PLANNING FOR DEPLETION: OPTIMAL IRRIGATION IN THE PINAL AMA UNDER CHANGING WATER SOURCES

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF HYDROLOGY AND ATMOSPHERIC SCIENCES

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

WITH A MAJOR IN HYDROLOGY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2018

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Abstract

As a shortage declaration on the Colorado River appears likely in the near future, farmers in the Pinal Active Management Area face decreases in Central Arizona Project water and the prospect of returning to groundwater for irrigation. Among other differences, these two sources of water have different costs. Here a simple profit maximizing model along with a modelled water-yield curve is used to calculate a cotton farmer's optimal profit and irrigation level, finding in some situations an incentive to increase the amount of water used for irrigation when switching from CAP to groundwater due to lower cost. Results also highlight the need for better knowledge of well costs and groundwater infrastructure to predict groundwater cost and usage as well as the possible economic/water management implications across the AMA due to a switch from CAP to groundwater. The profit maximizing model is used with well data to examine the relationship between the amount of water available to irrigators and profit as well as spatial differences within the Active Management Area. This one crop model is also used to show the relationship between profit and the maximum amount of water available under different marginal water costs. The profit maximizing approach is expanded to a two crop model with alfalfa and cotton, which indicates a preference for cotton over alfalfa when the amount of water available for irrigation is limited. Results could likely be greatly improved with updated water-yield curves for alfalfa.

1. Introduction

As the likelihood of shortage on the Colorado seems to grow, its effects on water use in the Pinal Active Management Area is important to managing water for future use and meeting the goals of the Active Management Area. This study examines how cotton farmer incentives in the Pinal Active Management Area change under a switch from CAP to groundwater based irrigation. This has implications for both the economic welfare of the farmers and county, but also for groundwater drawdown in the region.

These different water sources (CAP and groundwater) come with different costs, which will affect the behavior of irrigators. A simple model for farmer profit is used to examine the effects of water cost on farmer profit and water use. The model is optimized with respect to profit for different water costs using prices and costs representative of central Arizona. Crop response to irrigation water is modeled using AquaCrop, a biophysical crop simulator that simulates crop yield response to water in leafy plants from the Food and Agriculture Organization (Raes D. , Steduto, Hsiao, & Fereres, 2018). This allows for an estimate of profit based on irrigation water applied and provides an idea of how much water a profit maximizing farmer will use. This process is also applied to both cotton and alfalfa to see how crop choice changes under different water costs.

Arizona has seen success in reducing groundwater overdrafts after the adoption of the Groundwater Management Act (GMA) of 1980 and construction of the Central Arizona Project (CAP). The CAP allowed Arizona to use its entire share of Colorado River water by importing water to central Arizona for various users and for water banking. The Groundwater Management Act preserves groundwater reserves by placing limits on who has rights to pump groundwater. There have been reductions in groundwater overdrafts in Active Management Areas where the more stringent sections of the GMA apply, but this progress has been aided by the addition of water to these areas by the CAP. These two features of Arizona water management are entwined in goals as well as origin, with the U.S. Secretary of the Interior threatening to refuse approval for the CAP (at the behest of Arizona governor Bruce Babbitt) if Arizona did not enact tough groundwater laws (Arizona Department of Water Resources, 2014). Large scale importation of Colorado River water via the CAP has played an important part in slowing groundwater pumping in Central Arizona, however conditions at Lake Mead and in the Colorado River Basin suggest that long term allocations to the CAP could be smaller in the future.

According to U.S. Bureau of Reclamation guidelines (U.S. Department of the Interior, 2007), if Lake Mead is projected to drop below 1075 feet above mean sea level in the August 24-Month Study for a given year, a shortage is declared on the Colorado River starting January 1 of the next year. Due to Arizona's junior status, Arizona will see the greatest reduction among Lower Basin states. For a tier 1 shortage (below 1075') Arizona must forego 320,000 acre-feet of water out of a total allocation of 2.8 million acre-feet, while Nevada loses 13,000 acre-feet and Mexico 50,000 acre-feet (Central Arizona Project, 2015). Even bigger reductions are associated with lower water levels (triggering at 1050' and 1025' above mean sea level (MSL) in Lake Mead.

Arizona's entire share of the cut is absorbed by the Central Arizona Project, with the only CAP users that will be affected under a Tier 1 shortage being the Arizona Water Banking Authority and non-Indian agriculture users. Users who will stop receiving Colorado River water may pump groundwater to offset their reductions in surface water deliveries. Increased pumping will affect the improvements observed in groundwater overdraft. Of special import under a shortage on the Colorado is the Pinal Active Management Area.

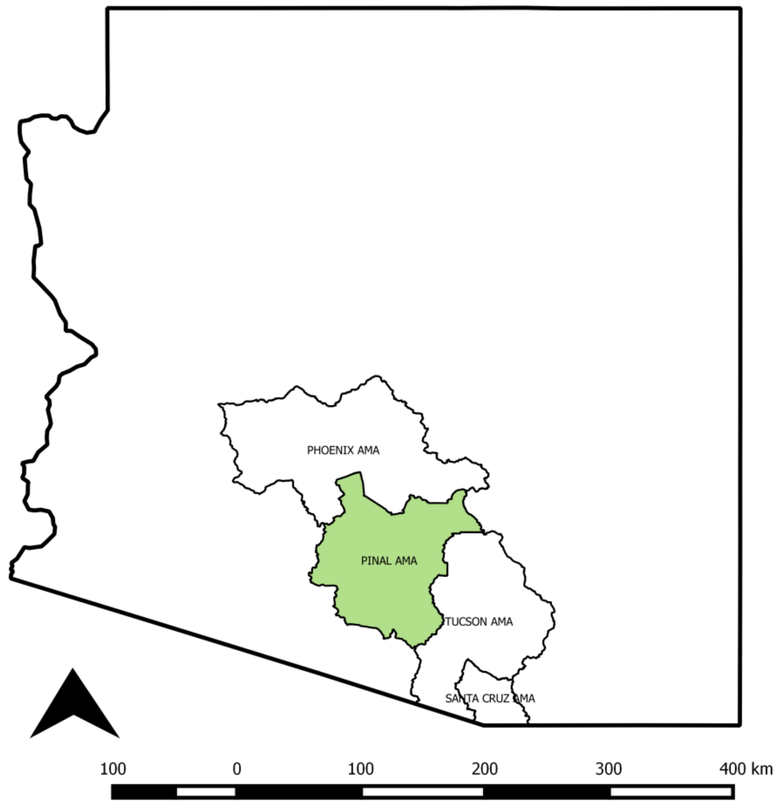


Figure 1: Location of Pinal Active Management Area. Map made with data from ADWR Open Data and political boundaries from the U.S. Census Bureau (ADWR GIS, 2018) (United States Census Bureau, 2018).

1.1 Pinal Active Management Area

The Groundwater Management Act of 1980 designated critical areas of the state as Active Management Areas. (Arizona Department of Water Resources, 2014) This provided regulations within Active Management Areas (AMAs) to discourage groundwater usage and meet management goals. These AMAs are Phoenix, Pinal, Tucson, Prescott, and Santa Cruz. While most AMAs have a goal of safe yield, where groundwater withdrawals and recharge are equal, the Pinal AMA (Figure 1) targets "optimal yield". The Pinal goal

> is to allow the development of non-irrigation water uses and to preserve existing agricultural economies… for as long as feasible, consistent with the necessity to preserve future water supplies for non-irrigation uses (A.R.S. § 45-562(B))" (ADWR)

This goal is often referred to as "planned depletion".

The Pinal AMA has a history of groundwater-based irrigation and still continues to use a significant amount of groundwater even with current CAP water, making future reductions in imported surface water important to groundwater levels in the area. The highest recorded groundwater pumping in the AMA was 637,000 acre-feet in 1985 and the lowest 256,000 acre-feet in 1993 (Arizona Department of Water Resources, 2018).

Furthering the Pinal AMA's challenges, much of the CAP water used is excess CAP water. Excess CAP water is water that legally belongs to a CAP subcontract holder, but is not ordered, making it available for use in that year. Other water users can enter contracts with the CAP for delivery of this water on a one year basis, but it is the most junior priority among CAP users. (Central Arizona Project, 2018)

As irrigators look at replacing surface water with groundwater, it is important to examine how the different water sources will affect behavior. The Colorado River Modeling group at USBR estimates a 52 percent chance of shortage of any kind in 2020 and a 68 percent chance in 2021 (United States Bureau of Reclamation Water Resources Group, 2017). With a likelihood of a shortage declaration, the possible effect on agricultural groundwater pumping becomes important for water management in Pinal County. This paper examines how differences in water source could change the behavior of a profit maximizing cotton farmer in Pinal County.

1.2 Agricultural Water Use in Pinal AMA

Agriculture is an important part of Arizona's economy both historically and currently. In 2014 agribusiness contributed $23.3 billion to the state economy (Bickel, Duval, & Frisvold, 2017). By far the two most prominent crops in the Pinal AMA are alfalfa and cotton making up approximately 38 and 37 percent (respectively) of total crop coverage in the county according to the USDA Cropscape dataset (USDA , 2018) when ignoring fallow/idle cropland (Figure 2). The next largest category is winter wheat with 7.5 percent of coverage. This has changed in recent years: in 2011 cotton made up approximately 48 percent of crop coverage and alfalfa 29 percent.

Agriculture is the largest use of water in the Pinal AMA, making up approximately 80% of total water use. In 2015, which is the latest historical data available in the ADWR Pinal AMA budget, 834,976 acre-feet of water were used for irrigation in the AMA of which 256,136 acre-feet (31%) came from the CAP. The largest water source for agriculture is groundwater, which makes up 49% of agricultural water use. Figure 3 shows historical water sources for agricultural use in recent years. Other sources include in lieu groundwater which is renewable surface water used in place of groundwater pumping to get a long-term storage credit for the groundwater not pumped. Non-imported surface water comes mainly from the Gila River. Use of treated effluent is very small and not visible at the scale on Figure 3. The draft for the Pinal AMA projects a phasing out of CAP water and increasing groundwater use in the future (Figure 4).

1.2.1 Role of Irrigation Districts

The majority of agricultural water use in the Pinal AMA (approximately 87%) is associated with four irrigation districts (Arizona Department of Water Resources, 2010). Irrigation districts largely use a mix of CAP and groundwater, with CAP deliveries making up roughly 45% of water use by volume within irrigation districts as of 2015 (Betcher, 2015). Users in irrigation districts will also be most affected by a call on the Colorado River as that is where agricultural use of CAP water occurs; farmers outside irrigation districts pumping groundwater can continue with few immediate effects during a cut. Due to users in irrigation districts representing the most water use and facing the biggest effects from a loss of CAP water their behavior is the most important to agriculture in the Pinal AMA during a call on the Colorado.

Following the construction of the Central Arizona Project pursuant to the Colorado River Basin Project Act of 1968 (CAP act), the Secretary of the Interior contracts water to the state agency (the Central Arizona Water Conservation District), which then subcontracts the water to irrigation districts. “The landowners formed their own agreements with the districts on terms of delivery pursuant to which the districts would provide CAP water through their facilities, while the landowners would pay taxes and service fee and relinquish right in certain irrigation wells to the districts” (DeStefano III, 2006). Prior to the introduction of the CAP many wells had begun to show reduced yields as groundwater levels dropped in the region requiring farmers to reduce planted acres. Facing large investments to increase yields and ever increasing pumping energy costs among other possible issues, the relinquishment of groundwater wells for CAP water seemed appealing.

The CAP water as predicted by some economists, (Bush & Martin, 1986 among others) was prohibitively expensive which in the face of lackluster cotton prices, led to fallow acreage and irrigation districts unable to meet their financial obligations and in a few cases bankruptcies (Hanemann, 2002). In exchange for subsidies to CAP water cost, irrigation districts agreed to shorter 10 year contracts to water. The financial pressures still remained leading to, in 2002, another agreement to relinquish long term rights to the CAP in return for further subsidy. Now with junior rights to CAP water and excess water rights planned to phase out, many irrigators and irrigation districts have the option to make up for lost CAP water with increased groundwater pumping tied to grandfathered irrigation rights.

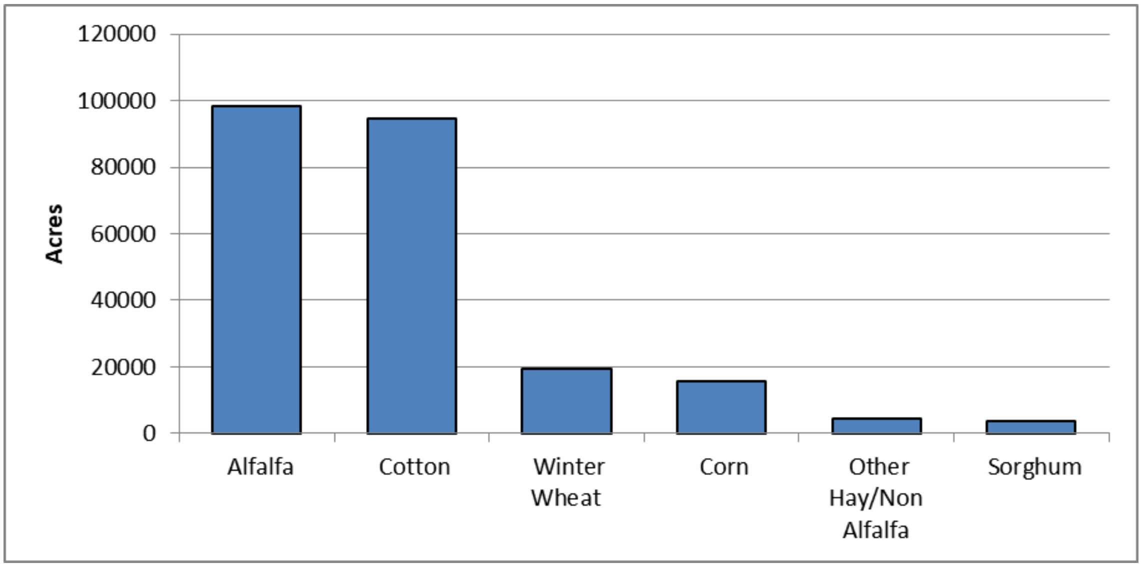


Figure 2: Acreage of largest crops by acreage in Pinal County in 2017 according to USDA Cropscape dataset (USDA , 2018).

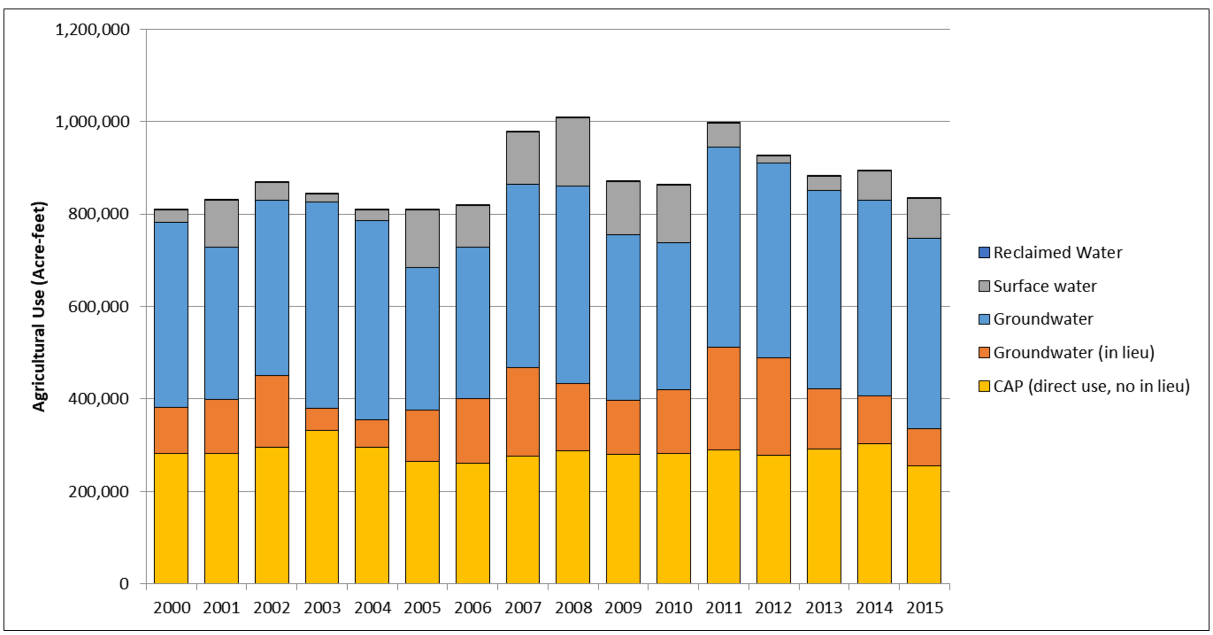


Figure 3: Historical water source for agriculture in the Pinal AMA. (Arizona Department of Water Resources, 2011)

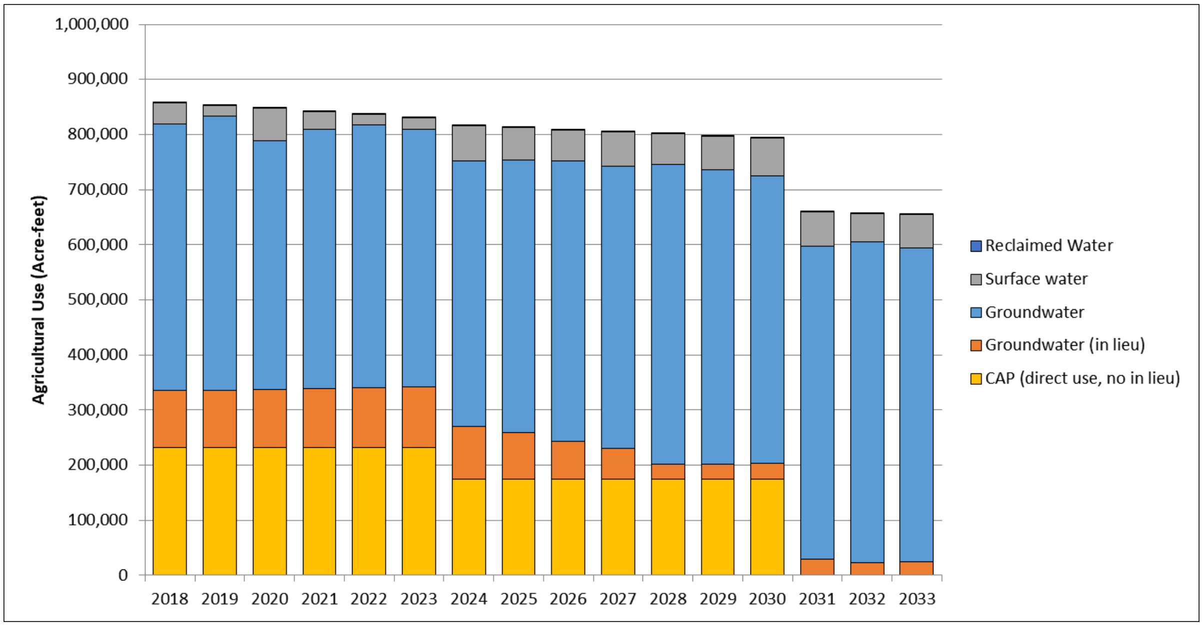


Figure 4: Projected water source for agriculture in the Pinal AMA according to the latest 10 year plan (Arizona Department of Water Resources, 2011)

1.3 Groundwater Management Act of 1980

The Groundwater Management Act of 1980 limits groundwater withdrawals in several ways, many important to agriculture. Irrigation is limited to existing agricultural lands, so only land that has already been used for farming may be irrigated in the future. As former agricultural lands are converted to other uses, like municipal or industrial, there is less land available for groundwater based irrigation. Grandfathered irrigation rights are required for agricultural use; these are associated with historical groundwater irrigation between 1975 and 1980 and are tied to the associated land. Figure A2 shows the locations of grandfathered rights in the Pinal AMA. Lastly there are requirements for measuring withdrawals and annual reporting along with withdrawal fees. This allows for better knowledge of withdrawals along with funding for the cost of management as well as conservation assistance and augmentation projects (ADWR, Overview of the Arizona Groundwater Management Code).

While there are many restrictions on groundwater use, farmers with existing rights who have been using CAP water may return to pumping water when facing reductions in their CAP supply (Central Arizona Project, 2015). Irrigation Grandfathered Rights are also assigned based on historical water use from a time (1975-1980) when groundwater pumping was much higher than current levels. The ADWR database of grandfathered rights shows 972,856 acre-feet of irrigation rights on 416,441 acres in the Pinal AMA (ADWR GIS, 2018).

1.4 Literature Review

Ayer and Hoyt (1981) created crop-water production functions specific to Arizona for several common crops, including cotton based on experimental data. A motivation for their study was to maximize production for water applied in the face of a future where water “prices will increase dramatically”. Their study is pre-CAP and only looks at groundwater as a source. Ayer and Hoyt find an elasticity of -0.013 to -0.118 for irrigation water based on water price under a cotton price of 0.65$/lb. This is an inelastic demand for water, so cost changes in water will have little effect on water use. This sensitivity decreases as cotton prices increase and increases at lower prices (Ayer & Hoyt, 1981).

Bush and Martin (1986) look at the potential economic costs and benefits of Central Arizona Project water on agriculture in Central Arizona. They projected that farmers would realize no net benefit in substituting CAP water for groundwater and that CAP is not a competitive alternative to groundwater. The report does project a reduction in variable pumping costs to 80 or 90 percent of those that would be observed without the CAP, but only two out of the eight irrigation districts studied would be better off with the CAP in 2034 and one of these positive outcomes is solely due to infrastructure investment.

Foster, Brozovic and Butler (2015) estimate water use and irrigated acreage under maximum profit using Aquacrop to simulate the response of a corn crop to applied water. They find pumping capacity important to buffer farmer incomes during drought. Farmers with lower well yields show much smaller profits during droughts. The study approach using Aquacrop and a profit maximizing function are similar to that used here.

Many studies including Lin, Dean and Moore (1974) have found a utility function a better fit for observed farm production than simply profit. Kim & Kaluarachchi (2016) use AquaCrop together with a utility model. They found that risk averse behavior led to water allocation strategies with less variable profits. Due to this, under high water stress in south central Utah maize productivity is favored over cotton.

Many studies have found a relationship between water use and other factors like government farm programs can have a large effect on crop production and water use. Frisvold (2004) summarizes that “commodity programs had significant impacts on production and national irrigation use”, but “there is great regional variation in impacts…” Lee and Lacewell (1990) found that commodity program participants pumped 74% more groundwater than nonparticipants did.

2. Material and methods

Farmers have the ability to replace CAP deliveries with groundwater, so it needs to be determined how much of the foregone water is likely to be replaced with groundwater pumping. A purpose of this study is to examine how farmer incentives for irrigation use change under a switch from CAP to groundwater. This is accomplished using a simple model for farmer profit based on inputs and outputs of production. This model is optimized with respect to profit for different water costs.

2.1 Profit Equation

It is assumed that a farmer makes the decision to apply irrigation water and in what volume based on maximizing profit. To examine how water use changes with a changing water source, the height of water applied as irrigation and the area under irrigation is determined under profit maximizing conditions for farming upland cotton. The equation used to calculate profit is Eq. 1

$$\pi = Y(H_i) \cdot A_i \cdot (P_c - C_h) - A_i \cdot C_f - (H_i \cdot A_i) \cdot C_v \qquad \textbf{Eq. 1}$$

Where π is profit in dollars per year ($\$ \ yr^{-1}$), this is the value that is maximized.

H_i (m) is the depth of water applied over the growing season. It is assumed that the same height of water is applied uniformly over the entire field.

Y is the crop-water production function (ton $year^{-1}$ m^{-2}). It provides the crop yield based on the amount of water applied to the field (H_i).

A_i is the irrigated area (m^2) on which a depth of water H_i *(m)* is applied. The product of these values provides the volume of water used. H_i and A_i are the variables that profit will be maximized for.

P_c is the price of the crop *($ ton^{-1})*. This is a constant value. It is estimated from USDA data (United States Department of Agriculture Economic Research Service , 2018)

C_h is the cost of harvesting *($ ton^{-1})*. This value is constant and estimated from USDA data (United States Department of Agriculture Economic Research Service , 2018).

C_f is constant cost of production per area of field *($ $m^{-2}yr^{-1}$)*, estimated from USDA data.

C_v is the variable costs of irrigation ($\$ \ m^{-2} \ m^{-1}$), the per unit cost of water.

Constant	Value
Pc - Price of Crop ($/ton)	1062.1
Ch – Variable Cost of Harvest ($/ton)	172.6
Cf – Fixed costs of production ($/ha)	823

Table 1: Values obtained from USDA "Recent Commodity Costs and Returns" (United States Department of Agriculture Economic Research Service, 2017)

2.2 Crop Data (Pc, Ch, and Cf)

The USDA document "Recent Costs and Returns: Cotton" (United States Department of Agriculture Economic Research Service , 2018) breaks down costs and income for cotton farms divided into regions. The "Fruitful Rim" data is used here as this is the region including the Pinal AMA. The data is based on the Agricultural Resource Management Survey, which targets about 5,000 fields and 30,000 farms nationwide each year. This provides a basis for fixed and variable costs as well as the price of harvest. There is data from 1997-2016 available with the 2016 data used.

The CropScape dataset (USDA National Agricultural Statistics Service) provides estimates on crop types and the geographical location of agriculture through 2017 using remote sensing. Alfalfa and cotton are by far the most common crop types in the region with alfalfa the most common in 2017. AquaCrop is set to simulate a planting of cotton. Cotton prices are obtained from the USDA (United States Department of Agriculture Economic Research Service , 2018) .

2.3 Cost of Water (C_v)

The profit equation is maximized using the cost of CAP water, irrigation district costs and the cost of groundwater. CAP cost is the per unit cost charged for agricultural users and the cost of groundwater is estimated by the energy cost to lift groundwater to the surface, calculated using Eq. 2.

$$C_v = h \cdot \gamma_w \cdot k^{-1} \cdot C_e + w \qquad \textbf{Eq. 2}$$

C_v gives the cost of pumping per unit of water ($ m^{-3}).

h is the height of lift (m),

γ_w is the specific weight of water (kg m^{-2} s^{-2}), k is the coefficient of efficiency of the pump (generally ranges from .5 to .7, 0.65 is used here),

C_e is the cost of electricity (\$ $Watts^{-1}s^{-1}$) In Electric District Number Four this value is $2.1x10^{-8}$or \$0.0786 per KWH.

w is the withdrawal fee for groundwater in the Pinal AMA (\$ m^{-3}). In 2017 this value is 0.0024 (\$3 per acre-foot).

2.3.1 Water Cost Structure

This analysis provides a low estimate for the cost of groundwater as only ADWR fees and energy costs for a somewhat efficient pump are considered. The marginal cost of additional water is assumed to be flat in that irrigators can pump an unlimited amount of water at the lift cost detailed in Eq. 2. There are other possible forms the marginal cost could take with some illustrated in Figure 5**.** It is unclear what additional pumping capacity exists in the AMA and at what costs additional groundwater can be obtained.

It should be noted that only some irrigators will see these groundwater prices. The energy cost approach used here provides an estimate for average water cost below the rates charged by the Central Arizona Irrigation and Drainage District. Some of this is due to some costs not considered making it a low estimate. Irrigation district managers have concerns related to resource management, subsidence, quality degradation, reduced hydropower availability with drought, electricity costs and increased maintenance costs to consider that may add to the cost of groundwater withdrawals. Also the possibility that greatly increased groundwater withdrawals may lead to additional regulation may make using groundwater less appealing. (Betcher, 2015).

Around the time of construction of the CAP canal, one thing that made its expensive importation of water and construction of infrastructure to transport it so appealing, was that it helped farmers facing low well yields due to groundwater depletion. The CAP allowed farmers to plant their entire fields, whereas before some had to fallow land because of wells beginning to produce less with declining groundwater levels (Coates, 2018).

With the rebound of groundwater levels in portions of the AMA it may be possible that pumping from existing wells may have sufficient yield and be cheaper than the current surface water rates for some users as indicated by the pumping equation and depth to groundwater method used. Costs will vary based on individual situations. The depths to groundwater observed in the AMA indicate that if a farmer has existing pumping infrastructure, in some cases a switch to groundwater could lead to lower water costs, at least in the short-term. However, if an irrigator faces constructing a new well or maintenance costs, the cost of groundwater could be much higher than seen here. Also, if groundwater levels begin to decline again with increased pumping, limited well yields would again eventually lead to the fallowing of fields.

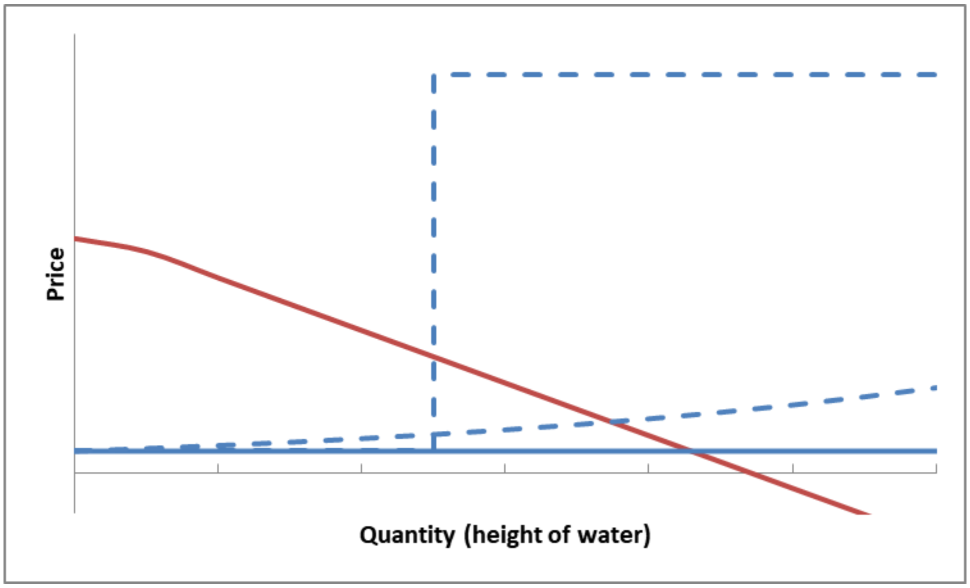


Figure 5: Marginal Revenue and Marginal Cost of Water. This chart shows the relationship between marginal revenue (red) and the marginal cost of water (blue) based on the amount of irrigation water applied. The solid blue line represents the marginal cost of water curve used in this thesis. The gradually increasing MC (sloped blue line) represents water getting more expensive as more water is used. The spiking MC curve represents a case where water costs greatly increase after a certain amount of water, like amortization and maintenance of new large capacity wells. The profit maximizing quantity of water occurs where the red and blue lines intersect, showing the importance of how the cost of water is represented in the model. The marginal cost of water is exaggerated on this chart to better illustrate how curves may differ.

It is assumed that irrigation delivery efficiency is the same for both sources of water (CAP and groundwater), that is, the same percentage of water will be lost to evaporation or canal leakage regardless of water source. Water sources are also assumed to be the same production wise (e.g. water quality differences do not affect crop production), so that 1 acre-foot of CAP water can be replaced with 1 acre-foot of groundwater.

Values for each variable, except π, A_i, and H_i, are determined from data and remain constant. The value of H_i and A_i that maximizes π in Eq. 1 is then determined in MATLAB. The function fminsearch is used to find the value of H_i that minimizes the negative of Eq. 1 and the accompanying P value for the positive function. This process is completed for different water costs based on depth to water via Eq. 2. MATLAB quickly solves the optimization problem and can be used for the thousands of water levels in the GWSI database (The MathWorks, Inc., 2018).

2.4 Water-Crop Production Function (Y)

Water-crop production curves (Y in equation 1) were generated using AquaCrop, a biophysical crop simulator. AquaCrop is a discrete time model that simulates crop yield response to water in leafy plants. It uses relatively few parameters compared to other models and is aimed at practical end-users. AquaCrop requires climate, crop, soil, and management inputs to simulate crop yield.

It simulates and outputs, among other things, crop canopy cover with time, plant evapotranspiration and biomass (Raes D. , Steduto, Hsiao, & Fereres, 2018). The FAO publication Crop Yield Response to Water (Steduto, Hsiao, Fereres, & Raes, 2012) details a case for developing water production functions using AquaCrop for use in decision support systems which is used here. The data requirements for this are historical data on ET and daily rainfall along with the crop and soil characteristics necessary to run AquaCrop.

The model is run by targeting different allowable soil water depletion levels ranging from 0-100%. This causes the model to add irrigation water during the simulation to meet the soil water depletion target. The model produces crop output in tons/ha for each height of irrigation water applied. This creates a relationship between crop-production and water applied. A quadratic regression is performed in MATLAB to use as Y in the profit equation (equation 1).

2.4.1 AquaCrop Data Sources

The Aquacrop default cotton crop parameters are used to meet the crop characteristic requirement in developing the crop yield to water relationship. These parameters are derived from cotton data in Cordoba, Spain (Raes D. , Steduto, Hsiao, & Fereres, 2018). Sandy loam is a good choice for soil type based on the USDA Soil Survey of the Casa Grande Area (USDA Natural Resources Conservation Service) and the location of irrigated agriculture within the county (USDA Natural Resources Conservation Service, 2018) so default values for sandy loam soil are used. Near optimal field management techniques are assumed with settings for water runoff and weed presence set very low, making production values likely a high estimate. At this time effects of salinity in irrigation water are not considered. The crop simulation is started on April 1, which is close to the most common date to reach a consecutive day soil temperature criteria for planting cotton in central Arizona (Brown P. , N.D.).

The daily ET and precipitation data for running AquaCrop comes from the Arizona Meteorological Network (University of Arizona College of Agriculture and Life Sciences Cooperative Extension, 2018). The station at Maricopa, Arizona is used, which is in the Stanfield-Maricopa sub-basin of the Pinal AMA. At this site there are daily reference evapotranspiration values from 1987 to present. Starting in 2003 values calculated by the Penman-Monteith equation as recommended by the American Society of Civil Engineers special Task Committee (Walter, et al., 2000) are available, but to stay consistent, the AZMET method available for all years is used. The AZMET method is consistently slightly lower compared to Penman-Monteith. Ratios to approximate Penman values from the older AZMET method are available by month (Brown P. W., 2005) if a conversion is necessary.

2.4.2 Water-Crop Production Function Form

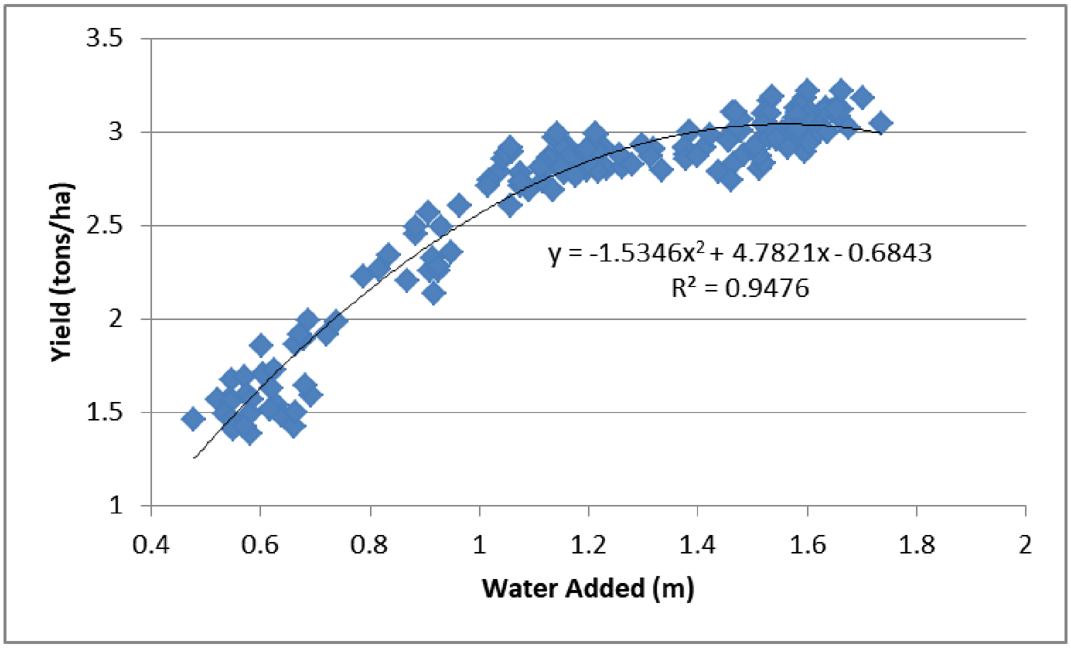


Figure 6: Yield vs. Height of irrigation water added best fit. Quadratic curve fit to AquaCrop outputs using Maricopa AZMET daily weather data

An overall crop-production function is created by changing irrigation criteria in AquaCrop for each year in the AZMET data set as described above targeting a different allowable soil water depletion level. The resulting regression between irrigation water applied and yield is the equation used for Y in calculations. A quadratic curve is fit to the values output from AquaCrop shown in Figure 6.

$$Y = -1.5346H_i^{\,2} + 4.7821H_i - 0.6843 \qquad \textbf{Eq. 3}$$

The quadratic curve produces a reasonable fit to modelled yields (r^2=0.948), but does create a maximum value around 1.5m (4.9 feet) rather than the asymptotic behavior observed in cotton yields. However, the flat section of the yield curve is of less concern in the analysis of a profit maximizing farmer under the assumptions used here. It never increases farmer profit to produce the same yield with more water as the third term of Eq. 1 becomes more negative with increased H_i (C and A must be positive values) and the other terms in the profit equation remain the same. It is more important to represent other portions of the curve, which the quadratic fit does reasonably well. It is notable that using the quadratic form makes the peak in Eq. 3 (and visible in Figure 6) the highest possible value of H_i that optimizes Eq. 1. For any value to the right of this peak a farmer could produce the same output with less water at a lower cost. Compared to the USDA Farm and Ranch Irrigation Survey (FRIS) data, the peak at 4.9 feet of water added corresponds fairly closely with average of 4.5 feet applied to cotton in Arizona. The modelled crop produces significantly more than Arizona farms in FRIS data. The 4.5 feet added in Arizona produces on average 0.75 tons/acre while the model produces about 1.13 tons/acre for the same height of water. This could be related to the optimal field management settings used or crop parameters calibrated in Spain. This model seems to be an overestimate for production, but using realistic volumes of water.

2.5 Well Data (h)

Depth to groundwater provides an important basis for the cost of groundwater as detailed in Eq. 2. The wells from the ADWR Groundwater Site Index database listed in the Pinal AMA (Arizona Department of Water Resources GIS) are used for groundwater data. Any entry in the comments line that indicates that a reading may not be indicative of static water levels like "well clogged", "well-destroyed", or "recently-pumped" (Arizona Department of Water Resources GIS) (Table 2) is removed from the data set. 1,718 entries were removed for this reason. Other reasons for removing a well included a lack of water level reading date, well readings that erroneously indicated a depth to water of 0 feet, well readings without a date, and well measurement dates from the future.

WLWA_REMARK_CODE
CASCADING WATER
FOREIGN MATERIAL (OIL)
NEARBY PUMPING
NEARBY RECENTLY PUMPED
OTHER
PUMPING
RECENTLY PUMPED
UNDETERMINED
WELL DESTROYED

Table 2: Water Level codes excluded from analysis

From this list, only wells with a connection to agriculture are used. This is determined by either its use noted as "irrigation" in the GWSI database or proximity to an irrigation district. The location of each well is mapped in QGIS (QGIS Development Team, 2018) and every well not within 1 mile of a Pinal AMA irrigation district or otherwise noted as for irrigation is removed. Wells outside the Eloy and Maricopa-Stanfield sub-basins are also removed as there is comparatively very little agriculture and few water levels from outside these basins. These steps reduce the number of well readings from 26,508 to 17,499.

To look at how water levels have changed over time wells are then separated by year. One depth to water value for each well each year is used and the rest removed. Only readings from

November-January are used so that readings are from a similar time of year. This time period is used because most wells only have one reading and this most often occurs in one of these months. Readings outside of November-January are removed along with multiple entries for the same well, leaving about 4,000 entries. This provides an idea of water levels in the late fall/early winter. This also means that the years used here represent the water year, not necessarily the calendar year with November and December 2016 falling in the water year 2017.

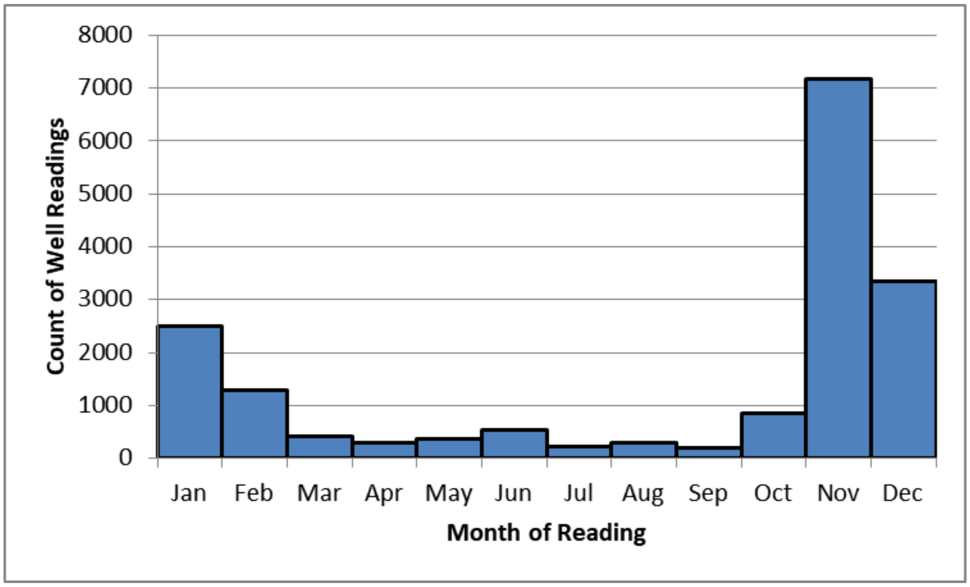


Figure 7: Month of well data reading in ADWR Groundwater Site Index database.

2.5.1 Seasonal Drawdown

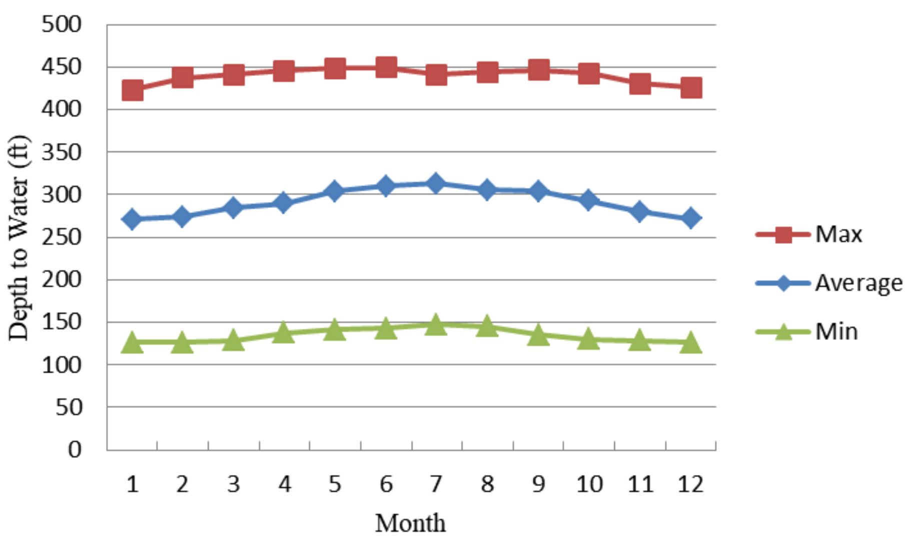


Figure 8: Average, Min, and Max Depth to Water by Month in auto logged wells. Depth to water is on average greatest in July and smallest in the winter.

There is noticeable drawdown of groundwater levels during summer months (Figure 8), but the vast majority of wells with long records have only one reading per year, most taken in the months of November and December (Figure 7), so the data set poorly represents any seasonality in water levels. There are 3 wells with automatic water level readings near irrigation areas capturing depth to water throughout the year in the AMA. Records for these wells start in 2005 and continue through today. These so-called auto wells have different start dates and have intermittent missing values, but have a recording every 6 hours for most of the period.

According to the AquaCrop simulations performed, the expected date of the 50th percentile of irrigation water is July 20. Because most water levels are from winter, in order to use a value closer to actual depth to groundwater during time of irrigation, a simple linear relationship is created between the average winter water level (Nov, Dec, and Jan) and the July 20 depth to water.

The linear coefficients that minimize the sum squared error (equation 4) between observed and predicted depth to groundwater (n=28) are selected using Excel's (2010) GRG Nonlinear solver.

$$(July\ 20\ DTGW) = 1.0132 \cdot (Winter\ DTGW) + 12.9981 \qquad \textbf{Eq. 4}$$

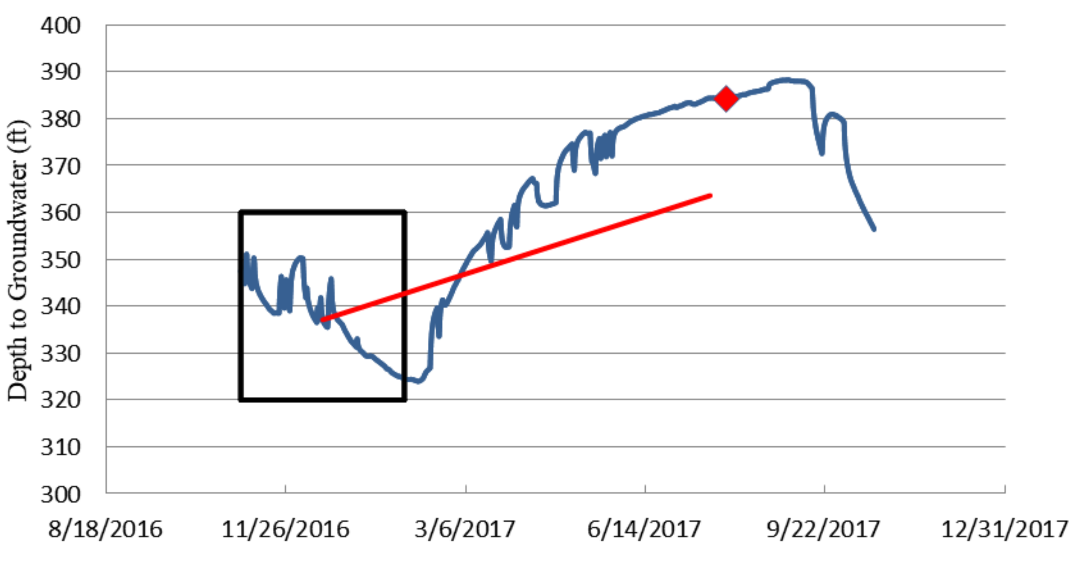


Figure 9: Seasonal change observed in auto well 323635111330001 compared with linear prediction model. The black box represents the winter period when most water levels are sampled. The average value from this period is calculated. The red diamond represents July 20th when the 50th percentile of irrigation water is expected. The red line is the predicted value for July 20th based on the average winter depth to groundwater.

A mean error of 8.32 feet indicates that these values are still off from the true value. Figure 9 shows an example of the linear model compared to known data. While there is a significant improvement from simply using the winter value, the linear model still is nearly 20 feet from the true value. Summer drawdown during 2017 in well 323635111330001 was unusually high compared to other years and wells, but it does illustrate the possibility for error in single value wells. This method provides an improved estimate, but still off from the true value. Furthermore, because the level of groundwater decline during the growing season is not necessarily at a constant rate, using July 20 as the date where half of irrigation is applied will not necessarily reflect average depth to groundwater during pumping and accordingly not average cost, but should provide a reasonable estimate of pumping height during the growing season. Results are also not very sensitive to depth to groundwater, so some error in this value will have little effect on overall results.

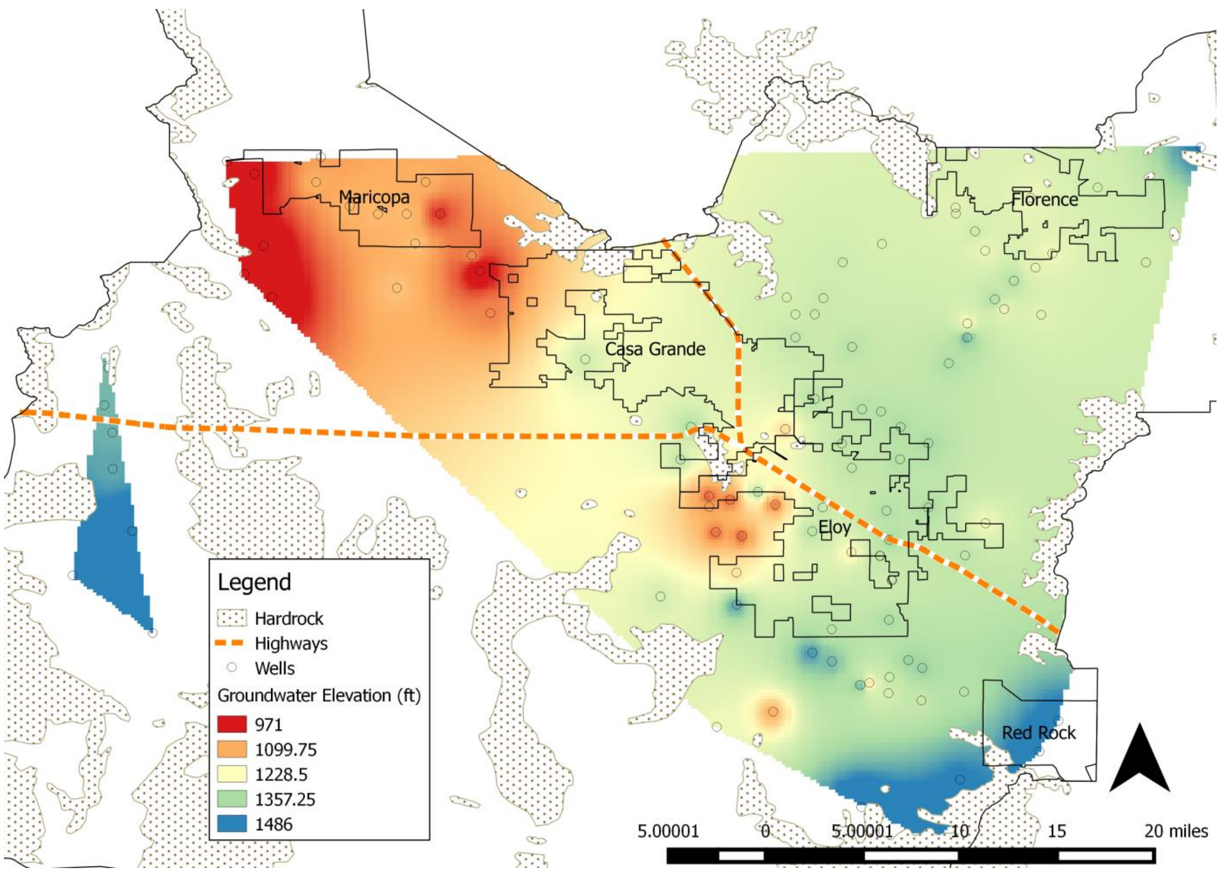


Figure 10: Interpolated (IDW) groundwater elevation in the Pinal AMA in 2017 based on ADWR Groundwater Site Index wells. Groundwater flow is generally towards the north/northwest in the direction of the Gila River. Several groundwater depressions exist, most noticeably near Eloy and Maricopa. Depth to groundwater in GWSI wells averages approximately 248 feet with a standard deviation of 130 ft. (Arizona Department of Water Resources GIS) (The Arizona Geological Survey, 2000)

2.6 Comparative Costs of Water

The per acre-foot cost of CAP water is published by the CAP. For 2016 the price per acre-foot for the agricultural settlement pool water is $76 per acre-foot. Historical data and estimates through 2022 are available (Central Arizona Project, 2016). Prices for agricultural water from the CAP are scheduled to decrease in the future with an advisory rate of $68 per acre-foot in 2019. Agricultural users pay only the pumping energy rate faced by the Central Arizona Project with no charges for items like capital costs, operations, or management. Municipal and industrial customers pay much higher rates, with the 2016 long-term subcontract rate at $161 per acre-foot. Irrigation districts use a mix of CAP and groundwater, so the cost paid by members is lower than the CAP cost, with members of the CAIDD paying about $58.50 per acre-foot. This value provides a basis for current irrigation water costs

The electric cost to lift groundwater provides a low estimate for the cost of groundwater. Possible costs like subsidence, quality degradation, electricity costs and increased maintenance costs are not considered. Better information about these factors could improve the possible range of groundwater pumping costs. Electrical District Number Four, an electricity provider inside the Central Arizona Irrigation & Drainage District in the Eloy Basin of the Pinal AMA provides a basis for electricity costs that farmers in the region face. Its 2016 agriculture related commercial rate is $0.0786 per KWH. Approximately 78% of its electricity in the district is used for irrigation pumping. Its charge per acre-foot of water ($58.50) in 2016 reflects the mix of CAP and groundwater delivered to irrigation district members. Approximately 50% of water used in 2014 was surface water sourced from the CAP directly, as In-Lieu Water or Water Banking Water. (Electrical District Number Four of Pinal County and the State of Arizona, 2011)

2.7 Expansion of Model to Two Crops

Farmers are not limited to a single crop, so the profit maximizing model is changed to include two crops to better represent this behavior. Crop coverage in the Pinal AMA is dominated by cotton and alfalfa (Figure 2), so these two crops are used. The profit equation is altered to include the sum of incomes minus costs for two crops. The two-crop profit equation is:

$$\begin{aligned} \pi = {} & Y(H_i) \cdot A_i \cdot (P_i - C_i) - A_i \cdot C_{fi} - (H_i \cdot A_i) \cdot C_w \\ & + Y(H_j) \cdot A_j \cdot \left(P_j - C_j\right) - A_j \cdot C_{fj} - \left(H_j \cdot A_j\right) \cdot C_w \end{aligned} \qquad \textbf{Eq. 5}$$

Where the variables and constants are the same as those used in Eq. 1, and i and j represent values for cotton and alfalfa, respectively. The profit equation is now maximized for four variables: H_i, H_j, A_i, and A_j. These values must be zero or positive and crop area is subject to the constraint:

$$A_i + A_j \leq constant \qquad \textbf{Eq. 6}$$

where the constant is the size of the farm. When the value of $A_i + A_j$ is smaller than the farm size, this indicates fallow land. This approach can be expanded to any number of crops, but difficulty maximizing the equation increases with each addition, adding two variables per crop. In Pinal county, cotton and alfalfa make up approximately 80% of planted acreage (Figure 2), so using these two crops is fairly representative of the AMA. The values of crop coverage and water usage at maximum profit under a range of water costs and availabilities are determined. A hypothetical farm with 50 hectares available to plant (value of constant in Eq. 5) is used to examine how crop planting decisions change with limited water and changing water cost.

2.7.1 Crop Production Functions for Two Crop Model

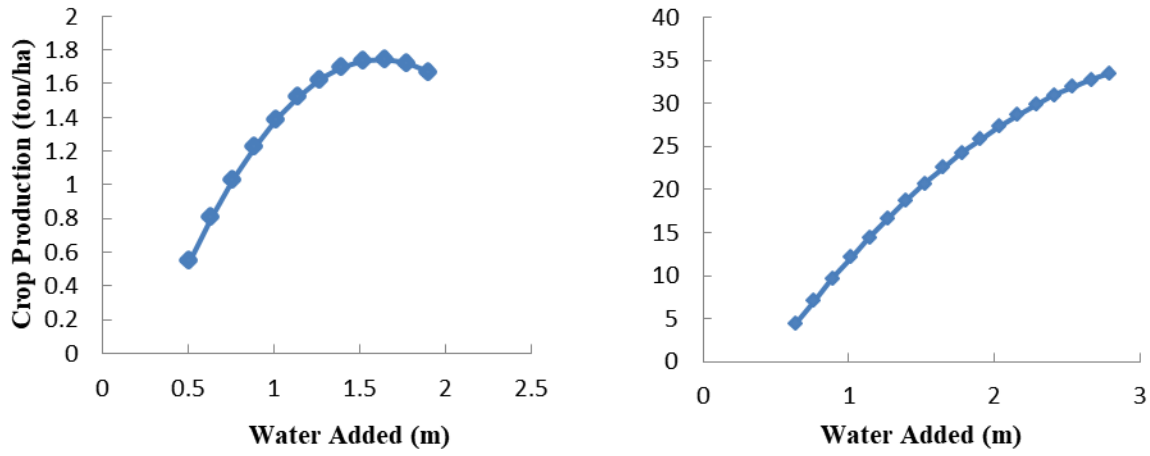
AquaCrop does not include parameter values for alfalfa, so the procedure followed in Section 2.4 Water-Crop Production Function (Y) for cotton cannot be used to create a production function for alfalfa. Instead crop-water production functions from the technical bulletin “Crop-Water Production Functions: Economic Implications for Arizona” (Ayer & Hoyt, 1981) are used (Figure 11). These functions are based on experimental data from sites across Arizona for cotton and using data from Las Cruces, New Mexico for Alfalfa, which should be reasonably similar to conditions in the Pinal AMA. However, these functions and the data they are based on are from the 1970’s making it likely that yields have changed since the creation of these relationships. Equation 7 produces significantly lower values for yield than equation 3 derived from AquaCrop, which is expected to be a high estimate as discussed in section 2.4.1. Even if these functions do not accurately predict yield, this analysis still provides value by showing optimal crop and irrigation decisions between two crop under different water cost and supply scenarios.

$$Y_a = -4.4285 + 0.2668 \cdot H_j - 0.00099{H_j}^2 \qquad \textbf{Eq. 7}$$

$$Y_c = -636.919 + 128.359 \cdot H_i - 0.503{H_i}^2 - 64.124H_i \qquad \textbf{Eq. 8}$$

Where H_j and H_i are water added in inches, Y_a yield of alfalfa in tons per acre, and Yc yield of cotton in pounds per acre.

As discussed in Ayer and Hoyt, the yield estimate for alfalfa in equation 6 is very high at higher applications of water. To prevent unrealistic yields during maximization, the value of H_j is limited to 2.8 ha-meters (9.1 feet) per hectare. This provides a maximum yield of around 12 tons per acre, a high value, but one obtained by the best farms. The average value across all Arizona in 2013 was 8.3 tons per acre with 1.6 m (5.4 feet) of water added. These functions are also based on data with fairly well watered crops and little data on water stressed plants, making their accuracy at low water levels questionable. This could cause the model to not well represent scenarios where crops receive little water over a large area.



Cotton

Alfalfa

Figure 11: Crop production functions used in two-crop analysis (Ayer & Hoyt, 1981). Left plot is cotton and the right plot is Alfalfa. Alfalfa ends at 2.8m (9feet) so that unrealistic values are not obtained. Cotton peaks around 1.5 meters (4.9 feet) of water added with a production of 1.6 tons/ha (0.65 tons/acre).

2.7.2 Sources of Data for Two Crop Model

The USDA Economic Research Service which was used for cotton price and cost values in the single crop model does not provide values for alfalfa. For two crop calculations values were obtained from UC Davis current cost and return studies based on California farms. The most recent cotton study is from 2012 and alfalfa from 2016 (UC Davis Agricultural & Research Economics, 2018). Like the crop-water production functions, this may not reflect true current conditions in central Arizona, but they do provide reasonable values for comparison.

3. Results

The cost of water makes a small difference in both quantity of water used and farmer profit. After a switch to groundwater from CAP, a cotton farmer with the water costs modelled would increase water use if able. There is a small spatial difference in optimal water use and profit for groundwater irrigation due to differences in depth to groundwater throughout the AMA, but temporally there have been few significant differences in average optimal profit over the past 25 years due to groundwater levels. Farmers facing the water costs modelled here are incentivized by increased profit to use slightly more water under a switch to groundwater; the amount of water available and at what cost will play an important role in the profits that farmers are actually able to achieve.

3.1 Groundwater compared to CAP

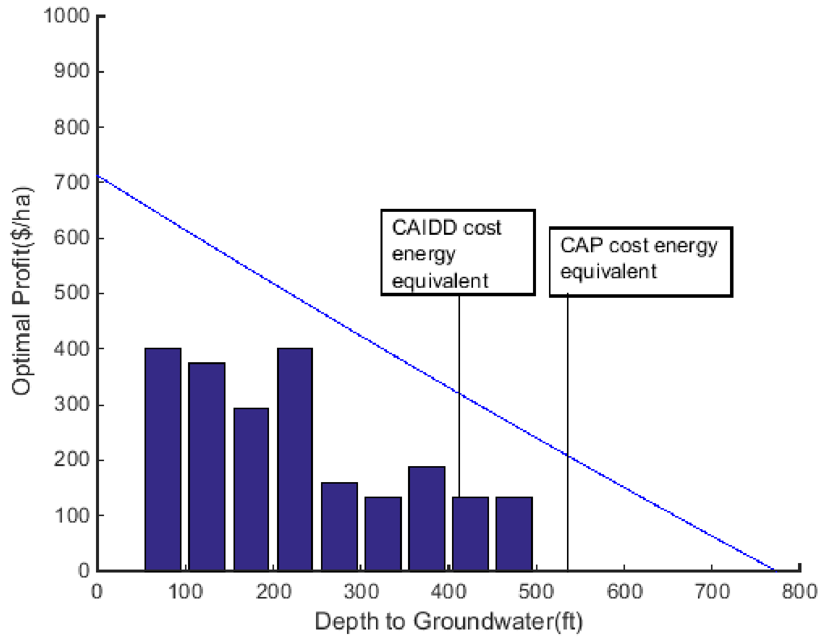


Figure 12: Change in Optimal Profit Based On Energy Cost to Pump Groundwater of Differing Heights. Profit decreases slowly with depth to groundwater. The decreasing blue line represents the optimal profit that a farmer can earn by pumping groundwater from that depth. Cost of CAP water is equivalent to a depth to groundwater of approximately 536 feet. CAIDD water charges are equivalent to 420 feet to groundwater given constant pump efficiency. The relative frequency of depth to groundwater observed in 2018 wells near irrigation districts is shown in dark blue bars. All wells in the GWSI index are well below CAP cost levels.

For the situation where an irrigator has available well capacity, the energy cost of groundwater is cheaper than costs charged by the Central Arizona Project for irrigation water, which is offered at cost and at a large discount compared to municipal and industrial water. Depth to groundwater would have to increase approximately 300 feet for cost parity between the two water sources (Figure 12). However, the current cost paid by farmers is not the pure CAP cost, but a mix of surface and groundwater. The Central Arizona Irrigation and Drainage District (CAIDD) provides water at a rate of $58.8 per acre-foot, this is likely closer to the cost that most users see. Converting the energy cost of pumping groundwater from 248 feet below the surface is equivalent to $35.89 per acre foot with the assumptions given above. Table 3 shows the calculated optimal profit and height of irrigation for each of the three water costs. Going from CAIDD water to purely groundwater would result in a cotton farmer using approximately 2.9% more water which would increase profit by 40 percent. With the ability to take advantage of existing pumping capacity, it is in a cotton farmer's best interest to replace surface water with groundwater to the degree possible.

In many situations, however, there will be factors like drilling or maintenance costs associated with expanding groundwater use. The CAP price of $76 per acre-foot provides a basis for a case of more expensive groundwater. Increasing water costs by $17.5 per acre-foot (~30%) results in a drop in profit of $45 per acre (33%). More information is needed to determine the likely range of groundwater costs, but higher water costs in any form will slightly discourage water use while lowering profits.

	Optimal Profit ($/ha)	**Optimal Height of Applied Irrigation (m)**
CAP ($76/AF)	227(92$/acre)	0.78 (2.56 ft.)
CAIDD($58.5/AF)	339(137$/acre)	0.80 (2.62 ft.)
Average Groundwater Well ($38.2/AF eqvlnt)	473(191$/acre)	0.82(2.70 ft.)

Table 3: Calculated Optimal Profit and Height of Irrigation.

3.2 Spatial Differences

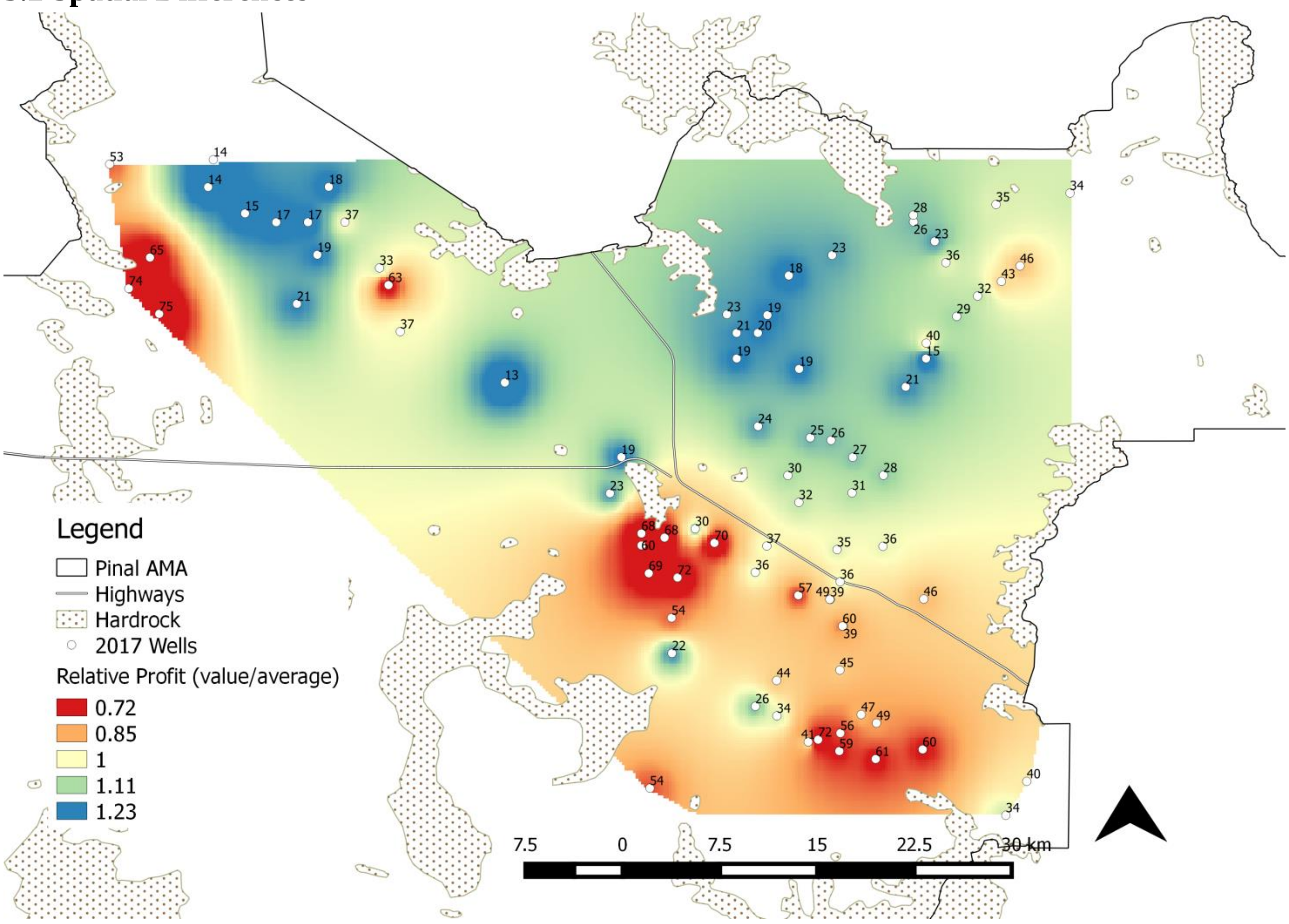


Figure 13: Relative (local value divided by mean) optimal profit possible based on depth to groundwater in 2018 water year. Interpolated display of maximum profit at each well divided by average optimal profit across all wells. Marginal cost of groundwater at each well listed in $/acre-feet

Depth to groundwater varies spatially across the AMA creating differences in energy costs for groundwater (depth to groundwater in Figure A4). Figure 13 shows how a cotton farmer's per acre optimal profit varies from the average based solely on depth to groundwater. The map shows how the maximum profit of a hypothetical farm with the exact same conditions would change based on a location's depth to groundwater compared to the average value. The difference in cost due to pumping leads to differences in cost and optimal profit across the AMA. Among farmers using purely groundwater, among the most extreme water levels, optimal profit can be about 60 percent lower in deep wells. The highest water levels produce an optimal profit of 267 $/acre at a depth to water of 73.1 feet while the lowest produce a profit of 100 $/acre with a depth to water of 510 feet. While the extreme values show large differences most wells are much closer to the average. The cost of water between all wells has a standard deviation of $17/acre-foot with an average of $38.2 per acre-foot.

Figure 10 highlights lower water levels in the southern portion of the AMA as seen in Figure 13 as lower optimal profit, so farmers in the southern portion are more limited in profit compared to their northern neighbors. Irrigation districts may spread the costs somewhat by using many wells to supply members so that high and low water levels average out. There are definite areas of high depth to groundwater though, so if irrigation district boundaries coincide with an area of low or high groundwater there may be differences in water costs due to pumping energy costs between irrigation districts.

3.3 Changes over Time

Average profit and water use for all wells show small changes from year to year. Figure 14 shows that although groundwater levels have changed during the period from 1993 to 2017, and in some wells dramatically, over the entire period there has rarely been a significant change in the median values.

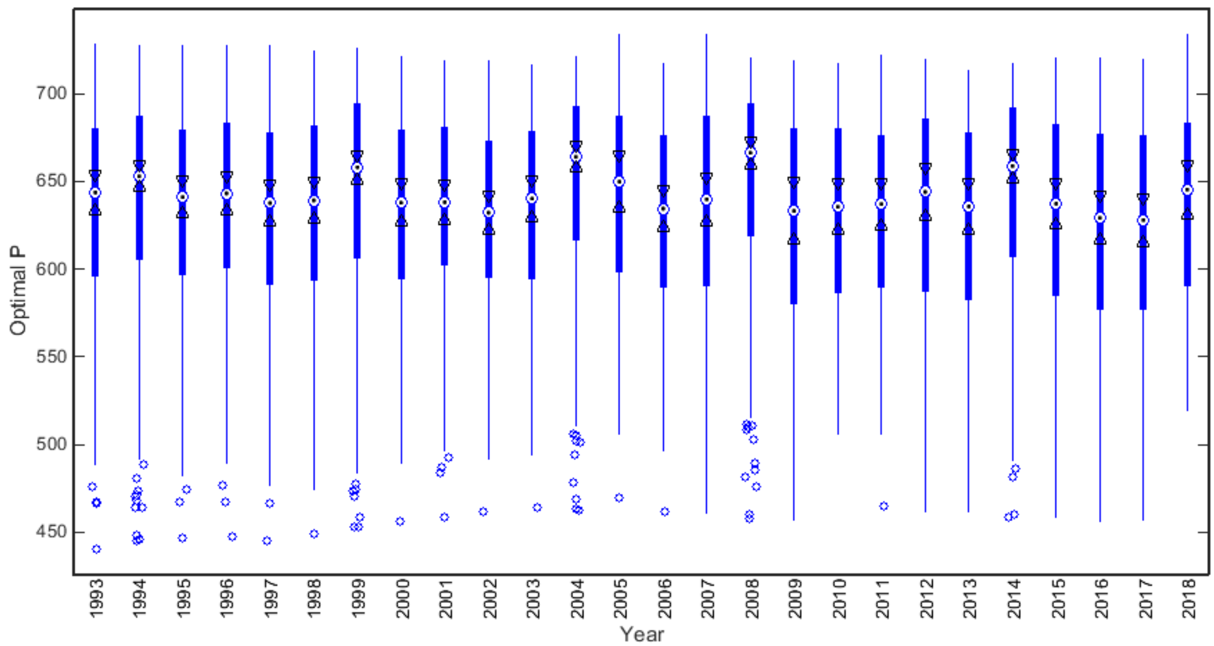
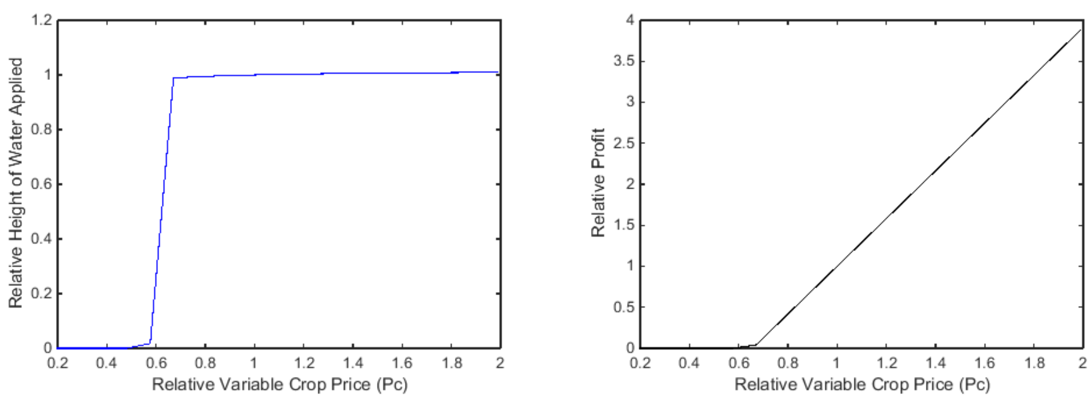


Figure 14: Statistics for optimal profit by year. Differences due to depth to groundwater at all wells deemed near agriculture in GWSI database. The top and bottom of each box represent the 25th and75th percentiles. The center dot is the sample median; a non-centered dot shows sample skewness. Whiskers show 2.5 times the interquartile range. Open dots show outlier values. Notches display variability of the median between samples. Any boxes whose notches do not overlap have different medians at the 5% significance level.

3.4 Sensitivity of Results



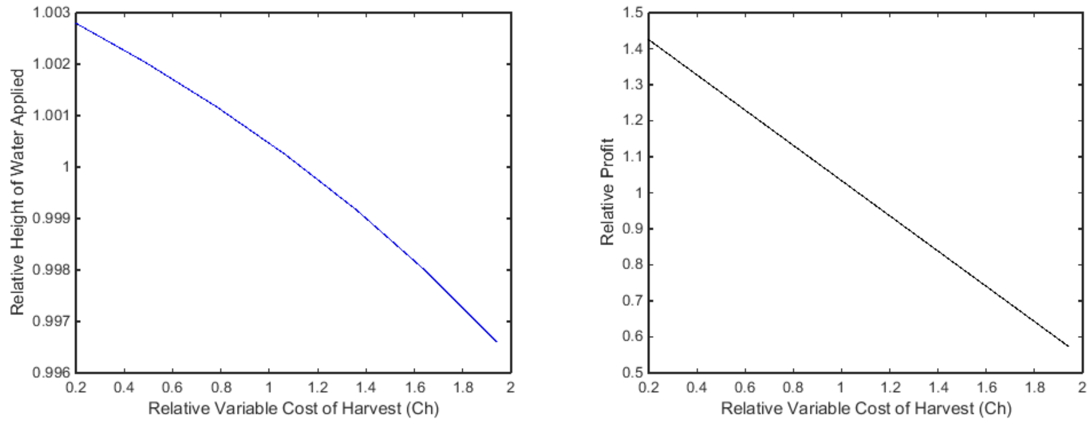


Figure 15: Sensitivity of maximum Profit and associated height of water applied with select constants relative to values used in study.

Figure 15 shows how maximum profit and its associated height of water changes with the constants in eqn. 1. While maximum profit is fairly sensitive to most constants, they generally have little effect on H_i, with an exception being large decreases in crop price. A forty percent drop in crop price would make farming cotton a money losing proposition. This is a possible, but not common occurrence; in the USDA "Cotton and Wool Yearbook" changes in price greater than 30% only occur 4 out of 46 years (9%) (United States Department of Agriculture Economic Research Service, 2017). A 20 percent drop in crop price would reduce profit by approximately two-thirds (191 $/acre to 62 $/acre). According to the USDA data, a 20 percent change in cotton price would not be unusual from year to year, occurring 14 out of 46 years (30%). This makes crop price one of the most important factors on profit. Any changes in profit due to limits on water or water source will occur with changing cotton prices also affecting profit. Cotton prices could offset or exacerbate losses from forgone water. Sensitivity for the other constants is generally small and visible in the Appendix (A3 and A4).

3.5 Profit under limited water

So far results have been presented assuming that a farmer is able to use enough water to maximize profit, but it is possible that well capacity will not be sufficient to reach H_i max. Figure 16 shows how profit changes with the maximum height of water that can be applied as irrigation compared to the maximum possible profit with other water costs presented as horizontal lines. Any time the black line is underneath a horizontal line indicates a loss of profit compared to that water source. While profit drops off below the optimal Hi of 0.85 meters (2.8 feet) there are amounts of irrigation where using groundwater is still more profitable than more expensive sources of water, even if limited in quantity. Compared to

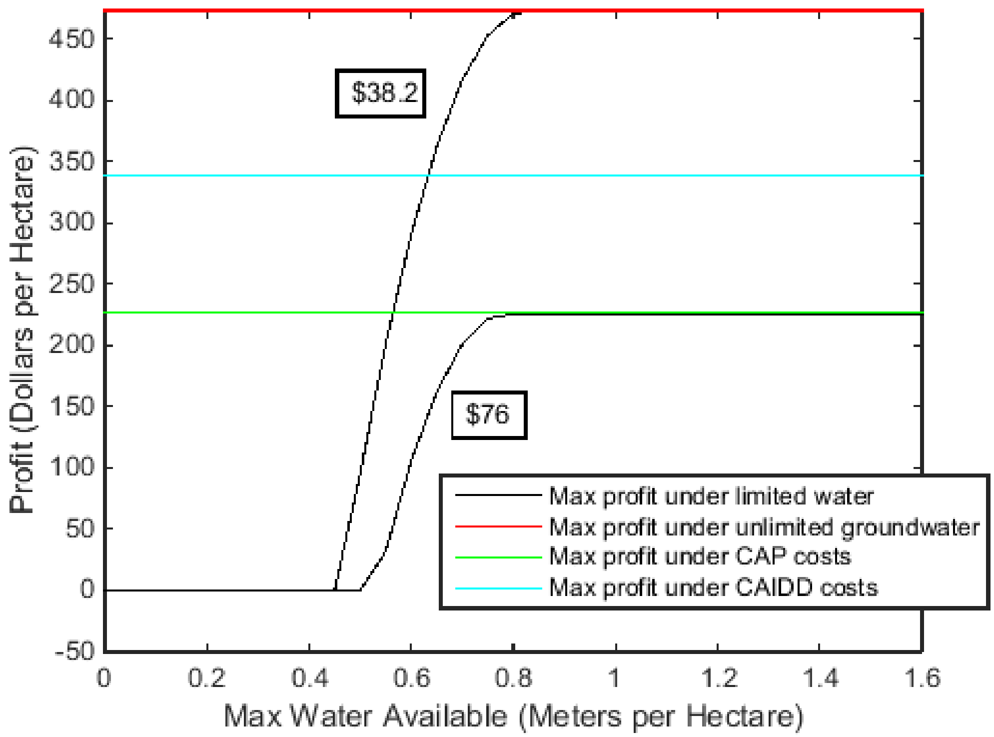
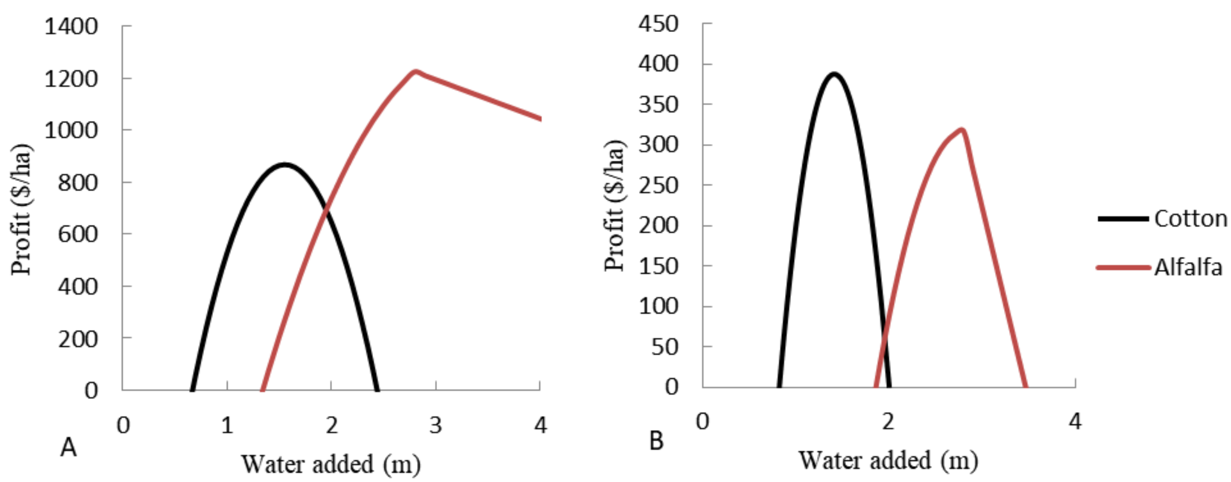


Figure 16: Optimal profit based on the maximum height of water that can be applied (black line)based on water cost and compared to the max profit under pure groundwater (red), CAP costs (cyan), and Central Arizona Irrigation and Drainage District (green). Top line is with water cost at $38.2 per acre-foot. Bottom line is with water cost at $76 per acre-foot. Differences in profit are greatest when optimal quantities of water are available, and cotton is profitable longer with cheaper water available. This highlights the importance of water cost on profit if water is limited.

3.6 Profits from Cotton and Alfalfa



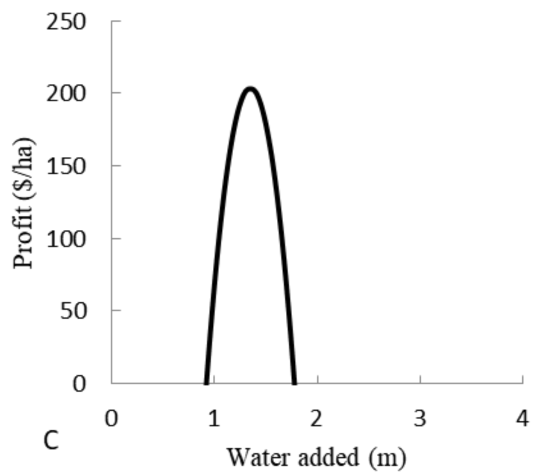


Figure 17: Farmer profit based on irrigation water added. Farmer profit for each crop based on the two-crop model, cotton is plotted in black and alfalfa in red. Each plot represents a different water cost. A is low cost water at $16.90 per acre-foot (pure groundwater cost). B is medium cost water at $58.60 per acre-foot (Electrical District Four rate). C is High cost water at $75 per acre-foot (CAP cost). Alfalfa is negative for all of C.

Based on the two crop model and associated crop-water production functions, alfalfa is a higher water crop than cotton. Figure 17 shows that profits are sensitive to water cost, especially alfalfa which has a smaller difference between the price of the crop and variable costs. Alfalfa is not profitable with any amount of irrigation at the $75 per acre-foot cost level. The peak profit for each crop occurs at around 1.4 meters (4.6 feet) of water for cotton and 2.8 meters (9.2 feet) of water for alfalfa. Compared to the USDA Farm and Ranch Irrigation Survey (FRIS), the average amount of water applied to cotton in Arizona is 1.37 meters (4.5 feet) per acre, which matches this calculated peak very well. Alfalfa fits data much poorer with the FRIS indicating 1.65 meters (5.4 feet) applied per acre on average to alfalfa in Arizona (United States Department of Agriculture National Agricultural Statistics Service, 2018).

3.7 Optimal Crop Coverage and Irrigation

Looking at a hypothetical 50 ha (124 acre) farm with the option of planting cotton or alfalfa, the optimal planting and irrigation changes based with the cost of water and the amount of water available. Generally speaking cheaper water tends to favor alfalfa. In this model with no limit on water used there is very little reason to plant more than one crop. Figure 18 shows the quick changeover from alfalfa to cotton when water costs more than approximately $50 per acre-foot. Profit wise it makes the most sense to maximize the area of the most profitable crop type.

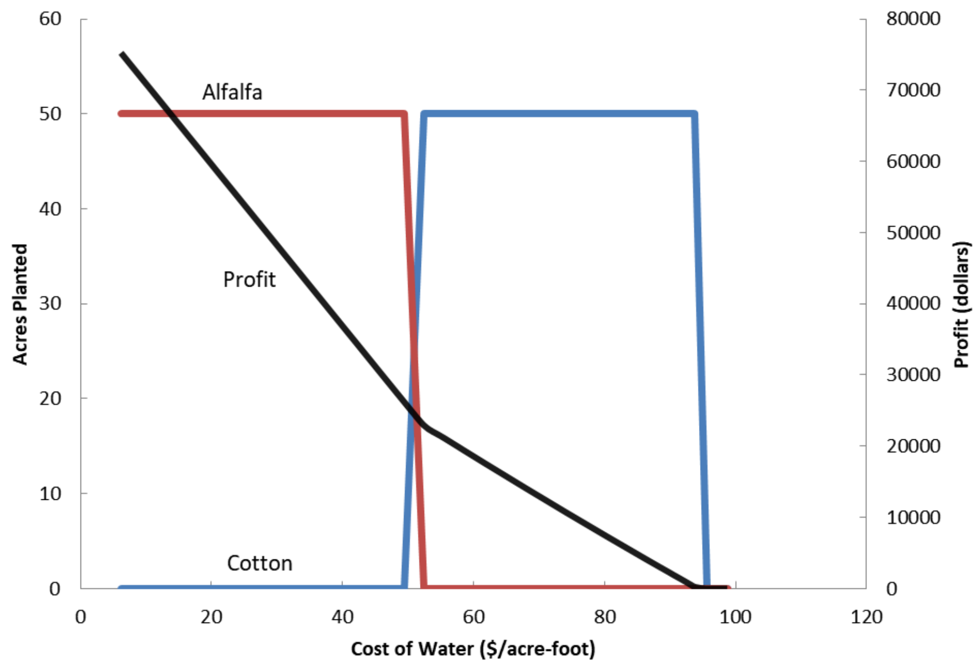


Figure 18: Profit and crop acreage with cost of water for a 50 ha (124 acre) farm. The black line displays optimal profit based on cost of water on the right axis. The blue (cotton) and red (alfalfa) display optimal crop acreage based on cost of water on the left axis. There is no limit on the amount of water that can be applied to fields in this scenario.

When facing limited water, the optimal crop area changes based on the amount of water available. The best type of crop depends on water cost and availability. With low cost and high availability alfalfa is favored. As water becomes more limited cotton acreage increases. At higher prices of water alfalfa is never planted according to this model (Figure 19 A. The full 50 acres are planted as cotton for higher water costs and high water availability (Figure 19 B and C) with acres being fallowed as water becomes more limited. Fallowing land allows irrigating the remaining cotton at near optimal rates (peaks in Figure 17).

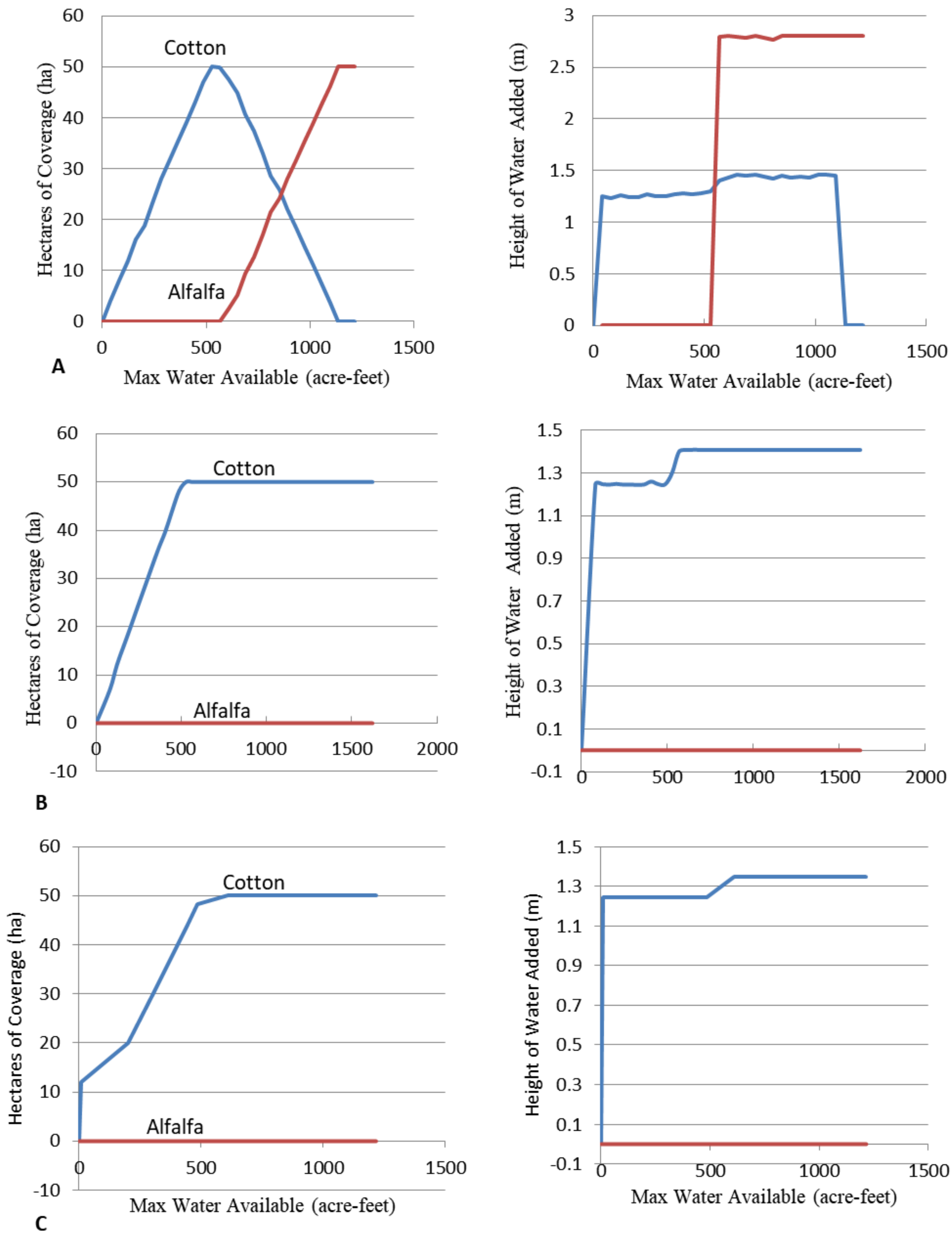


Figure 19: Optimal crop acreage and irrigation Levels under limited water on a 50 ha farm. Blue lines represent cotton and red lines represent alfalfa. Each row displays the optimal acres planted and height of water added for different costs

of water. A is low cost water ($16.90 per acre-foot), B is medium cost water ($58.60 per acre-foot), and C is high cost water ($75 per acre-foot).

4. Discussion

While the behavior of farmers will likely not be entirely profit maximizing or will not be perfectly reflected by the profit equation used here, there is a small, but clear incentive for irrigators to use more water if a switch from CAP water to groundwater is made. When planning for the future of the Pinal AMA, it is likely that any cuts in surface water deliveries to irrigators will be replaced by groundwater to the degree possible. This makes policies that limit groundwater withdrawals important to avoiding increases in groundwater depletion.

Spatial differences with respect to maximum profit and water use with groundwater within the AMA are generally small (Figure 13), but among some outliers there is the potential for differences due solely to local groundwater conditions. Irrigation districts may help offset the effects of a few very deep wells by operating many wells and spreading costs, so that many shallower wells will average out the costs in the deep well. There is also the potential to choose which well to pump from, using the high cost wells less often.

In 2015 according to the Pinal AMA Fourth Management Plan draft 256,136 acre-feet of CAP water was used for agriculture. If all this use was replaced with groundwater under the cotton growing conditions examined above, these results suggest that farmers would want to use about 272,270 acre-feet from groundwater if they are profit maximizing. This would be more than a fifty percent increase from the 2015 groundwater use observed in figure 3. This is also almost 100,000 acre-feet greater than the peak groundwater withdrawal year in 1985. There is not infrastructure to pump this volume of groundwater, but it does indicate that there may be a great demand for groundwater use under shortage scenarios. For determining actual use after a switch from CAP water, further knowledge on the number of irrigators with grandfathered rights and the well capacity will be important. These results show that farmers have an incentive to increase water use if possible, so it needs to be determined how much they can possibly pump both legally and physically.

In the case where groundwater is limited below the optimal use level, irrigators will see a loss in profit. This is very likely if there are large reductions in surface water deliveries to the AMA. Discussions related to the draft Drought Contingency Plan suggests as much as 50% of land may be fallowed in Pinal, indicating a large shortfall (Arizona Department of Water Resources, 2018).Using cheaper groundwater may provide an opportunity to limit the pain of water cuts. If irrigators do not increase irrigation amounts after a switch to groundwater they will not optimize their profit, but can still see increases (or smaller decreases) in profit. If an estimate for groundwater pumping capacity is made, then the profit calculations used here can provide an estimate of economic losses to farmers in the Pinal AMA due to a shortage on the Colorado River. Figure 16 shows how important water price is on farmer profit when water is limited. Farmers with access to relatively cheap groundwater will see smaller decreases in profit if land must be fallowed. This highlights the importance of determining what marginal water costs for producers look like and how it is distributed across the AMA.

When looking at the two crop model there are situations where a mix of cotton and alfalfa maximize profit, but this only occurs at relatively low water costs. Cotton, with its relatively lower water use, is favored at water prices seen at irrigation districts and as availability of water decreases. If there is a decrease in the available water in the Pinal AMA it is likely that we would see a decrease in alfalfa acreage.

4.1 Shortcomings of this Study

As discussed in section 2.3.1, the method of calculating the marginal cost of groundwater should represent the short term water cost for irrigators with the ability to use existing pumping infrastructure. This covers some users, but many will have higher groundwater costs. Results here show that higher water costs result in lower profit and slightly lower water use, but more information on cost is needed to estimate the cost of water beyond the energy cost. Further complicating matters, farmers have options not modelled here like leasing groundwater wells to irrigation districts trying to expand capacity. While the lower end of groundwater costs was determined here using the energy cost to lift water, more information is needed to estimate upper bounds of groundwater costs. More information is needed for a complete look at how a call on the Colorado will affect the entire AMA.

Figure 5 shows that using a constant marginal groundwater cost results in the highest water use value compared to other likely cost curves. This makes results here high for groundwater withdrawals and farmer profit. This may be good news for limiting groundwater overdraft, but farmers may see a greater economic loss than indicated here. Better information on groundwater costs and infrastructure, through something like farmer surveys, could easily be used to improve the cost function and results presented here.

Rising costs with increased depth to groundwater make recovering groundwater less attractive, but depth to water will not have a large effect on water costs due to energy costs alone. While water use decreases slowly with an increase in drawdown; the average well would have to see an additional drawdown of approximately 300 feet before being the same cost as current CAP water. However, there are several possible costs with declining groundwater that are not considered here. These results likely represent a high estimate for groundwater withdrawals as only the energy costs with a relatively efficient pump are used for groundwater cost. A large change in energy costs could compound lift costs. Decreasing well yield due to a lower saturated thickness could limit production or require new deeper wells. Water quality may degrade with depth. Investments in well components and maintenance costs generally increase with well depth, so actual costs would likely increase faster with depth to water than modelled here. Subsidence caused by lowering groundwater levels could also increase costs by damaging property or infrastructure.

The AquaCrop simulations used to construct the water-productivity relationship is uncalibrated. Calibrating the cotton settings to local conditions would make for a much better estimate of crop production and profit. This may make the absolute value of profit determined here unreliable, but comparison between different water costs using the relationship should still provide useful insight into the direction and magnitude of water use. The values for tons of cotton produced are similar to values in the USDA FRIS (1.74 tons/ha modelled vs 1.85 tons/ha average in Arizona). It, however, uses an unrealistically low amount of water to produce this amount using 2.7 feet compared to an Arizona average of 4.5 feet (United States Department of Agriculture National Agricultural Statistics Service, 2018).

The AquaCrop derived water-production function includes variability due to weather during the growing season by using AZMET data and the very good fit of the data (r^2=0.94) suggests little variance due to weather as most variance is explained by water added to crops. There are, however, several sources of crop production variability that are kept constant during simulations like soil type and field management techniques among others. There will likely be sizable variance of crop production on different farms based on many factors not considered here.

It is possible that this model favors fallowing by lowering costs unrealistically for fallow land. The fixed cost (C_f) term only applies to planted acres, so fallowing land can greatly reduce costs. Some costs like fertilization and planting costs are avoided, but things like property tax and depreciation would still apply. A more sophisticated model of costs could improve estimates, but given the fairly limited fallowing observed in the model (only at low water availability and high water cost) the benefits from this may be limited.

Water Quality may have an effect on the quantity of water used as farmers go from relatively salty Colorado River Water to groundwater. This could potentially have an important effect on the crop-water productivity function and change results. Further complicating matters, groundwater quality will change as sources of recharge change.

4.2 Possible Improvements with Utility Function

It has been found that a utility maximizing model is better than a profit maximizing model at representing farmer behavior (Lin, Dean, & Moore, 1974) (Kim & Kaluarachchi, 2016).

Following similar methods to this study with a utility maximizing model could improve analysis. Such a model could be developed, like that used by (Kim & Kaluarachchi, 2016):

$$U = E(\pi) - \Phi * \sigma_P \qquad \textbf{Eq. 9}$$

Where E(π) is the expected profit much like equation Eq. 1 used above its units are dollars ($), Φ is the risk aversion coefficient of the farmer (unitless) and σ_P is the standard deviation of profit($). Two major sources of uncertainty in farmer profit are climate and price uncertainty. Implementing a model like this would likely better reflect real life behavior. This might show increased value in diversified crops unlike the rather narrow set of circumstances where planting two crops make sense in the two crop model used here.

4.3 More Current and More Localized Data

Improving the sources of data mentioned in this thesis as uncertain would greatly improve results. Details like better understanding farmer groundwater cost along with fixed and variable costs and returns specific to central Arizona could be obtained by farmer survey. Better crop-water production functions would greatly improve results for the two crop model either by calibrating parameters for alfalfa in AquaCrop or creating functions based on experimental data like Ayer & Hoyt, 1981. Both of these would require data on crop inputs and outputs which would likely involve lengthy data collection. The cotton function derived in AquaCrop also seems to be an overestimate as discussed in section 2.4.2. Changes to field management in the model, or parameterizing the AquaCrop cotton characteristics to more local data could improve the representation of crop production. The data should also do a better job of representing water stressed plants so that the crop-water production function is more robust for many water levels.

4.4 Implications

Results here provide a general idea of farmer behavior under changing water sources and costs, which has great implications for water management in the Pinal AMA.

1. It is likely that effects on farmers will be mixed depending on individual situations. Based on depth to groundwater and the lift energy cost, it is possible that some farmers will be able to see increased profits and will want to replace any lost surface water with groundwater to the degree possible. It is unclear how many farmers have available pumping capacity and the costs to increase pumping capacity. This makes determining pumping capacity and costs important to the overall effect a switch from CAP water will have.
2. What ability farmers have to increase groundwater pumping and at what cost is important to groundwater management and economic output in the Pinal AMA. The models used here provide a basis for estimating water use and farmer profit under a variety of cost

structures, more data on farmer cost is needed to estimate possible economic losses following a shortage on the CAP.

3. Increasing costs of water due to increased depth to groundwater will only have a small effect on water use. Cost increases slowly with depth, so any reduction in water use due to this effect is modest. The groundwater withdrawal fee in the AMA increases groundwater cost somewhat ($3 per acre-foot), but does not have a large effect on water usage. Effects due to decreased well yield and costs associated with new wells are likely more significant.
4. Cotton is likely to be favored over alfalfa in water limited situations and with high price water. In a shortage scenario acreage of cotton planted is likely to increase barring any changes in factors like crop price.
5. Quantity restrictions on water can have a large effect on farmer profit, so efforts to conserve groundwater resources should be carefully balanced with economic considerations. Advances in more efficient irrigation could help offset economic losses to farmers.

Appendix

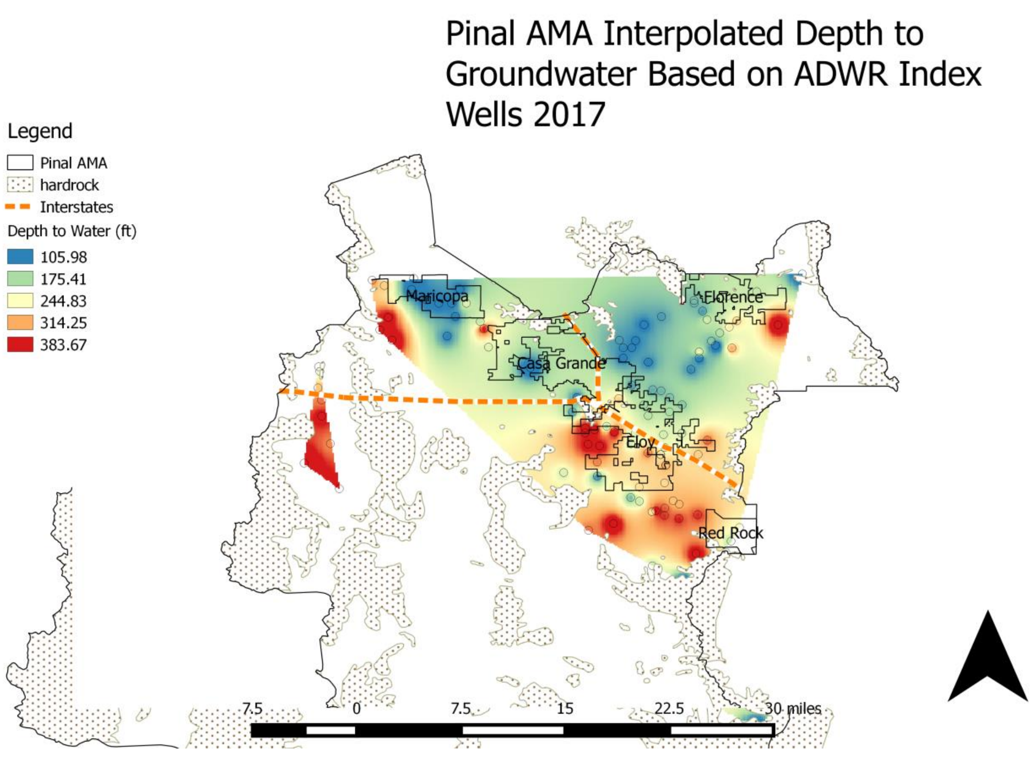


Figure A1: Depth to groundwater interpolated across Pinal AMA based on 2017 index well readings. (Arizona Department of Water Resources GIS)

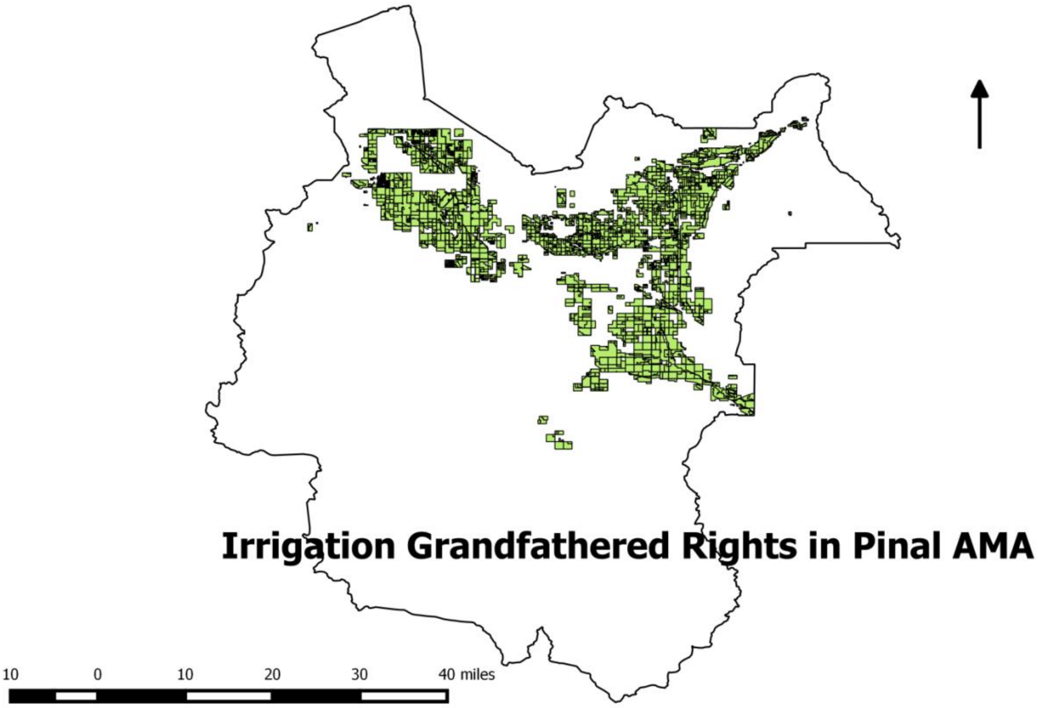


Figure A2: Locations of grandfathered irrigation right in Pinal AMA. Data from ADWR (ADWR GIS, 2018)

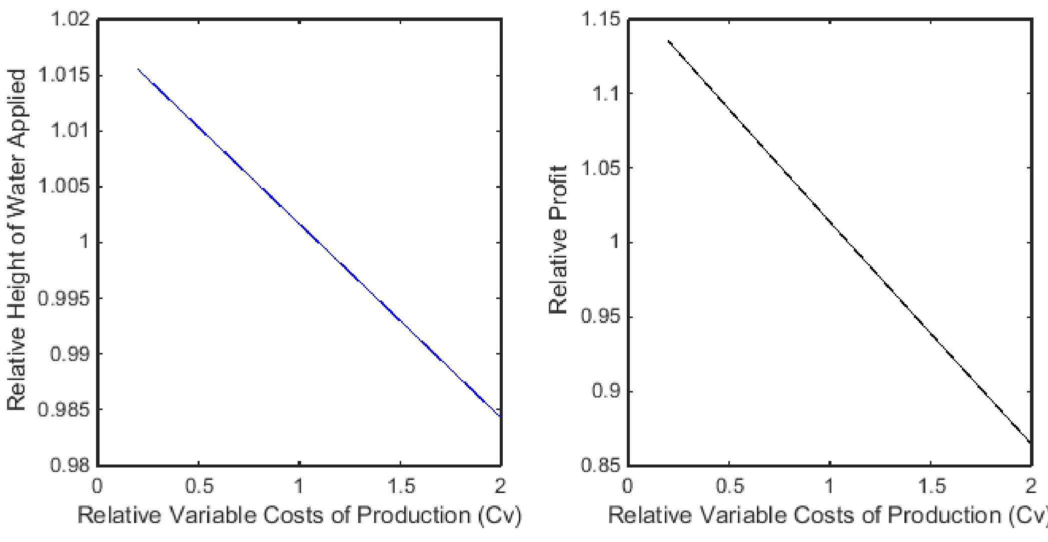


Figure A3: Sensitivity of maximum profit and associated height of water with variable costs of production relative to value used in study

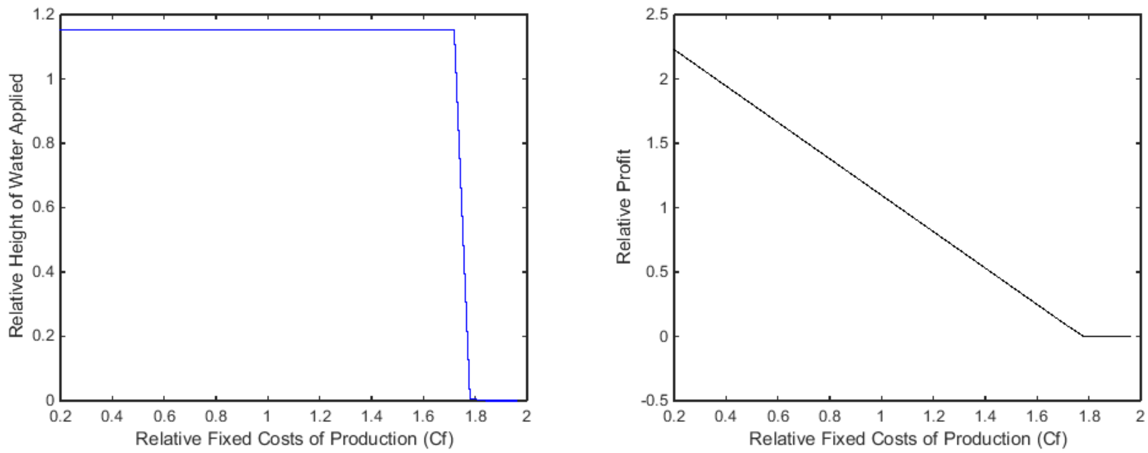


Figure A4: Sensitivity of maximum profit and height of water with fixed costs of production (Cf) relative to values used in study.

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