IMPROVED MODELING USING AN INTEGRATED APPROACH FOR WATER POLICY EVALUATION IN TEXAS

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ABSTRACT

Irrigated agriculture is becoming challenging to sustain with diminishing water levels worldwide and increasing population. Groundwater is a nonrenewable resource throughout much of the world, and in instances when it is renewable, it is often a time-intensive rate of recharge. Producers of the High Plains region within Texas are facing this growing concern of groundwater depletion of the Ogallala Aquifer. Producers are faced to make changes in production decisions to remain profitable as their well capacities diminish. A two-stage integrated optimization model was developed to evaluate changes in crop mix, water availability, and profits for producers within Hartley County, Texas.

An integrated model was developed to incorporate changing agronomic, hydrogeological, and economic components, then further evaluate how these changing components influence both the resulting output and the producers' decision. The model was developed using a general non-linear optimization package called 'Rsolnp' in RStudio (RStudio, 2020). The model compared the results of seven different scenarios to the baseline scenario over a 30-year study period. The scenarios would include water restriction scenarios, acreage restriction scenarios, an increase and decrease in fuel price scenarios, and an increase and decrease in commodity price scenarios.

The model was broken into two stages; stage one is where producers decide to make planting decisions to maximize profit based on the expectation of receiving the average annual precipitation for the specific crop and the availability of water they can apply to the planted crop that is determined by their well capacity. In stage two, the crop acreage is already planted based on decisions in stage one; producers will now decide how to actually allocate their water based on the received variable precipitation. Results of profits were compared between stages one and two, which calculates profits producers would expect to see as compared to the profits they may actually receive.

Results of the scenarios give the comparison to producers and policymakers on what actions are needed to take in order to stay profitable. All scenarios suggest that there will be a decline in water availability throughout the 30 years. In stage two, a 50 percent acreage reduction brought the producer the most stable profit with a standard deviation of $6,362 per year. To conclude, both policymakers and producers should include the use of a two-stage modeling technique to evaluate their management decisions and potential applications of policies. The two-stage modeling technique represents producers' actual behavior and operating environment. This modeling technique gives better intel to producers on how to expect profits to vary year to year so they can further prepare and mitigate their financial risks. It also illustrates to policymakers how the changing precipitation conditions will impact groundwater availability from year to year.

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CHAPTER 1: INTRODUCTION

Irrigated agricultural production is essential in keeping the world fed. Irrigation covers 20 percent of all cultivated land worldwide while making up 40 percent of agricultural production (Colette & Guillaume, 2021). The use of irrigation helps in achieving high yields, which leads to plentiful supply. Water for irrigation comes in many forms: rivers, lakes, runoff, reservoirs, and groundwater aquifers. However, irrigated agriculture is becoming challenging to sustain with the diminishing water levels worldwide and increasing population. One water source of growing concern is groundwater. Groundwater is a vital resource in countless countries worldwide and aquifers are a critical reserve for over two billion people in the world (Famiglietti, 2014). Groundwater also plays a considerable part in agricultural production, where many countries like India, China, and United States heavily rely on this diminishing resource for production (Rosegrant et al., 2009). Groundwater is a nonrenewable resource throughout much of the world, and in instances when it is renewable, it is often a time-intensive rate of recharge.

One aquifer of significant concern in the United States is the Ogallala Aquifer located in the High Plains. This aquifer underlies 175,000 square miles in parts of eight states: Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, which includes the vast majority of the Texas Panhandle (McGuire, 2017), Figure 1. The water from this aquifer serves as the primary source of agricultural and public water supplies. The High Plains is a powerhouse for the United States, producing 30% of total crop and animal production. This agricultural production is responsible for 90% of the water pumped from the aquifer (Cano et al., 2018). The aquifer provides a value of $20 billion of food and fiber to the world's market (Little, 2009), mainly due to the availability of water which has allowed for irrigated agricultural production. The vital resource is delicate as farmers continue to deplete this aquifer faster than the recharge rate. Farmers for years have been utilizing this water resource to mitigate their climate risk; this has given them the ability to maintain a certain level of profitable yields. The High Plains region frequently has prolonged periods of drought and hot weather (Cano et al., 2018). As levels continue to decrease, highly variable yields will challenge the regional economy.

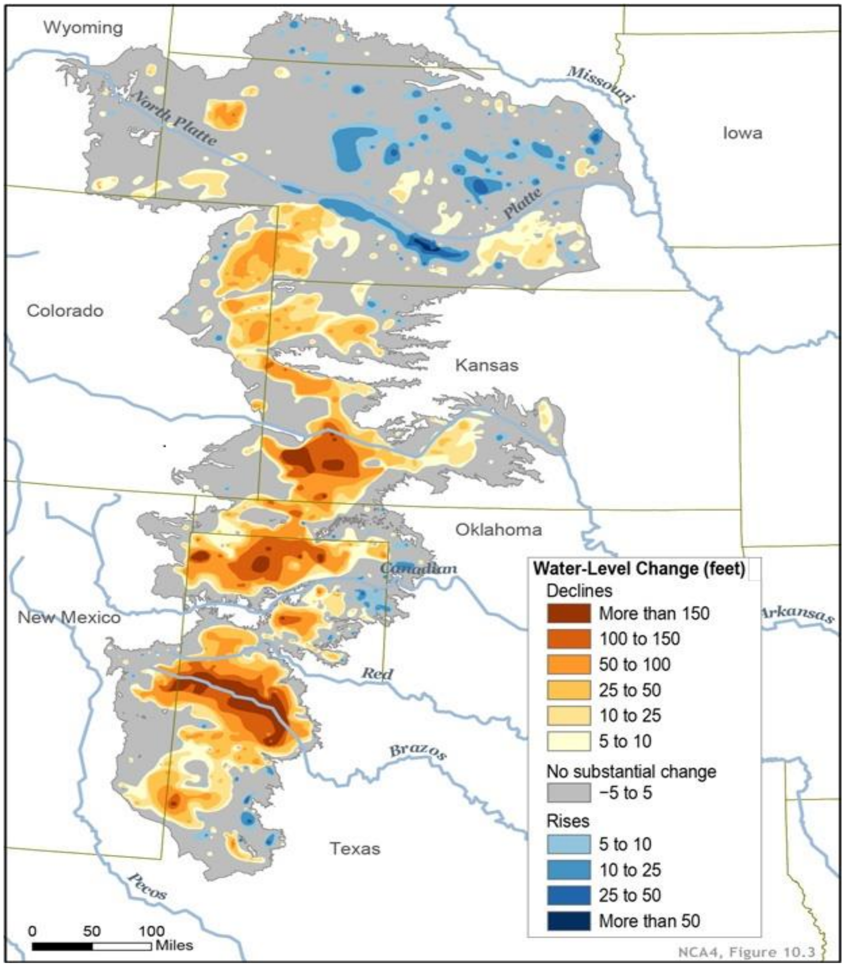

Figure 1. Changes in Ogallala Aquifer water levels, 1940-2015.
Source: (Scott, 2019)

The groundwater resource was not always accessible in previous generations of farming. Without the proper pumping technology, irrigation within the High Plains would not be in existence. Large withdrawal of water began after World War II when diesel-powered pumps replaced windmills. This increased the output of water to hundreds of gallons a minute instead of just a few gallons (Little, 2009). It was believed that there was nearly unlimited water availability in this aquifer at this point. By 1949, there were 2.1 million acres of irrigated cropland across the High Plains. Irrigated acres peaked in 2005 at 15.8 million and then fell to 15 million acres by 2015 (McGuire, 2017). As irrigated acres increased, water levels have declined rapidly, which has increased the incentive to irrigate more efficiently. Irrigation technology improved from flood and furrow to today's techniques of center pivot sprinkler systems and sub-surface drip.

The Texas High Plains is an area within the Ogallala Aquifer Region with low levels of saturated thickness and a particularly high concern for water depletion. The economy is largely driven by agricultural production. The primary crops produced are corn, cotton, sorghum, and wheat. Producers are experiencing above-average water level declines, which is increasing pumping costs and leading to sub-optimal crop yields (Taghvaeian et al., 2016). Depletion will impact both producers and consumers through decreased and more volatile profit, increased food prices, loss of jobs, and decreased land values. Thus, producers, consumers, and policymakers are looking for ways to continue agricultural production and maintain economic viability as water levels become critically low in the near future (McGuire, 2017).

The management and regulation of groundwater within Texas is carried out by 95 underground water conservation districts. Texas legislation has recognized the growing concerns of the groundwater supplies and requires the Texas Water Development Board to develop a comprehensive statewide water use plan. Although the law of the right to capture groundwater beneath the land still exists, the Senate has passed a Bill that has increased the authority of groundwater districts to regulate the use of groundwater within their jurisdiction. Corrective action from groundwater districts and policymakers could limit the use of the groundwater resource to preserve the resource for future use (Mace et al., 2006).

A model that acts in profit-maximizing producer behavior under a set of constrained resources can be useful in examining different policies and scenarios and the effect on important variables such as saturated thickness, well capacity, crop mix, water use, yield, and profit. Similar models have been developed and used in the past, but most of these models fail to incorporate accurate agronomic and hydrogeological relationships. In addition, previous models only include the decision variables of crop and irrigation amount. They do not include how a producer's decision may change given knowledge about precipitation events during the growing season. Thus, the overall objective of this study is to develop a model that integrates agronomic, hydrogeological, and economic interactions to examine producer behavior in Hartley County under the changing conditions of their operation. Specifically, a two-stage model will be developed in which planting decisions are determined in the first stage under the expectation of average precipitation and irrigation decisions are determined in the second stage with knowledge of variable precipitation during the cropping season. In addition to a baseline, seven different scenarios will be examined over a 30-year study period including: (1) maximum available water limited to 75 percent of capacity, (2) maximum available water limited to 50 percent of capacity, (3) irrigated acreage restricted to 50 percent of total acreage, (4) increase in fuel price, (5) decrease in fuel price, (6) increase in commodity prices, and (7) decrease in commodity prices. The results will be useful in providing policymakers with information about the changing conditions of producer resources and profits under different water conservation policies and market scenarios. This will aid the formulation of policies as regional leaders attempt to conserve resources while continuing to support the agricultural industry and the regional economy that depends on the production.

CHAPTER 2: LITERATURE REVIEW

The development of optimization models has been a significant area of research interest in response to concerns about natural resource utilization. Several economic models have been developed to predict and evaluate the impact of suggested water conservation policies and how water levels change over a given timeline (McGuire, 2017; Johnson et al., 2011). Optimization models create tremendous tools for research and developing policies that may influence both natural resources and the economic environment. Optimization models minimize or maximize the solution to an objective function under a bound of constraints to evaluate scenarios where resources are limited, representing real-life decisions. Models vary in complexity, ranging from simple models on paper to more rigorous models using data analysis programs. These models are often built using previous models as a foundation and expanding them as technology develops and software availability and commonality of use changes.

Segarra and Feng (1994) derived dynamically optimal rates of groundwater use in agriculture to maximize the net present value of returns to the producer's groundwater stock, land, capital, management, and risk. The decision variables included crop acres (cotton, grain sorghum, and corn), irrigation technologies, and water application. Two models were used, a dynamic programming model and a bio-simulation model of crop growth, over a 50-year time horizon. Two different tillage practices, conventional and conservation tillage, and six irrigation technologies, conventional furrow, improved furrow, sprinkler-high pressure, sprinkler-drop, low energy precision application, and dryland farming, were included (Segarra and Feng, 1994)

Results indicated a shift in the crop pattern; irrigated cotton increased from 40 to 74 percent, dryland cotton decreased from 36 to 0 percent, dryland sorghum increased from 13 to 23 percent, and irrigated corn decreased from 4.5 to 0 percent over the first 40 time periods (Segarra & Feng, 1994). Only three irrigation technologies (less than five percent improved furrow, 60 percent low energy precision application, and the remaining percentage in dryland farming) and conventional tillage were included in the solutions. Net present value of returns varied from $819.10 to $3,230.40 per acre. Producers willing to adopt advanced irrigation technologies increased expected returns by 52 percent. The authors concluded that irrigated acres are unlikely to decline due to inefficient irrigation technologies, resulting in water reduction and lower net present values. The best policies to conserve water do not increase profitability for continuing irrigation.

Terrell et al. (2002) conducted one of the earlier studies analyzing economic impacts from the depletion of the Ogallala Aquifer using linear programming. This study consisted of 19 counties in the Texas Panhandle. Two analytical tools were used in this study: dynamic linear programming models and IMpact analysis for PLANning (IMPLAN), an input-output modeling program. The dynamic linear programming models were used to estimate optimal cropping patterns, groundwater use, irrigation technology adoption, saturated thickness, and pumping lifts within the study region over 30 years. IMPLAN was used to estimate the regional economic impacts resulting from changes in crop production given the constraints of water supply by evaluating changes in final demand for the goods and services the region produced. This provided output, income, employment, and value-added impact estimates to quantify “shocks” to the economy. (Terrell et al., 2002)

The dynamic optimization model included crop choices of irrigated and dryland cotton, grain sorghum, wheat, and irrigated corn (Terrell et al., 2002). This model included the constraints of the crop and irrigation technology adjustment rate, the percent of cotton grown, and the inclusion of a wheat enterprise. The irrigation technologies were: conventional furrow, low-energy precision application (LEPA) sprinkler, and dryland farming. Hydrogeological equations were included within the model to describe the characteristics of the aquifer and depletion rate depending on pumping cost and irrigation availability.

The results indicated that as saturated thickness of the Ogallala Aquifer diminishes, and pumping lifts increase, regional cropping patterns will shift towards dryland production (Terrell et al., 2002). Saturated thickness of the aquifer decreased 22.1 percent by 2025, while the pumping lift increased by 10.6 percent and pumping capacity decreased by 43.6 percent on average across the region. As a result, dryland production increased by 4.9 percent and producers switched to a less water-intensive crop, cotton, decreasing all corn, grain sorghum, and wheat production values. In addition, producers increased adoption of the more efficient sprinkler irrigation systems by 9.8 percent, while furrow irrigation decreased by 7.5 percent. The total value of production increased with the change in crop mix; however, there was a downward trend after the peak production year of 2000, causing a loss to the regional economy of $190 million (including direct, indirect, and induced effects) (Terrell et al., 2002)

Almas et al. (2006) developed an economic optimization model to analyze alternative water management strategies to conserve groundwater resources from the Ogallala Aquifer for 23 counties in the Texas Panhandle over a 60-year planning horizon. Irrigated and non-irrigated harvested acres were determined by county and included a crop mix of pasture, corn, cotton, sorghum, soybean, wheat, peanut, alfalfa, and sorghum forage. Variable crop production costs and energy prices were calculated using a five-year average (1999-2003) and were adjusted from projected budget values for specific county crop yields and water coefficients. Hydrologic data included saturated thickness, groundwater volume, and the depth from the surface to groundwater bed (Almas et al., 2006).

The study objective was to maximize net income from crop production using a set of variables under given constraints. The decision variables included water application rate (under the assumption of all sprinkler irrigation) and crop mix. Constraints of the model were broken into five different categories: water availability, production, cropland use, total cropland, input, and marketing transfer (Almas et al., 2006).

Crop mix shifted significantly as corn acreage declined by 18 percent, making up only four percent of total production by 2060. Irrigated wheat was no longer profitable by the end of the study period, while dryland wheat production increased from 26 percent to 82 percent. Overall, dryland crop acres increased by 212 percent. A noteworthy result of this model was the increase in alfalfa production from 0.04 percent to five percent of crop acres (Almas et al., 2006)

This model demonstrated a loss of net revenue for the first six years due to the adjustment of crop mix based on water availability. For the next five years, there was an increase in revenue as crop mix switched to the more profitable choice, and the remainder of the study period indicated a downward trend in revenue. Overall results indicated an increase in dryland farming and a decrease in irrigation. However, even with decreased irrigation, saturated thickness dropped significantly by approximately 58 feet by year 60 (Almas et al., 2006).

Wheeler-Cook et al. (2008) used a nonlinear optimization model to analyze and evaluate the impacts of selected policy scenarios. This model was developed using General Algebraic Modeling System (GAMS) software. The objective was to maximize the net present value of net returns to land, management, groundwater, and irrigation systems over a 60-year time period for 24 of the 26 counties over the Southern Ogallala Aquifer. In these counties, the primary crop mix was cotton, corn, grain, sorghum, peanut, and wheat (Wheeler-Cook et al., 2008).

The authors used different drawdown policies to compare how the present value of the land was affected as the aquifer levels change. A baseline non-restricted access to water was compared to three different drawdown policies: 0, 50, and 75 percent using net present value per acre and the amount of water conserved. An estimate determined by Stovall using Texas Water Development Board data was used in the study (Wheeler-Cook et al., 2008).

The zero percent drawdown policy required production of only dryland crops. This resulted in a significant amount of conserved water and a substantial negative impact on the net present value of the land and overall economic activity. Both the 50 and 75 percent drawdown policies decreased the net present value and conserved water as expected. It was noted that these two policies might be very impactful in the long-run for high water use counties. In high water use counties such as Hale County, NPV only decreased by 16 percent (compared to seven percent) under the 50 percent drawdown policy while conserving 16 more feet of water than the 75 percent drawdown policy. The study concluded that overarching regional policies are challenging to implement due to significant differences in characteristics across the study region. Policy, and the use of tax money, is more effective if designed specifically for areas with similar characteristics. In addition, policymakers can make a more considerable difference in water conservation and mitigate the regional economy's risk when focusing on heavier irrigated counties (Wheeler-Cook et al., 2008).

A study by Almas et al. (2017) also used GAMS to develop optimization models to analyze the effects of potential water conservation policies for five counties in the Texas Panhandle. The study evaluated five different policies compared to a baseline scenario in terms of saturated thickness, water use, crop mix, and profit. The policies were (1) permanent conversion to dryland production, (2) irrigation technology adoption, (3) water use restriction, (4) biotechnology adoption, and (5) temporary conversion to dryland production (Almas et al., 2017).

All policies resulted in water conservation relative to the baseline; however, the biotechnology adoption and water use restriction policies had the largest water conservation. It was determined that biotechnology adoption had the best returns for producers by increasing yield, while the water restriction returned a very low net present value of returns, causing monetary loss for producers and the regional economy (Almas et al., 2017).

Crouch et al. (2020) conducted a study to estimate the potential water savings and implementation costs for different water conservation strategies in the Texas Panhandle over a 50-year planning period. The strategies that were identified for evaluation were: changes in irrigation scheduling, irrigation equipment changes, changes in crop variety, changes in crop type, conversion to dryland production, improved soil management, and advances in plant breeding, as well as different combinations of these strategies. While this study did not utilize optimization techniques, the focus was instead on calculating the potential for water savings as well as the cost of implementation (Crouch et al., 2020).

Results indicated that using a combination of strategies was the most effective in conserving water. The combination of irrigation scheduling, irrigation changes, changes in crop type, and advances in plant breeding generated the largest amount of water savings at 25,139,531 thousand m^3 of water. The authors concluded that when evaluating which strategies to adopt, policymakers should consider a good alignment with the water savings goals of the region and a strategy that will result in the largest water savings per dollar spent for implementation. Maintaining the Ogallala Aquifer for irrigation production in the future is essential but it is also vital to consider the regional impact and how local producers will be affected (Crouch et al., 2020).

Predicting changes in water levels is essential when evaluating policies and strategies conserve water. Groundwater based models, such as Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW), are used to predict the change in water levels of the Ogallala Aquifer (Harbaugh, 2005). The knowledge of groundwater conditions gives a better understanding of the water resources available in a given scenario (Hughes et al., 2017). Land and water management strategies have been evaluated utilizing these models to minimize groundwater depletion while maintaining adequate crop yield. These modeling techniques are classified into three modeling groups: (1) groundwater-based, (2) agronomic-based, (3) linked agronomic-groundwater-based models. Agronomic-based models, such as Decision Support System for Agrotechnology Transfer (DSSAT), predict the change in yield based on certain environmental factors for specific crops. DSSAT can simulate growth, development, and yield based on environment, soil, weather, and management for over 40 crops. DSSAT has the capability to analyze seasonal, spatial, sequence, and crop rotations to assess economic risks and environmental impacts associated with irrigation, fertilizer, nutrient management, climate variability, climate change, and precision management (Xiang et al., 2020).

Combining agronomic and hydrogeologic models with an economic optimization model creates a great analytical tool for the Ogallala Aquifer. In recent studies, there has been an attempt to integrate these models into one. Bulatewicz et al. (2010) adopted the strategy of linking individual domain models together to build a multidisciplinary integrated model. The study evaluated the impacts of two alternative water-use policies aimed at reducing irrigated water use of the Ogallala Aquifer (Bulatewicz et al., 2010).

Open Modeling Interface (OpenMI) was used, which gives the ability for models to exchange data with each other. Each model had to have the capabilities required by the OpenMI in order for the linkage to be possible. The capabilities were implemented in a helper program called a wrapper. The wrapper generated the model input files for the next time span to simulate any input quantities that it received from the linkable components. It then executed the model and read the output files to provide to other linkable components for the next time span. The input for each model was: (1) agriculture: crop choice, (2) groundwater: pumping rate and recharge, and (3) economic: saturated thickness. The resulting output from each model was: (1) agriculture: irrigated water use, yield, ET, PET, runoff, and percolation, (2) groundwater: groundwater head and saturated thickness, and (3) economic: crop choice and irrigated water use. At the start of the simulation, the groundwater model provided the saturated thickness to the economic model, and then the economic model decided which crops to grow and then informed the agricultural component. The agricultural component then simulated the growth and total water pumped for that year to the groundwater component. Lastly, the groundwater model calculated the water level at the end of the year and provided the saturated thickness back to the economic model to restart the cycle (Bulatewicz et al., 2010).

Model results indicate the estimated effect of two water policies assuming they were adopted in 2004 for a county in Western Kansas. The first policy was to restrict groundwater consumption to match the natural recharge rates and the second policy was to offer an incentive-based water-right buy-back program (Bulatewicz et al., 2010).

Models continue to be improved through the years to examine different policies that could be implemented to conserve water in the Ogallala Aquifer. However, these models still have their challenges and shortcomings. This study contributes to the previous literature and improves modeling techniques by using RStudio (RStudio, 2020) to incorporate information from agronomic, hydrogeological, and economic models. The integrated model includes the changing conditions of groundwater using MODFLOW, yield simulation with DSSAT, and effect on producer profit with economic optimization.

This study is also unique because it compares producer profits in two stages. Similar to previous studies, producers make planting decisions (acreage and expected water application) based on water availability and expected rainfall. However, this improved model includes a second stage which represents producer adjustments to water application relative to variable rainfall they might receive during a single growing season. This will demonstrate how total water use could increase or decrease each year as well as profit become volatile with yields reacting to both irrigation and changing precipitation levels.

CHAPTER 3: DATA AND METHODS

The statistical program R Studio was used to develop an integrated model that was designed in a two-stage profit-maximizing approach. This optimization model was developed using the non-linear optimization package Rsolnp within RStudio (2020). The model projected over a 30-year study horizon to predict producer behavior. The objective of the optimization model was for the producer to maximize profit, also referred to as the competitive market solution. The decision variables included the choice to plant a variety of crops and the irrigation amount to apply to each crop. The crop choices included corn, cotton, sorghum, wheat, and an average dryland crop to represent the primary crops grown in the study region. In stage one of the optimization model, the decision variable was the number of crop acres to plant to each crop based on the assumption of stationary average annual precipitation. In stage two, the decision variable is the amount of irrigation to apply to each crop choice based on variable precipitation, which reflects the risk surrounding pre-plant decisions and the inelastic producer supply curve during the cropping season.

The constraints of the model included the given limited resources of land, water, and assumption of historical average precipitation for the cropping season. The maximum land availability was 247 acres, which is equivalent to one MODFLOW cell. This single cell was assumed to represent the behavior of all of the producers within Hartley County. Water availability was limited by the initial well capacity in gallons per minute (GPM).

Study Region

The selected study region was Hartley County, where the economy is highly driven by agriculture. Hartley County is located in the northwestern part of the Texas Panhandle, Figure 1, and has a small population of nearly 5,400 people according to the U.S. Census Bureau (2021). What Hartley County lacks in population, it makes up for in crop production with 305,518 planted acres in both dryland and irrigated crops (USDA, 2021). This includes corn (30%), cotton (9%), sorghum (13%), wheat (46%), and dryland (2%).

Figure 2. Study region of Hartley County, Texas.

Profit

Profit maximization under constrained land and water resources was the objective function for both stages of the model. Profit in stage one was maximized subject to several constraints, Equations 1-8.

Annual Stage One profit maximizing objective function

1 $$\max_{A,EW} \sum_{i=1}^{n} P_i Y_i(EW_i, EP_i)A_i - CF_i A_i - CHSF_i(Y_i)A_i - CW_i(EW_i)A_i$$

Subjected to Constraints

2 $$\sum_{i=1}^{n} EW_i\, A_i \leq MAW$$

3 $$15 \leq Corn_A \leq 78$$

4 $$15 \leq Cotton_A \leq 23$$

5 $$15 \leq Sorghum_A \leq 33$$

6 $$15 \leq Wheat_A \leq 113$$

7 $$15 \leq Dryland_A \leq 247$$

8 $$75 \leq \sum_{i=1}^{n} A_i \leq 247$$

The profit equation included both revenue and costs, Equation 1. First, revenue was calculated where *i* represents the crop grown, P_i is the per unit crop price, Y_i is the per acre yield which is a function of EW_i and EP_i, EW_i is the 'expected' irrigation water allocation, EP_i is the expected seasonal crop-specific precipitation, and A_i is the number of acres allocated to the crop. In the cost portion, CF_i is the fixed cost per acre, $CHSF_i$ is the variable cost per unit of yield based on the variable costs of harvest, seed, and fertilizer, and CW_i is the per acre-inch cost of water which is a function of EW_i.

The objective function was maximized subject to several constraints, Equations 2-8. The first constraint states that the model generated total water use has to be less than or equal to the maximum available water (*MAW*), Equation 2, which will depend on the well capacity in the MODFLOW cell. The initial crop mix for year one was calculated based on the historical average ratio of each irrigated crop in the county. This initial crop mix is represented by the maximum values in Equations 3-6 with the lower bound set at 15 acres for each crop with no limit on the dryland option, Equation 7. After year one, irrigated acreage was allowed to increase by one percent per year for corn and wheat and by seven percent per year for cotton and sorghum. Total acreage (*TA*) must be greater than or equal to 75 (15 acres per crop) and less than or equal to 247 and cannot increase over time, Equation 8. In this stage, acreage allocation and the expected water allocation for each crop was chosen, given the well capacity and assuming average precipitation.

Stage two profit is very similar to stage one with water as the only constraint, Equations 9-10:

Annual Stage Two profit-maximizing objective function

9 $$\max_{AW} \sum_{i=1}^{n} P_i Y_i(AW_i, AP_i) A_i - CF_i A_i - CHSF_i(Y_i) A_i - CW_i(AW_i) A_i$$

Subjected to Constraints

10 $$s.t. \quad \sum_{i=1}^{n} AW_i \, A_i \leq MAW$$

where AW_i is the 'actual' irrigation water allocation, AP_i is the 'actual' seasonal crop-specific precipitation, and A_i is the acreage allocation for crop *i* determined in the stage one optimization. In this stage, the producer uses the acreage allocation determined in stage one and maximizes profit by choosing water allocation based on actual (and not expected) precipitation. The producer can apply more or less water to the crops as precipitation changes from one year to the next. Since precipitation in actuality is variable, producers are faced with years of drought and excess precipitation, which impacts yield, profit, risk, and ultimately, the water application decision. The average season precipitation *(EW)* by crop is displayed in Table 1, and the variable precipitation *(AW)* is illustrated in Figure 3.

Table 1. Average seasonal precipitation by cropping season.

Crop	Average Growing Season Precipitation (inches)
Corn	11.67
Cotton	10.15
Sorghum	12.51
Wheat	6.51

Source: (Uddameri and Ghaseminejad, 2022)

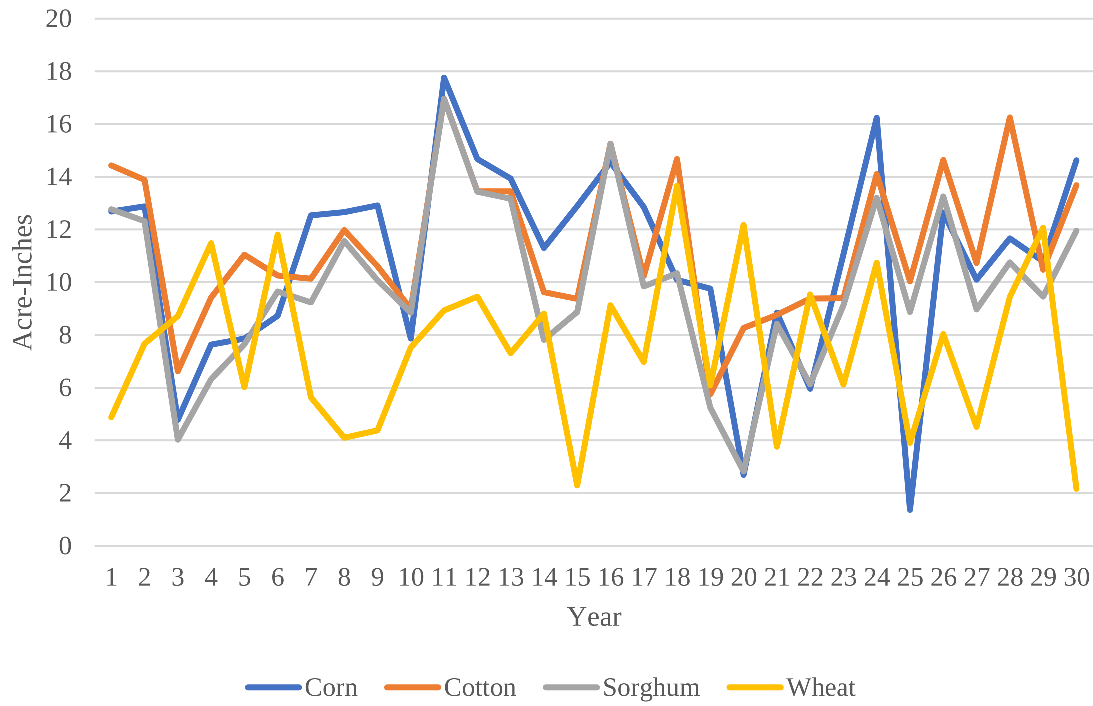

Figure 3. Variable seasonal precipitation based on historical values by crop.
Source: (Uddameri and Ghaseminejad, 2020)

Crop Yield

Mathematical production functions were defined to determine changes in crop yield (output) that occur due to changes in irrigation water applied (input) in acre-inches.

A quadratic equation was estimated for each crop by applying regression analysis to a data set generated from DSSAT to represent the study region, Equations (11-14) and Figure 4 (Uddameri and Ghaseminejad, 2022).

Hartley County Production Functions

11 $Corn_Y = -0.25IRR^2 + 15IRR - 0.25PRCP^2 + 15PRCP - 135$

12 $Cotton_Y = -1.7IRR^2 + 80IRR + 38.89PRCP - 41.83$

13 $Sorghum_Y = -0.25IRR^2 + 12IRR - 0.325PRCP^2 + 10.34PRCP - 56.79$

14 $Wheat_Y = -0.16178IRR^2 + 6.19152IRR - 0.62533PRCP^2 + 13.7491PRCP - 38.6496$

where *IRR* is the amount of irrigation applied in acre-inches and *PRCP* is the amount of precipitation the crop receives during the growing season. Specific crop yields were more reactive to an additional acre-inch of water than others, with wheat being the least reactive.

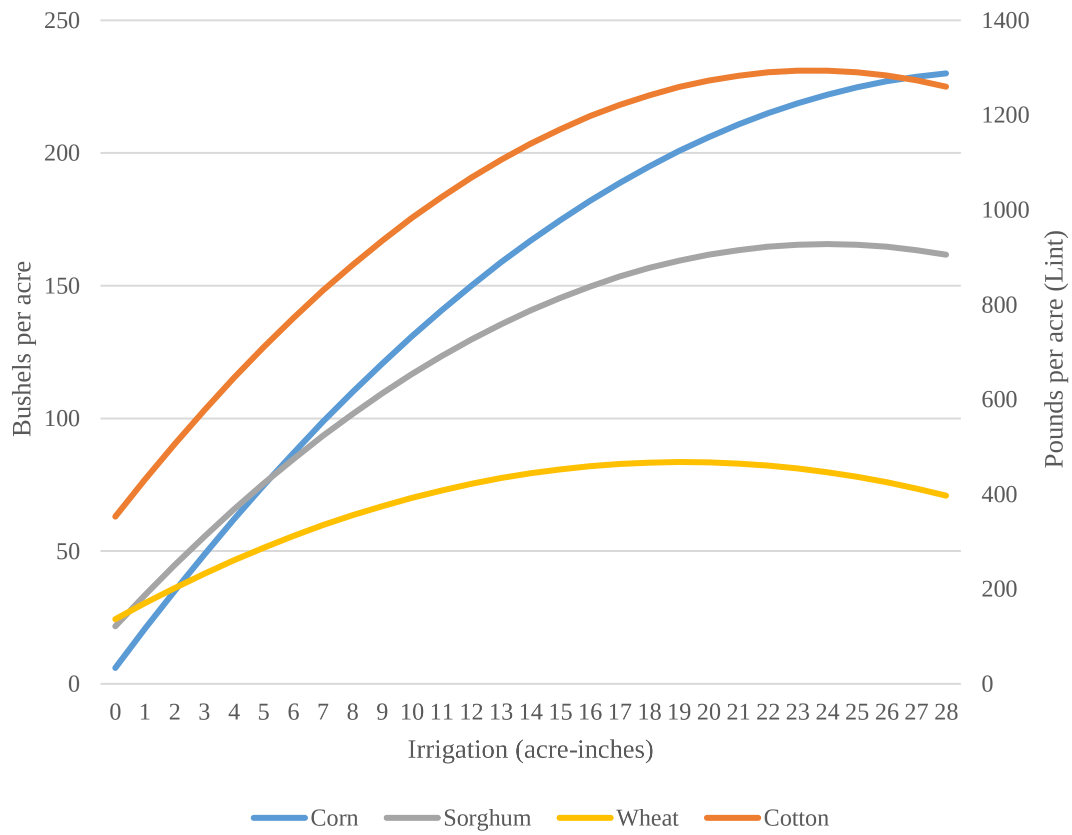

Figure 4. Production functions by crop in the Palo Duro Watershed graphed at average seasonal precipitation for varying levels of irrigation applied.
Source: (Uddameri and Ghaseminejad, 2020)

Maximum Available Water

The producer has a limited amount of groundwater to pump during the cropping season. As the producer pumps groundwater from the aquifer, depth to water increases and saturated thickness decreases. As saturated thickness decreases, the well capacity (GPM) also decreases. A new saturated thickness was calculated every year of the model based on annual water withdrawals, Equation 15:

15 $$HartleyST_t = 1.49445ST_{t-1} - 0.005287ST_{t-1}^2 - 0.173881AW \quad - 9.259834$$

where ST_t is the saturated thickness at the end of year *t*. This equation was developed for the given study region using an autoregressive model to predict the groundwater condition (Uddameri and Ghaseminejad, 2022). The starting saturated thickness for Hartley County was 62 feet, and the starting well capacity was 300 GPM.

Well capacity directly determines the MAW for the producer. As the MAW declines, crop yields decrease, crop mix changes, and profits become more volatile. A new well capacity was calculated every year for the start of the cropping season, Equation 16:

16 $$GPM_t = GPM_0 (\frac{ST_t}{ST_0})^2$$

where GPM_t and ST_t are the well capacity and saturated thickness at time *t*, respectively, and GPM_0 and ST_0 are well capacity and saturated thickness at the beginning of the simulation period. The maximum available water *(MAW)* for irrigation was calculated and expressed in acre-inches per season, Equation 17.

17 $$MAW = 4.42 GPM_t$$

Prices and Expenses

Prices and expenses were calculated using a three-year average of data from the Texas A&M AgriLife Extension Service crop enterprise budgets, using the years 2018-2021, Table 2. Prices were determined per unit of yield. The price for wheat was adjusted to include income from grazing, and cotton was adjusted to include the additional income received for cottonseed. Lastly, the dryland acreage crop choice was represented as the average revenue and costs from dryland cotton, sorghum, and wheat. The expenses were broken into three different classes. First, the majority of expenses were calculated on a per-acre basis, and were considered fixed for the purposes of this study. The fixed expenses per acre included: herbicide, fertilizer, and insecticide application, crop insurance, operator labor, fuel for tractors and pickup trucks, and repair and maintenance for implements, tractors, and general use equipment. The variable (HSF) expenses per unit of yield included: harvesting, seed, and fertilizer costs. Should a producer plan to use less water or expect less water to be available for irrigation, the seed application rate will be lower and fertilizer will be applied at a lower rate. Additionally, harvesting costs change based on the output required to be harvested, hauled, and processed. Irrigation expenses increase per acre-inch of water applied and included energy and pivot repair. The total irrigation expense was $8.59 per acre-inch for all crops analyzed (Texas A&M AgriLife Extension, 2021).

Table 2. Average price, fixed cost per acre, and harvest, seed, and fertilizer variable cost per yield (HSF) by crop, 2018-2021.

Crop	**Unit**	**Price**		**Fixed Cost**		**HSF**	
Corn	Bushel	$	5.12	$	224.09	$	1.52
Cotton	Pound (Lint)	$	0.90	$	233.52	$	0.37
Sorghum	Bushel	$	5.02	$	177.49	$	1.27
Wheat	Bushel	$	7.15	$	123.56	$	1.75

Policy Analysis

Alternative policies were examined and evaluated against the baseline model. The baseline model was a status-quo scenario, representing no change in producer behavior. Alternative scenarios were included to represent realistic situations in which a producer with factors that change water availability and profit over time. The following scenarios were modeled and compared against the baseline model: (1) maximum available water limited to 75 percent of capacity, (2) maximum available water limited to 50 percent of capacity, (3) irrigated acreage restricted to 50 percent of total acreage, (4) increase in fuel price, (5) decrease in fuel price, (6) increase in commodity prices, and (7) decrease in commodity prices.

The first two scenarios include reductions in MAW. This reduction was accomplished by modifying well capacity to 75 and 50 percent of baseline well capacity. Initial well capacity started at 225 GPM and 150 GPM for the two scenarios, respectively. The acreage reduction scenario limited the producer to half of the original acres (123.5 acres). All of the constraints were also multiplied by 50 percent to represent a 50 percent reduction in acreage. Producers often sell in a volatile commodity market. In the two commodity price scenarios, producers were faced with both high and low commodity prices. These prices were determined by historical commodity price data, where the highest and lowest prices over the past twenty years were used, Table 3 (Texas A&M AgriLife Extension, 2021).

Table 3. Historical high and low commodity prices by crop, 2001-2021.

Crop	**Unit**	**High Price**		**High Year**	**Low Price**		**Low Year**
Corn	Bushel	$	8.55	2013	$	2.09	2002
Cotton	Pound (Lint)	$	1.85	2012	$	0.27	2003
Sorghum	Bushel	$	7.93	2013	$	1.76	2005
Wheat	Bushel	$	10.64	2013	$	2.53	2002

The two fuel price scenarios again utilized the highest and lowest fuel prices producers had been faced with over the previous twenty years (Texas A&M AgriLife Extension, 2021). These increased and decreased fuel prices impact both the fixed cost per acre as well as the irrigation cost. The fixed costs changed relative to the price of fuel, as truck and tractor fuel were included. Likewise, the cost of irrigation changed with the energy required to pump the water and run the center pivots.

CHAPTER 4: RESULTS

The model was run under the seven scenarios and the results were compared against the baseline model. The comparisons included: total acres planted, total crop acreage mix percentages, total water use, saturated thickness, well capacity, yield per acre, and profit between stage one and stage two.

Year one of Hartley County's percentage of acres planted by crop were: corn (30%), cotton (9%), sorghum (13%), wheat (46%), and dryland (2%). A change in acreage happens for all scenarios, where both corn and sorghum acreage decrease. Cotton, wheat, and dryland acreage increased over the 30-year study period. Each model estimated a total of 7,410 acres planted over the study period, excluding the acreage reduction scenario, with a total of 3,705 acres planted. The total acreage amounts planted for the entire 30 years were compared between all scenarios, as shown in Table 4. The crop acreage percentages are rounded to the nearest whole number in the parentheses. The decreased commodity price scenario estimated that all acreage of the crops would be a minimum of six percent except for dryland acres, which made up 76 percent. The entire crop mix is represented in all scenarios; however, the way each scenario used the groundwater available is significantly different.

Table 4. Total crop acreage by scenario with relative percentage by crop over the study period.

Scenario	Corn	Cotton	Sorghum	Wheat	Dryland
Baseline	450 (6%)	1,981 (27%)	450 (6%)	3,455 (47%)	1,074 (14%)
75% of MAW	450 (6%)	1,760 (24%)	450 (6%)	3,677 (50%)	1,074 (14%)
50% of MAW	450 (6%)	1,471 (20%)	450 (6%)	3,965 (54%)	1,074 (14%)
50% of acreage	251 (7%)	1,117 (30%)	240 (6%)	1,594 (43%)	503 (14%)
Increase Fuel Price	450 (6%)	516 (7%)	450 (6%)	3,965 (54%)	2,028 (27%)
Decrease Fuel Price	513 (7%)	1,876 (25%)	469 (6%)	3,560 (48%)	992 (14%)
Increase Commodity Price	838 (11%)	2,173 (29%)	667 (9%)	3,211 (43%)	522 (8%)
Decrease Commodity Price	450 (6%)	450 (6%)	450 (6%)	450 (6%)	5,610 (76%)

The total water use of each specific crop in the baseline scenario is illustrated in Figure 5. The total water use increased for the first four years and then steadily declined for the remaining of the study period. The model projected that the producer would not apply all of the maximum available water during the first four years and then allocated more additional water as the acreage of cotton increased. Wheat is kept as a dryland crop over the entire study period for the baseline scenario. Keeping wheat, a dryland crop suggested that profitability is greater when the producer allocates the available groundwater to the crops that are more receptive to an increase in yield from the applied water. To further understand this, reference the production functions, Figure 4. Corn, cotton, and sorghum crops have a more significant increase in yield per every additional acre-inch of water applied than the crop wheat.

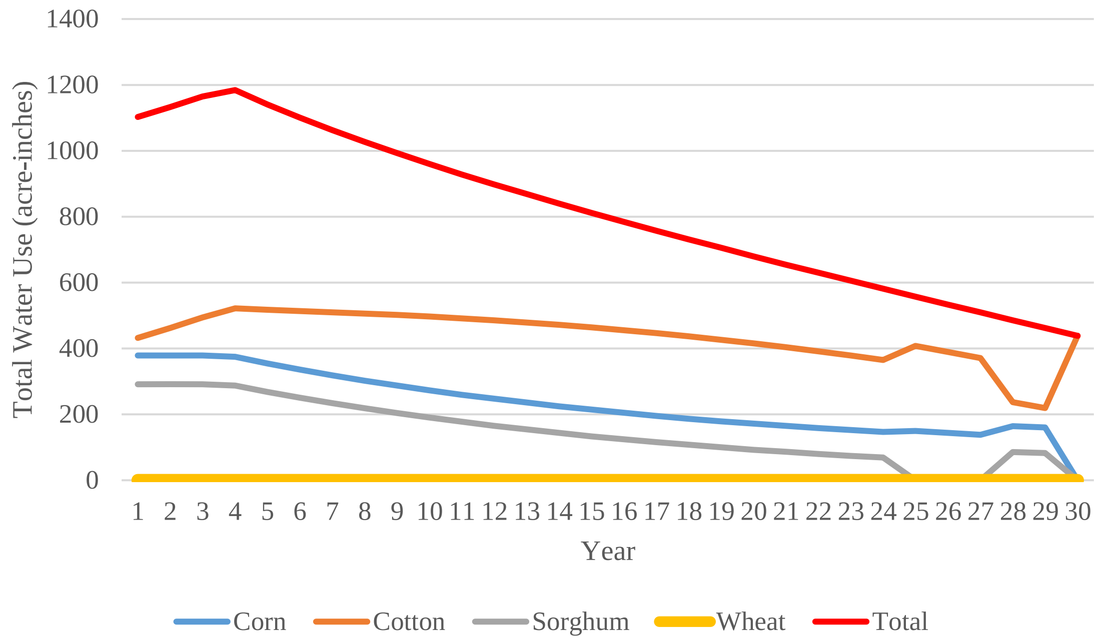

Figure 5. Change in total water use by crop for the baseline scenario.

The total water use for every policy is compared to the red dotted line of the maximum available water during the baseline scenario, Figure 6. Some of the scenarios increased total water use for the first couple of years; the increased water use is applied as cotton becomes a more prominent crop. Once the models reached peak total water use, there is a steady decline year by year. The scenario of the 50 percent acreage reduction does exceed the baseline maximum available water. It suggests that this scenario has a greater maximum available water in later years in comparison to the baseline scenario, concluding that the well capacity diminishes at a slower rate in the acreage reduction scenario. The outlier of the group was the scenario of decreased commodity price where the model predicted that producers would apply zero water over the study period. In a scenario faced with decreased commodity prices, irrigating crops would negatively impact the profits.

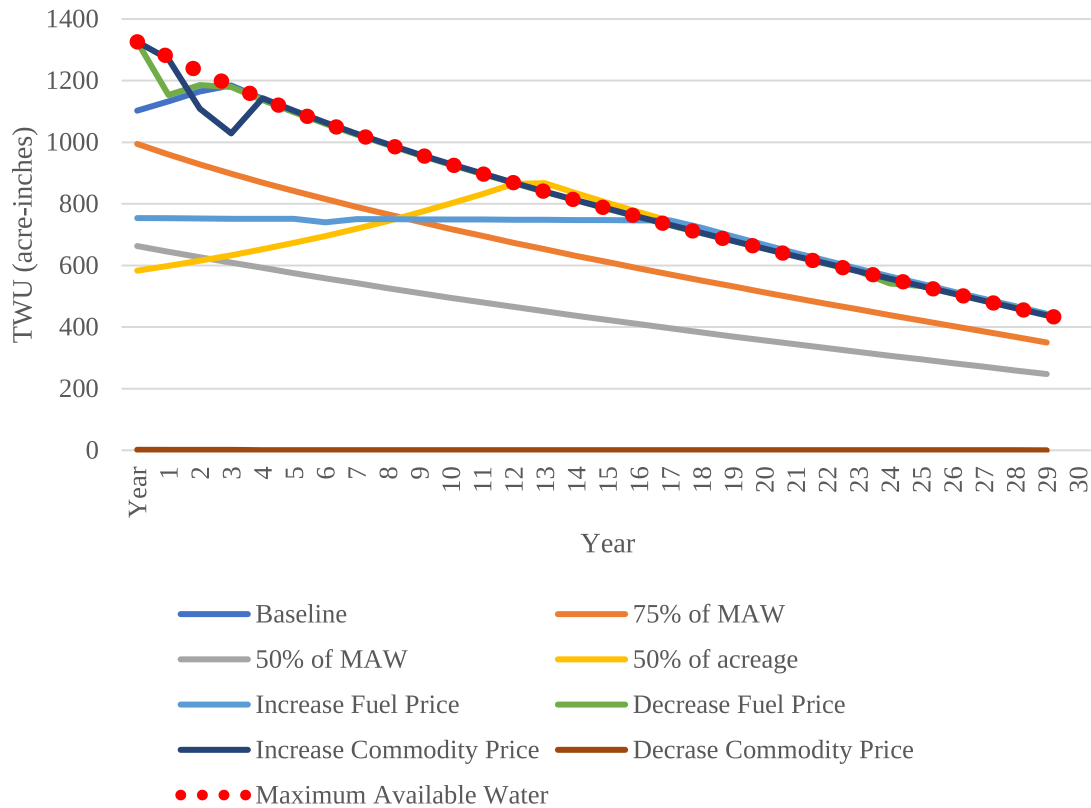

Figure 6. Change in total water use by scenario relative to baseline MAW.

The total water use for all 30 years is in acre-inches, Table 5. The percent change column illustrates how the total water use increased or decreased from scenario to scenario when compared to the baseline. The four scenarios of water conservation were 75 and 50 percent of MAW, 50 percent acreage reduction, and decreased commodity price. The decreased fuel price and increased commodity price scenarios had a slight increase in total water use.

Table 5. Total water use by scenario compared to the baseline scenario over the study period.

Scenario	30-year total (acre-inches)	Average annual (acre-inches)	% change
Baseline	24,328	811	0%
75% of MAW	19,138	638	-21.3%
50% of MAW	13,176	439	-45.8%
50% of acreage	20,127	671	-17.3%
Increase Fuel Price	20,440	681	-16.0%
Decrease Fuel Price	24,554	818	0.9%
Increase Commodity Price	24,490	816	0.7%
Decrease Commodity Price	11	0	-100.0%

The maximum available water is determined by the current state of the well capacity. Each of these scenarios has a different rate of diminishing well capacity based on its total water use. Well capacity diminishes for each of the scenarios for the 30-year study period, as shown in Figure 7. The decreased commodity price scenario has the greatest well capacity at year 30 since this scenario has the least amount of total water use.

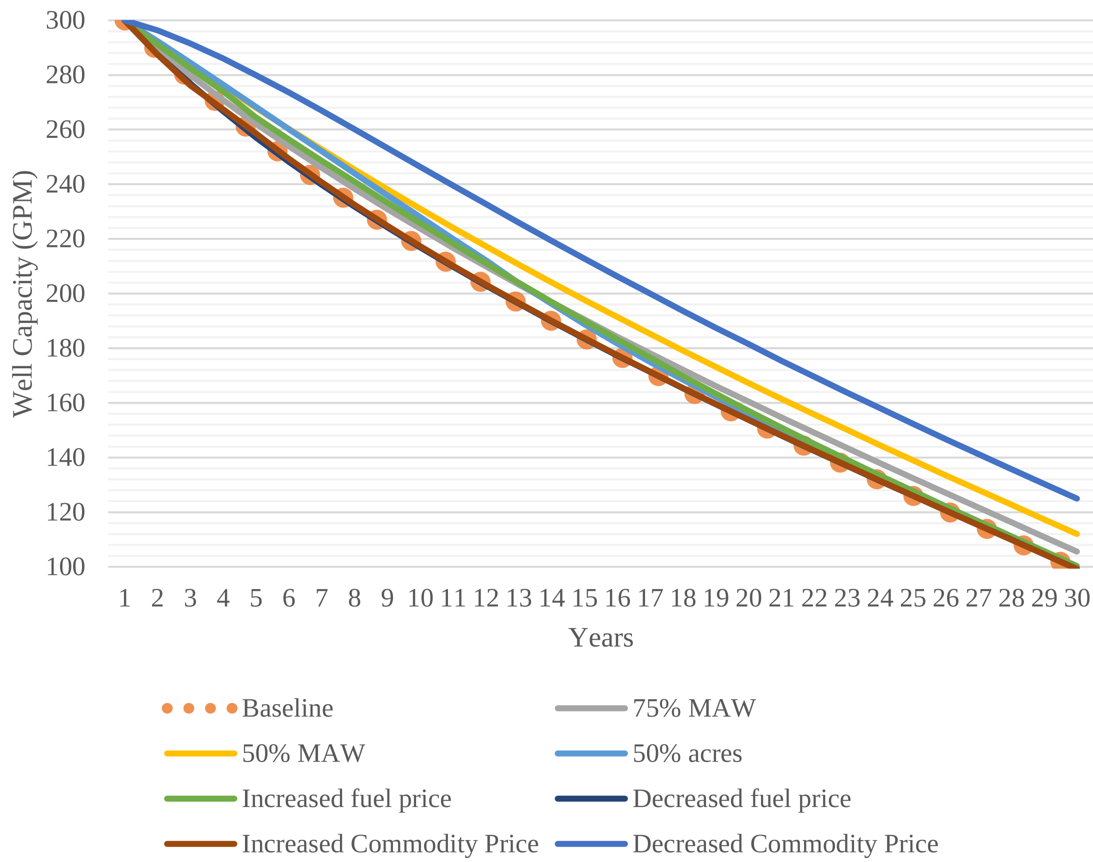

Figure 7. Change in well capacity by scenario.

Well capacity is calculated by saturated thickness, equation (18). Saturated thickness has a negative linear result for all scenarios over the entire 30-year period of the model, Figure 8. The baseline scenario has the greatest change in saturated thickness where the saturated thickness decreased by 44.1 percent over the 30-year study. The decreased commodity price scenario had the greatest saturated thickness at the end of the 30-year study; this specific scenario decreased saturated thickness by 36.8 percent.

Figure 8. Change in saturated thickness by scenario.

The irrigation application and crop-specific precipitation directly impacted yield. Yield is indirectly impacted by well capacity, limiting how much irrigation application the producer can apply to the specific crop. Yield diminished over time in stage one as well capacity diminished, as shown in Figure 9. The yield in stage two is exceptionally receptive to irrigation and became more volatile in later years of the study period when well capacity can no longer provide enough additional water to mitigate the risk of drought conditions, Figure 10. The yield was the most significant determining factor when calculating the producer's profit. Therefore, the yield results had a direct impact on how much profit would be received by the producer in a given year.

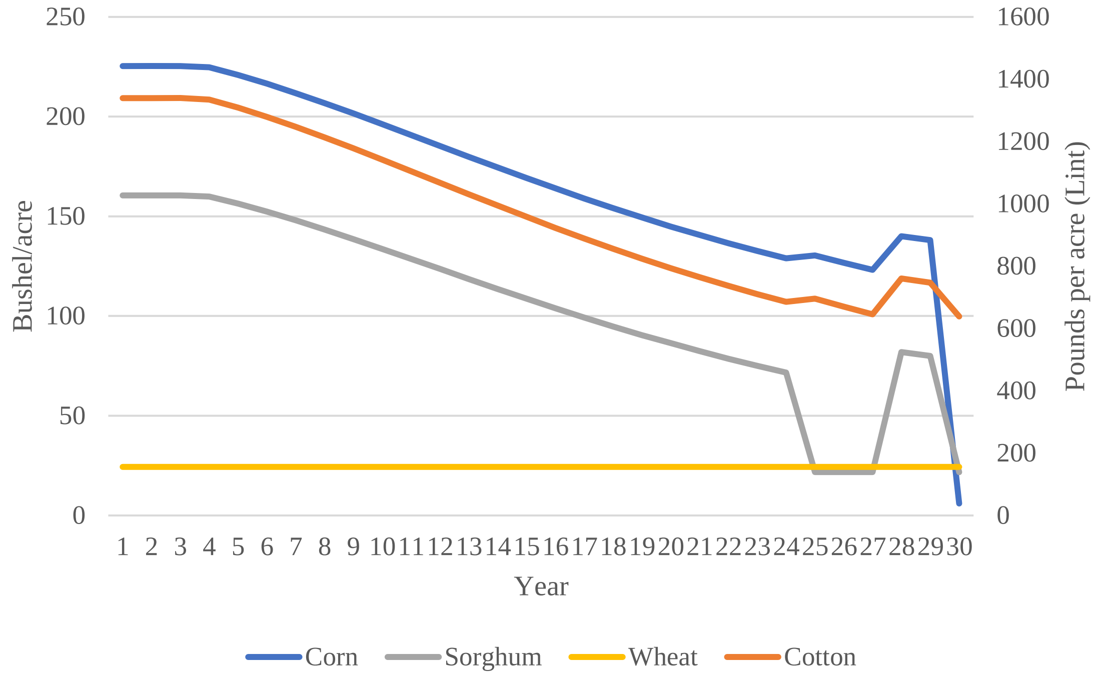

Figure 9. Change in yield per acre by crop in the stage one baseline scenario.

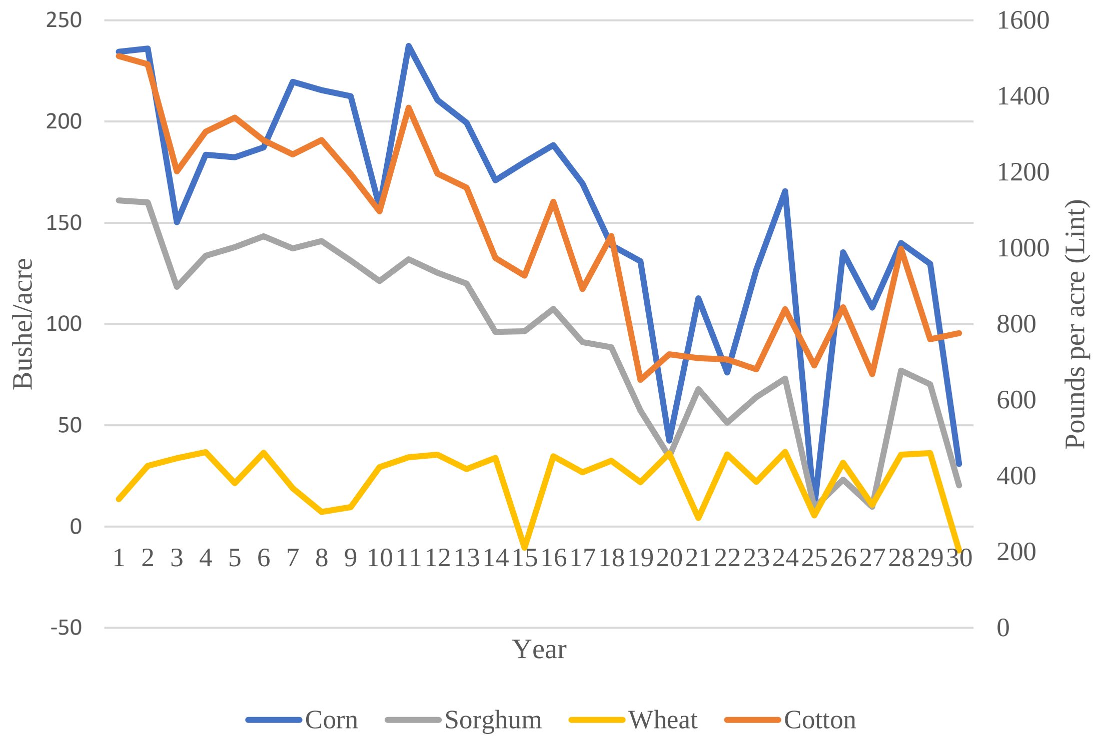

Figure 10. Change in yield per acre by crop in the stage two baseline scenario.

Stage one resulted in a more constant expected profit, while stage two profit has increased volatility where producers are faced with variable precipitation, as shown in Figure 11. Stage one in the baseline scenario has a minimal increase in profit in the first ten years before it diminished year by year. The model estimated an increase in profit in the beginning years as the model starts to include more cotton in the crop mix as the cotton upper bound constraint increased. The cotton crop was a popular pick for the scenarios where cotton brought the producer the greatest profitability per acre. Stage two profit in the baseline scenario is highly correlated with the precipitation amounts year by year. Reference how the gray line of precipitation and blue line of stage two profit directly follow the behavior of each other.

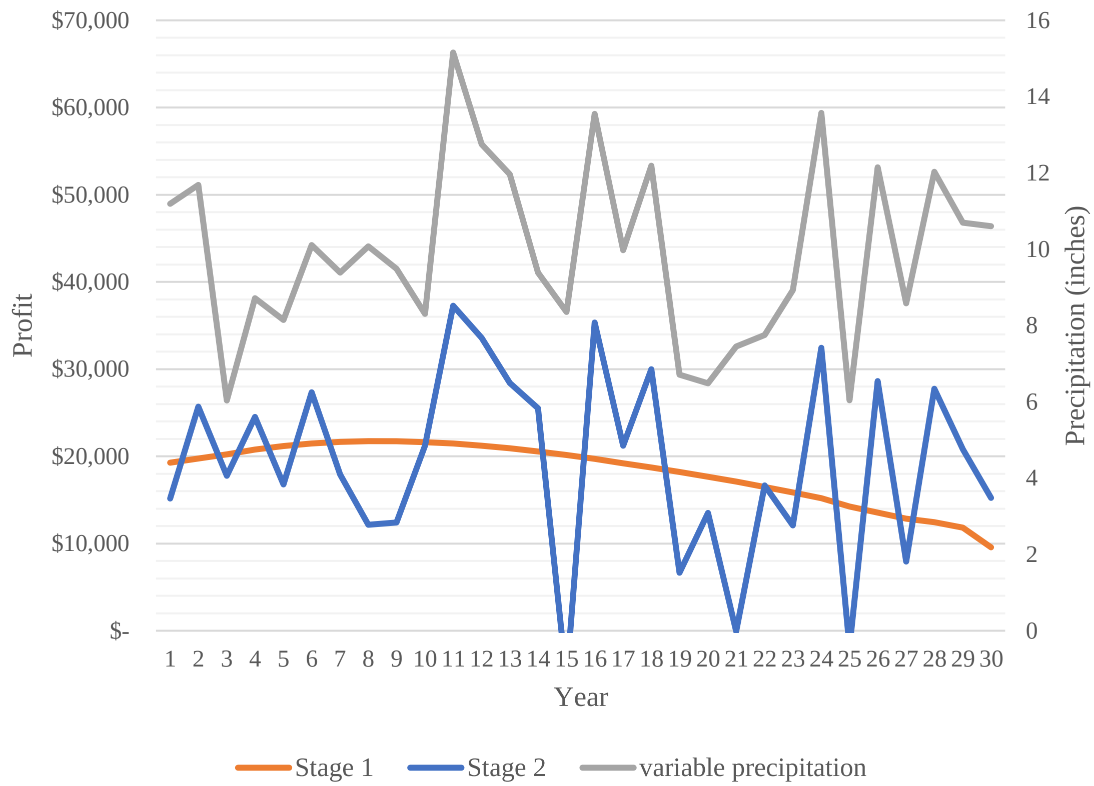

Figure 11. Change in total profit under the baseline scenario in stages one and two relative to variable precipitation.

The profit comparison was broken down to compare all profits of stage one scenarios, Figure 12, and all of stage two scenarios, Figure 13. During both stage one and stage two, the increased commodity price scenario outperformed all other scenarios regarding profitability. Respectively, the decreased commodity price is on the other side of the spectrum, wherein both stage one and stage two, this scenario averaged negative profits. Different scenarios within stage one estimated the expectations the producers would receive over the study period, whereas the different stage two profit scenarios estimated the profits producers may actually face. In previous models, producers would make decisions based on the average expected precipitation, whereas now, producers in this model make decisions based on precipitation that resemble actual variances that may occur. The two-stage technique improves the modeling technique to represent how producer decisions adjust given their variable rainfall condition.

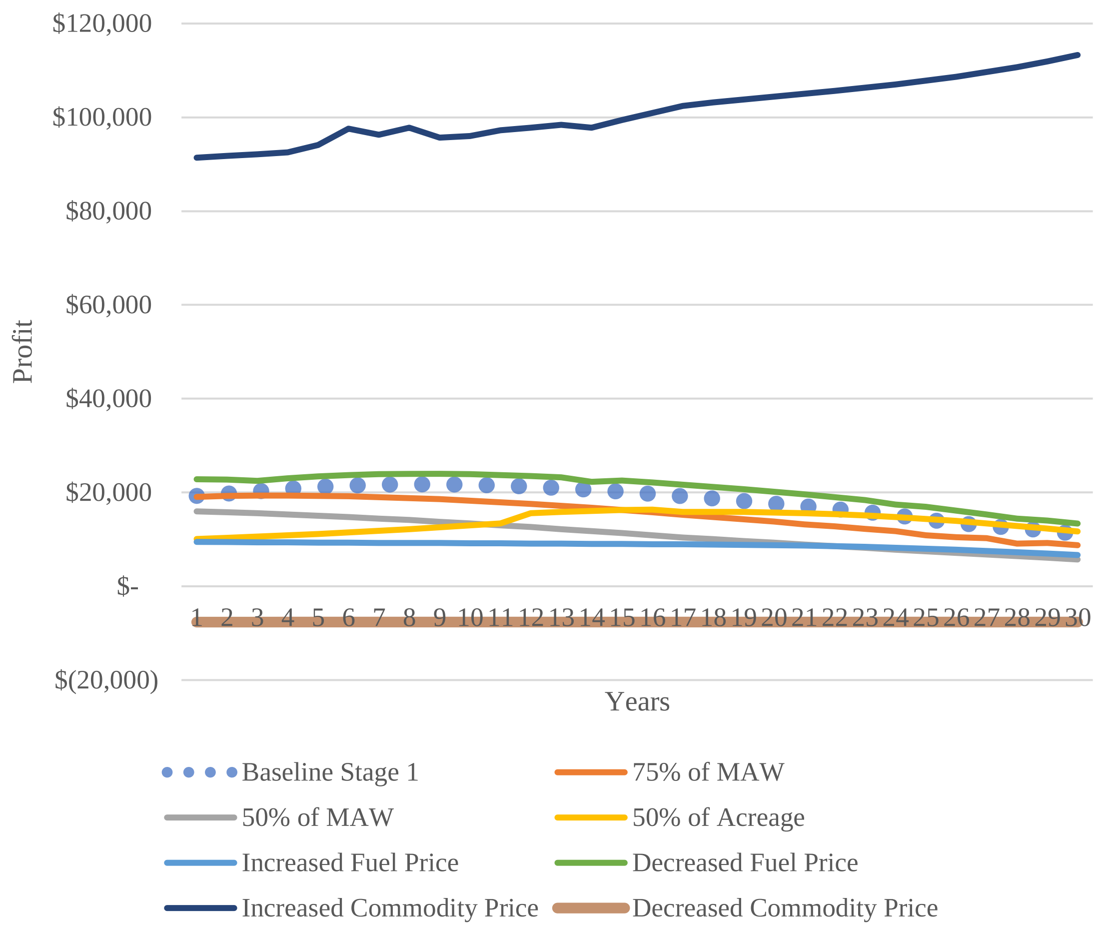

Figure 12. Change in total profit by scenario in stage one.

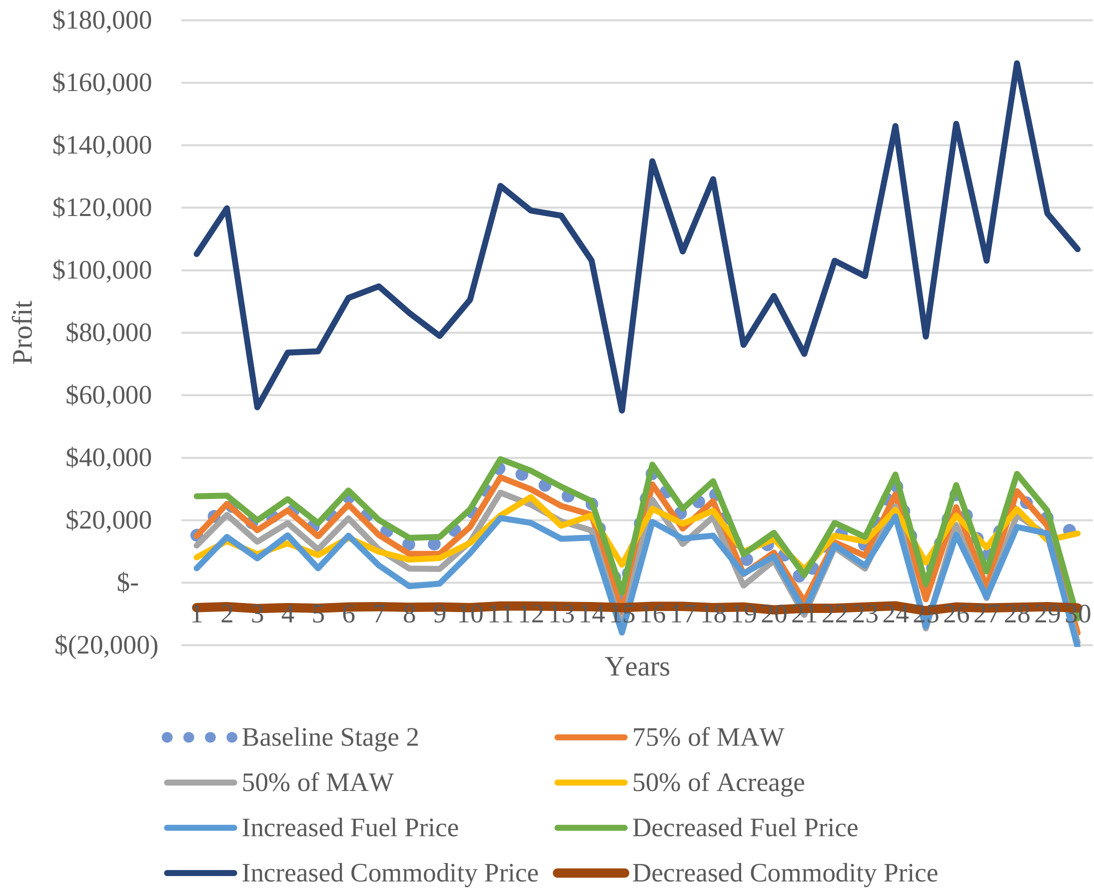

Figure 13. Change in total profit by scenario in stage two.

Profits for all scenarios in stage two were compared over the entire 30-year study period, Table 6. In stage two, results indicate that producers are faced with enormous volatility of profit. The standard deviation results for each scenario calculate the volatility of producer profit. The scenario that offered the greatest positive profit stability year to year is that of the 50 percent acreage reduction scenario with the lowest standard deviation of $6,362. The 50 percent acreage reduction also offered one of the greatest profits per acre, $117.78 per acre. The greatest profit per acre scenario is the increased commodity price, $414.46 per acre. Although this scenario has a considerable profit, it does not consider increased input prices that generally happen when commodity prices increase. Table 6 is an excellent tool for producers and policymakers to use when considering different scenarios.

Table 6. Stage two profit by scenario over the study period.

Scenario	Average Profit	Standard Deviation	% Change in Profit	Profit per Acre
Baseline	$ 19,217	$ 10,927	5.2%	$ 77.80
75 % of MAW	$ 15,075	$ 10,928	-1.4%	$ 61.03
50% of MAW	$ 10,604	$ 12,878	-4.3%	$ 42.93
50% of acreage	$ 14,546	$ 6,362	6.4%	$ 117.78
Increase Fuel Price	$ 7,562	$ 11,267	-13.1%	$ 30.62
Decrease Fuel Price	$ 20,786	$ 12,914	0.6%	$ 84.15
Increase Commodity Price	$ 102,372	$ 26,789	1.1%	$ 414.46
Decrease Commodity Price	$ (7,899)	$ 336	-3.4%	$ (31.98)

CHAPTER 5: CONCLUSIONS

This model can be utilized by policymakers and producers to estimate how different scenarios and policies impact producer profitability, decisions, and sustainability based on expected precipitation versus how it impacts producer profitability, decisions, and sustainability based on variable precipitation. Producers decided to adopt more cotton acreage throughout the years while minimizing corn and sorghum acreage planted. In all scenarios, cotton acres increased in production, with the exception of the decreased commodity price scenario. Within this model, producers continue to increase acreage in the most profitable crop and apply the majority of total available water to the cotton crop.

Cotton is the crop that received the most water in the crop mix, while wheat received zero water, staying a dryland crop throughout the 30-year study period of the baseline scenario, Figure 5. The decreased commodity price scenario was the outlier of the scenarios for the total water used. The total water used for the decreased commodity price scenario was zero throughout the 30-year study. The 50 percent acreage reduction scenario and increased fuel price did not use all the maximum available water until later in the model. In these scenarios, the producer decided to save that water until they could apply it to more cotton acres. The total water use impacted how well capacity and saturated thickness changed throughout the years. The decreased commodity price scenario had the highest well capacity and saturated thickness at the end of the 30-year period. The two scenarios of water restriction ended with the second (50% of MAW) and third (75% of MAW) highest saturated thickness and well capacity and continued to irrigate crops throughout the entire 30 years.

Water availability had a considerable impact on what level of yield producers would receive over the 30-year study. Yield gradually declined as available water to irrigate declined in correspondence over the 30 years, Figure 9. Stage two yield is highly volatile year to year where water availability continued to decrease over the years, and the producer is faced with receiving above or below average precipitation, Figure 10. As profits in stage one slightly increased before decreasing due to a shift in increased cotton acreage.

Stage two of the model estimated that producer profit will have high volatility year to year, which could impact the regional economy's GDP. Therefore, it is important to consider the different scenarios and conclude which policy brought the producer the most stable profitability from year to year. In stage two, a 50 percent acreage reduction brought the producer the most stable profit with a standard deviation of $6,362 per year. The producer within this policy had the available water to continually irrigate the planted crops to make up for the decreased amount of precipitation in drought years. They also have the ability to not irrigate all available water during years of high precipitation, which ultimately will allow for the conservation of water during above-average precipitation years.

To conclude, both policymakers and producers should include the use of a two-stage modeling technique to evaluate their management decisions and potential applications of policies. The two-stage modeling technique will better represent producers' actual behavior and operating environment. Stage one will allow producers to make management decisions of planting based on prior historical data of prices, expected rainfall, and water availability. Stage two allows the producer to now manage water application based on the variable precipitation received. This modeling technique gives better intel to the producer on how to expect profits to vary year to year so they can further prepare and mitigate their financial risks. It also illustrates to policymakers how the changing weather conditions will impact groundwater availability from year to year.

CHAPTER 6: DISCUSSION

It is no news that the producers within the study region face challenging production issues with drawdowns of their wells. This model illustrates to producers and policymakers that action needs to be taken as a collective to keep these producers' production practices sustainable. Even with policies geared towards conserving water, results demonstrate that producers will still be left with less water in future years than they have today.

Some limitations faced within this model were the use of lower bound constraints on total water use. Using lower bound constraints on water application can bring significant value to the modeling and results. Lower bound constraints were attempted within this model where the producer would have to at least irrigate one acre-inch of water if they decided to plant corn, cotton, sorghum, or wheat. If they wanted to plant acreage where they applied zero water, they could then choose to plant the dryland acreage crop. However, when the model was given lower bound constraints, it could not converge the results and had modeling errors.

This model does lack the stochastic process of market prices year by year, the model currently calculates results using a three-year market price average. A stochastic process of market prices would include changing input, commodity, and fuel prices year by year. Therefore, in future research, stage one would be modeled to choose a specific crop mix planted based on prices in the year prior, then the profit would be adjusted to actual specific prices of that year in stage two. This would create a very accurate model of how producers react to changing precipitation conditions and changing market price conditions. This represents how producers’ decisions to plant crops change by the market prices, where crop mix year to year will have a significant shift in acreage planted as compared to the prior year. To further expand on future research, the modeling technique should consider the practice of a crop rotation where producers will allocate the acreage available with a different crop than they planted last year.

Additionally, this study models the behavior and results under the producer having a well capacity of 300 GPM. The study assumed that producers are faced with all the same water constraints and changing water conditions year by year. This study could bring further result detail if one could model those results of producers faced with lower well capacities and higher well capacities in the same study region. Future research could be conducted on how groundwater levels change based on the behavior of all producers within the study region.

Lastly, this model did not consider improved yield and water efficiency with the technological advancements that happen with improved irrigation techniques and crop varieties. Therefore, considering the yield improvement in dryland crops could result in a quicker transition into dryland acreage than expected.

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