EFFECTS OF LAND USE CHANGE AND DROUGHT ON GROUNDWATER HYDROLOGY IN THE MESILLA VALLEY

BY

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ABSTRACT

EFFECTS OF LAND USE CHANGE AND DROUGHT ON GROUNDWATER HYDROLOGY IN THE MESILLA VALLEY

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Land use change caused by population growth and drought is an extremely important issue in regards to groundwater dynamics in the southwestern United States. These factors impact the relationship between land use patterns, changes in surface water delivery, and groundwater depletion/recharge levels. Few studies have been conducted on controlled experimental areas at local scales.

Production and monitoring wells in two contrasting areas were tested and analyzed over a thirteen year period (2000 – 2012) to determine whether land use change and/or drought have effects on the groundwater hydrology in the Mesilla Valley region of Doña Ana County, New Mexico. The control area was categorized as having minimal land use change, and the experimental area was categorized as having major land use changes within the time period. Parametric and non-parametric statistical tests were performed on static water levels and production rates at nearby wells over the thirteen year span after data normality was appropriately determined. Analysis of Variance (ANOVA) and the Kruskal-Wallis tests were the statistical tests selected to use on the impact of drought on three selected time periods on both areas (2000-2002), (2003-2006), and (2007-2012) that corresponded to severity of drought in the region. Student's T-Test and Mann-Whitney U Test were conducted to test the impact of land use change on two selected time periods (2000-2005), and (2006-2012) within the experimental area that corresponded to before/after land use change.

The results from this study indicated that the severity of drought on static groundwater levels and production rates were found to be statistically significantly different at the 95 percent probability level in the control area. However, the severity of drought was not found to have a statistically significant impact on static groundwater levels in the experimental area. Additionally, land use change results on static groundwater levels were found to be statistically significant difference in the experimental area. Production rates were not found to be affected by either drought or land use change at either area. It was determined through this research that direct trends and patterns do exist between population growth, resultant land use change, and climate change on the groundwater hydrology in the Mesilla Valley region of New Mexico.

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1. INTRODUCTION

The population of Doña Ana County, New Mexico (Figure 1) has been growing at an average annual rate of 4.5% for the last fifty years (Buenemann and Wright 2010). In 2010, the county's population reached 209,233, which was a 19.8% increase in population since 2000 (US Census Bureau, 2011). With population growth comes an increase in water use associated with the phenomenon (Mace et al., 2008); there is a need to build more houses, grow the economy, and add more jobs to sustain the growing population. As Buenemann and Wright (2010) found while quantifying land use changes in the region, open desert and row farming are decreasing, while residential areas, pecan orchards, and land fragmentation are all increasing. These land use/land cover changes have impacts on the relationship between land use patterns, surface water withdrawals, irrigation water return flows, and groundwater recharge.

Understanding the impacts of land use/land cover changes on the hydrologic cycle is needed to optimize natural resource management over time in New Mexico's Lower Grande region (which includes Doña Ana County) (Scanlon et al., 2005). Monitoring of the region's interrelated hydrology of surface water and groundwater is important due to the reduced reliability in surface water supplies in the southwestern United States during the next 50 years (Scanlon et al., 2005).

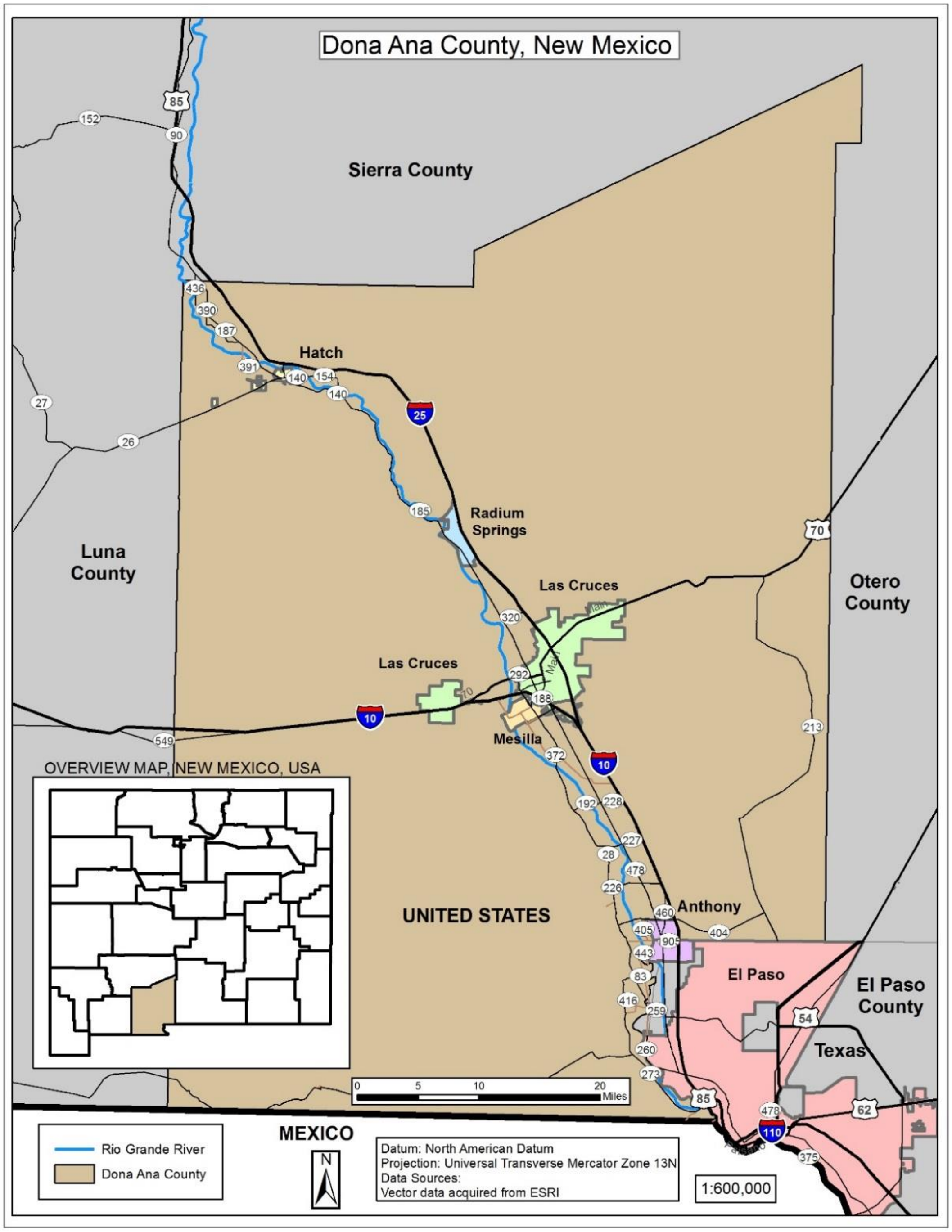

Figure 1: Doña Ana County, New Mexico

A 2007 report released by the Intergovernmental Panel on Climate Change (IPCC) suggested that, in the future, the southwestern United States will likely see a warmer climate, a decrease in mean annual runoff, an increase in flow seasonality, an increase in extreme precipitation events and subsequent flooding, and an increase in the number of extreme drought events (Meehl et al., 2007). These potential climate change impacts could adversely affect the groundwater and surface water resources used to support the region's growing population and economy. In order to effectively plan for the region's water future, it is imperative to consider the impact of land use/land cover change on the hydrologic cycle and specifically, the environment in the Elephant Butte Irrigation District (EBID).

EBID is located in the Mesilla Valley sub-region of New Mexico's Lower Rio Grande, and is the largest manager of surface water in Southern New Mexico encompassing more than 90,000 water righted acres (Esslinger EBID, 2011). The EBID was created in 1918 to manage, operate, and maintain diversion dams, canals and drainage systems from Elephant Butte Reservoir to the El Paso County Water Improvement District in Texas (Kennedy, 2005). Prior to 1951, Mesilla Valley farmers would receive full-supply surface water allocations of three acre feet/acre every year. The process of pumping groundwater to supplement the surface water supply began in 1951 due to the severe drought that hit the region (EBID, 2012). During this time there was no monitoring of wells nor were permits required to drill a well, which made this method of supplementing water supplies unsustainable during times of drought and subject to over-withdrawal (EBID, 2012).

Drought is an integral factor when discussing the hydrological cycle in the southwestern United States. From 1979 to 2002, the EBID was considered to be in full supply of irrigation water due to sufficient precipitation runoff reaching the Rio Grande. Farmers during this 23-year stretch enjoyed the previously established allocation of three acre feet/acre of water for the entire irrigation season (EBID, 2011). However, since 2003, there has been an ongoing drought in the area that has forced the EBID to have to reconsider the amount of surface water allotment (SWA) given to farmers. (EBID, 2011).

In a full supply year, approximately 125,000 acre-feet of surface water from the Rio Grande are extracted by the EBID. Approximately 44,000 acre-feet of the total get apportioned to municipal and industrial uses downstream in El Paso, while the remainder is consumed by agricultural uses (Winchester et al., 2009). During low surface water supply years, municipal and industrial wells pump around the same amount, and farmers who use irrigation for their crops increase their pumping to between 200,000 and 300,000 acre-feet (Winchester et al., 2009). It is difficult to determine to what extent groundwater aquifers have been drawn down or recharged in the region, because data on historical groundwater use haven't been collected using a seamless comprehensive wide system (Winchester et al., 2009). However, analysis of static water levels by Shoemaker and Associates, a firm that specializes in hydrology, determined that a cone of depression is developing beneath Las Cruces (Winchester et al., 2009). This cone of depression indicates that the city is pumping water at a faster rate than it is being replenished. Increased pumping during periods of short supply should be of great concern to EBID's customers as well as to downstream customers in Texas and Mexico (Winchester et al., 2009).

During an extreme drought year, such as 2011, the EBID determined that farmers would only receive four acre inches/acre (11 percent of a full supply allocation) for the entire season due to lack of water produced by rain or snow (EBID, 2011). Due to the drought, there was a strain on pecan farmers because in order to produce a successful crop, pecans need two inches of water per week from April thru October for a total of about 48 inches per acre (Fonsah et al., 2006). In some cases, farmers can purchase water through the EBID conservation pool, which is water that is not ordered or delivered by July 1st, designated as conserved water and placed into the conservation pool. EBID can then sell the water to its users on a first come, first served basis, to ensure that all of EBID's project water is put to beneficial use (Winchester et al., 2009). Additionally, large farm users can purchase temporary water from a list of willing sellers in EBID. The number of sellers and the amount of water for purchase greatly depends on the water supply for that year (Winchester et al., 2009). However, the prolonged drought has greatly reduced the amount of water both to be sold by EBID owners and available in the conservation pool. Thus, farmers have found an increased need to supplement surface water use with increased groundwater use to ensure their crops have enough water to thrive (King, 2005).

Groundwater over-pumping is another major factor of concern in the region as it is defined as pumping water to an extent that there become large drawdowns of the groundwater table without the proper time for the aquifer to replenish itself

(Kinzelbach et al., 2003). The primary means of aquifer recharge in the region is through the use of surface water for irrigation because it reduces the need for groundwater withdrawals and recharges the aquifer directly through deep percolation and canal seepage (King, 2005). Steadily falling groundwater levels, which lower the water table, can result in land subsidence (Kinzelbach et al., 2003), and higher pumping costs. Another concern for decreasing groundwater levels is the potential for saline intrusion into the water. These potential outcomes point to an immediate need to quantify groundwater declines in order to make hydrologic predictions under various land use change scenarios across the region.

Identification and quantification of the consequences of land use change and drought in the region are complicated by a variety of factors. Relatively short lengths of hydrological records are available; high natural variability is associated with hydrological systems; relatively small number of controlled experimental studies have been successfully performed; and lastly, challenges exist in generalizing results from experimental studies to other watersheds (Defries et al., 2004). Incorporating effects of land use change and drought into water resource management requires the collaboration among scientists and methods from a variety of disciplines (Defries et al., 2004).

The overall goal of this thesis research was to examine the effects of land use change and drought on groundwater dynamics through examining water resource use in controlled and experimental areas. This study will focus on determining whether changes from agricultural to residential land use has an effect on groundwater hydrology. Due to many factors that are involved with surface water in the region such as: the variability of land use types within close proximity, lateral movements of water through multiple diversion/drainage canals, and data availability, quantifying land use change and drought on surface water dynamics will not be incorporated into this research.

The outcomes of this research are valuable to all water managers in agriculture, municipal and industrial (M&I), and the Water Resources Research Institute (WRRI) as water is a major concern for the region's future. EBID officials will be interested in the results of whether drought or land use change has had an effect on the groundwater hydrology as they deal with these issues. Farmers and ranchers will also be interested in the study's findings as production of crops and livestock depend on surface water allocation and supplemental ground water supply in the area.

2. BACKGROUND AND STUDY AREA

2.1. Global Land Use Change

Human transformation of the Earth's land surface has a multitude of consequences for biophysical systems at all scales, ranging from alterations of stream flow patterns, creation of urban heat islands, altered patterns of the global atmosphere, and extinction of species (Defries et al., 2004). Land use change can be characterized by the complexity of behavioral and structural factors associated with population increase, demand, and technological capacity, which affect the natural environment in question (Verburg et al., 2007). Over the next fifty years, urban expansion, intensification of agriculture, and extraction of natural resources will most likely increase due to the growing demands of the global population (DeFries et al., 2004).

One of the major effects of urban expansion on the groundwater and surface water hydrology is the conversion of vegetated covers to impermeable surfaces, such as buildings, roads, and parking spaces (Poelmans et al., 2010). Land use change in a watershed can greatly impact local or regional water supply by altering the hydrological processes such as runoff, stream flow, evapotranspiration, and groundwater recharge (Lin et al., 2008). The consequences of anthropogenic land use changes on hydrology is a growing issue on a global scale. Understanding these consequences and focusing on them as a land change science, especially in semi-arid regions are a major need for the future (Defries et al., 2004). Due to the diversity and complex nature of land use changes around the globe, satisfactory mathematical techniques for analyzing and reliably predicting hydrological effects are still in their early stages in some parts of the world (Defries et al., 2004).

2.2. Land Use Change in the Southwest

The American Southwest is a region where biological and ecological diversity are accompanied by extreme terrain and high variability in climate. Natural vegetation dominates tracts of public land used for livestock grazing and other anthropogenic land uses (Allen et al., 2012). Over the last fifty years, low-density suburban developments in cities across the western United States have fragmented regional landscapes. Urban sprawl, extensive urban development, and discontinuous development have fragmented socio-ecological systems, leading to negative consequences. Some of the resulting consequences are decreased agricultural productivity, increased groundwater pumping, increased stream runoff, and increased costs for public services (York et al., 2002). The region is characterized by water resource limitations, including high temporal and spatial variability of rainfall, high rainfall intensities, sparse vegetation cover, intermittent stream runoff, and a large number of dams and reservoirs (D'Agostino et al. 2010). The fact that water is such a relatively scarce commodity means that numerous entities are vested in determining how land use change could ultimately affect the region's limited water resources.

2.3. Geography of the Region

Doña Ana County covers an area of more than 3,800 square miles north of El Paso, Texas and Ciudad Juarez, Chihuahua, Mexico (Doña Ana County, 2012). The entire county, except for the eastern mountain areas, lies within the Chihuahuan

Desert, which has an influence over the local climate. Elevations range from 3700 feet in the Rio Grande Valley to about 5000 feet on the upland plains (Terracon, et. al., 2003). The presence of the Organ and San Andres Mountains to the east causes a rain shadow effect which results in less precipitation over the desert basin (City of Las Cruces, 2009). Two important factors that contribute to an area's classification as desert include average annual rainfall (ten inches or less) and an evaporation rate that exceeds the annual rainfall. From 1959 to 2007 the average annual rainfall in Las Cruces was 9.41 inches (City of Las Cruces, 2009).

Two general sources of water exist in the region: groundwater and surface water (City of Las Cruces Infrastructure and Utilities, 2009). The only source of potable water throughout Doña Ana County is groundwater from one of the four groundwater basins in the area: the Jornada del Muerto Bolson, the Mesilla Bolson, the Hueco Bolson, and the "Rincon" Valley Basin (City of Las Cruces Infrastructure and Utilities, 2009). Usable surface water is contained within the Rio Grande Basin watershed, which begins in southern Colorado and ends in the Gulf of Mexico with a journey of 1,800 miles (Esslinger, 1998). The Rio Grande serves as an 800-mile international boundary between the United States and Mexico and has helped populate Las Cruces and the Mesilla Valley region for centuries (Esslinger, 1998) (Figure 2 below).

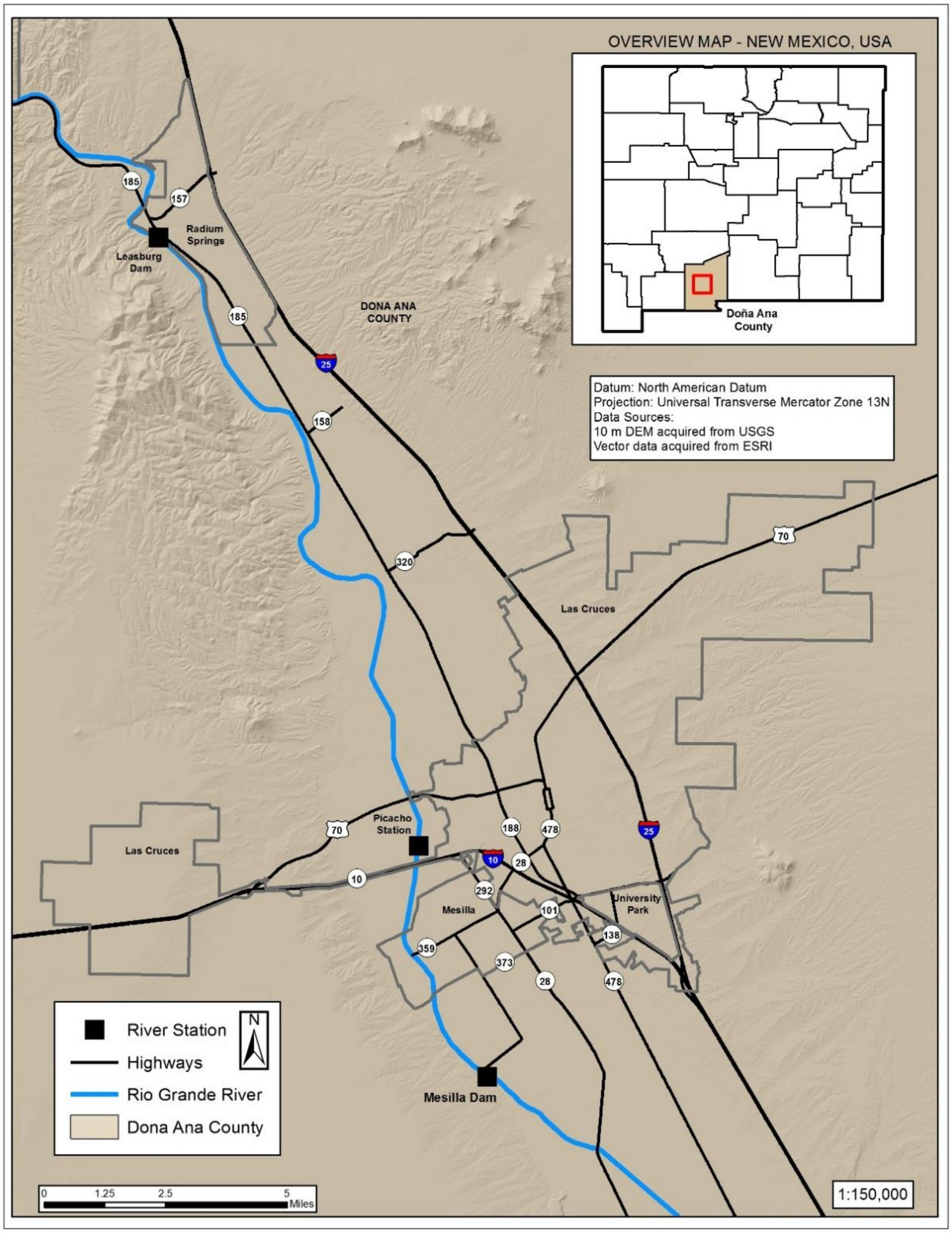

Figure 2: Las Cruces, New Mexico Map

2.4. History

Doña Ana County was established in 1851 right after the signing of the Treaty of Guadalupe-Hidalgo that ended the Mexican-American War in 1848 (City of Las Cruces Comprehensive Plan, 1999). Las Cruces itself was established in 1849 in the Mesilla Valley as there were overcrowded conditions in the nearby town of Doña Ana. Las Cruces became a farming and livestock community with plenty of natural resources up until the 1890s. The agricultural community began constructing various canals and diversion channels for irrigation purposes because the Rio Grande constantly flooded during that time, causing significant losses in livestock and crops. The flooding ultimately brought about the construction of the Elephant Butte Dam and Reservoir near the town of Hot Springs in 1916 (City of Las Cruces Comprehensive Plan, 1999). This was an extremely significant event as it provided farmers protection against future floods as well as provided much needed water in times of drought. In 1918, the Elephant Butte Irrigation District (EBID) and the United States Bureau of Reclamation (USBR) began constructing an irrigation system capable of handling the needs of the entire community consisting of Southern New Mexico, Southwest Texas, and Northern Mexico (Esslinger 1998).

The adoption of the first zoning ordinance for Las Cruces was in 1930. The city's tremendous growth from 1930 to 1950 necessitated a comprehensive plan to address issues of population, climate and topography, mineral resources, tourism, transportation, zoning districts, city boundaries, and flood protection (City of Las

Cruces Comprehensive Plan 2040, 2013). The city's first comprehensive plan was developed in 1955.

In a ten-year span from 1950 to 1960, Las Cruces went from a small agricultural based town to a sprawling urban area with a 138 percent population increase to 29,367 people. The establishment of White Sands Proving Grounds, NASA Research Facility, the growth of New Mexico State University, and the addition of a north to south interstate highway (I-25) were major contributors to the growth (City of Las Cruces Comprehensive Plan, 1999). The additions of Interstate 10 and the Las Cruces Dam were major contributors to growth during the 1970s with an increase to 37,857 people by 1970 and up to 45,086 people in 1980. Agriculture was still the most prominent land use class in the northwest and southwest areas of the city, with more residential and commercial areas in the center, western and eastern areas of the city (City of Las Cruces Comprehensive Plan, 1999) (Figure 3 below). By 1990, the city reached 62,126 people and has continued to grow at relatively high rates due to the excellent "quality of life" that the area provides (City of Las Cruces Comprehensive Plan, 1999).

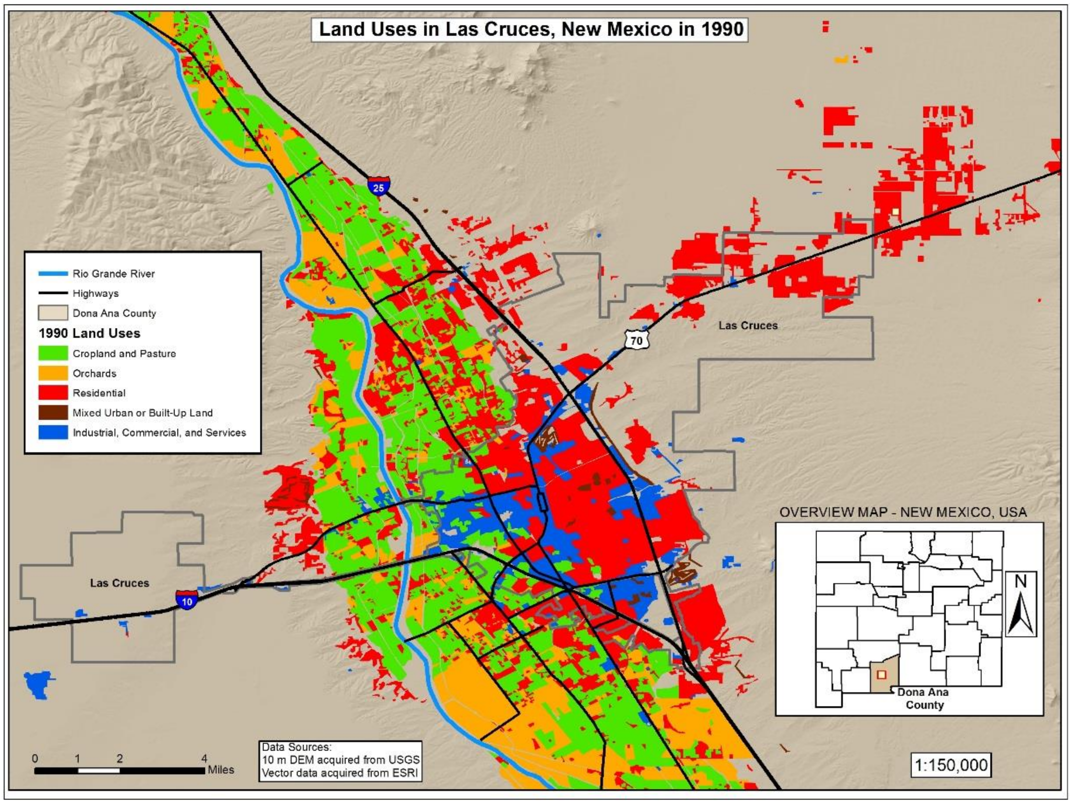

Figure 3: Land Uses in Las Cruces, New Mexico in 1990

As of the latest 2010 Census, Doña Ana County was the second most populous county in New Mexico with a population of 209,234 (US Census Bureau, 2013). Las Cruces is the county seat and has been ranked as one of the fastest-growing cities in the United States for the past decade, with a population of 97,618 (US Census Bureau, 2013). Over the next thirty years, the predicted population estimate of the county is 300,000, which would have impacts on public services, infrastructure, environment, and most importantly water resources (Bureau of Business & Economic Research 2012).

2.5. Drought and Water Conservation

Drought is an integral factor when discussing the hydrological cycle in the southwestern United States. From 1979 to 2002, the EBID was considered to be in full supply of irrigated surface water, due to there being sufficient precipitation runoff reaching the Rio Grande. Farmers during this 23-year stretch enjoyed the allotment of three acre feet per acre of water for the entire irrigation season (EBID, 2011). However, since 2003, there has been an ongoing drought in the area that has forced the District to have to reconsider how much water they can supply to farmers (EBID, 2011). For example in 2011, the EBID determined that farmers would only receive about 11 percent of a full supply allocation for the entire growing season (EBID, 2011). Due to the lack of precipitation near the Rio Grande headwaters in Southern Colorado, there is a strain on pecan farmers in the Mesilla Valley. In order to produce a successful crop, pecans need upwards of four acre-feet per acre during the growing season (Fonsah et al., 2006). In some cases, farmers are allowed to purchase water from other farmers and/or from EBID's conservation pool (Winchester et al., 2009). However, the prolonged drought has greatly reduced the amount of water both to be sold by EBID owners and in the conservation pool (Winchester et al., 2009). If farmers are unable to purchase the water, they are forced to supplement surface water use with increased groundwater use (King, 2005), which puts a strain on local aquifers.

Other important factors that have compromised water conservation in the region are irrigation inefficiencies and evapotranspiration (ET). The evapotranspirational loss of water is the basis for estimating irrigation water needs and scheduling irrigation (Miyamoto et al., 1995). A trend has been observed by researchers where irrigation duration has been longer on smaller farms (2<acres<5) than on larger farms (>20 acres) due to bad infrastructure, out of date canals, and/or easement disputes. As a result, lower irrigation efficiencies result from smaller farm size (Skaggs et al., 2005). Canal lining may make delivery more efficient, but at the cost of depleting water from the basin-wide hydrologic system (Samani and Skaggs, 2008). Low levels of on-farm application efficiency (water consumed by plants/water applied to plants) is a good source for groundwater recharge (Skaggs et al., 2011). Sloppiness helps to improve resiliency in upstream areas as it helps to recharge the shallow aquifer (Samani and Skaggs, 2008). ET is responsible for most water depletion in the West and it's very important to correctly calculate ET for on farm efficiency because incorrectly adjudicating water rights could result in over-allocation of water resources, groundwater depletion, and failure to meet downstream obligations (Skaggs et al., 2011).

Based on analysis of this pattern in a study of EBID conducted by Skaggs and Samani (2005), it was found that 16 percent of 340 pecan farms were applying an excess of the optimal 5 acre feet/acre of water, 52 percent of 524 alfalfa farms were applying excess of the optimal 4 acre feet/acre, and 40 percent of cotton farms were applying excess of the optimal 2.5 acre feet/acre. If pecan, alfalfa, and cotton farms are typically allotted 3 acre feet/acre of water on a full supply year, and evidence is found that an excess amount is being applied, then there are a few conclusions that can be drawn about how these farmers are able to sufficiently produce their crop: farmers may be leasing more water from other farmers; farmers are receiving more water than allotted due to mis-estimations in water release and poor management; and/or the most likely reason is that farmers are using groundwater pumped from individual wells (Skaggs et al., 2005).

As shown in Table 1 below, the on farm irrigation efficiency, which is calculated by the consumptive irrigation requirement divided by farm delivery, is estimated to be 83 percent as of 2001 in EBID. The conveyance efficiency, which is calculated by on farm delivery divided by diversion, is estimated to be 54 percent. The overall efficiency, which is calculated by dividing the consumptive irrigation requirement by diversion, is estimated to be only 44 percent. The two latter efficiency estimations are extremely low percentages that can be greatly attributed to fragmentation of land (Skaggs et al., 2005).

Table 1: EBID Irrigation Efficiencies (Magallanez et al., 2001)

Types of Efficiency	**Calculations Involved**	**Actual Efficiency**
On-farm irrigation efficiency:	Consumptive Irrigation Requirement / Farm Delivery	83%
Field Irrigation efficiency:	(Consumptive Irrigation Requirement + Leaching Fraction) / Farm Delivery	92%
Transmission Efficiency:	Farm Delivery / Diversion	54%
Overall Efficiency:	Consumptive Irrigation Requirement / Diversion	(0.83) * (0.54) = 0.44 or 44%

In conjunction with these land splits, the land use in some areas has changed from agricultural to residential, in which less surface water is used and more groundwater pumping is occurring (Choy, 2014). Since residential areas do not have crops, the water rights are forgone as there is no need for surface water consumption. Multiple private or public wells get drilled and groundwater becomes the key source of water for residential areas (Choy, 2014). Studies have demonstrated that when this change occurs over time, there is a direct impact on the groundwater/surface water dynamics and subsequent return flows to the river (Choy, 2014).

The amounts of surface water and pumped groundwater have the greatest influences on groundwater levels as input and output factors (Dongyuan et al. 2011). Groundwater for new residential areas will most likely become depleted at increasing rates, while not allowing for proper replenishment because of the lack of irrigation (Dongyuan et al., 2011). There will also be less groundwater percolation in residential areas due to the existence of impermeable features such as concrete, asphalt, structures, etc., instead of open fields. In addition, higher runoff to storm sewers will occur, which increases the return flows to the river that ultimately recharges the alluvial aquifer downstream in Texas and Mexico. This is a major issue in the dynamics of the hydrological recharge and the impact to the groundwater table.

The rapid growth in the region's population has also become a major challenge as there is a need to provide water to meet the needs of the 20% population increase that has occurred during the last ten years, without impairing downstream users. In order for that to happen water must be transferred from an existing use (King, 2005). As of 2004, over 90% of the existing water use along the Lower Rio Grande (LRG) went towards irrigated agriculture, with public water systems use being the next highest percentage at 7%, and commercial use being at just over 1% (King, 2005). Figure 4 below portrays the surface water/ground water distributions in the LRG (King, 2005).

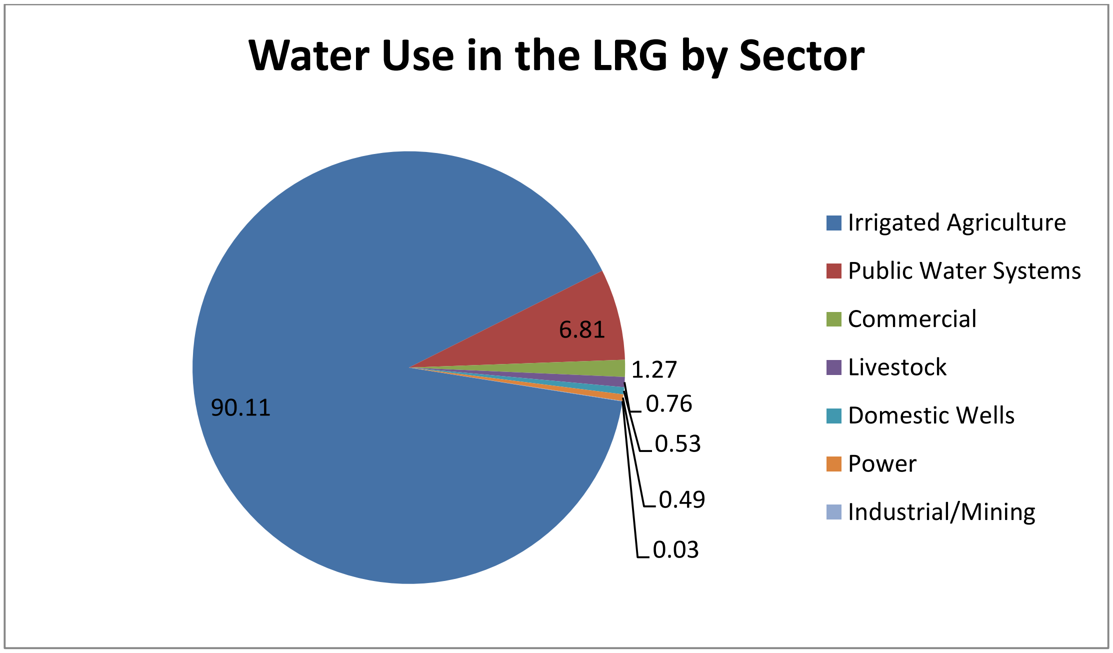

Figure 4: Water Use in the LRG by Sector (King, 2005)

Since Doña Ana County does not currently have a surface water treatment plant that would process water to potable standards and direct surface water for potable consumptive use, the most likely source of water use to satisfy future growth would be residential well use. Another important factor is that irrigated agricultural use is dependent on farms with water rights to persist, but if there continues to be a 20 percent population increase, then further urban expansion is imminent to occur which would reduce the irrigated agricultural water use (King, 2005). This scenario would inevitably reduce the aerial extent of agriculture and create more residential areas. This is another major reason why understanding land use/land cover change and its impact on water management in the EBID is extremely important to the future water supply.

3. PROBLEM STATEMENT AND RESEARCH OBJECTIVES

3.1. Problem Statement

The population of Las Cruces, New Mexico in Doña Ana County has been growing and will continue to grow at high levels during the next fifty years. Open desert and row farming have been on the decline while residential areas, pecan orchards and land fragmentation are all increasing (Buenemann and Wright 2010). The land use is changing from agricultural to residential, in which less surface water is being used but more groundwater pumping is occurring. Since residential areas do not have crops, the water rights are forgone as there is no need for surface water. Groundwater becomes the key source of water for residential areas, which is pumped from nearby wells for all consumptive use. Using groundwater in residential areas ensures less percolation into the aquifer due to the existence of impermeable features such as concrete, asphalt, structures, etc., instead of open fields. These inevitable land use changes along with prolonged drought in the region directly impact the groundwater/surface water dynamics and subsequent return flows to the river. In order to effectively plan for the region's water future, it is imperative to consider the impact of land use change and drought on groundwater dynamics in the Elephant Butte Irrigation District.

3.2. Research Objectives

In this study, the interaction of land use change and severity of drought with static groundwater levels and production rates were examined at two contrasting areas in the Mesilla Valley to better understand how each is related (Figure 5 below).

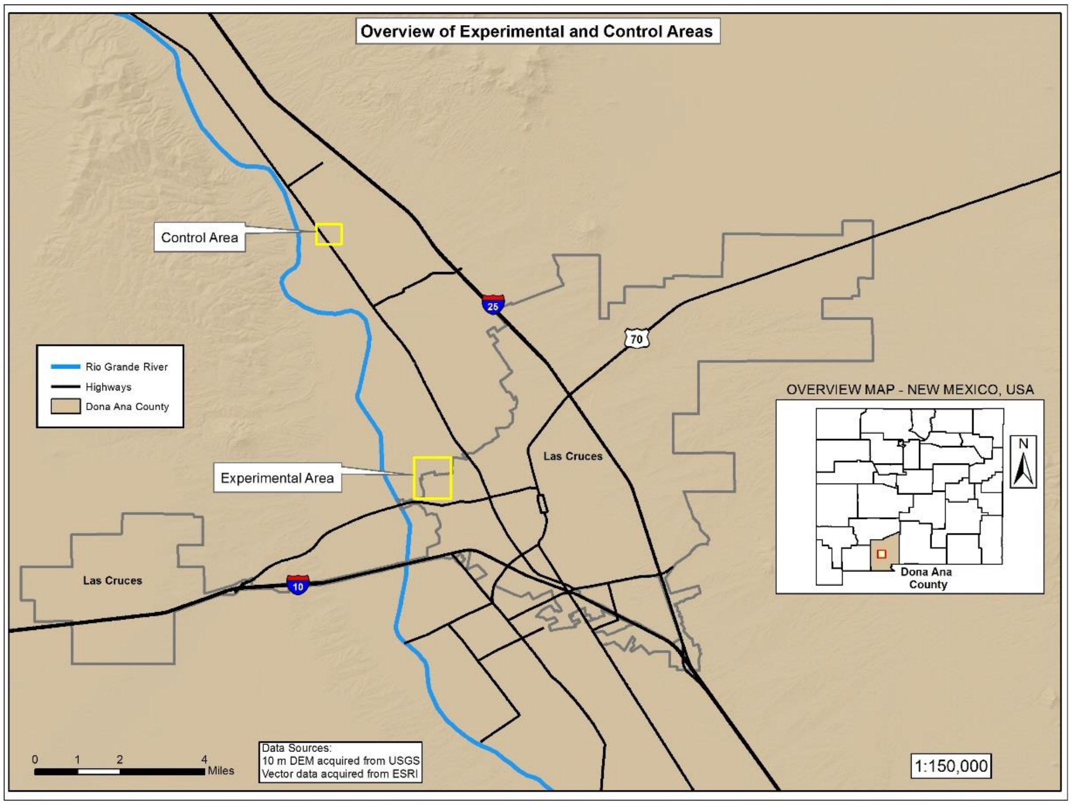

Figure 5: Overview of Experimental and Control Areas

There were two research objectives for this study. The first objective was to determine the impact of drought by comparing static groundwater levels from monitoring wells and by comparing well production rates from production wells for three timeframes on a control area (area that has undergone minimal land use change during a certain period) and an experimental area (area that has undergone major land use change during a certain period). Since land use did not change in the control area, the changes in static groundwater levels and production rates must be solely from drought. The three timeframes used are:

1. 2000 to 2002 - considered wet/full supply years,

2. 2003 to 2006 - considered beginning/continued drought years, and
3. 2007 to 2012 - considered severe/prolonged drought years.

The second objective was to determine the effects of land use change by comparing static groundwater levels from monitoring wells and comparing production rates from production wells for the experimental area (area that has undergone major land use change during a certain period). The two time periods used are:

1. 2000 to 2005 – No land use change
2. 2006 to 2012 – Major land use change

These years were chosen due to the change in land use at Legends West Subdivision from agricultural to residential in 2005.

4. DATA AND METHODS

4.1 Control and Experimental Areas

Two contrasting study areas were selected within the Mesilla Valley that serve as experimental and control areas for this research. These specific sites were selected after conducting change detection analysis using land use/land cover classification data from 2001 to 2009 and will be further discussed in chapter 4.5.1 (Figure 6 below). The control area was chosen due to being in a section with minimal land use change and having sufficient data availability, including an EBID monitoring test well (20) and a Salopek Farms LLC (04546 S-2) production well site. The experimental area was chosen as a result of its classification as the largest section that has experienced land use change from agricultural to residential as well as having sufficient data availability, including an EBID monitoring test well (45) and the City of Las Cruces (00430 S-18) production well site.

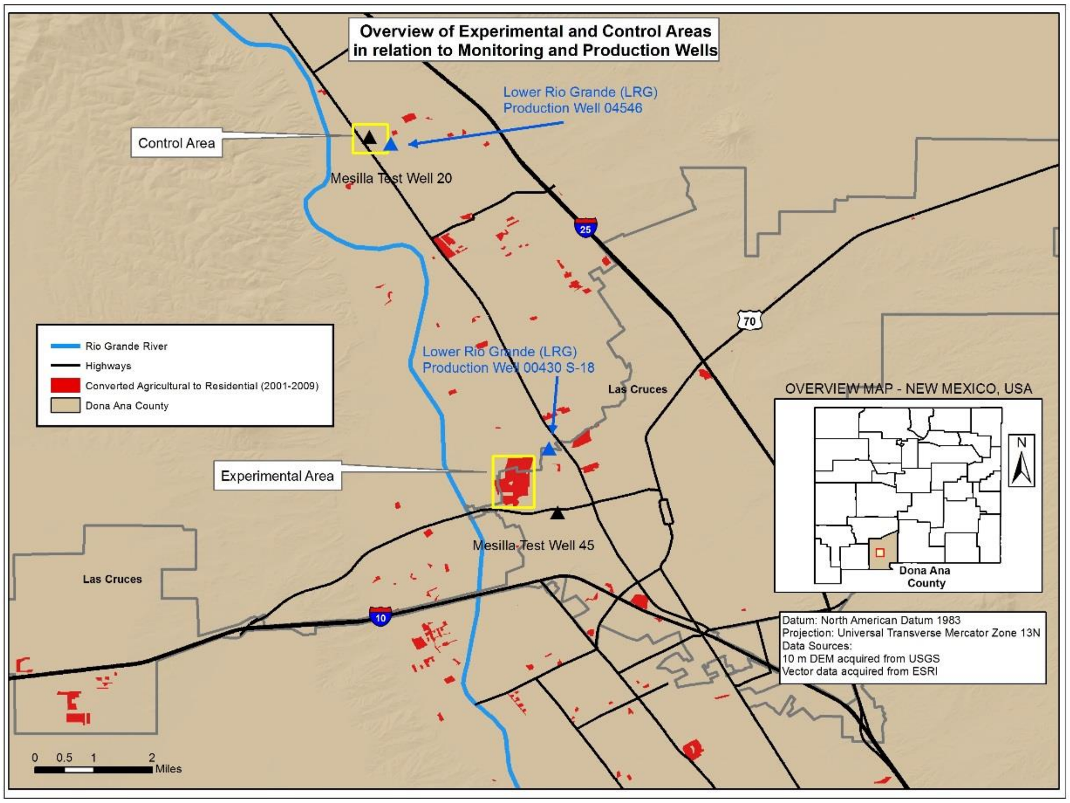

Figure 6: Overview of Experimental and Control Areas in relation to Monitoring and Production Wells

The control area consists of the area surrounding EBID's monitoring test well 20, located at 32.4027, -106.8487, near the intersection of Harvey Farms Road and North Valley Drive (Figure 7 below). The Lower Rio Grande production well 04546 S-2 is owned by Salopek Farms LLC and is located at 32.402, -106.847, which lies 0.3 miles southeast of test well 20. These particular wells were chosen due to sufficient data availability between 2000 and 2012 to perform statistical analysis. The area consists of primarily agricultural lands, including row crops and pecan orchards, and has undergone minimal land use change between 2000 and 2012.

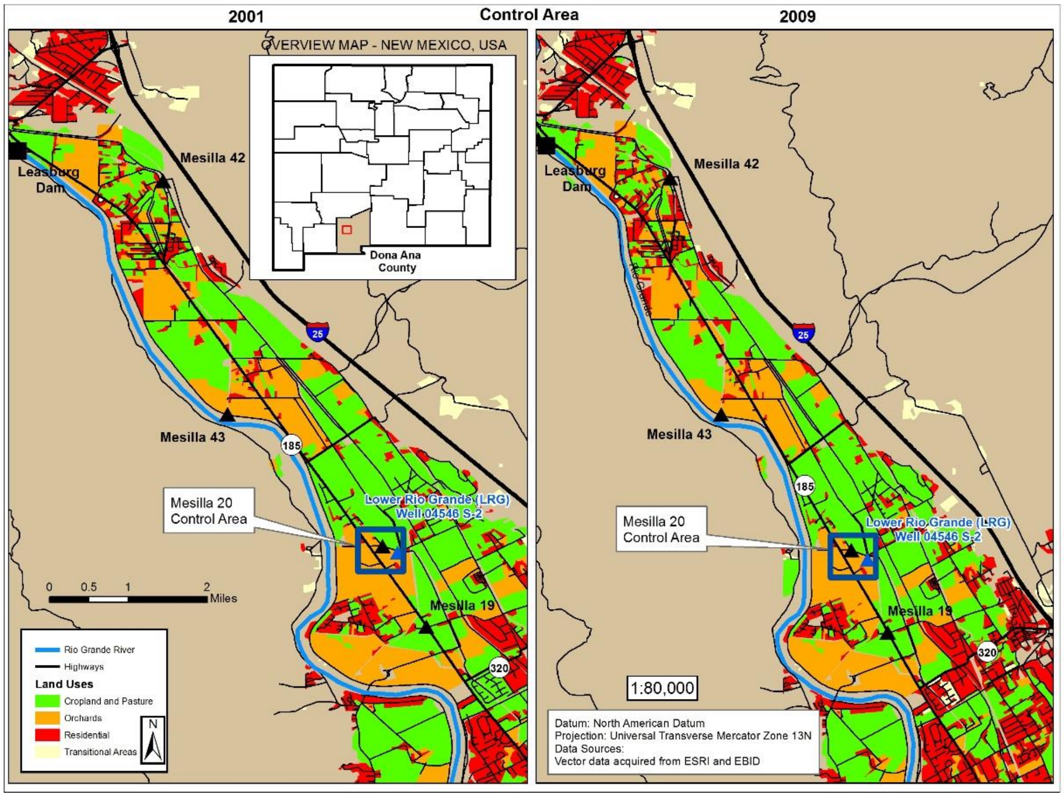

Figure 7: Control Area Map

The experimental area consists of the area surrounding EBID's monitoring test well 45, located at 32.3091, -106.8048, found near the intersection of North 17th Street and Hadley Avenue (Figure 8 below). The Lower Rio Grande (LRG) Production Well 00430 S-18 is owned by the City of Las Cruces and is located at 32.327, -106.808, which lies 1.0 mile north of test well 45. Like the wells chosen for the control area, sufficient data are available from 2000 and 2012 to perform statistical analysis. The area consists of mixed agricultural, residential, and industrial lands, as well as Legends West Subdivision which is a residential neighborhood built in 2005 that lies 0.5 miles northeast of the monitoring well and 0.3 miles southwest of the production well. This area has undergone major land use changes from agricultural to residential within the study time period.

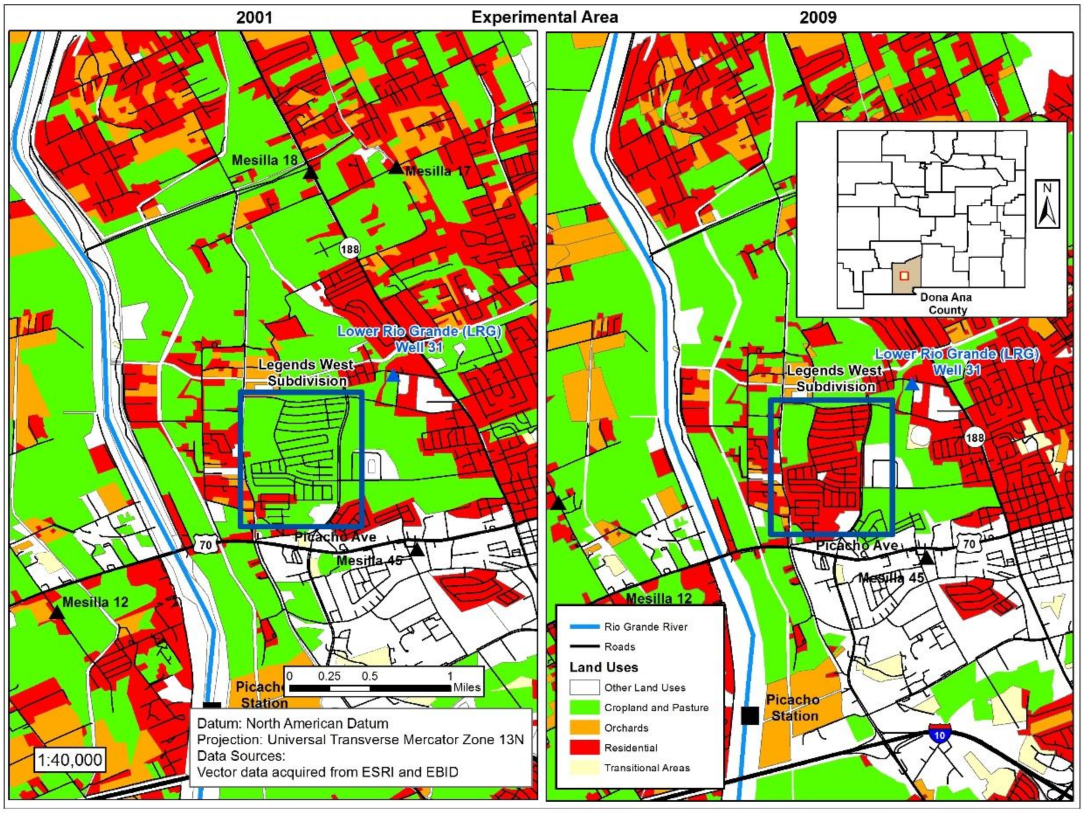

Figure 8: Experimental Area Map

4.2. Data

Data for this research were acquired from a variety of sources. Land use/land cover classification data were acquired from Dr. Michaela Buenemann, Geography professor at New Mexico State University. The data consist of polygon shapefiles containing land use/land cover classification descriptions of the entire Mesilla Valley (which included the study areas) for the years 2001, 2005, and 2009.

The static groundwater level data from monitoring test wells were acquired from EBID test well reports. The data consist of monthly hydrostatic groundwater levels that include identification number and coordinates in decimal degrees for each well, the top of inner casing in feet (TOIC), depth to water in feet (DTW), and surface elevation in feet for the years 2000 to 2012. The data could be accessed through the EBID website and the output was in both excel format and as a shapefile. The data were available for all monitoring wells in the Mesilla Valley.

Experimental area production well meter readings were acquired in PDF format from the City of Las Cruces (CLC) water administrator, which consisted of monthly data, including, well identifier, address, and production (in gallons) for each CLC well for the years 2001 to 2011. Control area production well meter readings were acquired in HTML format from the New Mexico Office of the State Engineer website, which consisted of quarterly data, including, the well identifier, driller name, owner name, casing size, depth of the well, reading frequency, unit of measure (in acre-feet), meter multiplier, date of the meter reading, meter reading, and meter amount for the years 2001 to 2011. The original goal was also to acquire static groundwater level data from production wells from the CLC and/or the New Mexico OSE to determine whether they follow the same trends and patterns as the monitoring wells; however, neither the CLC nor the OSE officially track static water levels on production wells unless the well is not performing correctly (Widmer, 2014). Since water meter readings for each production well were the only quantifiable datasets tracked (Widmer, 2014) they were consolidated to quarterly and used in this study.

4.3. Research Design

The research approach taken for this thesis was to determine the trends and patterns for two contrasting hydrologic areas in the Mesilla Valley to understand how land use change and drought affect groundwater elevations. Few studies have been done comparing two study sites, as the majority of research on this subject has been on a larger spatial scale using many observation points. The research design implemented in this thesis uses a variety of approaches from related projects to answer the overall objectives.

The conceptual model developed for this research identified the relationship between land use/land cover change and drought and their effects on groundwater hydrology. The first conceptual model (Figure 9) shows the connections between elements of surface and groundwater hydrology, community irrigation and land use, and grazing of lowland and upland pastures (Fernald et al., 2012). The model was modified to show how groundwater pumping occurs more frequently in the urban area, while groundwater recharge occurs in irrigated areas through surface water deliveries and returns to/from the river.

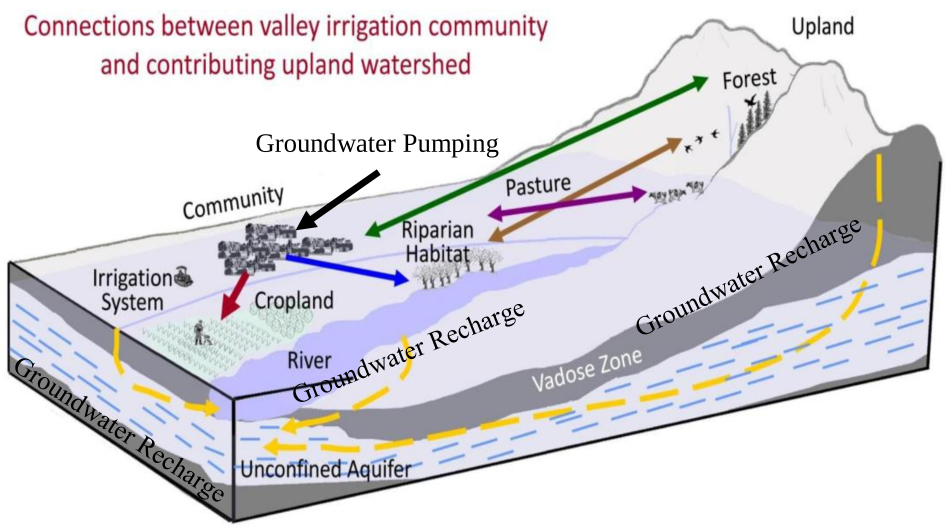

Figure 9: Watershed Model showing connection between a Valley Irrigation Community and contributing Upland Watershed (Fernald et al., 2012)

The second model (Figure 10) shows the connection of inflows/outflows of surface water/groundwater dynamics in a subsystem (Fernald et al., 2012). Blue colored variables belong to the hydrology system, green are the ecosystem, red are land use, black are critical variables across multiple subsystems and orange are urbanization (Fernald et al., 2012). This model is used to show how upstream precipitation (or lack thereof - drought) and domestic or residential pumping play an intricate part of the hydrology system. Domestic pumping, likely from urbanization, does not contribute to the overall system as much as irrigation diversion and canal seepage does. The next few sections will explain just how much of an impact land use change and drought potentially have on a hydrology system.

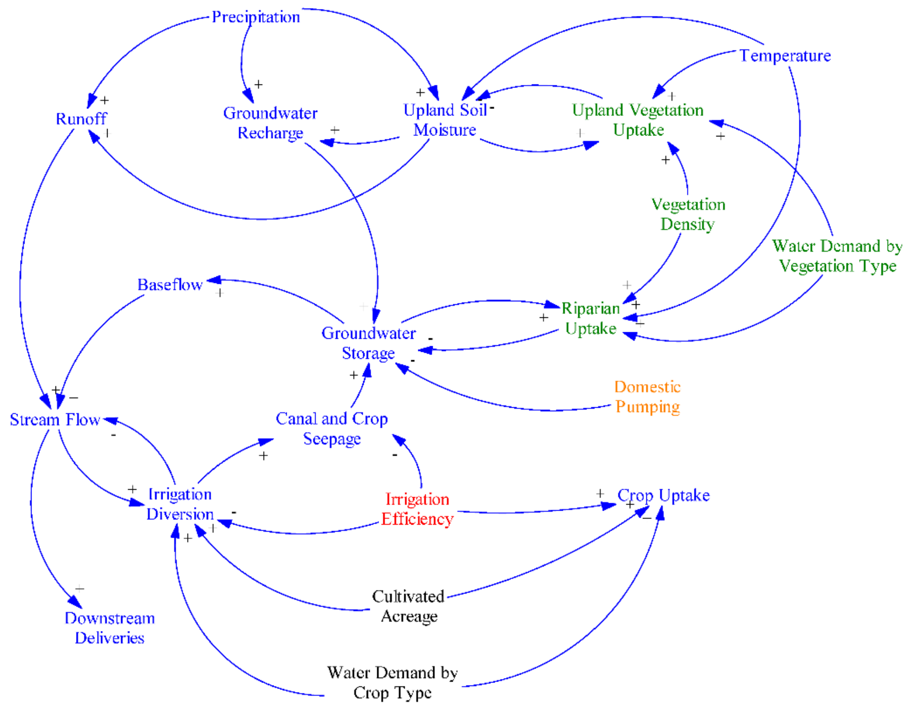

Figure 10: Hydrology Subsystem causal loop Diagram (Fernald et al., 2012)

4.4. Pre-Processing Data

In order to conduct statistical and temporal analysis, it was necessary to determine that there were sufficient data for two contrasting areas within the Mesilla Valley. In addition, it was necessary to check for normality in the distribution of the available data before performing any spatial modelling or statistical analysis (Hamad, 2009). A significant violation of the assumption of normality can seriously increase the chances of committing a Type I or Type II error (Osborne, 2002). In the case of non-normality, transformations would be necessary to drive the data to normal distribution. Several transformations, including Box–Cox, also known as power transformations, arcsine, square root, and logarithmic transformation, can be used to make the data more normally distributed (Hamad, 2009).

The first steps were to pre-process the EBID monitoring test well data for the years 2000 to 2012 for both the control (Mesilla test well 20) and experimental areas (Mesilla test well 45) by calculating central tendency, dispersion and symmetry. These wells were selected because they lie in closest proximity to the selected study areas. Mesilla test well 20 had 139 available records out of a possible 156 (monthly records for 13 year period between 2000 and 2012), while Mesilla test well 45 had 126 available records out of the possible 156. Next, the minimum, maximum, mean, median, standard deviation, skewness, and kurtosis were calculated, the datasets ranked, probabilities determined, and the normal and log normal distributions calculated for both sets of years.

After graphing the normal distributions of Mesilla test well 20 depth to water (DTW) in feet for the years 2000-2012 as a scatterplot (Figure 11 below) and as a histogram (Figure 12 below), it was determined that the data were normally distributed. When displaying normal distribution as a scatterplot, the f(x) False, also known as zero, signifies the height of the bell-shaped probability density curve for the raw values (Microsoft Office Support, 2014). The F(x) True signifies the cumulative probability that the observed value of a normal random variable with mean mu and standard deviation sigma will be less than or equal to the observed value x (Microsoft Office Support, 2014). Table 2 below, depicts where the mean value is approximate to the median value, typically meaning it’s normally distributed. There was a slight positive skew in the data but a transformation is only needed when the data are excessively skewed positively or negatively (Kleiner, 2014). Therefore, no transformations were needed to be able to use the appropriate statistical tests.

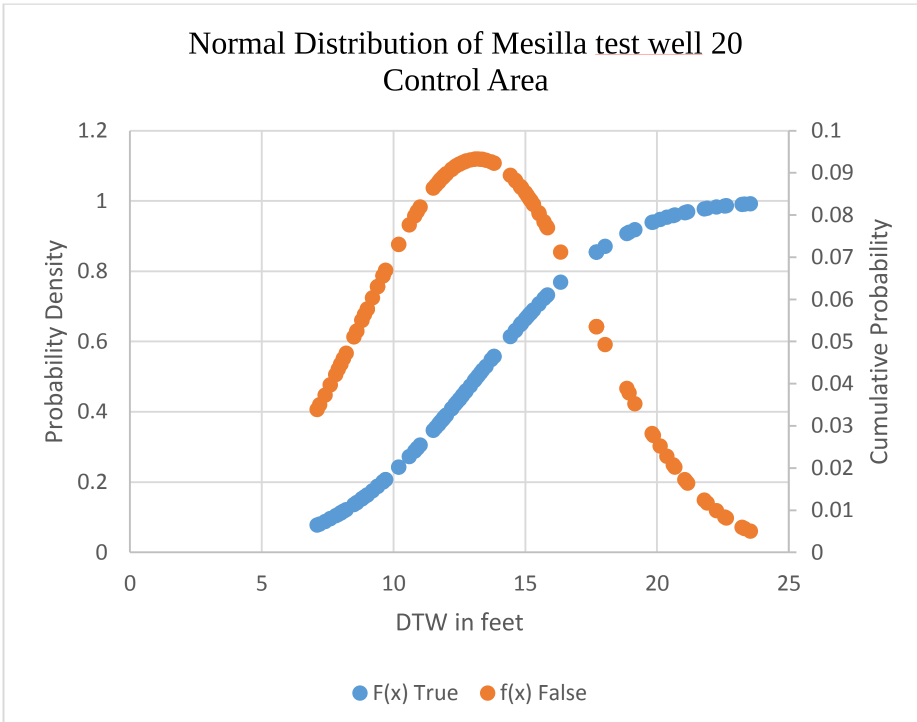

Figure 11: Scatterplot of Normal Distribution of Mesilla test well 20 DTW for years 2000-2012

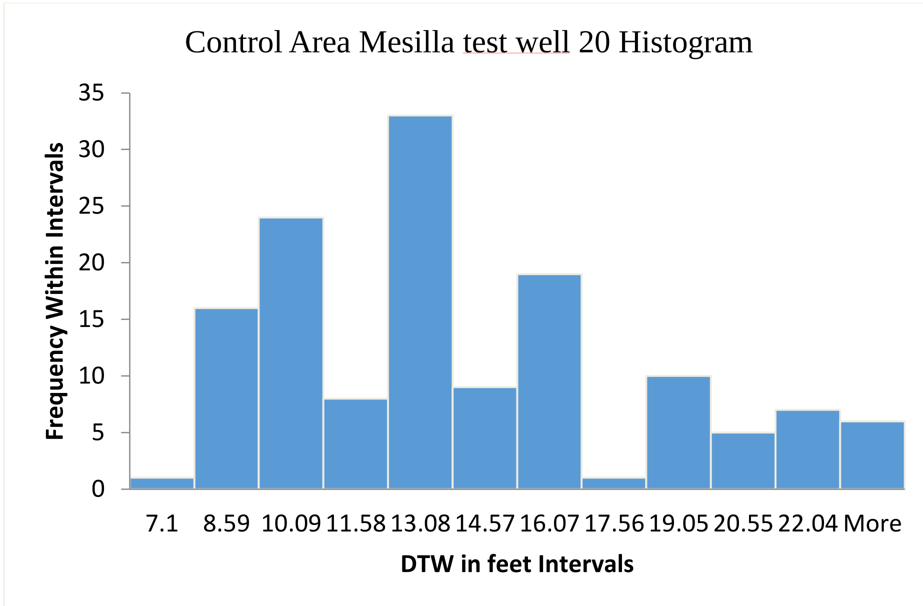

Figure 12: Histogram with slight positive skew for Mesilla test well 20 DTW data

Table 2: Statistics of DTW data in feet for Mesilla test well 20

2000-2012 Data	feet
min	7.100
max	23.536
mean	13.190
median	12.210
st dev	4.277
skewness	0.718
kurtosis	-0.330

After graphing the normal distributions of Mesilla test well 45 depth to water in feet for the years 2000-2012 as a scatterplot (Figure 13 below) and as a histogram (Figure 14 below), it was determined that the data were normally distributed. This was also observed from the statistics in Table 3 below, where the mean value is approximate to the median value. There was a slight positive skew for the data but no transformation was needed to use the appropriate statistical tests.

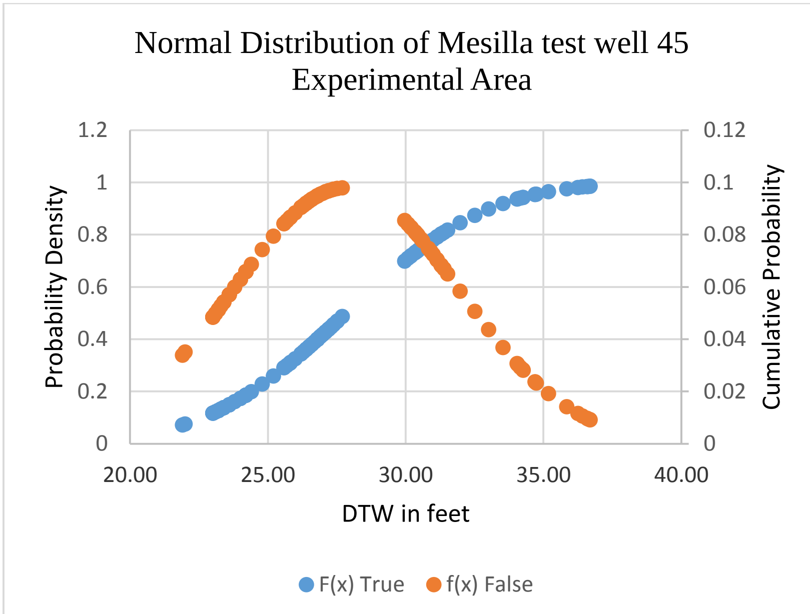

Figure 13: Scatterplot of Normal Distribution of Mesilla test well 45 DTW data

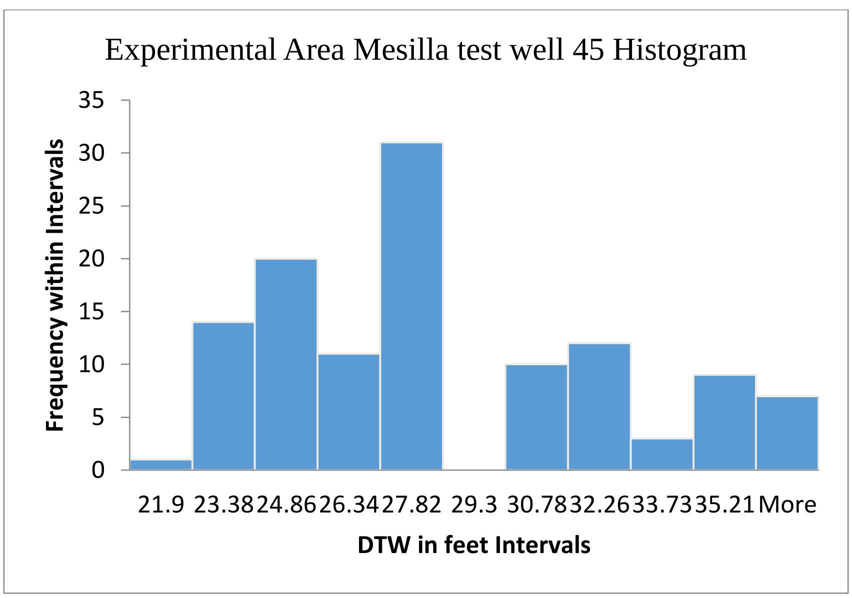

Figure 14: Histogram with slight positive skew for Mesilla test well 45 DTW data

Table 3: Statistics of DTW data in feet for Mesilla test well 45

2000-2012 Data	feet
min	21.900
max	36.694
mean	27.833
median	26.800
st dev	4.072
skewness	0.650
kurtosis	-0.636

The next dataset that needed to be pre-processed by calculating central tendency, dispersion, and symmetry contained the water meter readings from the production wells for years 2001-2011 (Unable to acquire data for years 2000 and 2012). The New Mexico OSE had a robust dataset including all 7,121 production wells in Doña Ana County either owned by the CLC or by private owner. Production well 04546 S-2, owned by Salopek Farms LLC, was selected because it lies directly within the control area and because it had sufficient data availability for the years in question. Also selected was production well Lower Rio Grande (LRG) 00430 S-18, owned by the CLC, because it is the closest well to the experimental area that had sufficient data for the years in question. While data from production well LRG 00430 S-18 were available by month and in gallons, data from production well 04546 S-2 were available by quarter and in acre-feet. Thus, there was a need to consolidate the data into quarterly readings and convert gallons to acre-feet to properly analyze it, which created a possible 44 records for the 11 year period between 2001 and 2011. In order to convert gallons to acre-feet, the equation 1 gallon

= 3.068E-6 (Online Unit Converter Pro, 2014) was used. It was determined that production well 04546 S-2 had 35 available records, while production well LRG 00430 S-18 had 37 out the possible 44. I then calculated the minimum, maximum, mean, median, standard deviation, skewness, kurtosis, ranked the datasets, determined probabilities, and calculated the normal and log normal distributions for both sets of years.

After graphing the normal distributions of quarterly water meter readings in acre-feet from production well 04546 S-2 for years 2001-2011 as a scatterplot (Figure 15 below) and as a histogram (Figure 16 below), it was determined that the data were not normally distributed, as it is also observed from the statistics in Table 4 below, where the mean value is larger than the median value and there was an excessive positive skew. Therefore, a transformation was needed to transform the data to be approximately close to the normal distribution to carry out the appropriate statistical tests.

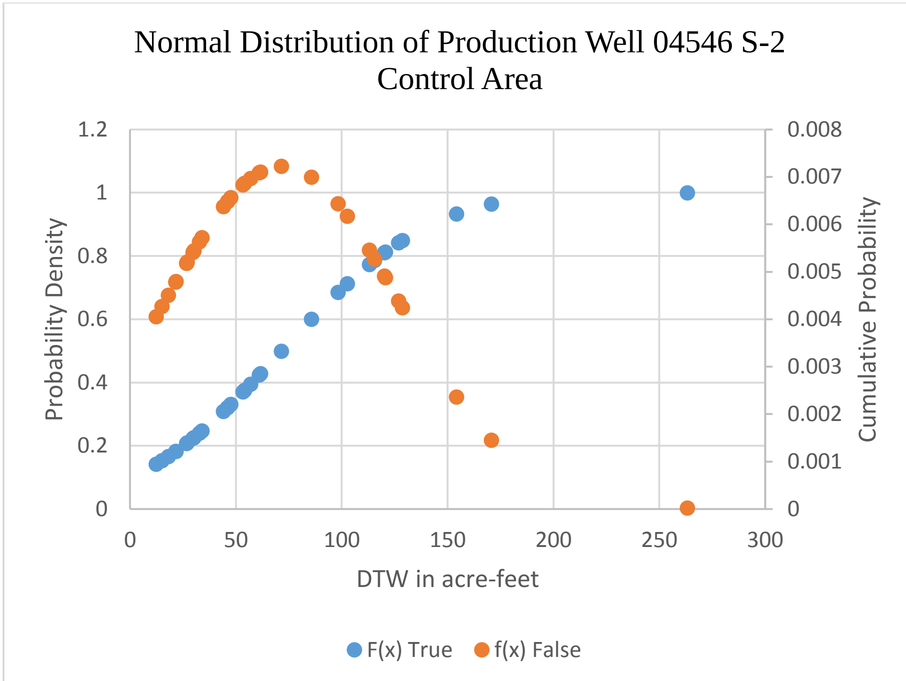

Figure 15: Scatterplot of Normal Distribution of production well 04546 S-2 water meter readings before transformation

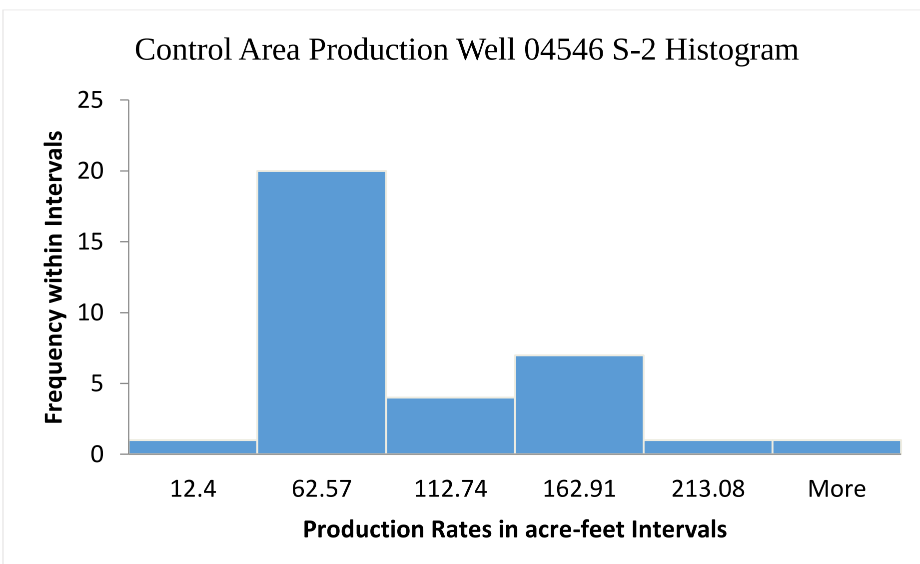

Figure 16: Histogram with excessive positive skew for production well 04546 S-2 water meter readings

Table 4: Statistics of water meter readings in acre-feet for production well 04546 S-2

2001-2011 Data	acre-feet
min	12.395
max	263.249
mean	71.731
median	53.770
st dev	55.247
skewness	1.515
kurtosis	2.933

The logarithmic transformation was selected because it is widely used as a valid statistical inference for positively skewed data, which results in a better measure of central tendency than the usual sample mean (Olivier et al., 2008). The purpose of the logarithmic transformation is to create a model that conforms to the requirements of the normal law of error for inferential purposes (Leysdedorf et al., 2005). In contrast to the normal distribution, which is centered on the arithmetic mean, the log normal distribution is centered on the geometric mean, which can be calculated by first calculating the arithmetic mean of the logarithmically transformed data and then taking the mean's antilogarithm (Leysdedorf et al., 2005). The log transformation consists of taking the log of each observation. It doesn't matter whether base-10 logs or natural logs are used for a statistical test because they differ by a constant factor (McDonald, 2014). For this research, the base-10 logs were used because it is possible to view the magnitude of the original number: log(1)=0, log(10)=1, log(100)=2, etc (McDonald, 2014). The scatterplot (Figure 17 below), the histogram (Figure 18 below), and statistics of the base-10 logs (Table 5 below) of the log transformation were calculated in Microsoft Excel.

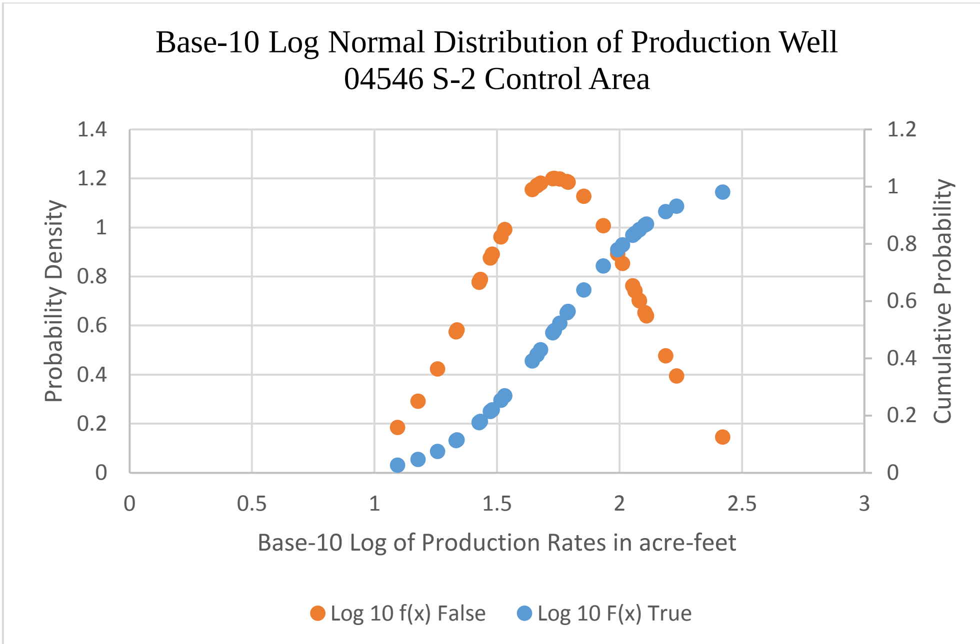

Figure 17: Scatterplot of Log Normal Distribution of production well 04546 S-2 water meter readings after logarithmic transformation

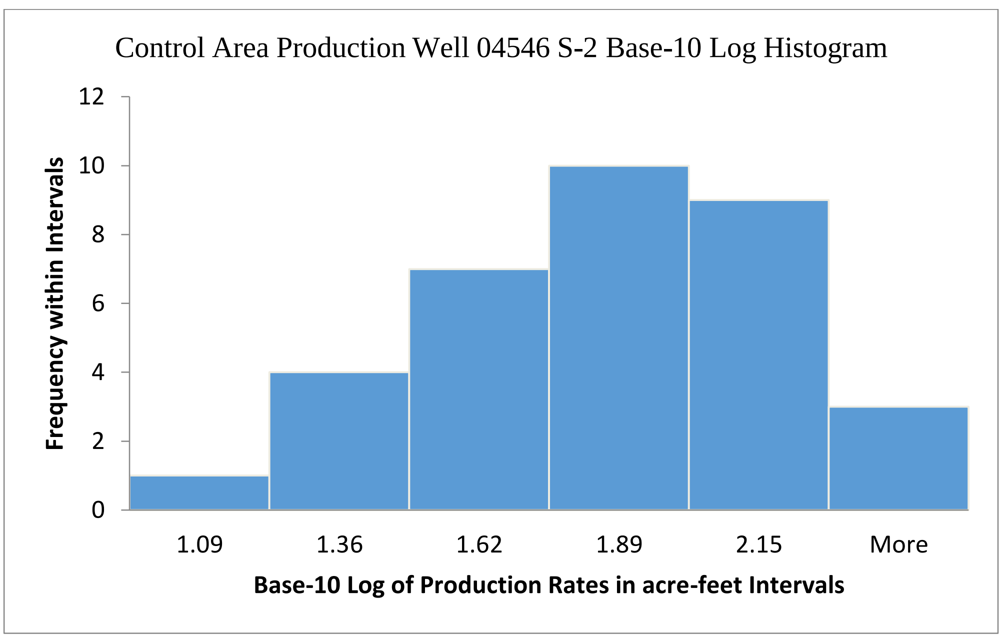

Figure 18: Histogram for production well 04546 S-2 water meter readings after logarithmic transformation

Table 5: Statistics of water meter readings for production well 04546 S-2 after logarithmic transformation

2001-2011 Base-10 Log Data	
min	1.093
max	2.420
mean	1.737
median	1.731
st dev	0.333
skewness	0.003
kurtosis	-0.813

After graphing the normal distributions of quarterly water meter readings in acre-feet from production well LRG 00430 S-18 for years 2001-2011 as a scatterplot (Figure 19 below) and as a histogram (Figure 20 below), it was determined that the data were not normally distributed, as it is also observed from the statistics in Table 6 below, where the mean value is larger than the median value and there is an excessive negative skew. Since a transformation is needed when data is excessively skewed positively or negatively (Kleiner, 2014), the logarithmic transformation was used to ensure the data would be normally distributed to carry out the appropriate statistical tests.

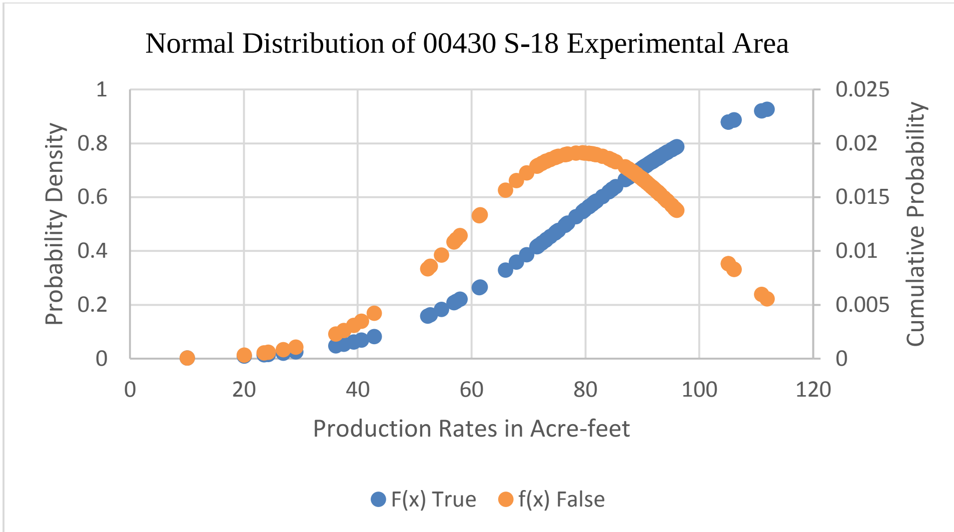

Figure 19: Scatterplot of Normal Distribution of production well 00430 S-18

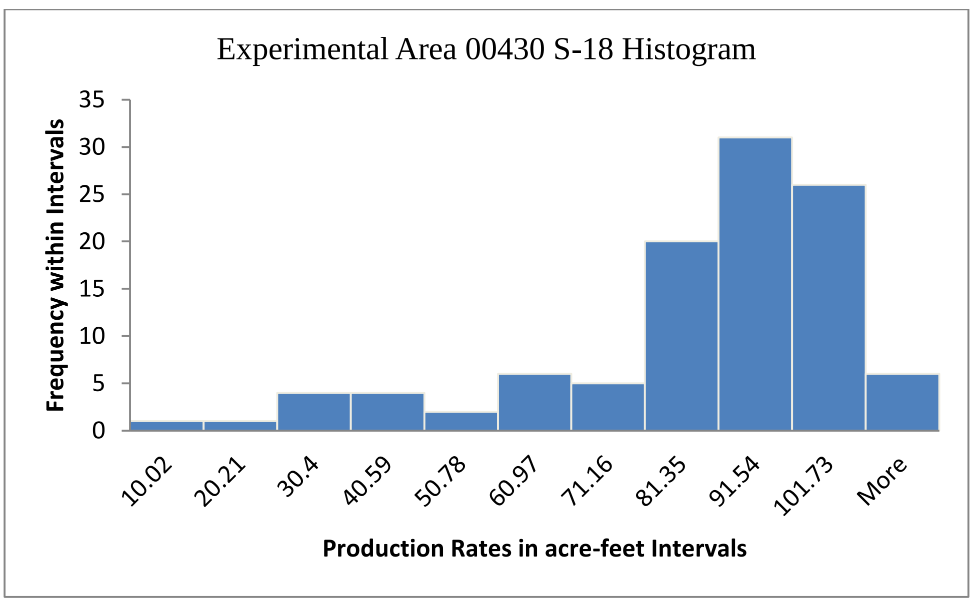

Figure 20: Histogram with excessive negative skew for production well 00430 S-18 water meter readings before transformation

Table 6: Statistics of water meter readings for production well 00430 S-18 before logarithmic transformation

2001-2011 Data	acre-feet
min	10.02
max	111.92
mean	79.14
median	87.63
st dev	20.86
skewness	-1.41
kurtosis	1.64

Data that are negatively skewed require a reflected transformation, which means that each data point must first be reflected and then transformed (Kleiner, 2014). To reflect a variable, one must create a new variable where the original value of the variable is subtracted from a constant of 1 (Osborne, 2002). The constant is calculated by adding one to the largest value of the original variable (E.g. (Larger value nL + 1) – (original value nX). This is followed by transforming the reflected dataset (Kleiner, 2014). The scatterplot (Figure 21 below), the histogram (Figure 22 below), and statistics of the base-10 logs (Table 7 below) of the log transformation were calculated in Microsoft Excel. After reflecting the negatively skewed data and performing a log transformation, the skewness became slightly better as it went from 1.41 to 0.98, however, the data would still not be considered normal. A variety of other transformations, including exponential, power, and inverse transformations, were performed that tend to be successful with negatively skewed data (IBM, 2014); however, none of these tests were able to make the data normal. Therefore, non-parametric tests were necessary for this non-normal dataset.

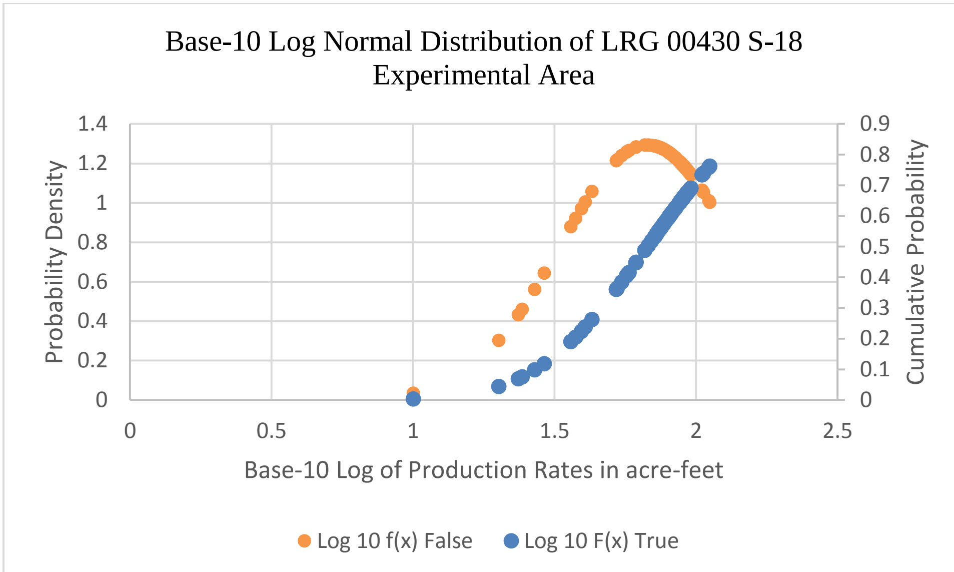

Figure 21: Scatterplot of Log Normal Distribution of production well 00430 S-18 water meter readings after reflection and log transformation

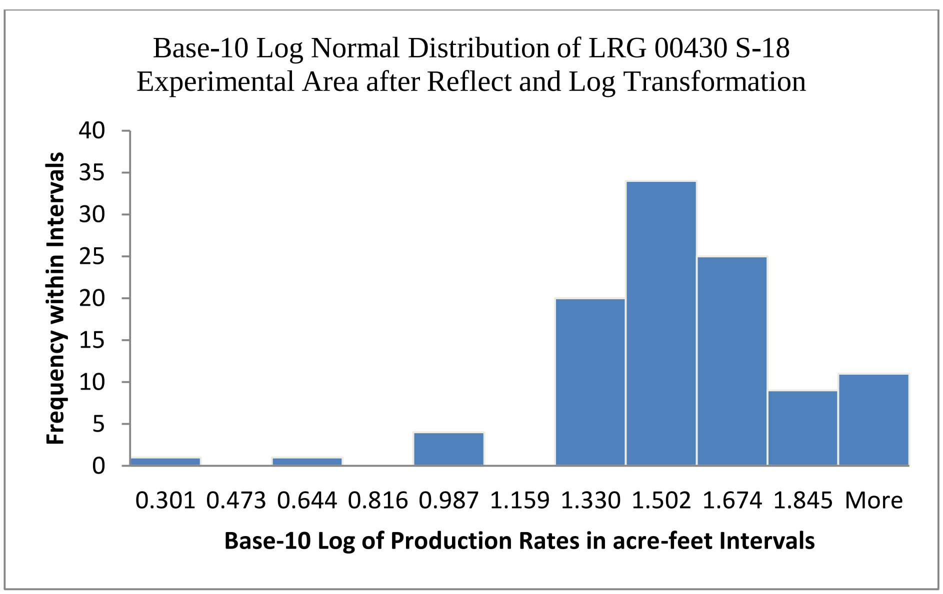

Figure 22: Histogram for production well 00430 S-18 water meter readings after reflection and log transformation

Table 7: Statistics of water meter readings for production well 00430 S-18 after reflection and log transformation

2001-2011 Base-10 Log Data	
min	0.30
max	2.01
mean	1.46
median	1.41
st dev	0.27
skewness	0.98
kurtosis	3.89

4.5. Methods

Once all of the required data to be used for statistical analysis had been pre-processed, the identification of appropriate statistical tests could be performed to answer the research objectives. This section will explain how and justify why statistical analysis was performed.

4.5.1. Land Use Change Detection

Before any statistical analysis could be performed, it was necessary to identify which study sites would be best to use to have the most significant results for the study. For this research, land use change from agricultural to residential was the only land use change analyzed in the region. Buenemann (2011) notes that change detection is very important for monitoring human, environmental, and land use/land cover change over a temporal scale. Some of the techniques and methods Buenemann teaches were used for this study.

First, three land use/land cover shapefiles were acquired for years 2001, 2005, and 2009 in the Mesilla Valley, since these were within the study time period and area of interest. The data was overlaid on ESRI (roads, rivers, cities, counties, states, etc.) and USGS (Digital Elevation Model) shapefiles in ArcGIS 10.1. There are a few different kinds of change detection techniques that include different processes, such as, write memory function insertion, multi-date composite image, image difference, and post-classification comparison (Buenemann, 2011). The write memory function insertion is a quick way to detect change without using quantitative data. It involves inserting bands from both dates into each of the three WFM banks (red, green, blue). The problem with this technique is that there is no from-to change data; it's only a visual form of detecting change. The multi-date composite image incorporates multi-date imagery into one single dataset, which then gets analyzed using a tool, such as Principal Component Analysis (PCA). Major PCA components tend to account for variation in the image data that is not due to change, these are called stable components. Minor PCA components tend to enhance spectral contrasts between dates, these are called change components. The image differencing function involves subtracting imagery of different dates. When the images are atmospherically corrected, the results in areas of change are either positive, negative, zero for no change. Post-Classification comparison is the most commonly used technique to detect change, as it uses quantitative data for its comparison. It involves rectification and classification of both images, and a pixel-by-pixel comparison using a change detection matrix to detect change (Buenemann, 2011).

The image differencing function was used to determine where the land use change from agricultural to residential was highest, as this would be the basis for the experimental area. A section of no land use change would be selected for the control area. Another reason for selecting image differencing is that it can be processed in ArcGIS, whereas the others can only be done in ENVI or ERDAS IMAGINE (Buenemann, 2011). First, the polygon to raster tool was used for the three (2001, 2005, and 2009) shapefiles in the ArcGIS conversion toolbox as the files must be in raster format for processing. Next, the Minus tool in the Spatial Analyst toolbox was used for years 2001-2005, 2001-2009, and 2005-2009. The minus tool subtracts the value of the second input raster from the value of the first input raster on a cell-by-cell basis (Figure 23 below) (ESRI, 2014).

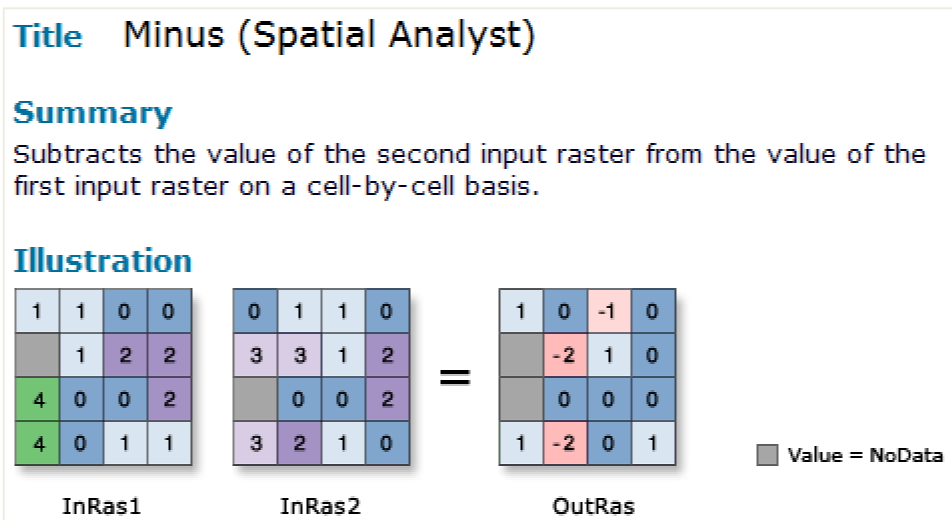

Figure 23: Minus (Spatial Analyst) Tool used for Image Differencing (ESRI, 2014)

The results of the image differencing process gave a geospatial profile of the Mesilla Valley and highlighted areas that were strictly changed from agricultural to residential lands. The area with the highest amount of land use change was confirmed as Legends West Subdivision (32.32, -106.82) covering about 0.5 square miles. The area was completely agricultural in 2001, but by 2005 when construction began, the southern portion of the subdivision had been developed and was still receiving surface water rights from EBID (Figure 24 below). Between 2005 and 2009, the entire subdivision had been developed and no longer received surface water rights from EBID (Figure 25 below). Figure 26 highlights the total change from 2001 to 2009. Due to these findings, the experimental area was selected.

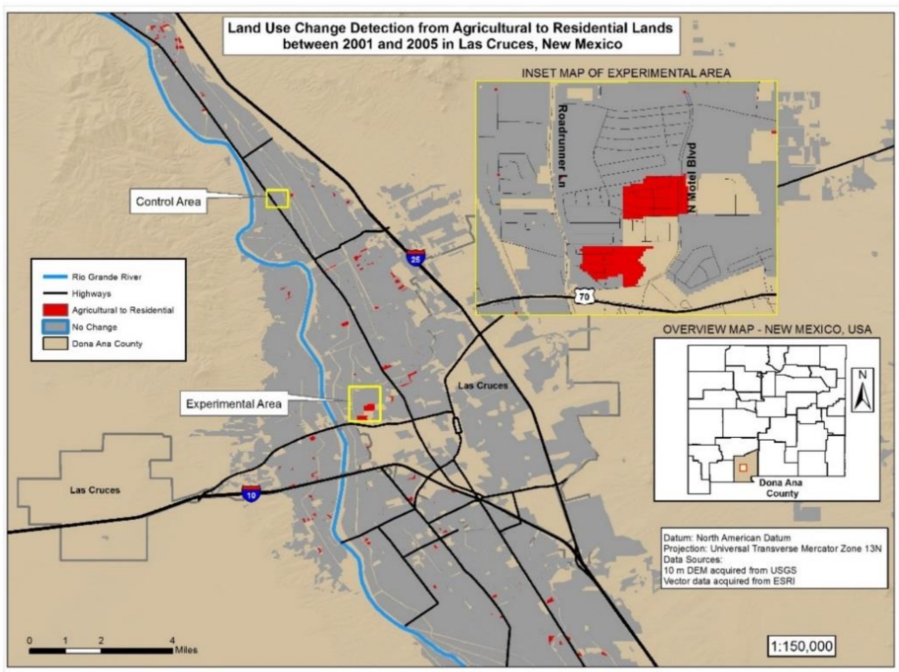

Figure 24: Land Use Change Detection from Agricultural to Residential Lands using Image Differencing between 2001 and 2005

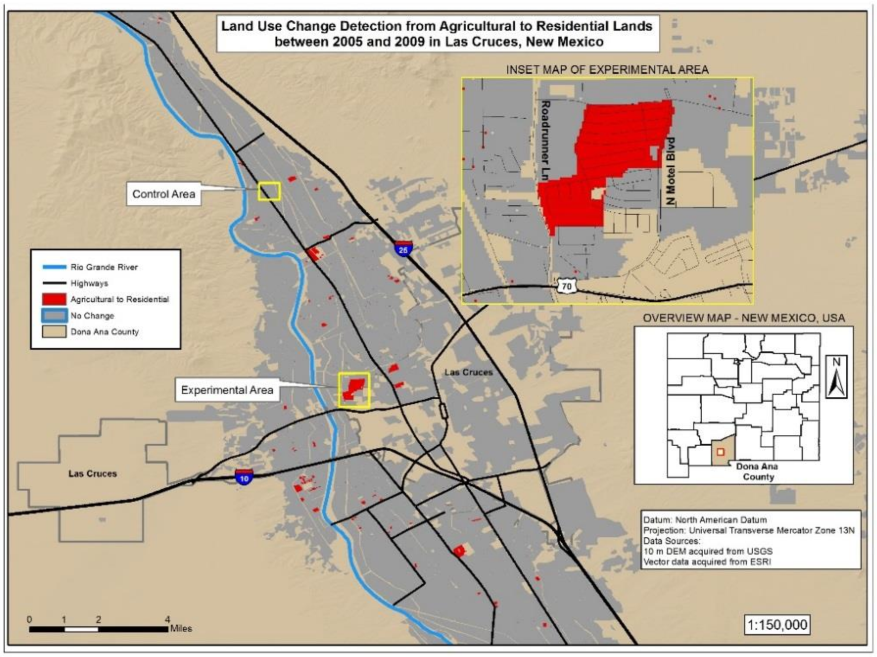

Figure 25: Land Use Change Detection from Agricultural to Residential Lands using Image Differencing between 2005 and 2009

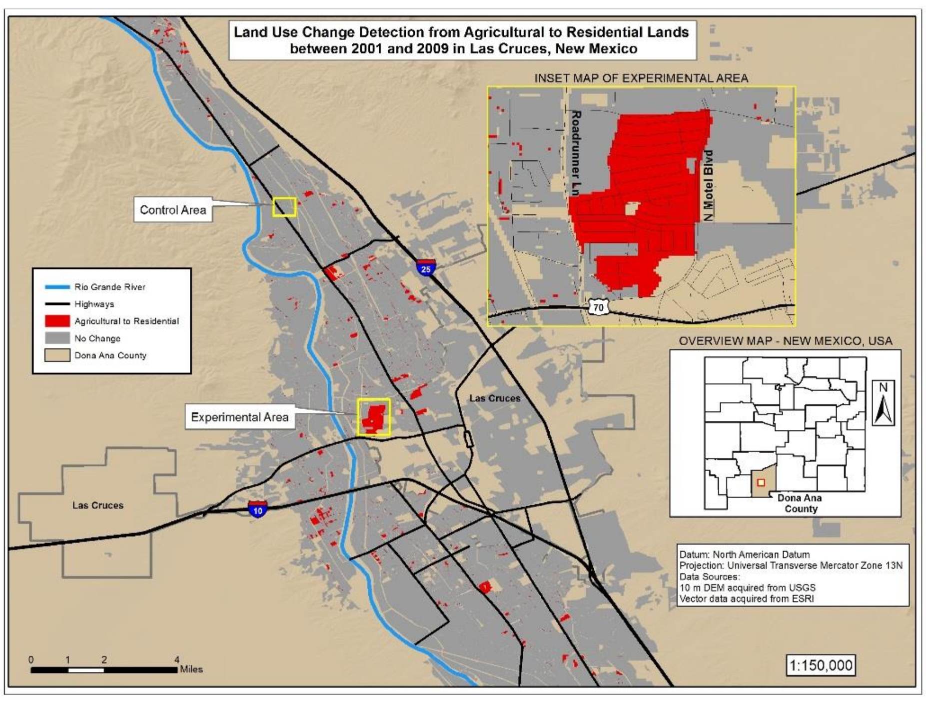

Figure 26: Land Use Change Detection from Agricultural to Residential Lands using Image Differencing between 2001 and 2009

The results of the agricultural to residential pixel counts after each reiteration of the image differencing tool show that the highest amount of change was between 2001 and 2009 with 1.44 percent of the total pixels in the areas being examined changing from agricultural to residential land use (Table 8 below). The majority of the pixel counts had no change, but the experimental sub-region where Legends West lies saw major change in the 2001-2009 period of time. There was very little land use change found in the control area.

Table 8: Pixel Counts as Percent of Total after using the Image Differencing Tool in ArcGIS

Years	**Value**	**Count (Pixels)**	**Percent of Total**
2001-2005	Ag to Res	7396	0.57
	No Change	1299137	99.43
	Total	1306533	
2005-2009	Ag to Res	7595	0.57
	No Change	1334654	99.43
	Total	1342249	
2001-2009	Ag to Res	18323	1.44
	No Change	1256625	98.56
	Total	1274948	

4.5.2. Examined Monitoring and Production Well Data

In order to determine whether drought had an effect on groundwater hydrology in two contrasting areas in the Mesilla Valley, the parametric analysis of variance (ANOVA) test was conducted on Mesilla monitoring test wells 20 and 45, and production well 04546 S-2 data that were normally distributed by analyzing the differences of between and within group means. The non-parametric Kruskall-Wallis Test was performed on production well 00430 S-18 data that was found to be non-normal.

To determine whether land use change had an effect on groundwater hydrology in the experimental area, the parametric Student's T-Test was conducted on the static groundwater levels for the two time periods to determine whether the population means were statistically different. Similarly, the non-parametric Mann-

Whitney U Test was used on the production rates at the experimental area due to data non-normality.

There are certain difficulties in identifying a valid statistical framework for groundwater monitoring in that there's a governing fundamental assumption almost every statistical procedure and test must contain (EPA, 2012). It is the presumption that sample data from a given population should be independent and identically distributed, commonly abbreviated as i.i.d (EPA, 2012). If it is not satisfied, statistical conclusions and test results may be invalid or in error (EPA, 2012). Random sampling of a single, fixed, stationary population will guarantee independent, identically-distributed sample data. Routine groundwater sampling typically does not guarantee independent, identically-distributed sample data (EPA, 2012). This means that one must take extra precaution to not assume the data is normally distributed and have spatial variability as explained below.

Spatial variability refers to statistically identifiable differences in mean and/or variance levels across the well field (EPA, 2012). The existence of such variation spread across multiple monitoring and production wells is found by comparing the upgradient to downgradient monitoring well data against distinct production wells (EPA, 2012). The usual approach is to perform intra-well comparisons, where specific depth to water data is analyzed at each well. The Analysis of variance (ANOVA) test with the aide of side-by-side box plots are conducted graphically to check for spatial variability (EPA, 2012).

The one-way ANOVA, used to determine whether there are any significant differences between the means of three or more independent (unrelated) groups (Laerd, 2013) can be used to understand temporal effects of a dataset by identifying traces on a time series plot of multiple wells. The procedure assumes homogeneity or equality of variance in ANOVA tests, which simultaneously evaluates multiple groups of data representing a sample from a distinct statistical population (EPA, 2012). The null hypothesis when ANOVA is $H0: \mu 1 = \cdot \cdot \cdot = \mu k$, which states that all sample means are not statistically significantly different, without restricting what the common value is (Seltman, 2007). The alternative hypothesis is written as "HA : Not $\mu 1 = \cdot \cdot \cdot = \mu k$ or one or more sample means come from a different population (Seltman, 2007).

A sample variance is calculated as SS/df where SS is "sum of squared deviations from the mean" and df is "degrees of freedom." In ANOVA, variances are calculated as SS/df and these quantities are called mean squares or MS. i.e., MS = SS/df. For one-way ANOVA, one works with two different MS values called "meansquare within-groups", MSwithin, and "mean square between-groups", MSbetween (Seltman, 2007). The F-statistic is an important factor in ANOVA, defined by $F = MSbetween/MSwithin$. When large F values are found, one must reject the null hypothesis (Seltman, 2007). To determine whether one should accept or reject the null hypothesis, ANOVA calculates the observed F-statistic and compares it to F-critical. If the statistic is smaller than the critical value, we accept the null hypothesis because the p-value must be bigger than α, and if the statistic is equal to or bigger than the critical value, we reject the null hypothesis because the p-value must be equal to or smaller than α (Seltman, 2007).

ANOVA can be run using the data analysis toolpak in Microsoft Excel. There are three separate ANOVA tests that can be run, including one-way, two-factor with replication, and two-factor without replication. For this analysis, the one-way factor ANOVA was used as only one variable was being investigated. Once the assumptions were made about the normality, dispersion, central tendency, symmetry and the null hypothesis was understood, the one-way ANOVA could be run.

4.6. Research Objective 1

As previously discussed in chapter 3.2., the first objective was to determine the impact of drought by comparing static groundwater levels from monitoring wells and comparing well production rates (water meter readings) from production wells for three timeframes on a control area (area that has undergone little to no land use change during a certain period) and an experimental area (area that has undergone major land use change during a certain period). Since land use did not change in the control area, the trend must be solely from drought. The three timeframes used are:

5. 2000 to 2002 - considered wet/full supply years,
6. 2003 to 2006 - considered beginning/continued drought years, and
7. 2007 to 2012 - considered severe/prolonged drought years.

To answer the first research objective in regards to the control area, a one way ANOVA between subjects was conducted to test the differences between means for different time periods for the overall time period selected (2000-2012) to determine whether drought had an effect on static groundwater levels taken from monitoring wells and water meter readings from production wells. Land use change was not tested in the control area due to being very little (if any) change over the course of the time period. After pre-processing both the monitoring and production well data, all of the assumptions used for ANOVA were met by the EBID monitoring well Mesilla 20 and by production well 04546 S-2. The null hypothesis for all tests were that there were no differences in means. The data were split into three time periods:

- 2000 – 2002 – considered wet/full supply years,
- 2003 – 2006 – considered beginning/continued drought years, and
- 2007 - 2012 – considered severe/prolonged drought years.

The statistics for the three time periods for Mesilla test well 20 and Well 04546 S-2 are found in Tables 9 and Tables 10 below, respectively. Groundwater DTW data from Mesilla test well 20 were found to be normally distributed and had similar variances; however, the sample sizes were unequal. After a reflection and log transformation to ensure normal distribution of water meter levels for production well 04546 S-2 the sample sizes were also found to be unequal. When sample sizes differ, the chances of incorrectly rejecting the null hypothesis becomes greater, particularly if one sample is much larger than the others (University of Northwestern, 1997). If the larger samples are associated with the populations with the larger variances, then the F statistic tends to be smaller than it should be, reducing the chance that the test would correctly identify a significant difference between the means. In contrast, if the smaller samples are associated with the populations with the larger variances, then the F statistic will tend to be greater than it should be, increasing the risk of incorrectly reporting a significant difference in the means when none exists (University of Northwestern, 1997). The chance of incorrectly rejecting the null hypothesis when dealing with unbalanced sample sizes can be substantial even when the population variances are not very different from each other (University of Northwestern, 1997), as it is in this case. It is still useful to conduct the ANOVA test; however, a logartihmic transformation must be employed to ensure no Type I or Type II errors occur (University of Northwestern, 1997).

Table 9: Statistics of Mesilla test well 20 DTW Data in feet

2000-2002 Data	N=34	**2003-2006 Data**	N=46	**2007-2012 Data**	N=59
min	7.10	**min**	8.10	**min**	8.90
max	10.80	**max**	17.70	**max**	23.54
mean	8.59	**mean**	13.23	**mean**	15.81
median	8.60	**median**	12.56	**median**	14.86
st dev	0.88	**st dev**	2.53	**st dev**	4.33
skewness	0.42	**skewness**	0.41	**skewness**	0.30
kurtosis	-0.21	**kurtosis**	-0.42	**kurtosis**	-1.18

Table 10: Statistics of Well 04546 S-2 Base-10 Log of Production Rate Data in acre-feet per quarter of year

2001-2002 Data	N=8	**2003-2006 Data**	N=9	**2007-2011 Data**	N=18
min	1.48	**min**	1.33	**min**	1.09
max	2.08	**max**	2.42	**max**	2.19
mean	1.78	**mean**	1.78	**mean**	1.68
median	1.74	**median**	1.66	**median**	1.63
st dev	0.20	**st dev**	0.39	**st dev**	0.35
skewness	0.48	**skewness**	0.45	**skewness**	-0.07
kurtosis	-0.31	**kurtosis**	-1.03	**kurtosis**	-1.39

To answer the first research objective in regards to the experimental area, a one way ANOVA between subjects was conducted to test the differences between means of different time periods for the overall time period selected (2000-2012) to determine whether drought had an effect on groundwater levels in the experimental area. To test land use change, the Student's T-Test was conducted to test the differences between means for the same overall time period (2000-2012). After pre-processing both the monitoring and production well data, all of the assumptions used for ANOVA were met by the EBID monitoring well Mesilla 45. However, the assumptions were not met by the water meter reading data from production well 00430 S-18, meaning non-parametric tests would have to be conducted. The null hypothesis for all tests remain that there were no differences in means. The data were split first into three time periods to test the effects of drought (In the same manner as the control area):

- 2000 – 2002 – considered wet/full supply years
- 2003 – 2006 – considered beginning/continued drought years
- 2007 - 2012 – considered severe/prolonged drought years

The statistics for the three time periods for Mesilla test well 45 and Well 00430 S-18 are found in Tables 11 and Tables 12 below, respectively.

Table 11: Statistics of Mesilla test well 45 DTW Data in feet

2000-2002 Data	N=28	2003-2006 Data	N=33	2007-2012 Data	N=57
min	21.90	**min**	23.40	**min**	25.20
max	24.80	**max**	27.52	**max**	36.69
mean	23.36	**mean**	26.09	**mean**	31.04
median	23.25	**median**	26.49	**median**	30.99
st dev	0.61	**st dev**	1.18	**st dev**	3.38
skewness	-0.12	**skewness**	-0.91	**skewness**	0.04
kurtosis	1.50	**kurtosis**	-0.43	**kurtosis**	-1.04

Table 12: Statistics of Well 00430 S-18 Production Rate Data in acre-feet per quarter of year

2001-2002 Data	N=6	2003-2006 Data	N=13	2007-2011 Data	N=18
min	76.12	**min**	64.73	**min**	191.85
max	294.65	**max**	323.15	**max**	280.17
mean	178.12	**mean**	207.88	**mean**	252.22
median	179.37	**median**	229.05	**median**	254.77
st dev	89.66	**st dev**	83.43	**st dev**	25.72
skewness	0.11	**skewness**	-0.49	**skewness**	-1.15
kurtosis	-2.23	**kurtosis**	-0.92	**kurtosis**	0.81

When an ANOVA test provides a significant result, this indicates at least one group differs from the other groups. Yet, the test does not indicate which group differs. To analyze the pattern of difference between group means, post-hoc group comparisons are conducted, and the most commonly used involves comparing two means called pairwise comparisons (Williams and Herve, 2010). The post-hoc comparison tests most commonly used are the Least Significant Difference (LSD) t test, Bonferroni adjustment, Sidak adjustment, Scheffe test, and the Tukey test

(Williams, 2014). For this research, the Bonferroni adjustment test was used if and when the ANOVA F-value was statistically significant because it's the simplest, most conservative to use, and can be done in Microsoft Excel (Williams, 2014). The Bonferroni adjustment multiplies each of the significance levels from the LSD test by the number of tests performed (Williams, 2014).

In order to conduct the Bonferroni adjustment, one needs to understand the LSD test. The LSD test computes the smallest significant difference between two means as if these means had been the only ones to be compared and to declare significant any difference larger than the LSD (Williams and Herve, 2010). The data to be analyzed comprise A groups, a given group is denoted a. The number of observations of the a-th group is denoted Sa. If all groups have the same size it is denoted S. The total number of observations is denoted N. The mean of Group a is denoted Ma+. From the ANOVA, the mean square of error (i.e., within group) is denoted MSS(A) and the mean square of effect (i.e., between group) is denoted MSA (Williams and Herve, 2010).

When the null hypothesis is true, the value of t statistics evaluating the difference between groups a and a' is equal to

$$t = \frac{M_{a+} - M_{a'+}}{\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)}}$$

and follows a t distribution with N – A degrees of freedom (Williams and Herve, 2010). The ratio t would therefore be declared significant at a given α level obtained from the t distribution and denoted $t_{\nu,\alpha}$ (where $\nu = N - A$ is the number of degrees of freedom form the error, and can be obtained from a standard t table) (Williams and Herve, 2010). Rewriting the equation shows that a difference between the means of group a and a' will be significant if

$$|M_{a+} - M_{a'+}| > \text{LSD} = t_{\nu,\alpha}\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)}.$$

In order to evaluate the difference between the means of group a and a', the absolute value is taken of the difference in the means and comparing it to the value of LSD. If

$$|M_{i+} - M_{j+}| \geq \text{LSD},$$

then the comparison is declared significant at the chosen α-level (0.05). This procedure is then repeated for all A(A – 1)/2 comparisons (Williams and Herve, 2010). Because LSD does not correct for multiple comparisons, it severely inflates Type I error, which is why the Bonferroni adjustment is used (Williams, 2014).

The Bonferroni adjustment multiplies each of the significance levels from the LSD test by the number of tests performed, i.e. A(A – 1)/2. Due to it being so conservative it ensures a Type II error no greater than α after all comparisons are made (Gertsman, 2006). The results from these tests on Mesilla test well 20 and production well 04546 S-2 are discussed in the next chapter.

4.7. Research Objective 2

As previously discussed in chapter 3.2., the second objective was to determine the effects of land use change by comparing static groundwater levels from monitoring wells and comparing production rates from production wells for the experimental area (area that has undergone major land use change during a certain period). The two time periods used are:

- 2000 – 2005 – before conversion from agricultural to residential land,
- 2006 – 2012 – after conversion from agricultural to residential land.

These years were chosen due to the change in land use at Legends West Subdivision from agricultural to residential in 2005.

The statistics for the two time periods for Mesilla test well 45 and Well 00430 S-18 are found in Tables 13 and Tables 14 below, respectively.

Table 13: Statistics of Mesilla test well 45 DTW Data in feet

2000-2005 Data	N=51	**2006-2012 Data**	N=67
min	21.90	**min**	25.20
max	27.39	**max**	36.69
mean	24.43	**mean**	30.42
median	24.00	**median**	30.45
st dev	1.51	**st dev**	3.45
skewness	0.60	**skewness**	0.32
kurtosis	-0.88	**kurtosis**	-1.12

Table 14: Statistics of Well 00430 S-18 Production Rate Data in acre-feet per quarter of year

2001-2005 Data	N=15	**2006-2011 Data**	N=22
min	64.73	**min**	155.46
max	323.15	**max**	280.17
mean	193.70	**mean**	245.68
median	229.05	**median**	254.77
st dev	90.29	**st dev**	35.96
skewness	-0.20	**skewness**	-1.37
kurtosis	-1.56	**kurtosis**	1.03

The two sample Student's T-Test was conducted to determine whether land use change had an effect on groundwater levels. There are two types of T-Tests, one that assumes homogeneity of variances and the other that does not assume homogeneity of variances (Microsoft Office, 2014). In Microsoft Excel, they are referred to as T-Test: Two-Sample Assuming Equal Variances and T-Test: Two-Sample Assuming Unequal Variances, respectively. They can be used to determine whether the two samples are likely to have come from distributions with equal population means (Microsoft Office, 2014). The following equation is used to determine the statistic value of t:

$$t = \frac{M_{a+} - M_{a'+}}{\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)}}$$

where the data to be analyzed comprise A groups, a given group is denoted a. The number of observations of the a-th group is denoted Sa. If all groups have the same size it is denoted S. The total number of observations is denoted N. The mean of

Group a is denoted Ma+. From the ANOVA, the mean square of error (i.e., within group) is denoted MSS(A) and the mean square of effect (i.e., between group) is denoted MSA (Williams et al., 2010).

The way to read the T-Test table to determine statistical significance, is to perform a two-tail test (inequality) (Excel Easy, 2014). If the t Stat < -t Critical two-tail or if t Stat > t Critical two-tail, reject the null hypothesis (Excel Easy, 2014). The Student's T-Test were run on the Mesilla test well 45 data using the data analysis Toolpak in Microsoft Excel; the results of this analysis are discussed in chapter 5.

Production water meter level data from Well 00430 S-18 were not found to be normally distributed, even after attempts to transform the data; thus non-parametric tests were conducted.

The Kruskal-Wallis H test is a non-parametric test which is used in place of a one-way ANOVA. It is an extension of the Wilcoxon Rank-Sum test to more than two independent samples (Zaionts, 2014). Even though ANOVA is usually quite robust, there are many situations where the assumptions are violated, and the Kruskal-Wallis test becomes very useful, in particular, when:

- Group sample data strongly deviate from normal (this is especially relevant when sample sizes are small and unequal and data are not symmetric), and
- Group variances are quite different (especially when there are significant outliers (Zaionts, 2014)

Some characteristics of Kruskal-Wallis test are:

- No assumptions are made about the type of underlying distribution.

- However, it is assumed that all groups have a distribution with the same shape (i.e. a weaker version of homogeneity of variances).
- No population parameters are estimated (and so there are no confidence intervals) (Zaionts, 2014).

The test statistic is defined as:

$$H = \frac{12}{n(n+1)} \sum_{j=1}^{k} \frac{R_j^2}{n_j} - 3(n+1)$$

Where k = the number of groups, where nj is the size of the jth group, Rj is the rank sum for the jth group and n is the total sample size, i.e.

$$n = \sum_{j=1}^{k} n_j$$ (Zaionts, 2014)

It can also be written as such:

$$H = \frac{SS_B}{n(n+1)/12}$$

where SS_B is the sum of squares between groups using the ranks instead of raw data (Zaionts, 2014).

Similarly with ANOVA, if the Kruskal-Wallis test shows a significant difference between the groups, then non-parametric pairwise comparisons should be used by employing the Mann-Whitney U Tests (Zaionts, 2014). This test is an alternative form of the Wilcoxon Rank-Sum test for independent samples and is equivalent (Zaionts, 2014). The test statistic to be defined is for samples 1 and 2 where n1 is the size of sample 1, n2 is the size of sample 2, R1 is the adjusted rank sum for sample 1, and R2 is the adjusted rank of sample 2 (Zaionts, 2014).

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \qquad U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2$$

$$U = \min(U_1, U_2)$$

If the observed value of U is < U crit then the test is significant (at the α level). The values for U crit are provided in the Mann-Whitney Tables (Zaionts, 2014). The results from these tests on production well 00430 S-18 are discussed in the next chapter.

5. RESULTS

5.1. Results

This chapter first presents the results from groundwater drawdown and production rate graphs depicting differences and similarities between 2000 and 2012 for both study areas. These trends and patterns will be discussed. Secondly, the chapter discusses the results from parametric and non-parametric tests conducted to determine if drought and/or land use change had an effect on both groundwater levels and production rates in both the experimental and control areas in Mesilla Valley.

It should be noted that this research incorporated depth to water data for both the EBID monitoring test wells 20 and 45 from 2000 to 2012. However, production water meter readings from production wells 04546 S-2 and 00430 S-18 only incorporated data from 2001 to 2011. Both sets of wells were compared separately.

5.2. Results of Drawdown Comparisons between Control and Experimental Areas

This section provides visual comparisons of both drawdown of groundwater and production rates for both the control and experimental area wells. Figure 27 below displays the average depth to water for EBID's monitoring test wells 20 (control area) and 45 (experimental area) between 2000 and 2012 in relation to drought. Figure 28 below displays the average depth to water for the same monitoring wells between 2000 and 2012 but in relation to land use change. There is an obvious downward trend in average depth to water for both figures. Average depth to water signifies the difference between the top of the inner casing and the groundwater elevation. In regards to Mesilla test well 20, the top of the inner casing was recorded at 3928.10 feet. At the beginning of the time period used in this research (January 2000), the average groundwater elevation was 3919.89 feet, meaning the average DTW was at 8.21 feet. By the end of the time period in December 2012, the average DTW was 21.87 feet, which equates to a 166 total percent increase, meaning higher rates of water were being pumped over time. In comparison, for Mesilla test well 45, the top of the inner casing was recorded at 3900.00 feet. In January 2000, the groundwater elevation was at 3876.90 feet, meaning the depth to water was at 23.23 feet. By December 2012, the average depth to water was 35.61, which is a 53 total percent increase, also meaning higher rates of water were being pumped over time.

A simple linear regression model was used to determine the relationship between time equaling 144 total months during the specified time period (January 2000 to December 2012) by the average DTW for monitoring wells at the control and experimental areas. The trend line displays the slope, y-intercept and R-squared value. The R-squared value is the square of the correlation coefficient which provides a measure of the reliability of the linear relationship between the x and y values (Clemson University, 2000). As the R^2 value approximates one, there is a higher statistical chance that the input x will correctly produce term y (Clemson University, 2000). The R^2 value for the experimental area test well 45 was found to be 0.88, while the R^2 for the control area test well 20 was found to be 0.65. Therefore, a statistically considerable significance of regression was found between the variable of time and static groundwater levels at both areas.

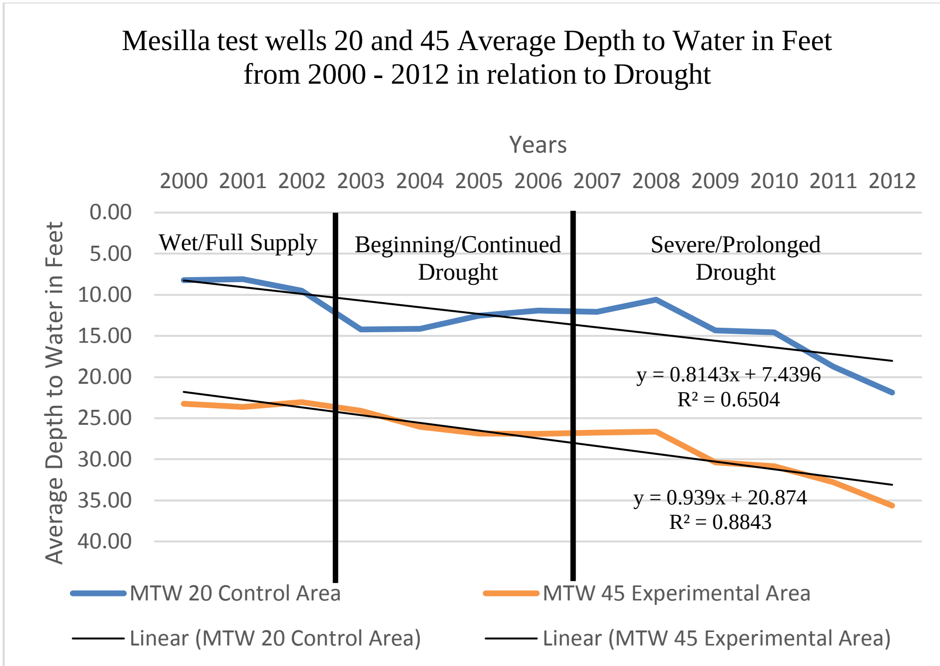

Figure 27: Mesilla test wells 20 and 45 Average DTW in Feet from 2000-2012 in relation to Drought

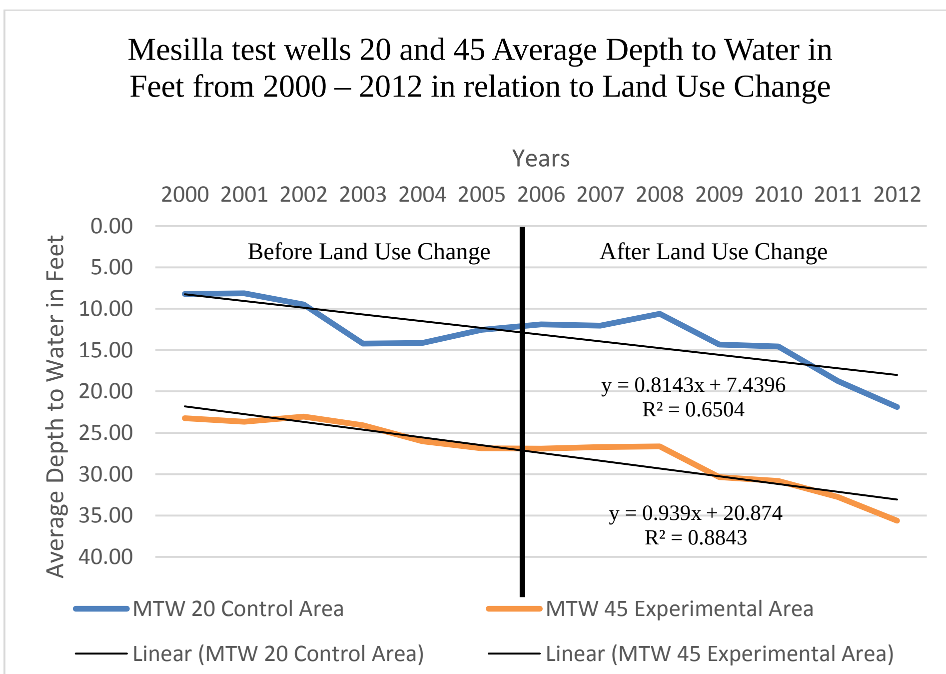

Figure 28: Mesilla test well 20 and 45 Average DTW in Feet from 2000-2012 in relation to Land Use Change

The well production average water meter readings in acre-feet between 2001 and 2011 for both the control and experimental areas are displayed in Figures 29 and 30 below. Figure 29 is displayed in relation to drought and Figure 30 is displayed in relation to land use change. Since the trends for both production wells 04546 S-2 and 00430 S-18 are very sporadic, it is difficult to ascertain a pattern; however, production well 04546 S-2 in the experimental area did have an increasing trend line, meaning that a higher rate of water was pumped over time. There is a large spike in production between 2004 and 2005, which could be atrributed to the Legends West Subdivision development that had begun to be built. In contrast, well 00430 S-18 has level trend line, meaning that pumping rates have remained steady over the course of the study. A similar spike in production was found between 2003 and 2004, which could be attributed to the much smaller amounts of surface water release to EBID farmers that occurred in 2003 due to the drought. There was a total percent increase of 21 and 17 from 2001 to 2011 on a quarterly basis for wells 04546 S-2 and 00430 S-18, respectively. The R^2 values differed greatly, as there was a slight significance in regression between the variable time and production rates in the experimental area (0.41), while there was absolutely no significance in regression in the control area (7E -05).

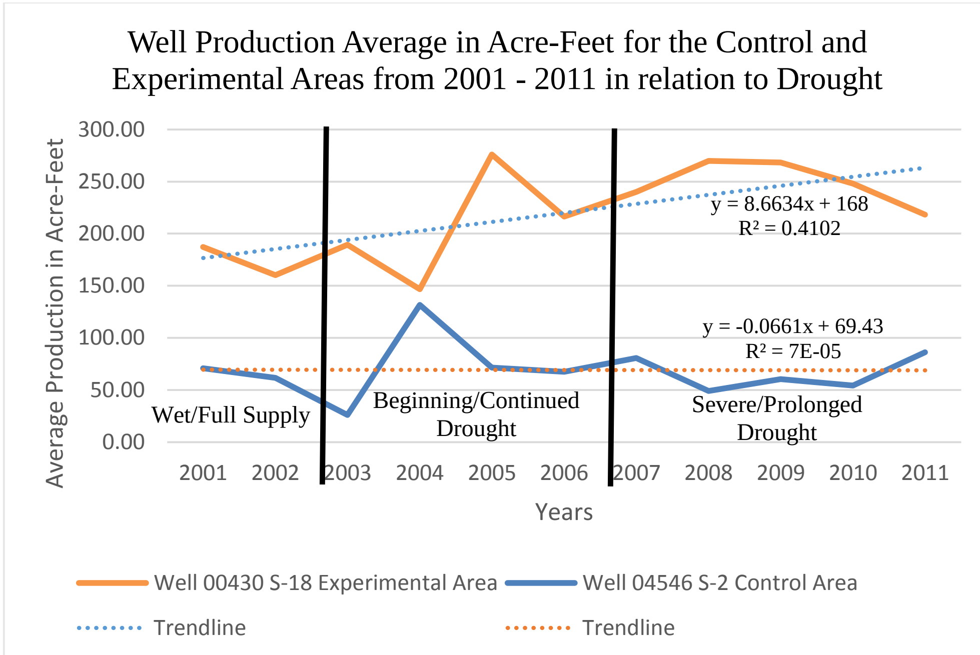

Figure 29: Production Well Water Meter Readings in Acre-Feet from 2001-2011 in relation to Drought

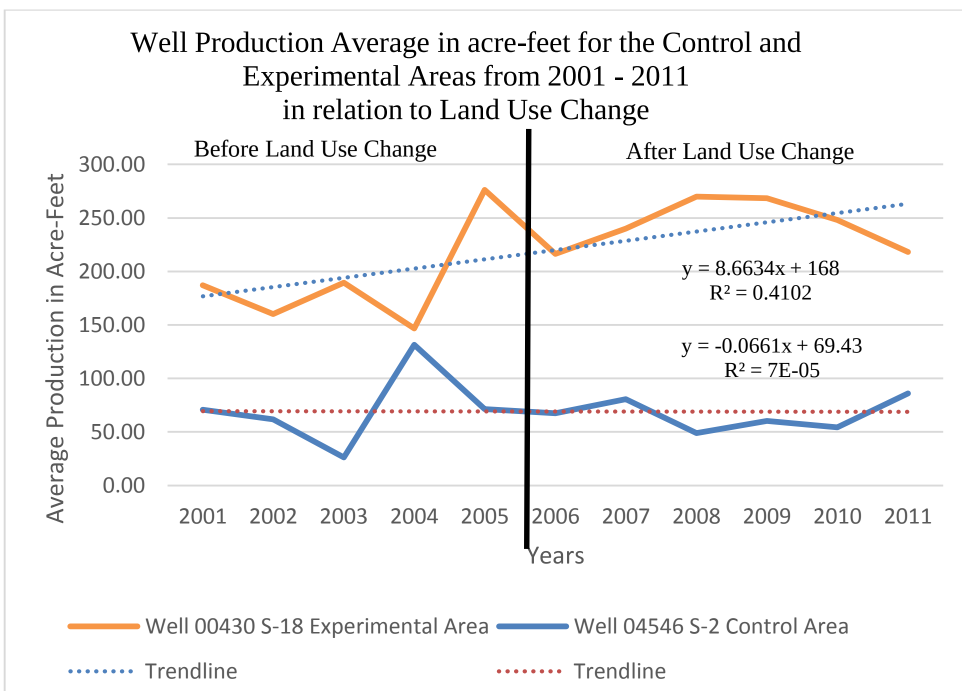

Figure 30: Production Well Water Meter Readings in Acre-Feet from 2001-2011 in relation to Land Use Change

5.3. Results of Research Objective 1 (Control Area)

This section reveals the results from the parametric tests conducted to determine if drought had an effect on groundwater levels in a specified control area in the Mesilla Valley.

The first test to be conducted used the null hypothesis, written as H0: μ1 = · · · = μk, for Mesilla test well 20, meaning that all group means were not statistically significantly different. The statistics are observed in Table 15.

Table 15: Statistics of Mesilla test well 20 DTW in feet

					95% Confidence Interval for Mean			
Groups	N	Mean	St Dev	St Error	Lower Bound	Upper Bound	Min	Max
2000-2002	34	8.59	0.87	0.73	8.285	8.894	7.1	10.8
2003-2006	46	13.23	2.53	0.69	12.476	13.983	8.1	17.7
2007-2012	59	15.81	4.33	0.63	14.682	16.937	8.9	23.54

Since the depth to well groundwater data met all of the ANOVA assumptions, a one way ANOVA was conducted in Microsoft Excel, the results are shown in Table 16 below. There are two ways to determine whether the null hypothesis should be accepted (statistically significant) or rejected (not statistically significant).

- If F > F crit, reject the null hypothesis that all groups have equal means (statistically significant)
- P-value < 0.05 (α) reject the null hypothesis that all groups have equal means (statistically significant) (Gaten, 2000)

In this case, F is ~ 54.42 and F crit is ~ 3.06, meaning F > F crit, which would indicate statistical significance at the 0.05 probability level. In addition, the P-value is ~ 4.33 E-18, which is much smaller than the α of 0.05. The null hypothesis is therefore rejected, and post-hoc pairwise comparison tests were conducted to determine which group means differed from the others. A side-by-side boxplot was plotted for Mesilla test well 20 (Figure 31 below), which revealed a significant difference in variances within the three groups.

Table 16: ANOVA Results for Mesilla test well 20 DTW in feet

Anova: Single Factor						
2000-2012						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	34	292.2	8.594117647	0.7684492		
Column 2	46	608.673	13.23202174	6.40735211		
Column 3	59	932.576877	15.80638775	18.7659882		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1122.1174	2	561.0586995	54.4205542	4.33023E-18	3.06
Within Groups	1402.11698	136	10.30968369			
Total	2524.23438	138				

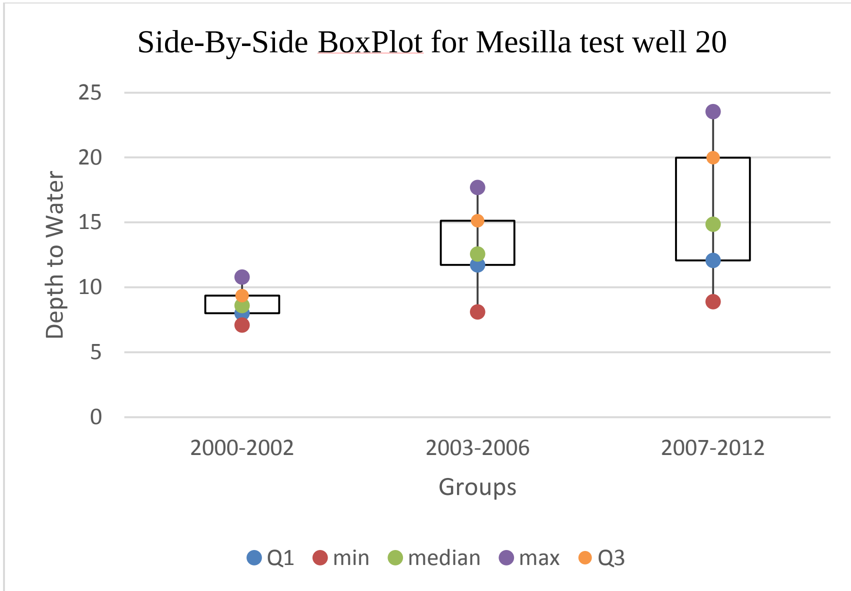

Figure 31: Side-By-Side BoxPlot for Mesilla test well 20

The LSD test was conducted followed by the Bonferroni adjustment to detect statistically significant differences within the group means. These tests incorporated the unequal sample sizes where the different degrees of freedom were taken into account in the equations. The following three tests were conducted for the post-hoc comparisons:

- Test 1: H_0: $\mu_1 = \mu_2$ vs. H_1: $\mu_1 \neq \mu_2$
- Test 2: H_0: $\mu_1 = \mu_3$ vs. H_1: $\mu_1 \neq \mu_3$
- Test 3: H_0: $\mu_2 = \mu_3$ vs. H_1: $\mu_2 \neq \mu_3$

Using the equation,

$$|M_{a+} - M_{a'+}| > \text{LSD} = t_{\nu,\alpha}\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)}$$

the data to be analyzed comprised three groups, a given group is denoted a. The number of observations of the a-th group is denoted Sa. Since all groups did not have the same sample size it was not denoted as S but Sa and Sa'. The total number of observations is denoted N. The mean of Group a is denoted Ma+. From the ANOVA, the mean square of error (i.e., within group) is denoted MSS(A) and the mean square of effect (i.e., between group) is denoted MSA (Williams et al., 2010).

After inputting all of the required information using the equation above, the Bonferroni adjustment was used, A(A – 1)/2 where A is the amount of groups, to ensure that the significance levels aren't misleading and to account for the multiple comparison tests. Table 17 depicts all of the pertinent information to understand how the LSD test and Bonferroni adjustment were conducted. The results indicate that since the Mean Difference (4.64) > the Bonferroni adjustment (4.314), then the group means of 2000-2002 were found to be statistically significantly different than that of the group means of 2003-2006. Additionally, the Mean Difference (7.22) > Bonferroni adjustment (4.107), then the group means of 2000-2002 were also found to be statistically significant different than that of the group means of 2007-2012. Since the Mean Difference (2.58) < Bonferroni adjustment (3.751), then the group means between 2003-2006 and 2007-2012 were found to not be statistically significantly different. Table 18 also depicts the difference between means and significance of pairwise comparisons. The * indicates that there is a statisically significant difference between the groups. The ns indicates not statistically significant.

Table 17:Statistics for LSD and Bonferroni Tests for Mesilla test well 20 DTW in feet

N1	N2	Mean Diff (I-J)	St Error	df	T stat	LSD	Bonferroni Adjustment	Significant?
2000-2002	2003-2006	4.64	0.72	136	1.98	1.437852973	4.314	YES
2000-2002	2007-2012	7.22	0.69	136	1.98	1.368875248	4.107	YES
2003-2006	2007-2012	2.58	0.63	136	1.98	1.250482414	3.751	NO

Table 18: LSD and Bonferroni Statistical Significance Results for Mesilla test well 20 DTW in feet

	2000-2002	2003-2006	2007-2012
2000-2002	0	LSD 1.44 Bonf 4.31 *	LSD 1.37 Bonf 4.11 *
2003-2006		0	LSD 1.25 Bonf 3.75 ns
2007-2012			0

The null hypothesis, written as H0: μ1 = · · · = μk, was also used for production well 04546 S-2, meaning that all group means were equal. Due to the original water meter level readings being positively skewed and not meeting all of ANOVA assumptions, a log transformation was conducted and found to be normally distributed, improving the skew to a large degree. Therefore, the base-10 log data was used for the ANOVA. The statistics are observed in Table 19.

Table 19: Statistics of Well 04546 S-2 Base-10 Log of Production Rates in acre-feet

					95% Confidence Interval for Mean			
Groups	N	Mean	St Dev	St Error	Lower Bound	Upper Bound	Min	Max
2001-2002	8	1.78	0.2	0.164	1.613	1.947	1.48	2.08
2003-2006	9	1.78	0.39	0.143	1.48	2.08	1.33	2.42
2007-2011	18	1.68	0.35	0.137	1.506	1.48	1.09	2.19

After performing a one-way ANOVA in Microsoft Excel on the base-10 log data, the results are shown in Table 20 below. In this case, F is ~ 0.375 and F crit is ~

3.29, meaning F < F crit, which would not indicate statistical significance at the 0.05 probability level. In addition, the P-value of ~ 0.69 is greater than the α of 0.05. The null hypothesis is therefore accepted, meaning that the group means of all groups were not found to be statistically significantly different. Thus, post-hoc pairwise comparison tests were not necessary, although, due to the unequal sample sizes in the groups, a post-hoc comparison was done to ensure a type I or type II error wouldn't occur. A side-by-side boxplot was plotted for production well 04546 S-2 (Figure 32 below), which revealed homogeneity of variances within the three groups.

Table 20: ANOVA Results for Well 04546 S-2 Base-10 Log of Production Rates in acre-feet

Anova: Single Factor						
Base-10 Log 2001-2011						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	8	14.222117	1.7777646	0.0418197		
Column 2	9	16.040922	1.7823247	0.1507747		
Column 3	18	30.268641	1.6815912	0.1250988		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.0850645	2	0.0425322	0.3753932	0.6900045	3.2945368
Within Groups	3.6256155	32	0.1133005			
Total	3.7106799	34				

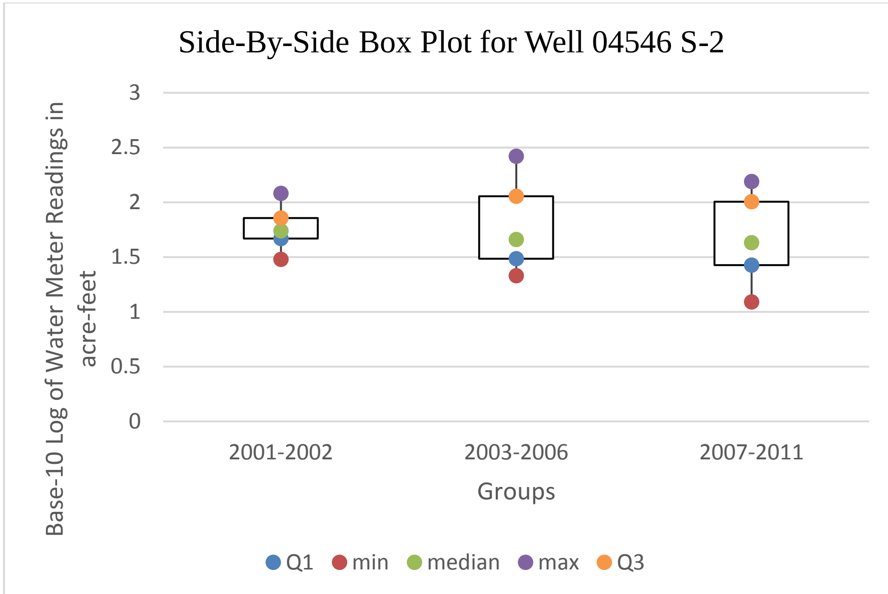

Figure 32: Side-By-Side BoxPlot for Well 04546 S-2

Once again the LSD test and Bonferroni adjustment were used to account for the unequal sample sizes. The following three tests were conducted for the post-hoc comparisons:

- Test 1: H_0: $\mu_1 = \mu_2$ vs. H_1: $\mu_1 \neq \mu_2$
- Test 2: H_0: $\mu_1 = \mu_3$ vs. H_1: $\mu_1 \neq \mu_3$
- Test 3: H_0: $\mu_2 = \mu_3$ vs. H_1: $\mu_2 \neq \mu_3$

Using the equation,

$$|M_{a+} - M_{a'+}| > \text{LSD} = t_{\nu,\alpha}\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)}$$

Table 21 depicts all of the statisics on how the LSD test and Bonferroni adjustment performed. The results confirm that the Mean Differences for all groups were less than the Bonferroni adjustment, meaning that all group means were not found to be statistically significantly different. The results match the ANOVA.

Table 22 also depicts the lack of differences between means and significance of pairwise comparisons. The "ns" indicates not statistically significant.

Table 21: Statistics for LSD and Bonferroni Tests for Well 04546 S-2 Base-10 Log of Production Rates in acre-feet

N1	N2	Mean Diff (I-J)	Std Error	df	T stat	LSD	Bonferroni Adjustment	Significant?
2001-2002	2003-2006	0.00	0.16	32	2.03	0.3320245	0.9960735	NO
2001-2002	2007-2011	0.10	0.14	32	2.03	0.290347	0.871041	NO
2003-2006	2007-2011	0.10	0.13	32	2.03	0.2789564	0.8368691	NO

Table 22: LSD and Bonferroni Statistical Significance Results for Well 04546 S-2 Base-10 Log of Production Rates in acre-feet

	2001-2002	2003-2006	2007-2011
2001-2002	0	LSD 0.33 Bonf 0.99 ns	LSD 0.29 Bonf 0.87 ns
2003-2006		0	LSD 0.28 Bonf 0.84 ns
2007-2011			0

5.4. Results of Research Objective 1 (Experimental Area)

This section reveals the results from the parametric and non-parametric tests conducted to determine if drought had an effect on groundwater levels in the experimental area of Mesilla Valley.

The null hypothesis, written as $H0: \mu 1 = \cdot \cdot \cdot = \mu k$, was used to test for drought on Mesilla test well 45, meaning that all group means were equal. The statistics are observed in Table 23.

Table 23: Statistics of Mesilla test well 45 DTW in feet

					95% Confidence Interval for Mean			
Groups	N	Mean	St Dev	St Error	Lower Bound	Upper Bound	Min	Max
2000-2002	28	23.36	0.61	0.63	23.123	23.597	21.9	24.8
2003-2006	33	26.09	1.18	0.57	25.518	26.662	23.4	27.52
2007-2012	57	31.04	3.38	0.54	30.145	31.935	25.2	36.69

Since the depth to well groundwater data met all of the ANOVA assumptions, a one way ANOVA was conducted in Microsoft Excel, the results are shown in Table 24 below. A very large F ratio was found as F was ~ 102.83 and F crit was ~ 3.08, meaning F > F crit, indicating statistical significance at the 0.05 probability level. In addition, the P-value was ~ 2.47 E-26, which is much smaller than the α of 0.05. The null hypothesis is therefore rejected, and post-hoc pairwise comparison tests were conducted to determine which group means differed from the others. A side-by-side boxplot was plotted for Mesilla test well 45 (Figure 33 below), which revealed a significant difference in variances within the three groups.

Table 24: ANOVA Results for Mesilla test well 45 DTW in feet

Anova: Single Factor						
2000-2012						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Column 1	28	654.2	23.3642857	0.3705291		
Column 2	33	861.022	26.0915758	1.38868013		
Column 3	57	1769.1044	31.0369193	11.4531848		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1244.32848	2	622.164239	102.82666	2.47213E-26	3.07
Within Groups	695.820398	115	6.05061215			
Total	1940.14888	117				

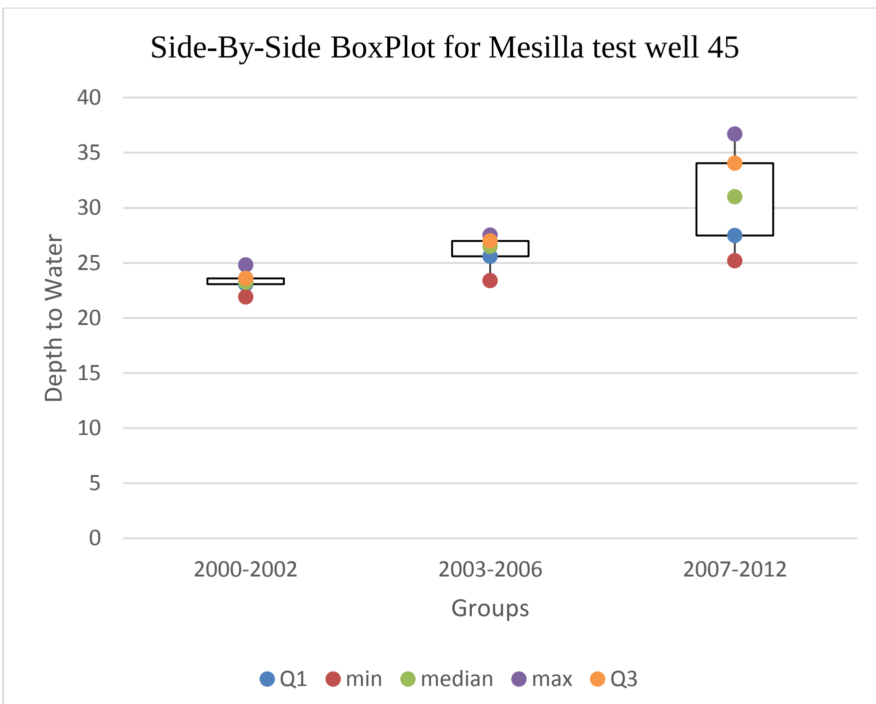

Figure 33: Side-By-Side BoxPlot for Mesilla test well 45

The LSD test and Bonferroni adjustment were used once again to account for the unequal sample sizes. The following three tests were conducted for the post-hoc comparisons:

- Test 1: H_0: $\mu_1 = \mu_2$ vs. H_1: $\mu_1 \neq \mu_2$
- Test 2: H_0: $\mu_1 = \mu_3$ vs. H_1: $\mu_1 \neq \mu_3$
- Test 3: H_0: $\mu_2 = \mu_3$ vs. H_1: $\mu_2 \neq \mu_3$

Using the LSD equation,

$$|M_{a+} - M_{a'+}| > \text{LSD} = t_{\nu,\alpha}\sqrt{MS_{S(A)}\left(\frac{1}{S_a} + \frac{1}{S_{a'}}\right)}$$

Table 25 depicts all of the statistical information to determine how the LSD test and Bonferroni adjustment were performed. The Mean Difference (2.73) < the Bonferroni adjustment (3.754), meaning the group means of 2000-2002 were found not to be statistically significantly different to the group means of 2003-2006 (accept the null hypothesis). For the second group, the Mean Difference (7.67) > Bonferroni adjustment (3.37), meaning the group means of 2000-2002 were found to be statistically significantly different than that of the group means of 2007-2012 (reject the null hypothesis). Lastly, since the Mean Difference (4.95) > Bonferroni adjustment (3.19), then the group means between 2003-2006 and 2007-2012 were found not to be statistically significantly different (reject the null hypothesis). Table 26 also depicts the differences between means and significance of pairwise comparisons. The * indicates that there is a statisically significant difference between the groups. The ns indicates that there is no statistical significance.

Table 25: Statistics for LSD and Bonferroni Tests for Mesilla test well 45 DTW in feet

N1	N2	Mean Diff (I-J)	St Error	df	T stat	LSD	Bonferroni Adjustment	Significant?
2000-2002	2003-2006	2.73	0.63	115	1.98	1.2513932	3.7541795	NO
2000-2002	2007-2012	7.67	0.56	115	1.98	1.1239781	3.3719344	YES
2003-2006	2007-2012	4.95	0.53	115	1.98	1.0653485	3.1960455	YES

Table 26: LSD and Bonferroni Statistical Significance Results for Mesilla test well 45 DTW in feet

	2000-2002	2003-2006	2007-2012
2000-2002	0	LSD 1.25 Bonf 3.75 ns	LSD 1.12 Bonf 3.37 *
2003-2006		0	LSD 2.09 Bonf 3.19 *
2007-2012			0

The other well in the experimental area to analyze was production well 00430 S-18. The null hypothesis, written as H0: $\mu 1 = \cdot \cdot \cdot = \mu k$, was used to drought on production well 00430 S-18, meaning that all group means were equal. The statistics are observed in Table 28.

Table 27: Statistics of Well 00430 S-18 Production Rates in acre-feet

					95% Confidence Interval for Mean			
Groups	N	Mean	St Dev	St Error	Lower Bound	Upper Bound	Min	Max
2001-2002	6	178.12	89.66	31.1	84.01	272.01	76.12	294.64
2003-2006	13	207.88	83.43	29.7	157.46	258.3	64.73	323.14
2007-2011	18	252.22	25.72	22.93	239.43	265.01	191.85	280.16

Since the production well 00430 S-18 water meter level readings were not found to be normally distributed, even after multiple transformation attempts, the Kruskall-Wallace Test was conducted instead of the ANOVA as it doesn’t assume a normal underlying distribution. It is an extension of the Wilcoxon Rank-Sum test to more than two independent samples (Zaionts, 2014).

The test statistic is defined as:

$$H = \frac{12}{n(n+1)} \sum_{j=1}^{k} \frac{R_j^2}{n_j} - 3(n+1)$$

Where k = the number of groups, where nj is the size of the jth group, Rj is the rank sum for the jth group and n is the total sample size, i.e.

$$n = \sum_{j=1}^{k} n_j$$

It can also be written as such:

$$H = \frac{SS_B}{n(n+1)/12}$$

where SS_B is the sum of squares between groups using the ranks instead of raw data (Zaionts, 2014). It works by ranking the raw scores and then calculating the sum of the ranks for each group. If the p-value < α (0.05), reject the null hypothesis that all group means are equal (Zaionts, 2014). Results of the Kruskal-Wallis Test are found on Table 29 below. Since the p-value was found to be 0.172 > 0.05, then the null hypothesis is accepted, meaning that all group means were not found to be statistically significantly different.

Table 28: Results of Kruskal-Wallis Test for Well 00430 S-18 Production Rates in acre-feet

	A	B	C	D	E	F	G	H	I
1		Raw Data				Ranking			
2									
3		2001-2002 Q Prod	2003-2006 Q Prod	2007-2011 Q Prod		2001-2002 Q Prod	2003-2006 Q Prod	2007-2011 Q Prod	Results
4		129.5021207	173.8261953	191.8543961		5	9	10	
5		229.2359478	323.1498464	244.4116984		14	37	17	
6		294.6488849	72.38540928	276.4318342		36	2	31	
7		95.15270246	146.1914322	246.8915218		4	6	19	
8		244.079148	229.0494333	253.9759161		16	13	21	
9		76.12143403	64.73096991	280.166257		3	1	34	
10			269.4453035	275.9792077			26	30	
11			282.2846857	269.1207231			35	24	
12			276.4646252	255.5612551			32	22	
13			267.7478796	271.313833			23	28	
14			272.2041805	277.0096804			29	33	
15			169.5046859	269.1993724			8	25	
16			155.4552186	251.0868233			7	20	
17				225.6242987				12	
18				269.8346313				27	
19				245.1853608				18	
20				200.4686625				11	
21				235.8927822				15	
22	mean	178.123373	207.8799897	252.2226808	Rank Sums R	78	228	397	
23	variance	8038.681679	6960.319388	661.5008027	Group Size n	6	13	18	37
24	stdev	89.6586955	83.42852862	25.7196579	R squared/n	1014	3998.769231	8756.055556	13768.82479
25					H				3.515
26					df				2
27					p				0.172475514
28					α				0.05
29					sig				NO

It is also possible to conduct ANOVA using the rankings of the original data to verify that the Kruskal-Wallis Test performed correctly (Zaionts, 2014). In this case, the F was ~ 1.385 and F crit was ~ 3.304, meaning F < F crit, which would not indicate statistical significance at the 0.05 probability level. In addition, the P-value of ~ 0.265 is greater than the α of 0.05. The null hypothesis is therefore accepted, and confirms the Kruskal-Wallis Test was successful. Post-hoc pairwise comparison tests were not necessary in this case. A side-by-side boxplot was plotted for Mesilla test well 45 (Figure 34 below), which revealed a significant difference in variances within the three groups.

Table 29: Results of ANOVA Test on Rankings for Well 00430 S-18 Production Rates in acre-feet

Anova: Single Factor						
2001-2011						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
5	5	73	14.6	176.8		
9	12	219	18.25	180.93182		
10	17	387	22.764706	49.941176		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	312.46176	2	156.23088	1.3851409	0.2653497	3.30
Within Groups	3496.5088	31	112.79061			
Total	3808.9706	33				

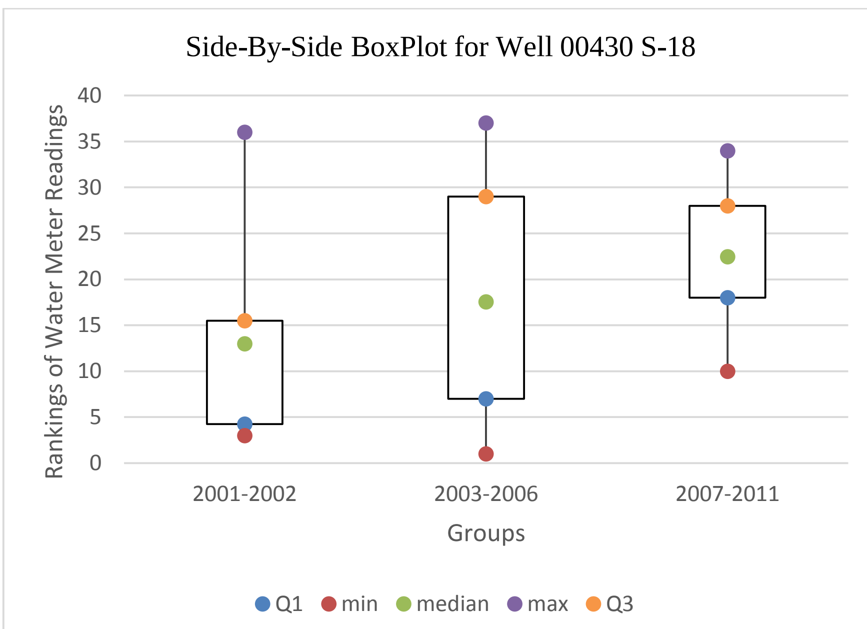

Figure 34: Side-By-Side BoxPlot for Well 00430 S-18

5.5. Results of Research Objective 2 (Experimental Area)

This section reveals the results from the parametric and non-parametric tests conducted to determine if land use change had an effect on groundwater levels and production rates in the experimental area of Mesilla Valley.

The null hypothesis, written as H0: μ1 = · · · = μk, was used to test land use change on Mesilla test well 45, meaning that all group means were equal. The Student's T-Test was performed using the data analysis Toolpak in Microsoft Excel. The two groups that were selected for analysis were 2000-2005 and 2006- 2012, due to the fact that Legends West Subdivision began residential development in 2005. The results of the test are found in Table 27 below. Since the variances of the two groups were somewhat unequal, the Student's T-Test Assuming Unequal Variances was chosen.

Table 30: Student's T-Test Statistical Significance Results for Mesilla test well 45 DTW in feet

t-Test: Two-Sample Assuming Unequal Variances		
	2000-2005	*2006-2012*
Mean	24.4323333	30.4220508
Variance	2.28925687	11.9209317
Observations	51	67
Hypothesized Mean Difference	0	
df	95	
t Stat	-12.689289	
P(T<=t) one-tail	1.8114E-22	
t Critical one-tail	1.66105182	
P(T<=t) two-tail	3.6228E-22	
t Critical two-tail	1.985251	

In order to determine statistical significance in the T-Test, the t Stat < -t Critical two-tail or t Stat > t Critical two-tail (Excel Easy, 2014). Since the t Stat -12.689 < t Critical two-tail -1.985, reject the null hypothesis because the group means were found to be statistically significantly different.

Land use change was also tested on water meter readings of production well 0043- S-18. The non-parametric Mann-Whitney U Test was performed due to the non-normality of the data and the inequality of sample sizes. The Mann-Whitney U Test was performed by following certain equations in Microsoft Excel. The two groups that were selected for analysis were 2001-2005 and 2006- 2011, due to the fact that Legends West Subdivision began residential development in 2005.

The test statistic to be defined is for samples 1 and 2 where n1 is the size of sample 1, n2 is the size of sample 2, R1 is the adjusted rank sum for sample 1, and R2 is the adjusted rank of sample 2 (Zaionts, 2014).

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 \qquad U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2$$

$$U = \min(U_1, U_2)$$

If the observed value of U is < U crit then the test is statistically significantly different (at the α level). The values for U crit were provided in the Mann-Whitney Tables (Zaionts, 2014). The results from these tests on production well 00430 S-18 are found on Table 31 below. In this case, the U value (308) > the U-Crit (90), meaning that there was no statistical significance between group means of 2001-2005 and 2006-2011. The null hypothesis was therefore accepted.

Table 27: Results of Mann-Whitney U Test for Well 00430 S-18 Production Rates in acre-feet

Raw Data				Rankings				
	2001-2005 Q Prod	2006-2011 Q Prod		2001-2005 Q Prod	2006-2011 Q Prod		2001-2005	2006-2011
	129.5021207	267.7478796		5	23	Count	15	22
	229.2359478	272.2041805		14	29	Rank Sum	78	275
	294.6488849	169.5046859		36	8			
	95.15270246	155.4552186		4	7			
	244.079148	191.8543961		16	10	α	0.05	
	76.12143403	244.4116984		3	17	tails	2	
	173.0051892	276.4318342		9	31	U	308	
	323.1498464	246.8915218		37	19	U-Crit	90	
	72.38540928	253.9759161		2	21	sig	NO	
	146.1914322	280.166257		6	34	U1	372	
	229.0494333	275.9792077		13	30	U2	308	
	64.73096991	269.1207231		1	24			
	269.4453035	255.5612551		26	22			
	282.2846857	271.313833		35	28			
	276.4646252	277.0096804		32	33			
		269.1993724			25			
		251.0868233			20			
		225.6242987			12			
		269.8346313						
		245.1853608						
		200.4686625						
		235.8927822						
mean	193.6964755	245.6781918	Rank Sums R	78	275			
variance	8151.871558	1292.845085						

All of the results will be discussed in detail in the next chapter.

6. DISCUSSION

A thirteen-year period was analyzed using a variety of methods and techniques that aided in the understanding of the relationship between drought, land use change, and groundwater hydrology in two contrasting areas of the Mesilla Valley. Understanding groundwater hydrology in general, much less in the southwestern United States, is challenging due to a lack of solid historical and current data. Yet, groundwater is a resource that is an absolute necessity for human survival across the world. This research aimed at understanding how the lack of precipitation (drought), urbanization (land use change from agricultural to residential), and groundwater hydrology interacted with one another in a semi-arid region.

In reviewing the drawdown and pumping rates of four wells in the Las Cruces area, positive total percent increases of DTW levels and production rates were evident for both the monitoring and production wells over a thirteen year period (2000-2012). This is significant because there are hundreds of shallow aquifer wells in this region, and if they all follow this pattern, then the aquifer is not being replenished as fast as it is being depleted. The EBID has done an excellent job maintaining historical and present well records in the area by monitoring daily/monthly static water levels and supplying them to the public. They also collect an abundant number of historical and current records of surface water deliveries, diversion canals, etc. even though it is a difficult task at hand. The CLC collects production water meter reading levels at all of its production wells in the city; however, they do not make them readily available to the public and do not collect historical/present static water levels at any of their locations. This poses a challenge for identifying and addressing both onsite and down hydrologic gradient water quantity and water quality resource concerns.

In answering the first research objective of determining whether drought had an effect on the control and experimental area, there were some extremely interesting findings. Beginning with the control area findings, the group means of Mesilla monitoring test well 20 were statistically significantly different at the 0.05 probability level between the years of 2000-2002 and 2003-2006, and also between 2000-2002 and 2007-2012. This means that it is likely that the drought that had been well documented by multiple sources, beginning in 2003 and enduring through 2012, did have an effect on static groundwater levels. Since there was no land use change in the area during that time period, the only explanation as to why the group means would be statistically significantly different is that increased groundwater extraction during the drought caused the water levels to drop. Of note, due to the variability and complexity when dealing with groundwater, it is possible other factors could have affected water levels that were not related to drought. From 2003-2006 and 2007-2012, the group means were not found to be statistically significantly different (accepted the null hypothesis), meaning the prolonged drought caused a larger drop in static groundwater levels over time. Drought plays a major role in this area due to agricultural fields not being able to receive a full supply of surface water during times of drought, making farmers supplement their crops with groundwater, which causes more depletion of the aquifer. It will be interesting to determine what long-term effects the drought could have on groundwater levels.

All of the group means of water meter readings from production well 04546 S-2 located in the control area were analyzed and found not to be statistically significantly different. This is a significant finding in that drought apparently did not have an effect on pumping rates of the production well. However, the only true method to determine whether this is true is to analyze static groundwater levels at the production wells to determine the actual drawdown to the aquifer. A few factors that could have attributed to the lack of statistically significant differences include changing of crop types during the time period, the age of growing orchards, implementation of new orchards, removal of old orchards, human errors in reviewing meter readings, meter malfunction (outliers were removed before analysis), unit conversions from gallons to acre-feet, seasonal variability of pumping rates, and/or recording quarterly meter reading records as opposed to daily/monthly.

The experimental area findings were also very interesting. In regards to drought, the average monthly depth to water level group means for the Mesilla monitoring test well 45 from 2000-2002 and 2003-2006 were not found to be statistically significantly different at the 0.05 probability level. This is significant in that it means that groundwater extraction during drought did not have an effect on groundwater level data in the experimental area.

Lastly, in regards to drought, the group means of average meter reading levels from production well 00430 S-18, for years 2001-2002, 2003-2006, and 2007-2011, were all found not to be statistically significantly different. This means that groundwater extraction during drought did not have an effect on groundwater production pumping in the experimental area. The same factors mentioned above for the other production well data could be attributed to this well. The CLC needs to invest into properly monitoring its production static water levels to better know what environmental or anthropogenic factors are affecting them.

To answer the second research objective in determining whether land use change had an effect on groundwater hydrology in the experimental area, some very interesting results were found. The group means of groundwater level data for Mesilla test well 45 from 2000-2005 and 2006-2012 were found to be statistically significantly different at the 0.05 probability level. This is a significant finding in that there was evidence that land use change does indeed have an effect on groundwater levels. The drawdown was much more pronounced after the land use change occurred. The sole factor in the experimental area was the large area of land use that changed from agricultural fields to residential subdivisions called Legends West that occurred in 2005. One of the reasons for the increase in drawdown was that surface water rights were lost when agricultural fields were no longer present in 2005, meaning that there would be less groundwater recharge through irrigation. At the same time, residential subdivisions brought impermeable features, such as asphalt, concrete, structures, etc., that would not permit nearly as much recharge of the aquifer as it had been receiving before. Another factor was that there would be a lot more groundwater pumping for human consumption to sustain the needs of the subdivisions, given potable water in the region is 100 percent groundwater. With further urban expansion likely to occur in the region, monitoring of groundwater levels in areas such as these where there is a great deal of land use change from agricultural to residential.

The group means of production well 00430 S-18 data were not found to be statistically significantly different for years 2001-2005 and 2006-2011. This means that land use change did not have an effect on production groundwater pumping rates even after Legends West subdivision was implemented in 2005. This is most likely attributed to the factors mentioned above of the variability of pumping rates by season as well as the marginal hydraulic connectivity between the production well and the monitoring well.

In summary, the overall findings of this research contribute to a better understanding of what methods and tools can lend insight into the interaction of drought, land use change and groundwater. It was determined that the EBID monitoring static water level data were much more robust and recorded with such a higher frequency and detail than the production meter reading level data from the CLC. As was found in this case, the better the data, the better the results will be.

7. CONCLUSION AND FURTHER RESEARCH

7.1. Conclusion

Understanding the effects of drought and land use change on groundwater hydrology in the Mesilla Valley is an extremely important issue for the future of this semi-arid region of the southwestern United States. Through this research and analysis, it was determined that both drought and land use change do indeed have an effect on the groundwater hydrology in contrasting areas within the region. It was found that EBID's monitoring wells provided valuable data on the static groundwater levels in the area, and other agencies should mimic their recording methods to ensure that groundwater levels are properly recorded and monitored. Direct trends and patterns exist between the amount of precipitation/depth of drought, population growth, resultant land use change, and groundwater dynamics that could limit the supply within a short amount of time with serious consequences on the regional economy and quality of life.

Land use change in the Mesilla Valley is a very important factor for irrigators, planners, educators, and engineers to understand. Water is a scarce resource in this semi-arid region that deserves to be protected and evaluated on an ongoing basis. As a society, we need to continue finding better ways to quantify and preserve this resource as it remains our livelihood in the southwest.

Understanding surface water hydrology and how it is affected by land use change and drought in the region would be an extremely important factor to understand in this region as surface water is interrelated with groundwater. However, in this research due to the variability of land use types within close proximity to one another, lack of canal and drainage infrastructure, wastewater issues, and data availability, it was difficult to be able to quantify land use change on surface water dynamics. Further research on the relationship between groundwater/surface water dynamics should be conducted for the region.

The outcomes of this research should be of interest to regional water resource managers as water is a major concern for the region's future. EBID officials will be interested in the results of whether drought or land use change has had an effect on the groundwater hydrology as they deal with these issues on a yearly basis. The CLC should be interested in this study as it highlights the need to monitor static groundwater levels at production wells to provide a much clearer picture of what is happening underground. Farmers and ranchers should also be interested in the study's findings as their yearly crop depends on the relationship between surface water allocation and supplemental ground water supply in the area.

7.2. Further Research

Due to the intricacies of all of the variables used to determine the effects of land use change on groundwater hydrology in the Mesilla Valley, future work will need to be performed to fully understand and quantify the issue. Future research should determine the interaction of the lateral hydrological connectivity between production wells and increasing residential areas. There is a need to quantify groundwater declines in order to make hydrologic predictions under various land use change scenarios within the area of investigation. Two further research objectives should be examined spatially to study this difficult issue. The first objective is to incorporate a land use change model called the Dynamic Land Use and its Effects (Dyna-CLUE) Model to simulate future land use scenarios through 2040 for the City of Las Cruces and Doña Ana County (DAC). The Dyna-CLUE model is a dynamic, spatially explicit, land use and land cover change model (Verburg, 2007). It is among the most frequently used land use models globally due to its flexibility and framework. The model's range varies from small scale (i.e. area of the state of New Mexico) to large scale (i.e. area of a small town) (Verburg, 2007).

The model is sub-divided into two distinct modules, a non-spatial demand module and a spatially driven allocation procedure (Figure 35 below). The non-spatial module calculates the area change for all land use types. The second part of the model takes the non-spatial demands and translates them into land use changes at different locations within the study region using a raster-based system (Verburg, 2007).

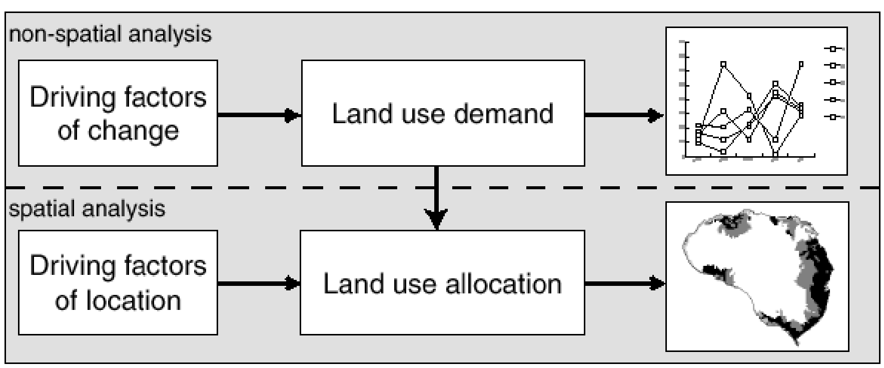

Figure 35: Dyna-Clue Model Approach

The second research objective would be to incorporate the Dyna-CLUE model outputs of the land use scenarios, as new parameters into the groundwater flow model (MODFLOW) to simulate how land use changes will interact with shallow and deep groundwater aquifers in this region through 2040. The model would also identify likely problem areas, such as cones of depression, and challenges that result from projected major land use changes from agricultural to residential. The USGS's modular ground-water flow model is the basis to the MODFLOW 2000 used to simulate groundwater conditions in the Lower Rio Grande Basin Groundwater Model. It takes into account pumping, recharge rates, aquifer storage, hydraulic conductivity and transmissivity, as well as using a calibration tool called PEST (Parameter Estimation) that calculates sensitivities, correlations, and estimates parameters (Gastelum, 2007). The model should simulate flux and water elevations occurring in the simulated area and is well-suited for prediction of long-term water-level fluctuations at a regional scale (Gastelum, 2007).

The research conducted for this thesis was done on a large cartographic scale (small pieces of earth at a large cartographic scale), analyzing the differences between two contrasting areas within the Mesilla Valley. The benefits of doing a regional scale study would be to analyze all of the EBID monitoring wells, CLC, and private owner production wells to better understand the spatial variability of groundwater drawdown in the entire region to potentially identify problem areas. This type of information would greatly help policymakers, urban planners, and decision makers in the area to make better informed decisions on future water allocation and land use.

This would also assist farmers to more efficiently utilize their dwindling water resources as they deal with the effects of drought and population growth.

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