

STATISTICAL RELATIONSHIPS BETWEEN GROUNDWATER, CLIMATIC, AND  
ECONOMIC FACTORS IN SOUTHEASTERN ARIZONA

by

Mekha Pereira

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In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE  
WITH A MAJOR IN HYDROLOGY

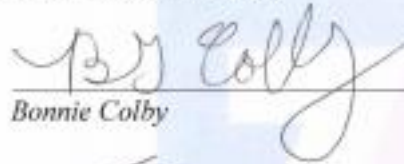
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As members of the Master's Committee, we certify that we have read the thesis prepared by Mekha Pereira, titled *Statistical Relationships Between Groundwater, Climatic, and Economic Factors in Southeastern Arizona* and recommend that it be accepted as fulfilling the thesis requirement for the Master's Degree.

  
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Bonnie Colby

Date: 4-22-22

  
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Laura Condon

Date: 4-22-22

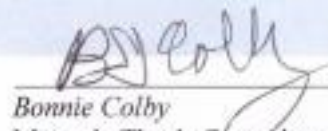
  
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Thomas Meixner

Date: 4/22/22

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We hereby certify that we have read this thesis prepared under our direction and recommend that it be accepted as fulfilling the Master's requirement.

  
\_\_\_\_\_

Bonnie Colby  
Master's Thesis Committee Co-Chair  
*Agricultural & Resource Economics*

Date: 4-22-22

  
\_\_\_\_\_

Laura Condon  
Master's Thesis Committee Co-Chair  
*Hydrology & Atmospheric Sciences*

Date: 4-22-22

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# 1 INTRODUCTION

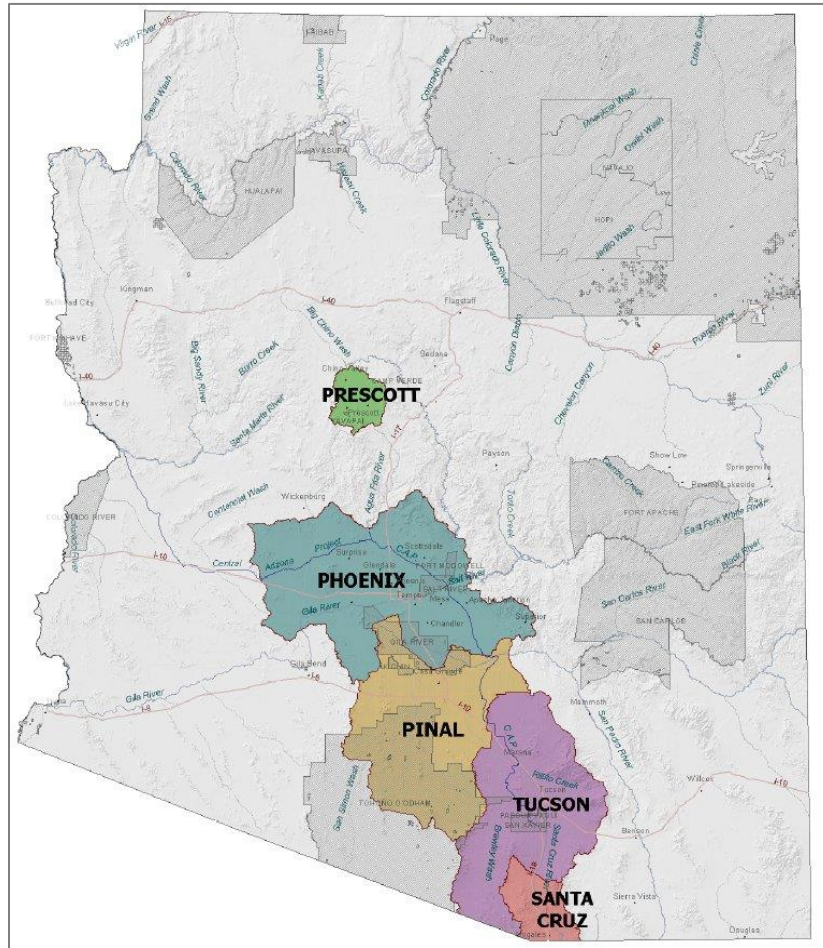
Hydrologic, climatic, and economic factors interact in complex ways to influence groundwater conditions. These relationships can be difficult to measure and simulate but are important to understand for long-term water resource planning purposes. Knowledge of the factors strongly linked with groundwater levels in a basin can help water managers develop targeted and effective strategies to incentivize the desired water use outcomes. The goal of this study is to explore the statistical relationships between groundwater levels and various economic and climatic variables in two rural basins in southeastern Arizona.

Statewide, groundwater supplies 41% of Arizona's annual water demand (ADWR, 2020). Rural basins, especially those off the mainstem of the Colorado River and outside of the Central Arizona Project service area, often have much a higher rate of groundwater dependence. Despite the importance of groundwater to these areas, groundwater use and conditions in rural areas of the state are not as well understood as within Arizona's large cities, which largely fall into Active Management Areas (AMAs) (Figure 1). The AMAs, established by the 1980 Groundwater Management Act, contain the main urban centers of the state and implement groundwater use restrictions and conservation requirements for the municipal, industrial, and agricultural sectors, among other measures to achieve the desired groundwater management goal (ADWR, n.d.). The five AMAs (Prescott, Phoenix, Pinal, Tucson, and Santa Cruz) comprise 82% of the state's population, 87% of the state's municipal water use, 72% of the state's industrial water use, and 34% of the state's agricultural water use (ADWR, 2016). Much of the economic activity occurs in the central AMAs (Phoenix, Pinal, and Tucson), whereas the Prescott and Santa Cruz AMAs are relatively more rural. The regulated nature of these areas results in higher degree of monitoring, so data is available for annual groundwater withdrawals. Outside of the AMAs, no such metering and reporting requirements exist with the exception of community water system wells. As a results, in much of the state's land area, the amount of groundwater being withdrawn from water supply wells on an annual basis is both unknown and unregulated, which is a precarious combination. Without data on what sectors are using groundwater and in what quantity, it is difficult to craft protective measures to encourage sustainable groundwater use.

Data availability in rural areas, especially those outside of AMAs, limits the spatial and temporal resolution with which questions regarding water use patterns, groundwater conditions, and links between economic productivity and groundwater conditions can be answered. Because water use data is unavailable in much of the state, is it important to consider other metrics that can be used to evaluate influences on water use decisions from various economic sectors. In this research, we are interested in exploring statistical relationships between hydrologic, climatic, and economic factors for which data are available. We focus on the use of a groundwater level metric to assess the state of groundwater in a basin and explore signals of economic variables in the groundwater level metric. This is a unique approach as other studies exploring the connections between water use decisions and economic influences are able to utilize water use data, and this study explores the potential for groundwater level data to serve as a proxy. The advantage of this method is that water level data is more widely available, easier, and cheaper to record.

This research is timely as development in various sectors increases throughout Arizona, introducing new pressures on groundwater supplies. Understanding the influences on water use

in groundwater dependent regions is critical for long-term water resource planning, especially in rural areas where demand from various sectors is growing and changing in proportion. In the absence of detailed and seasonal data on groundwater conditions and economic inputs and outputs in various sectors, a basin-wide annual perspective can serve as a useful starting point. This type of evaluation has not been conducted in rural Arizona settings. Beyond Arizona, many other rural areas in the world lack water use data and could potentially benefit from a similar approach in which economic signals are investigated in groundwater level trends.



**Figure 1. Map of Arizona’s Active Management Areas (source: ADWR)**

## **2 PREVIOUS COUPLED HYDROLOGIC AND ECONOMIC STUDIES**

### **2.1 Irrigated Agriculture**

The intersection between groundwater and economic evaluations often occurs in the context of irrigated agriculture, either through empirical econometric modeling or dynamic hydro-economic modeling. Econometrics involves the application of statistical models to economic data in order to address questions with an economic component. Hydro-economic modeling involves the coupling of water system models with water demand functions or economic models to address

economic optimization problems (Harou et al., 2009). In the U.S., these complex models have often been applied to optimization questions in irrigated agriculture, especially in California's Central Valley (Bourque et al., 2019; Nelson et al., 2016; Medellín-Azuara 2015; MacEwan et al., 2017) and the Ogallala Aquifer region (Bertone Oehninger, 2021; Quintana Ashwell et al., 2018; Bulatewicz et al., 2010).

In hydro-economic models, the linkage between groundwater and agricultural productivity is specified based on current knowledge of relationships between crop yields and irrigation water application. The linkage to overall agricultural profitability is usually made through pumping costs (pumping costs increase as groundwater levels decrease, directly impacting agricultural profitability), in addition to the effects of irrigation on crop yield. This in turn impacts the use of other inputs (fertilizer, labor), influencing the overall cost of producing crops.

Hydro-economic modeling has revealed interesting relationships between water use decisions and cost. Foster et al. (2015) performed an empirical evaluation of hydrogeologic influences on irrigation demand and found that while increased pumping costs did reduce profit, they had little influence on irrigation water application, whereas declines in well yield significantly reduced irrigated area. Several previous studies have found irrigation water demand to be price inelastic, meaning the amount of water farmers use is not sensitive to the cost of obtaining and applying water to crops (Scheierling et al., 2006; Hendricks et al., 2012; Wheeler et al., 2008). Additionally, Sukcharoen et al. (2020) found that in the western Kansas portion of the Ogallala Aquifer, expected crop price had no significant impact on groundwater extraction rates.

These studies were performed in areas with very large-scale agriculture operations. In southeastern Arizona, the relative scale of commercial agriculture is much smaller and there are also small, non-commercial hobby farms. Prior research does not explore the responsiveness of groundwater use for irrigation to economic factors under these conditions. Additionally, these studies focus on a large enough spatial scale for which it is possible to obtain actual or estimated data on irrigation water application. In much of Arizona, and much of the world, water use data is unavailable - especially when it comes to groundwater use in unregulated areas. This reality of insufficient water use data provides motivation to find other measurable groundwater metrics that can be used to evaluate impact of economic drivers on groundwater conditions. Groundwater levels measured in wells are one such metric which are easier to obtain than water use data, and are also more politically achievable in areas resistant to mandated metering and reporting requirements for groundwater use.

## **2.2 Urban Water Use**

On the municipal side, many western cities have observed changes in the relationship between growth and water demand. Traditional thought on the subject assumes increased population growth results in increased total water demand for municipalities, and many water providers continue to use this assumption to developed projected demand estimates (Richter, 2020). In recent decades, studies have shown decreases in per capita water use over time, so much so that total water use has also declined in major western cities despite population increase. Abraham et al. (2020) documented this trend in 10 major California water providers, and Richter et al (2020) further explored the trend in 20 major western cities with data available for such an analysis. All study areas saw decreases in per capita water use since 2000, and most saw decreases in overall water demand during a period of population increase. This trend, commonly referred to as a

“decoupling” of growth and water demand, in part occurs due to water efficiency regulations and the impact this has on inventory available to outfit new homes. New developments are forced to use water efficient appliances and fixtures (low flush toilets, low flow showerheads, high efficiency clothes washers, etc.) because state and federal regulations have resulted in low water use items being the predominant stock of supplies in stores. The service area populations of the municipalities explored in these studies ranged from approximately 100,000 to over 4 million people. It is unclear whether this decoupling phenomenon is also true in rural, groundwater dependent areas that generally experience different diversity in their water portfolios and population growth rates.

Within Arizona, a recent study demonstrated the importance of groundwater to the state’s economy, focusing on Arizona’s Active Management Areas (AMAs) that contain the state’s main urban centers (James et al., 2020). The authors estimated groundwater use by municipal, industrial, and agricultural users in the AMAs was responsible for generating \$1.2 trillion in state GDP between the years 2010 and 2018. On average, this accounts for 43% of the annual state GDP. The study relies on a counterfactual approach by comparing observed economic activity to estimated economic activity in a scenario with no groundwater availability, assuming no water source for substitution. This method overestimates the value of groundwater, given the likelihood that other sources of water would be substituted for groundwater if it were unavailable, but still illustrates the importance of exploring a human, economic, perspective when making recommendations on groundwater use and sustainability. Groundwater sustains industries and livelihoods so we must understand the feedbacks between human systems and natural systems to better manage scarce resources. This study is one of several in Arizona that focus on areas under state mandated groundwater regulation and further study is needed in unregulated, predominantly rural areas. This is difficult to accomplish because actual water use data is not available in unregulated areas, so other groundwater metrics need to be explored.

### **2.3 Outstanding Research Questions**

The described previous work at the intersection of hydrology, water use, and economics has revealed interesting and sometimes counterintuitive relationships between economic metrics and water use decisions. Many of the relationships explored focus on water use for large scale irrigated agriculture or large urban populations. This study is motivated by a desire to explore these interesting relationships in rural, groundwater dependent areas of southeastern Arizona. In the absence of adequate water use data for a small-scale case study, we explore the use of a groundwater level metric in an econometric evaluation. We use the groundwater metric as the dependent variable, and various climatic and economic factors as explanatory variables in a regression model. Broadly speaking, we explore three topics that can impact groundwater conditions: physical, economic, and regulatory. From a physical perspective, groundwater levels are controlled by climate, topography, and geology, with climate being the main factor that varies on human time scales. From an economic perspective, changes in the municipal and agricultural sectors are two major human systems that impact groundwater demands. Finally, from a regulatory perspective, policy structures impact the rate at which groundwater can be used. With this framework in mind, key research topics include:

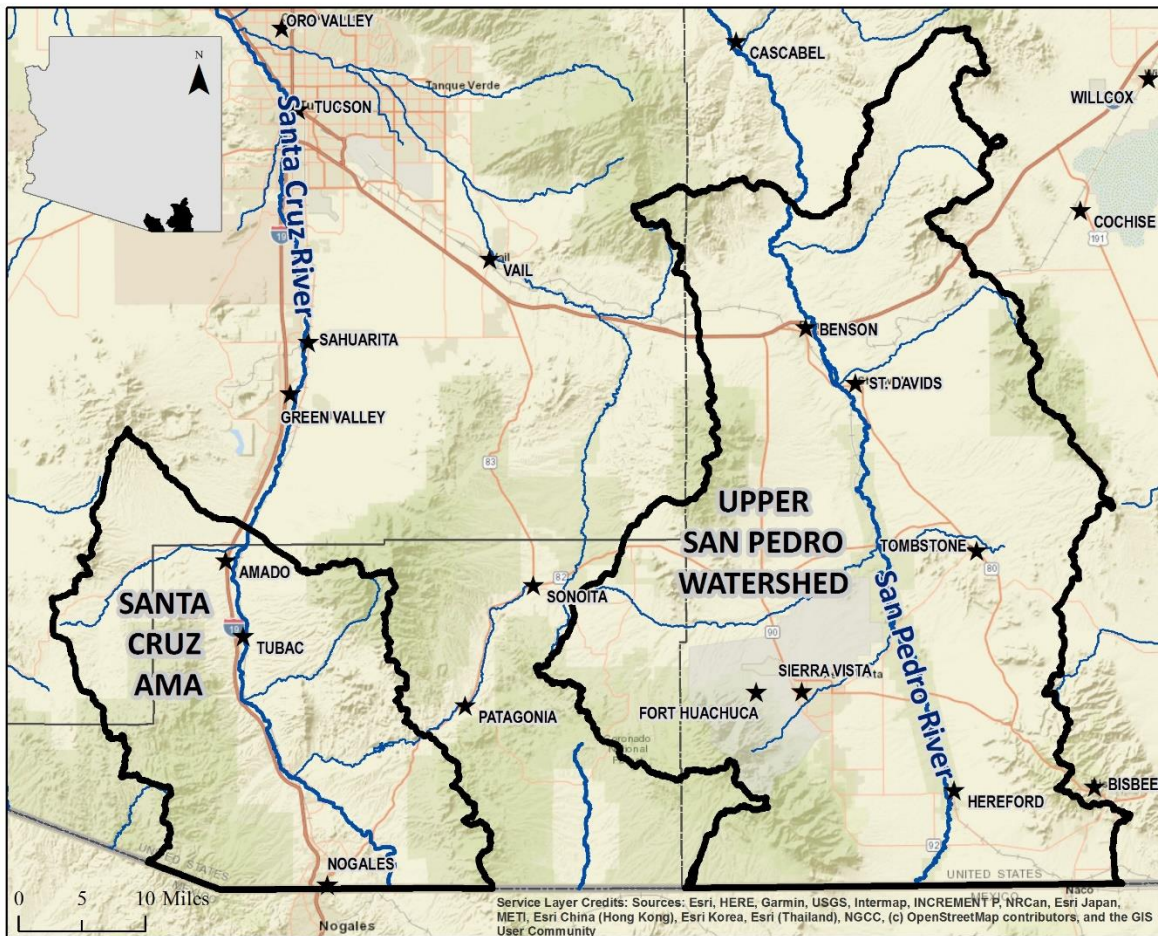
- 1. What groundwater metric is most appropriate to use for statistical analysis with economic factors?*

2. *Which climatic and economic factors are significantly related with groundwater levels in rural southeastern Arizona?*
3. *What are the key differences in groundwater and economic trends observed within and outside of regulated areas?*

### **3 STUDY AREA**

This study focuses on two neighboring areas in southeastern Arizona, the Santa Cruz AMA (located in the upper portion of the Santa Cruz River watershed) and the Upper San Pedro watershed (Figure 2). These regions present a unique opportunity for this case study because they are both rural, groundwater dependent basins with intimately connected groundwater and surface water conditions, and have circumstances that provide for greater data availability than is usually present in rural Arizona. Unlike the highly urbanized central AMAs (Phoenix, Pinal, and Tucson), the Santa Cruz AMA has a rural identity but is still regulated by ADWR and therefore enforces the monitoring and reporting requirements. The Upper San Pedro is outside of the AMAs but has been the subject of extensive study from an environmental and adjudication perspective. Though data in the area is still not as plentiful as within AMAs, both of these special interests have resulted in efforts to monitor water levels, compile reported and estimated groundwater pumping, and other data needs for hydrologic modeling.

The southern portion of the Tucson AMA was also considered as a potential subarea in this study but was ultimately excluded due to distinct differences in economic profile. An overview of this subarea is provided in Appendix I.



**Figure 2. Location of study area along the upper portion of the Santa Cruz and San Pedro Watersheds**

### 3.1 Santa Cruz Active Management Area

The Santa Cruz AMA subbasin is bounded by the U.S. - Mexico border to the south and extends north of the Santa Cruz County line, with the Santa Cruz River flowing north through the center of the basin (Figure 2). The headwaters of the Santa Cruz are in the neighboring San Rafael Valley to the east, which is a desert grasslands basin. The river begins in Arizona, flows south into Mexico, then changes course to flow north back into Arizona near Nogales and continues to its eventual confluence with the Gila River. The Santa Cruz River had perennial stretches under pre-development conditions but due to subsequent groundwater pumping, the river has become ephemeral flowing only in response to storm events. The AMA contains one perennial stretch of river which is artificially maintained by effluent releases from the Nogales International Wastewater Treatment plant in Rio Rico. The Santa Cruz AMA is completely groundwater dependent and much of the pumping occurs in close proximity to the streambed.

The watershed is located in the Basin and Range geologic province, which is marked by numerous roughly parallel north-south trending mountain ranges with flat basins between them.

This geology is a result of crustal extension and normal faulting, where valley floors drop down between mountain ranges as the crust thins. As sediment filled the troughs between ranges, large alluvial aquifers with prolific groundwater resources were created. Though the quantity of groundwater stored in these basins over time is large, recharge to the groundwater system, primarily through mountain front recharge and focused streambed recharge, happens slowly and often cannot keep up with the rate of groundwater extraction for human use.

Existing hydrologic investigations in the area have focused on groundwater and surface water modeling (ADWR, 2020a; Niraula et al., 2012) and effluent related water quality (Boyle and Fraleigh, 2003; Sanders et al., 2013; McAndrew, 2011). From an economic perspective, a contingent valuation study estimated the recreation and ecosystem value of instream effluent flows (Weber et al., 2016). Additionally, Arora et al. (2014) employed a hedonic analysis to demonstrate that maintaining biodiversity and open spaces associated with proximity to the Santa Cruz River provides an economic benefit to home prices. In a hydroeconomic study, Gosh et al. (2016) found groundwater use to produce higher net benefits in the municipal sector than in the agricultural sector. Finally, a recent economic impact study by Audubon Arizona (2019) quantified the economic impact of water-based recreation in Arizona at the county level. In Santa Cruz county, water based recreation supports 1,600 jobs, and contributes \$99 million annually to state GDP, with total output generation (including multiplier effects) of \$189 million annually.

### **3.2 Upper San Pedro Watershed**

The Upper San Pedro watershed is also bounded by the U.S. - Mexico border to the south and is located largely within Cochise County (Figure 2). The San Pedro River forms at the foothills of the Sierra Madre Mountains in Mexico and flows north through the center of the watershed until its eventual confluence with the Gila River. The San Pedro is composed of a combination of perennial and intermittent stretches (Turner and Richter, 2011). Groundwater is also the primary water supply in this basin and streamflows have been significantly diminished by groundwater pumping that occurs in close proximity to the stream (Thomas, 2006). A recent investigation of groundwater level change in the Sierra Vista subbasin showed 78% of monitored wells experienced a decline in water levels during the period 2007 to 2019, with an average basin-wide decline of 3.9 feet (ADWR, 2021). The general geologic setting of the Upper San Pedro is the same as described in the previous section regarding Basin and Range province, therefore groundwater extraction rates in excess of limited natural groundwater recharge is a major concern.

The San Pedro River itself is often noted as the last major undammed river in the American Southwest and its stretches of intermittent and perennial flows provide important habitat for many plant and animal species that exist only within the narrow ribbons of riparian habitat provided by desert rivers (Audubon Arizona, n.d.). The presence of flowing water and lush habitat has attracted decades of study by environmentalists and hydrologists. Additionally, the San Pedro is a tributary of the Gila River and is therefore part of the Gila River general stream adjudication, with adjudication petitions filed on the San Pedro in the 1970s (Maricopa Superior Court, n.d.). The state level adjudication has been slow moving but much of the activity has focused on the San Pedro watershed which was the site of the first subflow zone delineation as well as development of subflow depletion testing procedures, again attracting the attention of many hydrologists (ADWR, 2018). Subflow is a legal term defined as “saturated floodplain Holocene alluvium” and represents the Arizona courts’ attempt to provide a linkage between

groundwater and surface water in an otherwise bifurcated legal system. Subflow is essentially shallow groundwater near a river that is legally considered surface water and would require a surface water right to pump. The same legal concerns regarding groundwater-surface water connections exist along the Santa Cruz as it is also a tributary of the Gila, but little action regarding the adjudication has occurred in the Santa Cruz watershed.

Several hydrologic modeling efforts have been undertaken in the Upper San Pedro, primarily to understand baseflow, surface water groundwater interactions, and impacts to streamflow from pumping and other climatic factors (Freethy, 1982; Goode and Maddock, 2000; Pool et al., 2007; Lacher, 2011; Leake and Gungle, 2012; Gungle et al., 2016; Lacher, 2018). From a natural resource economics perspective, studies have again focused on valuation of instream flows (Weber and Berrens, 2006) and recreation spending associated with birding along the river (Orr and Colby, 2002). The 2019 Audubon Arizona study found that in Cochise County, water based recreation supports 2,000 jobs, and contributed \$147 million annually to state GDP, with total output generation (including multiplier effects) of \$279 million annually. A comprehensive USGS report by Bagstad et al. (2012) uses the San Pedro as a case study to implement various methods and tools for valuation of ecosystem services provided by the river.

## 4 METHODS

In this study, an econometric approach is taken to evaluate statistically significant relationships between groundwater conditions and climatic and economic factors. A regression model is employed with a groundwater level metric used as the explanatory variable, and various climatic and economic factors used as explanatory variables. This approach seeks to highlight statistical relationships but not to establish cause and effect in relationships among variables, which in reality provide complex feedbacks to each other.

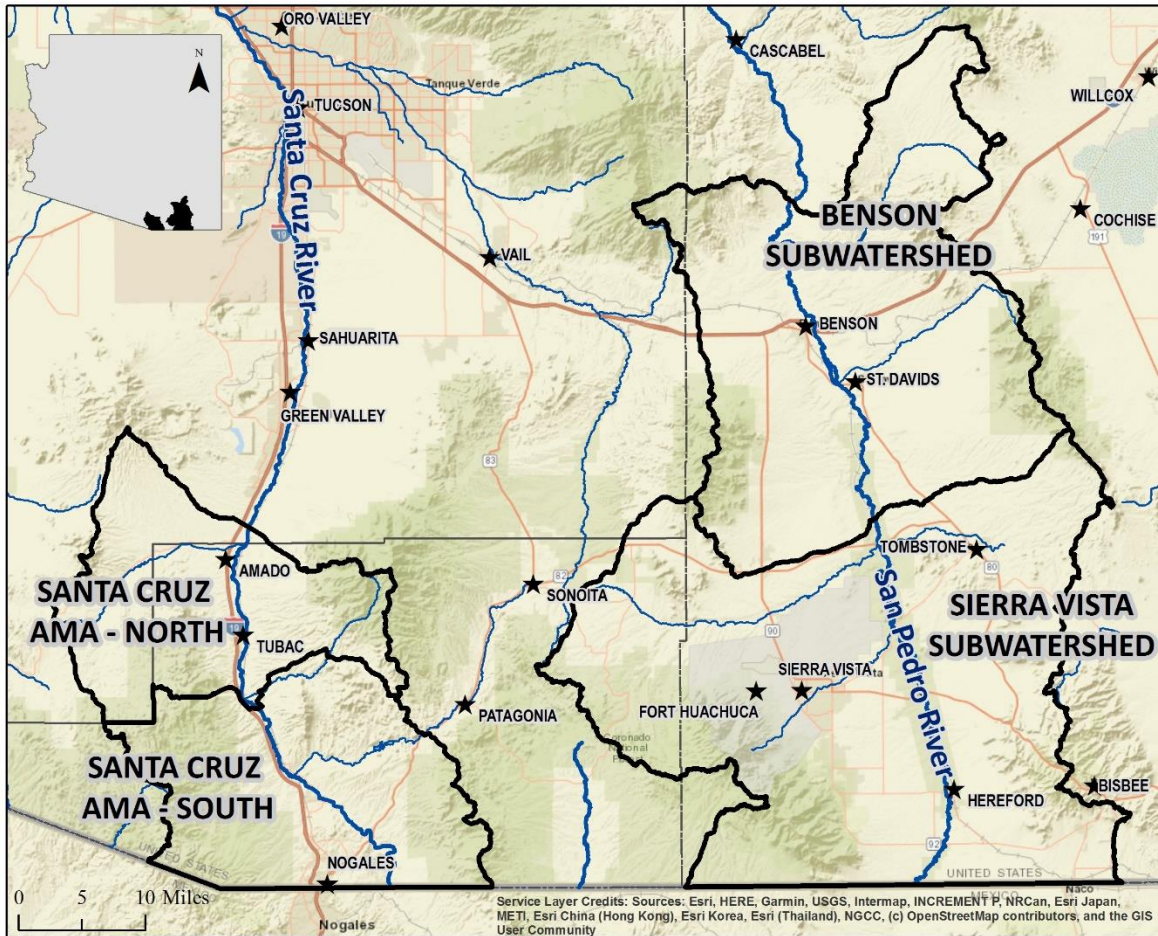
Due to limitation in the number of years for which land cover and economic data is available at the necessary spatial scale, the study area was first subdivided to increase the number of observations. The areas were subdivided to reflect uniqueness in economic profiles.

The Santa Cruz AMA was subdivided to separate the southern portion with higher population cities (Nogales and Rio Rico) from the northern portion with low population towns (Amado, Tubac). To simplify the compilation of economic data for these two areas, particularly census data, the Santa Cruz AMA was subdivided along a census tract line.

The Upper San Pedro Watershed was subdivided along a hydrologic divide to separate the Sierra Vista Subwatershed in the south from the Benson Subwatershed to the north. This division is used in several hydrologic studies, many of which focus on the Sierra Vista Subwatershed. It is also an economically convenient decision because the Sierra Vista region is influenced by economic activity of the Fort Huachuca Army base, with no comparable economic hub in the Benson Subwatershed. Additionally, the scale of agriculture is larger in the Benson Subwatershed than in the Sierra Vista Subwatershed, where much of the agricultural land has been retired.

These divisions, shown on Figure 3, resulted in four subareas with 11 years of data (2010-2020), creating 44 observations for the econometric model. It is worth noting that there is recognition that this is a limited number of observations to develop an econometric model with strong

explanatory power, but several key annual datasets only began in recent years (2008 for land cover and 2010 for annual census updates). After about a decade, we now have sufficient time series to begin to explore these data and allow for initial analyses. We acknowledge that such analyses will grow more robust as additional years of data become available to increase the number of observations in the statistical model.



**Figure 3. Four subarea divisions, Santa Cruz AMA – North, Santa Cruz AMA – South, Benson Subwatershed, and Sierra Vista Subwatershed**

For the econometric approach, subarea level fixed effect regression modeling was employed to estimate the effects of the explanatory variables on groundwater levels. A fixed effect regression is an advantageous model form to use in this case study because the subareas are hydrologically and economically heterogeneous. Depth to water is generally shallower along the Upper Santa Cruz than Upper San Pedro, and the magnitude of economic metrics such as population, housing units, planted acreage, etc., varies significantly across areas. Because we are primarily interested in investigating relationships over time within each subarea, the fixed effects regression demeans each variable at the subarea level. This demeaning is a process of subtracting the subarea mean of each variable from each observation within that subarea. This approach preserves the trend without flattening out any variability, flattening being a risk with other normalization approaches. This approach also preserves a high number of degrees of freedom, which would be

lost if subarea fixed effects had to be accounted for through use of subarea dummy variables in an Ordinary Least Squares (OLS) model.

A panel dataset was compiled on an annual temporal resolution for each subarea. While seasonal patterns are of great interest, temporal resolution is limited by the resolution of many important data sources including groundwater levels, crop acreage, and census data. The analysis period is 2010-2020, primarily determined by availability of tract level census data for the state of Arizona.

## **5 DATA SOURCES**

This section summarizes key data sources used to compile a panel dataset. Several climate and economic variables hypothesized to be statistically related to groundwater use decisions were investigated and tested during model development. Not all datasets described in this section are used in the final model.

### **5.1 Dependent Variable**

Groundwater level data was obtained from ADWR's Groundwater Site Inventory (GWSI). This state database contains field verified information for wells throughout the state, including measurements of depth to water (DTW). To transform this data into a metric to be used in statistical evaluation, an average value was calculated for each year based on DTW in wells with at least one measurement in each year of the period of interest. If wells contained multiple measurements within a year, a monthly average was calculated first, and then an annual average. Anomalous pumping water levels, indicated by a note from field staff, were excluded from the annual average measurements. Most water level measurements were taken during winter months, making the averages hydrologically comparable year to year. For the Benson Subwatershed, this process resulted in only two wells with sufficient data to meet the criteria. As a result, data for wells with only a single missing year of data was estimated based on a linear interpolation to fill the one-year data gaps in this subarea. To create the variable used in the econometric model, the average DTW was lagged by one year to represent the expected delayed physical response of groundwater levels to changes in climate or water demand. The number of wells in the average DTW calculation for each subarea is: 14 wells in the Santa Cruz AMA north and south subareas, 15 wells in the Sierra Vista Subwatershed, and 6 wells in the Benson Subwatershed. Locations of wells with sufficient data to utilize in the average DTW calculation for each subarea are shown on Figure 4.

To address the first research question regarding an annual, basin-wide groundwater metric, several approaches were conceptualized but ultimately foregone in favor of a lagged average DTW metric. Because the goal was to determine a groundwater metric representative of the subareas as a whole, analysis methods that limited the number of wells included in each subarea were not used in the final analysis. The number of wells with complete records is limited in these areas, especially in the unregulated Benson and Sierra Vista Subwatershed. It was therefore not possible to analyze deep and shallow well water level data separately, which would only leave one well to represent some entire subareas. Additionally, a groundwater level metric to represent year to year change in depth to groundwater was also calculated, but this metric resulted in excessively noisy datasets due to the variable nature of groundwater levels. This change metric

did not reflect the general trends over time and was therefore abandoned in favor of an averaged depth to water approach.

Groundwater pumping was originally planned to be used as a dependent variable in the econometric modeling. Data on annual total groundwater pumping from large capacity wells is available for the Santa Cruz AMA. It was expected that efforts to compile pumping estimates in the Upper San Pedro for previous modeling efforts would be robust enough for use in this statistical analysis (Pool et al., 2007; Lacher, 2018). However, it was found actual pumping data was only available for the municipal sector, obtained by reaching out directly to water providers. Previous modeling efforts estimated pumping data for several other key sectors, many of which were held constant for each year of the model simulation. Constant annual estimates, particularly for the agricultural sector, are not suitable for the statistical approach outlined here. Groundwater pumping was therefore not included in this analysis.

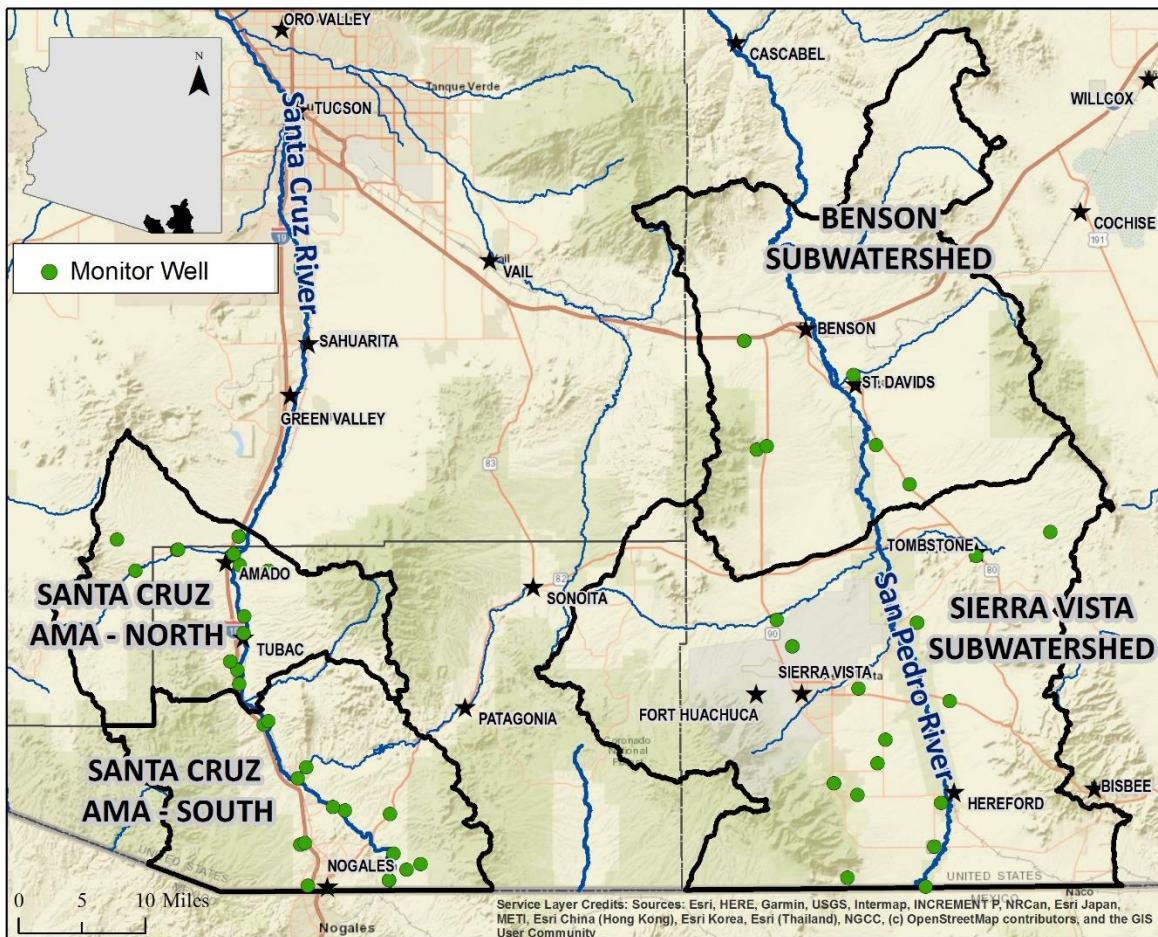


Figure 4. Locations of wells used in average depth to water calculation

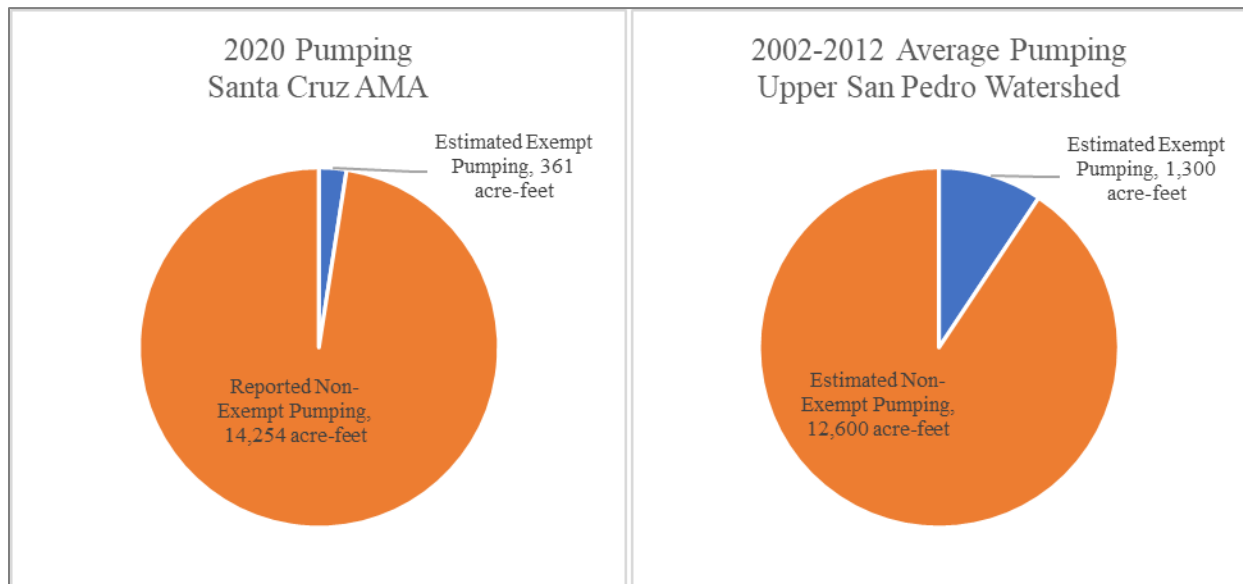
## 5.2 Explanatory Variables

### 5.2.1 Climate Variables

Mean annual precipitation and temperature were obtained from the National Oceanic and Atmospheric Administration’s Monthly U.S. Climate Gridded Dataset (NClimGrid). This resource creates a gridded product from point observations at weather stations to interpolate monthly precipitation and temperature on a 5 kilometer (km) by 5km grid cell basis. Using the Python tool Easymore (Gharari et al., 2019), a spatial average of all grid cells intersecting each subarea was calculated to develop the final metric used in the panel dataset. Analysis of precipitation and temperature separately was favored to a combined approach using an index such as the Standardized Precipitation and Evapotranspiration Index (SPEI). Precipitation and temperature act on SPEI in opposing ways, so it was considered more informative to include the variables separately in the econometric analysis.

### 5.2.2 Well Count

The ADWR’s 55 Well Registry provides an inventory of all registered wells in Arizona. In this database, the well installation date is available for most registered wells. Non-water supply wells (monitoring, cathodic protection, exploratory, grounding, etc.) were filtered out of the database and a count of the number of water supply wells in each subarea by year was used for the econometric model. Water supply wells statewide are classified as either high capacity (greater than 35 gallons per minute) non-exempt wells, or small capacity (less than 35 gallons per minute) exempt wells. A previous study estimates average rates of groundwater withdrawal from exempt wells to be 0.24 acre-feet per year, and upscales that use by 5% to account for water use inefficiencies often associated with unmetered water service (Gungle et al., 2016). This method was used to estimate exempt well pumping in both the Santa Cruz AMA and Upper San Pedro Watershed. Non-exempt well pumping is reported in the Santa Cruz AMA and estimated by Gungle et al. (2012) for the Upper San Pedro Watershed. Non-exempt wells were determined to account for over 90% of groundwater withdrawals both regions (Figure 5), therefore, only non-exempt well count was used as an explanatory variable in the econometric model.

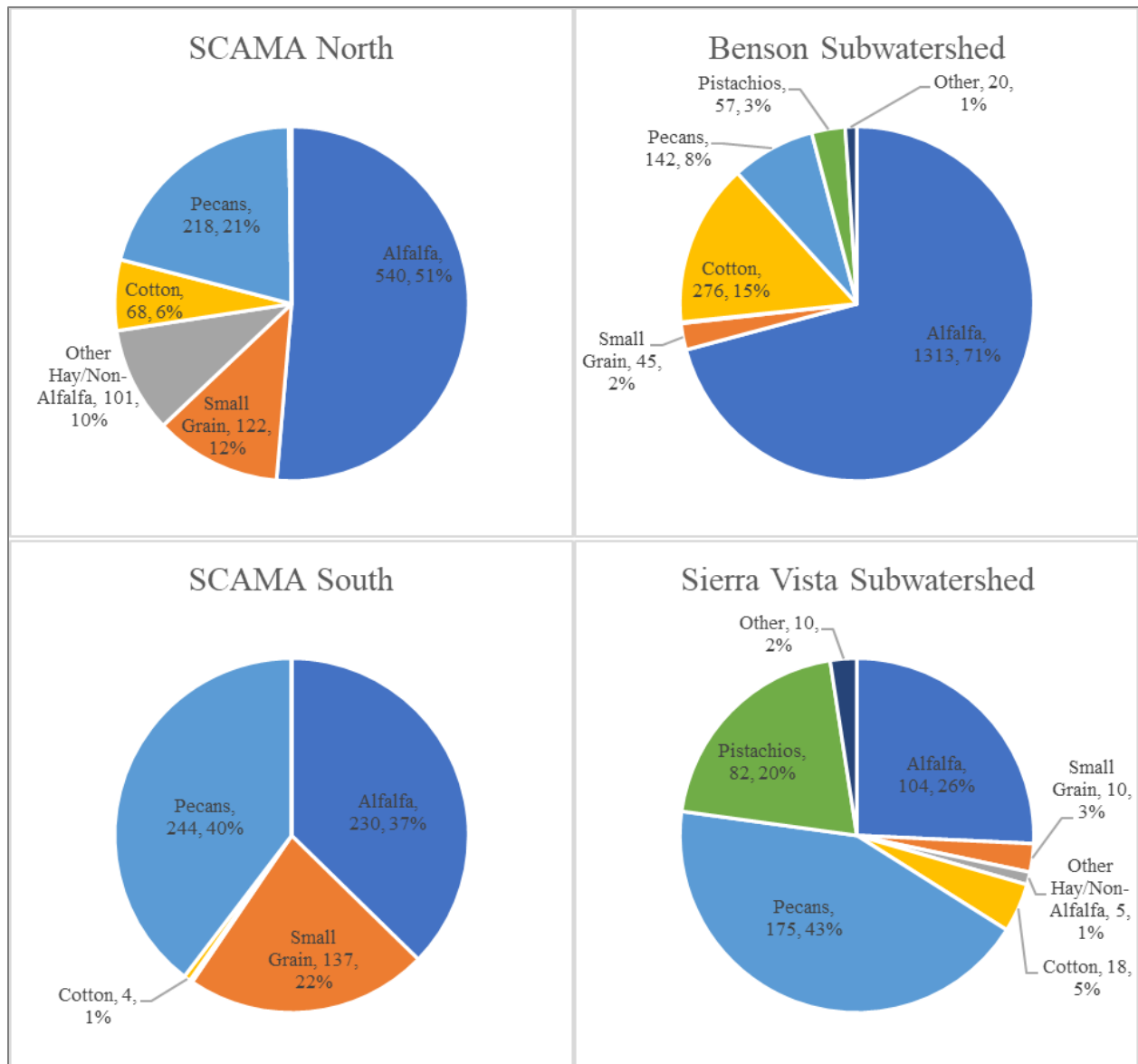


**Figure 5. Exempt and non-exempt pumping estimates**

### 5.2.3 Land Cover

Land cover data was obtained from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Cropland Data Layer, known as CropScape. CropScape is a remote sensing (satellite) data product that contains annual data for the state of Arizona beginning in 2008. The dataset consists of 900 square meter (30 meter by 30 meter) pixels of imagery that has been classified into a variety of land cover categories by processing through an image classification algorithm. With this resolution, mapping is possible at the field scale. The primary purpose of CropScape is to identify crop types (alfalfa, cotton, pecans, wheat, etc.), but every pixel is classified into a category so fallowed land, grasslands/pasture, developed land, forest, open water, and other non-crop acreage are also identified.

In the econometric model, total annual acreage of developed land, overall planted acreage, and crop specific acreage were summed within each subarea and compiled in the panel dataset. The distribution of crop types based on 2020 CropScape data for each subarea is shown on Figure 6. Changes in fallowed land and grasslands/pasture designations were conceptually acknowledged to have potential impact on groundwater demands and therefore groundwater levels, but the level of error provided by the USDA for these classifications is high. Time series data for fallowed land and grasslands/pasture in all subareas showed anomalous and unrealistic spikes in acreage, likely indicating the difficulty in image classification of these two categories in a desert landscape. Therefore, these two land cover categories were omitted from the econometric model testing.



**Figure 6. Distribution of crop types (acres and percent planted area) in each subarea based on 2020 CropScape data**

### 5.2.4 Census Data

Economic data was obtained from the American Community Survey (ACS), which publishes annual updates at the census tract scale representing 5-year moving average conditions. This data is available for the period 2010-2020 for Arizona tracts. Data on population, housing units, mean/median/per capita income, unemployment rates, and percent of people below the poverty line were all summarized on an annual basis for each subarea by selecting tracts that overlaid the major towns/cities in the subarea. These factors were compiled in the panel dataset and tested during model development. It is acknowledged that the 5-year moving average approach flattens out variability in the data, but this is the only dataset available with economic/demographic updates on an annual basis for rural areas. For metropolitan areas with population size greater

than 60,000, annual updates are available that do not employ a 5-year moving average. None of the cities/towns within the study area meet the population requirement for this dataset.

### 5.2.5 Crop Price Data

Price received per unit of crop was obtained from the USDA NASS for major crop types in the subareas, which include alfalfa, pecans, and pistachios. For alfalfa and pecans, Arizona specific prices were found. For pistachios, price received in the state of California was used because Arizona specific data is not available. For cotton, farmers often receive federal payments and anticipate prices prior to the growing season. Therefore, the future price of cotton as indicated by the New York Cotton Exchange December Futures price, issued prior to planting, was considered for the econometric model. All price variables were adjusted to reflect the real price in 2020 dollars based on the Consumer Price Index (CPI).

### 5.2.6 Energy Price Data

Average energy price information at the state/regional level was obtained from the Energy Information Administration (EIA). Due to confidentiality issues and difficulties in obtaining provider specific rates within timeline of this study, the EIA’s publicly available energy price information was compiled for the panel dataset. Annual west coast diesel and Arizona electricity price were tested during model development. Again, price variables were adjusted to reflect the real price in 2020 dollars based on the CPI.

A summary of data sources and their resolution are provided in Table 1.

**Table 1. Data Sources and Resolution**

Data Description	Source	Temporal Resolution	Spatial Resolution
Depth to groundwater	ADWR GWSI	Variable	Point
Precipitation and temperature	NOAA	Monthly	5 km x 5 km
Well count	ADWR Wells 55	Day of install	Point
Land cover	USDA NASS, CropScape	Annual	30 m x 30 m
Population, income, housing units	American Community Survey	Annual	Census tract
Crop prices (alfalfa, cotton, pecan, pistachio)	USDA NASS	Annual	State
Energy prices (diesel and electricity)	EIA	Annual	State

## 6 OVERVIEW OF DATA TRENDS

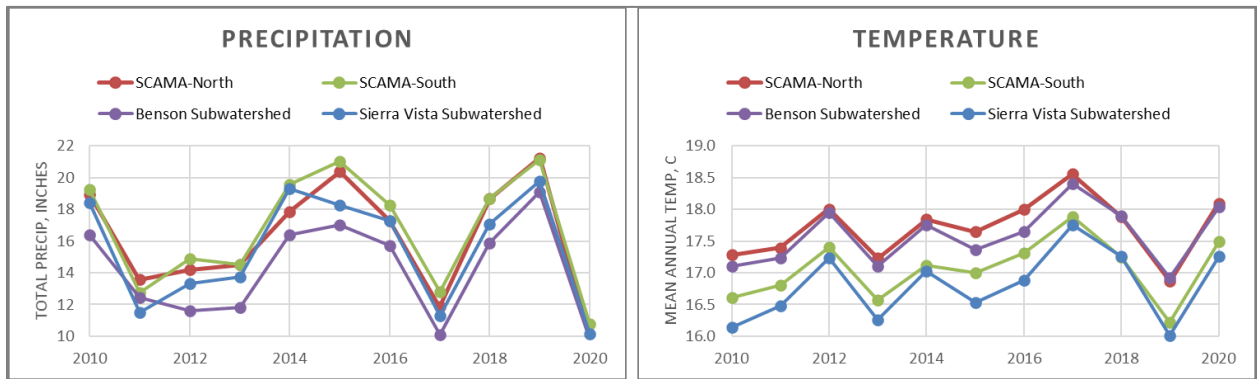
This section provides an overview of observations in key datasets for each subarea.

### 6.1 Trends across all subareas

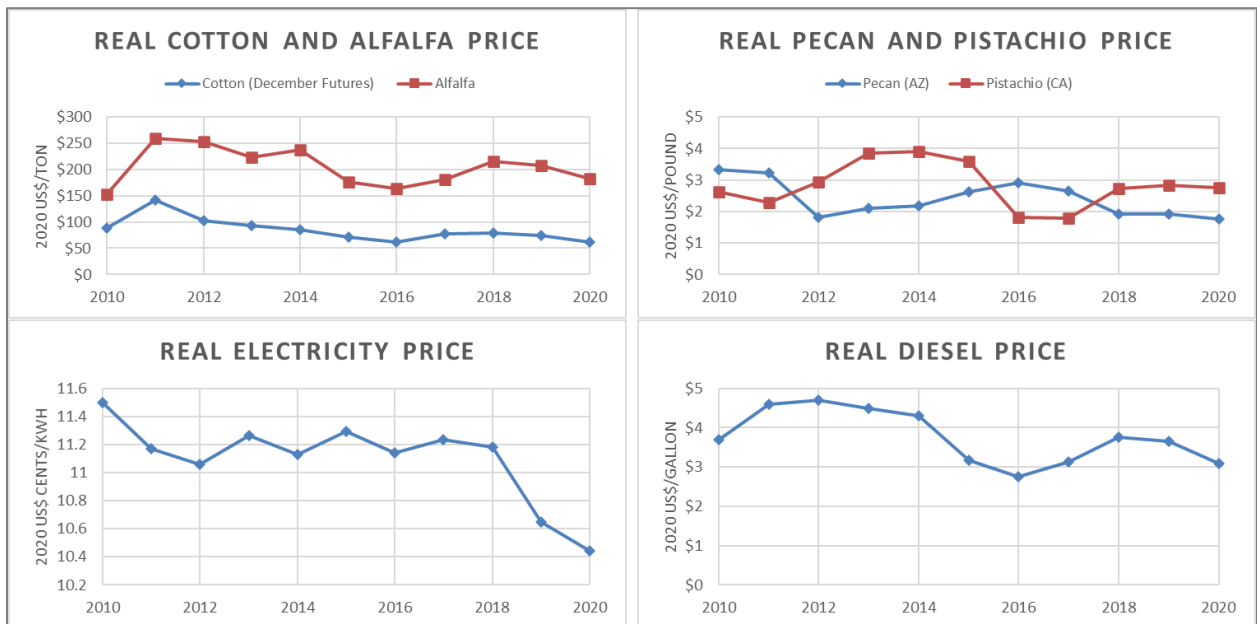
All four subareas are in close enough proximity that they experience the same climate trends in terms of annual precipitation and mean temperature, as displayed on Figure 7. All subareas

experienced the wettest years of the analysis period in 2014/2015 and 2019, and driest years in 2017 and 2020. Mean annual temperature has generally fluctuated within a 2-degree Celsius range, with maximum temperature for all subareas in 2017 and minimum in 2019.

Crop and energy price data is available at the state level resulting in these metrics being the same for each subarea, with variation only over time. All units measured in dollars are adjusted using CPI to 2020 dollars, so trends discussed here and displayed on Figure 8 reflect changes beyond inflation. Cotton and alfalfa prices peaked in 2011, with an overall declining trend thereafter. Pecan and pistachio prices show more variation over time, alternating which nut crop is higher value. Average per unit electricity costs peaked in 2010, declined dramatically in 2019 and 2020, and were relatively stable in the period between. Diesel price peaked in 2012, experienced a trough in 2015-2017, and again peaked in 2018. Electricity price may better reflect actual groundwater pumping costs, but diesel price was also considered because it is often an important input to agricultural operations.



**Figure 7. Time-series graphs for precipitation and mean temperature variables**



**Figure 8. Time series graphs for state level price variables**

## **6.2 Santa Cruz AMA – North Subarea**

Figure 9 presents a panel of time series of key datasets describing the profile of the Santa Cruz AMA – North subbasin as it relates to the econometric approach. In the Santa Cruz AMA – North subarea, although average DTW shows year to year variation during the analysis period, there is no statistically significant decreasing or increasing trend over time. This finding is consistent with the AMA’s management goal which aims to achieve stable groundwater levels. For three of the AMAs, (Prescott, Phoenix, and Tucson), the management goal is to achieve safe yield, which is a long-term balance between groundwater recharge and withdrawal on an AMA wide basis. The Santa Cruz AMA is unique in that its goal is maintain, rather than achieve, safe yield, and also to “prevent local water tables from experiencing long-term declines,” introducing a groundwater level component to its overall goals (ADWR, 2020).

Very few additional non-exempt wells were installed during the analysis period. Housing units and population in the subarea generally increased through 2016, with slight decreases thereafter. Overall population is very low, peaking under 3,000. Real per capita income, measured in inflation adjusted decreased through 2014 then increased through 2018.

Developed acreage in the subarea has generally increased over time, while overall planted acreage has remained fairly stable, except in early years. High variation in 2010 and 2011 CropScope data is reflected in acreage of individual crop types (alfalfa, cotton, and nut crops). The dramatic increase in acreage from 2010 to 2011 could be due to issues with the satellite imagery those years.

## **6.3 Santa Cruz AMA – South Subarea**

Figure 10 presents a panel of time series graphs of the Santa Cruz AMA – South subarea. The profile in the southern subarea is similar to the northern subarea, with the main difference being population size and trend. Overall population is much larger, over 40,000, but has decreased over time through 2016. Housing units remained stable through 2016 and then increased, which coupled with the population trends potentially indicates development of new subdivisions that have not yet been sold. Per capita income has an increasing trend over all, which is also a departure from observations to the north. The southern subarea has two relatively large cities, Nogales and Rio Rico, the economy of which dominate the subareas profile. No comparable economic hubs exist in the northern subarea, which likely has a proportionately larger retirement population.

## **6.4 Benson Subwatershed Subarea**

Figure 11 presents a panel of time series graphs for the Benson Subwatershed subarea. The Benson Subwatershed exhibits an overall declining trend in average DTW. This trend is statistically significant at the 95% significant level using the Mann-Kendall trend test. The declining trend is supported by recent groundwater level monitoring results released by ADWR (2021) for the Upper San Pedro Basin. The number and rate of installation of non-exempt wells is higher in the Benson Subwatershed than in either subarea of the Santa Cruz AMA.

The overall population trend in the subarea is declining with housing units showing unexpected variability, possibly a data anomaly. Real per capita income increased starting in 2014. Developed acreage has increased, as has alfalfa acreage, which is the dominant crop type in the subarea.

## **6.5 Sierra Vista Subwatershed Subarea**

Finally, Figure 12 present a panel of time series graphs for the Sierra Vista Subwatershed subbasin. The Sierra Vista Subwatershed also exhibits a statistically significant declining trend in average DTW, based on the Mann-Kendall trend test at 95% significance level. The number and rate of installation of non-exempt wells is similar to that of the Benson Subwatershed.

The number of housing units in the subarea grew steadily through 2016 and flattened out afterward, while population exhibits unexpected variability. Real per capita income has a general increasing trend, but to a slightly lesser extent than the Benson Subwatershed. Developed acreage, as in the other subareas, has increased over time. Planted acreage is overall lower than in the Benson Subwatershed, likely due to retirement of much of the larger agricultural operations in recent years (Richter, 2022). Anomalously high 2012 cotton acreage and 2014 nut crop acreage are likely a result of satellite image classification error.

## **6.6 Overall Observations**

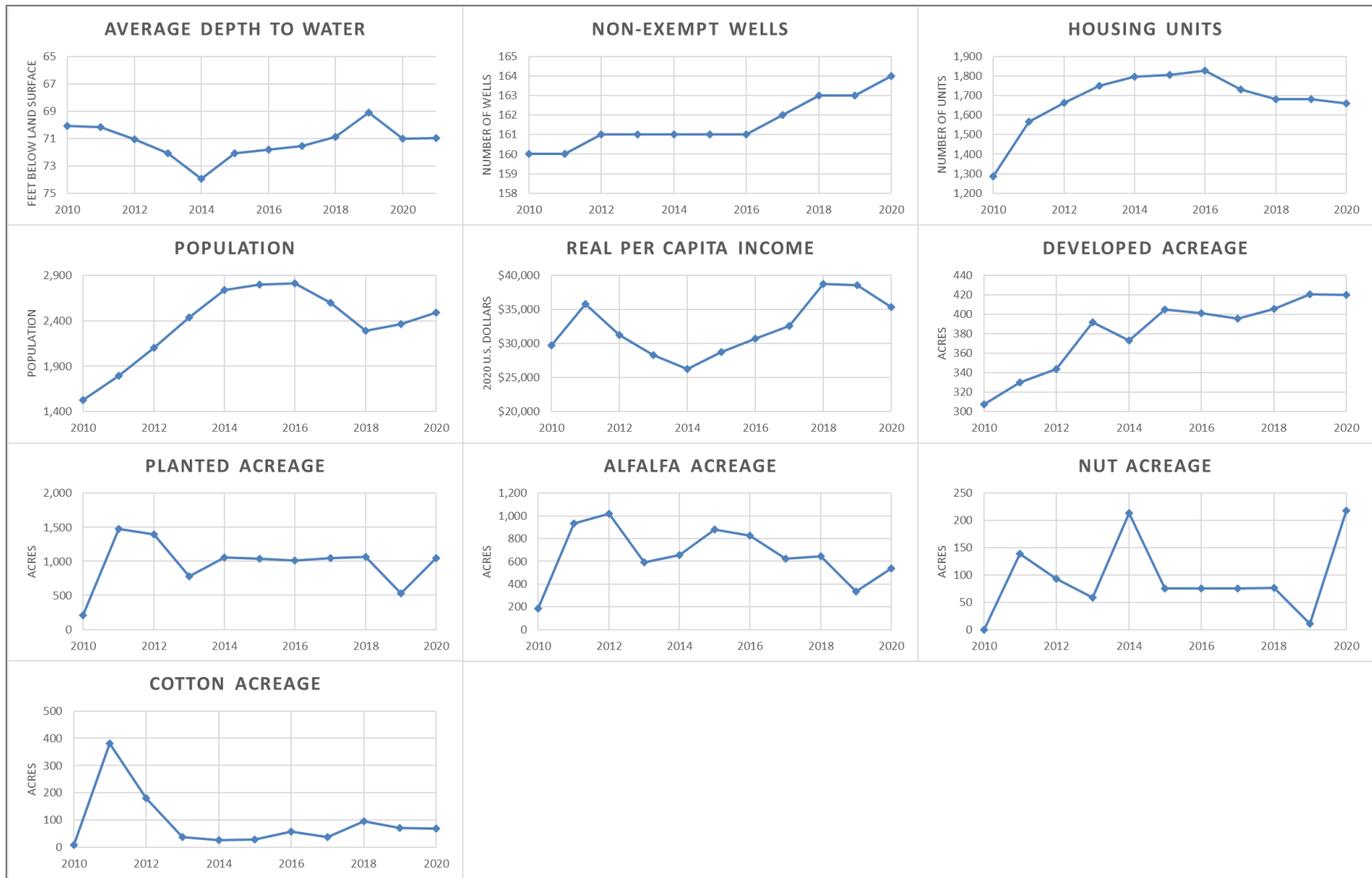
A few key observations stand out when examining trends across all subareas. First, declining water level trends are observed in the two subareas where groundwater use is unregulated and not reported. Second, these unregulated areas also have greater rates of new non-exempt (large capacity) well installation. Third, all subareas show clear increases in developed acreage over time. Finally, only the Benson Subwatershed exhibits any clear trend in planted acreage, specifically alfalfa. This could be due to regulations on agricultural expansion in the Santa Cruz AMA, and also due to CropScope accuracy for these regions.

## **6.7 Data Challenges**

The data compilation and review process highlighted several challenges in pursuing economic analysis in small, rural areas. Several datasets show anomalous variations at a small scale that are likely smoothed when analyzing data on a state, regional, or national level. For example, at the tract level, the Benson Subwatershed shows unrealistic peaks and valleys in housing unit count, and the Sierra Vista shows unrealistic peaks and valleys in population count. Additionally, early years of land cover data show unrealistic peaks and valleys in all subareas. An example is the peak in cotton acreage in the Sierra Vista Subwatershed in 2011. Not utilizing these data sources would severely limit the scope of this analysis, but some degree of error and inconsistency is recognized.

Variable trends in several of these key metrics, which have potentially opposing consequences for groundwater use, demonstrate the difficulty in using a simple trend or correlation approach to establish relationships. It is advantageous to use an econometric approach in which we not only determine whether two given metrics are increasing or decreasing simultaneously (or

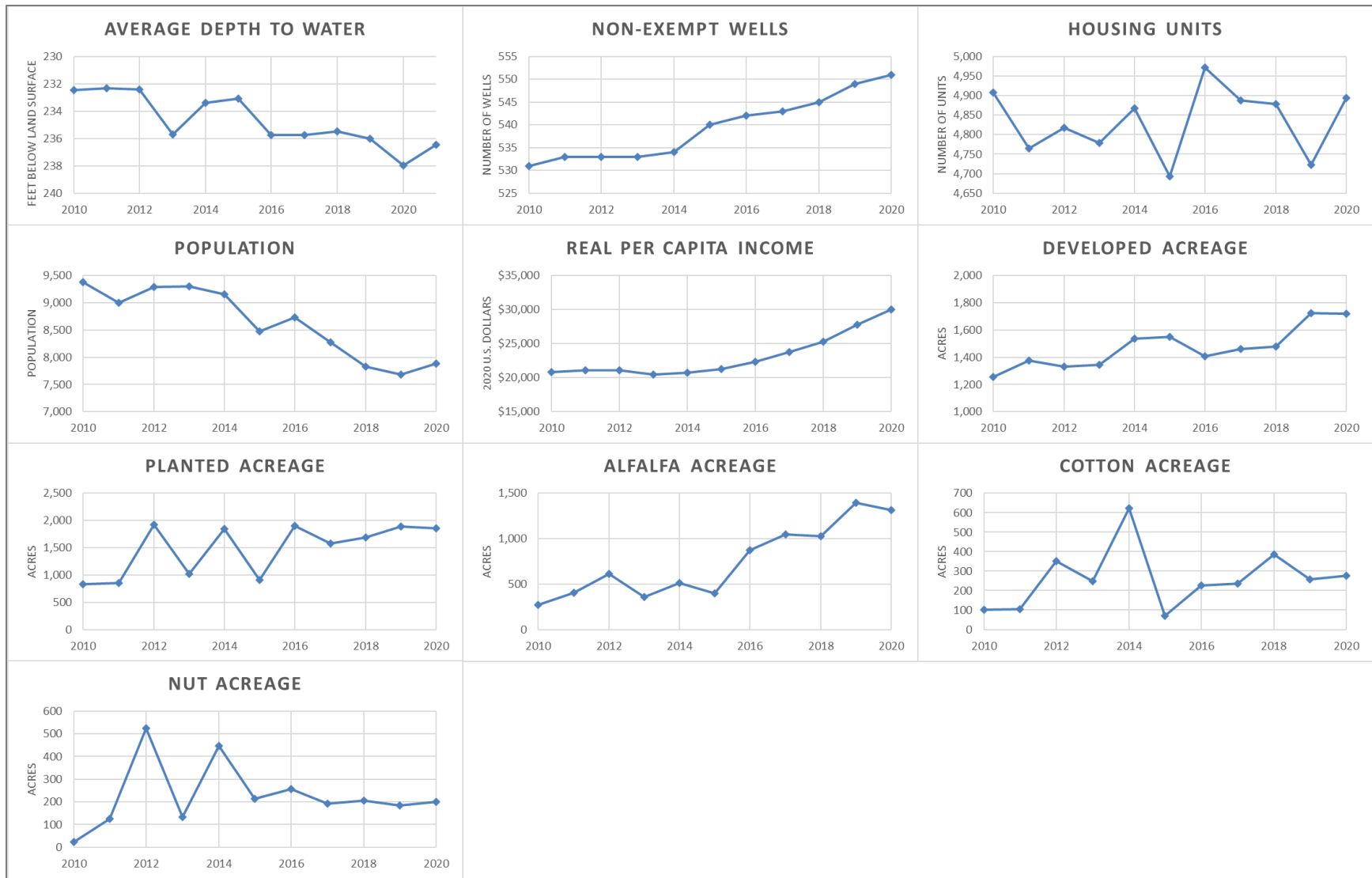
opposingly), we ask instead what linear combination of metrics best matches our observed data. In the absence of a dynamic systems model, this statistical approach attempts to capture some of the dynamic relationships.



**Figure 9. Panel of time series graphs for Santa Cruz AMA – North subarea**



**Figure 10. Panel of time series graphs for Santa Cruz AMA – South subarea**



**Figure 11. Panel of time series graphs for Benson Subwatershed subarea**



**Figure 12. Panel of time series graphs for Sierra Vista Subwatershed subarea**

## 7 ECONOMETRIC MODEL AND RESULTS

Due to correlation between some of the variables described in the Data section of this report, not all the variables assembled in the panel dataset could be used as explanatory variables in the same regression model. After testing several combinations of explanatory variables, the regression with the most interesting results about relationships among variables and with reasonable explanatory power was selected as the final model being presented here.

The fixed effects regression model is specified as:

$$DTW_{it+1} = \beta_0 + \beta_1 Precip_{it} + \beta_2 Temp_{it} + \beta_3 NonEx_{it} + \beta_4 House_{it} + \beta_5 PerCapInc_{it} + \beta_6 Plant_{it}$$

Model components are as follows:

- $DTW_{it+1}$  is average depth to water in subarea  $i$  in time  $t+1$ , which is one time step lagged from the explanatory variable observations
- $\beta_0$  is the constant and  $\beta_{1,2,3,4,5,6}$  are variable coefficients
- $Precip_{it}$  is total annual precipitation in subarea  $i$  in time  $t$
- $Temp_{it}$  is mean annual temperature in subarea  $i$  in time  $t$
- $NonEx_{it}$  is a count of non-exempt wells in subarea  $i$  in time  $t$
- $House_{it}$  is a count of housing units in subarea  $i$  in time  $t$
- $PerCapInc_{it}$  is the per capita income in subarea  $i$  in time  $t$
- $Plant_{it}$  is the planted acreage in subarea  $i$  in time  $t$

The model was tested for heteroskedasticity, which refers to unequal scatter of residuals, likely a result of time dependent variance in some model variables. The modified Wald test is employed to test for groupwise heteroskedasticity in the fixed effects model. Results show a p-value below the 0.01 threshold for assuming heteroskedasticity. These results, in combination with the fact that CropScape’s land cover data for planted acreage appear to have higher variability in early years, prompts use of robust standard errors in the fixed-effects model. Similar conclusions regarding heteroskedasticity are found by McGreal (2021) in a similar econometric analysis in central Arizona, with robust standard errors employed in that case as well. Model results are summarized in Table 2, and Stata code for the model and heteroskedasticity testing are provided in Appendix II.

The fixed-effects model reports both “ $R^2$  within” and “ $R^2$  between”. The  $R^2$  within indicates how much variation in the dependent variable over time within each subarea is accounted for by the model. The  $R^2$  between indicates how much variation in the dependent variable between each subarea is accounted for by the model. This is accomplished by calculating the average values of the dependent and independent variables within each subarea, which eliminates the time component. For this study, the goodness of fit metric of primary importance is  $R^2$  within, because we are interested in responsiveness of groundwater conditions to variations in climate and economic factors over time.

**Table 2. Fixed-effects model results for lagged average depth to water**

	<b>Average Depth to Water lagged by 1 year</b>
$R^2$ within	0.512
$R^2$ between	0.723
$n$	44
Precipitation	-0.170 (0.0890)
Temperature	-1.620 (0.785)
Non-exempt wells	0.259*** (0.0249)
Housing units	0.000997** (0.000211)
Per capita income	-0.000280** (0.0000487)
Planted acreage	0.00135** (0.000391)
Constant	68.96** (16.04)

Table reports coefficient, robust standard errors in parentheses

\*\*\* indicates  $p < 0.01$  (coefficient is significant with 99% confidence)

\*\* indicates  $p < 0.05$  (coefficient is significant with 95% confidence)

\* indicates  $p < 0.1$  (coefficient is significant with 90% confidence)

The  $R^2$  within value of 0.51 is within an expected range for econometric models examining phenomena across both time and space, especially with limited number of observations. Such models often have lower  $R^2$  values than are expected in a “good” quantitative analysis of physical data in hydrology. Unlike in hydrology, there are no physics-based laws governing underlying equations in econometrics, so the  $R^2$  value of an econometric model reflects some of the inherent uncertainties in analyzing human systems governed by economic choices.

To address the second research question regarding identification of climatic and economic factors related to groundwater levels, statistically significant coefficients are present on the non-exempt well, housing units, per capita income, and planted acreage variables, with significance level ranging from 95% to 99% (Table 2). The non-exempt well variable carries the largest coefficient of 0.21, while coefficients on the other significant variables are smaller in magnitude. Three of the statistically significant coefficients carry positive signs, indicating an increase in the explanatory variable is correlated with an increase in (meaning deeper) average DTW within each subarea. One of the statistically significant coefficients carries a negative sign, indicating an increase in the explanatory variable is correlated with a decrease (meaning shallower) average DTW. We will interpret increase in depth to water to imply increase in groundwater extraction, given all subareas are groundwater dependent. Although these results only demonstrate statistical relationships and not causal effects, the coefficient signs can be interpreted with physical and economic context to prompt future research.

The positive sign of the coefficient on non-exempt wells is intuitive, as an increase in the number of pumping wells withdrawing groundwater presumably means an increase in the total volume of groundwater withdrawn in the subarea, which would lower water levels by the following year. Because the coefficient on non-exempt well variable is the largest of the statistically significant coefficients, separate testing was performed to explore drivers of well installation. Table 3 presents the results of the fixed-effects regression with non-exempt well count as the dependent variable, and population, developed acreage, and planted acreage as explanatory variables. The only statistically significant coefficient in the model is for developed acreage, significant at the 95% level. This result indicates developed acreage may be a more significant driver of groundwater level (and therefore groundwater use) changes in these rural areas than agriculture.

**Table 3. Fixed-effects model results for non-exempt well installation**

	<b>Non-Exempt Well Count</b>
$R^2$ within	0.523
$R^2$ between	0.0575
$n$	44
Population	-0.00350 (0.00233)
Developed Acreage	0.00222** (0.000384)
Planted Acreage	0.00343 (0.00148)
Constant	437.6*** (67.97)

Table reports coefficient, robust standard errors in parentheses

\*\*\* indicates  $p < 0.01$  (coefficient is significant with 99% confidence)

\*\* indicates  $p < 0.05$  (coefficient is significant with 95% confidence)

\* indicates  $p < 0.1$  (coefficient is significant with 90% confidence)

Back to the original model (Table 2), the positive sign of the housing unit coefficient indicates an increase in housing developments is related to increased water use and therefore lower water levels. If we interpret an increase in housing units to imply an increase in population, the result is inconsistent with trends established in urban areas of decoupled population growth and water demand. However, the subarea level does not always demonstrate a clear relationship with housing units and population. The Santa Cruz AMA – North being the only subarea for which housing unit and population data exhibits the same, increasing trend. In the Santa Cruz – AMA south, trends are opposing, and in the Benson and Sierra Vista Subwatersheds, data shows high variability.

The negative coefficient sign on per capita income is initially counterintuitive. The result indicates increased income is correlated with shallower depth to water, which we assume implies less groundwater use. Higher household income is generally thought to be related to increased water demand due to higher income families consuming more water through landscape choices,

pools, and/or higher indoor water use. The results of this analysis indicate those relationships may not be true in rural areas. It is possible that in rural areas, higher-income households could generally own newer homes with less pasture and more efficient appliances than traditional rural households that may be also be older, higher water use homes.

The positive coefficient sign on planted acreage is also intuitive, as almost all agricultural land in Arizona is irrigated and these subareas rely on groundwater for irrigation. This is especially true because the dominant crops in the subareas include alfalfa, cotton, pecans, and pistachios, all relatively high water use crops. This result may be dominated by data in the Benson Subwatershed.

Climate variables - precipitation and temperature - were not found to be statistically significant. This result was anticipated by experts interviewed who hypothesized that in systems with high degrees of groundwater use, human impacts on groundwater conditions could obscure climate signals in observed data. It is hypothesized that climate variables may be statistically related to groundwater conditions at the seasonal level, especially when large summer and fall/winter storms results in large streamflow events.

Crop and energy price variables were tested in various regressions but were also found not to be significant. Due to the large number of price variables (alfalfa, cotton, pecan, pistachio, electricity, natural gas, diesel), the metrics were omitted from the final model to prevent artificial impacts to the  $R^2$  value. This result is supported by previous studies demonstrating the price inelasticity of irrigation water application rates.

To address the third research question regarding key observations within and outside of regulated areas, distinct differences are noted in depth to water and well installation trends over the analysis period. We observe declining average DTW trends in subareas outside of AMAs (Benson Subwatershed and Sierra Vista Subwatershed), and no significant trend within the Santa Cruz AMA subareas. We also observe greater number of non-exempt wells installed in subareas outside the AMAs. These results are consistent with the regulatory restrictions in the AMAs. Non-exempt wells within AMAs must withdraw water pursuant to a groundwater right, which limits the opportunity for new large-capacity wells. Additionally, regulations prevent expansion of irrigated agriculture beyond the footprint present when the 1980 Groundwater Management Act was established. It is therefore not surprising that the only overall increasing agriculture trend exists for alfalfa in the Benson Subwatershed. Variations in planted acreage in the AMA subareas likely represent variations in actively planted acreage, as opposed to new fields being developed on previously non-agricultural land.

Separate econometric modeling for AMA versus non-AMA subareas was not possible due to the limitation that would place on number of observations, but future research could expand on this approach given additional years of data or inclusion of other AMAs and unregulated portions of the State. It is not clear, however, whether the Santa Cruz AMA would be comparable to the other AMAs due to the highly urbanized nature of the Phoenix, Pinal, and Tucson AMAs. The

Prescott AMA could be comparable in rural nature, although Prescott also has access to surface water supplies which complicates the analysis.

## **8 CONCLUSIONS AND POLICY IMPLICATIONS**

In the absence of water use data in much of the world, especially rural areas, this study aims to explore signals of economic variables in a basin-wide groundwater level metric developed in southern Arizona. This is a unique approach as much of the previous work that has developed our understanding of the relationship between groundwater use decisions, irrigated agriculture, and municipal growth has utilized water use data. Though we acknowledge limitations in the time period of data availability, as well as potential error in landcover and economic datasets on a small spatial scale, initial statistical testing on available datasets can provide useful starting point for future research. We aimed to develop an econometric model with a groundwater level metric as the dependent variable, and various economic and climatic factors as explanatory variables to test for statistically significant coefficients.

With a focus on the upper portions of the Santa Cruz and San Pedro watersheds to serve as a case study for this rural investigation, we divided the study area into four subareas based on a combination of regulatory, economic, and hydrologic boundaries. This collection of boundaries can seem strange for a hydrologic investigation but highlights the need to employ unconventional approaches when incorporating human influences in a hydrologic study.

After exploring some of the challenges of working with groundwater level data, both in terms of interannual variability and limited number of wells, we found the most appropriate basin-wide groundwater level metric to be average depth to water in wells with a complete record for the period 2011-2021. In the econometric model, the average DTW metric is lagged by one year to account for the expected delayed hydrologic response of water levels in the aquifer to external influences. Estimates of groundwater pumping outside of the AMA were found to be not suitable for this statistical analysis due to pumping from certain sectors being held constant year to year.

A large panel dataset was then compiled with a host of climate (precipitation, temperature) and economic (well installations, population, housing units, income, developed acreage, planted acreage, crop prices, energy prices) variables for the period 2010-2020. Data processing highlighted the uncertainty exposed in some economic datasets when parsed out at small scales. Planted acreage in particular showed higher variability in early years. In some subareas, housing units or population also displayed unexpected variability. To account for the difference in magnitude across spatial scale as well as high, potentially time-dependent variability in some explanatory variables, a fixed-effect regression model with robust standard errors is employed.

Model results show statistically significant coefficients on non-exempt wells (99% confidence level), housing units (95% confidence level), per capita income (95% confidence level), and planted acreage (95% confidence level). The largest coefficient is on the non-exempt well count variable. Further econometric testing shows well installation is most strongly related to developed acreage. Climate variables (precipitation and temperature), crop prices, and energy prices were not found to be statistically significant in relation to average DTW.

Average DTW exhibited an overall declining trend in both subareas outside the AMA while the subareas within the Santa Cruz AMA did not show declining trends. Additionally, unregulated areas show higher rates of non-exempt well installation, and the Benson Subwatershed shows an increasing trend in planted acreage driven by alfalfa. These observations are consistent with expected impacts of regulation, which in the AMA prevents pumping from non-exempt wells without a permit, prevents expansion of irrigated agriculture, and has a management goal that includes preventing long-term declines in groundwater levels. Due to limited number of observations, additional study areas or years of data are needed to run statistical models of regulated and unregulated areas separately.

In terms of policy implications, results of the statistical modeling and data overviews shed light on options for local, targeted water management. It appears that price signals in the form of crop or energy prices have little impact on water use decisions, based on both prior research and results of this study. This may be due to the small-scale type of agriculture in these areas, and may not hold true where large commercial agriculture is the predominant water use.

These results do suggest that regulations on well installations can be a valuable tool in managing groundwater withdrawal and impacts to water tables, evidenced both by model results and observations in the Santa Cruz AMA subareas where such regulations exist. Under ADWR's regulations, a well permit is generally only required for non-exempt wells drilled within the AMAs, with few exceptions outside the AMAs. Well spacing rules also generally only apply within the AMAs (ADWRa, n.d.). In these rural areas, municipal and agricultural sectors both pose comparable demands for groundwater. Under these conditions, development may be driving the installation of new large capacity wells, so it is important to further explore the relationship between developed acreage and groundwater conditions as large new developments are proposed in these areas. This is different from areas in which agriculture is the predominant water use, which is the case for many other rural areas in other parts of the world.

Overall, use of a groundwater level metric to explore signals from economic metrics shows promising results but is currently greatly limited by time period of data availability and lack of seasonal data. Several key datasets, including land cover and tract level census data, are just beginning to have long enough time series to develop statistical models. Such analysis will become more robust as additional years of data become available.

## **9 FUTURE RESEARCH**

Due to the scope and timeframe of this masters thesis, several interesting topics were not further explored in this research but could provide basis for future work. In terms of methodology, the relationships examined in this study could be further tested using a hydroeconomic-modeling approach. However, is it difficult to simulate and define algorithms for all the dynamic feedbacks between hydrologic and economic factors. A machine learning approach could be valuable to explore, as this method can take advantage of a large variety of observations without needing to specify relationships. As additional data is made available, machine learning can also adapt to evaluate relationships without the need for a researcher to manually specify a new regression model form. Further research could also explore non-linear relationships between groundwater

level metric and the climatic and economic variables posed in this study. Finally, in terms of methodology, within the AMA, a water use model could also be developed using non-exempt well pumping data to determine whether the results of the groundwater level model are reflective of signals of economic factors in water use decisions.

This study performed a preliminary investigation into the drivers of well installation, but the topic could be explored in further detail. Developed acreage was most closely correlated with well installation, but in the main econometric model, housing units were found to be more closely related with the DTW metric than developed acreage. Developed acreage and housing units are related so connections and uncertainties in these datasets should be further explored.

As discussed, the annual temporal scale of this analysis was limited by current datasets, but seasonality is of great interest. Seasonal data is limited in groundwater level measurements and is not available in the land cover and economic datasets we used. Satellite data on groundwater storage (monthly GRACE data) provides a possibility for a monthly dependent variable metric. Methods to estimate seasonal variations in population and land cover should be investigated, given current government datasets are updated annually.

If seasonality is explored, the impact of summer monsoons, fall hurricanes, and winter rains on groundwater recharge and levels would be of great interest. Data collected annually on wet/dry mapping of the San Pedro as well as maximum length of flow of effluent from the Nogales International Wastewater Treatment Plant could also be interesting to incorporate into statistical analysis. For this annual study, peaks in streamflow were conceptualized to be reflected in precipitation data, so only mean annual precipitation was incorporated into the panel dataset. Finally, with respect to temporal resolution, a one-year lag was employed in this analysis, but further testing of lag times could be valuable. It is especially interesting to explore the impact of extremely large flood events, and potentially employ a weighting scheme to account for groundwater conditions in the number of years since a large recharge event.

The increasing trend of alfalfa acreage in the Benson Subwatershed is an interesting observation to explore in future study. Non-governmental organizations (NGOs) have had active efforts in the Sierra Vista Subwatershed to retire agricultural land for conservation efforts. Activity of NGOs or local organizations in the Benson Subwatershed is not widely known and could be further investigated. Additionally, drivers of alfalfa growth in this subarea were not investigated. Possible drivers include expansion of existing farms, new operations, or relocation of operations from other areas. Potential drivers of relocation include lowering groundwater levels in other areas, pressures on surface water supplies in central Arizona, or groundwater regulations in AMAs. The Benson Subwatershed also contains the two remaining surface water diversions from the San Pedro River, the St. David Ditch and Pomerene Canal. Though water from these diversions is primarily used for irrigation of pasture, irrigation of alfalfa and small grains also occurs (Lacher, 1994). The extent to which surface water use accounts for irrigation of the increasing alfalfa acreage in the Subwatershed was not explored in this study.

## 10 APPENDIX I: TUCSON AMA SUBAREA OVERVIEW

A small portion of the Tucson AMA, also within the Santa Cruz River Watershed, was originally considered for inclusion as a fifth subarea in the econometric analysis. The area is bounded by the Santa Cruz AMA to the south and was artificially cutoff at Pima Mine Road to the north (Figure 13). The northern boundary was set to capture the full extent of the large pecan orchard in Green Valley, but to avoid extending into the Tucson metropolitan area. This delineation maintained the “rural” identity for the subarea. However, presence of a large mining operation and inconsistent water level trends resulted in this subarea ultimately being excluded from the analysis. Given the small size of the panel dataset, extremes in the Tucson AMA-Green Valley subarea dominated the regression results when this subarea was included. Nevertheless, this is an interesting subarea and some observations from data compilation efforts for the study are included here.

Depth to water trends in this subarea vary spatially to a greater degree than observed in other subbasins. Figure 14 shows hydrographs for wells in the northern portion of the subarea, 1-4 miles east of the pecan orchard. These wells exhibit relatively stable depth to water trends over time, and even one well that shows recovery in the early period. Figure 15 shows hydrographs for wells located in the southernmost portion of the subarea, which have a strong declining trend through 2014, and dampened recovery trend thereafter. When DTW for wells with sufficient data was averaged, the trend in the south dominated the final average DTW. This declining and recovery trend is inconsistent with the explanatory variables assembled for analysis, particularly planted acreage which has stayed constant in this subarea (pecan orchard was detected by CropScape to be approximately 5,000 acres).

Irrigation water for the pecan orchard was historically supplied by groundwater. Farmers Investment Co (FICO), which owns the orchard, recently jointly funded a pipeline to deliver CAP water to the orchard, with construction completed in 2020. Until this time, groundwater was the primary source of irrigation to the fields. The stable water levels near the farm were initially surprising for this reason. However, a state permitted recharge facility exists at Pima Mine Road, which likely contributes to the water level stability

The drawdown and recovery trend in the southern portion of the subarea is likely related to groundwater pumping for mining operations. Initial review of overall pumping by sector for the entire subarea showed slight decrease in pumping starting in 2014 (Figure 16). Further investigation into non-exempt wells in close proximity to the southern portion of the subarea revealed that in this area, mining-related pumping dramatically decreased beginning in 2014 (Figure 16). The localized water level drawdown and recovery trend is responding to this change in pumping. The large Sierrita Mine is located within this subarea and specific operational decisions resulting in the decline in pumping are not known. Though world copper and molybdenum prices experienced declining trends during this time period, the onset of the price declines do not coincide with the timing of declines in pumping. It is possible the effect was delayed, or operational decisions resulted in movement of the locations of pumping. A review of

news sources from the time period shows considerations for mine closure in 2015, but those plans were ultimately delayed, and the mine continues operation.

These significant differences in water level trends, mining activity, agricultural activity, and therefore overall economic drivers, presented challenges when trying to fit this subarea into a model with rural economic drivers in mind. The scale of economic activity in this small area is more comparable to central Arizona than rural, southeastern Arizona towns. To perform a similar econometric analysis with this subarea, additional economic metric relevant to mining in particular must be incorporated.

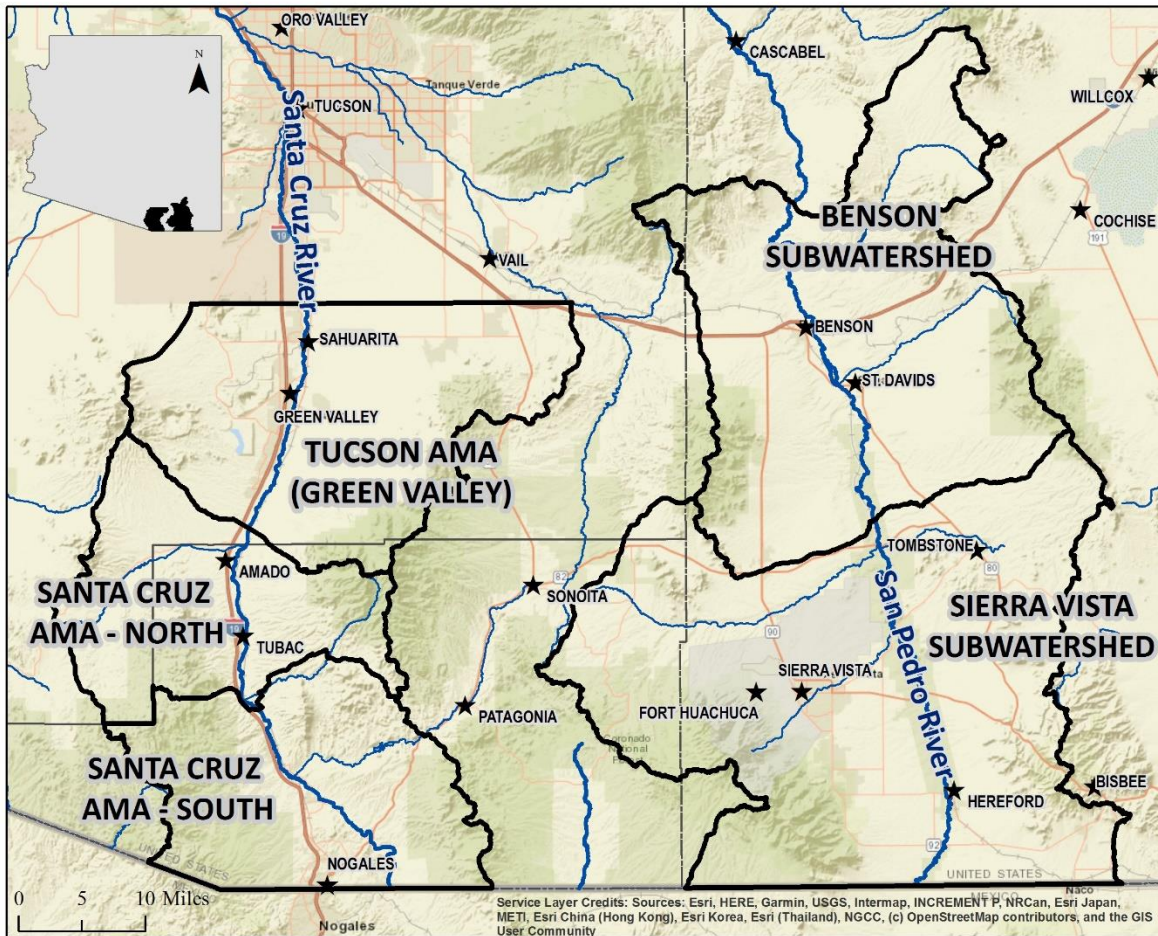


Figure 13. Map of subareas including proposed Tucson AMA – Green Valley subarea

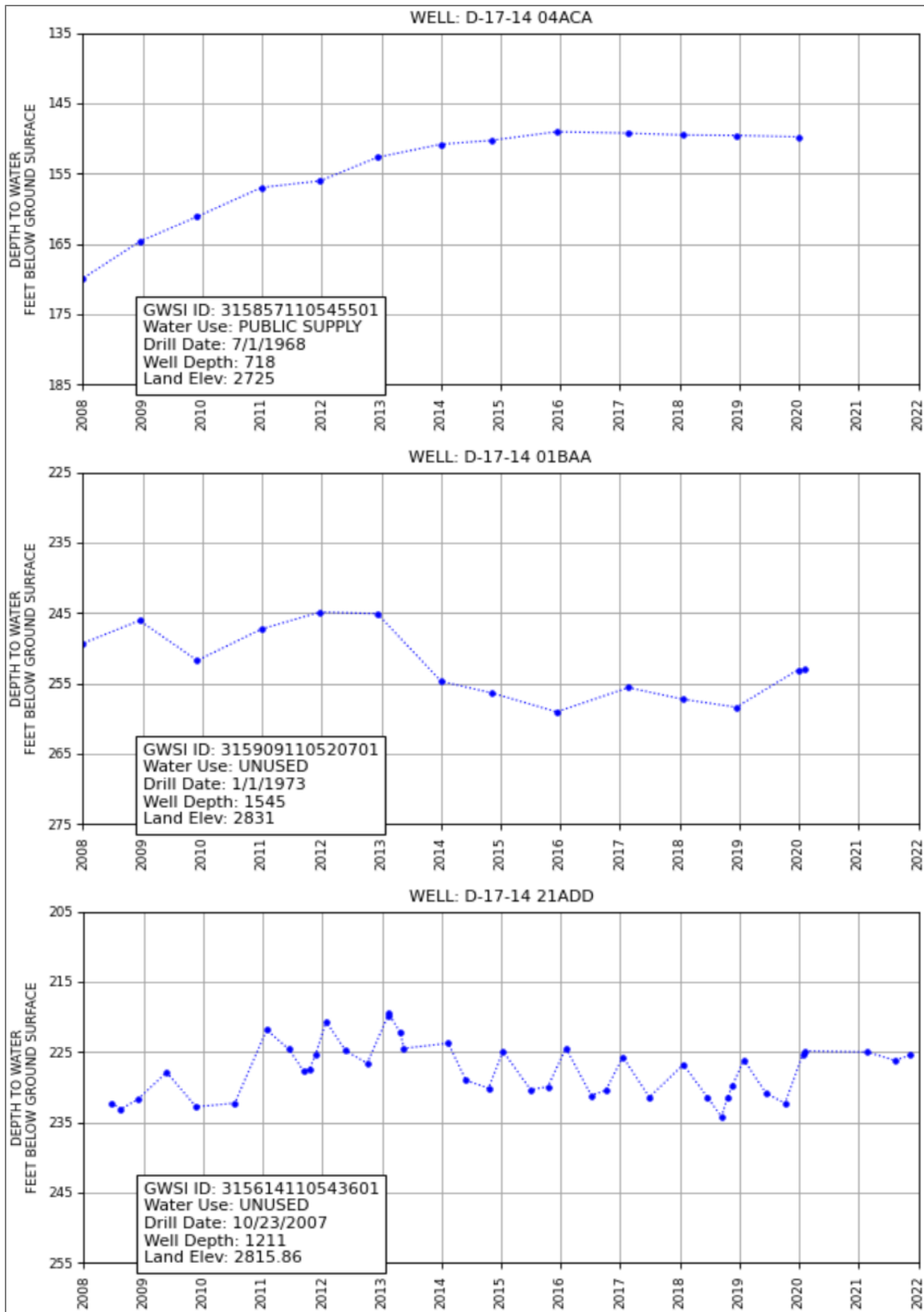


Figure 14. Depth to water in a wells 1-4 miles east of the pecan orchard

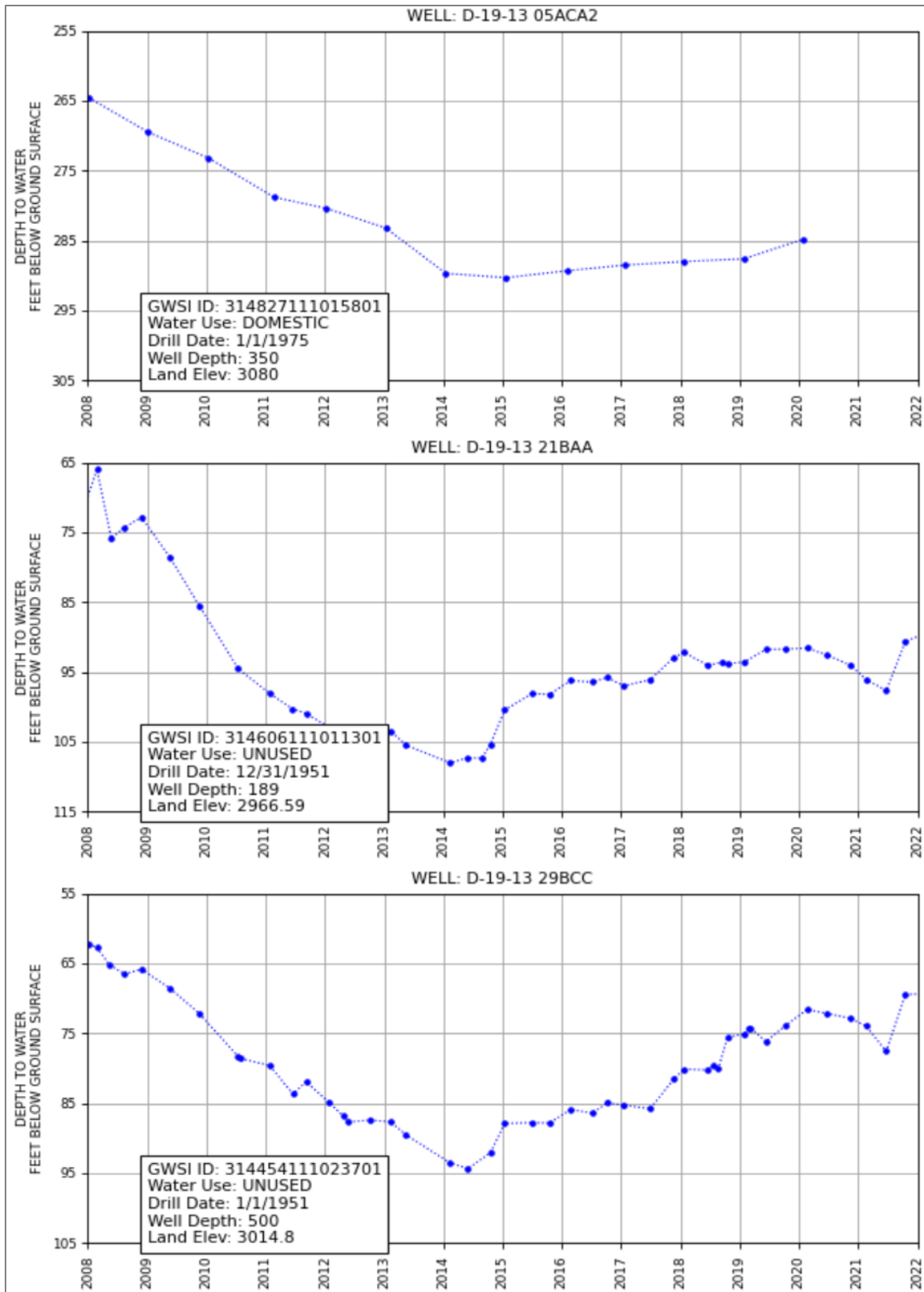
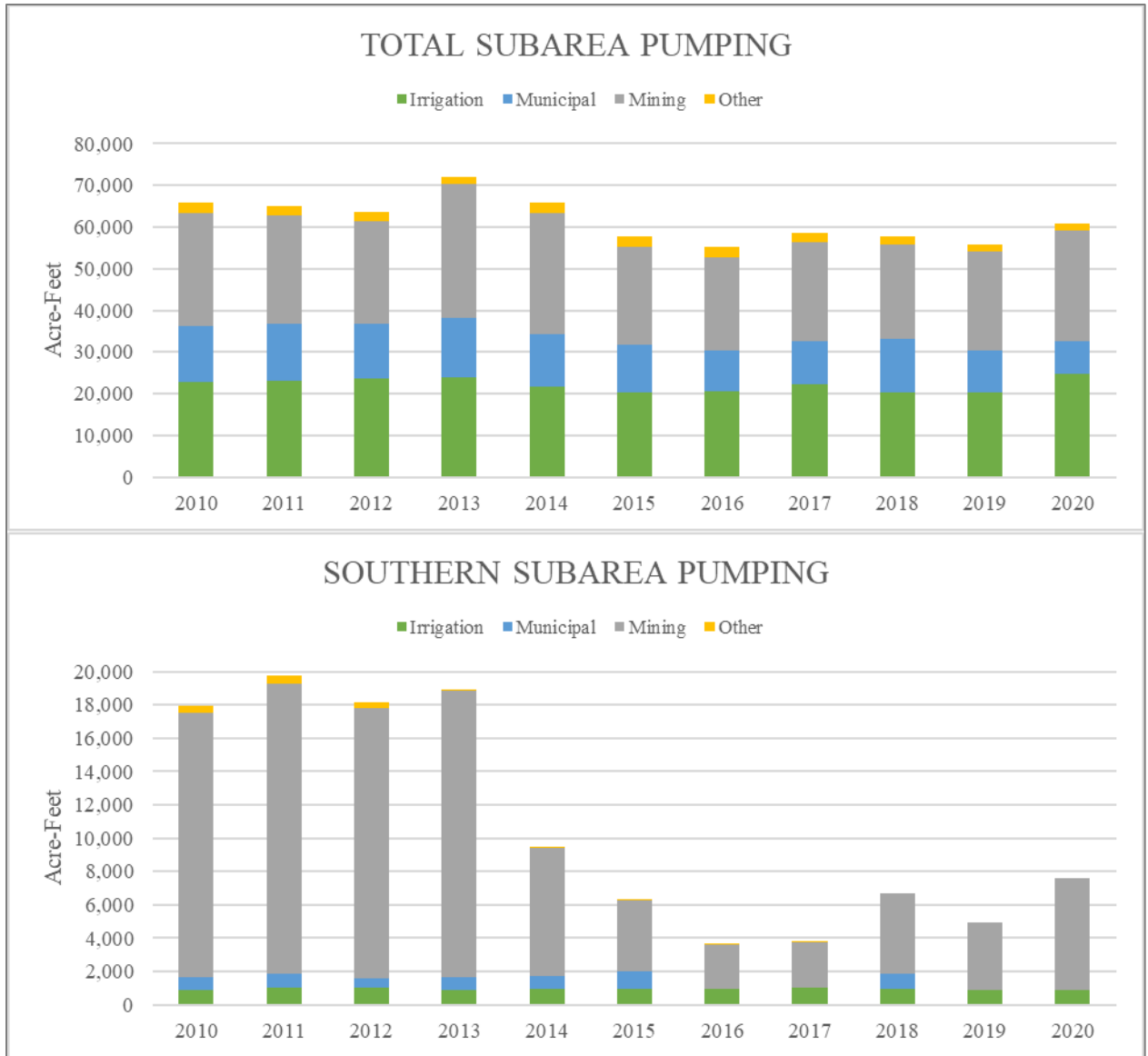


Figure 15. Depth to Water in wells in the southernmost portion of the subarea



**Figure 16. Tucson AMA – Green Valley subarea pumping**

## 11 APPENDIX II: STATA CODE

```
. xtreg DTW_lg Precip Temp NonEx House PerCpInc Planted, fe vce(robust)

Fixed-effects (within) regression           Number of obs   =       44
Group variable: AreaID                    Number of groups =        4

R-squared:                                Obs per group:
  Within = 0.5122                          min =          11
  Between = 0.7228                         avg =         11.0
  Overall = 0.7227                         max =          11

corr(u_i, Xb) = 0.1031                     F(3,3)          =        .
                                           Prob > F        =        .
```

(Std. err. adjusted for 4 clusters in AreaID)

DTW_lg	Coefficient	Robust std. err.	t	P> t	[95% conf. interval]	
Precip	-.1695874	.0890219	-1.91	0.153	-.4528948	.11372
Temp	-1.620057	.7850662	-2.06	0.131	-4.118488	.8783745
NonEx	.2591687	.0248769	10.42	0.002	.1799993	.338338
House	.0009966	.0002107	4.73	0.018	.0003261	.001667
PerCpInc	-.0002798	.0000487	-5.74	0.010	-.0004349	-.0001247
Planted	.0013457	.0003915	3.44	0.041	.0000999	.0025915
_cons	68.95646	16.04272	4.30	0.023	17.90137	120.0116
sigma_u	41.452692					
sigma_e	1.1593567					
rho	.99921839	(fraction of variance due to u_i)				

```
. xttest2
```

Correlation matrix of residuals:

```

      __e1      __e2      __e3      __e4
__e1  1.0000
__e2  0.1749  1.0000
__e3  0.3398  0.4540  1.0000
__e4  0.0298 -0.5212 -0.3318  1.0000
```

```
Breusch-Pagan LM test of independence: chi2(6) =      8.082, Pr = 0.2321
Based on 11 complete observations over panel units
```

```
. xttest3
```

Modified Wald test for groupwise heteroskedasticity  
in fixed effect regression model

H0:  $\sigma(i)^2 = \sigma^2$  for all i

```
chi2 (4) =      17.45
Prob>chi2 =      0.0016
```

```
. xtreg NonEx Pop Dev_HML Planted, fe vce(robust)
```

```
Fixed-effects (within) regression      Number of obs   =      44
Group variable: AreaID                 Number of groups =       4

R-squared:                               Obs per group:
  Within = 0.5228                        min =          11
  Between = 0.0575                       avg =          11.0
  Overall = 0.0573                       max =          11

corr(u_i, Xb) = -0.5891                  F(3,3)          =      219.22
                                          Prob > F        =      0.0005
```

(Std. err. adjusted for 4 clusters in AreaID)

NonEx	Coefficient	Robust std. err.	t	P> t	[95% conf. interval]	
Pop	-.0035024	.00233	-1.50	0.230	-.0109177	.0039128
Dev_HML	.0022195	.000384	5.78	0.010	.0009975	.0034416
Planted	.0034302	.0014829	2.31	0.104	-.001289	.0081493
_cons	437.6189	67.97088	6.44	0.008	221.3052	653.9325
sigma_u	258.45859					
sigma_e	2.7211493					
rho	.99988917	(fraction of variance due to u_i)				

```
. xttest2
```

Correlation matrix of residuals:

```

__e1    __e2    __e3    __e4
__e1  1.0000
__e2  0.7254  1.0000
__e3 -0.6734 -0.6854  1.0000
__e4  0.1616  0.1128  0.2371  1.0000
```

```
Breusch-Pagan LM test of independence: chi2(6) = 16.990, Pr = 0.0093
Based on 11 complete observations over panel units
```

```
. xttest3
```

Modified Wald test for groupwise heteroskedasticity  
in fixed effect regression model

H0:  $\sigma(i)^2 = \sigma^2$  for all i

```
chi2 (4) = 33.83
Prob>chi2 = 0.0000
```

## 12 APPENDIX III: CONTACTS

Bonnie Colby, Professor  
University of Arizona Department of Agricultural & Resource Economics  
email: bcolby@email.arizona.edu

Laura Condon, Professor  
University of Arizona Department of Hydrology & Atmospheric Sciences  
email: bcolby@email.arizona.edu

Thomas Meixner, Professor  
University of Arizona Department of Hydrology & Atmospheric Sciences  
email: tmeixner@email.arizona.edu

Holly Richter, Upper San Pedro Program Director  
The Nature Conservancy  
email: hrichter@tnc.org

Mike Crimmins, Professor, Extension Specialist  
University of Arizona Department of Environmental Science, Cooperative Extension  
email: crimmins@email.arizona.edu

Josh Sherman, Associate Area Agent, Commercial Horticulture  
University of Arizona Cooperative Extension  
email: jdsherman@arizona.edu

Dave DeWalt, Arizona State Statistician  
United States Department of Agriculture - National Agricultural Statistics Service  
email: dave.dewalt@usda.gov

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