future. Understanding potential future water demands and potential future water supply shortages allows for an evaluation future water system weaknesses. Knowledge of these weaknesses informs current planning to obtain a comfortable balance of water supply reliability, resiliency, and vulnerability.

The three primary water sources in the Tucson region are groundwater, Colorado River surface water brought to the area by the Central Arizona Project (CAP) Canal, and reclaimed water or effluent. The City of Tucson is the largest urban water provider in the metro area and supplies its obligated service area, which does not encompass the whole metro Tucson region. This study is concerned with the greater Tucson metro area and so I will base much of this discussion on water use information and data from the Arizona Department of Water Resources (ADWR) and their work in the Tucson Active Management Area (AMA). Water use information from the City of Tucson will also be used to supplement and enhance information from ADWR.   Figure 5.1 illustrates the Tucson Water's current service area, their obligated service area, and potential service area (City of Tucson and Pima County 2009).

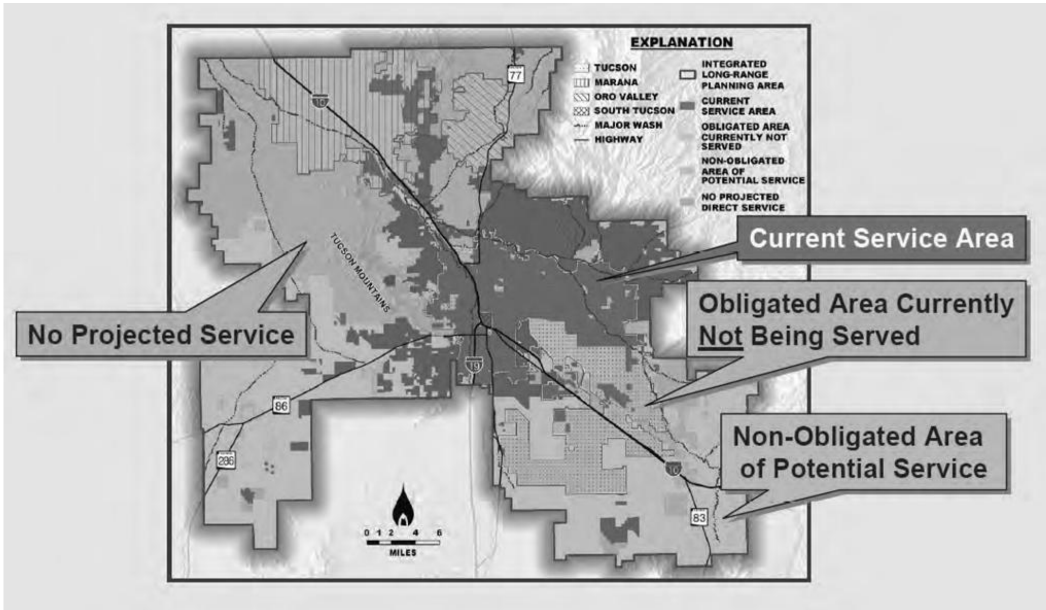

Figure 5.1 Tucson Water Service Area

The Groundwater Management Act of 1980 established the Tucson AMA, along with several other AMAs. The AMAs are urban areas with stricter groundwater use regulations, enacted due to years of overdraft. The AMAs are managed by ADWR. The Tucson AMA covers 3,866 square miles, with water use coming primarily from municipal, industrial, agricultural, and Indian users. Municipal uses are the highest share of overall water use (ADWR 2010b), Table 5.1 lists the major municipal water providers in the Tucson AMA.

Table 5.1 Major Municipal Water Providers in the Tucson AMA

Major Municipal Water Providers within the Tucson AMA	Community Water Company of Green Valley
	Flowing Wells Irrigation District
	Marana Water Department

	Metro Water District
	Oro Valley Water Utility
	Tucson Water

Industrial water use is primarily for metal mines, and “Indian water” is defined as water rights designated to Native American tribes through water rights settlements. Portions of the Tohono O’odham Nation Reservation are located within the Tucson AMA. Figure 5.2 is a map showing the layout of the City of Tucson, the Tucson AMA, and Pima County, (Barker 2009).

Figure 5.2 Map of the City of Tucson, the Tucson AMA, and Pima County

The most recent publication from ADWR is the "Tucson AMA Draft Demand and Supply Assessment." The assessment reports observed water use data from 1985-2006 and then projects three Baseline Scenarios for future water use for the period of 2007-2025. "Baseline Scenario One represents the lowest reasonable water demand, Baseline Scenario Three the highest reasonable water demand, while Scenario Two is a mid-level projection," (ADWR 2010b, 50). Figures 5.3 and 5.4 show water use by sector, Municipal, Agriculture, Industrial, and Indian for 1990 and 2010, with 2010 based on Baseline Scenario Two projections (ADWR 2010b).

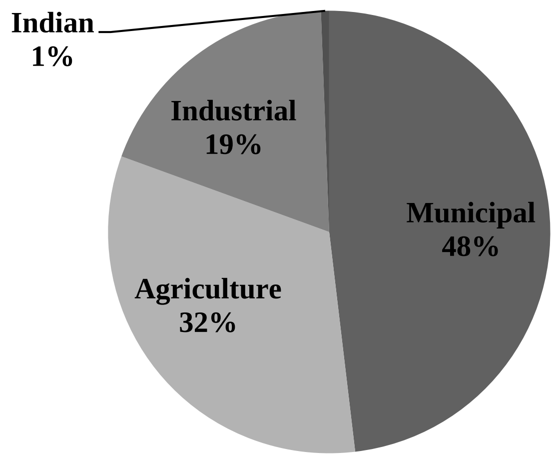

Figure 5.3 Tucson AMA Water Use by Sector, 1990

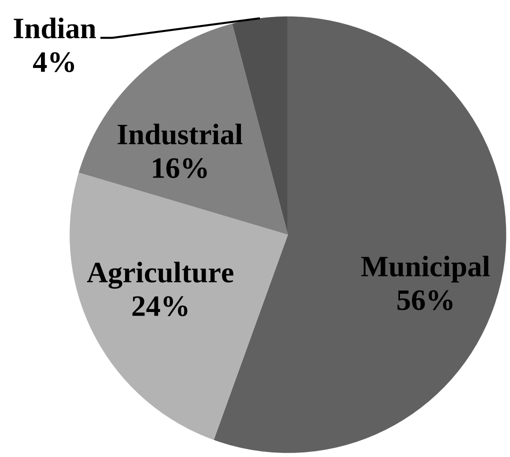

Figure 5.4 Tucson AMA Water Use by Sector, 2010 (projected)

In addition to the three Baseline Scenarios, ADWR includes three additional scenarios based on supply shortages and one scenario looking at reclaimed water maximization. The purpose of the assessment is to gain a better understanding of future water use scenarios and to see how the Tucson AMA may attain its Safe Yield goal of sustainable groundwater use by 2025. Several acronyms are used in this discussion; the following table provides a reference.

Table 5.2 List of Tucson Case Study Acronyms

ACRONYM	**DESCRIPTION**
ADWR	Arizona Department of Water Resources
AF	Acre Feet
AMA	Active Management Area
AWBA	Arizona Water Banking Authority
BOR	Bureau of Reclamation
CAGRD	Central Arizona Groundwater Replenishment District
CAP	Central Arizona Project
GMA	Groundwater Management Act
GSF	Groundwater Savings Facilities
ICS	Intentionally Created Surplus
USF	Underground Storage Facilities

5.2.1 Diversity and Governance of Supply Sources

Water supply diversity affects supply reliability since an urban area relying on several water sources has a more reliable system than if the area relied exclusively on one source. The reason being, if there is only one source, and that source is in shortage, then the entire water system is in shortage. If there is more than one source and one source is in shortage, then there are other sources to draw from. The system is less likely to fail so long as shortages in the sources are not highly correlated, that is they are not all subject to simultaneous shortage. Tucson, with its three sources of water, groundwater, effluent and Colorado River surface water, is diversified in its water supply portfolio. Shortages in these three supplies are unlikely to be highly correlated. However, each source has its own associated risks and benefits.

How each source is governed or managed also affects supply reliability. Issues ranging from water rights and priorities among uses to use restrictions on water sources all play a role in current and future water supply reliability. In the following sections I discuss each of the supply sources in the Tucson AMA, how the source contributes to the overall supply portfolio, and how management and use of each source affects its reliability.

Groundwater

Until the 1990's, groundwater was Tucson's only source of potable water. Although reliable historically, groundwater in this arid region is very slow to recharge and is therefore not resilient. Over time, the amount of groundwater pumped continually grew with the population until the amount pumped far exceeded the amount of natural recharge. Tucson still relies on groundwater, and the area still has vast groundwater reserves. However, state water regulations recognize that using more water than is recharged will eventually deplete the recoverable water, leaving water users continually more vulnerable to shortage. If surface water from the Colorado River were to be in shortage or if effluent supplies were interrupted, groundwater could be relied upon to serve the area. However, years of cumulative overdraft is not a reliable strategy in the long run.

Groundwater for each AMA in Arizona is governed by the Groundwater Management Act of 1980 (GMA) with implementation of the Act overseen by ADWR.

As stated above, the goal for the Tucson AMA is to attain Safe Yield, or sustainable groundwater use, by 2025. While the GMA prohibits new well construction for irrigation purposes within the AMA, there are Irrigation Grandfathered Rights for those who legally irrigated with groundwater between 1975 and 1980. Also within the AMA are Non-Irrigation Grandfathered Rights, which have caps on annual pumping volumes. For municipal use, there are Service Area Rights, and new groundwater permits, usually for industrial permits, allow for new withdrawals only outside of municipal service areas (ADWR 2010b).

The majority of groundwater users are required to comply with one of the following in an effort to meet the Safe Yield groundwater sustainability goal by 2025: the Agricultural Conservation Program, the Municipal Conservation Program, or the Industrial Conservation Program (ADWR 2010b).

Reclaimed Water

Reclaimed water is effluent which has been treated for re-use. Currently in Tucson effluent is treated to a quality suitable for, "turf and ornament landscaping, firefighting, toilet flushing, orchards, and the irrigation of some edible food crops," (City of Tucson 2008p4-3). Reclaimed water has the unusual characteristic of increasing in magnitude with the population. However, using reclaimed water has implications for water quality and public satisfaction. Increasing reclaimed water use can improve system reliability as it frees potable sources to be used strictly for potable uses. The importance of maximizing reclaimed water use in the Tucson AMA is evident in the ADWR scenario projections. Findings suggest that only the scenario which maximizes the use of reclaimed water allows the Tucson AMA be close to the Safe Yield goal by 2025 (ADWR 2010b).

Expanding the use of reclaimed water in the Tucson area is both an infrastructure capacity issue and an economic issue. Demand for reclaimed water is seasonal, since many customers are turf irrigators, such as golf courses. During peak water use seasons, the reclaimed water delivery system is often at capacity, where as the off-peak water use may be zero (City of Tucson 2007). Plans are in place to increase the amount of reclaimed water available for supply and to expand the ability to supply to new customers.

However, expanding infrastructure capacity and attracting new customers is only one facet of expanding the use of reclaimed water, another is establishing the cost to customers. Many potential reclaimed water users choose not to use effluent if it is more expensive than another available source. "There are several large water-using sites located near the existing reclaimed distribution system…While there have been discussions with each of these entities over the last five years, they continue to pump groundwater from their wells since it is about one-third of the cost of purchasing reclaimed water," (City of Tucson 2007, 12). The cost of purchasing reclaimed water is based on meter size and usage. Meter sizes range from 5/8 inch with a flat monthly charge of $5.87, to 12 inches with a flat monthly charge of $694.92, while usage charges are $1.83 per Ccf. One Ccf = 748 gallons. To compare, potable water costs have the same flat monthly fee based on meter size, and non-residential usage charges range from $1.80 to $2.47 per Ccf not including summer surcharges of $0.25 to $0.95 per Ccf (City of Tucson 2010). Reclaimed water prices per Ccf are comparable to the lower range of potable prices.

According to the City of Tucson's "Reclaimed Water System Status Report-2007," the governance of effluent entitlements is based on several agreements with the following entities: the City of Tucson, Pima County, the Secretary of the Interior (Bureau of Reclamation), Metro Water, and the Town of Oro Valley. Total approximate effluent production in 2004 was 68,200 acre feet. Of this amount, the Secretary of the Interior is entitled to 28,200 acre feet, under provisions of the Southern Arizona Water Rights Settlement Act. As part of the settlement Tohono O'odham Nation will receive this water as treated effluent discharged to the Santa Cruz River to restore river flows (ADWR 2010a). Of the remaining amount, 10,000 acre feet were set aside in the year 2000 for habitat projects, although the allocation has not yet been put to use for this purpose. The final provisions allocate the remaining 10% to Pima County and 90% to the three major municipal providers (City of Tucson, the Town of Oro Valley, and Metro Water). The importance of the reclaimed water recipient structure is to note that the Tucson area municipalities do not have rights to all of the effluent production, which could also affect future expansion of reclaimed municipal supplies.

CAP Surface Water

Colorado River surface water is Tucson's most abundant source of renewable water. With the completion of the CAP canal and the addition of surface water to Tucson's water portfolio, overall water reliability improved since the area was no longer totally dependent on groundwater for meeting all potable water use. Although Colorado

River surface water is a renewable water source, two significant factors may decrease its reliability overtime and increase Tucson's vulnerability to drought-induced water shortages. These factors are over-allocation of the Colorado River and climate change.

Studies of paleohydrologic streamflow reconstructions using tree rings suggest that Colorado River allocations were made based on a period of uncharacteristically high river flow (Garfin et al. 2007). Furthermore, reconstructions also indicate periods of drought which are much longer and more severe than any the southwest has experienced in recent history. Although the exact effects of climate change in the future are not fully understood, current research states that Arizona will likely see, "higher minimum and maximum temperatures, increased precipitation intensity, enhanced rates of evaporation and increased precipitation variability," (Garfin et al. 2007 p 69-70)

Arizona and the most of the western U.S. are governed by the prior appropriation doctrine of water rights. Therefore, those with the oldest water claims, or rights, have the highest level of seniority. A senior water user is able to take full advantage of their right before a lower priority junior user. These rights also apply to water rights held by municipalities, so those cities with more senior water rights are less vulnerable than municipalities with junior rights. The Tucson AMA CAP allocation is subject to the overall laws governing water allocations from the Colorado River and also the subsequent policies governing allocations of CAP water. With respect to Colorado River water rights Arizona's CAP allocation is a low priority, or junior, use. The lower basin of the Colorado River has a total annual allocation of 7.5 million acre feet per year, with

California being the most senior right holder of the lower basin states (AZ, CA, and NV). Arizona's annual CAP allocation is 2.8 million acre feet (Secretary of the Interior 2007).

Due to significant drought in the late 1990s and early 2000s and concerns about future shortages, the Bureau of Reclamation and the three Lower Basin States entered into a new Colorado River shortage agreement, where supply cutbacks are enacted depending on the elevation of Lake Mead. Since California has the highest priority allocation Arizona and Nevada are the two states subject to supply cutbacks. The "trigger" elevations for Lake Mead and the subsequent supply cutbacks to Arizona are as follows: 1) below elevation 1075 and down to elevation 1050, Arizona's allocation is cut by 320,000 acre feet; 2) below elevation 1050 and down to elevation 1025, Arizona's allocation is cut by 400,000 acre feet; 3) below elevation 1025, Arizona's allocation is cut by 480,000 acre feet. If Lake Mead's elevation does drop below 1,025 feet, then the lower basin states and the Bureau of Reclamation will need to agree on further shortage agreements for Lake Mead elevation's of below 1000 feet (Secretary of the Interior 2007).

Although Arizona holds a lower priority water right for Colorado River, and this affects CAP supplies during shortage declarations, there also exists a priority system within the CAP. How CAP water users are affected depends on their CAP priority. The highest priority users of CAP water are municipalities, which includes the Tucson metro area, other cities, and eleven Native American Tribes. Due to their higher water priorities, municipalities and Tribes are not expected to experience any supply cuts during the first two stages of shortage declarations when Lake Mead elevations drop to

1,075 and 1,050 feet respectively. Municipalities and Tribes may also be free of supply cutbacks even it Lake Mead elevation drops to the third stage of shortage declaration at elevation 1,025 feet.

If at some future point Lake Mead elevation does drop below 1,025 feet, then the Lower Basin States will meet again to develop a new set of shortage agreements for elevations below 1,025. If CAP does experience greater cutbacks in the future corresponding to Lake elevations below 1,025 feet, then municipalities and tribes could be impacted (City of Tucson 2008).

If municipalities served by the CAP do experience supply cutbacks at a future date, the supply reductions, "would be reduced on a proportional basis, and within each class on a pro-rata basis, based on the amount of water actually delivered to each entity in the latest non-shortage year," (City of Tucson 2008, D-8). Therefore, if Tucson area municipalities are not using their full allocation, their cutbacks are based on their previous use, not their full allocation. For this reason and also to mitigate groundwater mining, one of Tucson Water's priorities is to maximize use of its CAP allocation. As of their 2008 Water Plan Update, the City of Tucson was able to accept and deliver about 50% of their CAP allocation. However with planned facility upgrades on the horizon, Tucson Water estimates that the majority of its service area will be served by renewable CAP supplies by 2012, (City of Tucson 2008). Figures 5.5 and 5.6 show Tucson AMA Municipal Water Sources for 1990 and 2010, with 2010 based on Baseline Scenario Two projections (ADWR 2010b).

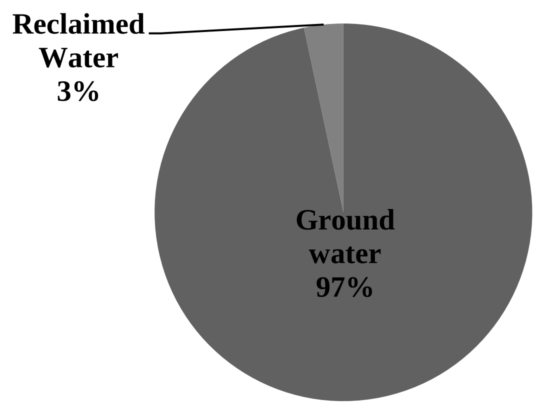

Figure 5.5 Tucson AMA Municipal Water Sources 1990

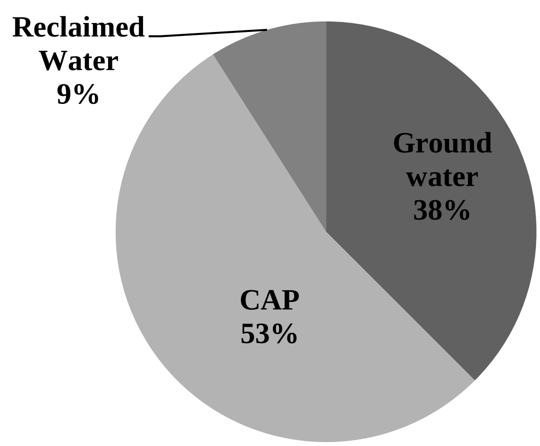

Figure 5.6 Tucson AMA Municipal Water Sources 2010 (projected)

5.2.2 Water Storage and Back-up Supplies

The reliability of Tucson's CAP surface water is the product of the expansive reservoir storage system on the Colorado River and other water allocation arrangements in the Colorado River Basin and within the CAP (discussed previously). This section focuses on direct, local water storage for the Tucson AMA including water banking and back-up groundwater supplies.

Water Banking

The governing laws and regulations for water storage are overseen and enforced by ADWR (Megdal 2007). Water is stored in the Tucson AMA by several municipalities and water users and also by the Arizona Water Banking Authority. Two important mechanisms for storing water in Arizona's AMAs are through Underground Storage Facilities (USF) and Groundwater Savings Facilities (GSF). A USF is a state permitted facility that stores water in underground aquifers, while a Managed USF uses a natural means of discharging water (such as a stream bed) to allow water to percolate into the aquifer. The GSF provides a legal means for a user who would otherwise use groundwater (such as an irrigator), to be compensated by an interested party to use another water source (usually CAP water) in order to conserve the groundwater for that interested party's future use (ADWR 2010b). Several entities in the Tucson AMA, such as municipalities and private water providers, utilize USFs and GSFs to store water for future uses.

Water which remains in a USF or GSF for over a year is considered long term storage, and is accounted for using a system of credits. These long term storage credits are credited to the account of the entity storing the water. All long term storage credits are subject to deductions for evaporation, transpiration, and a one-time "cut to the aquifer" of 5 percent (ADWR 2010b). The reason for having a cut to the aquifer is to reduce overdraft. Water withdrawn or recovered within the same year it is placed in storage is not subject the 5 percent cut. For example, Tucson Water accepts its CAP water at USFs and recovers water for delivery in the same year, therefore avoiding any water deductions for short term use, but Tucson Water also accrues long term storage credits for any CAP water delivered to a USF for its use, but not withdrawn in the same year, and these are subject to the 5 percent cut (ADWR 2010b).

The Arizona Water Banking Authority (AWBA) was created in 1996 for the purpose of storing unused CAP water to enhance the reliability of the State water supplies (ADWR 2010b). USFs and GSFs are the most common mechanisms used the AWBA for storage. Funding for the AWBA is collected through various fees, such as groundwater pumping fees, in the Tucson, Phoenix, and Pinal AMAs. The water purchased to accrue storage credits with these funds must be used to benefit the AMA where the funds were collected (AWBA 2010).

Groundwater Reserves

Groundwater overdraft has been recognized as a problem in the Tucson AMA for several decades. Tucson does have groundwater reserves which are estimated to be around 70 million acre feet, with about 12.7 million acre feet of that total located above a depth of 1,000 feet (ADWR 1999). However, serious consequences come with continued over use of groundwater such as land subsistence. Also, constructing deeper wells to access deeper water is costly and the aquifers are more susceptible to damage. Deeper aquifer layers are often less productive and the water has higher mineral content, compromising water quality (ADWR 1999).

In the event of a severe drought, or to bridge a water supply gap before new sources become available, Tucson's water supply can remain reliable due to its storage of excess CAP water and the regional groundwater reserves. These supplies are unsustainable and depleting them diminishes water supply resilience. If used strategically these reserves can ease area water shortage vulnerability concerns in times when water use outpaces supply.

5.2.3 Rate of Water Use Growth

For the Tucson AMA, the rate of total water use growth is the sum of growth in the four primary water use sectors: municipal, industrial, agricultural, and Indian. Future municipal water use is highly dependent on population growth, and industrial water use in Tucson is largely dependent on mining operations. Agricultural water use is harder to project, as many unpredictable factors influence agricultural activity in the area such as crop prices, federal farm programs and conversion of agricultural land to urban use. Water use by Indian communities is dependent on Indian agricultural growth, which is expected to continue to increase (ADWR 2010b).

In order to analyze and plan for future water use growth, the ADWR uses their yearly projections of growth out to the year 2025 based on three water use scenarios. As actual water use data becomes available each year, ADWR can see how closely actual water uses are tracking with each of the projected scenarios. Future water use planning can then be re-evaluated depending on how current water use is matching up with previously projected water uses.

Since Tucson is a rapidly growing urban area, municipal water use makes up the largest sector of water use. Population is the primary driver of municipal water use, so focusing on population growth in Tucson is imperative for water supply reliability planning. Table 5.3 illustrates projected water use by sector for the year 2025 for all three Baseline Scenarios (ADWR 2010b).

Table 5.3 2025 Projected Tucson AMA Water Use by Sector and Scenario

	Scenario One	Scenario Two	Scenario Three
Municipal Use	**251,018**	**279,264**	**308,237**
Agriculture Use	**57,038**	**71,342**	**112,245**
Industrial Use	**55,682**	**63,782**	**71,282**
Indian Use	**19,033**	**21,455**	**34,043**
TOTAL	**382,771**	**435,843**	**525,807**

As a comparison, Tucson Water forecasts four water use scenarios (A,B,C and D) out to the years 2030 and 2050 based on projected changes in their area of service and implementing further demand management strategies. The demand management strategies would aim to cut potable water use by 7.5% while also decreasing internal system water losses. Together these two strategies forecast a total cut of at least 10% in potable use (City of Tucson, 2008). Scenario A would provide water to the current obligated service area, accompanied with stricter demand management strategies; Scenario B would provide water to the current obligated service area, but without any further demand management strategies; Scenario C would provide water to the potential service area accompanied with stricter demand management strategies; Scenario D would provide water to the potential service area, but without any further demand management strategies. Table 5.4 displays water use for Tucson Water under each of the four scenarios and for the years 2000, 2030, and 2050 in acre feet (City of Tucson, 2008).

Table 5.4 Tucson Water Use Scenarios for the Years 2000, 2030, and 2050

Scenario	**Year 2000**	**Year 2030**	**Year 2050**
A	**128,141 af**	**180,000 af**	**215,000 af**
B	**128,141 af**	**200,000 af**	**235,000 af**
C	**128,141 af**	**200,000 af**	**235,000 af**
D	**128,141 af**	**220,000 af**	**255,000 af**

5.2.4 Ability to Secure New Water Sources

Tucson's ability to obtain new sources of water is based on a combination of economic, environmental, and political decisions. Current short term supply augmentation ideas are all based on increasing Tucson's use of Colorado River surface water. To increase supplies in the short term Tucson's possibilities range from reallocations of CAP water or leases/purchases of water from other entities. For example, Tucson could push for a higher portion of CAP allocation or lease excess water from farmers or Indian Tribes during dry years.

In looking toward long term possibilities of acquiring new sources, the most recent developments involve the creation of the ADD Water Project. The ADD Water Project, which stands for Acquisition Development and Delivery of new Water supplies, is headed by the Central Arizona Project and forms partnerships between the three Arizona Counties receiving deliveries of CAP water (Central Arizona Project 2010a). Instead of each individual municipality looking for and developing its own new water supplies, the ADD Water project will seek out new supplies and work out a framework for how to allocate the new supplies and how to share the costs. Delivery of water under this project would be through the CAP canal. Although a final framework is still in the works, if the project is successful, Tucson as well as other Arizona municipalities can enhance their water supply reliability while collectively sharing the costs.

Where the new supplies will come from is still unknown, but prospects include currently undeveloped groundwater and surface water supplies in Arizona, increased use and treatment of effluent, as well as desalination. Arizona is investigating construction of a seawater desalination plant in either a U.S. or Mexican coastal community (City of Tucson 2008). The idea would be to construct a facility to provide water to that coastal community and in exchange, that community's higher seniority Colorado River water rights would be transferred to Tucson and any other participating partners (City of Tucson 2008). A project of this size would not be realized for years or decades to come, and many economic, environmental, and political concerns all play a crucial part in its plausibility.

Lastly, Arizona is participating in Intentionally Created Surplus (ICS) projects. Intentionally Created Surplus (ICS) is a mechanism for creating an intentional surplus of water in Lake Mead, accruing "credits" for the surplus, and then being able to use the "credits" to withdraw the water at a later point in time (SNWA 2009b). ICS projects can be used to enhance CAP supply reliability. The manner in which ICS projects will directly benefit the Tucson region is not clear at this time, but they are a potential tool that could augment supplies for Tucson and other parts of Arizona. The amount of water received by the states participating in ICS projects depends on the amount of water conserved and how the project financing is shared

Two ICS projects involving Arizona are the Yuma Desalting Plant pilot project and Drop 2 Reservoir (Bureau of Reclamation, 2010d). The Yuma Desalting Plant was constructed in 1992 to treat brackish agricultural drainage. Treating the water allows it to count towards Mexico's Colorado River allocation and frees up additional sources for the lower basin states. Currently, the brackish water is too saline to qualify as part of Mexico's allocation, but operations at the plant ceased shortly after construction due to flood damage on the delivery canal. Pilot operations are currently underway to test its current desalting efficiency and determine whether costs can be lowered and efficiency improved with new technology. The plant will run at one-third capacity for 12-18 months (Colorado River Project 2010b). Although Arizona will receive a small amount of water from the pilot project, the potential for future YDP operations is dependent on the success of the pilot run.

The Drop 2 Reservoir will store water which is ordered by Lower Basin irrigation districts on the Arizona/California border and released from Lake Mead, but then ends up not being used and flowing to Mexico. Changes in the weather and increases in precipitation are common reasons for water to be ordered and released from Lake Mead, but then not used by irrigators since the water takes around three days to travel from Lake

Mead to the irrigation districts (Holmes 2010). The Drop 2 Reservoir will allow the irrigation districts to utilize any stored reservoir water, which keeps more water in Lake Mead. By contributing to the project financing, Arizona will receive a total of 100,000 acre feet of water from the project, but a maximum of 65,000 acre feet per year, beginning in 2016 (Bureau of Reclamation, 2010d), Again, the direct benefit to the Tucson area is not known, but similar future projects could contribute to new supplies for Tucson. Deliveries from the reservoir are scheduled to begin in October of 2010 (Colorado River Project 2010a).

5.2.5 Vulnerability to Climate Impacts

Although climate change predictions point towards increasing precipitation variability with more extreme droughts and floods, the magnitude of these predictions is much more challenging to forecast. Climate change models have not yielded consistent results regarding precipitation changes in the Colorado River Basin. However, these models have shown consistency in forecasting temperatures. “Models show increased Colorado River Basin temperatures in both summer and winter, with seasonal increases of 2 degrees Celsius by 2050 and annual increases of 4-5 degrees Celsius by 2099,” (Garfin et al 2007 p70). Higher temperatures could affect both the supply and the amount of water used leading to a changing balance of Tucson’s water reliability, resiliency, and vulnerability.

With respect to supply, higher temperatures could lead to less precipitation infiltrating into Rocky Mountain soils during summer and fall storms, which could have an effect on how much spring snowmelt reaches the Colorado River and the basin's reservoirs. Higher temperatures could also affect supply by causing snowmelt to occur earlier in the spring, and increasing evaporation rates throughout the year. Natural groundwater recharge in the Tucson area could also be reduced if precipitation decreases, exacerbating aquifer overdraft. With respect to water use, higher temperatures could cause farmers to consume more irrigation water, and urban users to consume more water for cooling and landscaping needs (Garfin et al 2007).

Even without the uncertainties of human-induced climate change impacts, the Colorado River is vulnerable to a large range of natural variability. As stated earlier, tree ring reconstructions of drought over the past 500 years show that longer and more severe droughts than we have experienced in recent history are possible on the River. Since severe droughts could lead to shortages on the Colorado River, ADWR, uses their three baseline scenario projections for water supply and water use to project three additional scenarios based on CAP shortages.

For each of the CAP shortage scenarios, water use remains the same as the Baseline Scenarios, but CAP shortages decrease supply. Using computer simulations of supply shortages for the years 2012-2019, ADWR looks at the total supply impacts for each year. The yearly shortages for the period range from 320,000-480,000 acre feet depending on the Lake Mead elevation. The total shortage amount for the eight years is 3,280,000 acre feet. For each scenario, ADWR states that the shortages will mostly affect those using excess CAP water instead of those who have CAP contracts, such as municipalities. However, without any excess CAP water, the Arizona Water Banking Authority will be affected as they will not have any water to store for state water firming. The Central Arizona Groundwater Replenishment District (CAGRD) would also be affected. The CAGRD allows communities and developments to use groundwater as long as another water source (usually CAP water) is artificially recharged in the same AMA. If the CAGRD does not have access to water it can use to offset groundwater use, such as CAP water, then new development may be curtailed (ADWR 2010b). Once the CAGRD recharges water into groundwater aquifers, the water cannot with withdrawn at a future time. If CAP shortages over the next decade reach beyond those simulated by ADWR models, then groundwater overdraft could become an even more pressing issue and the need to develop additional supplies more urgent.

The previous sections discussed the diversity and governance of supply sources, water storage and emergency back-up supplies, rate of water use growth, ability to secure new sources, and vulnerability to climate impacts for the Tucson AMA and how each of these areas affect water supply reliability and vulnerability. This next section looks at what measures Tucson employs to evaluate its own water reliability and vulnerability status.

5.2.6 Water Supply Reliability and Vulnerability: Tucson Self-Assessment

The City of Tucson in their 2009 Annual Drought Monitoring Report discusses several indicators used to assess the area's current drought conditions in the context of water supply and use for the City. The report is in accordance with the City of Tucson's Drought Preparedness and Response Plan developed in 2006, which calls for an annual update on current drought impacts to the area's water supply sources. Arizona state legislation passed in 2005 requires all community water providers to prepare a Drought Preparedness Plan and submit the Plan to ADWR (ADWR 2010c).

Regional indicators the City assesses are the statuses of the Colorado and Santa Cruz Watersheds. For the Colorado, they look at snow water equivalent snowpack and reservoir changes in Lakes Mead and Powell. For the Santa Cruz they use short term and long term watershed drought conditions as established by ADWR. Tucson also looks at four local system indicators which are: Aquifer Storage Index, Potable Production Capacity Index, Reclaimed Production Capacity Index, and Gallons Per Capita Per Day water production levels.

1. **"Colorado River Status"** When looking at the status of the Colorado River, the first factor is annual snowpack, which for March 2009 was at 18 to 120 percent of normal. The second factor is to look at any reservoir level changes from the previous year for Lakes Mead and Powell. For example, in Spring 2009 there was 1.5 million acre feet more of storage in both reservoirs compared to Spring 2008. Due to these conditions, the Secretary of the Interior did not declare a shortage on the Colorado River (City of Tucson, 2009).

2. **"Santa Cruz Watershed Drought Status"** For this indicator Tucson Water looks at the drought status of the Santa Cruz Watershed, which is established by ADWR (City of Tucson, 2009). As of spring 2009 the status is stated as being, "abnormally dry," (City of Tucson, 2009).
3. **"Aquifer Storage Index (ASI):** captures the net effects on water table levels from pumping and from natural and artificial recharge. It is a measure of the change in water storage volume relative to a base year of 2000. Tucson Water's production wells are grouped into 11 regions of hydrologic similarity for this calculation. Each region is represented by one average water level, simplifying water level change comparison," (City of Tucson, 2009 p10). The year 2000 is the baseline with an index level of 0.0 and the year 2003 is the lowest index level to date at -9.3. The value for 2007 is 11.9, and while a more current value in not reported, the report states that the index has continued to steadily rise since 2003 (City of Tucson, 2009).

4. "**Potable Production Capacity Index (PPCI):** a ratio of potable production capacity available for the coming year (in millions of gallons per day, mgd) divided by the predicted maximum 30-day demand period for the upcoming year (in mgd). An index score of 1.1 or higher is considered good; lower than 1 indicates some degree of system stress. Production Capacity = 184.2 MGD; Forecasted Max 30-Day Demand (2008) = 148.28; 184.2/148.28 = 1.24," (City of Tucson, 2009 p11).

5. "**Reclaimed Production Capacity Index (RPCI):** a ratio of maximum reclaimed water production capacity for the upcoming year to the peak day forecast for reclaimed water demand for the upcoming year. An index score of 1.1 or higher is considered good. Production = 33.5 MGD; Demand = 31.8 MGD; 33.5/31.8 = 1.05," (City of Tucson, 2009 p12). Since the City is below the threshold value of 1.1, we can infer that reclaimed production capacity is under some degree of stress.
6. **"Gallons Per Capita Per Day (GPCD):** the total potable water produced for the previous year divided by the estimated service area population for that year. The 2008 report for GPCD is 140.4, down from 150.7 reported in 2007," (City of Tucson, 2009 p11).

5.2.7 Tucson, Arizona Water Supply Reliability, Vulnerability, and Resiliency Indicators

This final section looks at water supply reliability, vulnerability, and resiliency from a quantitative perspective using observed and projected data on water use in the Tucson AMA. Quantitative indicators developed in this section are Storage Vulnerability, Withdrawal Ratio, Natural Variability, and Groundwater Depletion. Discussion and interpretation of the indicator values follows after all indicator calculations are explained, and in the chapter conclusion.

The primary source of data used to calculate the indicators is ADWRs 2009 projections for Baseline Scenario Two. Unless stated otherwise, the figures used in calculating the indicators come from ADWRs 2009 projections for Baseline Scenario Two.

"Storage Vulnerability (>1) *– "Measure of region's ability to cope with extreme water events; reservoir yield, which is approximated by consumptive demand divided by regional reservoir storage capacity (internal and upstream),"* (Lane, et al 1999, p195).

The size of the Colorado River reservoir storage system and the number of entities it serves proves difficult when trying to evaluate the Tucson AMAs precise benefit from the vast storage system. In modifying this indicator for the Tucson AMA I use storage of water that is legally available for use during times of drought or Colorado River shortage. Also, since the indicator definition is a measure of a region to cope with extreme weather events, calculating storage which can be used when there are shortage declarations on the Colorado River is more applicable to the design of the Tucson AMA water system. Although Tucson has access to groundwater reserves, I do not include them in this calculation. Groundwater overdraft has long been a problem in the Tucson AMA, so focusing on the efforts of the AMA to build storage reserves which do not deplete groundwater reserves when used, is more applicable for Tucson.

The data needed to calculate the indicator include a measure of consumptive water use and a measure of total water in storage that is accessible during periods of water shortage, and does not deplete groundwater reserves. Consumptive water use is approximated using 2009 annual water use projections for Tucson AMA Baseline Scenario Two. For water storage values, total Long Term Storage Credits as reported in

ADWRs 2009 Long Term Storage Account Summary are used to calculate total water in storage.

Total projected 2009 AMA water use = 371,210 acre feet (ADWR 2010b). Total Tucson AMA Long Term Storage Credits sum to 800,380.04 acre feet (ADWR 2010d). Annual projected water use (371,210 af) divided by available storage (800,380.04 af) = 0.46.

The storage number used reflects AMA Long Term Storage Credits as a whole. Individual municipalities and entities within the AMA accrue their own storage credits and so may be subject to differing ratios of storage to water use. However, Long Term Storage Credits can be leased, sold, and gifted, so individual credits can be transferred to another party given that the new party qualifies for Long Term Storage Credits (ADWR 2010e).

***"Withdrawal ratio** – Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems,"* (Lane, et al 1999 p196).

To calculate this indicator I need, first, a value that represents annual water withdrawals in the Tucson AMA. Second I need a value that represents the sum of internally generated water and water imports. For both data needs I use projected data from ADWRs Baseline Scenario Two for the year 2009. In measuring the first part, annual withdrawals, I approximate the value using projected 2009 annual AMA water use, which is the sum of water use from each sector, municipal, industrial, agriculture, and Indian. Also included is riparian water use, since a measurable amount of water is used by riparian areas. Total projected annual AMA water use for 2009 is 373,985 acre feet (204,067 af (municipal); 61,082 af (industrial); 91,089 af (agriculture); 14,972 af (industrial); 2,775 af (riparian)) (ADWR 2010b).

To obtain a value for the second part of the equation, internally generated water plus water imports, I look at the sum of water sources available for use in the AMA from CAP surface water, reclaimed water, and groundwater.

Beginning with CAP surface water, I use the total amount of CAP allocation available for use in the Tucson AMA, which is 215,333 acre feet. Although the full allocation amount is not currently being consumed, the amount reflects what is available for use. The reason the full allocation is not being used is due to current capacity constraints at recharge and recovery sites. For example, Tucson Water, the largest municipal water provider in the AMA is recovering about 70% of its CAP allocation (CAP 2010b). Any CAP allocations that are accepted at recharge sites, but not recovered for consumption, are counted toward storage.

For groundwater, calculating annual groundwater recharge is complex since recharge can be natural, artificial, or incidental. Net natural recharge is any recharge that flows into Tucson's groundwater aquifers from precipitation, minus any outflow into other groundwater aquifers, which is not accessible to the Tucson AMA.

Artificial recharge refers to water which is recharged into the aquifer, but not available for withdrawal at a later date. The purpose of artificial recharge is to reduce groundwater overdraft, so artificial recharge values are not counted towards available groundwater withdrawals. Examples of artificial recharge are the mandatory 5% cuts to the aquifer for long term water storage, and the CAGRD.

The final category of groundwater is incidental recharge. I do count types of incidental recharge as available groundwater since this water is considered available for withdrawal. An example of incidental recharge is water used for landscaping or agriculture, in which a percentage of that percolates into the ground and reaches the groundwater table, thereby recharging groundwater. Another example is CAP canal seepage that also reaches the groundwater table. This source is carefully calculated by ADWR and included in projected water use and supply assessments.

In summing the two types of groundwater recharge that are available for withdrawal, net natural groundwater recharge and incidental types of recharge, the total projected groundwater supply for 2009 Baseline Scenario Two is 119,481 acre feet.

The last supply source is reclaimed water. One could argue that including reclaimed water is double counting of water, but since using reclaimed water is an important mechanism for augmenting supplies and meeting demands, I include reclaimed water in the supply calculation. ADWR also lists reclaimed water amounts as water supply, and the total projected 2009 Baseline Scenario Two amount is 19,262 acre feet.

Taking the first part of the equation, total 2009 AMA projected water use is 373,985 acre feet. Adding together available supply from surface water, 215,333 acre feet; groundwater, 119,481 acre feet; and reclaimed water 19,262 acre feet, the total available water is 354,076 acre feet. Calculating the Withdrawal Ratio, total projected water use (373,985 af) divided by total available water (354,076 af) = 1.06.

"Natural Variability - *Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of unregulated annual streamflow to the unregulated mean annual streamflow. Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes,"* (Hurd, et al 1999 p1401).

Since Tucson's surface water supply is Colorado River water, using the coefficient of variation for unregulated Colorado River streamflow is the most logical modification of the indicator for the Tucson AMA. With the Colorado River we can look at the observed gauge record, as well as flow reconstructions from tree rings. Observed data between 1906-1995 show a coefficient of variation of 0.28, while observed and reconstructed data from 1490-1997 show coefficients of variation that range from 0.27-0.31 (Woodhouse, et al 2006).

"Groundwater Depletion - *Ratio of average groundwater withdrawals in year [i] to annual average baseflow reflecting the extent that groundwater use rates may be exceeding recharge. Regions with high depletion rates are vulnerable to long-run changes in hydrology,"* (Hurd, et al 1999 p1401).

For calculation of this indicator I need values for total groundwater withdrawals and for total annual average baseflow. I use ADWRs Baseline Scenario Two 2009 projections to obtain both values. Beginning with groundwater withdrawals, I approximate withdrawals using a sum of the total projected annual groundwater use from the various sectors (79,723 af, (municipal); 59,148 af (industrial); 87,454 af (agriculture); 1,043 af (Indian); and 2,775 (riparian)). ADWR indicates that groundwater use for agriculture includes direct groundwater use, as well as CAP water used in-lieu of groundwater at GSFs. When CAP water is used in-lieu of groundwater, the groundwater will be used at a later date, so for ADWR accounts, the groundwater is listed as used even though its actual withdrawal will be in the future. Using 2009 Baseline Scenario Two projections, the total annual groundwater use is 230,143 acre feet.

In calculating a value for average annual baseflow, this part of the equation is modified for Tucson to include all projected groundwater recharge, natural, artificial, and incidental for 2009. Natural recharge is net natural recharge from area snowpack and precipitation. For artificial recharge I include the CAGRD contributions and the 5% cuts to the aquifer from long term storage, since these are groundwater recharges that are not available for withdrawal in the future. For incidental recharge I include incidental recharge values listed for all sectors (municipal, industrial, etc.) as well as other types of recharge that is counted as usable supply, such as CAP canal seepage. Including all types of recharge allows for the calculation to reflect groundwater use versus groundwater offsets, whether the groundwater recharge is available for use, or not. Net natural groundwater recharge is listed as 77,356 af; artificial recharge is 29,149 af; and incidental recharge is 42,125 af, for a projected 2009 total of 148,630 acre feet (ADWR 2010b).

Calculating the indicator, annual groundwater use (230,143 af) divided by groundwater recharge (148,630 af) = 1.55. As is well documented, the Tucson AMA is using groundwater well in excess of recharge.

Reservoir System Resiliency *– A measure of a reservoir system's ability to recover from drought; 1) Reservoir capacity divided by average annual inflows; 2)*

Annual water demand or system outflows divided by average annual inflows; 3) multiply both values together.

Applying this indicator for Tucson I use the Lower Colorado River reservoir system. The first value needed is total reservoir capacity. The primary storage reservoirs on the Lower Colorado River are Lakes Powell and Mead with a combined storage capacity of 54,752,000 acre feet (Bureau of Reclamation 2010a and 2010b). These two reservoirs are used since they are the largest and most important for Colorado River system management. To find a value for average annual inflows I use the mean value of streamflow using the existing observed record and also the record reconstructed using tree rings, which is estimated to be about 15 million acre feet (SNWA 2010). The final value needed for the indicator calculation is average annual outflows or water use from the system. The upper and lower Colorado River Basins both have an annual allocation of 7.5 million acre feet of water. The lower basin is using their full 7.5 million acre foot allocation, but the upper basin is not. Upper basin uses are about 4.2 million acre feet per year (Bureau of Reclamation 2008). Along with upper and lower basin uses, there is also an annual 1.5 million acre foot allocation for Mexico, which is delivered in full each year (Secretary of the Interior 2007).

To calculate current Colorado River water use I sum the upper basin use of 4.2 million acre feet, the lower basin use of 7.5 million acre feet, and Mexico's allocation of 1.5 million acre feet, which equals 13.2 million acre feet per year of Colorado River use.

The first equation for the indicator calculation, reservoir capacity (54,752,000 af) divided by average annual inflows (15,000,000 af) = 3.65. The second part of the equation, annual water use (13,200,000 af) divided by average annual inflows (15,000,000 af) = 0.88. Lastly, multiplying both parts together, 3.65*0.88 = 3.212.

5.2.8 Summary of Tucson Area Case Study

Examining the indicator values, some strengths and weaknesses emerge for the Tucson AMA with respect to their water supply system. The Storage Vulnerability indicator illustrates that projected 2009 AMA water uses are less than half of the amount the AMA has in storage, which shows the AMA's strength in storing water for future use. The Withdrawal Ratio and Groundwater Depletion indicators are both greater than one, signaling that the AMA general water use and groundwater use are outpacing water supply. Natural variability on the Colorado River is not extreme, but given the high water use on the system, and current drought effects, even moderate variability is proving to be a challenge. Finally, the size of the Colorado River reservoir system coupled with annual allocations that are greater than average annual inflows reasons that the system is not as resilient as other reservoir systems with smaller inflow to capacity ratios and smaller annual water use to inflow ratios.

5.3 Las Vegas, Nevada

Similar to Tucson, the climate of the Las Vegas metro area is arid, and in recent years the area has experienced periods of extremely high growth rates. The current population of the Las Vegas area is around two million (SNWA 2009b) and 90 percent of the water supply is from the Colorado River (SNWA 2009b). The remaining ten percent of the water supply is from groundwater and reclaimed water. Water use in the Las Vegas area is composed of residential uses (59%), commercial and industrial uses (14.5%) resorts and golf courses (14%), schools, parks, and common areas (10%), and other (2.5%). Figure 5.7 illustrates displays water use by sector (SNWA 2009b).

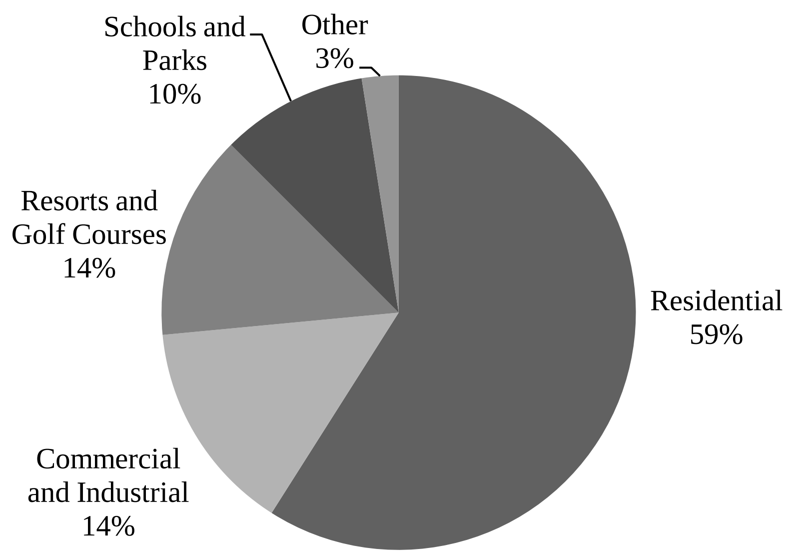

Figure 5.7 Las Vegas Area Water Use by Sector

Several separate municipalities are part of the Las Vegas area and in 1991 a partnership between seven water and wastewater agencies in the area formed the Southern Nevada Water Agency (SNWA). Table 5.5 lists the seven SNWA member agencies.

Table 5.5 SNWA's Seven Member Agencies

The Seven Municipal Member Agencies that Comprise SNWA	Big Bend Water District
	Boulder City
	Clark County Water Reclamation District
	Henderson
	Las Vegas
	Las Vegas Valley Water District
	North Las Vegas

SNWA is now the wholesale water provider and is, "responsible for water treatment and delivery, as well as acquiring and managing long-term water resources for Southern Nevada," (SNWA 2009b). In order to reflect water supply reliability, vulnerability, and resiliency in the Las Vegas area, data and information from SNWA is used whenever possible. The primary information source from SNWA is their "Water Resource Plan," which is reviewed on an annual basis and updated when needed. The most recent revision is from 2009 and incorporates water resource planning based on population growth out to the year 2060, while also looking at the impacts on Colorado River declared shortages on municipal water supplies. Figure 5.8 depicts the greater Las Vegas area (Forensic Science Center 2010) followed by a table of acronyms used in this discussion.

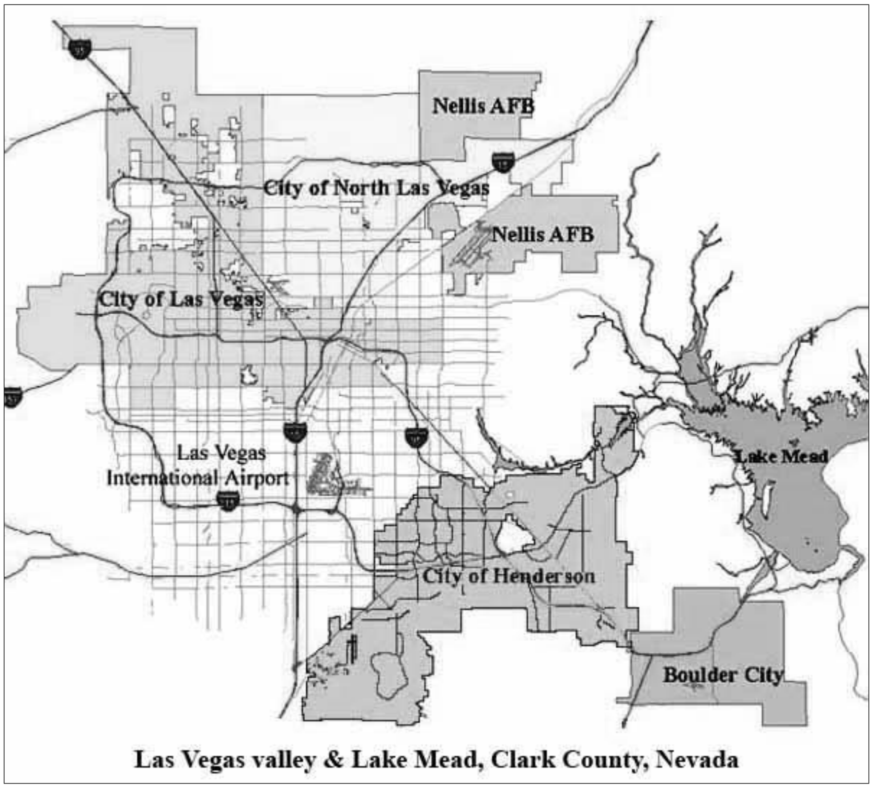

Figure 5.8 Greater Las Vegas Area

Table 5.6 Las Vegas Area Case Study Acronym List

ACRONYM	**DESCRIPTION**
AF	Acre Feet
AWBA	Arizona Water Banking Authority
BOR	Bureau of Reclamation
ICS	Intentionally Created Surplus
SNWA	Southern Nevada Water Authority

5.3.1 Diversity and Governance of Supply Sources

Although the Las Vegas area relies on three different water supply sources; groundwater, Colorado River surface water, and reclaimed water, 90% of the supply comes from Colorado River surface water which leaves the area vulnerable to any supply impacts on the Colorado River. The Las Vegas area has plans to augment its supply portfolio with non Colorado River water, discussed in a later section. In this section I focus on the current supply sources and supply governance.

Groundwater

Groundwater served as the Las Vegas area's primary supply source until the early 1970s (Holmes, 2010). In Nevada, use of groundwater resources is regulated by the State Engineer, and the Nevada Division of Water Resources. During the 1950s the Las Vegas area began considering expanding infrastructure to access more water from the Colorado River. However, knowing that this process would be years in the making, the State Engineer began to issue revocable groundwater well permits. The ideas was to allow the area to grow knowing that groundwater resources would be over-used, but then have the ability to revoke the permits once water from the Colorado River came online (SNWA 2009b). The revocable permits were issued in addition to the permanent groundwater rights already in use. After years of groundwater overdraft in the Las Vegas Valley, the State Engineer issued an order in 1992 that, "with few exceptions, all applications to appropriate groundwater in the Las Vegas Valley that are filed after March 23, 1992 will be denied," (SNWA 2009b, 29).

Groundwater resources in Nevada follow the prior appropriation doctrine, which give priority to the water right holder with the earliest permitted use. The permanent groundwater rights held by SNWA agencies total 46,340 acre feet per year and are some of the highest priority rights in the Las Vegas Valley (SNWA 2009b). Natural groundwater recharge rates for the Las Vegas Valley are estimated to be 57,000 acre feet per year. Although municipal use of groundwater is below the natural recharge rate, there are also a variety of private groundwater users. Municipal and private use of groundwater use in the Las Vegas Valley in 2007 was around 70,000 acre feet per year, far exceeding natural recharge (SNWA 2009b).

Colorado River Surface Water

Most of Nevada's groundwater and surface water resources are managed by the State Engineer. However, management of the Colorado River is overseen by the Bureau of Reclamation and governed by a complex set of policies. Nevada is therefore subject to the laws and guidelines for use of the Colorado River as established by "The Law of the River," (Bureau of Reclamation 2010c).

Nevada's allocation of the Colorado River is 300,000 acre feet per year. However, using a system of return flow credits, the Las Vegas area is able to significantly increase its intake and consumptive use of the River. The region discharges treated wastewater to the Las Vegas Wash where it flows back to the Colorado River (SNWA 2009b). Therefore, SNWA now has annual contracts to deliver around 500,000 acre feet of Colorado River water, of which 40% (200,000 acre feet) are returned for return flow credits (Holmes 2010) and Nevada's net allocation remains at 300,000 acre feet per year. Looking ahead, Las Vegas is hoping to improve their return flow credits from 40% to 50% or 60%, which would yield huge supply increases (Holmes 2010). Although the use of return flow credits increases the ability to use Colorado River water, the flipside is that by relying heavily on one water source, the overall water supply is more vulnerable to droughts and supply restrictions than if the region had a more diverse water supply portfolio.

The priority of water rights on the Colorado River for the Lower Basin states, as determined by the "Law of the River," impacts Nevada. Nevada, along with Arizona has a lower water right priority than California and both states are subject to supply shortages according to Interim Shortage Agreements. For Nevada, the cutbacks based on Lake Mead elevations are as follows: 1) below elevation 1075 and down to elevation 1050, Nevada's allocation is cut by 13,000 acre feet; 2) below elevation 1050 and down to elevation 1025, Nevada's allocation is cut by 17,000 acre feet; 3) below elevation 1025, Nevada's allocation is cut by 20,000 acre feet. If Lake Mead's elevation nears 1000 feet, then the lower basin states and the Bureau of Reclamation will need to agree on further shortage agreements for Lake Mead elevation's of below 1000 feet (Secretary of the Interior 2007).

The Las Vegas area is taking various measures in response to Colorado River water supply vulnerability, described in the following sections.

Reclaimed Water

Due to its ability to treat a large portion of its wastewater and return it to the Colorado River for return flow credits, the Las Vegas area has less of an incentive to use this treated water as reclaimed water. If instead, the region did use this treated water as reclaimed water and did not return the water to the Colorado River for return flow credits, then SNWA would not be able to increase its Colorado River intake above 300,000 acre feet per year and would have less consumptive use water available. Although the total amount of water available for use would not change, the important point is that the total amount of consumptive use would decrease. Without returning a large portion of treated wastewater to the Colorado River for return flow credits, the Las Vegas area would not be able to "extend" their consumptive use allocation.

None the less the Las Vegas area does reuse a portion of its treated wastewater locally, about 26,842 acre feet per year for the following uses: golf courses, highway landscaping, parks, power plants, schools, and construction (SNWA 2009b).

5.3.2 Water Storage and Back-up Supplies

When thinking of the Las Vegas area and water storage, it is hard not to think of nearby Lake Mead with its capacity to store over 28 million acre feet per year, or two years worth of average Colorado River flow (Bureau of Reclamation 2010b). However, the Las Vegas area has a net annual allocation of Colorado River water of only 300,000 acre feet that the region can consume. During times of declared shortages on the Colorado River, this amount will decrease. So, despite the proximity to a vast reservoir, this section will focus on stored water that is legally accessible to the region on an as needed basis during time of drought or shortage. The two categories of water storage and back-up supplies that fall in this section are Water Banking and Intentionally Created Surplus (ICS).

Water Banking

The Las Vegas area has water storage in three different water banks. The first is locally banked water through the Las Vegas Valley Water District (which is now part of SNWA). The second is with the Arizona Water Banking Authority (AWBA), and the third is the California Water Bank. The Las Vegas Valley Water District began banking water in the underground aquifers in 1987 and to date has banked 333,639 acre feet of water (SNWA 2009b).

Agreements for Nevada to store water in Arizona's aquifers came to fruition in 2004, with Nevada able to bank 1.25 million acre feet of water through the AWBA. Nevada can withdraw 30,000 acre feet per year of that banked water in 2009 and 2010 and 40,000 acre feet per year thereafter until supplies are exhausted (SNWA 2009b). Logistically, when Nevada withdraws water from the Arizona Water Bank, the water is withdrawn from Lake Mead for Nevada and less water flows to Arizona. Arizona is able to make up for the supply decrease by accessing water banked water within Arizona.

Nevada is also participates in a California Water Bank, where SNWA and the Nevada Colorado River Commission entered into an agreement with Metropolitan Water District in Southern California. The agreement began in 2004 and allows Nevada to bank store unused water in California. The Bureau of Reclamation operates the agreement (SNWA 2009b). Nevada has banked 70,000 acre feet of water through 2008. To access the stored water, SNWA must give Metropolitan six months notice and they are able to withdraw 30,000 acre feet per year (SNWA 2009b).

Intentionally Created Surplus

As stated above in the Tucson section, Intentionally Created Surplus (ICS) is a mechanism for creating an intentional surplus of water in Lake Mead, accruing “credits” for the surplus, and then being able to use the “credits” to withdraw the water at a later point in time. The Las Vegas area ICS projects include: Tributary Conservation ICS on the Virgin and Muddy Rivers, Imported ICS from Coyote Spring Valley groundwater, and System Efficiency ICS from the Drop 2 Reservoir.

For Tributary Conservation ICS on the Virgin and Muddy Rivers, SNWA is able to develop up to 95% of their water rights on these rivers which pre-date the Boulder Canyon Project Act (June 25, 1929) (SNWA 2009b). SNWA began receiving credits of around 30,000 acre feet per year from this project in 2009. The method for acquiring water rights on these rivers involves active purchasing and leasing of senior agricultural rights on the rivers, which are fully appropriated and naturally flow into Lake Mead. So, water which would otherwise be used for agriculture is left in the rivers and flows to Lake Mead.

SNWA expects to begin receiving 9,000 acre feet per year of credits from Imported ICS from Coyote Spring Valley groundwater in 2010 (SNWA 2009a) Coyote Spring is located north of Las Vegas and SNWA is constructing a 15 mile pipeline which will connect to the Moapa Valley water system and then Lake Mead. The total annual amount of ICS credits that can be used from this project is 15,000 acre feet per year (SNWA 2009b). Both Tributary Conservation and Imported ICS credits can be created and used even during declared shortages. However, if the ICS credits are not used in the same year they are created then they become known as Extraordinary Conservation ICS credits. Extraordinary Conservation ICS credits can be accrued up to 300,000 acre feet, but cannot be used during times of declared shortage (SNWA 2009b).

The final ICS project under development by SNWA is the Drop 2 Reservoir System Efficiency ICS. SNWA agreed to finance a portion of the reservoir and in turn will receive 40,000 acre feet of Colorado River water per year for a total of 10 years, or 400,000 acre feet. This project expires in 2036 or when SNWA has used a total of 400,000 acre feet of water under this arrangement, whichever happens first.

SNWA's continuing ability to look for additional supplies and to store water against future shortage increases the reliability of its water supply by decreasing the likelihood of a water supply system failure during time of drought or shortage, or to bridge any gaps in supply until new sources are developed.

5.3.3 Rate of Water Use Growth

Since residential water use currently makes up the largest portion of water use, population growth will be the major component of future water use growth. The Las Vegas area is also a popular tourist destination and currently receives an average of 35 million tourists each year. Resorts in Las Vegas currently account for about 6.5% ofwater use, while not insignificant, residential water use is almost ten times higher. Although SNWA acknowledges the difficulty in long forecasting horizons, the agency is attempting to be as prepared as possible to provide a continued reliable water supply. Current SNWA water use forecasts extend to the year 2060 and are, "based on both population projections and expected conservation," (SNWA 2009b, p38).

Looking at population, SNWA uses population forecasts prepared by the University of Nevada Las Vegas Center for Business and Economic Research for the years 2008-2035 and extends them out to 2060. The current population of the Las Vegas area is about 2 million people and per capita water use is about 250 gallons per day. Population projections for 2035 are forecasted at 3.6 million, but SNWA recently enacted a goal to reduce per capita daily water use to 199 gallons per day by 2035. Planning scenarios incorporate population growth coupled with projected use rates in gallons per capita per day. Even with more conservation, overall water use is expected to grow and this will require SNWA to bring on additional supplies in order to maintain reliability. Using SNWA's current water use projections for 2010 and 2035 (SNWA 2009b), 2010 water use is 553,000 acre feet while 2035 water use is 739,000 acre feet, representing a growth in water use of about 34% over 25 years.

5.3.4 Ability to Secure New Water Sources

For the Las Vegas area the Colorado River is the largest and most important water supply source. Looking for new ways to augment the amount of water supplied to the Las Vegas area from the Colorado River will continue to be a top option; however, given the potential for supply shortages on the River coupled with a growing population, SNWA also had the foresight to explore developing non-Colorado River supply sources. Developing new water supply sources can take several years, can be costly, and is subject to political and environmental challenges. Proper planning is essential to minimize vulnerability to severe shortages and drought. This section discusses potential ideas for expanding Colorado River supplies and development of non-Colorado River supplies.

Expanding Colorado River supplies for the Las Vegas area primarily involves transfers and exchanges of water from its current use to a new use. The first of these transfers would be for the Las Vegas area to purchase or lease water rights currently used for agriculture. The second involves treating brackish water by resuming operations at the Yuma Desalting Plant, and the third is desalination. Resuming operations at the Yuma Desalting Plant and desalination are also options Arizona is considering, and could involve partnerships between the two states to share in the funding costs as well as augmented water sources. Year-long Pilot Operations at the Yuma Desalting Plant are underway to determine how efficiently the Plant can desalt the brackish water (Colorado River Project 2010b).

Currently, desalination technology is too expensive, but if technology improves and costs are reduced, then desalination may become a real possibility. As stated above in the Tucson section, potential plans to use desalination would involve construction of a desalination plant for a coastal community that is currently using Colorado River water. The community would then use desalinated water, freeing up senior Colorado River rights for the entities who fund the desalination project.

The issue with expanding Colorado River sources for the Las Vegas area, however, is that Las Vegas is already heavily dependent on the River for its water supply, which is vulnerable to drought and shortages. To diversify the region's water supply portfolio, SNWA is in the process of importing new in-state groundwater sources.

The Las Vegas Valley Water District began filing permits for un-appropriated groundwater rights in several eastern Nevada counties in 1989. After years of negotiations with the local counties over developing groundwater resources, some resources are still under negotiation or review by the State Engineer. However, currently quantifiable resources are in the neighborhood of 134,000 acre feet per year (SNWA 2009b). Part of the lengthy review process is to determine the rate of natural groundwater recharge in each of the basins as SNWA will only have permits for the amount of groundwater which can be sustainably used.

SNWA plans to build a pipeline from eastern Nevada (Clark, Lincoln, and White Pine Counties) to bring the water to the Las Vegas area. Under normal conditions, meaning no shortage declarations on the Colorado River, SNWA is planning for these sources to be available in 2020 (SNWA 2009b). Since SNWA is able to treat its wastewater for return flow credits, these additional in-state groundwater sources will also be treated and used for return flow credits allowing SNWA to also increase its use of Colorado River (Maher 2010). So, the new groundwater sources augment the water supply directly and also indirectly through return flow credits. The exact quantity of supply increase is not yet known (Maher 2010).

5.3.5 Vulnerability to Climate Impacts

Since the Las Vegas area depends on the Colorado River to supply the majority of its water, the region, like Tucson, is concerned about the River's natural variability and vulnerability to climate change. As stated above for Tucson, recent reconstructions of Colorado River flow from tree rings indicate the River is vulnerable to more severe droughts than those experienced recently (Woodhouse, et al 2006). Also, climate change models indicate that temperatures in the Colorado River Basin will increase, which could have many implications on water supply and water use. Given these challenges and uncertainties, SNWA has examined at their current water supply and portfolio to see where water supply reliability would stand at each shortage declaration stage on the Colorado River.

For the Las Vegas area, the concern of declining Lake Mead levels not only impacts supply through shortage declarations. Another serious concern is due to SNWAs current and planned intakes being at a Lake Mead elevation of 1,000 feet. Any drop of the Lake elevation 1,000 feet will greatly impair SNWAs ability to draw out of Lake Mead.

The first stage of shortage declarations takes effect when Lake Mead reaches an elevation of 1,075 feet. At this elevation SNWA will begin construction to import groundwater from Eastern Nevada, if construction is not already underway. Tributary and Imported ICS water from the Muddy/Virgin Rivers and Coyote Spring Valley will be used; however System Efficiency ICS credits from the Drop 2 Reservoir are not usable during declared shortages (SNWA 2009b). Also, any ICS credits stored as Extraordinary Conservation ICS credits cannot be used during declared shortages. Other usable supplies during declared shortage are interstate and intrastate banked resources, as well as considering further demand management strategies. These measures will continue until elevation drops reach 1,025 feet.

When Lake Mead drops below elevation 1,025, feet the Lower Basin States will meet with the Secretary of the Interior to discuss plans for maintaining Lake Mead elevations above 1,000 feet (SNWA 2009b). Also, SNWA will continue to look into possibilities for extending intake levels below 1,000 feet, and further demand management strategies will be assessed. Maintaining reliable water supplies will continue to depend on banked water and ICS credits.

If Lake Mead does reach an elevation of below 1,000 feet, Las Vegas plans to maximize its use of in-state groundwater and locally banked water, while at the same time restricting water uses to those essential for health and safety (SNWA 2009b). Natural variability of Colorado River flows coupled with climate change uncertainties pose real challenges to the reliability of the Las Vegas area's water supplies. Careful planning and monitoring is essential to minimize vulnerability to supply shortages.

5.3.6 Water Supply Reliability and Vulnerability: Las Vegas Self-Assessment

The SNWA Water Plan 2009 does not directly address or provide an internal assessment of supply reliability and vulnerability. However, the idea of planning for a reliable water supply that is less vulnerable than the current system of depending almost entirely on the Colorado River is apparent throughout the document. The document does not address reliability or vulnerability with respect to infrastructure outages or catastrophic events impairing the water supply, so its focus related to water supply reliability is on assuring adequate volumes of water for current and future populations, while also diversifying the supply portfolio.

5.3.7 Las Vegas Water Supply Reliability, Vulnerability, and Resiliency Indicators

Several quantitative indicators listed in the introduction of this Chapter are adapted and calculated for the Las Vegas area. These indicators, which are adopted from previous literature, complement and enhance the above discussions on water supply reliability, vulnerability, and resiliency in Las Vegas. Modifications from the exact definition of the indicators are made to suit the unique features of the Las Vegas area water supply, so included values are subjective, but still provide useful insight as to potential stressors on the water supply system. Unless otherwise stated, figures used in calculating the indicator values are from the SNWA Water Resource Plan 2009.

1. "Storage Vulnerability *– "Measure of region's ability to cope with extreme water events; reservoir yield, which is approximated by consumptive demand divided by regional reservoir storage capacity (internal and upstream),"* (Lane, et al 1999, p195).

To calculate this indicator, values for consumptive demand (water use) and regional reservoir storage capacity are needed. The 2009 SNWA water resource plan lists projected 2010 annual water use at 553,000 acre feet, so I use this figure for the first part of the equation. Calculating the second part of the equation, regional reservoir storage is more challenging.

As with Tucson, I do not include Colorado River reservoir storage when calculating storage capacity. In order to assess legally available water to the Las Vegas area during times of shortage, I focus on storage in the forms of banked water and ICS. However, with many of these storage mechanisms only a portion of the total amount can be used in a given year. So, I will sum together the maximum annual amount of water available to the Las Vegas area that is stored either through interstate water banking, intrastate water banking, or ICS. This measure will provide an assessment of annual available storage versus annual water use.

Annual amounts of ICS water which are currently available, or will be within the next couple of years, includes 28,500 acre feet per year (30,000 acre feet less 5%) from the Virgin and Muddy Rivers, 9,000 acre feet per year from Coyote Spring Valley, and 40,000 acre feet per year from the Drop 2 Reservoir. Available annual banked resources include 40,000 acre feet per year from the Arizona Water Bank, 30,000 acre feet per year from the California Water Bank, and total sum of 333,639 acre feet stored in the Nevada Water Bank (SNWA 2009b). The Las Vegas area is free to withdraw any amount from its own water bank, so I include the total sum in this calculation. Summing together the maximum annual storage amount for the Las Vegas area is 481,139 acre feet.

I also assume that the storage amount can be extended by return flow credits at a rate of 4 out of every 10 acre feet diverted (Holmes 2010). Using the return flow credit rate (481,139 x 1.4) = 673,594.6 acre feet. Calculating the Storage Vulnerability Indicator we have projected 2010 annual water use (553,000 af) divided by regional storage capacity (673,594.6 af) = 0.82.

2. "Withdrawal ratio *– Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems,"* (Lane, et al 1999 p196).

To calculate the withdrawal ratio a value for annual water withdrawals and a value of the sum of all internally generated and imported water are needed. To approximate annual water withdrawals I use 2010 projected annual water use, as stated in SNWAs Water Resource Plan, which is, 553,000 acre feet per year.

To evaluate internally generated and imported water in the Las Vegas area, I look at the total water supply based on values listed in the Water Resource Plan that are expected to be available for use in 2010. Water supply for the Las Vegas area is from the Colorado River (300,000 af); ICS from the Virgin and Muddy Rivers (28,500 af); ICS from Coyote Spring Valley (9,000 af); permitted groundwater rights (46,340 af), and reclaimed water (26,842 af). All sources except for reclaimed water are assumed to be augmented by return flow credits at a rate of 4 for every 10 diverted acre feet).

The sum of sources that can be augmented by return flow credits is (300,000 af + 28,500 af + 9,000 af + 46,340 af) 383,840 acre feet, which is multiplied by 1.4 to assess the full value with return flow credits, 383,840 * 1.4 = 537,376. Adding in reclaimed water supply (26,842 af) the previous total is equal to 564,218 acre feet per year of currently available water supply.

Calculating the Withdrawal Ratio Indicator we have annual water use (553,000 af) divided by annual supply (564,218 af) = 0.98. Annual water use is just below annual available supply for the Las Vegas area. If current supplies are close to current water use, then the current supplies will not support more water use growth without further demand management or supply augmentation.

3. "Natural Variability - *Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of unregulated annual streamflow to the unregulated mean annual streamflow. Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes,"* (Hurd, et al 1999 p1401).

The Natural Variability Indicator is the same for Tucson, Arizona as it assesses the natural variability of river flow on the Colorado River. From the above section on Tucson, Arizona, "With the Colorado River we can look at the observed gauge record, as well as flow reconstructions from tree rings. Observed data between 1906-1995 show a coefficient of variation of 0.28, while observed and reconstructed data from 1490-1997 show coefficients of variation that range from 0.27-0.31 (Woodhouse, et al 2006)."

4. "Groundwater Depletion - *Ratio of average groundwater withdrawals in year [i] to annual average baseflow reflecting the extent that groundwater use rates may be exceeding recharge. Regions with high depletion rates are vulnerable to long-run changes in hydrology,"* (Hurd, et al 1999 p1401).

In calculating Groundwater Depletion, values are needed for annual groundwater withdrawals and annual average baseflow. Total groundwater withdrawals (based on 2007 withdrawals) are about 70,000 acre feet per year (SNWA 2009b). Although municipal groundwater use is only 46,340 acre feet per year, total groundwater use includes not only municipal use, but also private well users. Natural groundwater recharge in the Las Vegas Valley is about 57,000 acre feet per year. Calculating the Groundwater Depletion Indicator we have total groundwater withdrawals (70,000 af) divided by natural groundwater recharge (57,000 af) = 1.23. The Las Vegas area is using groundwater in excess of natural recharge and depleting groundwater storage in the aquifer.

5. Reservoir System Resiliency *– A measure of a reservoir system's ability to recover from drought; 1) Reservoir capacity divided by average annual inflows; 2) Annual water demand or system outflows divided by average annual inflows; 3) multiply both values together.*

Since both the Las Vegas area and the Tucson AMA receive their surface water supply from the Colorado River, the Reservoir System Resiliency Indicator is the same for both metropolitan areas and I use the Colorado River reservoir system. The first value needed is total reservoir capacity. The primary storage reservoirs relevant to the Lower Basin on the Colorado River are Lakes Powell and Mead with a combined storage capacity of 54,752,000 acre feet (Bureau of Reclamation 2010a and 2010b). To find a value for average annual inflows I use the mean value calculated using the existing observed record and also the record reconstructed using tree rings, which is estimated to be about 15 million acre feet (SNWA 2010). The final value needed for the indicator calculation is average annual outflows or water use from the system. The upper and lower Colorado River Basins both have an annual allocation of 7.5 million acre feet of water. The lower basin is using their full 7.5 million acre foot allocation, but the upper basin is not. Upper basin uses are about 4.2 million acre feet per year (BOR 2008). Along with upper and lower basin uses, there is also annual 1.5 million acre foot allocation for Mexico, which is delivered in full each year (Secretary of the Interior 2007).

To calculate current Colorado River water use I sum the upper basin use of 4.2 million acre feet, the lower basin use of 7.5 million acre feet, and Mexico's allocation of 1.5 million acre feet, which equals 13.2 million acre feet per year of Colorado River use.

The first equation for the indicator calculation, reservoir capacity (54,752,000 af) divided by average annual inflows (15,000,000 af) = 3.65. The second part of the equation, annual water use (13,200,000 af) divided by average annual inflows (15,000,000 af) = 0.88. Lastly, multiplying both parts together, 3.65*0.88 = 3.212.

5.3.8 Las Vegas Area Case Study Summary

Two of the above indicators, Natural Variability and Reservoir Resiliency are the same for both the Tucson AMA and the Las Vegas area. Natural Variability on the Colorado River is not extreme, but the size of the built reservoir system and water use from the River point to a system which is not expected to recover quickly from drought. Water withdrawals in the Las Vegas area are just shy of water supply, indicating that without stricter conservation or new water supplies there is little room for water use growth. Groundwater Depletion is a problem in the Las Vegas area as the Indicator points out that more groundwater is withdrawn than is recharged. Although the Las

Vegas area does not have as much water in storage relative to annual water use as the Tucson AMA, the amount of currently accessible water is still greater than annual water use, which is a strength for Las Vegas.

5.4 Portland, Oregon

When comparing Portland with Tucson and the Las Vegas area, perhaps the most obvious difference is climate. Average annual precipitation totals for Portland are around 36 inches (NOAA 2010c), compared with about 12 inches for Tucson (NOAA, 2010d) and less than 10 for the Las Vegas area (NOAA 2010a). However, even though the Portland area receives much more precipitation that the other two cities, Portland is still subject to similar concerns with water supply reliability: diversity and governance of supply sources, water storage and emergency back-up supplies, rate of water use growth, ability to secure new water sources, and vulnerability to climate impacts.

Like the Tucson and Las Vegas metropolitan areas, Portland is composed of a major city (the City of Portland) and several surrounding towns. Retail water supply for the City of Portland is provided by the Portland Water Bureau and the Bureau is also a wholesale water provider to several surrounding suburbs and communities. Retail water provision totals 60% of the water supplied by the Bureau and wholesale water provision totals 40% (Portland Water Bureau 2008). The Bureau has wholesale contracts with 19 water providers in the area. Table 5.7 lists the largest wholesale contracts (Portland Water Bureau 2008 and 2010b).

Table 5.7 Portland Water Bureau's Largest Wholesale Contracts

Portland Water Bureau's Largest Wholesale Contracts	Tualatin Valley Water District
	Rockwood
	Gresham
	Tualatin
	Tigard
	West Slope

Although, the Portland Water Bureau does not serve the entire Portland metro area, its service area is the largest and most comprehensive as far as the population served and the depth of information provided by the Bureau about the area's water supply reliability. Consequently, the primary information source for this case study is the Portland Water Bureau's, "Water Management and Conservation Plan for the City of Portland, Oregon." The following table provides a list of frequently used acronyms.

Table 5.8 Portland Case Study Acronym List

ACRONYM	DESCRIPTION
ADD	Average Daily Demand
CSSWF	Columbia South Shore Well Field
MGD	Millions of Gallons Per Day
GPCD	Gallons Per Capita Per Day

5.4.1 Diversity and Governance of Supply Sources

The two water sources in Portland are surface water from the Bull Run Watershed and groundwater pumped from the Columbia South Shore Well Field. The Bull Run Watershed is Portland's main source of water year round, while groundwater serves as an emergency back-up supply and to augment surface water supplies as needed in the summer months. Both supply sources are replenished with Pacific Northwest precipitation. However, since groundwater is naturally stored in aquifers, it is less vulnerable to annual fluctuations in precipitation than Bull Run surface water. Therefore, during dry summer months when precipitation decreases and water use increases, Bull Run supplies diminish and groundwater is used to bridge the supply gap. The supply substitution of these two sources greatly increases the reliability of Portland's water supply, compared to reliance on just one source. Figure 5.9 illustrates the Portland water supply system with relation to the Bull Run Watershed, groundwater wells, and surrounding wholesale communities (Portland Water Bureau 2010b).

Figure 5.9 Portland Water Supply System

Bull Run Surface Water

The Bull Run watershed is located in the foothills of Mt. Hood, east of the City of Portland and has a total annual water yield of about 180 billion gallons (over 550,000 acre feet) of water a year, of which around 20% is diverted to Portland for consumption. Beginning as Bull Run Lake, the water then becomes Bull Run River and is subsequently stored downstream in two reservoirs before reaching the City. The Portland Water Bureau holds Bull Run surface water rights for municipal use that are senior to all other rights (Portland Water Bureau 2008).

Although the Bureau holds all senior water rights for the Bull Run watershed, it must comply with two federal laws, which can affect its use of its rights: the Endangered Species Act and the Clean Water Act. Four anadromous fish species in the Bull Run watershed are listed as threatened under the Endangered Species Act and water temperatures under the Clean Water Act are managed to ensure, “core cold-water habitat for salmonids,” (Portland Water Bureau 2008, 2-8). Complying with these laws could affect available supply, and the Bureau may need to adjust the level and timing of water releases from the two Bull Run reservoirs to ensure adequate water temperatures for fish species (Portland Water Bureau 2008).

Groundwater

Groundwater resources for the Portland Water Bureau are located on the Columbia River flood Plain northeast of downtown Portland and consist of 26 active wells drawing on three separate aquifers (Portland Water Bureau 2008). The well field is known as the Columbia South Shore Well Field (CSSWF) and water rights are held by the City of Portland through 5 permits. Although the permits total 342 millions of gallons per day (MGD), currently only 136 MGD is developed (Portland Water Bureau 2008). Of this developed amount, pumping capacity of the aquifers for periods of around 30 days is estimated to be 102 MGD. Plans to expand groundwater pumping capacity are discussed later.

Well contamination has been a problem in the past and continues to affect certain wells. To protect groundwater supplies from urban contamination leaching into the aquifers, the City of Portland implemented measures which require, “businesses that use, store, or transport hazardous material above a certain threshold amount to implement best management practices to prevent spills on the ground,” (Portland Water Bureau 2008, 2-14).

5.4.2 Water Storage and Back-up Supplies

Water storage for the Portland area is composed of the reservoir system in the Bull Run watershed, while groundwater is available for emergency back-up supplies.

Bull Run Reservoirs

Unlike the multi-year storage reservoir system on the Colorado River, the Bull Run reservoirs do not have multi-year capacity and depend on winter precipitation to fill each year. In this sense, the reservoir system is resilient in that it refills each year, but is also vulnerable to shortage during warm summer months when precipitation is low and water use increases (Portland Water Bureau 2008). Two man-made reservoirs, Reservoir

1 and Reservoir 2, along with the natural Bull Run Lake, compose the available storage of the watershed.

Although Bull Run Lake is naturally occurring, a small dam maintained by the City of Portland raises the level the Lake by about 10 feet (Portland Water Bureau 2008). Total storage capacity of the Lake is about 14.8 billion gallons, but only 4.3 billion gallons are considered usable storage. An easement provision in 1997 limits releases from the lake that could compromise a complete refill of the Lake in the spring and establishes a minimum lake elevation of 3140 feet. Concurrent with the establishment of a minimum lake level, the easement also states that lake levels can be below an elevation of 3148 for only two years during a 20 year period and must be above an elevation of 3148 for all of the other 18 years (Portland Water Bureau 2008). Lake level establishments are to protect bald eagle and trout habitats (Portland Water Bureau 2010a).

Moving downstream from Bull Run Lake, the first reservoir in the watershed is Reservoir 1. Maximum capacity of Reservoir 1 is 10 billion gallons with usable capacity at 7.3 billion gallons. The closest reservoir to the Portland area is Reservoir 2, which has a maximum capacity of 6.8 billion gallons and a usable capacity of 2.6 billion gallons.

Groundwater

As mentioned above, groundwater in the Portland area is used to bridge supply gaps when the Bull Run reservoirs run low in the summer months and also as an emergency back-up supply when Bull Run water cannot be used, due, usually to turbidity. Since groundwater use became available in the 1980s, the Bull Run water supply has been shut down seven times, lasting from 4 days to 27 days (Portland Water Bureau 2008).

The use of groundwater as an emergency back-up supply is reliable for the short term or about 30 days, but not long term (greater than 30-90 days) depending on water use intensity and the season. The three main limitations on the groundwater supply are limitations on, "the aquifer yields over extended periods of time, the mechanical reliability of the system, and the presence of manganese in some of the CSSWF wells," (Portland Water Bureau 2008). To expand the reliability of groundwater as an emergency back-up supply source, the Bureau does have plans to increase supply capacity.

5.4.3 Rate of Water Use Growth

In order to assess water use growth, Portland Water Bureau looked at key factors influencing past water use, from 1960-2006, and developed an econometric model to look at total daily water use and also to project future water use, extending out to the year 2030. The first 20 year period of water use, from 1960-1980, were characterized by population increases, economic expansions, residential lot size increases, inefficient water fixtures, and low water rates. All of these factors lead to higher water uses. After a leveling off period in the mid 1980s, the following years were characterized by decreasing water use, in spite population and economic growth. This was attributed to water conservation programs, smaller residential lot sizes, inclining block water rates, and new codes mandating water efficient fixtures (Portland Water Bureau 2008). Some more recent decreases in water use are also attributed to economic slowdowns and fluctuating wholesale water use.

While forecasting future water use, population growth is a primary factor. Population growth projections were provided to the Bureau by a regional governmental planning agency (Metro), which uses multifaceted planning tools for all demographic projections. Along with population, weather is another important variable in the equation. Since weather cannot be forecasted long term, the Bureau uses different past scenarios of normalized weather, and past peak seasonal water use to assess water use under the different conditions for each projection year. Using historical data based on 1967, which had the highest average daily demand (or water use) during the peak season, provides the Bureau of an idea of water use under warmer summer weather conditions (Portland Water Bureau 2008). Assessing models of high water use are important for adequate future water use planning as well as incorporating potential climate change impacts. Table 5.9 Shows population projections and annual average daily demand (ADD) (or average daily water use) projections based on 1) normalized annual weather conditions and 2) annual weather conditions with peak summer water use. The included years are 2010, 2020, and 2030 and water use is in Millions of Gallons per Day (MGD) (Portland Water Bureau 2008).

Table 5.9 Portland Water Use and Population Projections (MGD)

Year	ADD Normalized Weather	ADD Peak Seasonal Water Use	Population
2010	114.7	119.6	843,725

2020	125.4	130.9	924,920
2030	134.6	140.4	995,728

Population in the Portland Water Bureau service area is expected to increase, which will also increase water use. Annual average daily water use under normal weather conditions is expected to increase by about 17% from 2010 to 2030, and annual average daily water use with peak seasonal demands will be around 4% higher than water use under normal weather conditions (Portland Water Bureau 2008).

5.4.4 Ability to Secure New Water Sources

Portland has the ability and the need to develop additional water sources. There are two driving factors when assessing the need for supply expansion in Portland. The Bureau's primary reason is the increasingly important role groundwater will play in meeting future water use projections, and also needs for additional groundwater to offset Bull Run supply decreases due to: in stream flow requirements in Bull Run for fish habitat, decreases in summertime Bull Run supply due to potential climate change impacts, and turbidity impacting Bull Run.

The second reason for augmenting Portland's water supply is the need during dry years and hot, dry summers, "to meet annual average demands under higher demand weather years, projecting that the Bull Run system may be out-of-service for at least 90 days. The existing groundwater system is not capable of meeting annual average weather-normalized demands currently," (Portland Weather Bureau 2008, 5-26).

Portland has several options when considering new supply sources or augmenting existing sources. Water augmentation needs must be balanced with cost effectiveness and many options available to Portland are not currently cost effective, but may be cost effective in the future when water use growth is sufficient enough to support the financial costs. Currently the most cost effective option (which also has minimal environmental costs), is expanding the groundwater capacity of the CSSWF. Other options for supply augmentation that the Bureau considered include: development of a third dam in the Bull Run watershed, raising the dam levels on reservoirs 1 and 2 to allow for more storage, developing Bull Run groundwater, aquifer storage and recovery, and developing non-potable supplies.

Beginning in 2009 through 2028, the Bureau has plans to develop 48.54 to 53.39 MGD of its CSSWF groundwater rights, and full development of CSSWF groundwater rights held by the Bureau is expected within the next 75 years (Portland Water Bureau 2008). As stated above, the City of Portland holds rights to a total of 342 MGD of groundwater from the CSSWF, of which 136 MGD are currently developed (Portland Water Bureau 2008).

5.4.5 Vulnerability to Climate Impacts

Climate impacts can affect Portland's water supply through natural climatic variability and also through potential impacts of anthropogenic induced climate change. Natural precipitation variability plays an important role for the Colorado River water supplies of both Tucson and Las Vegas. For Portland, natural precipitation variability in the Bull Run watershed is currently not a pressing concern since only about 20% of the total water yield in Bull Run is used for Portland's water supply, and the resilient reservoirs refill each year (Portland Water Bureau 2008). However, increasing future water use on the Bull Run water supply primarily from population growth and fish habitat protection regulations could put greater stresses on the existing storage system. Natural temperature variability in the summer months plays a more pertinent role, as warmer summers increase water use from the water supply. Portland is currently preparing for increased water use on the Bull Run water supply by expanding the capacity of the groundwater system.

To prepare for human induced climate impacts that may go beyond any natural variability of climate seen in the past, the Portland Water Bureau not only commissioned a climate change study for the Bull Run watershed in 2002, but also stays informed of current climate science, monitors and revises long term planning, and connects with other western cities about climate change mitigation and adaptation strategies (Portland Water Bureau 2008). The commissioned climate change study on the Bull Run watershed in 2002 reported model results indicating higher average monthly temperatures in all months, but greatest in July and August. Average temperature increase of 1.5 degrees Celsius for the decade 2020 and temperature increase of 2.0 degrees Celsius for the decade 2040. Precipitation models suggested increasing winter precipitation and decreasing summer precipitation, although there was lower confidence in the precipitation models than the temperature models (Palmer and Hahn 2002). Newer climate models prepared in 2007 for the Intergovernmental Panel on Climate Change and reviewed by The University of Washington Climate Impacts Group project that temperature changes are an additional 10-20 years away than reported in 2002, and summer precipitation changes are unpredictable (Portland Water Bureau 2008).

Similar to climate change models looking at other parts of the West, precipitation models are inconsistent and unpredictable while increasing temperatures trends in the models are much more consistent. Increasing temperatures, particularly in the summer will undoubtedly impact summer water supplies in Bull Run. If groundwater supplies become insufficient at any future point to bridge the supply gap, then additional measure will need to be taken to augment supplies. These could include any of the supply enhancement options already discussed by the Bureau. Since the Bureau is aware of potential climate change impacts and monitoring long term supply plans, the odds are favorable that if supplies need to be augmented again in the future, the Bureau will be ahead of the curve.

5.4.6 Water Supply Reliability and Vulnerability: Portland Self-Assessment

This section looks at how the Portland Water Bureau views the reliability and vulnerability of its own water supply and provides an overview of any qualitative and quantitative measures the Bureau uses for its own assessment. Unless stated otherwise all figures used in calculating the indicator values are from the Portland Water Bureau's Water Management and Conservation Plan.

To decide how to assess the reliability and vulnerability of their water supply, Portland Water Bureau looked to other utilities to find common themes of assessment. Looking at what events are most likely to affect service such as power outages, storms, earthquakes, etc., is a common theme used by utilities and adopted by the Bureau to assess their reliability and vulnerability. The events and their estimated frequency of occurrence for the Portland area are: 1) supply system breaks (main breaks, pump station outages, etc.) every 5-25 years, 2) landslides or earthquakes around every 50 years, 3) 100 to 500 year earthquakes. The Bureau states that there are few events that could affect both supply sources (Bull Run and groundwater), but that Bull Run is particularly vulnerable to turbidity impacts. In the unlikely event that both supplies were fully or partially disrupted the Bureau has some options which include off loading wholesale customers that have other supply sources and receiving water from other wholesale communities that share interconnection pipes with Portland (Portland Water Bureau 2008).

Although Portland Water Bureau does not include any calculated indicators to assess its water supply reliability or vulnerability, they do look at the ability of the current groundwater system to supply peak summer water use for a period of time greater than 90 days if Bull Run service is disrupted. Long term groundwater reliability to meet future peak summer water use is assessed by looking at estimates of MGD production capacity for 30-90 days, which is estimated at 92 MGD, but also incorporating potential groundwater supply disruptions due to routine maintenance. If routine well maintenance affects supply by 10%, then the maximum production falls to 82.8 MGD, which would not be sufficient to meet the peak summer water use (simulating peak water use using 1967 weather conditions) projected for the year 2028 (Portland Water Bureau 2008). The inability of the groundwater system to meet projected peak summer water use for planning scenarios beginning in 2028 highlights the Bureau's need to expand groundwater capacities.

5.4.7 Portland Water Supply Reliability, Vulnerability, and Resiliency Indicators

Calculated indicators for Portland are Storage Vulnerability, Withdrawal Ratio, and Natural Variability. Modifications of the indicators to suit the Portland area and water supply system are discussed with the individual indicators below. Further discussion and comparison of the indicator values for all three cities is in the Conclusion:

1. "Storage Vulnerability *– "Measure of region's ability to cope with extreme water events; reservoir yield, which is approximated by consumptive demand divided by regional reservoir storage capacity (internal and upstream),"* (Lane, et al 1999, p195).

To calculate the indicator I need values for annual consumptive demand (consumptive water use) and regional reservoir capacity. Portland has projections of average daily water use for 2007-2030. So, to arrive at an approximate figure for annual consumptive water use, I use average daily water use for the year 2010, which is 114.7

MGD and multiply by 365 to get an approximation for annual water use. This figure includes both retail and wholesale water use is about 42 billion gallons a year.

For reservoir capacity I use the values for usable storage in Reservoirs 1 and 2 as well as usable storage in Bull Run Lake. As mentioned above, useable storage in Reservoir 1 is 7.3 billion gallons, useable storage in Reservoir 2 is 2.6 billion gallons, and useable storage in Bull Run Lake is 4.3 billion gallons. Adding the three values together is 14.2 billion gallons. Calculating the Storage Vulnerability Indicator we have annual water use (42 billion gallons) divided by reservoir capacity (14.2 billion gallons) = 2.96.

2. "Withdrawal ratio *– Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems,"* (Lane, et al 1999 p196).

To calculate the indicator, values are needed for annual water withdrawals and for the sum of internally generated and imported water. To approximate annual withdrawals I again use annual water use, which I calculated above using 2010 projections of daily water use, and multiplied the value by 365. The value for this first part of the equation is 42 billion gallons a year.

For the second part of the equation I need a value that represents the sum of internally generated surface and imported water, or total annual available supply. To approximate this value, I sum the median annual amount that Portland diverts from the Bull Run watershed, which is 36 billion gallons (Portland Water Bureau 2008) plus the total amount of current developed groundwater rights, which is 136 MGD or about 49.6 billion gallons annually. Adding those together, 36 + 49.6 = 85.6 billion gallons per year.

Calculating the Withdrawal Ratio is annual water use (42 billion gallons) divided by total available supply (85.6 billion gallons) = 0.49

3. "Natural Variability *- Coefficient of variation of unregulated streamflow, computed as the ratio of the standard deviation of unregulated annual streamflow to the unregulated mean annual streamflow. Relatively high ratios indicate regions of extreme variability and, therefore, greater vulnerability to small hydrologic changes,"* (Hurd, et al 1999 p1401).

Unregulated streamflow of the Bull Run River, just below Bull Run Lake and before either of the reservoirs is used in the calculation of this indicator. Annual streamflow for the years 1993-2009 is available from the US Geologic Service and the mean streamflow, standard deviation, and coefficient of variation are calculated from this data. The full gauge site name is Bull Run River at Lower Flume NR Brightwood, OR (USGS 2010). The coefficient of variation for Bull Run streamflow is 0.225. Table 5.10 (USGS 2010) below includes the annual streamflow data points for Bull Run River and Table 5.11 shows the calculated statistics.

Table 5.10 Average Annual Bull Run Streamflow

Year	Discharge, Cubic Ft. per Second
1993	18.5
1994	17.6
1995	24.4
1996	36.4
1997	37.5
1998	25.4
1999	30.5

2000	31.2
2001	17.4
2002	24.9
2003	23.8
2004	24.4
2005	21.7
2006	24.3
2007	26
2008	29.3
2009	30.2

Table 5.11 Bull Run Streamflow Statistics

Mean	Std Dev	Coeff of Var
26.088	5.862	0.225

4. "Groundwater Depletion - *Ratio of average groundwater withdrawals in year [i] to annual average baseflow reflecting the extent that groundwater use rates may be exceeding recharge. Regions with high depletion rates are vulnerable to long-run changes in hydrology,"* (Hurd, et al 1999 p1401).

Groundwater hydrology in the Portland area is complex due to a "paleochannel" connecting groundwater with the adjacent Columbia River (Koreny and Fisk, 2000). "The Paleochannel acts as a discharge sink during low-pumping periods and a recharge source during extended pumping," (Koreny and Fisk, 2000, p279). Therefore, establishing a "fixed" amount of groundwater recharge each year to use for calculating a groundwater depletion indicator is not possible. In modifying the indicator for the Portland area I use the 30 day operating capacity for the well field, which is 102 MGD.

As a substitute value for baseflow I use the value for currently developed groundwater rights, which is 136 MGD.

Calculating the Groundwater Depletion Indicator is 30 day operating capacity (102 MGD) divided by developed groundwater rights (136 MGD) = 0.75. Portland comes very close to using their full developed groundwater rights during periods of high pumping. Further planned development of groundwater rights will increase pumping capacity.

An interesting point, is that since groundwater is linked with the vast surface water resources of the Columbia River, increasing the use of groundwater may be an efficient way for Portland to expand supplies with less impact to the aquifers (Koreny and Fisk, 2000). Current groundwater supply pumping does not have a measurable impact on Columbia River streamflow (Portland Water Bureau 2008).

5. Reservoir System Resiliency *– A measure of a reservoir system's ability to recover from drought; 1) Reservoir capacity divided by average annual inflows; 2) Annual water demand or system outflows divided by average annual inflows; 3) multiply both values together.*

Calculating this indicator for Portland I use the Bull Run watershed reservoir system. Reservoir capacity for Bull Run is the sum of Reservoirs 1 and 2, which is 16.8 billion gallons. To approximate average annual inflows I use a value for total average annual yield of the Bull Run system, which is 180 billion gallons. The final value needed for the indicator is one for annual water use from the system. To approximate the value I use Portland's median annual diversion amount, which is 36 billion gallons.

Dividing total reservoir capacity (16.8 billion gallons) by total annual yield (180 billion gallons) = 0.093. Dividing annual water use (36 billion gallons) by total annual yield (180 billion gallons) is 0.2. Multiplying the two values together = 0.0186.

5.4.8 Portland Area Case Study Summary

The resiliency of Portland's reservoirs is a result of a small reservoir storage and low water use with respect to the annual yield of the Bull Run watershed. With a resilient reservoir system, the City does not need as much storage, so the Storage Vulnerability Indicator is quite high when compared to the vales of Tucson or Las Vegas. The Natural Variability of Bull Run is less than the Colorado River and Portland is not using more water in general or more groundwater than is supplied.

5.5 Concluding Remarks

This chapter discussed several aspects of urban water supply reliability, vulnerability, and resiliency using the cities of Tucson, Arizona, Las Vegas, Nevada, and Portland, Oregon as case studies. The varying water supply sources and system complexities of the cities provide interesting insights into the challenges of providing reliable water supply systems now, and projecting future water use. Descriptions were provided for each city on the diversity and governance of their supply sources, water storage and emergency back-up supplies, rate of water use growth, ability to secure new water sources, vulnerability to climate impacts, and how each city perceives its own water supply system reliability and vulnerability.

On a quantitative level, several indicators were calculated for each city to complement the discussion and provide further insight into water reliability, vulnerability, and resiliency status. Several challenges arise when calculating indicators, such as the geographic scope to consider, finding usable data, and deciding what components of the water supply system should be included with each indicator. For example, in Tucson, to calculate the Storage Vulnerability indicator I chose to use locally banked water to quantitatively assess Tucson's storage vulnerability. However, other relevant components that could be included in the indicator depending on what a researcher wants to measure are groundwater storage reserves, and Colorado River system reservoirs. Deciding what to include in an indicator is somewhat subjective and therefore, a thorough understanding of the make-up of a city's water supply system is essential in providing a context for the indicator.

As long as the indicator context is provided, as well as an understanding of the explanatory limitations of an indicator, then comparing the indicator values across cities can enhance understanding of the strengths and weaknesses of each city's urban water supply system. However, since several indicators were modified for each city, an understanding that the comparisons are not exact is warranted. If the same inputs were used to calculate indicators for each city, then, an across the board comparison would be more appropriate. Using indicators to compare across cites also negates the need to convert various water volume measurements. Tucson and Las Vegas use acre feet, while

Portland uses billions of gallons per day, but when a ratio is or indicator is used, the calculated values do not need a conversion. Table 5.12 displays each city's indicators as a means to quickly see how the cities compare with each other. Increasing, or higher values indicate higher water system stress for the aspect of the system being measured.

Table 5.12 Indicator Values for Tucson, Las Vegas, and Portland

	Tucson	Las Vegas	Portland
Storage Vulnerability	0.46	0.82	2.96
Withdrawal Ratio	1.06	0.98	0.49
Natural Variability	0.27-0.31	0.27-0.31	0.225
Groundwater Depletion	1.55	1.23	0.75
Reservoir Resiliency	3.21	3.21	0.0186

Note: Increasing, or higher values indicate higher water system stress for the aspect of the system being measured.

The indicators may also help cities to balance their strengths and weaknesses. Tucson and Las Vegas have a higher Natural Variability indicator value for their surface water source than Portland, but they also have a lower Storage Vulnerability indicator. A lower Storage Vulnerability indicator may help to balance out a higher Natural Variability. A large discrepancy exists between the Reservoir Resiliency of Portland contrasted with that of Tucson and Las Vegas. Portland's reservoir system would recover much more quickly from a short drought since they refill each year, but the arid climate and large water use of Colorado River water necessitate a system capable multi-year storage.

Indicator values are dynamic and can be calculated each year as a means for municipalities to assess their own status, or report on any status changes to the general public. The City of Tucson Drought Monitoring Indicators, discussed above, provide examples of indicators reported annually. Tucson also assigns threshold values to some of their indicators, giving the indicator values more context. Given the climate and geographic differences of Portland, Las Vegas, and Tucson, assigning a single threshold value for each indicator does not provide an appropriate context, however assigning threshold values at a regional or municipal level would add value to their interpretation. Some indicators point towards water stress with or without a threshold value. A value greater than 1 for Withdrawal Ratio or Groundwater Depletion indicates water use in excess of supply, which increases a municipality's vulnerability to drought and climate change.

As cities grow and urban water use increase along with the looming uncertainties of climate change, cities will benefit from a thorough examination of their own water supply systems to assess strengths and weaknesses, which contribute to enhanced reliability or increased vulnerability. Sharing their knowledge with other western cites who face similar challenges can help create a collective pool of information to guide cities toward cost effective and reliable urban water systems that are adaptive to future challenges and uncertainties.

Chapter 6 Conclusion

As previous research results have found, prices for water intended for municipal use are higher than water prices intended for agricultural use (Jones 2008 and Pullen 2006). Building from these results, this research empirically examines prices for municipal (or urban) use to gain a clearer understanding of price determinants in several markets in the western U.S. Independent variables in the models include economic and demographic variables, variables that are characteristics of the particular sale or lease, and climate variables. Although the results of the climate variables are mixed in the analyses, the influence of climate on water supply reliability is an increasingly important issue with many utilities incorporating climate change vulnerability assessments into their long term water reliability planning.

6.1 Significant Findings

For all sales models except Texas Sales, the housing price index variable, adj_cmhpi, is positive and significant. Population, pop_exp, is positive and significant in all models, both sales and leases, in which it is included. Population has long been considered to be an important component of water use growth, so in spurring water use growth, population may have an indirect effect on increasing water prices. Housing prices are a strong indicator of economic strength and have the ability to rise and fall in response to the state of the economy. Although other economic indicators used as variables in previous research, such as income, may show some variation in response to a changing economic climate, since housing and water prices are both real property, their fluctuations may have a stronger relationship.

Quantity, or the predicted value of quantity where 2SLS is used, is also a significant price determinant in several models. When significant, quantity is generally negative, which indicates economies of scales. Quantity is positive and significant in the Boulder model, which may indicate higher transaction costs. Although economic theory also suggests that resource scarcity increases prices, the results of drought on urban water prices are mixed.

Although the SPI variable is negative, as expected, in all models except Reno, it is significant only in the Colorado models. The Front Range, Boulder, CBT, Albuquerque, and Reno models included the SPI variable from the climate division representing where much of their water supply originates, but as a comparison, I also ran the models with the SPI variable from the climate division where the water is used. For Colorado, the results suggest that drought in the climate division where a significant source of their water supply originates increases urban water prices, while drought in the climate division where water is used is not statistically significant. This conclusion only applies to Colorado.

Determining the quantitative effects of drought on urban water prices is challenging. First, how quickly drought affects urban water transactions is likely very localized, so the SPI 12 may be a better fit for one region, while the SPI 24 or SPI6, etc., another. The reporting time lag discussed in previous chapters is also an issue. Some transactions may be reported a month or two after the actual transactions, while some may not be reported until several months after particularly if the transaction was met with any protest and ensuing delays. Lastly, urban water prices may be more influenced by economic and demographic factors, such as housing prices and population, than drought at this point in time. That said, after examining components of urban water supply reliability, vulnerability, and resiliency for Tucson, Las Vegas, and Portland, drought may play and increasingly important role as municipalities plan for population growth, severe droughts, and climate change.

Assessing each city highlighted both the strengths and weaknesses of each city's water supply system. Calculating indicator values provided an easy visual mechanism to compare across cities and also to recognize how some perceived strengths and weaknesses are a result of the area's climate. For example, Tucson has a low storage vulnerability index, but a high reservoir resiliency index, while Portland is the opposite. Arid climates benefit from larger reservoir systems due to fluctuating precipitation patterns, but larger reservoir systems are generally less resistant than smaller systems. Having additional water supplies in storage, as Tucson does, increases water supply reliability. Portland has a very high storage vulnerability index, but seeing that their reservoirs refill each year, and they have an ample groundwater supply, the city is not in need of additional storage.

6.2 Policy Implications

Municipalities or other entities looking to purchase water to augment current supplies would likely benefit if they purchased in the current economic climate. Water prices, following the trend of housing prices, are low compared to prices seen just a few years ago. Populations are expected to continue growing, placing ever higher demands on municipal water. Also, current drought conditions are affecting urban water prices in certain areas, so any future climate change impact that exacerbate drought conditions, would also be expected to increase urban water prices.

Until climate models attain a finer geographical resolution that is more useful for utilities, utilities have other options for assessing their own water supply vulnerability to climate change. Collaboration to identify key indicators would help utilities clarify their own strengths and weaknesses and, if calculated on an annual basis, are useful monitoring tools for measuring progress in alleviating any areas of water supply reliability weakness.

6.3 Future Work

Results from the empirical part of this research suggest that water markets are localized, with models encompassing a smaller geographic region generally performing better than those combining several regions into one larger model at the state level. Continuing to refine the geographic areas of specific water markets and find corresponding independent variables could lead to improved model performance. This is also applicable when looking for better instrumental variables. Instrumental variables used for this research were not always strong predictors of quantity, so a further refinement could also make a difference in correctly identifying endogeneity. Also, with respect to endogeneity, any observed patterns in markets where endogeneity tests consistently reject exogeneity or fail to reject endogeneity could be explored futher.

Future work could also investigate the use of climate and drought variables in each model to see if using different time scales and lags for different models could reveal any insight as to how long term versus short term drought affects different water markets. For example, I chose to use the same SPI for each model with just a different time lag sales and leases. My thoughts were to have a base for comparison across models. However, using different SPI's and lags for each model may be more fitting due to the local relationships between drought and water supply. Another possibility is to incorporate an interaction term between the SPI where the transfer is located and the SPI were water supply originates. Current limitations in this area involve the numerical range of SPI, which is -3 to +3, so multiplying two SPI variables together in order to explore their interaction affect is not applicable. If the SPI could be rescaled or recoded, an interaction term may be able to be used.

Other potential sources of price variation that could be explored include: looking at seasonal price variations and economic recession cycles. Seasonal prices variations could vary from region to region, so looking into seasonal price variation at a localized level would most likely illuminate any seasonality in urban water prices. Economic recession cycles may also impact urban water prices. This research explored the positive relationship between urban water prices and housing prices, and since housing prices are often closely related with regional economic conditions, future work could explore previous recessions and review any impact on past water prices.

Although I did a preliminary investigation into the number of buyers and sellers in each individual urban area, more work could be done to determine if any market power influences exist that affect water prices. Major buyers and sellers of water could negotiate special prices, as could pairs of buyers and sellers who routinely negotiate transfers together (Emerick 2007). An imbalance in the size of buyers or their water needs could also be investigated as a source of price variation. If a large water provider is in direct competition with a smaller water provider, then the water could be worth more to the small water provider than the larger water provider depending on the percentage increase the purchase would have on augmenting existing supplies. If the percentage is greater for the smaller provider, they may be willing to pay much more so secure the new supplies than another competitor.

Further development and refinement of indicator calculations and values for assessing urban water supply reliability, vulnerability, and resiliency could enhance the discussion and strengthen their quantitative application. Threshold values for indicator values could be addressed to provide a richer context about the status of the region's water supply. Also, data availability permitting, indicator values could be calculated for previous years, and into the future. This could allow for the indicators to be used as monitoring tools for changes in components of supply reliability, vulnerability, and resiliency. If several years of indicator values are developed, these values could then be used in future regression analysis as well.

APPENDIX A INSTRUMENTAL VARIABLES STAGE ONE RESULTS

Table A.1 Front Range Sales Stage One Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	895.179	130.533	6.86	<.0001
frminc_lag12	-4.607	1.484	-3.1	0.002
sup_dummy	-175.744	55.123	-3.19	0.0015
adj_cmhpi	-0.347	0.621	-0.56	0.5769
trans_Freq	-4.356	1.115	-3.91	0.0001
COSPI12_DIV2_L6	-20.149	37.791	-0.53	0.594
COSPI24_DIV2_L6	65.772	44.645	1.47	0.141
n=965				
adj R^2=0.0387				

Table A.2 CBT Sales Stage One Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	148.415	20.576	7.21	<.0001
frminc_lag12	-0.647	0.226	-2.86	0.0043
sup_dummy	-20.872	8.016	-2.6	0.0094
adj_cmhpi	0.055	0.086	0.64	0.5233
pop_exp	-0.000014	0.000007	-2.18	0.0294
trans_freq	-0.546	0.164	-3.34	0.0009
COSPI12_DIV2_L6	-8.288	5.454	-1.52	0.1289
COSPI24_DIV2_L6	12.654	6.613	1.91	0.056
n=940				
adj R^2=0.0313				

Appendix B Full Colorado and Nevada Regression Results

Table B.1 Colorado State Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	5.2448	0.1588	33.04	<.0001
adj_cmhpi	0.0123	0.0004	30.03	<.0001
pop_exp	0.0000004	0.00000003	11.32	<.0001
trans_Freq	0.0004	0.0008	0.49	0.6251
COSPI12_DIV2_L6	-0.0968	0.0196	-4.95	<.0001
quantity	-0.0004	0.0002	-2.41	0.0162
n=1052				
adj R^2=0.65824				

Table B.2 Nevada State Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	6.3455	0.3474	18.26	<.0001
adj_cmhpi	0.0116	0.0022	5.38	<.0001
pop_exp	0.000002	0.000001	2.22	0.0276
trans_freq	-0.0354	0.0261	-1.36	0.1765
SPI12_L6	0.0044	0.0632	0.07	0.945
quantity	-0.0015	0.0005	-2.73	0.0069
n=223				
adj R^2=0.2866				

APPENDIX C GRAPHS OF TRANSACTION FREQUENCIES AND TOTAL QUANTITY PER YEAR

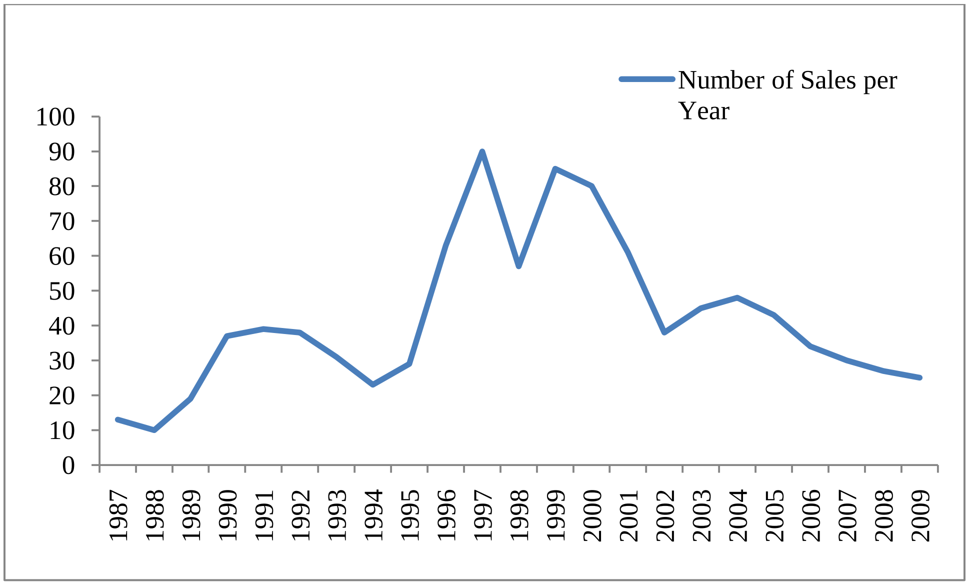

Figure C.1 Front Range, Number of Sales per Year

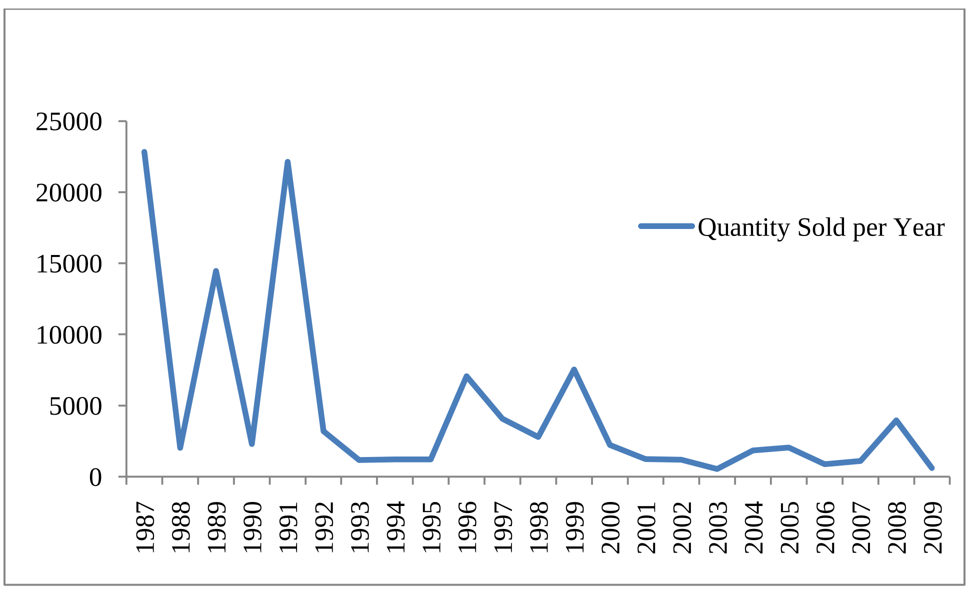

Figure C.2 Front Range, Quantity Sold per Year

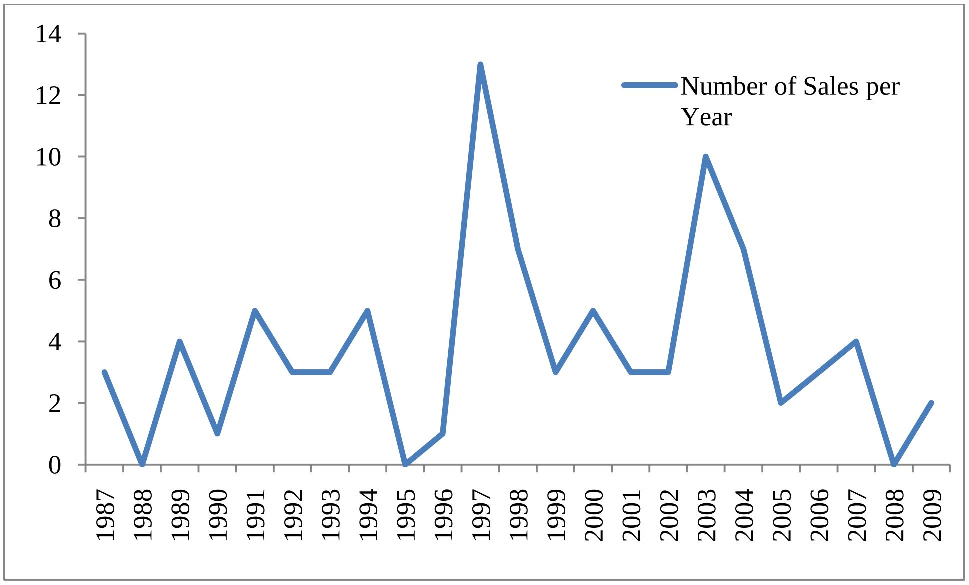

Figure C.3 Boulder, Number of Sales per Year

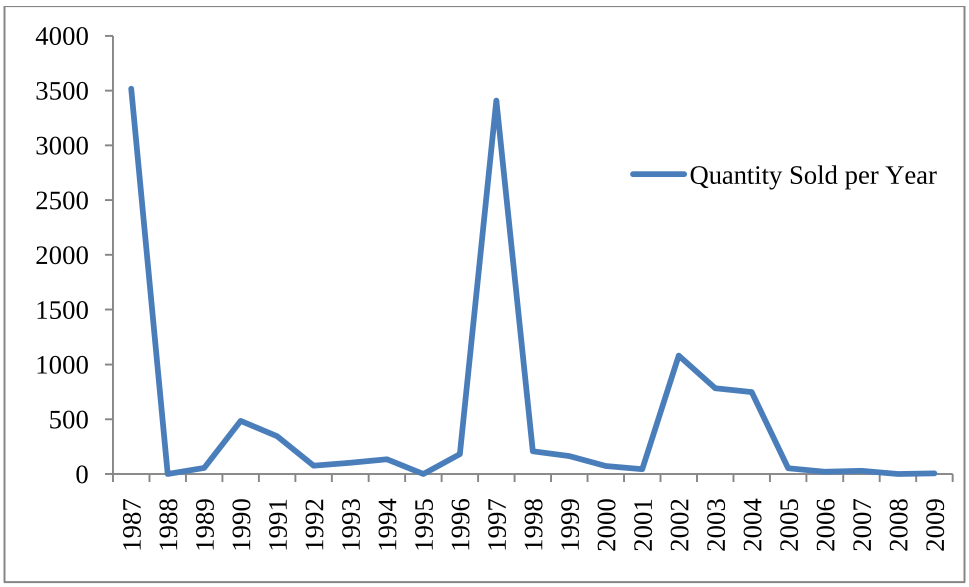

Figure C.4 Boulder, Quantity Sold per Year

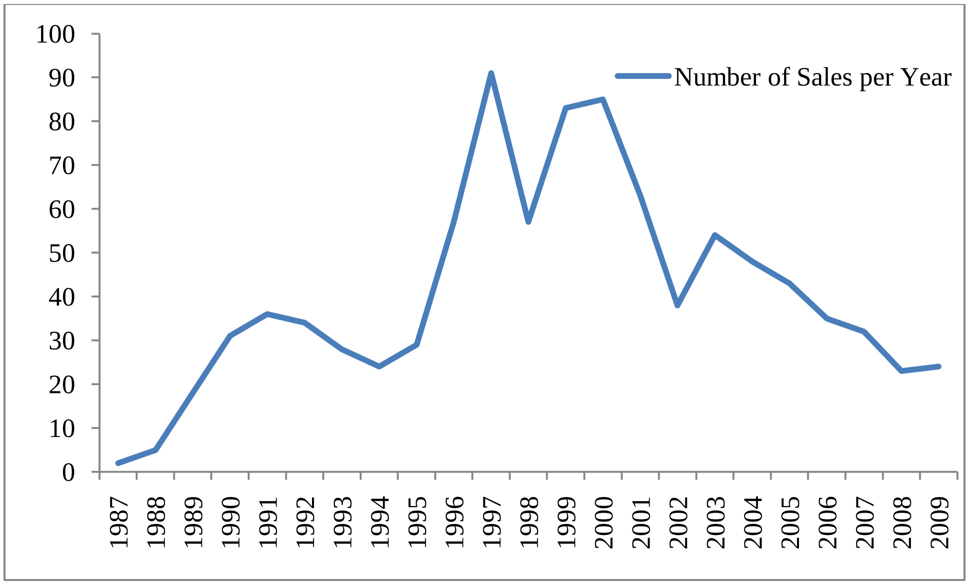

Figure C.5 CBT, Number of Sales per Year

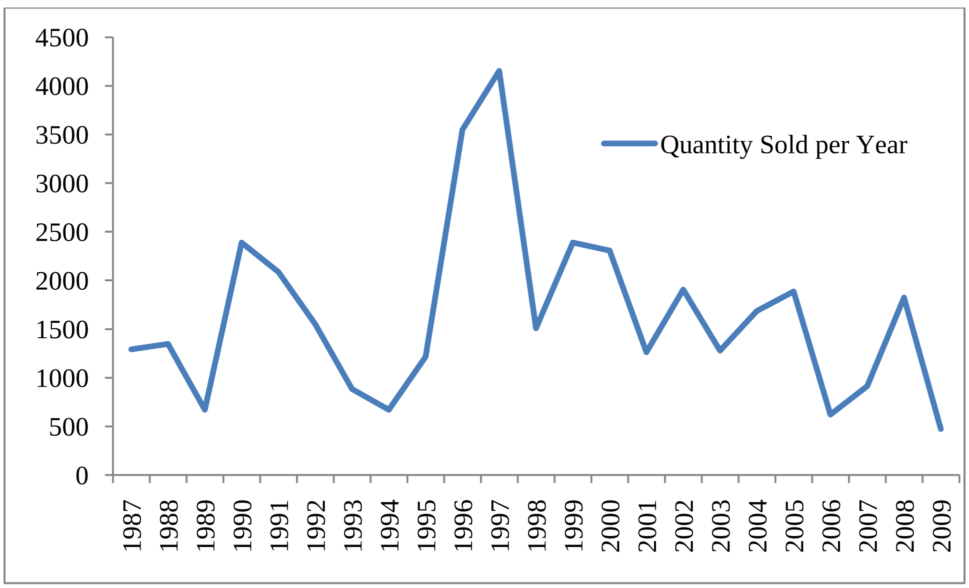

Figure C.6 CBT, Quantity Sold per Year

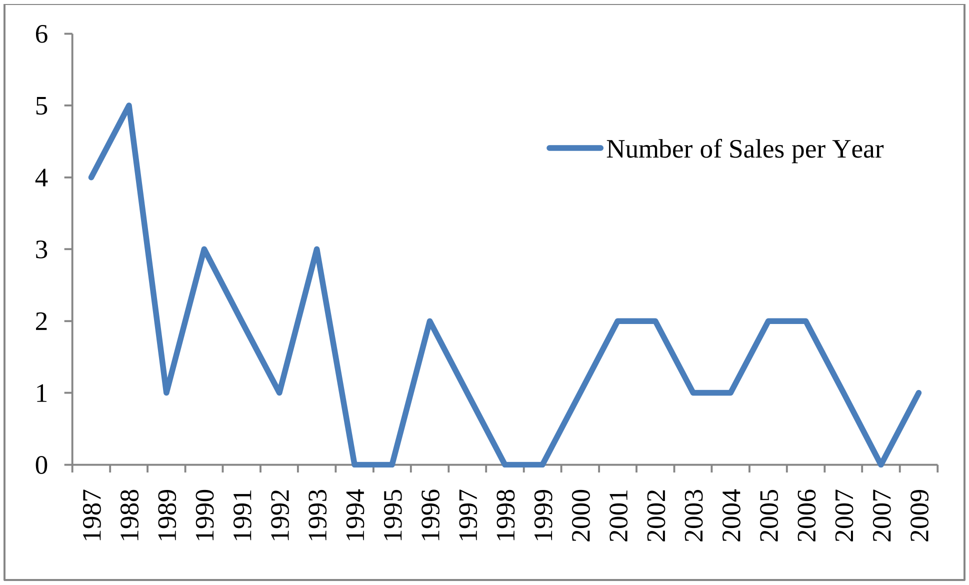

Figure C.7 Albuquerque, Number of Sales per Year

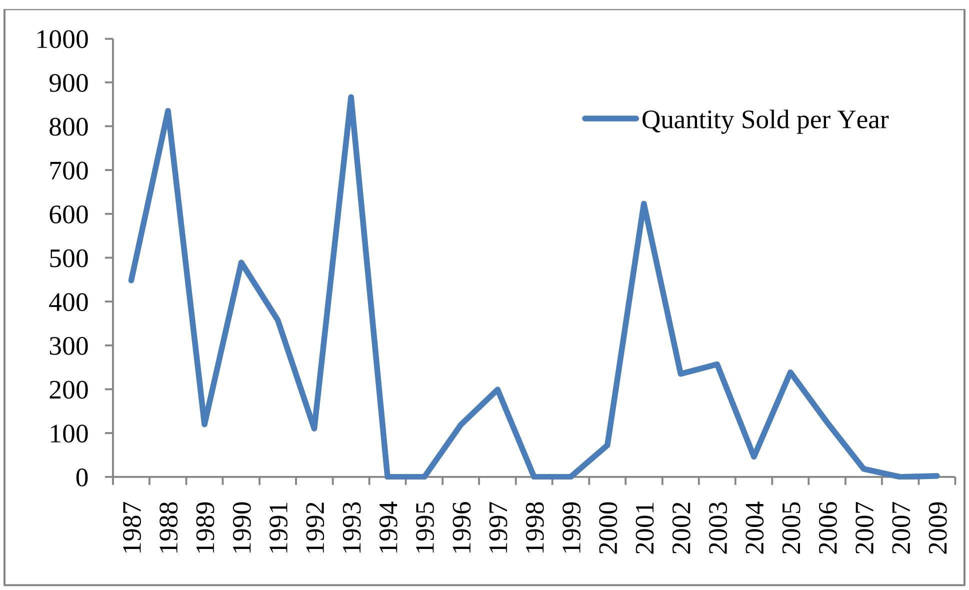

Figure C.8 Albuquerque, Quantity Sold per Year

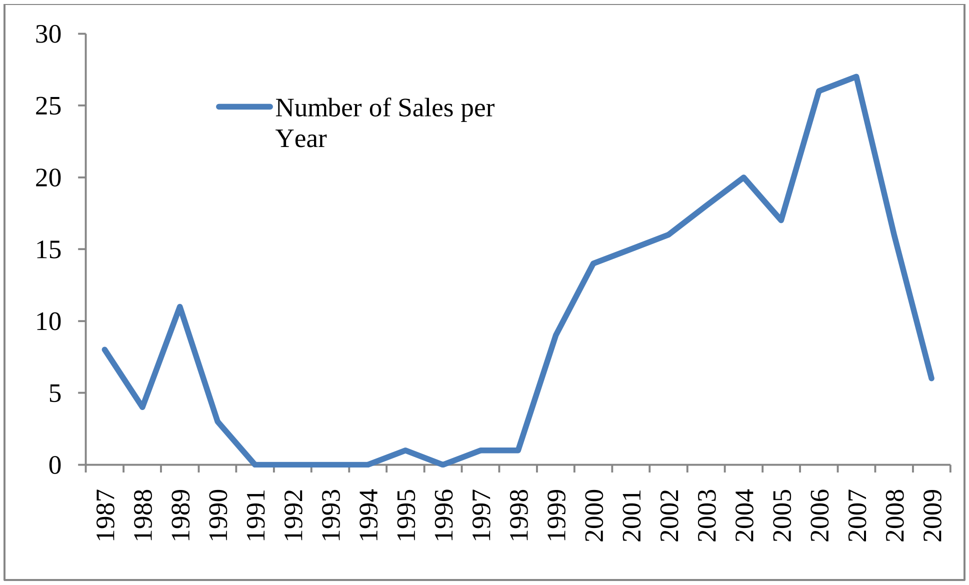

Figure C.9 Reno, Number of Sales Per Year

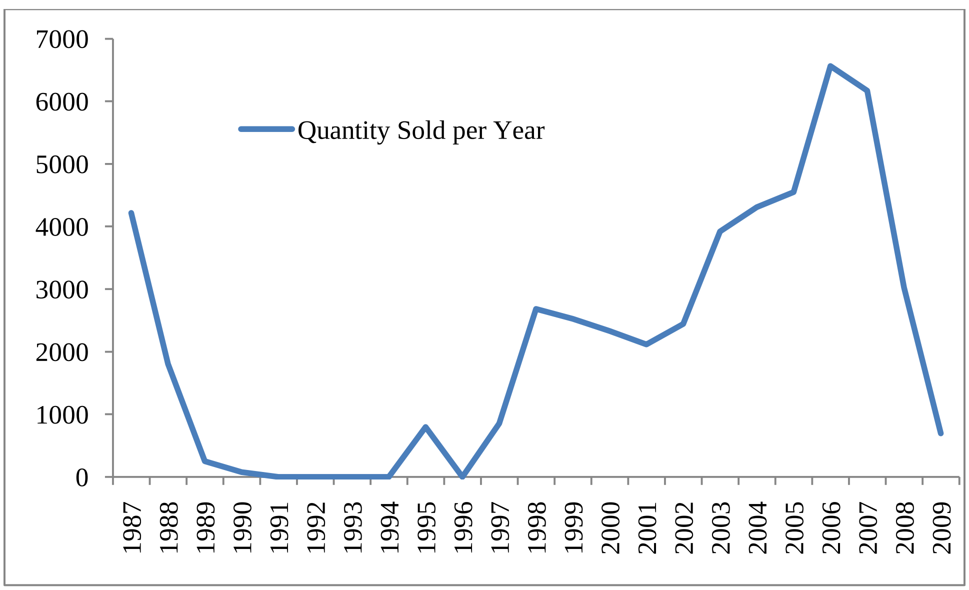

Figure C.10 Reno, Quantity Sold per Year

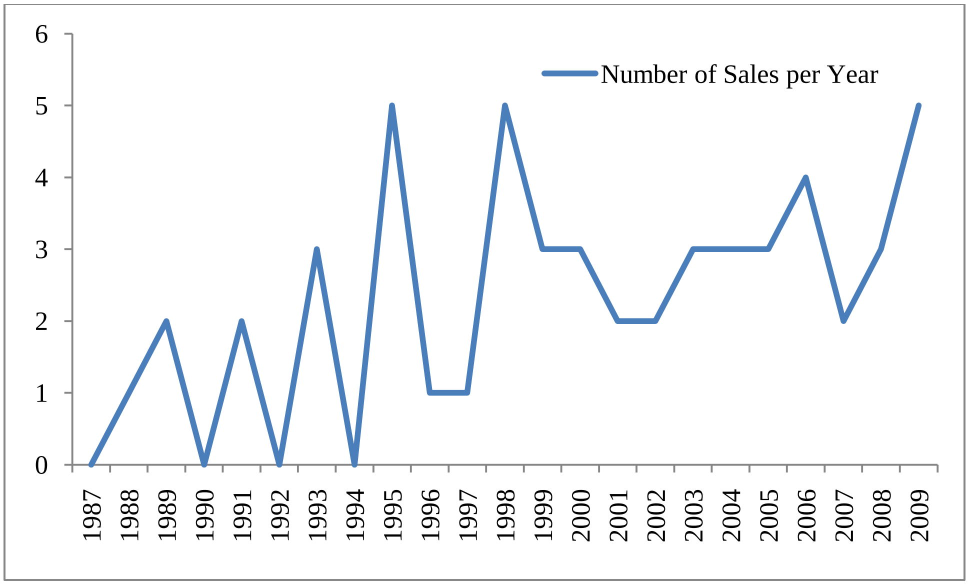

Figure C.11 Texas, Number of Sales per Year

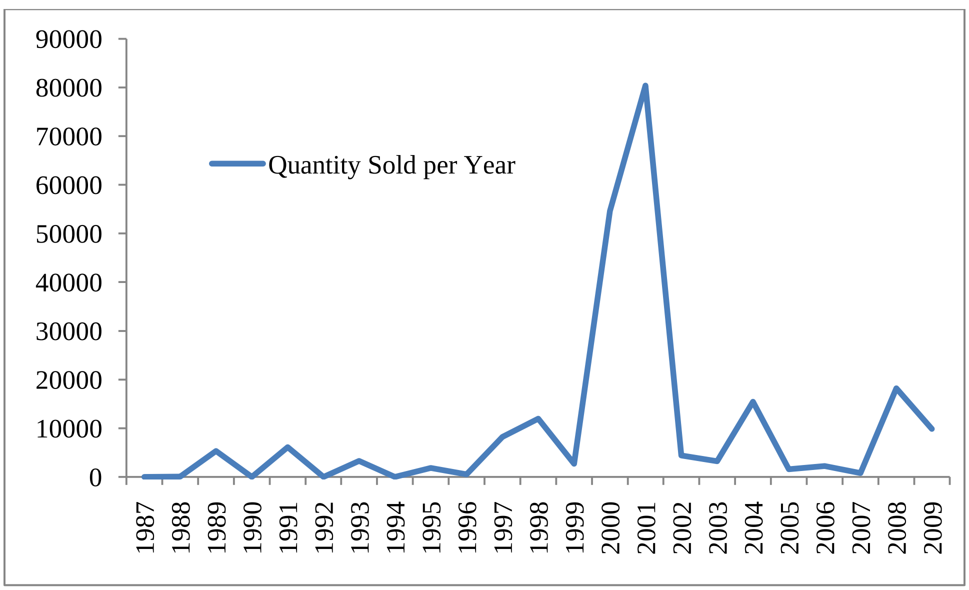

Figure C.12 Texas, Quantity Sold per Year

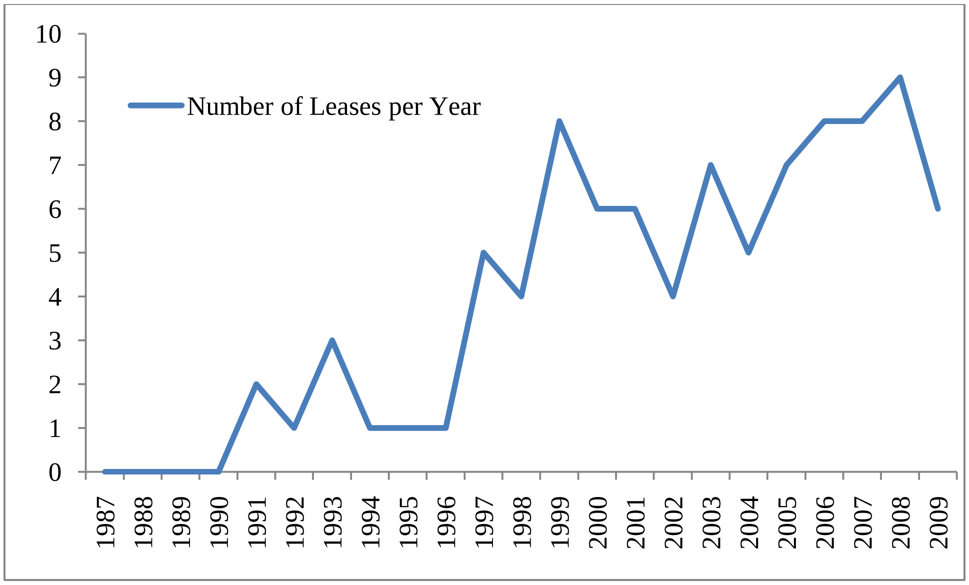

Figure C.13 Texas, Number of Leases per Year

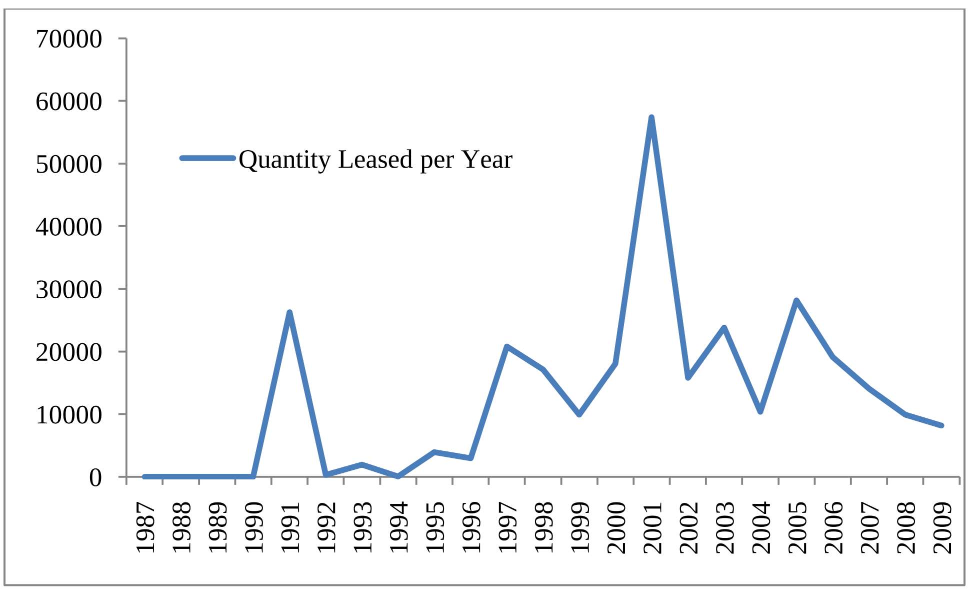

Figure C.14 Texas, Quantity Leased per Year

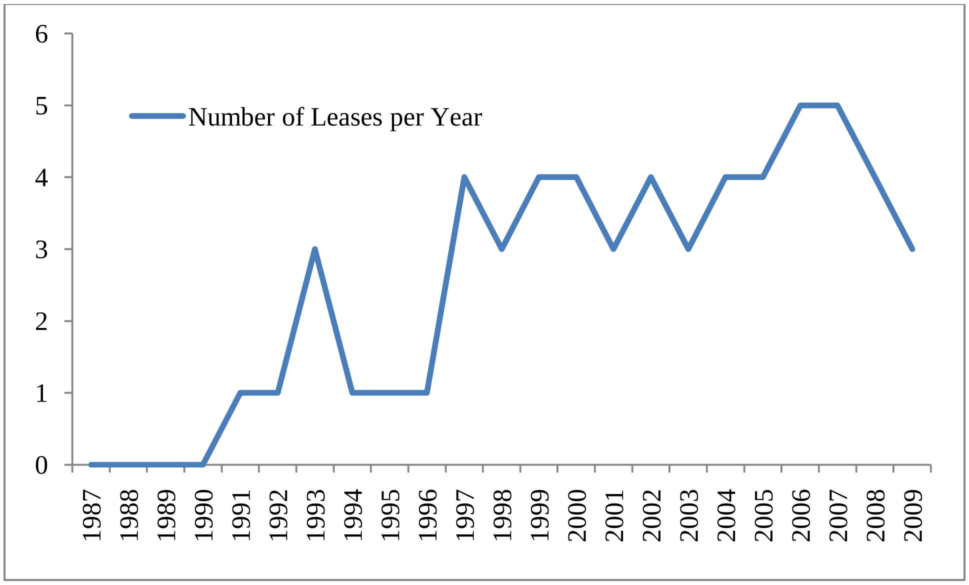

Figure C.15 McAllen, Number of Leases per Year

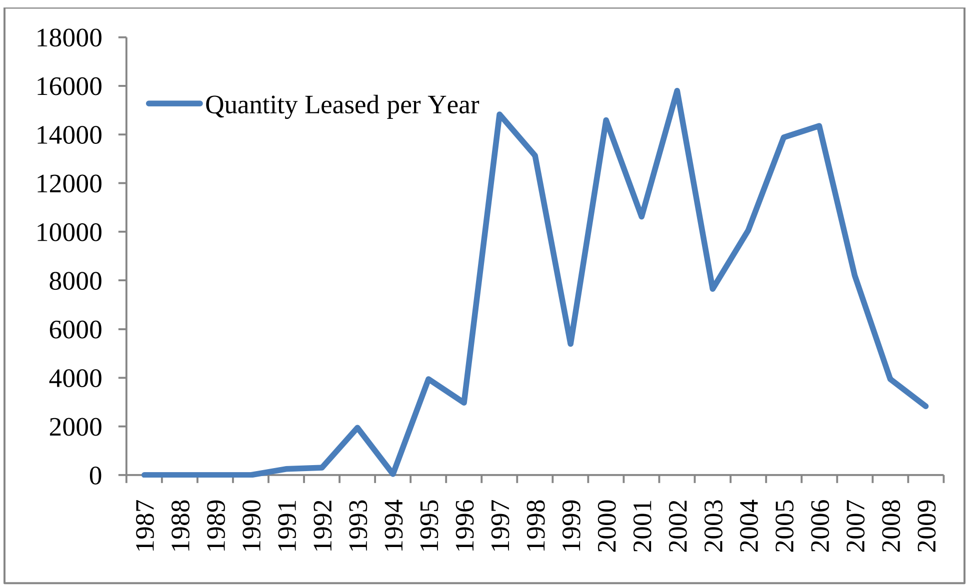

Figure C.16 McAllen, Quantity Leased per Year

Appendix D All Models with Income and Total Quantity Variables Included

This appendix contains all models with all the major variables that were considered for this analysis. I include this appendix to serve as a comparison between the models and in the main body of the text which are those that give the most robust and useful results, versus the models in this appendix. Variables included in these models, which are not included in the models in the main text are: 1) per capita income variable, and 2) variable which represents the total quantity of water sold or leased in a year. These variables are not included in the models presented in Chapter 4 for two reasons: 1) collinearity issues, in the case of the per capita income variable; 2) a determination that the variable did not add any new information to the model, as is the case with the total quantity variable. Also included in these models are variables which may be in some models, but removed from others due to collinearity issues, such as population. Below is a description of each variable not used in any of the models in Chapter 4, followed by the results for each model.

Adj_pcincome_exp: Per capita income by MSA. Annual data was interpoleted to monthly values using PROC EXPAND in SAS, and also adjusted for inflation to 2009 real dollars using the Consumer Price Index (Federal Reserve Bank of St. Louis Economic Research 2010).

Tot_q_yr: This variable is another measure of market activity, but measures the total quantity sold or leased in a given year. The sign on tot_q_yr could be positive or negative. If the total quantity sold in a year is high, then it could indicate more market activity leading to more competition and higher prices. On the other hand, for leases, if the total quantity leased in a year is high, then there may be more water available and less competition for water, leading to decreased prices.

Table D.1 Colorado 2SLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	4.60699	0.32459	14.19	<.0001
CBT_dummy	0.22300	0.16475	1.35	0.1762
adj_cmhpi	0.01324	0.00153	8.66	<.0001
pop_exp	0.00000039	0.00000005	8.58	<.0001
adj_pcincome_exp	0.000003	0.000016	0.19	0.8488
trans_Freq	-0.00075	0.00088	-0.85	0.3934
tot_q_yr	0.00003	0.00001	2.86	0.0043
COSPI12_DIV2_L6	-0.08952	0.01988	-4.5	<.0001
qhat	-0.00047	0.00027	-1.73	0.0844
n=1052				
adj R^2= 0.66418				

Table D.2 Front Range OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	5.4607	0.2382	22.93	<.0001
CBT_dummy	0.4326	0.0491	8.82	<.0001
adj_cmhpi	0.0164	0.0012	13.43	<.0001
pop_exp	-0.000002	0.0000002	-8.72	<.0001
adj_pcincome_exp	0.000077	0.000014	5.41	<.0001
trans_Freq	0.0006	0.0006	1.02	0.3069
tot_q_yr	0.000004	0.000003	1.13	0.2604
COSPI12_DIV2_L6	-0.0038	0.0176	-0.21	0.8307
quantity	-0.000002	0.000020	-0.12	0.9069

n=965
adj R^2= 0.776

Table D.3 Boulder OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	8.2387	1.2480	6.6	<.0001
CBT_dummy	0.9126	0.1529	5.97	<.0001
adj_cmhpi	0.0130	0.0028	4.67	<.0001
pop_exp	-0.00003	0.00001	-3.31	0.0014
adj_pcincome_exp	0.00009	0.00004	2.28	0.0253
trans_freq	-0.0293	0.0249	-1.17	0.2437
tot_q_yr	0.0001	0.0001	0.64	0.5269
COSPI12_DIV2_L6	0.0068	0.0659	0.1	0.9185
quantity	0.0003	0.0001	2.79	0.0067
n=87				
adj R^2= 0.8423				

Table D.4 CBT 2SLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	5.94534	0.65441	9.09	<.0001
adj_cmhpi	0.01379	0.00282	4.89	<.0001
pop_exp	0.0000002	0.0000001	2.23	0.026
adj_pcincome_exp	-0.00001	0.00003	-0.27	0.7872
trans_freq	-0.00185	0.00318	-0.58	0.5598
tot_q_yr	0.00008	0.00007	1.06	0.2881
COSPI12_DIV2_L6	-0.11892	0.03711	-3.2	0.0014
qhat	-0.00914	0.00255	-3.59	0.0003
n=940				
adj R^2= 0.40871				

Table D.5 Albuquerque OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	2.7340	0.3197	8.55	<.0001
sup_dummy	-0.1722	0.0720	-2.39	0.0243
adj_cmhpi	0.0041	0.0020	2.01	0.0547
pop_exp	-0.0000002	0.0000015	-0.1	0.9176
adj_pcincome_exp	0.0002	0.00003	5.08	<.0001
trans_freq	0.0721	0.0383	1.88	0.071
tot_q_yr	-0.0004	0.0001	-2.9	0.0076
COSPI12_DIV5_L6	-0.0141	0.0453	-0.31	0.7581
quantity	0.0002	0.0002	1.03	0.3119
n=35				
adj R^2= 0.9143				

Table D.6 Reno OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	4.1791	0.4945	8.45	<.0001
sup_dummy	0.1236	0.6008	0.21	0.8372
adj_cmhpi	0.0099	0.0017	5.8	<.0001
pop_exp	0.00000002	0.00000024	0.09	0.9304
adj_pcincome_exp	0.00007	0.00001	4.68	<.0001
trans_freq	-0.0006	0.0110	-0.05	0.9575
tot_q_yr	-0.0001	0.00004	-2.63	0.0093
SPI12_L6	0.0047	0.0366	0.13	0.898
quantity	-0.00003	0.0001	-0.43	0.6647
n=223				
adj R^2= 0.5789				

Table D.7 Reno OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	6.47428	0.85813	7.54	<.0001

sup_dummy	-0.25433	0.59497	-0.43	0.6695
adj_cmhpi	0.00611	0.00118	5.16	<.0001
pop_exp	0.00001	0.000003	2.68	0.0079
adj_pcincome_exp	-0.00004	0.00004	-0.97	0.3343
trans_freq	-0.00216	0.01048	-0.21	0.8373
CASPI12_DIV3_L6	0.07110	0.04223	1.68	0.0938
quantity	-0.00025	0.00009	-2.8	0.0057
n=213				
adj R^2= 0.5606				

Table D.8 Texas Sales OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	5.9232	1.3572	4.36	<.0001
sup_dummy	-0.4936	0.3029	-1.63	0.1103
adj_cmhpi	0.0139	0.0072	1.92	0.0607
pop_exp	0.0000011	0.0000004	2.57	0.0138
adj_pcincome_exp	-0.0001	0.0000	-1.46	0.1518
trans_freq	-0.1243	0.0736	-1.69	0.0981
tot_q_yr	-0.000001	0.000005	-0.14	0.8891
SPI12_L6	-0.0768	0.0857	-0.9	0.3751
quantity	-0.00004	0.00001	-4.39	<.0001
n=53				
adj R^2= 0.4752				

Table D.9 Texas Leases OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	2.0546	0.7330	2.8	0.0063
sup_dummy	0.0618	0.0973	0.63	0.5273
adj_cmhpi	-0.0069	0.0046	-1.5	0.1379
pop_exp	-0.000002	0.000001	-1.73	0.0877
adj_pcincome_exp	0.0002	0.0001	2.17	0.0327
trans_freq	0.0606	0.0206	2.95	0.0041
tot_q_yr	0.000001	0.000003	0.31	0.7537

lease_yrs	0.0332	0.0203	1.63	0.1067
SPI12_L3	-0.0080	0.0381	-0.21	0.8342
quantity	0.000003	0.000013	0.27	0.7899
n=92				
adj R^2= 0.6551				

Table D.10 McAllen Leases OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	2.2638	1.0595	2.14	0.0376
sup_dummy	-0.0095	0.0839	-0.11	0.9105
adj_cmhpi	-0.0284	0.0100	-2.85	0.0064
pop_exp	-0.000002	0.000002	-1.2	0.2361
adj_pcincome_exp	0.0004	0.0001	3.09	0.0033
trans_freq	0.0580	0.0592	0.98	0.3324
tot_q_yr	0.000003	0.000011	0.28	0.7807
SPI12_L3	-0.0045	0.0276	-0.16	0.8703
quantity	0.00001	0.00001	0.72	0.4736
n=58				
adj R^2= 0.6108				

Appendix E Colorado Models, Albuquerque, and Reno Using an SPI Variable from the Urban Area where Water is used

These tables are the regression results from the Front Range, Boulder, CBT, Albuquerque, and Reno models using the SPI variable which corresponds to the climate division where the water for the urban area is used. The models in Chapter 4 have the same variables as the models presented in this appendix, except the SPI variable used in those models corresponds to the climate division where the primary source of water supply is located. These models are not in the main body of the thesis, as we focus there on the SPI representing the climate division location for the primary source of water supply. Since the SPI variable corresponding to the primary source of supply, used in the Chapter 4 Front Range, Boulder, CBT, Albuquerque, and Reno models, is significant in 3 out the four models, I use those models for the main body of the text, but provide the results for the models using the SPI variable from urban area where the water supply is used below.

As in the models in Chapter 4, the 2SLS models display correct standard errors using sigma squared calculated using the parameter estimates from the second stage regression and the actual, not predicted, variables.

Table E.1 Front Range 2SLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	5.4115	0.1353	40	<.0001

adj_cmhpi	0.0146	0.0004	33.56	<.0001
trans_Freq	0.0014	0.0009	1.68	0.0942
SPI12_L6	-0.0027	0.0204	-0.13	0.8951
qhat	-0.0003	0.0002	-2.26	0.0242
n = 965				
adj R^2=0.692				

Table E.2 Boulder OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	5.15409	0.34914	14.76	<.0001
CBT_dummy	0.96473	0.165	5.85	<.0001
adj_cmhpi	0.01078	0.00072	15.04	<.0001
trans_freq	-0.03438	0.01482	-2.32	0.0228
SPI12 _L6	-0.00782	0.04214	-0.19	0.8532
quantity	0.00044	0.00008	5.82	<.0001
n = 87				
adj R^2=0.8142				

Table E.3 CBT 2SLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	5.2215	0.1753	29.79	<.0001
adj_cmhpi	0.0137	0.0003	42.1	<.0001
pop_exp	0.00000026	0.00000004	6.81	<.0001
trans_freq	0.0016	0.0008	2.03	0.043
SPI12 _L6	0.0141	0.0179	0.79	0.4325
qhat	-0.0035	0.0012	-2.8	0.0052
n = 940				
adj R^2=0.74881				

Table E.4 Albuquerque OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	3.3289	0.3489	9.54	<.0001
sup_dummy	-0.2233	0.1081	-2.07	0.0482
adj_cmhpi	0.0062	0.0026	2.41	0.023
pop_exp	0.000005	0.000001	6.92	<.0001
trans_freq	0.0345	0.0281	1.23	0.23
SPI12 _L6	-0.0168	0.0326	-0.51	0.6107
quantity	0.000003	0.0003	0.01	0.9915
n=35				
adj R^2=0.8601				

Table E.5 Reno OLS Regression Results

Variable	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	5.6754	0.3205	17.71	<.0001
sup_dummy	-0.1502	0.5953	-0.25	0.8011
adj_cmhpi	0.0062	0.0012	5.02	<.0001
pop_exp	0.000006	0.000001	4.22	<.0001
trans_freq	-0.0005	0.0103	-0.04	0.9645
SPI12 _L6	0.0483	0.0370	1.31	0.1929
Quantity	-0.0002	0.0001	-2.72	0.0071
n=213				
adj R^2=0.5575				

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