

EFFECTS OF HIGH COMMODITY PRICES ON WESTERN KANSAS CROP PATTERNS  
AND THE OGALLALA AQUIFER

by

MATTHEW KEN CLARK

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Major Professor

Jeffrey M. Peterson

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## **Abstract**

The expansion of the biofuels industry, world demand, and various other factors are having a historic impact on the price of grains. These high prices have been creating a large increase in production of many water intensive crops such as corn. As corn is among the most input-intensive crops, this extra production has raised concerns about environmental impacts and pressures on water resources in particular. While water quality has been a longstanding concern in the cornbelt, much of the new production is in nontraditional corn regions including the southeast, the High Plains, and the western states. In these areas, there is mounting concern over depletion of already stressed water supplies.

In the High Plains, the chief water source is the Ogallala aquifer, one of the largest water resources in the world that underlies eight states from South Dakota to Texas. The Ogallala has enabled many agricultural industries, such as irrigated crops, cattle feeding, and meat processing, to establish themselves in areas that would not be possible otherwise. A consequence is that the economy of this region has become dependent on groundwater availability. Continued overdrafts of the aquifer have caused a long-term drop in water levels and some areas have now reached effective depletion.

This thesis seeks to estimate the impact of the rising commodity prices on groundwater consumption and cropping patterns in the Kansas portion of the Ogallala. The economy of this region is particularly dependent on water and irrigated crops, with more than 3 million head of feeder cattle and irrigated crop revenues exceeding \$600 million annually. Sheridan (northwestern Kansas), Seward (southwestern Kansas), and Scott (west central Kansas) counties have been selected as representative case study regions. These counties have a wide range of aquifer levels with Seward having an abundant supply, Sheridan an intermediate supply, and Scott nearing effective depletion. Cropping patterns in these counties are typical of the western

Kansas region, with most irrigated acreage being planted to corn and with dominant nonirrigated rotations of wheat-fallow and wheat-sorghum-fallow.

A Positive Mathematical Programming (PMP) model was developed and calibrated to land- and water-use data in the case counties for a base period of 1999-2003. The PMP approach produces a constrained nonlinear optimization model that mimics the land- and water- allocation decision facing producers each year. The choice variables in the model are the acreages planted to each of the major crops and the water use by crop. The model was run for each of the case counties. The PMP calibration procedure ensures that the model solutions fall within a small tolerance of the base period observations. Once calibrated, the models were executed to simulate the impacts of the emerging energy demand for crops over a 60-year period. After the baseline projections were found, the model was then run under increased crop prices that reflect the higher prices observed in 2006 and after.

The thesis found that under the high price scenario, both irrigated crop production and water application per acre increased significantly during the early years of the simulated period in all modeled counties. The size of the increases depended on the amount of original water available in each county. The increases generally diminished in magnitude toward the end of the simulation period, but led to smaller ending levels of saturated thickness as compared to the base price in all counties. Finally, in two of the three counties, it was observed that initial increases in irrigated crop acres and water application forces a decline in the aquifer such that less water can be applied per acre in the final years of the simulation. This suggests that high commodity prices forces a higher emphasis on early production levels than later production levels. Additionally, the higher prices have a significant effect on the rate of decline of the Ogallala aquifer.

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## **Chapter 1: Introduction**

### **1.1 Motivation**

Benjamin Franklin once said, “When the well is dry, they will know the worth of water” (ThinkExist.com). The truth behind this clever quotation is profound. This is a logical statement on both philosophically and economically. From an economic standpoint, an illustrative example is a farmer who uses water to grow crops. In theory, such a farmer will always seek to maximize his expected profit subject to certain constraints. These constraints generally include total available land, available labor, available water, etc. The water constraint is interesting because for farms located in certain areas, there is enough water that the constraint is never binding. However, in many situations the water use constraint is binding, and it would be much more profitable for the farmer to use a higher level of water if it were possible. It is at this point that the worth of water becomes evident.

This scenario exists in much of western Kansas that overlies the Ogallala portion of the High Plains Aquifer. The aquifer in this region has varying levels of saturated thickness, from over 300 feet to under 50 feet. Due to geological formations, aquifer thickness could vary greatly even between neighboring farms. This disparity in levels means that available water use will depend on the location of the farm, and could even vary within a farm’s borders.

The available water levels are in many ways the constraining force to the type of crop grown. Generally speaking corn, soybeans, and alfalfa require a high amount of water, and crops such as wheat and sorghum require much less water. A farmer in an area that receives little natural rainfall must decide whether he wants to irrigate (if possible). The alternative would be dryland crop production. Most dryland production in Kansas is in the form of wheat and sorghum, which require little water and can be grown in rather marginal land; however, there has been a rise in

dryland corn production lately (NASS). Dryland corn production is not as profitable as irrigated corn, but if water is a limiting factor some farmer's will choose this route. Finally, there are some observed acres in irrigated wheat and sorghum production although this is not a terribly common practice.

The fact that irrigated corn and soybeans are often the most profitable crops has created a large demand for, and consumption of, ground water in western Kansas over the years. However, the rates of consumption often outpace the rate of recharge. As a result the aquifer is in a state of continued decline, further tightening the water constraint. In some areas of the state this practice has led to effective depletion (conventionally defined as less than 30 acre feet of saturated thickness) of the aquifer. For the vast majority of the Ogallala aquifer, the rates of the depletion have caused significant reductions in the saturated thickness; however, there are still enough supplies that irrigation rates could continue at the present pace for anywhere from less than 25 years to more than 300 years depending on location.

To add to the already increasing pressures on the aquifer, the ethanol boom has added another dimension to consider. The Renewable Fuels Standard (RFS) has effectively mandated a large increase in corn-based ethanol, which has created a new demand for grain production. This along with other factors has led to a general price increase in all crop commodities. As such farmer's now have an added incentive to increase irrigation rates to receive a higher yield and hence a higher revenue. This phenomenon has caught the eye of many. For example, "it is accelerating the rate of decline," Gareston said of the aquifer, while noting that he, too, has boosted his corn acreage. "We were headed for a cliff and thought we needed to slow down, but instead of hitting the emergency break, we've hit the nitrous oxide button" (Bickel). However, it should be noted that not all of these effects are due to the ethanol industry, "Ethanol is just one

aspect of increased corn production’, said Kansas State University agricultural economist Kevin Dhuyvetter. ‘Farmers also supply cattle feeders and other markets, including overseas. But across western Kansas, virtually all of the water comes from the Ogallala – the prosperity of the economy depends on it’, he said” (Bickel).

While the exact cause of the increasing trend in corn production is uncertain we do know a few important facts. First, the majority of the Ogallala aquifer is experiencing a constant decline in saturated thickness levels. Second, despite the decreasing levels in saturated thickness irrigated production continues to rise, specifically irrigated corn. Finally, we know that part of this increase is due to the increased ethanol production.

## **1.2 Objectives**

Given the above facts, the purpose of this thesis is to quantify the effect that the changing commodity prices has on the levels of saturated thickness of the Ogallala aquifer over a sixty year horizon. To do this I chose two time periods, one that represent the current high price scenario (which we note is partially due to the ethanol boom), and the other a low price or base scenario. For the high price scenario I used the average of the years 2006 and 2007 for prices and yields, taken from National Agricultural Statistics Service (NASS), which were the most recent prices and yields that reflect the current high prices partially caused by the ethanol boom. To best capture the base scenario an average from the years 1999 to 2003 was taken for prices and yields. This time period accurately represents the conditions before the commodity prices began to increase. This will be explained in more detail in the “Data” chapter.

Additionally, I chose to study three case counties that overlie the Ogallala Aquifer. The case counties chosen (from south to north) are Seward, Scott, and Sheridan counties. The case

counties chosen have varying aquifer levels, cropping patterns, and other agronomic variables. This will enable the study to get a broad idea of the effect of increasing commodity prices on the Ogallala aquifer.

Finally, the model that was chosen for this study is a positive mathematical programming (PMP) process. Through use of a profit maximization problem the model simulates farmer's choices of which crop to produce and the level of water to apply per acre (note that this choice framework encompasses both irrigated and dryland crops because 0 acre inches per acre would imply that the farmer chooses dryland production). Additionally, hydrological equations calculate the aquifer effects and update the effects from year to year of the simulation.

### **1.3 Overview**

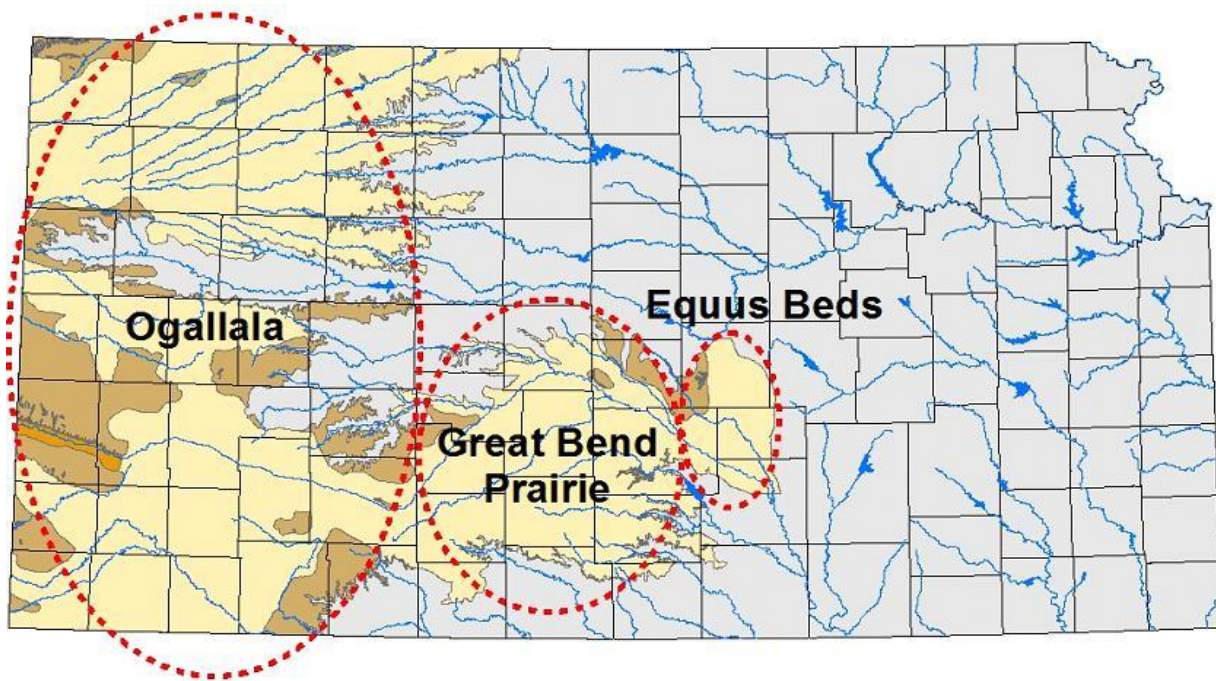
To help bring clarity to this situation this thesis is broken down into several different parts. First there will be a chapter that will explain the current state of the Ogallala aquifer. This chapter will examine the current levels of saturated thickness in the Ogallala and will provide some insight into issues that drive irrigation rates. The next chapter will review the body of literature that relates to this work. I will cover three types of literature: literature that pertains to mathematical programming and programming that solves natural resource (specifically water resources) problems, studies that have looked at irrigation use and biofuel effects, and finally other relevant studies that have looked at irrigation use in Kansas. The next chapter will cover the methods used in this analysis. Next I will explain where I obtained my data for the model. Then I will report and explain the results. Finally, I will derive overall conclusions and implications.

## Chapter 2: Status Quo of the Ogallala Aquifer

### 2.1 Current Aquifer levels

The High Plains aquifer lies over much of western Kansas and extends into south central Kansas. As Figure 2.1 illustrates, the Kansas portion of the High Plains aquifer consists of three parts: the Ogallala, Great Bend Prairie, and Equus Beds. This thesis will only focus on the Ogallala portion of the High Plains aquifer. The Ogallala has the majority share of both total water volume and land area covered by the aquifer in Kansas. Additionally this is the portion of the aquifer where the majority of withdrawals for irrigation take place, and where the majority of attention is paid to irrigation policy.

**Figure 2.1 Regions and Locations of the High Plains Aquifer**

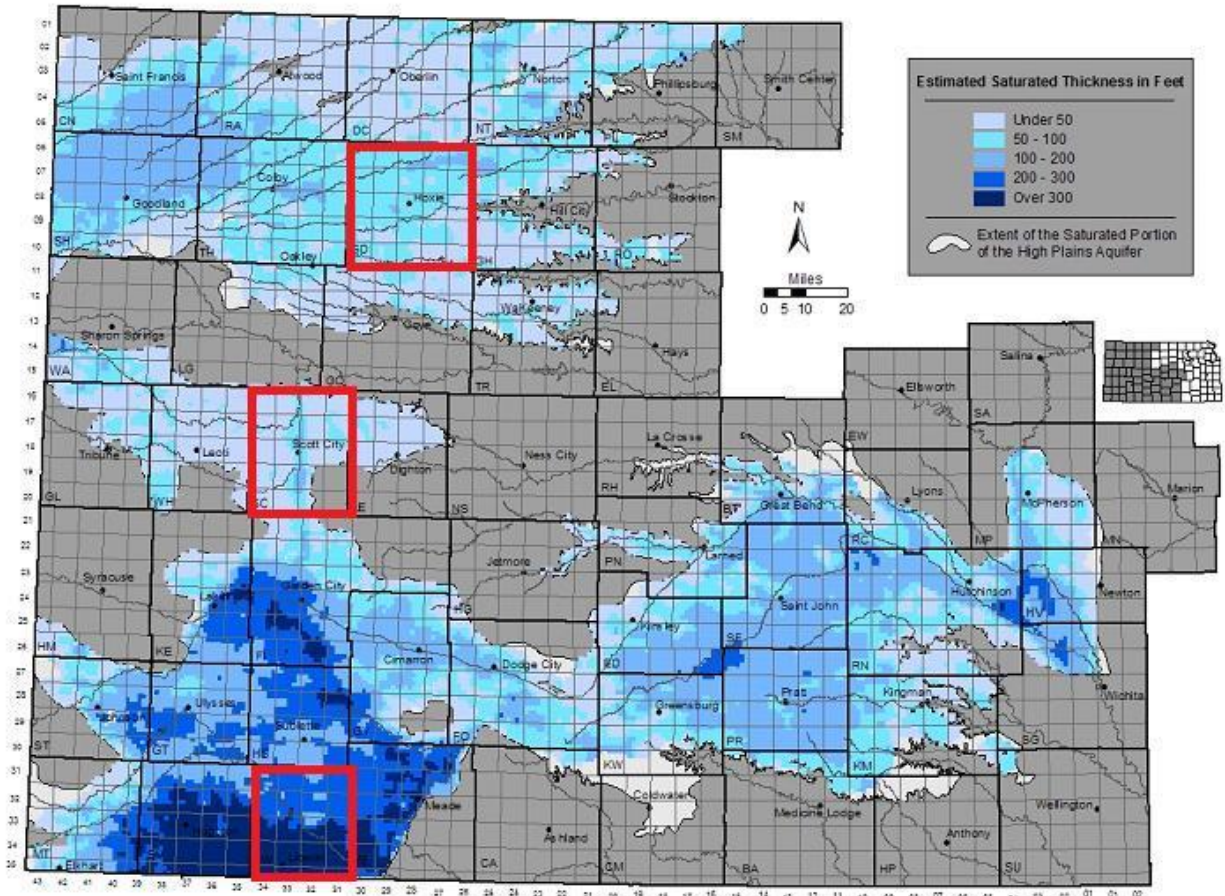


Source: Kansas Geological Survey

A hot topic at many western Kansas town hall meetings is the current level of the Ogallala Aquifer. Due to geological formations, differing consumption patterns, and different recharge rates the level of the aquifer, or saturated thickness, significantly varies from location to

location with an erratic pattern. Figure 2.2 shows the distribution of the average saturated thickness from 2004 to 2006.

**Figure 2.2 Average 2004 to 2006 Saturated Thickness**



Source: Kansas Geological Survey

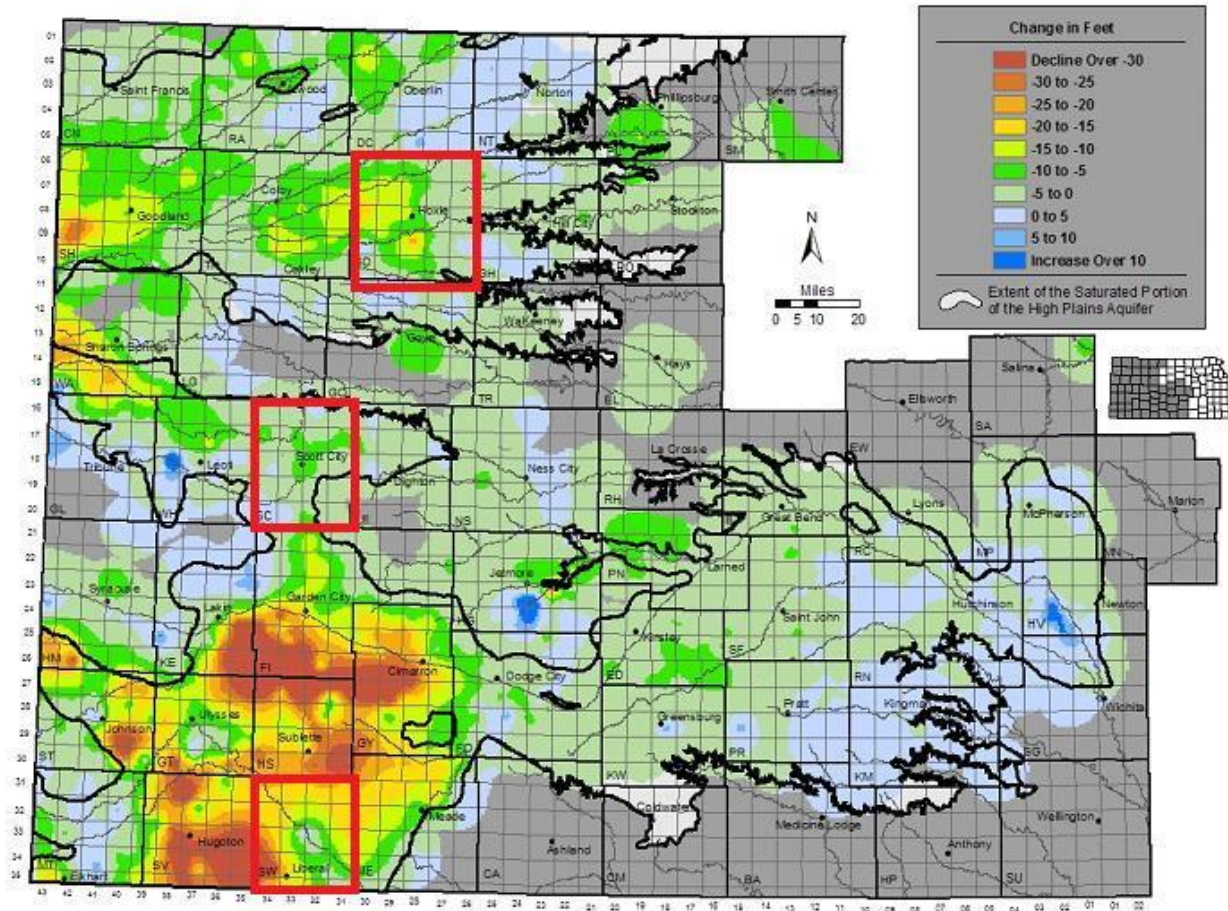
There are several important observations to make from this figure. First, there is a wide distribution of saturated thickness levels. It is clear that southwest Kansas currently has the most plentiful supply of aquifer water. It is also true that the majority of agricultural industries (such as cattle feed yards, packing plants, ethanol plants, intensive irrigation, etc.) that require high water inputs tend to locate around this area. Secondly, the central and northern parts of western Kansas range from nearly depleted to a medium level of water. Third, it is important to notice



that the counties selected for this study also have varying aquifer levels. Moving south to north, Seward County (SW), the third county to the east from the southwest corner) has an abundance of water ranging from about 100 feet to over 300 feet of saturated thickness. Scott County (SC) in central western Kansas has at a maximum of 100 feet of water, but the majority of the county has less than 50 feet and some areas have none. At this time it is important to note that if the aquifer falls below 30 feet it is considered unusable for irrigation. Finally, Sheridan County (SD) in northwest Kansas has intermediate levels of water, ranging from under 50 feet to 200 feet. Therefore, the counties that have been chosen for this study capture the variation in the Kansas portion of the Ogallala very well.

Figure 2.3 illustrates the rate of depletion of the Ogallala aquifer, mapping the level of water table depletion from 1996 to 2006. It is important to note that while a decline of 30 feet may seem innocuous it can easily make the difference between being able to raise irrigated or dryland crops. Additionally, it is important to compare Figure 2.3 to Figure 2.2 and observe that the areas of greatest depletion are generally located in the areas of greatest supply. In particular, the southwest region has seen very large levels of depletion.

Figure 2.3 Level of Depletion from 1996 to 2006

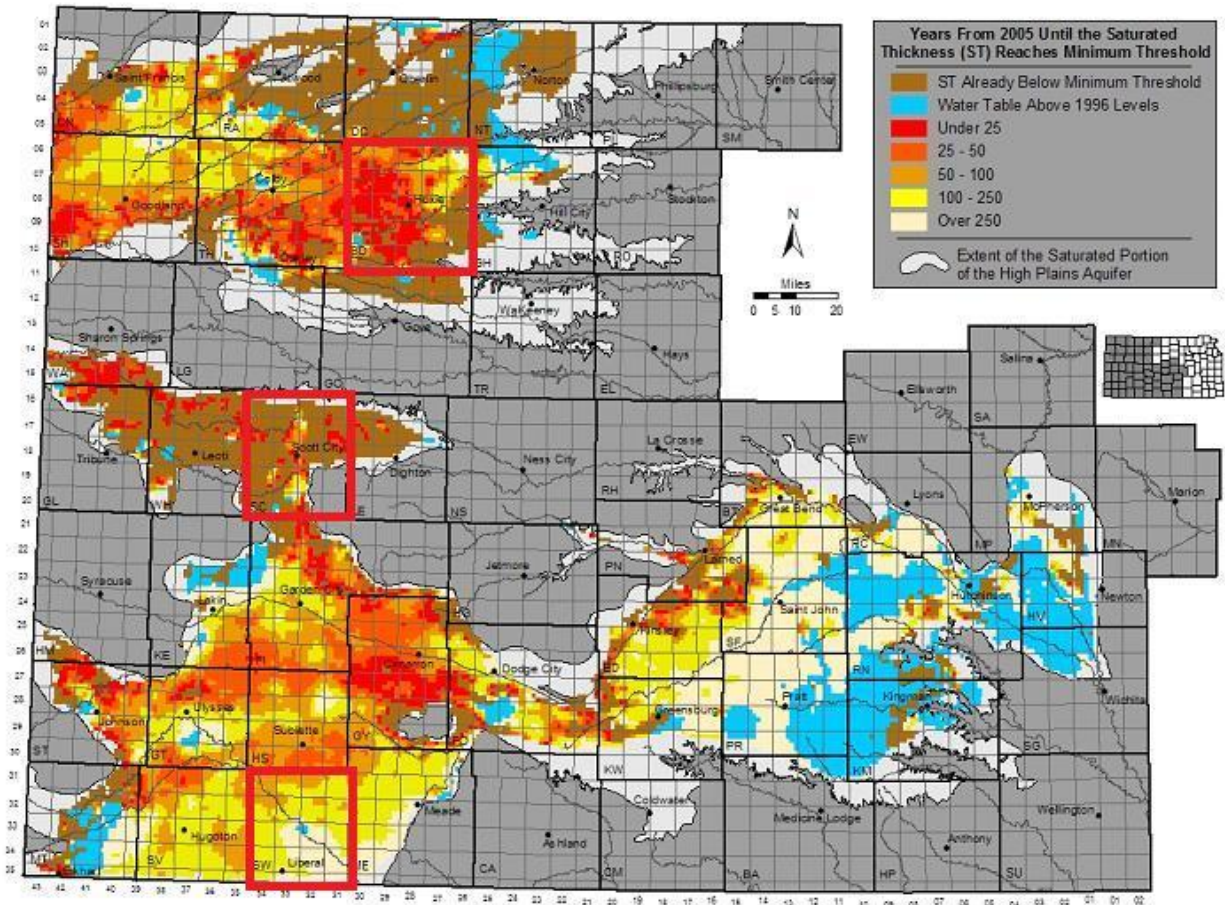


Source: Kansas Geological Survey

Additionally, there are moderate rates of depletion in and around Sherman and Sheridan counties. It is also important to point out that decline rates are small in many of the areas that have less than 50 feet of saturated thickness. This is a reflection of the level of aquifer reaching a critical point to where pumping is no longer feasible. Finally, it is important to note that depletion is only occurring in the Ogallala portion of the High Plains Aquifer. The Equus Beds and Great Bend Prairie portions have seen very little decline (in fact increases in some areas) mainly due to the higher precipitation levels in these areas.

Finally, Figure 2.4 displays the estimated useable life of the aquifer given current depletion rates. The important areas to note are shown in brown, indicating saturated thickness is already at the critical point, and red, indicating less than 25 years of useable life.

**Figure 2.4 Estimated Usable Life**



Source: Kansas Geological Survey

There are several important patterns that emerge from these figures. First, many areas in central and north central Western Kansas have either already reached critical levels or have less than 25 years of useable life left at current withdrawal rates. Moreover, excluding Sheridan County many of these regions are currently not seeing high decline rates. This would imply that water has become a constraining force in farmer's irrigation choices. This is in stark contrast to

southwestern and portions of northwestern Kansas where we see rapid declines coupled with long term useable life, meaning that these areas are consuming a lot of water but also have an abundance of saturated thickness. Second, the figure also shows the diversity of the counties chosen for this study. Scott County has very few areas that have over 25 years of useable life. The majority of Sheridan County hovers around 25 years of useable life with a few spots exceeding that mark. Seward has very large reserves and can continue pumping at the current rate for many, many years to come. A final note is that several large portions of both the Great Bend Prairie and Equus Beds have seen an increase in saturated thickness levels since 1996. This is likely due to a combination of factors related to the higher precipitation levels in that region: less demand for irrigation, higher recharge rates, and the prevalence of less water intensive crops.

These four figures give a very comprehensive picture of the state of the Ogallala Aquifer. It is clear that withdrawal rates, saturated thickness, and useable life vary greatly across the state. Because of this variation farmers across the state have been forced to deal with their water constraints in very dissimilar ways. This would also imply that different scenarios will effect different locations greatly. Therefore, this study has chosen three counties that capture the variability in the state of the Ogallala Aquifer.

## **2.2 Current Pumping Issues**

As Figure 2.3 shows, the rates of withdrawal vary greatly from location to location. Additionally, Figure 2.4 suggests that this is partly because many farmers have already reached their water constraints, which, in the most severe cases, limits water use to small amounts approximating natural recharge rates. However, there are many areas where irrigation withdrawals exceed recharge even though the water constraint is binding. Irrigation statistics

reveal that vast amounts of water are still withdrawn from the aquifer annually. For example, the U.S. Geological Survey estimated that 27 percent of irrigated land and 30 percent of irrigated groundwater in the United States comes from the Ogallala aquifer region (McElroy). These percentages translate into several million acre feet per year of consumed irrigation water for farmers (Bickel).

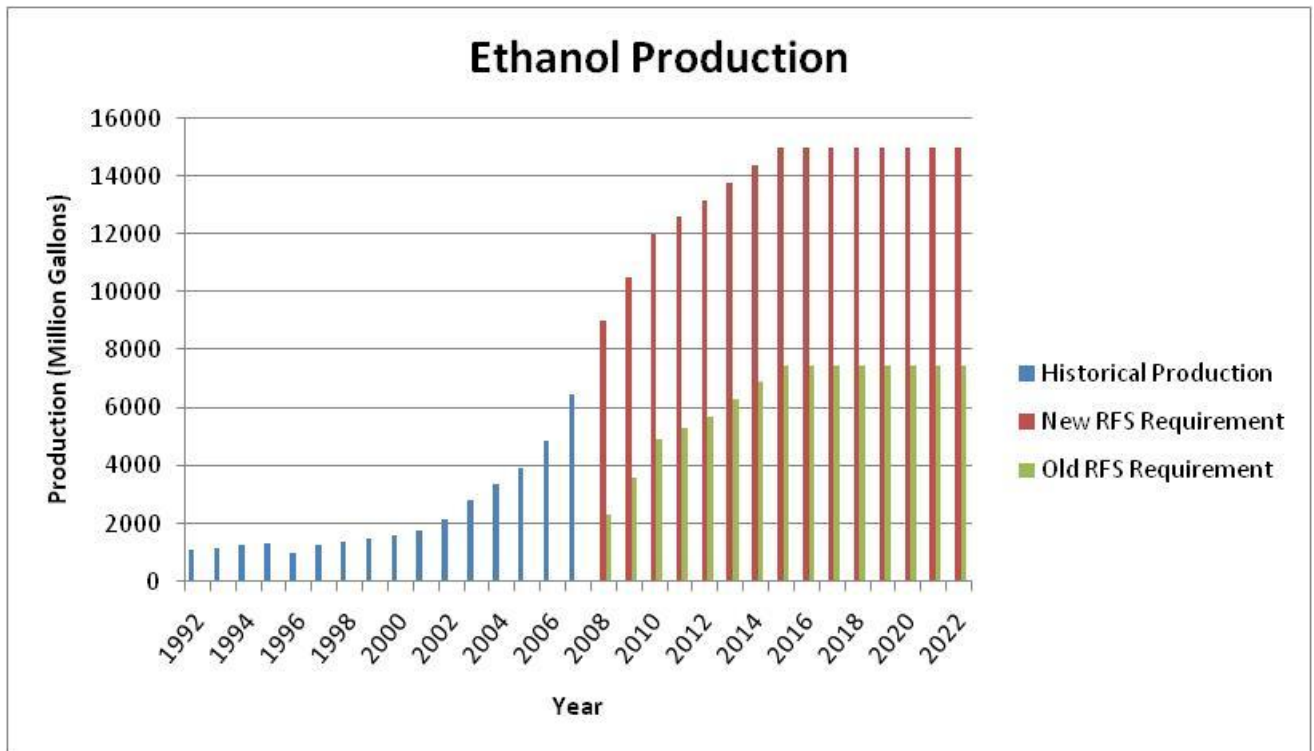
One of the largest concerns with the current level of irrigation is that the rate of irrigation is faster than the recharge rate. This would imply that current pumping rates are going to deplete the aquifer and leave no water resources for the future. Given Figure 2.4 this would seem like a logical conclusion for a majority of the Kansas portion of the Ogallala aquifer. In fact there are many areas (shown in brown of Figure 2.4) that have already reached effective depletion. Later in this thesis we will observe the effect that this has on crop mix with our scenarios of Scott County.

There is also a caveat to this section. As mentioned before, there are several areas where the rate of depletion is slower than the rate of recharge (implying that the level of saturated thickness has increased). These areas are shown in blue in Figure 2.4. Nonetheless, there has been ample research showing that the pumping rate exceeds the recharge rate for the aquifer as a whole. Two commonly cited articles of this genre are Patzek et al (2003) and Pimentel (2003). Patzek et al. estimated that irrigation was responsible for 96% of the 20 km<sup>3</sup> of freshwater withdrawn. Pimentel projected that ground water in the Ogallala is being “mined” 25% faster than the natural recharge rate. The exact figures are not important, but what is important is that it is true that the current irrigation water consumption is higher than the rate of recharge. This means that any policy or event that increases either the rate of application or the total amount of irrigated acres would only accelerate the pace of depletion.

### 2.3 Potential Biofuel Impacts

The United States and the rest of the world have been feeling the impact of a rising energy demand. This can be seen from recent price trends in the markets for crude oil, gasoline, home heating, natural gas, and other commodities. This rising demand has also helped the United States push for a renewable source of energy. One alternative energy source that has seen the largest growth is the biofuel industry, particularly ethanol. The United States has passed several acts of legislation to mandate ethanol production and protect the ethanol industry from outside competition. The latest revision to the Renewable Fuels Standard (RFS) calls for a significant increase in the previously mandated production of ethanol. The result of this mandate is graphically shown in Figure 2.5

**Figure 2.5 Ethanol Production**

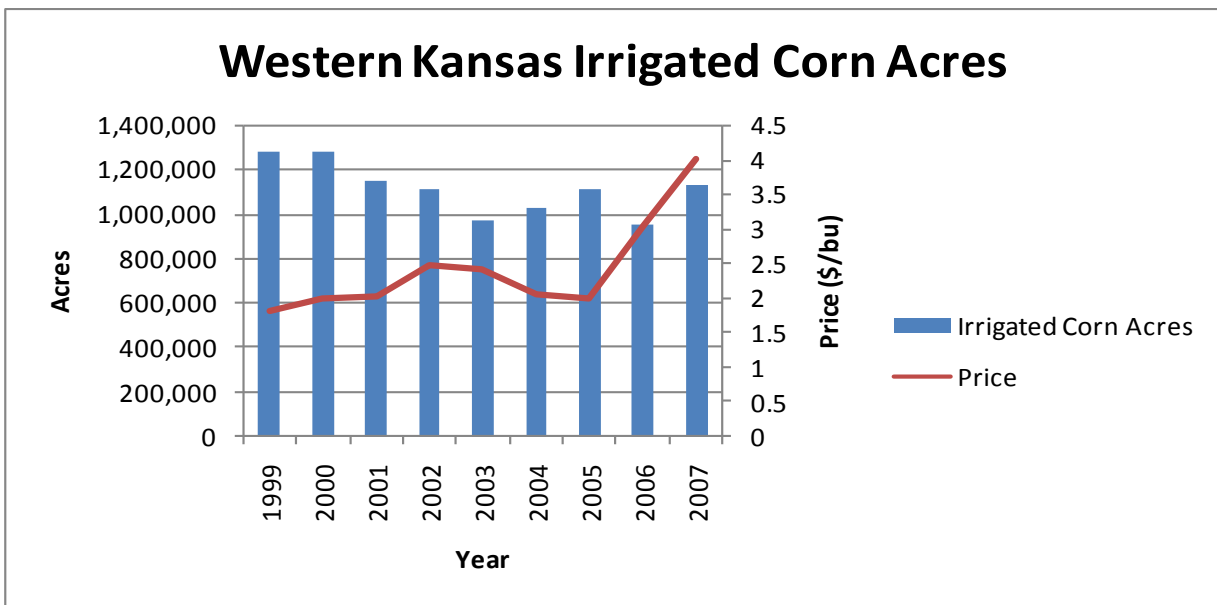


Source: Dhuyvetter, K. Personal communication, <June, 2008>.

There are several important messages to take from this graph. First, the new RFS requirement is significantly higher than the old requirement. In part this may be due to the fact that production was already exceeding the old requirement. Second, it is important to note that while the United States is on pace to meet the new RFS requirements the amount of corn production needed to make the jump will be very significant (assuming no major leap in technology). This is significant because most of the Corn Belt has already reached its production capacity given its available corn acres. This means that an increase in corn acres can only come from nontraditional locations such as the Great Plains region or southern and western states.

Western Kansas is one candidate for an increase in corn production. Figure 2.6 illustrates the current and past levels of corn production in western Kansas, as defined by the combination of the NASS crop reporting districts in western Kansas (Northwest, West central, and Southwest).

**Figure 2.6 Corn Production in Western Kansas**



Source: NASS

This graph shows that the amount of irrigated corn grown in western Kansas has been fairly sporadic between 1,000,000 and 1,300,000 acres. Obviously the majority of these acres overlie the Ogallala aquifer. Generally speaking corn and wheat are the predominant crops in this region; however, there is a large share of irrigated land in other crops that could be substituted into irrigated corn. It is also important to observe that the price of corn has been rising since 2005, but the increase in price has not directly correlated with a significant increase in irrigated corn over 2005 levels (yet). Bickel (2008) reports that the shift to irrigated crops has already begun as she reports, “Because of the prices for all crops, some famers have reinstated Conservation Reserve Program acres back to cropland and have begun pumping again from marginal wells. Others, many of whom had begun transitioning acres to dryland because of economics, are now irrigating every acre they can. Also, more producers are irrigating dryland corners around their center-pivot circles.” The main point to take from this is that there is room to increase the amount of irrigated corn in western Kansas.

Additionally, the demand caused by the emerging ethanol plants in Kansas has created a need for 117 million additional bushels of corn and grain sorghum (Kansas Corn Growers Association). The majority of this new demand is expected to be met by local farmers given proximity and high fuel / transportation costs. Given the increased demand caused by the ethanol plants, the mandatory increase of the Renewable Fuels Standard, and the available acres for an increase in corn production it is perfectly plausible to see an increase in corn production acres in western due to the “biofuel boom.”

## **2.4 Implications**

Referring back to Figures 2.2, 2.3, and 2.4 it is clear to see that many regions of the aquifer are already strained. In particular the majority of west central Kansas and portions of



northwest Kansas have already reached, or will reach within the next 25 years, critical levels so low that irrigation pumping is no longer feasible. Additionally, there are many areas that are not in danger of running out in the near future at current pumping levels; however, given the level of saturated thickness an increase in pumping levels could soon push these areas to threatened levels. These trends raise important questions when two facts about biofuels production are considered: that there will be an increased demand for corn and sorghum given the levels of biofuels required by the Renewable Fuels Standard, and that much of western Kansas has the potential to switch into growing more water intensive crops. So, pulling all of this information together the issue considered in this thesis becomes apparent; the increase in biofuels has the potential to push already depleted levels of the aquifer over the limit.

## **Chapter 3: Literature Review**

The literature review section is divided into three major sections. The first section is the aquifer / irrigation studies using mathematical programming. This section reviews the studies that are most closely related to the modeling approach in this thesis. The model developed for this research builds on the mathematical programming approaches to studying water resource issues that were introduced by the studies discussed below. The second section explores the literature that deals with the potential impact on water resources that the biofuel industry may have. The final section reviews literature that has looked at irrigators' decision to irrigate their crops given different price scenarios. This will be very similar to this thesis.

### **3.1 Aquifer / Irrigation Studies Using Mathematical Programming**

Schaible (1997) developed a multi-output, normalized restricted-equilibrium model for field crops and water demand. The first stage of the model uses restricted-profit functions to measure output when the market is in disequilibrium. The second stage takes the observed equilibrium costs and substitutes them into the implicit economic cost functions to make the long-run normalized restricted-equilibrium model. Finally, the third stage uses the Takayama and Judge's Reducibility Theorem to test the reliability of estimated values to the actual values observed. Schaible applied this model to the Pacific Northwest and found that if producers are allowed to substitute groundwater for surface water they will immediately do so. This implies that the price of water must be set significantly higher to preserve a given amount of surface water when groundwater use is restricted. Another implication is that government restrictions in groundwater consumption decrease producer welfare. The important contribution of this work for this thesis is its approach to modeling irrigators' responses to changes in groundwater availability

Vaux and Howitt (1984) analyzed the economic potential of interregional water trade. The model that the authors employ is similar to that of Takayama and Judge's model, but they added curvilinear supply and demand functions for each region. The model was applied to water regions in California. The authors found that when scarcity of water was increased the marginal price increased (*ceteris paribus*), implying there are substantial gains from interregional water transfers which could be realized through formalized market institutions. One of the important contributions of this study was that it showed how to incorporate supply and demand functions to simulate the potential gains from water transfers.

Provencher and Burt (1994) modified Howard's (1960) 'policy iteration approach' to solving dynamic programming problems by creating two stochastic modeling concepts for large scale water policy that avoid the "curse of dimensionality." First, they proposed using Monte Carlo simulations for the right hand side of the Bellman equation instead of using linear equations. Second, they applied a Taylor series approximation method to the equation. After applying these two alterations to Howard's model the authors concluded that the Taylor series approximation method showed the most potential because it is easy to program and can solve the equation in one iteration. The Monte Carlo simulations are also useful because the underlying equations can be approximated to any subjective level of precision. This article contributes to the understanding of solving the "curse of dimensionality" problem.

Yaron and Dinar (1982) developed a programming method to approach intra-farm water allocation and irrigation scheduling for major crops. Their process involves two subsystems. The first subsystem is a linear programming model that maximizes the farm's income subject to constraints with given technology. In this stage they assume predetermined irrigation schedules. One of the end results of this stage is determining the price of water per farmer. The second

subsystem is an intraseasonal dynamic programming model intended to generate new irrigation scheduling activities with shadow prices of water given by the LP solutions. The dynamic model has two parts: 1) a soil moisture model and 2) a crop response model. This stage ends up calculating the optimal total quantity of water and the optimal allocation of that water within a growing season.

Shani, Tsur, and Zemel (2004) published an article that examined the optimal irrigation pumping strategy within a given year. They developed a dynamic production process model that maximizes revenue subject to the biomass rate of growth and the total amount of water in the root zone. There are several unique aspects to this process model: 1) as opposed to looking across years (as most current literature does) it looks at each year individually; 2) the model also takes into account the effects of previous year's irrigation and the future effect of pumping now; and 3) they also use a production function that incorporates the above two aspects. After running the model they found that the optimal solution in every case is to irrigate until the soil moisture reaches the desired target level, and then irrigation operations should be shut off immediately. Additionally, they note that there is no reason to continue to irrigate up until harvest because the marginal return after the plant has matured is marginal or negative. Moreover, they observe that this does not have to be a very complicated process as simple monitors can observe the soil moisture thus the irrigation level can be changed accordingly. The final important implication is that the model can reflect a limited water quota by simply adding an additional state variable and constraint for the quota. It is also possible to do this by adding another element to the cost function where the quota is binding it is directly added to the price of water.

Finally, Bernardo et al. (1993) provided several insights for constructing regional water policy models. First, they suggest that the researcher must be able to break up the area into well

defined, relatively homogeneous sub regions (Sheridan County for our example). Secondly, they point out that regional groundwater modeling must include the following three ingredients: a crop production model to predict crop output in response to water use, a regional allocation model that predicts how landowners will allot their available land and water resources to different crops, and a hydrologic model to track the effects on the level of aquifer.

The specific method used in this thesis is Positive Mathematical Programming (PMP). The Positive Mathematical Programming (PMP) method was first brought into the “mainstream literature” by Howitt (1995). In this article he explains that versions of what he named PMP had been around for some time in the “grey literature;” however, he is widely credited for adding PMP to the published literature. In this publication Howitt explains that the PMP approach “automatically calibrates models using minimal data and without using ‘flexibility’ constraints”. The usefulness of this is twofold. First, it allows models that employ (or have available) limited data to be calibrated to the existing data. This gives a solid “base” or starting point that is accurate for the model to begin from. Secondly, the model does not need to utilize a lot of flexibility constraints to simulate potential changes (or decision variables) that could be allowed. This makes the PMP method ideal for policy modeling as it can easily solve programming problems given policy or industrial changes without over compensating to a result that would not be expected. For example, if the net revenue of wheat suddenly rose to become three or four times greater than the next closest substitute, a simple profit maximizing problem would allocate all of the acres to wheat unless a host of constraints were applied to prevent this occurrence. To put it another way, the resulting solution would be a corner solution of the linear programming problem. However, if this result was compared to the actual response of farmers the results would most often differ significantly.

The problem above can more generally be referred to as an over- or mis-specification issue. This often occurs when researchers attempt to model a region with little empirical information on the constraints and the production functions of operations in the area. This often leads researchers to use average data from a larger area that encompasses the small region of interest to estimate marginal behavioral reactions of the agent in the study region given different policy changes. This most often leads to a misspecification problem and normative models whose results are far different than the observed. Howitt notes that several researchers have attempted to solve this problem through various methods. He specifically mentions McCarl; Day; Meister, Chen, and Heady; Hazell and Norton; and Bauer and Kasnakoglu. Many of these papers have proved useful when applied to certain problems; however, Howitt notes that no one approach has withstood the tests to dominate the applied literature at any one point in time. Howitt contented that this is primarily due to the fact that their models are forced to calibrate by adding constraints that cannot be justified from an economic, technological, or agronomical points of view. Howitt's solution is to use optimal farm production (given a base year set of data) as a boundary point. This boundary point then is a combination of binding constraints and first order conditions. From this base year agents are allowed to change their behavior given different changes in policy scenarios.

### **3.2 Biofuels and Water**

Although a plethora of studies concerning the biofuel industry and irrigation application have been published, there are very few studies that have looked at the impact of an increasing biofuel industry on irrigation application. This section reviews the current pool of literature that has tackled this issue.

The National Research Council (2008) published a report concerning the effects and implications of the biofuel industry on water quality and availability. The report starts with an overall statement about water issues, considers the biofuel impact on crop water availability and water quality, the effect of biorefineries, offers methods for reducing agricultural impacts, and finally looks at various key policy questions. For the purpose of this review I will discuss only the reported impacts of biofuel production on crop water availability.

The report begins by pointing out that the main concern of an increase in biofuel production is the effect on the mix of crops grown. Generally speaking, an increase in biofuel production will lead to an increase in corn and sorghum production. This is troubling because corn is a very water intensive crop in the Midwest, especially compared to the types of crops that it would be substituted for (such as sorghum and wheat). These authors argue that any adverse effects from a shift in crop mix would not be felt for at least another 5-10 years. Another worry is that biofuel crops will expand into areas that currently do not support irrigation. The introduction of biofuel crops into these marginal (or retired) lands would exacerbate the existing water shortages in many of these areas. Finally, the authors make a note that future research needs to be done on cellulosic crops and their water requirements before any conclusions could be made about the impact(s) of their introduction.

Pate et al. (2007) also estimated the potential impacts of the biofuel industry on water resources. The authors point out that our demand for energy and consumable water are growing at relatively equal rates, and as more energy is supplied from the biofuels sector these two demands become direct competitors for water resources. They also point out several related facts:

- 1) Since 1980 there has been a decrease in water withdrawals for industrial applications and irrigation, with continued increases in water withdrawals for domestic supplies and energy development.
- 2) Fresh water withdrawals for the year 2000 were dominated by irrigated agriculture and thermoelectric power. This means that while it may be true that irrigation consumption is falling, it is still one of the main consumers of our fresh water resources.
- 3) Biomass currently supplies over 3 percent of the nation's total energy consumption, and represents nearly half of all United States' renewable energy use.
- 4) The Renewable Fuels Standard (RFS), established by the Energy Policy Act of 2005, mandates that at least 4 billion gallons of ethanol be used in motor fuels in 2006, increasing to 7.5 billion gallons by the year 2012.

At this point the authors begin their discussion of water use implications. They start by noting that current biofuels are dependent on starch-based ethanol, which in many regions is supplied largely from irrigated corn. This pattern is likely to continue until something major changes in either U.S. policy or other crop demands. The implication is that irrigation water supplies will be the main driver for our current biofuel industry. Additionally, the authors note that due to the large amount of water required for irrigation and ethanol production, almost all alternative transportation fuels (ethanol, biodiesel, etc.) will require more water than our current petroleum system. Finally, they estimate that given modest irrigation application for biofuel crops, the biofuel industry could require an additional 3 to 6 billion gallons per day of fresh



water by 2030. This they believe could have massive impacts on water resource levels both at the national and local levels. These are important implications to consider when we view the results of our model.

A study by Berndes (2008) looked at the impact of all biomass production on water issues. The article begins by noting that to meet the biofuel demands there will have to be an increase in irrigation and a corresponding decrease in water availability in the future. To test these effects they did a country by country (or in some cases regions) analysis of a 15% increase in irrigation to predict the reduction in the availability of water. They used a 'best guess' M scenario and used a target supply of 304 exajoule/year in the year 2100. After running the model they noted that countries that currently had water constraints quickly became depleted, other countries were able to maintain their supplies. The United States and Argentina had to withdraw more than 25% of their available water to meet the supply goal. This would put these countries at a significant risk for water shortage crises.

A similar study by Varis (2007) drew heavily from Berndes work; however, this paper also included a marginal increase in withdrawals estimate given certain biofuel expectations. They to acknowledge that water will be the main constraint for the bioenergy movement, and different regions of the world will be constrained differently. Additionally, they point out that the United States will be particularly interesting because of the levels of water required for corn based ethanol production (mainly irrigation) which is the United States chief bioenergy; whereas, other countries in more tropic regions can rely on crops such as sugarcane with little increase in water intake. To compound this matter the United States has mandated that biofuel production will be tripled between 2005 and 2012. The authors begin by estimating that 1-3% of all available water is currently being used for biofuels, and they estimate that by the year 2025 that

number will increase to around 12%. This figure includes all biofuel projects, not just corn based ethanol. This is an important article because it provides a baseline figure for the increase of water consumption due to the biofuel boom.

Finally, McPhail and Babcock (2008) developed a working paper that seeks to estimate the short-run price and welfare impacts of federal ethanol policies. The three policies that are measured are the Renewable Fuels Standard, the blenders' tax credit, and the tariff on imported ethanol. To do this they developed a multi-market, stochastic equilibrium model to simultaneously simulate the price and volatility of the U.S. corn, ethanol, and fuel for the 2008/09 marketing year. This model will solve for the equilibrium corn price, ethanol price, and gasoline price for the 2008/09 marketing year. The researchers are then able to manipulate the model to determine the effects of the aforementioned policies. After running the model the authors had several main conclusions. First, elimination of any one of the aforementioned policies would have a very small impact on short-run corn prices (an average reduction of less than 4%). If two or all three of the policies were eliminated the effect would be larger, but still modest, with an average price reduction of 10.025%. The direction of the estimated price impacts implies that corn growers, ethanol producers, and fuel consumers want to maintain high ethanol consumption, but gasoline and livestock producers want to decrease ethanol production (livestock producers are only worried about domestic production). The important implication for this thesis is that ethanol policies do have an effect on crop prices, but they are not the only force that has an effect on price. This is important to keep in mind when we discuss our "biofuel scenario."

### **3.3 Irrigators' Responses to Commodity Prices and Water Constraints**

A publication by Strickland and Williams (1997) considered the implications of water scarcity on irrigation rates in Kansas. While this paper does not directly deal with the biofuel boom, the basis of the study is very similar. They chose to group irrigated fields into six size classes (126, 98, 78, 66, 60, and 48 acres) and created combinations of irrigated corn, wheat, and grain sorghum. From these crops there were eight possible water application levels and six dryland options, totaling 225 cropping alternatives. Farmer's then choose cropping alternatives and water application rates that maximize their profits. This study finds that it is most profitable to slightly reduce the amount of irrigation per acre so that it is possible to irrigate all acres. They also note that is always most profitable grow irrigated corn and a dryland rotation of wheat-sunflower-fallow. The important implication from this study is that they observed that it is more profitable to decrease the rate of irrigation in order to continue to grow the maximum amount of irrigated acres.

Finally, Chanyalew, Featherstone, and Buller (1989) published an article that estimated the change in the crop mix (irrigated corn, irrigated sorghum, and dryland sorghum) as groundwater became more scarce, crop prices increased, pumping cost increased, and the water table decreased (each were measured individually) for the Ogallala aquifer area. The researchers assume that each farmer is acting as though they are maximizing their profits. So, they set up a model using Modular In-core Nonlinear Optimization System (MINOS) that optimizes returns to the farmer subject to constrained water and land quantity. From this net returns function they were able to vary the prices and constraint levels to see how the optimal crop mix changes. It should also be noted that they used a quadratic and a cubic response function for water applied to corn and sorghum.

After running each simulation they obtained several results. First, under current conditions, irrigated grain sorghum never enters into the optimal solution. They estimate that the cost of growing grain sorghum as opposed to another crop is about \$2.78 an acre. Secondly, if groundwater is limited, Kansas farmers will choose to trade off irrigated corn acres for dryland sorghum acres (assuming water pumping costs are held constant). The authors mention one caveat, which is that the model only considers short-run profit maximization; in the long-run it could be different. Third, as corn and sorghum prices increase, irrigated corn will be substituted for dryland grain sorghum (*ceteris paribus*). Fourth, they increase the pumping costs and found that the optimal mix of irrigated corn and dryland sorghum does not change until the pumping cost reaches \$4 per acre inch. Fifth, they note that as the aquifer level drops the pumping costs will increase, but this does not change the optimal mix until the above scenario is reached. Finally, they concluded by noting that as the aquifer level declines, the acres of irrigated corn produced decreases at the rate at which water becomes constrained. Although this study does not directly deal with the biofuel effect, its procedure and application to a decreasing water supply is the same as in my model. Additionally, the revenue maximization function that finds the optimal crop mix employed here is very similar to my modeling process.

### **3.4 Summary**

The model employed in this thesis builds on a number of publications. The basic approach of integrating a farm-level programming model with a hydrologic component to track water availability over time is similar to that of Vaux and Howitt (1984), Provencher and Burt (1994), and Bernardo et al. (1993). The yield-water relationships that determine revenue levels as water applications vary are built on the work of Yaron and Dinar (1982) and Shani, Tsur, and Zemel (2004).

This thesis also builds on the research considering the impacts of high commodity prices on water resources. Several studies (National Research Council, 2008; Pate et al., 2007; Berndes, 2008; Varis, 2007) estimated that irrigation water use would need to increase significantly to support additional production of biofuel feedstocks in the coming decades. However, these studies did not explicitly address the role of commodity prices in changing the crop mix in different regions. Strickland and Williams (1997) and Chanyalew, Featherstone, and Buller (1989) considered the impact of commodity prices and water availability constraints on irrigators land- and water-use decisions. This study contributes to the literature by estimating the long-term impact of increased commodity prices on water availability, and the degree to which future water scarcity limits future decisions.

## **Chapter 4: Model**

This chapter unveils the modeling procedures employed in this study. The modeling procedure is broken into portions. First, the reasons for applying the positive mathematical programming method is further explained. The second section considers the annual decision model. The decision model section explains the farmer's annual decision on what crops to grow and how much water to apply. The third section explains the calibration process used in the model. Finally, the last section clarifies the dynamic features of the model as the decision process is simulated over time.

### **4.1 Positive Mathematical Programming (PMP) method**

As mentioned in Chapter 3, the PMP method was chosen for this thesis. Two main factors guided this choice. First, there is limited individual farm data on water use, crop acre allocation, and costs structure. The majority of the data of this type are observed at the county level. Also reported at the county level are much of the weather and other agronomic data (such as ET, fully watered yield, etc.). Aquifer data, including depth to water and saturated thickness, are available from very high resolution (from the Kansas Geological Survey [KGS]) to a very coarse resolution and everything in between. Therefore, for the sake of consistency and accuracy, the data used was assembled at the county level. This situation is well suited to the PMP method because there is a limited amount of total data. As explained earlier the PMP method is designed to accommodate such instances.

Secondly, the model is created in the form of a policy scenario (a price shock) to be simulated over a 60-year time horizon. The PMP method was created for such instances because it allows the researcher to be free of countless flexibility constraints. This is because the PMP

process calibrates to the data observed in a base year, and then allows the model to change choice variables over time without additional constraints to prevent over-allocation to any one crop. This is especially important in this situation because the model, which will be discussed in full detail later, has multiple choice variables (optimal bundles of crop acreages and optimal water use per crop) that would need to be constrained in some fashion to prevent unrealistic corner solutions over the simulation period. Unfortunately, there is little to no empirical information to support any specification of these constraints. The PMP method circumvents this problem by calibrating the objective function of the problem in such a way that the model solutions reproduce observed data in the base year.

#### 4.2 Annual Decision Model

Consider a groundwater irrigator's land and water allocation problem, assuming a quadratic cost function:

$$(1) \quad \begin{aligned} \max \quad & \sum_i p_i f_i(w_i) x_i - c_i(w_i, x_i; \alpha_i, \gamma_i, \delta_i) x_i \\ \text{s.t.} \quad & \sum_i x_i \leq b \end{aligned}$$

where  $b$  is the size of the farm (available land area), and, for crop  $i$ ,  $p_i$  is the output price,  $f_i(w_i)$  is the production function (crop yield per acre as a function of water use per acre,  $w_i$ ),  $x_i$  is the land area planted,  $c_i(\cdot)$  is the per-acre cost function, and  $(\alpha_i, \gamma_i, \delta_i)$  are cost parameters.

While (1) represents the farmer's true optimization problem, it cannot be replicated on a computer without additional information because the functional forms of  $f_i(\cdot)$  and  $c_i(\cdot)$ , as well as the parameters  $(\alpha_i, \gamma_i, \delta_i)$  are initially unknown to the researcher. However, if functional forms are specified for  $f_i$  and  $c_i$ , estimates of the parameters can be imputed from observed data on farmers' chosen land allocations, irrigation levels, and costs of production. The functional forms are discussed immediately below and calibration process is described in the next section.

The production function is specified based on the work of Martin, Watts, and Gilley (1984), who developed a yield-water response function that is consistent with agronomic and water balance principles. Irrigation water use,  $w_i$ , varies crop yield between a lower bound of dryland yield,  $DY_i$ , and an upper bound of fully watered yield,  $FWY_i$ , where the latter is achieved when  $w_i$  is at or above the crop's gross irrigation requirement,  $GIR_i$ . The nonlinear function  $f_i(w_i)$  can be written:

$$(2) \quad f_i(w_i) = DY_i + (FWY_i - DY_i) \left[ 1 - \left( 1 - \frac{w_i}{GIR_i} \right)^{\frac{1}{IE}} \right],$$

where  $IE \in (0, 1)$  represents is irrigation application efficiency. This equation can equivalently expressed as:

$$(3) \quad f_i(w_i) = DY_i + (FWY_i - DY_i) - (FWY_i - DY_i) \left( 1 - \frac{w_i}{GIR_i} \right)^{\frac{1}{IE}}.$$

The marginal product of this function is.

$$(4) \quad \frac{\partial f_i}{\partial w_i} = \frac{(FWY_i - DY_i)}{IE * GIR_i} * \left( 1 - \frac{w_i}{GIR_i} \right)^{\frac{1-IE}{IE}}$$

This function was constructed from agronomic observations of irrigated and non-irrigated yields and water use, described in more detail in the following chapter. The parameters of the function were set for each crop so that when evaluated at observed water use,  $w_{i0}$ , it returns the observed yield,  $y_{i0}$ :

$$(5) \quad f_i(w_{i0}) = y_{i0}, \quad i = 1, \dots, I$$



Following the PMP literature (Howitt, 1995; Tsur et al., 2004) and the groundwater literature (Gisser and Sanchez, 1980) the per-acre cost function is specified to be linear in both land allocations and in water use:

$$(6) \quad c_i(w_i, x_i; \alpha_i, \gamma_i, \delta_i) = (w_i - w_{i0})\delta_i + \alpha_i + (\frac{1}{2})\gamma_i x_i.$$

When  $w_i = w_{i0}$  this function collapses to

$$(7) \quad c_i(w_{i0}, x_i; \alpha_i, \gamma_i, \delta_i) = \alpha_i + (\frac{1}{2})\gamma_i x_i.$$

These functional forms give the needed structure to the problem for calibration.

Substituting (6) into (1) and taking first order conditions, the optimal solutions to the farmer's problem satisfy:

$$(8) \quad p_i f_i(w_i) - \alpha_i - (w_i - w_{i,0})\delta - \gamma_i x_i - \lambda = 0, \quad \forall_i$$

$$(9) \quad p_i f'_i(w_i)x_i - \delta_i x_i = 0, \quad \forall_i,$$

along with the constraint  $\sum_i x_i = b$ , where  $\lambda$  is the Lagrange multiplier on the constraint.

### 4.3 Model Calibration

The calibration problem is one of setting cost parameters  $(\alpha_i, \gamma_i, \delta_i)$ , so that the solution to equations (8) and (9) coincide with observed data on land allocations,  $\mathbf{x}_0 = (x_{10}, \dots, x_{I0})$  and irrigation levels,  $\mathbf{w}_0 = (w_{10}, \dots, w_{I0})$ . In addition, the per acre cost function for crop  $i$ , when evaluated at  $x_{i0}$  and  $w_{i0}$ , must equal to observed costs per acre:

$$(10) \quad c_i(w_{i0}, x_{i0}; \alpha_i, \gamma_i, \delta_i) = c_{i0}.$$

The first step in determining the cost parameters is to solve the following problem, similar to (1):

$$\begin{aligned} & \max_{\{x_i\}} \sum_i p_i y_{i,0} x_i - c_{i,0} x_i \\ (11) \quad & s. t. \sum_i x_i \leq b \end{aligned}$$

$$x_i \leq x_{i,0} + \varepsilon$$

where the new constraint is known as a calibration constraint, and  $\varepsilon$  is a small positive number known as a calibration constant. Here, the production function,  $f_i(w_i)$ , has been replaced by observed yield,  $y_{i,0}$ , and the per-acre cost function has been replaced by observed costs,  $c_{i,0}$ . The Lagrangian for equation (11) can be written:

$$(11) \quad L_\varepsilon = \sum_i [p_i y_{i,0} x_i - c_{i,0} x_i] + \lambda [b - \sum_i x_i] + \sum_i \mu_i [x_{i,0} + \varepsilon - x_i]$$

where  $\mu_i$  is the Lagrange multiplier on the calibration constraint. The first order necessary conditions to the calibration problem are:

$$(12) \quad \frac{\partial L_\varepsilon}{\partial x_i} = p_i y_{i,0} - c_{i,0} - \lambda - \mu_i = 0, \quad \forall_i$$

$$(13) \quad \frac{\partial L_\varepsilon}{\partial \lambda} = b - \sum_i x_i = 0$$

$$(14) \quad \mu_i [x_{i,0} + \varepsilon - x_i] = 0,$$

where  $\mu_i$  is the multiplier on the  $i$ th calibration constraint. Problem equation (11) is computable because all parameters are known. By construction, its solutions will be within a small tolerance (namely  $\varepsilon$ ) of the observed acreages  $\mathbf{x}_0$ ; in the following discussion we will use  $x_{i,0}$  to denote both the observe acreage of crop  $i$  and the corresponding variable in the solution to equation (11).

If the cost function is calibrated correctly, then equation (8) will be satisfied when evaluated at  $x_{i0}$  and  $w_{i0}$ . Given that the production function is constructed so that  $f_i(w_{i0}) = y_{i0}$ , equation (8) then implies

$$(15) \quad \alpha_i + \gamma_i x_{i,0} = p_i y_{i,0} - \lambda.$$

Equation (12) reveals that the quantity  $p_i y_{i0} - \lambda$  can be computed from the solution to the calibration problem as

$$(16) \quad p_i y_{i,0} - \lambda = c_{i,0} + \mu_i.$$

Substituting equation (16) into equation (15), we have:

$$(17) \quad \alpha_i + \gamma_i x_{i,0} = c_{i,0} + \mu_i.$$

If the per-acre cost function is calibrated correctly, it will be equal to observed costs,  $c_{i0}$ , when evaluated at  $(w_{i0}, x_{i0})$ . By equation (7) this requirement is:

$$(18) \quad \alpha_i + \frac{1}{2} \gamma_i x_{i,0} = c_{i,0}.$$

Equations (17) and (18) are the system of two equations which uniquely determine the two unknowns for crop  $i$ ,  $(\alpha_i, \gamma_i)$ , given the observed data  $(x_{i0}, c_{i0})$  and the computed multiplier  $\mu_i$ .

This system can be solved explicitly:

$$(19) \quad \gamma_i = 2\mu_i/x_{i,0}$$

$$(20) \quad \alpha_i = c_{i,0} - \mu_i$$

The final cost parameter,  $\delta_i$ , can be calibrated from equation (9) as follows. If the function is calibrated correctly, then equation (4) will hold when evaluated at  $(w_{i0}, x_{i0})$ . After substituting equation (4) into equation (9) and evaluating at  $(w_{i0}, x_{i0})$ ,  $\delta_i$  can be found as

$$(21) \delta_i = \frac{p_i(FWY_i - DY_i)}{(IE)(GIR_i)} \left(1 - \frac{w_{i0}}{GIR_i}\right)^{\frac{1-IE}{IE}}$$

#### 4.4 Dynamic Simulations

Once the model is calibrated, it was exercised to simulate water allocation decisions over time. In the simulation phase, the annual decision problem, equation (1), was augmented with features that further constrain decisions based on water availability conditions through time. In particular, during each year of the simulation ( $t = 1, \dots, 60$ ), the planted acreages of the crops,  $\mathbf{x}_t = (x_{1t}, \dots, x_{It})$ , and the water application amounts,  $\mathbf{w}_t = (w_{1t}, \dots, w_{It})$ , were predicted by solving the following problem:

$$\max \sum_i p_i f_i(w_{i,t}) x_{i,t} - [c_i(w_{i,t}, x_{i,t}, \hat{\alpha}_i, \hat{\gamma}_i, \hat{\delta}_i) + k_t w_{i,t}] x_{i,t}$$

$$\text{s. t.} \quad \sum_i x_{i,t} \leq b$$

$$(17) \quad \sum_i x_{i,t} \leq b_a$$

$$w_i \leq m_t, \quad i \in Q$$

where  $(\hat{\alpha}_i, \hat{\gamma}_i, \hat{\delta}_i)$  are the calibrated values of the cost parameters,  $k_t$  represents the additional pumping cost in year  $t$  relative to the base year,  $Q$  is the set of indices of irrigated crops (i.e,  $i \in Q$  if and only if  $i$  is an irrigated crop),  $b_a$  is the legally authorized irrigated acreage, and  $m_t$  is the maximum feasible water application in year  $t$  given the state of the aquifer.

The second term in the brackets of the objective function,  $k_t w_{it}$ , is added to account for changing pumping costs over time, which will increase as the aquifer is depleted and water must be pumped from ever greater depths. As describe below,  $k_t$  is defined in such a way that it vanishes in the base year (i.e.,  $k_0 = 0$ ), so it is would not have affected the calibration of the cost function to base year data. The first constraint is identical to that in problem (1), but the second and third constraints are new. The second constraint limits the total acreage of irrigated crops to no more than the legally authorized acreage, while the third accounts for the fact that well yields (and thus maximum feasible irrigation levels) decline as the aquifer is depleted. Both the second and third constraints are nonbinding in the base year and so would not have affected the calibration (i.e, they could have been included in the calibration problem but would not have influenced the calibration outcome).

Several equations of motions update the hydrologic conditions through time and ultimately determine the values of  $k_t$  and  $m_t$ . These equations are described in detail below. It should be noted that the MATLAB code for the model used in this thesis is in included in the appendix. In this section the appendix will be referred to often to correlate the equation with the code. The code's lines are numbered so that a reference to an equation in the code may be easily found.

The first equation in the dynamic updating process simply calculates total water use in year  $t$ , denoted as  $W_t$ . This variable measures the volume of total water pumped from the aquifer (in acre feet) for each simulation year:

$$(18) \quad W_t = \sum_i x_{i,t} w_{i,t} / 12,$$

where acre-inches in the sum of the right hand side of the equation is converted to acre feet by dividing the result by 12. Note that  $W_t$  only accounts for agricultural irrigation; water consumed for domestic, industrial, and municipal purposes is implicitly assumed to stay constant over time. This equation is in the code on lines 323 and 412.

The second equation to consider is the equation for lift. The variable  $Lift_t$  is the distance (in feet) from the ground surface to the water level in the aquifer at the beginning of simulation year  $t$ . Its value is updated through time from the following mass balance equation (Gisser and Sanchez, 1980):

$$(19) \quad \mathbf{Lift}_t = \mathbf{Lift}_{t-1} + \frac{W_t}{S * A_b} - \frac{R}{12S},$$

where  $S$  is the specific yield of the aquifer,  $A_b$  is the area above the aquifer (measured in acres), and  $R$  is the rate of recharge (measured in inches/year). This equation can be found in the code on lines 286, 290, 375, and 379.

The third equation is the depletion variable, measured in feet, which determines how much the aquifer declined after a year of water consumption. This is one of the more straightforward equations as it is simply the difference between the current lift and the previous year's lift:

$$(20) \quad \mathbf{Depletion}_t = \mathbf{Lift}_t - \mathbf{Lift}_{t-1}$$

This equation can be seen in the code on lines 285, 289, 374, and 378.

Another more simplistic equation is the current level of saturated thickness, denoted as  $ST_t$  and measured in feet. The equation for saturated thickness is the previous year's saturated

minus the current depletion. This equation is shown below and can be observed in lines 287, 290, 376, and 380.

$$(21) \quad \mathbf{ST}_t = \mathbf{ST}_{t-1} - \mathbf{Depletion}_t$$

Another equation of motion is the gallons pumped per minute variable, denoted as  $GPM_t$ . This variable indicates the physical constraint of how much water a well could pump per unit of time given the current level of saturated thickness. From cross sectional data on well capacities and aquifer characteristics, Golden, Peterson, and O'Brien (2008) estimated the following relationship:

$$(22) \quad \mathbf{GPM}_t = -\mathbf{488.93} + * \mathbf{HC} + \mathbf{8.75} * \mathbf{ST}_t + \mathbf{.05} * \mathbf{ST}_t^2,$$

where  $HC$  stands for hydraulic conductivity, a measure of the speed of lateral flow in the aquifer. The equation can be observed in lines 294 and 383 of the code.

The next equation determines  $m_t$ , also known as the maximum allowable water application ( $MAWA_t$ ). This value is simply a conversion of units from the computed value of  $GPM_t$  in equation (22), translating the pumping rate in gallons per minute to the maximum amount of irrigation (in acre inches per acre) that can be applied over an irrigation season on a given sized field.  $MAWA_t$  is computed as

$$(23) \quad \mathbf{MAWA}_t = (\mathbf{GPM}_t * \mathbf{60} * \mathbf{24} * \mathbf{Days} * \mathbf{12}) / (\mathbf{7.48} * \mathbf{43560} * \mathbf{Acres}),$$

where  $Days$  is the length of the irrigation season and  $Acres$  is the size of a typical field irrigated from a single well. The  $Days$  value is 60 for Sheridan and Seward counties and 80 for Scott County. The  $Acres$  set at 126 acres for each county, representing the size of a typical irrigated field in western Kansas.

Finally, the updated value of  $Lift_t$  computes the marginal cost of pumping,  $MC_t$ , based on an irrigation engineering formula (Rogers, 1999):

$$(24) \quad MC_t = \frac{.114*FP*(PH+Lift_t)}{EF},$$

where  $FP$  is fuel price of natural gas (assumed to be \$14.75/MCF),  $PH$  is Pumping Head (feet) required to generate 20 pounds per square inch of pressure at the pivot point ( $PH$  is constant equal to 46.2), and  $EF$  energy efficiency of natural gas (a constant equal to 58.6). This equation can be found in the code on lines 293 and 382. The value of  $k_t$  in the objective function of problem (17) is calculated as:

$$(25) \quad k_t = MC_t - MC_0$$

#### 4.5 Summary

To summarize this chapter, this section discusses how each of the previous sections fit together to create the computational model. The complete model executes in four stages, following the sequence of the sections above. Stage I of the code (lines 11-46) reads in the necessary data on crop yields, prices, costs, water use, and crop acreages to construct the calibration problem presented in equation (11). Stage II (lines 47-58) then executes the calibration problem and compute the values of  $\alpha_i$  and  $\gamma_i$  for all crops (equations (19)-(20)).

Stage III (lines 59-225) is the verification stage. In this part all of the costs, revenue, agronomic data, and observed water use are established for each of the crops in the scenario (irrigated wheat, dryland wheat, irrigated corn, dryland corn, irrigated sorghum, dryland sorghum, irrigated soybeans, and irrigated alfalfa) in lines 87-184. The values of  $\delta_i$  are computed (equation (21) above) for each crop in lines 197-201. Next (lines 204-209), the model computes the water application level for each crop using the calibrated values of  $\delta_i$  and equation (9) above,



to ensure they match the observed water allocation. Then (lines 212-217), the model employs the production functions (equation (2)) to find the yield for each crop, again to verify that simulated yields match observed yields. Finally, this section verifies that the PMP process works by solving problem (1) with the calibrated cost function to ensure that its solution falls within a small tolerance of the observed acreages. This is done with a quadratic programming problem in line 223.

The final portion of this model, stage IV, is the simulation stage. All of the hydrological data is read into the model and run through a sixty year loop where the model chooses the optimal water and optimal acres and irrigation levels by solving problem (17) and then updating the hydrologic variables using equations (18)-(25). The model saves the computed values of land use, water use, and other information for later output. This simulation is then repeated a second time under a different assumption about prices. While the first simulation employs the base prices (average of 1999-2003 prices), and the second loop represents a higher prices level observed in a later period (average of 2006 and 2007 prices). This is the model process that this thesis will employ with the data established in the next chapter.

## **Chapter 5: Data**

The data for this thesis were obtained from a variety of sources. The data can be organized to four major categories: crop and price data, aquifer and hydrological data, Kansas farm budget data, and agronomic data. This chapter will describe where the data in each of these categories were obtained and give a general synopsis of the data.

### **5.1 Cropping Patterns and Price Data**

The data for cropping patterns and commodity prices (Table 5.1) were taken from the National Agriculture Statistics Service (NASS) website. There were two separate scenarios for which data were gathered. The first scenario was the baseline simulation which represents the low commodity prices. Crop acres, yields, and prices from the years 1999 to 2003 were taken from the NASS online database ([www.usda.nass.gov](http://www.usda.nass.gov)), and an average over this five year period was computed as the base values. The second scenario represents higher commodity prices observed after 2006. The prices for this scenario were calculated as an average of 2006-2007 prices, which were also obtained from the NASS online database.

**Table 5.1 Crop Production Parameters**

Item	Wheat		Corn		Sorghum		Soybeans	Alfalfa
	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Irrigated
<b>Price</b>								
Base Scenario	\$ 2.8/bu	\$ 2.8/bu	\$ 2.08/bu	\$ 2.08/bu	\$ 1.96/bu	\$ 1.96/bu	\$ 4.71/bu	\$ 83.2/ton
High Price Scenario	\$ 5.43/bu	\$ 5.43/bu	\$ 3.97/bu	\$ 3.97/bu	\$ 3.62/bu	\$ 3.62/bu	\$ 8.32/bu	\$ 111.33/ton
Percent Increase	194%	194%	191%	191%	185%	185%	177%	134%
<b>Yield</b>								
Sheridan	52.2 bu/acre	38.6 bu/acre	178.2 bu/acre	58.8 bu/acre	92 bu/acre	54.9 bu/acre	42.3 bu/acre	3.3 ton/acre
Scott	48.4 bu/acre	39 bu/acre	165 bu/acre	60.2 bu/acre	90.2 bu/acre	63.2 bu/acre	32.2 bu/acre	4.6 ton/acre
Seward	49.8 bu/acre	31.2 bu/acre	182.3 bu/acre	33 bu/acre	92.2 bu/acre	32 bu/acre	42.6 bu/acre	7.4 ton/acre
<b>Acres</b>								
Sheridan	5100	109542	58220	45386	1200	38197	8794	8794
Scott	14240	137300	27440	19440	5360	79720	2300	2040
Seward	24220	48780	59425	4250	6380	27940	10300	11740
<b>Gross Revenue (\$/Acre)</b>								
Sheridan	146.2	108.1	370.7	122.3	180.3	107.6	199.2	274.6
Scott	135.5	109.2	343.2	125.2	176.8	123.9	151.7	382.7
Seward	139.4	87.4	379.3	68.6	180.7	62.7	200.6	619.0
<b>Share of Planted Cropland (%)</b>								
Sheridan	2%	40%	21%	16%	0%	14%	3%	3%
Scott	5%	48%	10%	7%	2%	28%	1%	1%
Seward	13%	25%	31%	2%	3%	14%	5%	6%

Source: National Agricultural Statistic Service (NASS): [www.usda.nass.gov](http://www.usda.nass.gov)

There are several important notes to make about this table. First, it is noticeable that all of the prices increased dramatically between the 1999-2003 base period and 2006-07. Wheat and corn saw the largest increases of 194% and 191% respectively. The smallest increase was a pedestrian 134% for alfalfa. The important point to take is that when the model is shocked the new prices will all be significantly higher. This, along with the hydrological changes, could force significant changes in crop allocation over the 60-year simulation horizon.

The second important observation is the different crop patterns in each county. Sheridan County is a wheat dominated county; wheat comprises 41.65% of crop acres. However, corn is a close second with 37.61%, followed by sorghum (14.32%), soybeans (3.2%) and alfalfa (3.2%). It is also important to notice that all of the irrigated crops encompass only 29.84% of total crop acres. This is a fairly typical amount of irrigated acres for the western Kansas region, corresponding with Sheridan County's saturated thickness, which is also typical of the region. Within the irrigated portion of acres, corn is the dominant crop with 70.1% of irrigated acreage.

Irrigated corn and alfalfa are by far the two highest gross income crops, although they only account for 24.35% of the total crop acres. Moreover, the two lowest gross income crops, dryland wheat and sorghum, make up 53.68% of crop acres. This is most likely due to variances in land fertility (wheat and sorghum can grow on very marginal land), as well as cultural factors.

Scott County is much less diversified than Sheridan. In fact 52.65% of Scott's total crop allocation is dedicated to wheat, although only 4.95% of that share is irrigated wheat. Overall, only 17.85% of crop acres in Scott County are irrigated. The largest of the irrigated crops is corn with 9.53% of total acres or 53.4% of total irrigated acres. Additionally, 98.48% of the total crop acres are in wheat, corn, or sorghum. The majority of that percentage (82.15%) is in dryland production. The low levels of irrigation are due to that fact that Scott County has very low levels of saturated thickness and annual rainfall. Therefore Scott County is somewhat limited to low water input crops. This makes Scott County a particularly interesting county to study. Because the effects of aquifer decline may already be occurring, a price change may have very little effect.

Seward County also has many distinct characteristics from Sheridan and Scott. The first noticeable item is that Seward County is a heavily irrigated county with irrigated crops accounting for 58.06% of crop acres. This is expected as Seward has a high amount of saturated thickness, allowing many producers to take advantage of irrigation to raise higher-revenue crops. Additionally, Seward is a more diverse county with 6.4% of crop acres coming from soybeans and alfalfa. Like Sheridan and Scott, wheat is still the primary crop with 37.82% of crop acres, but corn is a close second with 32.98% of the crop acres. Irrigated corn also comprises about 53% of the total irrigated acres. It would be expected that both corn and alfalfa are more

prominent in Seward County given the large amount of beef stockyards and dairy cattle operations in that vicinity.

Each of these counties offers a different perspective on crop patterns and irrigated use. It is also true that each of these counties display very different gross incomes from crops. This will make for a diverse study of the effect of rising prices and decreasing aquifer levels.

### 5.2 Aquifer Level data

The next category of data is the aquifer level data. These data were obtained from a number of different sources. The variables lift, saturated thickness, specific yield, aquifer area,<sup>1</sup> hydraulic conductivity, recharge rate, and depth were all acquired from the Kansas Geological Survey section-level database. The “wells” variable was obtained from the Water Information Management and Analysis System (WIMAS) online database. These parameters are shown in Table 5.2.

**Table 5.2 Hydrological Parameters**

Parameter	Unit	Symbol	Sheridan	Scott	Seward
Initial Lift <sup>a</sup>	feet	Lift	111.5	112.1	189.5
Initial Saturated Thickness <sup>a</sup>	feet	ST	71.8	46.5	315.3
Specific Yield <sup>a</sup>	--	s	0.2	0.2	0.2
Land Above Aquifer <sup>a</sup>	acres	A	415620.5	319424.8	357470.8
Hydraulic Conductivity <sup>a</sup>	feet/day	HC	68.5	90.0	74.0
Annual Recharge Rate <sup>a</sup>	inches/year	R	0.8	0.6	1.0
Depth <sup>a</sup>	feet	D	183.3	158.6	504.7
Wells <sup>b</sup>	--	--	708.0	792.0	566.0
Min. Required Saturated Thickness	feet	Stmin	30.0	30.0	30.0

Sources: a) Kansas Geological Survey Section Level Database ([www.kgs.ku.edu/HighPlains/data/](http://www.kgs.ku.edu/HighPlains/data/)) and b) Water Information Management and Analysis System

Note: For calibration purposes the variable "Land Above Aquifer" was calculated from the formula:  $A_b = W_0 / ((s \cdot D) + (R/12))$  where  $W_0$  is total water use

<sup>1</sup> To ensure that the mass balance equations properly update the aquifer’s depth over time, the variable  $A$  was calculated by solving the following equation for  $A$ :  $\Delta = W_0/(As) - R/s$ , where  $\Delta$  is the observed rate of decline in the aquifer during the base period (in feet/year),  $W_0$  is the observed volume of water pumped per year (in acre feet),  $s$  is the specific yield of the aquifer, and  $R$  is recharge in feet/year. This method of calculating  $A$  ensures that historical decline rates are consistent with historical pumping and recharge rates given the updating formulas used in the model. The calculated value of  $A$  does not equal the geographic area overlying the aquifer within a given county, because it accounts for the hydrologic connection of the aquifer to land areas outside the county. For example, some precipitation initially falling in neighboring counties eventually recharges the aquifer underlying Sheridan County.

Here again it is important to notice the differences and similarities between the case counties. Sheridan County has the lowest lift (or distance between the land surface and aquifer) and second highest saturated thickness. These are very important factors when considering whether or not to irrigate land. Lift is important because as the lift gets deeper the cost to pump water gets higher. Saturated thickness is important for two different reasons. First, as the saturated thickness increases the length of time at which you can physically pump water (i.e., the usable lifetime of a well) also increases. This is an important decision when considering the cost of pumping, or more specifically for how many years you can spread out the costs of pumping equipment, setup, maintenance, etc. Additionally, this also factors into the decision of how much, or at what rate, to pump during a given year. Obviously the more saturated thickness available, a farmer will be able to pump at a faster rate; i.e., deliver a greater volume of water to the crop per unit of time pumping. So, it should be expected that farmers in Sheridan County will pump a fairly average amount of water for an average length of time.

There are some more positive statistics for the aquifer over Sheridan County. First, Sheridan County has a moderate rate of recharge due mainly to the higher amounts of rain (as compared to Scott County) and average hydraulic conductivity (or the soil's ability to transmit water when submitted to a hydraulic gradient). Overall, much like the cropping pattern data, Sheridan County is a fairly average county in terms of aquifer statistics.

Scott County is an entirely different county in terms of water resources. Scott County has a very low saturated thickness level (46 feet), which is only 16 feet above the minimum amount of saturated thickness required for irrigated operations (30 feet). This would imply the life of potential irrigation in Scott County is severely limited. These statistics also correspond with Figure 2.4, which predicts anywhere from 0-20 years of irrigation left in Scott County given the

present rates of irrigation. Even if irrigation were ceased, the aquifer would recover very slowly given the extremely low rates of recharge (.55 inches/year) and specific yield (.155). Curiously, the number of wells (792) is a very high number given the low amounts of water reserves. This would indicate that Scott County was formerly heavily involved in irrigation. Additionally, given the shallow lift (112 feet), it is easy to see why irrigation would have been very attractive. These statistics make Scott County a very interesting case study. Moreover, it will also be interesting to compare Scott County (with little useable life) to Sheridan County.

Finally, Seward County is also wholly unlike both Sheridan and Scott counties. Seward County is not experiencing water shortages. In fact, irrigators in Seward County have one of the largest aquifer resources in Kansas with 315 feet of saturated thickness. Additionally, they have a relatively high annual recharge rate of 1.01 inches/year and a hydraulic conductivity 73.98 feet/day. These are each indicators of a plentiful aquifer. Thus it is not surprising that irrigated crops are common in Seward County (as stated before 58.6% of all crops are irrigated). However, it is interesting that high levels of irrigation persist despite the depth of the lift (189 feet). Evidently, the high amounts of water that can be pumped from the aquifer result in high yields that generate enough gross revenue to offset the heavy energy cost of pumping. Seward County will also be an interesting county because the model may find that the aquifer levels are sufficiently high that an increase in price will not change the irrigation habits. Figure 5.7 gives an illustrative image of the heavily irrigated southwest Kansas region.

**Figure 5.7 Aerial Image of Irrigation in Southwest Kansas**



Source: National Aeronautic Space Administration

Figure 5.7 was taken in the area of a nearby county to Seward on June 24, 2001. It is easy to see that even before the commodity price increase this area was heavily irrigated. This only serves to add to the flavor that the three case counties bring to this study. Each case county has a distinctively different aquifer level, recharge rate, etc. Simulations of these counties will show how high prices affect a wide spectrum of irrigated areas in Kansas.

### **5.3 Kansas Farm Budget Data**

The third component of the model data deals with the production costs of the selected crops. The production costs were obtained from Kansas State University Extension budgets.



These costs were subdivided into several categories: irrigation costs, variable expenses, fertilizer and seed costs, and harvest and hauling costs. These parameters are reported in Table 5.3.

**Table 5.3 Production Costs (\$/acre)**

Expense	Wheat		Corn		Sorghum		Soybeans	Alfalfa
	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Irrigated
Irrigation	8.56	---	82.51	---	55.84	---	21.29	43.47
Variable Expenses	87.99	87.99	194.49	194.49	121.56	121.56	86.69	197.80
Fertilizer and Seed	62.10	62.10	188.99	188.99	99.63	99.63	54.56	54.56
Harvesting and Hauling								
Sheridan	17.91	15.86	15.84	8.94	22.22	16.66	22.13	41.25
Scott	20.58	18.14	47.85	17.46	28.37	21.62	20.48	68.03
Seward	20.69	15.85	31.42	9.57	27.87	12.82	23.21	110.04

Source: Kansas State University Extension Budgets

In this case the county differences are not large. The only differences occur in the Harvesting and Hauling expenses. The harvesting and hauling expenses are a function of a flat rate and an extra charge for yields exceeding a set base yield amount. The flat rate is the same for each county and there is a slight difference in the extra charge and set base yield; therefore, the real difference making in total harvesting and hauling expenses is the observed yield.

Overall there is not a set pattern as to which county has the highest costs. Sheridan County is not the high cost producer in any crop, but it is the low cost producer in irrigated wheat, irrigated corn, nonirrigated corn, and irrigated sorghum. Scott County is the high cost producer in nonirrigated wheat, irrigated corn, nonirrigated corn, and irrigated sorghum. They are the low cost producer only in soybeans. Seward County has the highest costs for irrigated wheat, soybeans, and alfalfa. At the same time it has the lowest cost for nonirrigated wheat and nonirrigated sorghum. Again the variability amongst the counties will allow for some interesting results in the model.

## **5.4 Agronomic Data**

The final component of the data is the agronomic data. There are many different components to the agronomic data, and it comes from a wide range of sources. The values and sources are listed the table 5.4.

**Table 5.4 Agronomic Data**

Parameter	Wheat Irrigated	Corn Irrigated	Sorghum Irrigated	Soybeans Irrigated	Alfalfa Irrigated
Water Use (acre inches/acre) <sup>a</sup>					
Sheridan	6.9	12.7	11.4	12.1	13.8
Scott	7.3	15.8	9.6	13.1	21.4
Seward	9.8	19.5	10.7	15.9	17.2
ET required for FWY <sup>b</sup>					
Sheridan	15.0	24.2	20.4	23.7	28.0
Scott	15.0	24.7	20.4	23.7	31.8
Seward	16.5	26.7	20.4	24.0	28.0
Growing Season Precip. (inches) <sup>c</sup>					
Sheridan	8.6	14.3	12.2	14.3	17.3
Scott	9.1	13.4	11.7	13.4	16.5
Seward	8.9	12.4	10.9	12.4	15.7
Gross Irrigation Requirement (inches/acre) <sup>d</sup>					
Sheridan	8.6	14.5	11.5	13.5	15.8
Scott	8.1	15.9	12.2	14.6	21.7
Seward	10.3	19.7	13.1	16.1	17.5
Net Irrigation Requirement (inches/acre) <sup>d</sup>					
Sheridan	6.5	10.9	8.6	10.1	11.8
Scott	6.0	12.0	9.1	11.0	16.3
Seward	7.7	14.8	9.8	12.1	13.1
Fully Watered Yield (FWY) <sup>e</sup>					
Sheridan	56.9 (bu/acre)	201.3 (bu/acre)	92.5 (bu/acre)	48.9 (bu/acre)	3.9 (ton/acre)
Scott	49.8(bu/acre)	166.1 (bu/acre)	100.5 (bu/acre)	37.2 (bu/acre)	4.7 (ton/acre)
Seward	51.1 (bu/acre)	183.7 (acre/bu)	111.5 (bu/acre)	43.3 (bu/acre)	7.6 (ton/acre)
Dryland Yield (DY) <sup>e</sup>					
Sheridan	38.6 (bu/acre)	58.8 (bu/acre)	59.9 (bu/acre)	---	---
Scott	39 (bu/acre)	60.2 (bu/acre)	63.2 (bu/acre)	---	---
Seward	31.2 (bu/acre)	33 (acre/bu)	32 (bu/acre)	---	---

Sources: a) Water Information Management and Analysis System; b) O'Brien et. al;

c) NOAA National Climatic Data Center; d) The National Engineering Handbook; e) Stone et. all

Note: 1)The variable "Total Water Use" is derived from the formula  $W_{0,i} = WaU_i * Acres_i$

where  $W_{0,i}$  is the water use by crop,  $WaU_i$  is Water Use per crop, and  $Acers_i$  is acres by crop

2) Net Irrigation Requirement (NIR) is calculated from the formula:  $ET_0 - (EP * GSP_0) - CSM$

where  $ET_0$  is base ET required for FWY,  $EP$  is Effectiveness of Precipitation,  $GSP_0$  is base growing season precipitation, and  $CSM$  is change in soil moisture

3) Gross Irrigation Requirement is calculate from the formula:  $NIR/IE$ , where  $IE$  is season long irrigation efficiency (.75 for this study)

Here again we see that this is a wide diversity among the case counties. Irrigators in Sheridan County used the least amount of irrigated acre inches per acre for wheat, corn, soybeans, and alfalfa. This is partly because they receive the most growing season precipitation for corn, sorghum, soybeans, and alfalfa. (It should be noted that because crops of different lengths of growing seasons the amount of growing season precipitation will vary across crops within a county.) Moreover, all crops in Sheridan County have the lowest (or are tied for the lowest) ET requirement for fully watered yield. This combined with the high growing season precipitation means that net irrigation requirement (to achieve fully watered yield) is much lower than the other counties. In fact Sheridan County has the lowest net irrigation requirement for every crop except irrigated wheat (they are the second lowest to Scott).

Scott County exhibits more variation across crops than Sheridan County. Scott has the lowest water use for irrigated sorghum, the highest for irrigated alfalfa, and ranks in the middle of the three counties for wheat, corn, and soybeans. This is a product of several different factors. First, Scott County has the highest level of growing season precipitation for irrigated wheat, and is second in all other crops. Secondly, the required ET for fully watered yield is also wide-ranging. Scott County is tied for the lowest ET (with Sheridan County) for wheat, soybeans, and sorghum (all counties have the same level); it has the second-lowest ET for corn, and the highest for alfalfa. These combinations result in Scott having the lowest net irrigation requirement for wheat, second for corn, sorghum and soybeans, and the highest value for alfalfa.

Finally, Seward County represents the water-rich county in this study. Seward County uses the most irrigation water for wheat, corn, and soybeans. It also uses the second most water for sorghum and alfalfa. This is not only due to the fact that they have the most water to use, but also because of several environmental / agronomic facts. First, Seward receives the lowest

growing season precipitation for every crop except wheat, where they are the second lowest. Moreover, Seward has the highest required ET for wheat, corn, and soybeans and is tied for the lowest in sorghum and alfalfa.

Once again we observe that there is variety among the counties. As a result of differing environmental and agronomic factors Sheridan County will be the low water user for most crops and Seward County will be the high water user. Scott County will again be interesting to observe as their water use is generally second among the counties, but is also the most in for alfalfa and the least for sorghum. However, given the low aquifer level in Scott County it may be observed that they become the low water-use county.

### **5.5 Data Summary**

The main point to take from the data chapter is the diversity of the case counties chosen. There is no one truly dominant county where farming, or irrigated farming for that matter, has a distinct advantage. For example, Seward County would seem dominant based on the large expanse of the aquifer underneath it. However, the high lift, high harvesting and hauling costs, and high net irrigation requirement could make irrigation in some areas of Seward County less desirable in the long run. Additionally, Scott County will be extremely interesting as they have a very low level of aquifer levels, but at the same time they have average net irrigation requirements and the irrigated crops gross far more profit than the dryland crops. It is important to keep the data values and the diversity of each county in mind as this study progresses into the results chapter.

## **Chapter 6: Results**

This chapter reports the results from running the model described in chapter 4 with the data reported in chapter 5. This chapter is organized in a similar way as the data chapter, covering in sequence the three main areas of interest in this research: acreage allocation over time, hydrological results, and net revenue earned by irrigators over time. Within each section, the base price and high price scenarios are compared in each of the three case study counties.

### **6.1 Acreage Allocation Results**

The first sets of results that will be covered are the acreage allocation results. In the data section there were a few overall observations about the base acreage allocations. First, Sheridan County is moderately diverse county with the majority of the acres in wheat (41.65%) and dryland cropping (70.17%). Secondly, Scott County is the most one dimensional with over 50% of its cropland in wheat production. Additionally, 82.15% of crop acreage in Scott County is dryland production. Finally, Seward County is the most diverse with wheat being the largest crop at 37.82% of total cropland. Seward County also is the most water plentiful county with 58.06% of its cropland under irrigation. It is important to keep these observations in mind as we look at the changes over the 60 year simulation.

#### *Sheridan County Results*

The first county that will be discussed is Sheridan. Before discussing the simulated acreages over the 60-year horizon, the performance of the model in reproducing recent years' acreage data is assessed. By definition, the model exactly reproduces the average acreages from 1999-2003. During the period 2004-2007, commodity prices escalated dramatically with an especially large increase in the year 2006. As such, we would expect the base price scenario to

reproduce observed acreages more accurately early in the period and the high price simulation to better predict observed acreages later in the period. Tables 6.5 and 6.6 report the prediction errors of the Sheridan County model for each crop, measured as percentages of total crop acres. Overall, the model was fairly accurate in predicting the observed acreage values (2004-2007). As expected, the base price scenario does the best job at estimating the years 2004 and 2005, and the high price model does the best job at estimating the years 2006 and 2007. This adds confidence in the predictions over the 60 year simulation period because the model has successfully calculated known years. Therefore, there is no reason to believe that it will not continue to simulate correctly.

**Table 6.5 Base Scenario Prediction Errors, 2004-2007, Sheridan County**

	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	<b>Average 04-05</b>	<b>Average</b>
<b>Irrigated Wheat</b>	-3%	-1%	-1%	-1%	-1%	-2%
<b>Dryland Wheat</b>	1%	-3%	6%	1%	1%	-1%
<b>Irrigated Corn</b>	4%	-1%	2%	-1%	1%	1%
<b>Dryland Corn</b>	-2%	-3%	-11%	-10%	-7%	-3%
<b>Irrigated Sorghum</b>	0%		-1%	0%	-1%	0%
<b>Dryland Sorghum</b>	-2%	6%	4%	3%	3%	2%
<b>Irrigated Soybean</b>	-3%	0%	0%	1%	-1%	-2%
<b>Irrigated Alfalfa</b>	1%	1%	1%	1%	1%	1%
<b>Total</b>	-5%	-2%	-1%	-6%	-4%	-3%

**Table 6.6 High Price Prediction Errors, 2004-2007, Sheridan County**

	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	<b>Average 06-07</b>	<b>Average</b>
<b>Irrigated Wheat</b>	-4%	-3%	-3%	-3%	-3%	-3%
<b>Dryland Wheat</b>	-4%	-8%	1%	-3%	-4%	-1%
<b>Irrigated Corn</b>	12%	7%	11%	7%	9%	9%
<b>Dryland Corn</b>	4%	4%	-4%	-4%	0%	-4%
<b>Irrigated Sorghum</b>	-1%		-1%	-1%	-1%	-1%
<b>Dryland Sorghum</b>	-6%	3%	0%	0%	-1%	0%
<b>Irrigated Soybean</b>	-5%	-2%	-2%	-1%	-2%	-1%
<b>Irrigated Alfalfa</b>	-2%	-2%	-3%	-2%	-2%	-2%
<b>Total</b>	-5%	-1%	-1%	-6%	-4%	-3%

There several important observations to take from each table. The base scenario fairly accurately replicates the observed acreages of most crops. Looking at the years 2004-2005, the

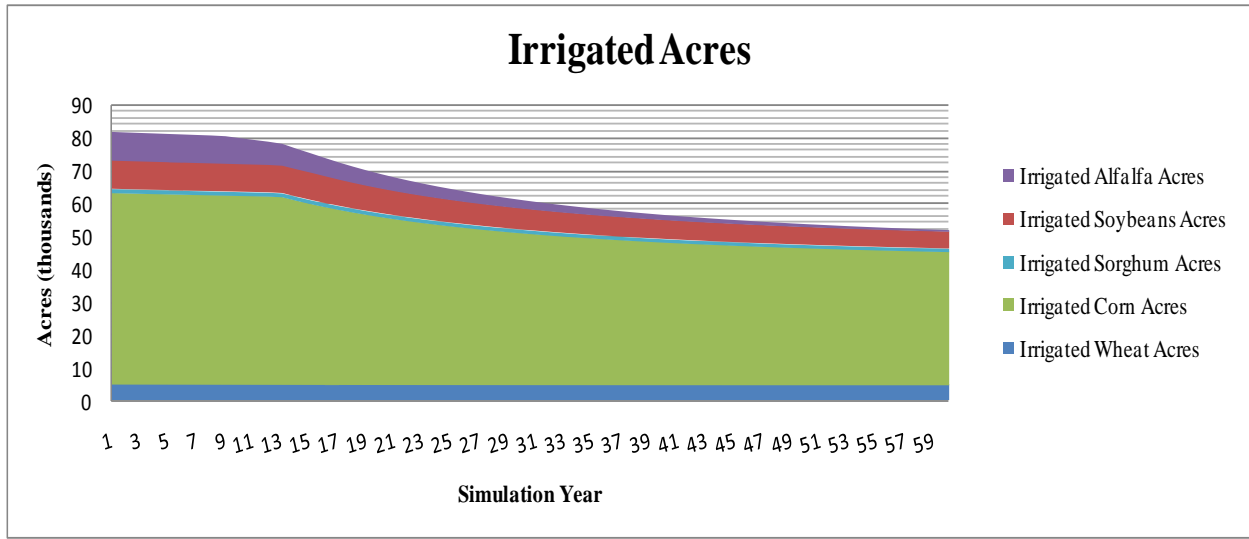
absolute average difference is 1.5% per crop, 1.2% for irrigated crops, and 2% for dryland crops. The model was the least accurate in predicting dryland corn (-3%), and the most accurate in predicting dryland wheat (-1%), irrigated corn (1%), and irrigated alfalfa (1%). Note that this does not include irrigated sorghum, despite the 0% error in year 2004, because the data was unavailable for the year 2005. The model also is also fairly accurate in predicting total acres, with an average prediction error of -3%. This error arises from the fact that total acreage is fixed in the model, while it rose slightly during the 2004-07 period as farmers brought previously idle land under production. The one oddity of this model is that the year 2006 actually outperforms 2004.

The high price model performs acceptably, but did not accurately predict irrigated corn acreage in 2006. However, irrigated corn acreage was predicted more accurately in 2007. Looking at the 2006-2007 average, the model is within 3% (absolute) error for all crops except irrigated and dryland corn. This is fairly expected as corn saw some of the largest changes both in price and known acres.

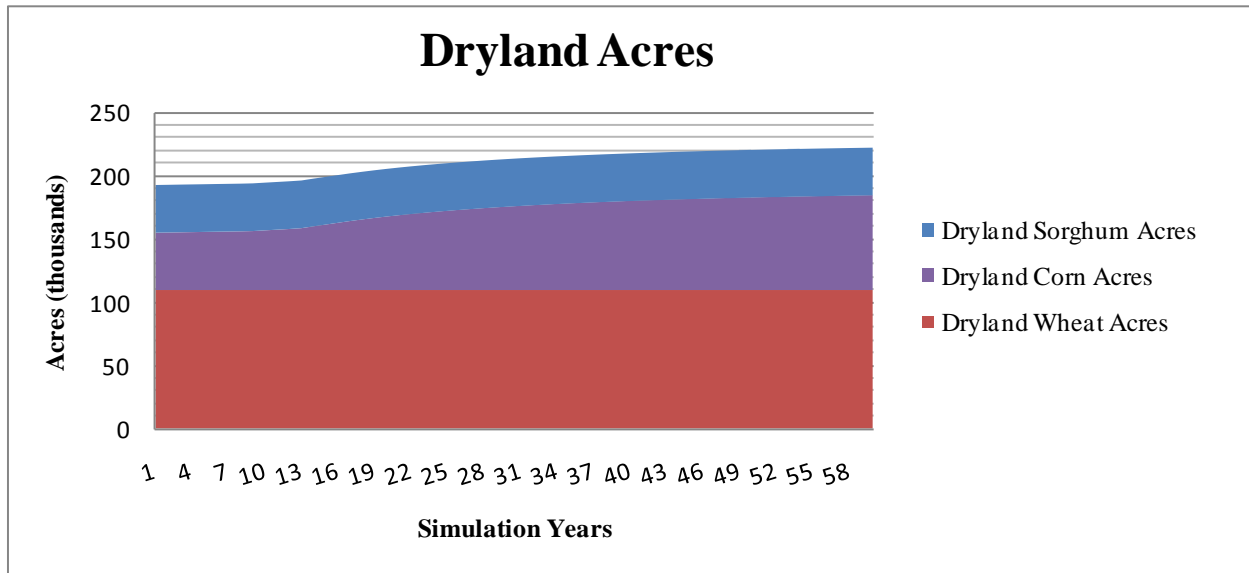
Overall the model performs in a satisfactory way in replicating the known acres. This lends some confidence to the model's ability to predict beyond the period of observation. Figures 6.8 and 6.9 display the simulated change in crop patterns over time given the base scenario prices. The "Simulation Years" start after 2003; in other words "Year 1" refers to the year 2004.



**Figure 6.8 Simulated Irrigated Acres, Base Price Scenario, Sheridan County**



**Figure 6.9 Simulated Dryland Acres, Base Price Scenario, Sheridan County**



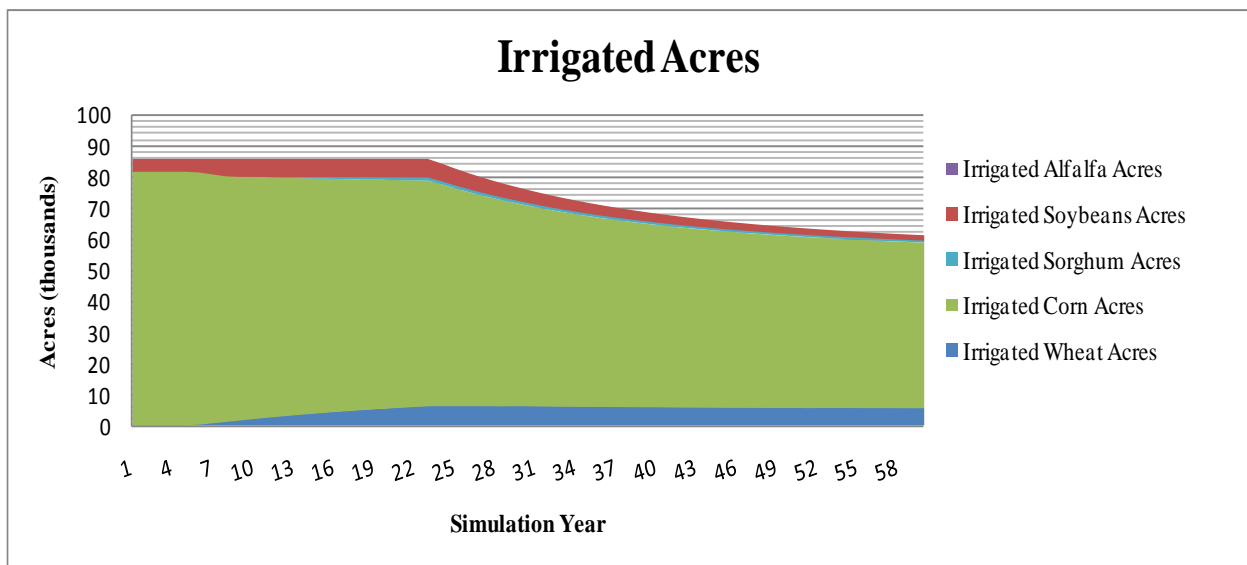
There are several important implications and notes to take from these two graphs. First, there is a general decline in all of the irrigated crops until around year 13. Around year 13 there is a noticeable kink in the area graphs and all irrigated crops, save irrigated wheat, follow a much steeper descent. As discussed in a later section, this kink corresponds to the time when the water availability constraint begins to bind and restricts irrigation application rates. Irrigated wheat

remains relatively constant throughout the simulation period, declining only 4.28% over the sixty year period. Irrigated alfalfa suffers the biggest acreage loss, declining 41.69%, followed by irrigated corn (30.23%) and irrigated sorghum (17.15%).

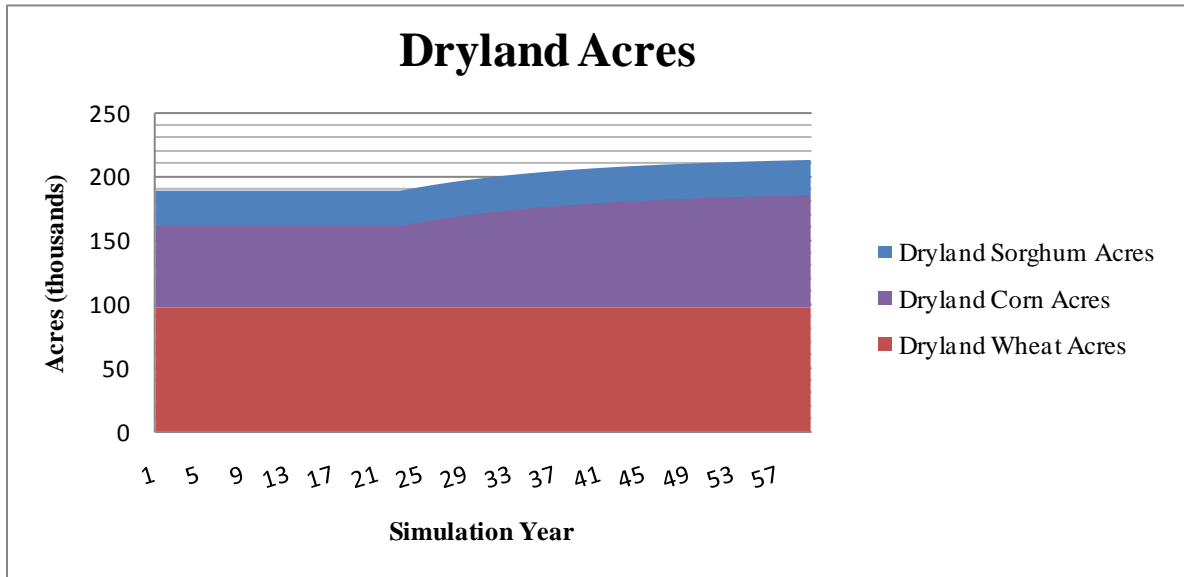
The rapid decrease after year 13 corresponds to an increase in dryland corn acres. The acreages for dryland wheat and sorghum do not change during the simulation period; all of the acres that come out of irrigated production go directly into dryland corn production. This equates to a 65.64% increase (29,894 acres) in dryland corn production. This is an expected result as dryland wheat and sorghum have remained relatively constant during the base years and observed later years (2004-2007). However, as the marginal cost of pumping (discussed later) has risen there has been a steady shift towards dryland corn from irrigated corn. As the simulated years go on it only makes sense to see that shift continue from other irrigated activities.

The next set of graphs (Figure 6.10 and 6.11) represents the crop allocation for Sheridan County under the high price scenario.

**Figure 6.10 Simulated Irrigated Acres, High Price Scenario, Sheridan County**



**Figure 6.11 Simulated Dryland Acres, High Price Scenario, Sheridan County**



There are several important inferences to take from these graphs. First, total amount of irrigated acres in the initial simulation periods is larger than in baseline simulation, hitting the 86,000-acre legally authorized limit. The majority of these acres are taken up by irrigated corn, which accounts for 81,585 acres in simulation year 1. Irrigated corn continues its dominance among irrigated crops but diminishes through time, falling by 35.02% over the simulation period. Irrigated soybeans also take a fairly similar to the baseline path, declining 58.69% (or 2,415 acres) over the simulation period.

While irrigated corn and soybeans followed paths similar to those in the baseline simulation, the trajectories for irrigated wheat, sorghum, and alfalfa were very different from the baseline. Irrigated wheat starts the simulation at 300 acres but finishes with 5,777 acres. The likely cause of this increase is that wheat requires very little irrigation (6.9 inches/acre in Sheridan County). This means that initially everyone who can put corn into irrigation does, but as the water resources start to deplete, wheat becomes more economically feasible for some farmers. In a similar way irrigated sorghum requires the second lowest water input in Sheridan

County, and initially it is not included in the profit maximizing bundle. However, starting in year 9 it enters into the bundle. By the final year of the simulation 1,059 acres are included into the bundle. Irrigated alfalfa never enters into the profit maximizing bundle. One explanation for this is that irrigated alfalfa is the highest water input crop in Sheridan County, and it has the lowest yield (3.3 tons/acre) among the three counties. Additionally, alfalfa saw the smallest increase in price (133.81%) increase of all the crops. As such, it makes sense that in Sheridan County alfalfa would not enter into the profit maximizing bundle under the high price scenario<sup>2</sup>.

The final implication is that dryland acres remain relatively constant until year 23. At this point we see a distinctive kink (much like the base scenario) that shifts more acres into dryland corn. As such dryland corn sees a general rise of 37.76% in its acres. Unlike the previous scenario, not all of the acres for dryland corn are coming directly from irrigated corn. In this case dryland corn is sharing some of those (albeit not many) acres with irrigated wheat and sorghum.

Table 6.7 presents a snapshot of the profit maximizing crop bundles at different time periods under the two scenarios.

**Table 6.7 Profit Maximizing Crop Bundles, Selected Years, Sheridan County**

	Base Price Scenario					High Price Scenario				
	Year 1	Year 10	Year 25	Year 50	Year 60	Year 1	Year 10	Year 25	Year 50	Year 60
<b>Irrigated Wheat Acres</b>	5092	5019	4934	4883	4874	300	2298	6433	5886	5777
<b>Dryland Wheat Acres</b>	109542	109542	109546	109549	109549	96551	96551	96552	96556	96557
<b>Irrigated Corn Acres</b>	58133	57363	48174	41664	40557	81585	77636	69791	55010	53011
<b>Dryland Corn Acres</b>	45543	47419	63006	73633	75437	64738	64738	67772	86605	89183
<b>Irrigated Sorghum Acres</b>	1197	1167	1088	1004	991	0	286	1337	1091	1059
<b>Dryland Sorghum Acres</b>	38197	38197	38199	38199	38200	27944	27944	27944	27946	27946
<b>Irrigated Soybeans Acres</b>	8772	8574	6922	5377	5115	4115	5780	5404	2140	1700
<b>Irrigated Alfalfa Acres</b>	8758	7951	3366	924	510	0	0	0	0	0

<sup>2</sup> <sup>1</sup> Note: This result may be skewed by the fact that alfalfa has a different irrigation pattern than other crops; therefore, further research needs to be done in order to verify or negate this result.

This table clearly shows several differences between the two scenarios. At first glance there may not seem to be many noticeable differences between the two pricing scenarios; however, there are several key distinctions to be discussed. First, in year 1 the irrigated acres in the high price simulation are almost exclusively allocated to corn and soybeans. Irrigated wheat is barely included in the profit maximizing bundle (300 acres), while sorghum and alfalfa are absent altogether. However, as the simulation continues, irrigated wheat increases by 5,477 acres to a more historically reasonable number of 5,777 acres. Irrigated sorghum acres also have a slow upward trend to a high of 1,370 acres in year 23 before it slowly trends down to 1,059 acres in year 60. Irrigated alfalfa acres never enter into the profit maximizing crop mixture, possibly due to its high water requirement.

The second main difference is that the total amount of irrigated acres is higher in the high price scenario. In the base scenario irrigated acres started at 81,951 and dwindle to 52,047 acres. In the high price scenario irrigated acres started at 86,000 (the maximum allowed) and settled at 61,547 acres. This is directly due to the high prices making irrigation economically feasible in areas where it previously was not. It should also be noted that the higher starting acres lead to larger declines in corn and sorghum acres, of 35.02% and 58.69%, respectively.

The final difference is the year at which we see the kink in irrigated acreage trend. In the base price scenario this occurred at year 13; however, in the high price scenario it occurred around year 23. Again, at this point acres begin to shift out of irrigated crops and into dryland corn production. The explanation for this is again that the high prices allow irrigation to be profitable, mainly in areas that where it previously was not, for a longer period of time before the more rapid decrease. It is also worth noting that one difference in this shift is that under the base scenario all irrigated crops eventually declined, and those acres were shifted into dryland corn

production. However, under the high price scenario irrigated sorghum and wheat acres actually increase over time. So, under elevated prices, the shift of acres from irrigated corn does not solely go into dryland corn.

### *Scott County Results*

The next county to discuss is Scott. The model does an accurate job of predicting the observed values of Scott County. As shown in tables 6.8-6.9, there are a few places to be concerned, but the overall predication errors are low.

**Table 6.8 Base Scenario Prediction Errors, 2004-2007, Scott County**

	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	<b>Average</b>	<b>04-05 Average</b>
<b>Irrigated Wheat</b>	-1%	-1%	-3%	-2%	-2%	-1%
<b>Dryland Wheat</b>	3%	2%	4%	3%	3%	2%
<b>Irrigated Corn</b>	-1%	-5%	-2%	-3%	-3%	-3%
<b>Dryland Corn</b>	7%	2%	2%	-2%	2%	5%
<b>Irrigated Sorghum</b>	-1%	0%	1%	1%	0%	0%
<b>Dryland Sorghum</b>	-3%	3%	4%	0%	1%	0%
<b>Irrigated Soybean</b>	0%	0%	0%	0%	0%	0%
<b>Irrigated Alfalfa</b>	0%	0%	0%	0%	0%	0%
<b>Total</b>	3%	1%	6%	-3%	2%	2%

**Table 6.9 High Price Prediction Errors, 2004-2007, Scott County**

	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	<b>Average</b>	<b>06-07 Average</b>
<b>Irrigated Wheat</b>	-1%	-1%	-3%	-1%	-1%	-2%
<b>Dryland Wheat</b>	-4%	-4%	-2%	-2%	-3%	-2%
<b>Irrigated Corn</b>	4%	0%	4%	2%	3%	3%
<b>Dryland Corn</b>	10%	5%	5%	-1%	5%	2%
<b>Irrigated Sorghum</b>	0%	0%	2%	2%	1%	2%
<b>Dryland Sorghum</b>	-6%	1%	2%	-2%	-1%	0%
<b>Irrigated Soybean</b>	-1%	0%	0%	0%	0%	0%
<b>Irrigated Alfalfa</b>	-1%	0%	-1%	0%	0%	-1%
<b>Total</b>	3%	0%	6%	-3%	2%	2%

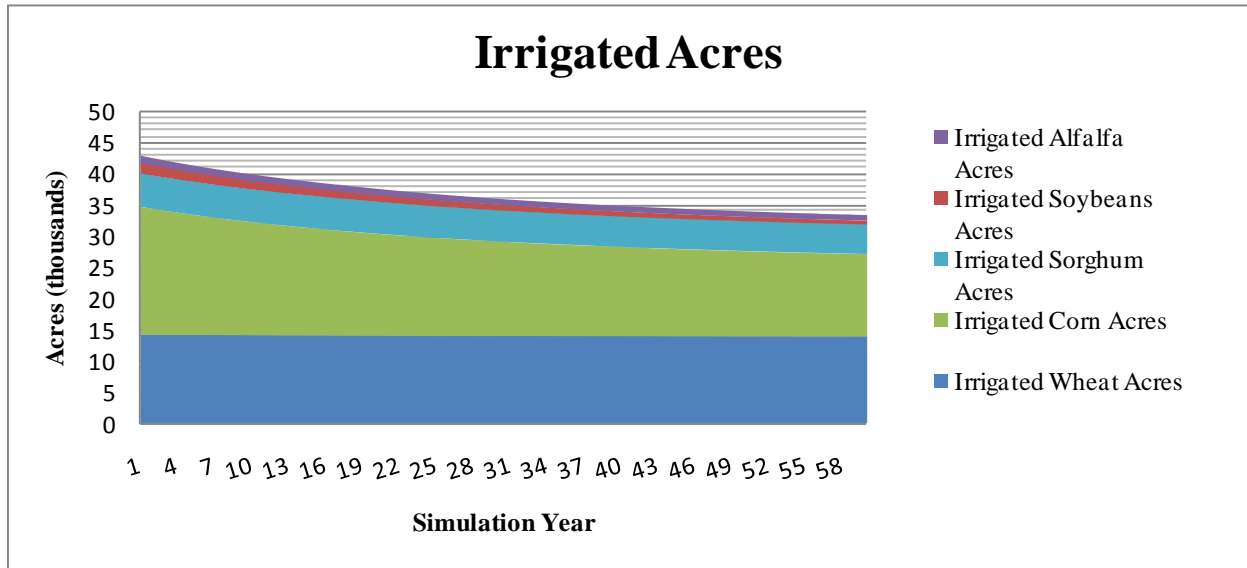
The base scenario model does a quite accurate job of predicting the observed values during the 2004-07 period, with dryland corn being the one area of concern. The base scenario model over- predicts dryland corn by an average of 5% in the years 2004 and 2005. The result of

this error is due to unusually low levels of dryland corn observed in 2004 and 2005. Otherwise the base scenario model performs very well. The 2004-2005 average error is zero for irrigated and dryland sorghum, irrigated soybeans, and irrigated alfalfa. The average 2004-2005 error for all crops is 2%; this is a slightly better result than observed for Sheridan County.

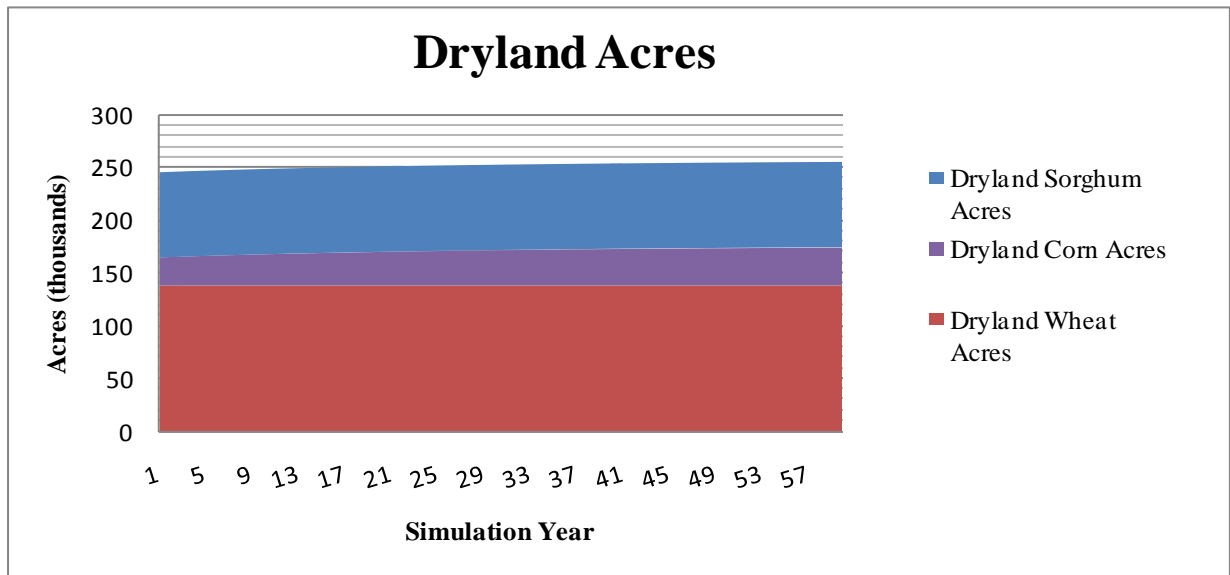
The high price scenario also performed well. As expected the model performed much better in 2007 than in 2006 (because the price increase was more fully observed in 2007). The high price model did have trouble simulating the 2006 year acres. The model has near zero error for irrigated soybeans and alfalfa in 2006. Corn (both irrigated and dryland) continued to be problematic as the model overestimated both, by 5% and 4% respectively. Additionally, the total acres were over estimated by 6%. However, these predictions improved dramatically in year 2007. The total acre prediction error dropped by an absolute value of 3%, and all of the crop acre errors improved save sorghum, which stayed the same. The final 2006-2007 averages were roughly the same as Sheridan County.

Figures 6.12 and 6.13 show the simulated optimal crop acres for the base price scenario over a sixty year simulation period.

**Figure 6.12 Simulated Irrigated Acres, Base Price Scenario, Scott County**



**Figure 6.13 Simulated Dryland Acres, Base Price Scenario, Scott County**



The results for Scott County under the base scenario are very interesting. The first easily noticeable observation is that there is a general decrease in irrigated acres from year 1 to year 60. The total decrease over this period is 22.55%, and it is driven mainly by the decrease in irrigated corn. Irrigated corn decreases 35.71% or 7,266 acres over the simulation period. All of the other irrigated crops decrease as well, but none of them except for irrigated wheat account for a

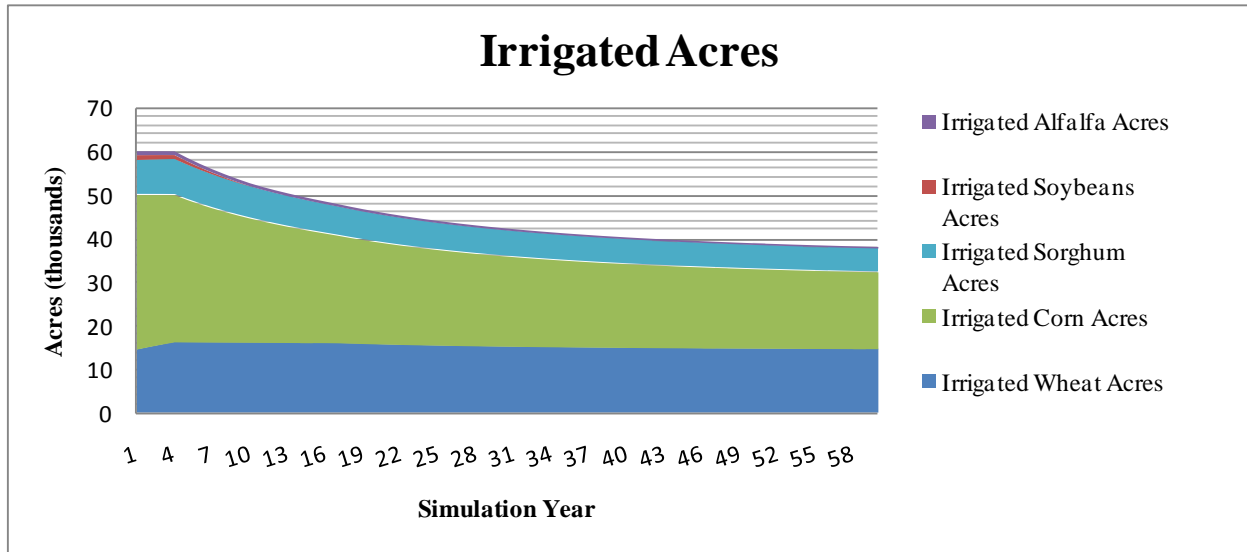


significant share of acreage. Irrigated wheat, however, remains surprisingly constant and decreases only 276 acres from its year 1 level of 14,220 acres. The likely explanation for this is that irrigated wheat uses a very small amount of irrigated water (7.28 acre inches/acre) in Scott County in the base period. As discussed later, this allows the amount of irrigated wheat grown to remain fairly stable. Irrigated sorghum, soybeans, and alfalfa enter with very little acres and also experience smaller decreases of 10.3%, 67.7%, and 27.27% respectively.

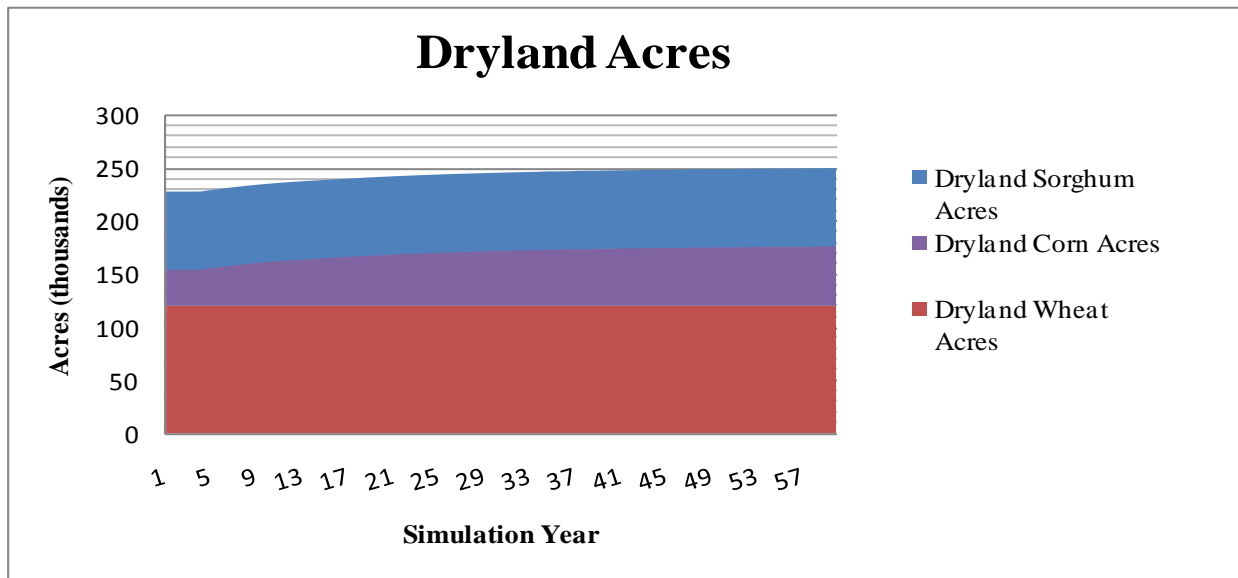
Dryland production follows the same consistent pattern, with dryland corn increasing and dryland wheat and sorghum remaining relatively constant. As dryland corn is the only crop that increases, it means that all of the irrigated acres lost are being shifted into dryland corn production. During the simulation period, dryland corn sees an increase of 9,682 acres. Not only was this observed under the base scenario of Sheridan County, but it is also logical given that Scott County has very limited water resources. So, as water resources continue to dwindle the shift to the most profitable dryland crop seems reasonable.

The next set of graphs shows the same sixty year simulation under the high price scenario.

**Figure 6.14 Simulated Irrigated Acres, High Price Scenario, Scott County**



**Figure 6.15 Simulated Dryland Acres, High Price Scenario, Scott County**



The Scott County results under the high price scenario are the most distinctive results observed in this study. Irrigated wheat acres increase for the first four years from 14,473 acres to 16,143. After year 4 irrigated wheat acres decreases 9.75% to 14,569 acres. Irrigated sorghum follows a similar pattern, increasing to a high of 8,070 acres in year 4 from a starting value of 7,823 acres. From year 4 onward, irrigated sorghum decreases 33.5% to 5,367 acres. All other

irrigated crops decrease during the simulation period. Irrigated corn sees the biggest decrease, losing over half of its year 1 acreage (35,631) by year 60 (17,721 acres); however, it should be noted that irrigated soybeans start at 1,098 acres and decreases to 0 acres by year 11. Finally, irrigated alfalfa starts at 875 acres and slowly diminishes 365 by the end of the simulation.

The dryland production is similar to what has been observed in other counties and scenarios. As previously observed, dryland wheat and sorghum remain constant throughout the simulation period. Dryland corn stays constant for the first three years, and then steadily increases by 63.02% or 21,840 acres over the rest of the simulation period. This is interesting because in those first three years, irrigated production does not exclusively switch into dryland production. Rather, dryland production stays relatively stable and a few irrigated crops actually increase. In fact for the first three years, acres switch from irrigated corn, soybeans, and alfalfa to irrigated sorghum and wheat. Then at year 4 acres start to go into dryland corn as well. After year 4 irrigated wheat and sorghum begin to lose acres into dryland corn as well. This is a much different pattern that observed in any other county scenario.

Finally, the table below compares the profit maximizing bundles at different points in time for the two scenarios.

**Table 6.10 Profit Maximizing Crop Bundles, Selected Years, Scott County**

	Base Price Scenario					High Price Scenario				
	Year 1	Year 10	Year 25	Year 50	Year 60	Year 1	Year 10	Year 25	Year 50	Year 60
Irrigated Wheat Acres	14220	14136	14044	13960	13944	14473	16038	15374	14680	14569
Dryland Wheat Acres	137310	137313	137317	137321	137321	120093	120102	120112	120118	120119
Irrigated Corn Acres	20344	17982	15566	13544	13078	35631	28665	22036	18345	17721
Dryland Corn Acres	27800	30844	34066	36848	37481	34655	41964	50575	55648	56496
Irrigated Sorghum Acres	5340	5260	5076	4839	4790	7823	7158	6051	5463	5367
Dryland Sorghum Acres	79725	79726	79728	79730	79730	73192	73196	73201	73204	73204
Irrigated Soybeans Acres	1881	1465	1041	688	608	1098	33	0	0	0
Irrigated Alfalfa Acres	1220	1113	1002	909	888	875	685	491	383	365

There are several key differences in the optimal crop mix between the base scenario and the high price scenario. First, it is important to notice that like Sheridan County, the high price scenario makes more irrigated acres economically feasible. As such the high price scenario has 16,894 more acres in irrigated crops in year 1 compared to the base scenario. However, it is also important to note that despite the high difference in the first year, by the final year of the simulation the difference is only 4,714 acres. This is most likely due to the fact that Scott County has very little water reserves. As such under the high price scenario farmers consume more water very rapidly, but many quickly start to feel the constraint and swiftly decrease their irrigated acres. This would explain why the final acres are fairly similar.

Another key difference is that irrigated soybeans and alfalfa are more prevalent in the base scenario than the high price scenario. In fact by year 60 the total acres in soybeans and alfalfa are over 4 times larger in the base scenario than the high price scenario. This is a testament to the dominance of corn in the high price scenario.

Finally, it is important to note that the overall difference between irrigated and dryland acres between the two scenarios by the final year is very little. In the first year in the high price scenario dryland crop production is 93% of the amount in the base scenario and ends up at 98% of the base scenario amount. Similarly, under the high price scenario irrigated production starts at 139% of the base scenario value, but by the final year it is 114% of the baseline value. Clearly, the low water reserve closes the gap of the price effect over the years.

*Seward County Results*

The final county to evaluate is Seward. In the previous chapter it was established that Seward County is the water rich county in this study. The first two tables show the error in the predicted values against the observed values of Seward County.

**Table 6.11 Base Scenario Prediction Errors, 2004-2007, Seward County**

	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	<b>Average</b>	<b>04-05 Average</b>
<b>Irrigated Wheat</b>	-1%	2%	0%	-1%	0%	0%
<b>Dryland Wheat</b>	2%	2%	6%	2%	3%	2%
<b>Irrigated Corn</b>		-1%	2%	-4%	-1%	-1%
<b>Dryland Corn</b>		1%	1%	0%	1%	1%
<b>Irrigated Sorghum</b>	-4%	1%	1%	0%	-1%	-1%
<b>Dryland Sorghum</b>	6%	5%	9%	6%	7%	6%
<b>Irrigated Soybean</b>	-1%	-2%	-2%	3%	1%	-1%
<b>Irrigated Alfalfa</b>			2%	1%	1%	
<b>Total</b>	3%	8%	19%	7%	10%	5%

**Table 6.12 High Price Prediction Errors, 2004-2007, Seward County**

	<b>2004</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	<b>Average</b>	<b>06-07 Average</b>
<b>Irrigated Wheat</b>	-10%	-5%	-6%	-6%	-7%	-6%
<b>Dryland Wheat</b>	7%	5%	10%	6%	7%	8%
<b>Irrigated Corn</b>		9%	12%	5%	9%	9%
<b>Dryland Corn</b>		-2%	-2%	-3%	-2%	-3%
<b>Irrigated Sorghum</b>	-5%	0%	0%	-1%	-1%	0%
<b>Dryland Sorghum</b>	4%	3%	7%	4%	5%	6%
<b>Irrigated Soybean</b>	-3%	-3%	-3%	1%	-1%	-1%
<b>Irrigated Alfalfa</b>			2%	1%	1%	1%
<b>Total</b>	-7%	8%	19%	7%	1%	13%

The model's prediction performance was lower for Seward County than the other two counties for both the base and high price scenarios. The base price scenario performed slightly better than the high price scenario. In the base price scenario the least accurately predicted crop was sorghum. More specifically, dryland sorghum was overestimated by 6% and 5% in 2004 and 2005, respectively. Irrigated sorghum was underestimated by 4% in 2004, but was overestimated by only 1% in 2005. The reason for the large overestimation of dryland sorghum is again that farmers planted more irrigated sorghum in 2004-2007 (despite the relatively little price change)

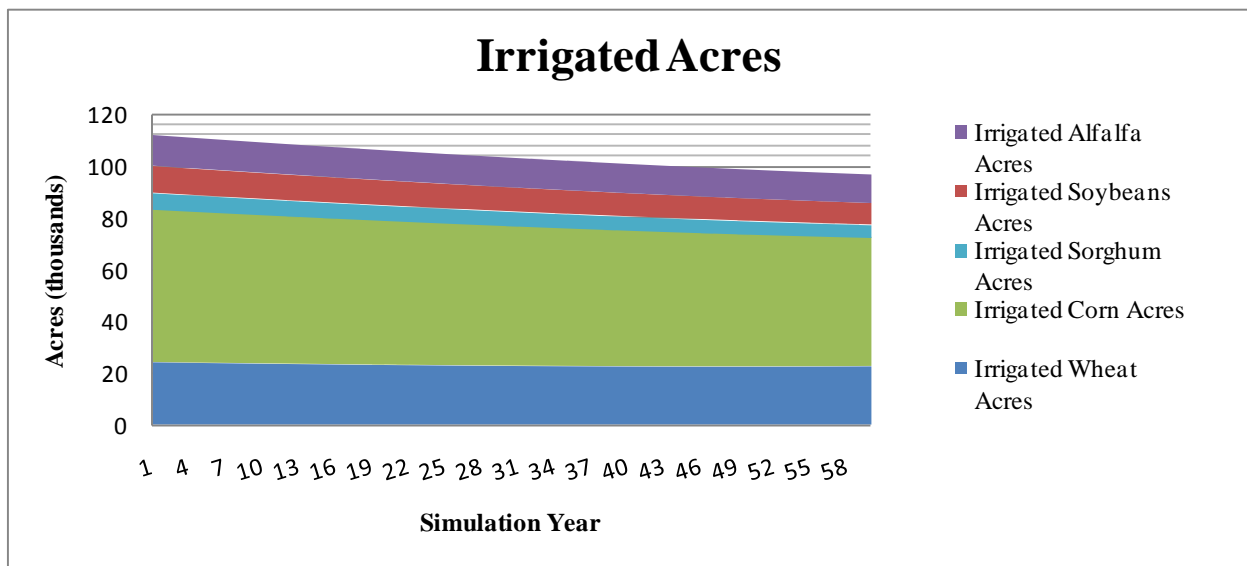
than they did in the base years (1999-2003). Because Seward County has large water reserves it does seem rational that many farmers would irrigate their sorghum; however, the model indicates that this may not be optimal given the price and production conditions in 1999-2003. The model performed relatively well in all other crops, with irrigated wheat and irrigated soybeans predicted within 1% of observed values in 2004 and irrigated corn, dryland corn, and irrigated sorghum within 1% of observations in 2005. All other crops (excluding those previously mentioned) had a 2% error or less, and the average 2004-2005 error was 1% or less for all crops except dryland wheat (2%) and dryland sorghum (6%). Finally the total error for 2004 and 2005 was 3% and 8% respectively.

Despite the issues with the base price scenario the model has a much tougher time under the high price scenario. Naturally, the model performed far worse in 2006 than 2007. In 2006 dryland wheat and irrigated corn both posted double digit errors, 10% and 12% respectively. Additionally, irrigated wheat and dryland sorghum also had larger errors at 6% and 7% respectively. All of the crops in 2006 had at least a 2% (absolute) error. These large errors lead to the high total error of 19% in 2006. However, most of these errors improved dramatically in 2007. Irrigated sorghum, irrigated soybeans, and irrigated alfalfa all had errors within 1% in 2007. The errors for dryland wheat, irrigated corn, and dryland sorghum all improved dramatically falling to 6%, 5%, and 4% respectively. The only crop that did not improve in 2007 was irrigated wheat which held constant at an under estimation of 6%. Finally, the total error for 2007 was 7%, down 12% from 2006. Overall, the 2006-2007 average for irrigated sorghum, irrigated soybeans, and irrigated alfalfa were within 1% error. All other crops, due to the poor estimation in 2006, were between 3% and 9% (absolute) error. While these errors are still fairly

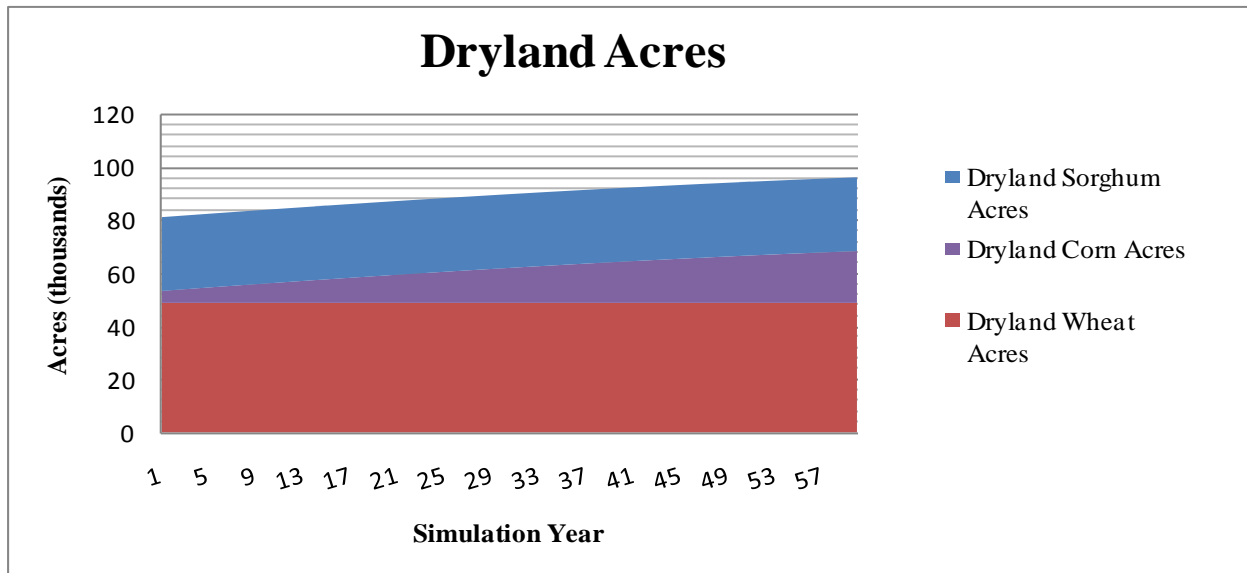
high, it does mean that the model is starting to converge on the correct acreages after the price shock.

The next set of results to discuss is the acreage allotments for Seward County. The following two graphs show the acreage allocation for the sixty year simulation period under the base price scenario.

**Figure 6.16 Simulated Irrigated Acres, Base Price Scenario, Seward County**



**Figure 6.17 Simulated Dryland Acres, Base Price Scenario, Seward County**



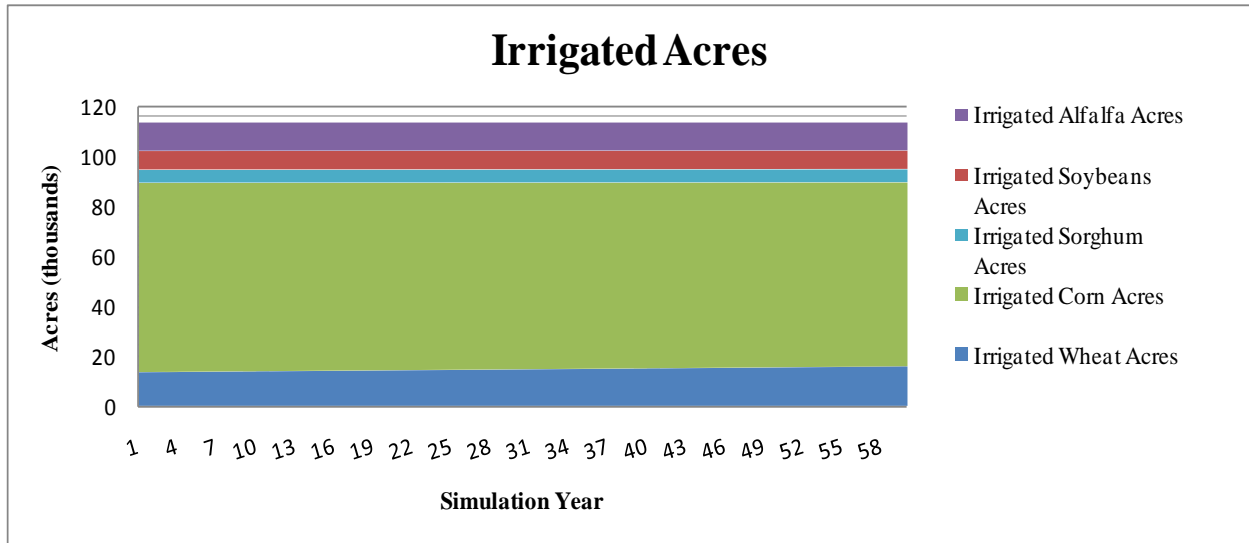
Seward County is much like Scott County under the base price scenario. All irrigated crops are decreasing (at a diminishing rate) over the sixty year period. Irrigated corn, in terms of acres, sees the largest decline, losing 9,278 acres over the sixty year period. Irrigated sorghum sees the largest decline in percentage terms, losing 23.27% of its total acres. What does not happen in this model is the distinctive kink where irrigated acres goes from losing a few acres (or actually gaining a few) to rapidly shifting acres out of irrigated production into dryland production. This phenomenon was observed in every other county simulation except here and Scott County under the base price scenario.

The results for the dryland acres are very similar to Scott under the base price scenario as well. Dryland wheat and sorghum do not change over the sixty year period. Dryland corn more than quadruples its acres from 4,576 to 19,671 acres (an increase of 15,094 acres) over the sixty year simulation period. This implies that all acres that are coming out of irrigated crops are shifted directly into dryland corn production. This is the same result observed in most other county simulations. However, it is interesting to note that even after the massive shift to dryland corn, it is still only the fifth largest crop in Seward, trailing irrigated corn, dryland wheat, dryland sorghum, and irrigated wheat.

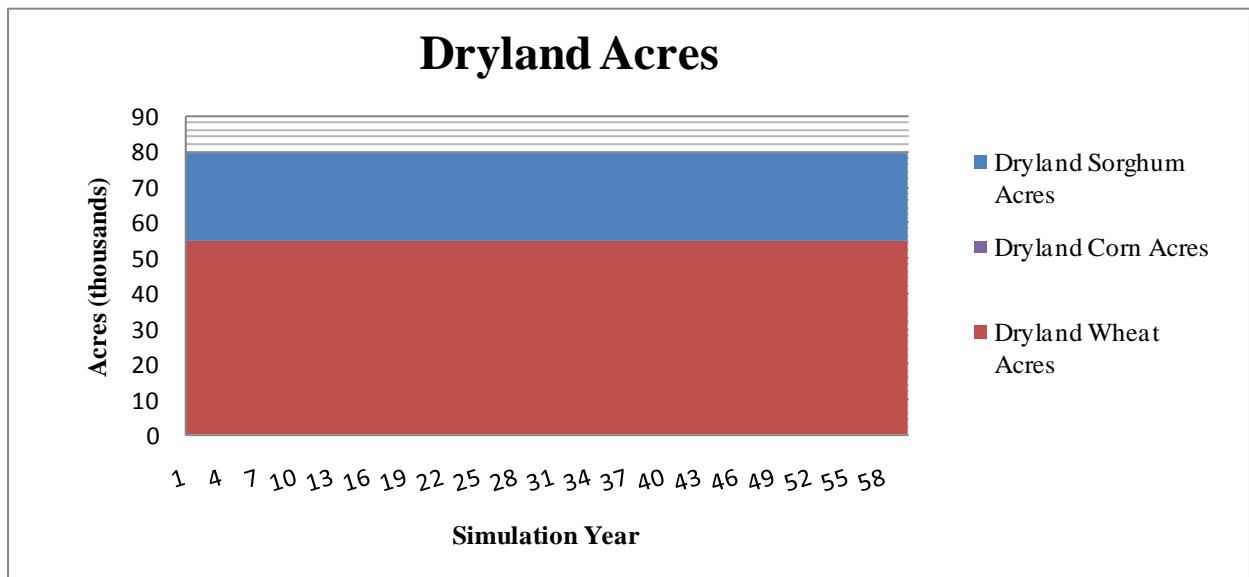
The second set of graphs is the crop acre allocation of Seward County under the high price scenario.



**Figure 6.18 Simulated Irrigated Acres, High Price Scenario, Seward County**



**Figure 6.19 Simulated Dryland Acres, High Price Scenario, Seward County**



It is easily noticeable that the results for Seward County under the high price scenario are extremely different from all of the other results observed. First, it is clear that the amount of irrigated acres has increased dramatically from the base price scenario. In year 1 of the high price scenario the total irrigated acres is 113,500 (the legally authorized limit) as compared to 111,739 acres in the base price scenario. Additionally, the total irrigated acres in the high price scenario do not vary, and the irrigated acreages of individual crops vary only slightly. The largest change

occurs in irrigated wheat, which increases 2,360 acres (or 18%). Irrigated sorghum acres also increase throughout the simulation period by 60 acres. Irrigated corn, soybeans, and alfalfa decrease over time by 2,184, 83, and 153 acres, respectively.

The dryland crop results are very simple. Dryland sorghum and wheat remain constant throughout the simulation period, at 54,673 and 24,862 acres, respectively, while dryland corn never enters into the optimal bundle. The latter is very interesting because at first glance dryland corn may seem a better choice than dryland sorghum or wheat. However, both dryland sorghum and wheat are known to be grown primarily on marginal lands (as they are both low input crops). Therefore, it would stand reason that producers would not be able to switch dryland wheat for dryland corn, for example. Additionally, we saw in previous scenarios that the majority of dryland corn acres came from the phasing out of irrigated crops while dryland wheat and sorghum remain constant. In Seward County the water is so high that there is not a general phasing out of irrigated crops. Rather there is a move from high input irrigated crops (corn, alfalfa, and soybeans) to low input irrigated crops (wheat and sorghum). So, in this light it would make sense that we do not see dryland corn.

The next table shows the profit maximizing bundles for Seward County in both the base and high price scenarios at different points in time.

**Table 6.13 Seward Profit Maximizing Crop Bundles**

	Base Price Scenario					High Price Scenario				
	Year 1	Year 10	Year 25	Year 50	Year 60	Year 1	Year 10	Year 25	Year 50	Year 60
Irrigated Wheat Acres	24157	23630	22932	22478	22606	13476	13826	14411	15412	15836
Dryland Wheat Acres	48780	48780	48780	48780	48780	54673	54673	54673	54673	54673
Irrigated Corn Acres	59248	57680	55180	51364	49970	75864	75534	74987	74064	73680
Dryland Corn Acres	4576	7432	11816	17810	19671	0	0	0	0	0
Irrigated Sorghum Acres	6347	6061	5629	5050	4870	5177	5189	5206	5230	5236
Dryland Sorghum Acres	27940	27940	27940	27940	27940	24862	24862	24862	24862	24862
Irrigated Soybeans Acres	10262	9925	9388	8573	8279	7416	7407	7390	7354	7334
Irrigated Alfalfa Acres	11724	11587	11370	11040	10919	11567	11544	11506	11441	11415

This table helps to capture the differences and similarities of the two scenarios. First, it is easy to notice that there is a significant increase in irrigated acres under the high price scenario over the long run. In the first year of the base price scenario there are 111,739 total irrigated acres. This number drops off to 96,644 acres by year 60. Under the high price scenario the total irrigated acres is 113,500 acres (the limit) for all years of the simulation. Initially this is only a difference of 1,761 acres, but by year sixty the difference increases to 16,856 acres. It is easy then to conclude the high price scenario allowed irrigation to be profitable in many areas where it previously was not.

Secondly, under the high price scenario, dryland corn never enters into the optimal crop bundle. At first glance this may seem unlikely, but dryland corn historically accounted for a very small portion of total cropland in Seward County. In fact the largest percent of the total cropland that dryland corn has accounted for was 2.8% (5100 acres out of 180900 acres) in 2007. In 2005 dryland corn accounted for less than 2% of total cropland. Therefore, it is not unlikely that under the high price scenario farmers would be more willing to irrigate their corn, even a little, to gain higher profits.

Finally, in the high price scenario the crop bundle becomes much less diverse. Irrigated corn and dryland wheat comprise almost 68% of the total crop under the high price scenario. In the base price scenario irrigated corn and dryland wheat comprise almost 56% of the total crop. That is a difference of 22,509 acres from the base scenario to the high price scenario.

Overall it is clear that each of the three counties have very different results under a price shock given their different cost structures and water resources available. In Sheridan County the price shock increased the total amount of irrigated acres for several “extra” years before an expected slowdown occurred. Scott County was similar in that we saw an initial increase in irrigated acres, but over time the acreage allotments between the base and high price scenarios became very similar. Finally, the water rich county of Seward was able to slightly increase its irrigation output in year one, but more importantly it was then able to maintain this level throughout the simulation period.

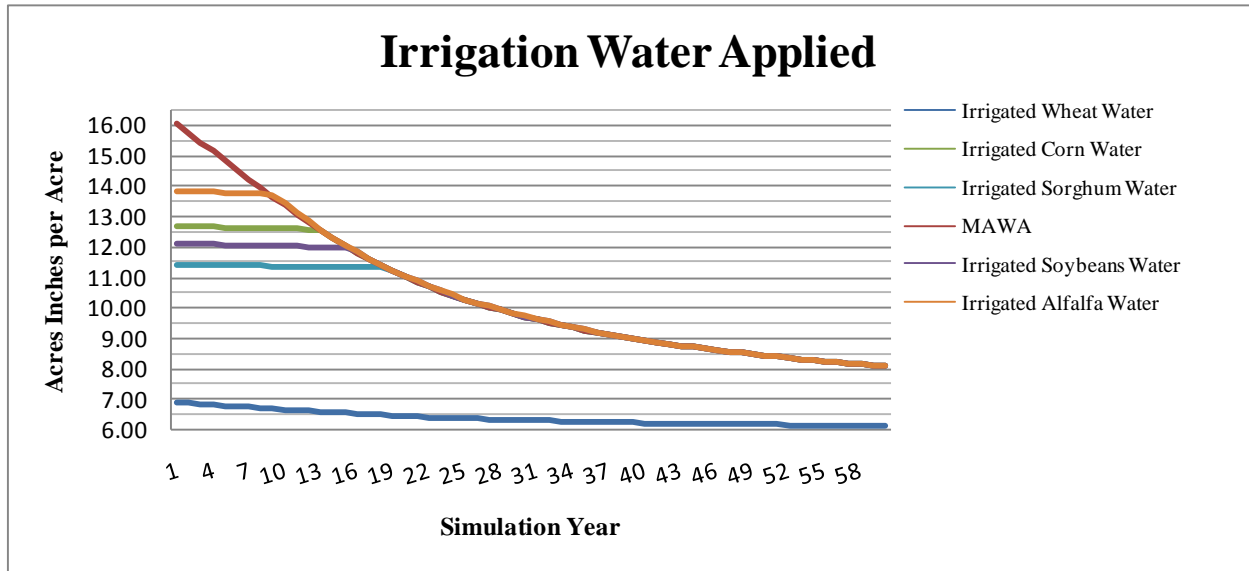
## **6.2 Hydrological results**

This section will focus squarely on the choice of the amount of irrigation applied to each crop, the amount of total water consumed, and the affect on the saturated thickness levels in each county. The first county that will be discussed is Sheridan County.

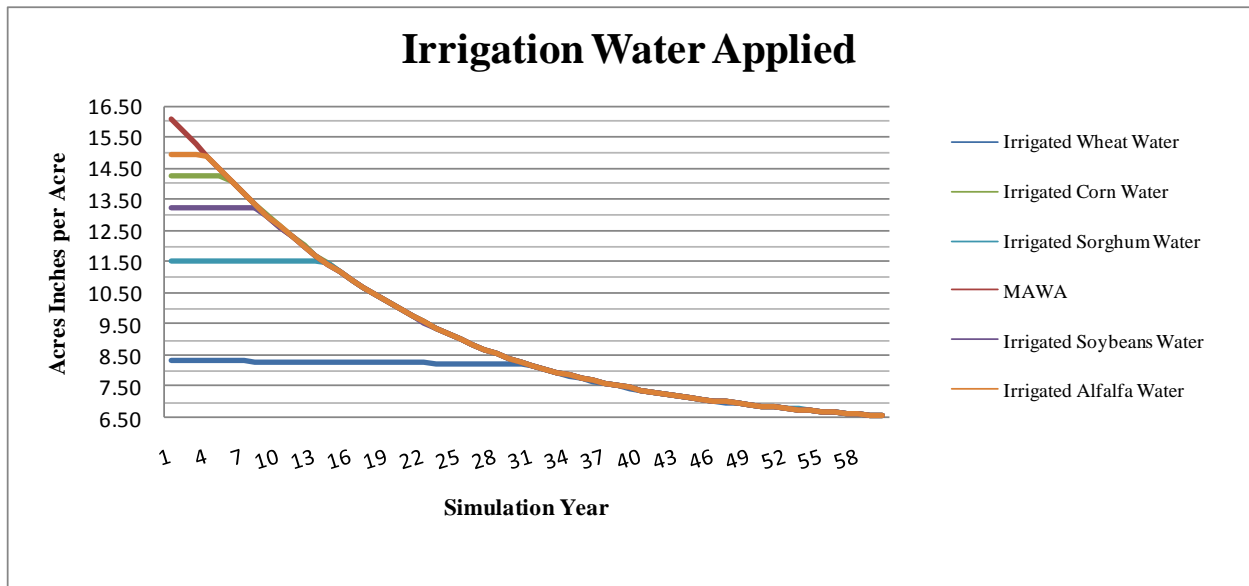
### *Sheridan County Results*

The next two graphs show the amount of irrigated water applied (acre inches per acre) for each crop grown in the two pricing scenarios. The variable MAWA stands for the maximum allowable water use and serves as the watering constraint. The derivation of the variable was described in chapters 4 and 5.

**Figure 6.20 Irrigation Application Rates by Crop, Base Scenario, Sheridan County**



**Figure 6.21 Irrigation Application Rates by Crop, High Price Scenario, Sheridan County**



From the two graphs it is clear that the price shock has several effects on the water use per crop. First, the amount of irrigation applied per crop increases for all crops. The largest increase was for irrigated corn, which jumped 1.55 acre inches per acre in year 1. The lowest increase was irrigated sorghum, which saw an increase of .09 acre inches per acre in year 1.

This coupled with the fact that more irrigated acres are grown under the high price scenario means that the maximum allowable water use constraint decreases faster as well (because the water supplies deplete more quickly). As such, we see the water applied per crop hit the constraint much earlier in the high price scenario than the base scenario. For example, under the base price scenario the first crop to hit the constraint is irrigated alfalfa in year 9 followed by irrigated corn in year 13. However, in the high price scenario irrigated alfalfa hits the constraint in year 4 followed even more closely by irrigated corn in year 6. The result of this is that by the end of the simulation farmers can apply more water per crop under the low price scenario than under the high price scenario. In other words the constraint decreases more, or becomes more constraining, under the high price scenario.

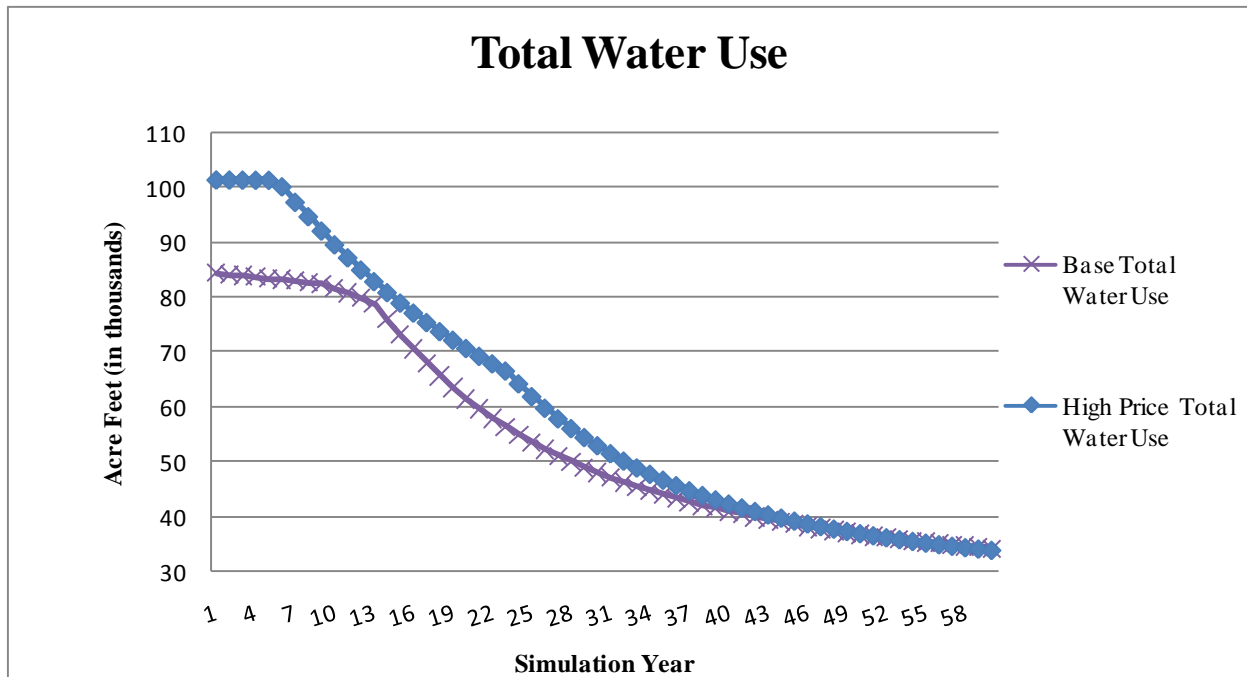
The overall effect of the latter result is that the amount of water applied decreases at a much faster rate over time under the high price scenario. One way of measuring this phenomenon is to compare the rates of decline in water applied over the simulation horizon. Measured in percentage terms, the decline rates are larger by at least 10 percentage points in the high price scenario versus the base scenario. Irrigated corn experienced the largest decrease both in percentage and raw terms. Under the base price scenario the amount of irrigation applied to irrigated corn decreased 36.22% over the simulation period; however, under the high price scenario the amount decreased 53.8%.

The one crop that serves as a caveat to most generalizations in Sheridan County is irrigated wheat. Under the base price scenario the amount of water applied for irrigated wheat never reaches the constraint. In fact, under the base price scenario irrigated wheat moves from 6.88 acres inches per acre in year 1 (9.19 acre inches per acre below the constraint) to 6.09 acre inches per acre in year 60 (2 acre inches below the constraint), a decline of 11.36%. The results

are similar under the high price scenario. Irrigated wheat starts at a higher value of 8.37 acre inches per acre in year 1 (7.7 acre inches under the constraint), then hits the constraint beginning in year 31, and ends the simulation with 6.58 acre inches per acre, for a 21.38% decline.

The next two graphs capture the total water for the county under the two scenarios. The total water use is simply the volume of water pumped for irrigation over the entire county in acre-feet, obtained by multiplying irrigation application rates and the number of irrigated acres for each crop and then summing over crops (see chapter 4 for definition).

**Figure 6.22 Total Water Consumption, Sheridan County**



The total water use results yielded some very interesting insights. First, because of the higher amounts of irrigation applied per crop and the increase in irrigated acres, the total water use for the base price scenario is initially much lower than the high price scenario. In the first year of the simulation the base price model uses 84,437 acre feet, and the high price model uses 101,560 acre feet an absolute difference of 17,123 acre feet. This is an expected result.

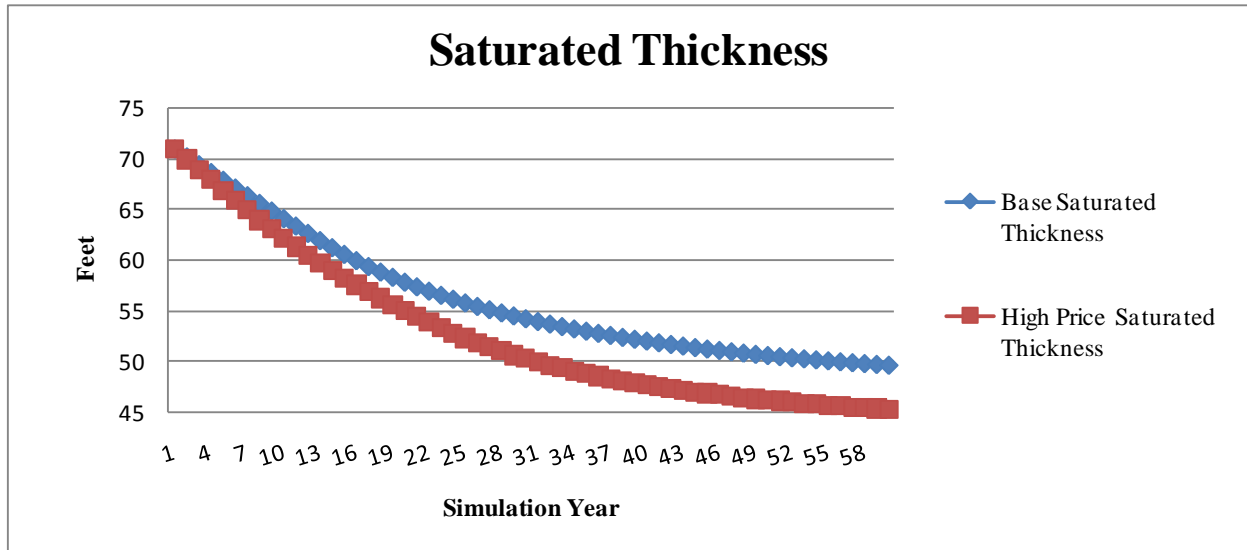
A second interesting difference is the shape of the total water use curves. Under the base price scenario the curve begins to decrease at a slow rate for the first 13 years, and then the curve takes a sharp downswing. This coincides with the drastic decrease in irrigated acres at year 13 under the base price scenario, which is induced by the water application rate for corn hitting the MAWA constraint that year. Under the high price scenario the total water consumption holds relatively constant for the first 6 years, and then the water consumption begins to significantly decrease over time, caused by the MAWA becoming active earlier in the time horizon for the key crops.

Finally, it is important to note that water consumption is highest under the high price scenario in year 1 (101,560 acre feet as compared to 84,437 acre feet under the base price scenario), but by year 60 the base price scenario uses more water than the high price scenario (34,292 acre feet as compared to 33,744 acre feet). This would imply that under the high price scenario farmers in Sheridan County deplete their water resources earlier and thus have less available by year 60. However, under the base price scenario water is more evenly distributed over time and therefore farmers have more by year 60. The first year that farmers use more water under the base price scenario than the high price scenario is year 49. From that point forth farmers use more water under the base price scenario than the high price scenario.

These water consumption patterns lead to differing effects on the saturated thickness levels over time. The next graph shows the effect that the total water consumption has on the saturated thickness levels in the two different scenarios.



**Figure 6.23 Saturated Thickness Levels, Sheridan County**



The above graph has only one large difference and that is the eventual ending saturated thickness. Both scenarios start at 71 acre feet of saturated thickness, but the higher water use in the initial periods under the high price scenario drive the saturated thickness down more quickly. However, over time the base price scenario begins to use more water than the high price scenario. This results in relatively close saturated thickness levels in the final year of the simulation. Under the base price scenario the final saturated thickness level is 49.63 acre feet (a decrease of 21.37 acre feet. The high price scenario results in 45.18 acre feet (a decrease of 25.82 acre feet). It is expected that the high price scenario will result in a lower saturated thickness; however, it is interesting that over the 60 year simulation the final absolute difference is 4.45 acre feet.

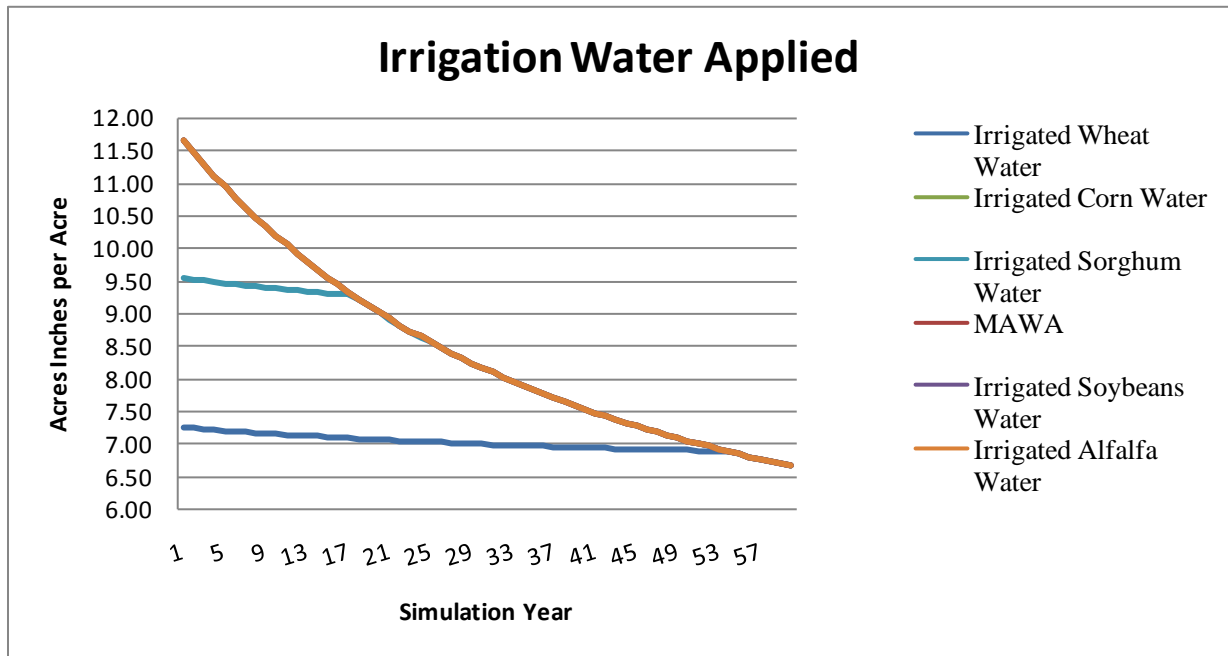
These results are fairly consistent with what the Kansas Geological Survey (KGS) reported in terms of useable life (discussed in the introductory chapter). The KGS had reported that while many areas in Sheridan County have already reached the saturated thickness constraint (30 acre feet), there were still many areas that had anywhere from 25 to 100 years of useable

saturated thickness left. It is clear from the results that after 60 years of simulation there are still some irrigated producers, but the total value of irrigation has significantly fallen.

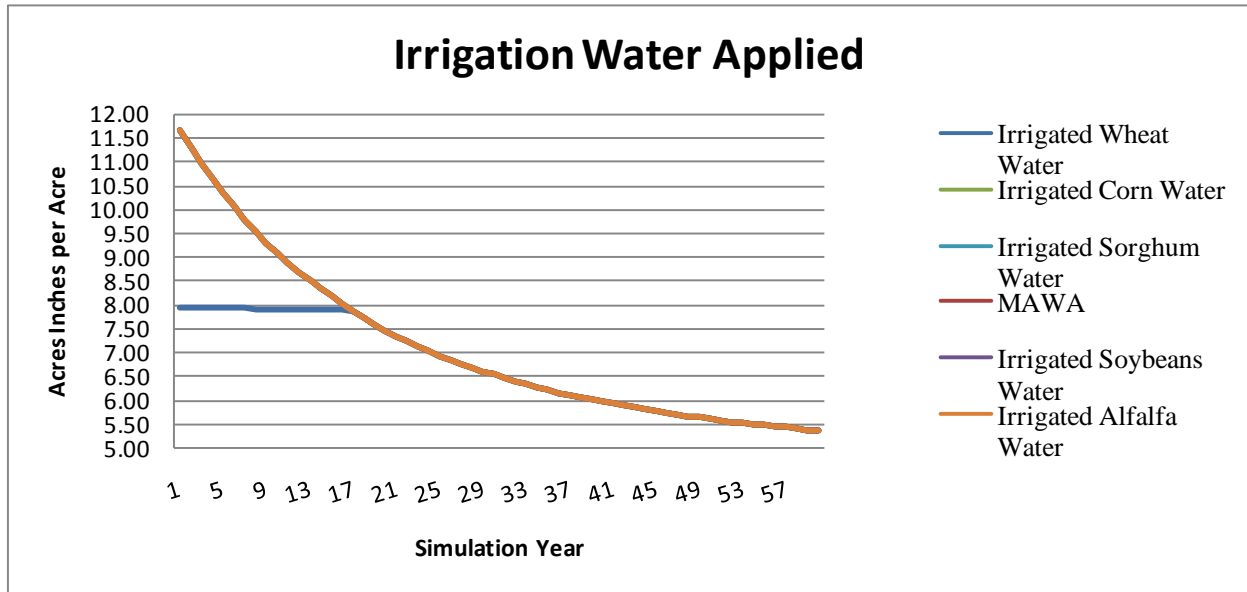
*Scott County Results*

The next county that will be discussed is Scott County. As previously observed Scott County has the least amount of water and irrigated crops of the three case counties. Additionally, as we saw previously the irrigated acres under the high price scenario were initially much higher than the base price scenario; however, over time this gap continued to lessen until the difference was only a few thousand acres (small in relative terms). So, it will be interesting to see how the water consumption changes.

**Figure 6.24 Irrigation Application Rates by Crop, Base Scenario, Scott County**



**Figure 6.25 Irrigation Application Rates by Crop, High Price Scenario, Scott County**



Clearly, the results for irrigation water applied are not the most diverse results among the simulations. Most of the crops in both simulations are binding with the MAWA from year 1 to 60. This would imply that farmers would use as much water as physically possible for most crops. There are two exceptions to that rule. First, irrigated wheat is not binding in either simulation for several years. Under the base price scenario, irrigated wheat starts at a value of 7.26 acre inches per acre, and does not become bound by the constraint until year 54 at 6.87 acre inches per acre. Under the high price scenario, irrigated wheat starts at 7.94 acre inches per acre and does not become bound until year 17 at 7.86 acre inches per acre. It is also interesting to point out that water applied to irrigated wheat starts higher under the high price scenario; however, by year 25 of the simulation water applied to irrigated wheat is higher under the base price scenario (7.03 acre inches per acre as compared to 6.93 acre inches per acre). This is a trend seen in all crops, which is purely a function of the MAWA as discussed later.

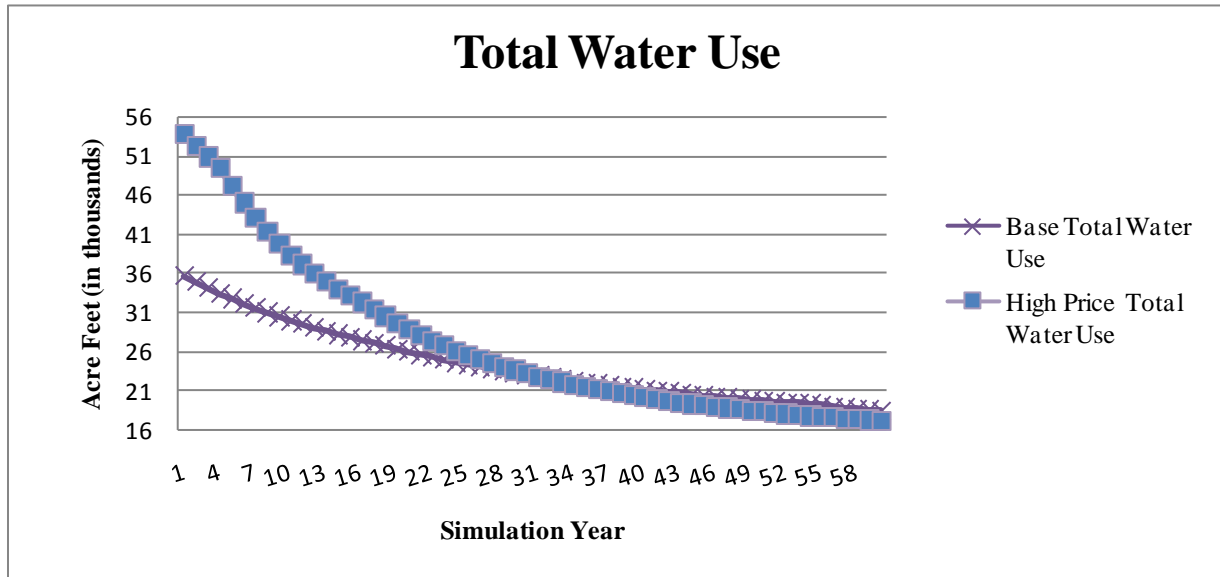
The second exception is irrigated sorghum under the base price scenario. Under the base price scenario irrigated sorghum starts at 9.54 acre inches per acre and does not become bound

by the MAWA constraint until year 18 at 9.21 acre inches per acre. This is vastly different than the high price scenario where irrigated sorghum is bound in all years. It should be pointed out that after year 9 the amount applied to irrigated sorghum under the base price scenario is higher than in the high price scenario.

Finally, the main difference between the two scenarios is the maximum amount of available water (MAWA) or the constraint. Because it is the constraint the initial value of MAWA is the same for both scenarios, 11.65 acre inches per acre in year 1; however, from that point on MAWA decreases much more under the high price scenario than the low price scenario. There are two reasons for this. First, there are more irrigated acres under the high price scenario than the low price scenario. More specifically, there is a higher amount of acres devoted to the most irrigation intensive crops, corn, soybeans, and alfalfa, under the high price scenario than the base price scenario (14, 159 more acres in year 1). Secondly, irrigated wheat and sorghum comprise 19,560 acres and 22,296 acres in the base and high price scenarios, respectively, in year 1. However, this number increases for several years under the high price scenario while it decreases under the base price scenario. All of this is to say that more water is used early on under the high price scenario. This coupled with the fact that Scott County does not have a lot of water, means that under the high price scenario a significant dent is forged into the water reserves so early that it significantly affects the remaining water for the rest of the period. As such the constraint immediately decreases and the crops become binding.

The next figure will display the total water consumption under the two scenarios for Scott County.

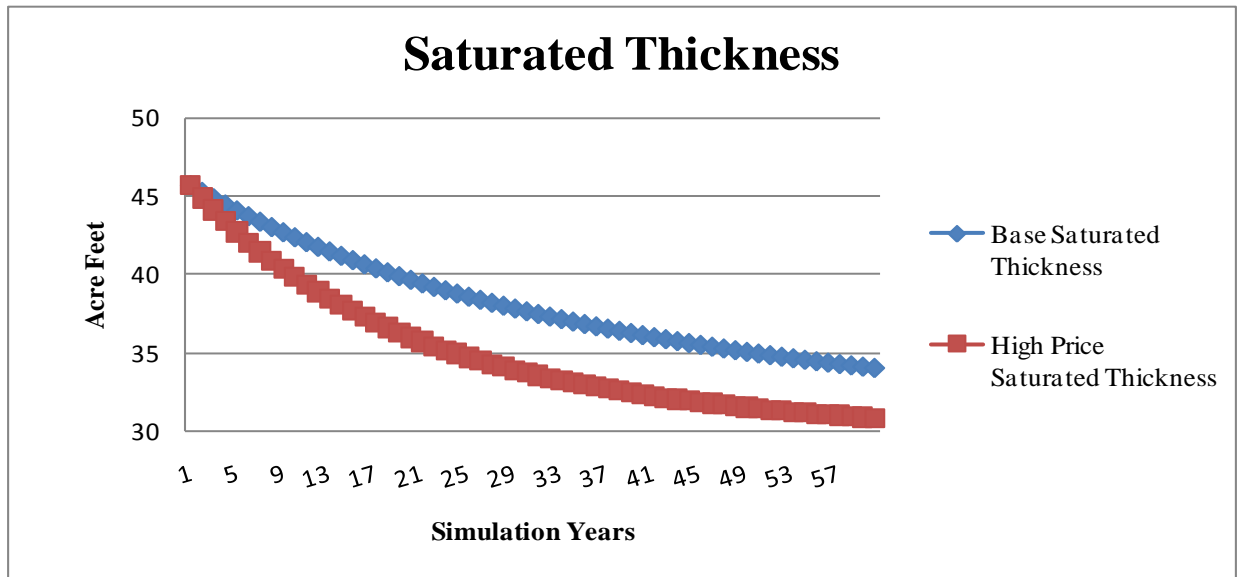
**Figure 6.26 Total Water Consumption, Scott County**



As a result of the lack of differences observed in water applied per crop we also observe very little difference in the water consumption graphs, at least in terms of shape. Both graphs have a fairly smooth curvilinear shape, although the total water use graph under the high price scenario has a slight kink after year 5. This kink corresponds to the decrease in irrigated acres after year 4. This is the same affect observed in Sheridan County. The biggest difference is simply in the magnitudes of water use. Because of the initially higher irrigated acres and water use per crop under the high price scenario, it starts with a higher total water consumption value of 53,668 acre feet as compared to 35,600 acre feet under the base price scenario. However, as previously discussed, the difference in total irrigated acres lessens over time and the base price scenario uses more water per crop than the high price scenario. Not surprisingly this results in the base price scenario using more water in the final year of the simulation (18,474 acre feet) than the high price scenario (17,003 acre feet). The first year that the base price scenario uses more water than the high price scenario is year 30 of the simulation.

The different water consumption patterns also result in different saturated thickness levels. As with Sheridan County it was observed that the high price scenario initially increases total water consumption, but over time the base price scenario actually uses more water than the high price scenario. Therefore, it would stand reason that the final saturated thickness levels would be relatively close (as observed Sheridan County). Figure 6.30 displays the changes in saturated thickness for the two scenarios across time.

**Figure 6.27 Saturated Thickness Levels, Scott County**



Here again the two curves have a fairly similar shape; however, the initially higher water use in the high price scenario increase the rate at which the saturated thickness declines in the high price scenario. Nevertheless, as also observed in Sheridan County, as the time progresses it becomes obvious that the base price scenario begins to use more water and the saturated thickness decreases quicker under the base price scenario. Both scenarios start with a saturated thickness level of 45.65 acre feet, but by the final year of simulation the base price scenario has a saturated thickness level of 34.01 acre feet and the high price scenario's saturated thickness level

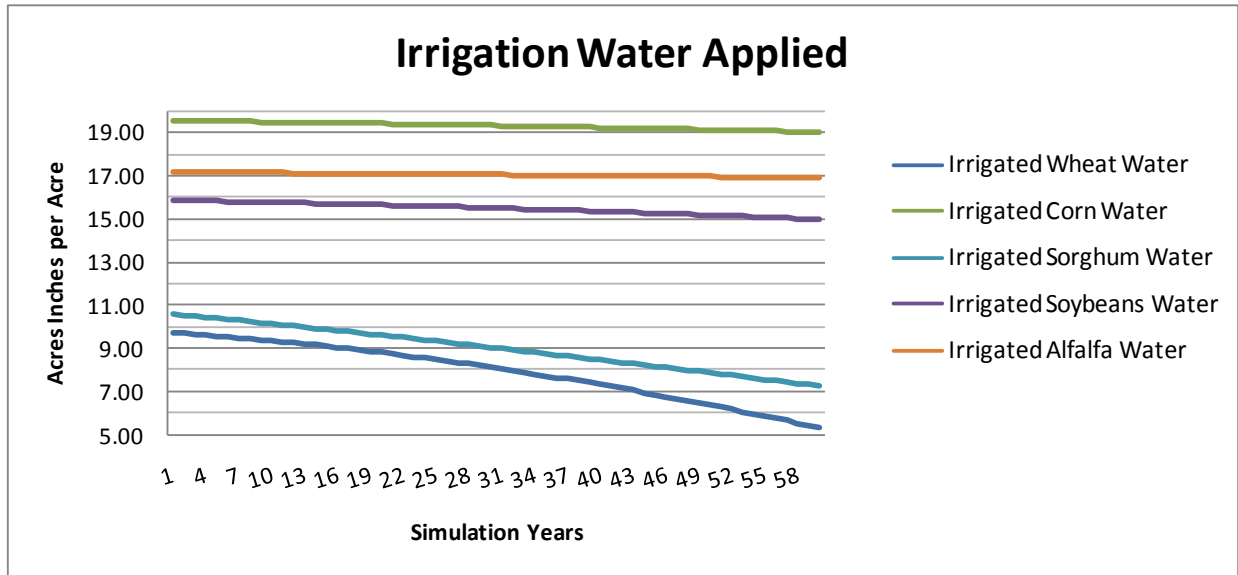
is 30.81 acre feet. The absolute difference between the two scenarios (3.2 acre feet), may seem fairly small, but translates into several more years of usable aquifer life.

Both scenarios have ending saturated thicknesses only slightly above 30 acre feet. At 30 acre feet of saturated thickness irrigation becomes essentially infeasible for any county (both from a financial and physical sense). Therefore, it is obvious that the amount of irrigated life is extremely limited in Scott County. Once again we see that this is consistent with the KGS estimation that there were only a few areas where irrigation could survive for 25 years and even fewer for 100 years. Clearly, we see that under both scenarios after 60 years of simulation there will be very few irrigated farmers.

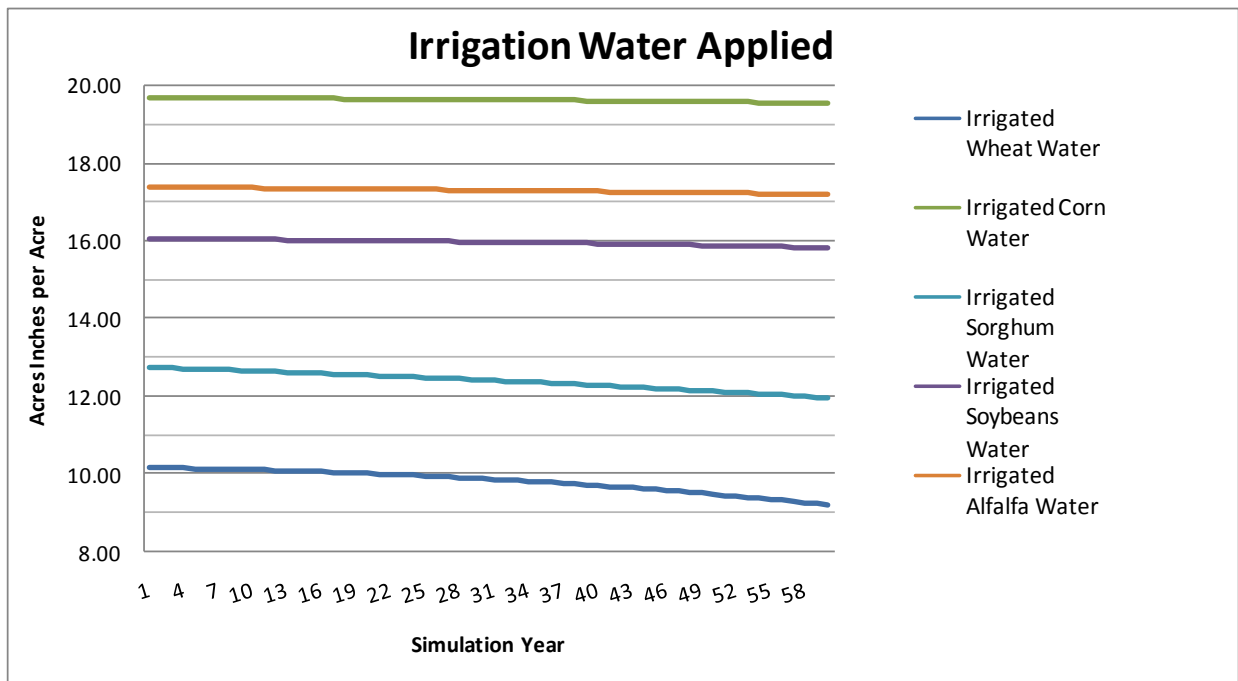
#### *Seward County Results*

The final county to consider is Seward County. Previously it was established that Seward County is the water rich county in this study. As such it was observed that Seward a significant portion of Seward's total acres was devoted to irrigation, especially under the high price scenario. Figures 6.32 and 6.33 display the amount of irrigation applied to each crop under the two simulations.

**Figure 6.28 Irrigation Application Rates by Crop, Base Scenario, Seward County**



**Figure 6.29 Irrigation Application Rates by Crop, High Price Scenario, Seward County**



These are some of the more unique graphs that are observed in this study. The first item of interest is that there is no constraint (MAWA) in either graph. Due to the high levels of saturated thickness the MAWA is an unattainable constraint. For example, in the year of the

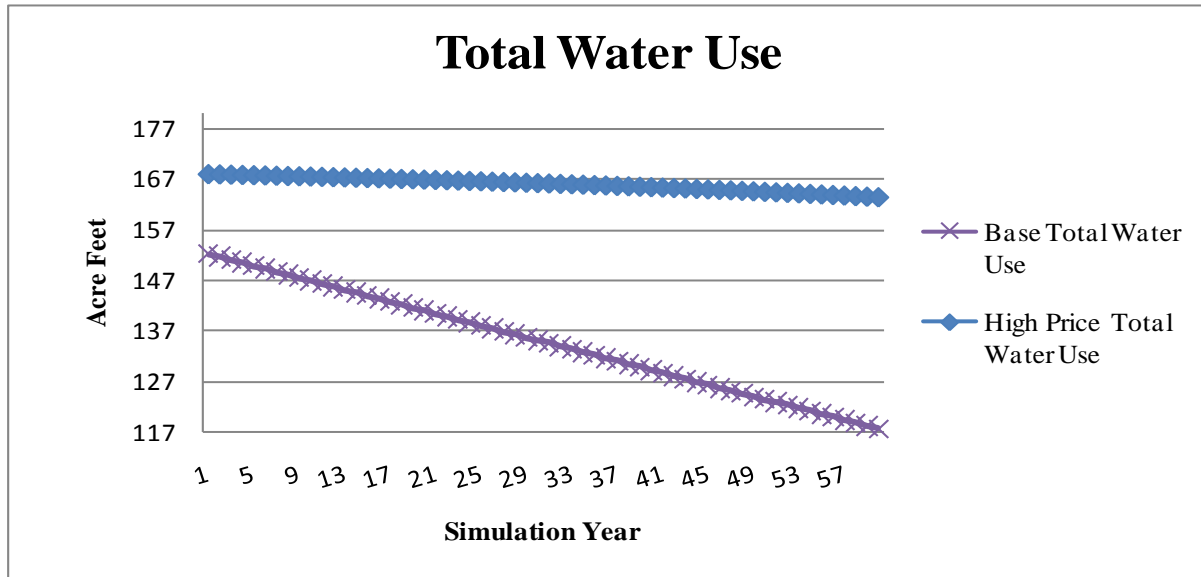


simulation the MAWA is 187.61 acre inches per acre, and in the final year of the simulation it is 75.01 acre inches per acre. Clearly, a farmer could not (or would not even if possible because of flooding) saturate their crops with that much water; maximum yields for all crops are achieved at much lower application rates. (Moreover, a typical water right in Kansas limits application rates to 24 acre inches per acre). As such the MAWA is never binding in the Seward County simulations.

A second main finding is again simply a matter of relative magnitudes. All of the crops remain irrigated throughout the entire simulation period for each of the scenarios. The main difference is that under the high price scenario more irrigation is applied to each crop. Additionally, it should be noted that unlike the other counties, each of the crops has a higher irrigation rate throughout the simulation period than in the base price scenario. The one small note to make is that in the base price scenario the difference between the amounts of water applied for irrigated wheat and sorghum is much less than in the high price scenario.

The next graph of this section depicts the total water use under the two price scenarios in Seward County.

**Figure 6.30 Total Water Consumption, Seward County**

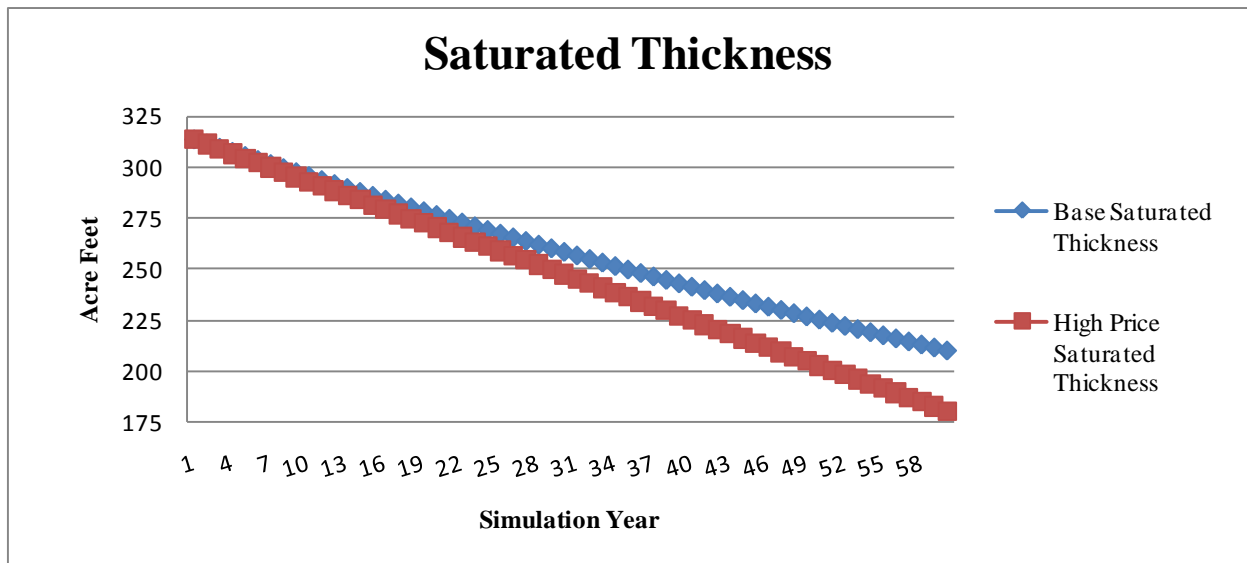


Consistent with the other Seward County results, there are two big differences between the two scenarios. The first difference is magnitude. This makes sense because under the high price scenario, irrigated acres and irrigation application levels were both higher than in the base price scenario. To put the difference in magnitudes into perspective in the first year of the simulation the base price scenario uses 152,022 acre feet and the high price scenario uses 167,902 acre feet (a difference of 15,880 acre feet). In the final year of the simulation the base price scenario uses 117,656 acre feet and the high price scenario uses 163,369 acre feet (a difference of 45,712 acre feet).

The second big difference between the two is the shape of the water consumption line. Under the base price scenario the shape is almost (though not quite) linear. However, under the high price scenario the shape is much more concave. For this reason, the difference between the two scenarios increases over time. This is a function of the increasing difference in irrigated acres and water applied to each crop over the simulation period.

The final analysis for this county concerns the saturated thickness levels of the two price scenarios. Unlike the other counties the high price scenario uses a lot more water than the base price scenario in each year. Additionally, unlike the other counties the reason for this shift is not due to constraint in water application. The next graph, Figures 6.36, displays the levels of saturated thickness for the two price scenarios.

**Figure 6.31 Saturated Thickness Levels, Seward County**



In this case the graph shows an almost linear decrease in the level of saturated thickness. Additionally it is clear that high water use for the high price scenario in each year decreases the saturated thickness much more than the base price scenario. Each scenario starts with a saturated thickness level of 313 acre feet. By the end of the simulation the saturated thickness is 210 and 180 acre feet for the base and high price scenarios respectively. The absolute difference between the two scenarios in the final year (31 acre feet) is the highest observed difference of any county. These results are expected and also consistent with the KGS which predicted that the majority of the county would have anywhere from 100 to over 250 years of irrigation left. Clearly, even under the high price scenario after 60 years there are still plenty of irrigated years left.

### 6.3 Social Planner's Dilemma

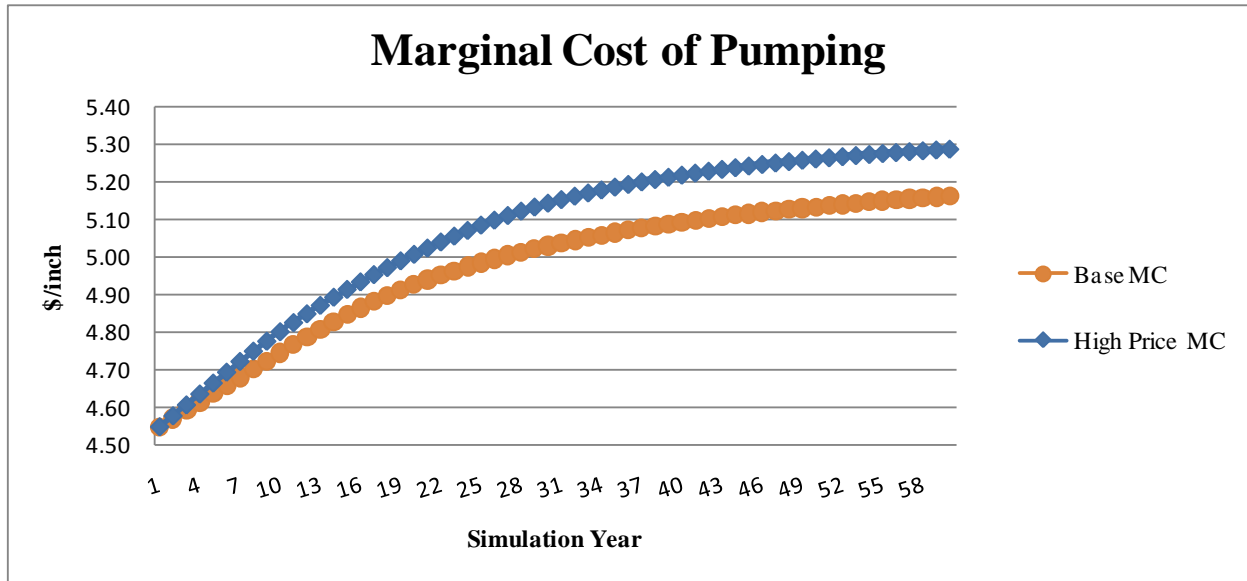
The question that the social planner must decide is: Given the effects that the high cost scenario imparts on the aquifer and farmer's net revenue, how should water use be allocated? To answer this question the social planner would consider how the impact on the aquifer affects farmer's income, and then weigh that against the impact on the aquifer itself and how those impacts reduce the potential to generate crop income. Determining the optimal trajectory of water use from a social planner's point of view would require the formulation and execution of a dynamic optimization problem, which is beyond the scope of this study. However, the results generated above can speak to this question by comparing the streams of income generated from the two simulation scenarios. This comparison is discussed in turn for each of the counties below.

#### *Sheridan County Results*

The first county that will be discussed is Sheridan County. As discussed earlier, the high price scenario significantly increased irrigated crop acres, water applied to each crop, initial water consumption, and the rate at which the saturated thickness declined. These changes will have an effect on the farmer's income both from a cost standpoint (more pumping expense due to greater lifts) and from a revenue standpoint (irrigated crops are replaced with less lucrative alternatives as water availability declines).

The first factor to consider is the marginal cost of pumping (or that amount that an additional foot of lift would cost the farmer to pump). The graph below displays the marginal cost of pumping under the two price scenarios.

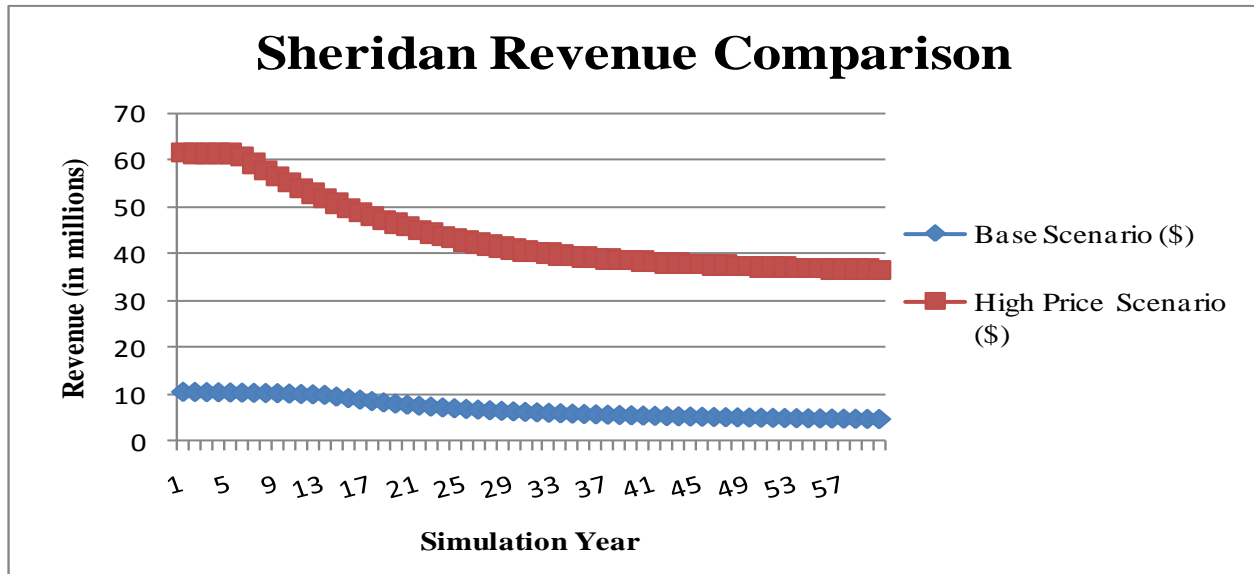
**Figure 6.32 Marginal Cost of Pumping, Sheridan County**



The above graph clearly shows that the high price scenario increases the marginal cost of pumping over time. This is because the high price scenario increases the amount of total irrigation and hence the lift. The increase in lift results in an increase cost. At year 1 both simulations start at the same values (\$4.55); however, by the end of the simulation the base scenario is somewhat lower (\$5.16) than the high price scenario (\$5.29). Again, this is purely the result of the increase in irrigated acres and irrigation rates.

The final factor to consider is the resulting total revenue. As a result of the increase in cost of irrigation the cost structure under the high price scenario is somewhat greater than the base price scenario. Despite this fact, it was observed that under the high price scenario there were more irrigated acres, and application rates were higher, than under the base price scenario. Therefore, there are two competing factors that are happening at the same time in regards to net revenue. The graph below compares the profits of the two scenarios over time.

**Figure 6.33 Sheridan Net Revenue Comparison**



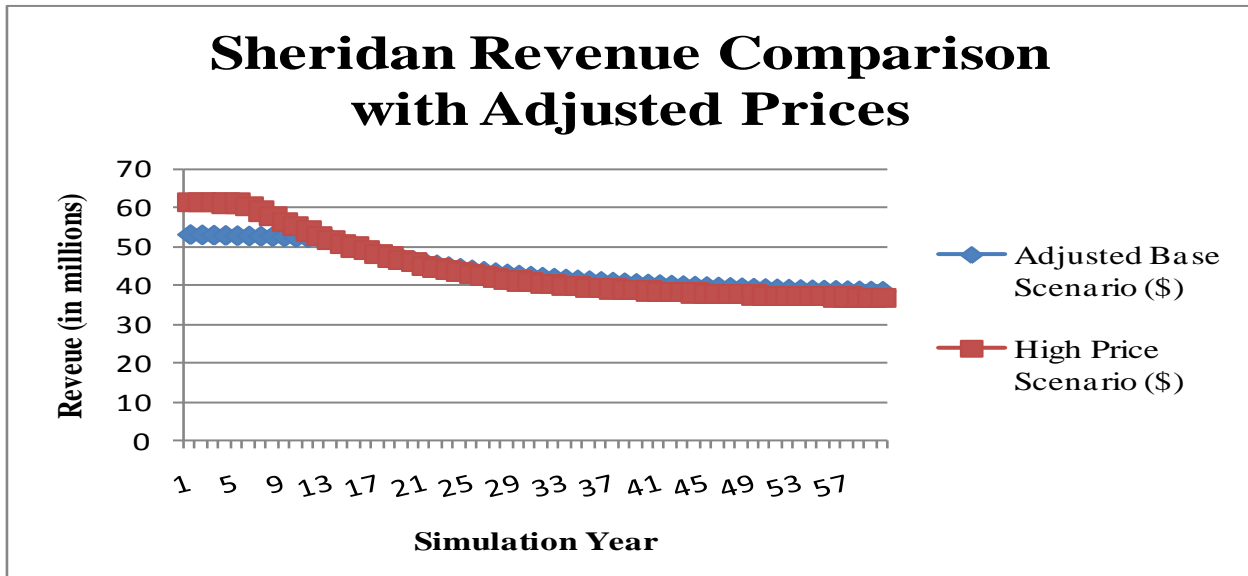
The structures of these two net revenue functions are becoming very familiar by now. Under the high price scenario net revenue remains fairly constant for the first 6 year and then takes a sharp downturn for the rest of the simulation. The base price scenario also slowly decreases for the first 13 years before taking a similar downwards kink. The rate of decline for the high price revenue is significantly higher than the base price scenario. The high price scenario starts at \$61.39 million and ends at \$36.72 million while the base price scenario starts at \$10.5 million and ends at \$4.69 million. A simple net present value calculation of each of these revenue streams (assuming a constant 5% discount rate) reveals that the high price scenario, a net present value of \$960 million, is worth almost six times the base price scenario, \$162 million.

However, this result is expected and does not directly speak to the policy question at hand. Clearly a significant portion of the increase in profits between the two scenarios is from higher commodity prices. The relevant question is, given high prices, whether a different allocation of water use through time could increase farmers' net present value of profits above

the simulated value of \$960 million. As noted above, a complete answer to this question would require the solution to a dynamic optimization problem. As has been shown in previous research (Gisser and Sanchez, 1980), the social planner's solution would use somewhat less water in the early periods compared to the high price simulation here, recognizing that a unit of water consumed today has value to generate income in the future. This would leave more water to be consumed in later periods and would also leave a larger ending stock of water in the aquifer.

While a dynamic optimization is beyond the scope of this study, we can test whether a different trajectory of water use could have increased the net present value of income. It seems plausible that the planner's "optimal" water use path in the high price scenario might actually look something like the pattern simulated under the base price scenario. As explained in previous sections, the baseline simulations are characterized by a less aggressive use of water in the early periods, allowing for more water use in later periods. To test the optimality of the water use in the high price simulation, the profit levels obtained under the baseline water use levels were computed with the high commodity prices. The procedure allows for a consistent comparison of the long-term income implications of the two water use trajectories. The graph below compares the profits of the two scenarios over time.

**Figure 6.34 Sheridan Net Revenue Comparison, Adjusted Prices**



Under higher commodity prices, the base scenario profits start at \$52.78 million and ends at \$38.45 million, which is much closer to the high price simulation in early years and in fact higher in later years. As expected, income is lower in the initial periods, but the gap closes over time as more water is left for later periods. In this simulation, the baseline profits are larger than the profits under high prices starting in year 16. The net present value of the baseline income stream (again assuming a 5% discount rate) is \$ 911.21 million, still below the high price scenario NPV of \$ 960 million. If the discount rate is lowered (meaning more emphasis is placed on income in later years) the gap between the two NPV's decreases. However, none of this considers the difference in the ending values of saturated thickness. The baseline simulation results in 4.4 feet of extra saturated thickness in the aquifer at the end of the 60-year horizon (Figures 6.24-6.25). This additional thickness will allow for a longer aquifer life and more income generating potential in years 61 and beyond. Thus each foot of saturated thickness left in the aquifer has value to future generations. Therefore, it is easily conceivable that the net present

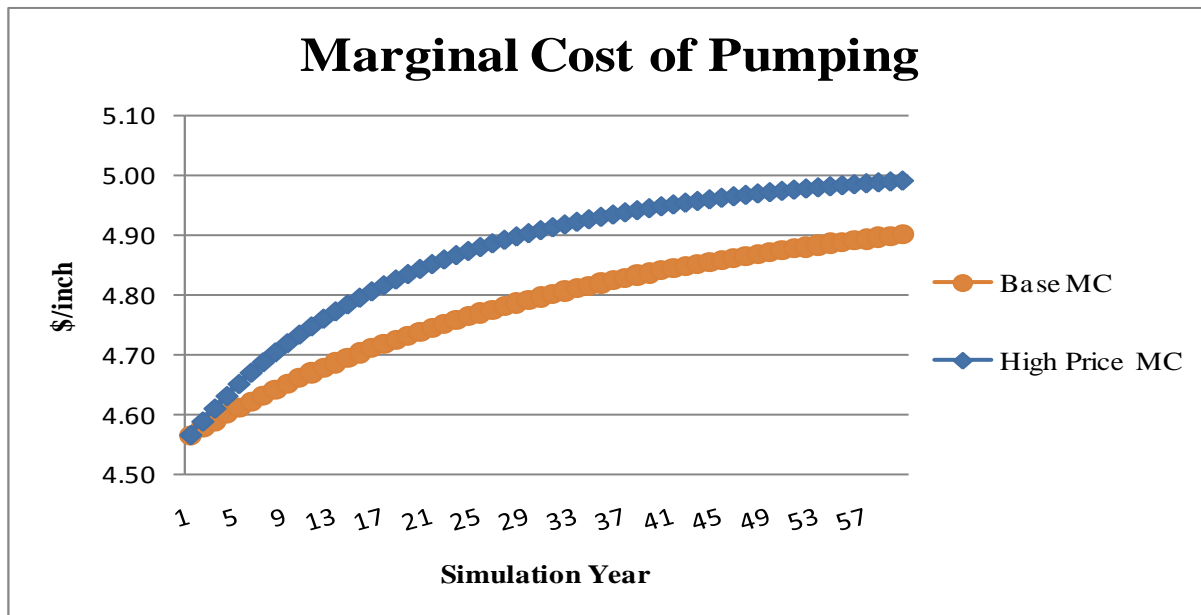


value would be higher in the adjusted base scenario if the remaining saturated thickness is taken into account.

### Scott County Results

The second county that needs to be examined is Scott County. Previously it was found that in Scott County the high price scenario increased initial irrigated acres, water applied, and total water consumption as compared to the base price scenario. However, over time the irrigated acre difference between the two scenarios significantly decreased. Additionally, both the application rate (for all crops) and total water consumption was significantly higher in year 60 for the base price scenario than the high price scenario. These results made for very interesting marginal pumping costs. The graph below shows the marginal pumping costs for the two scenarios.

**Figure 6.35 Marginal Cost of Pumping, Scott County**

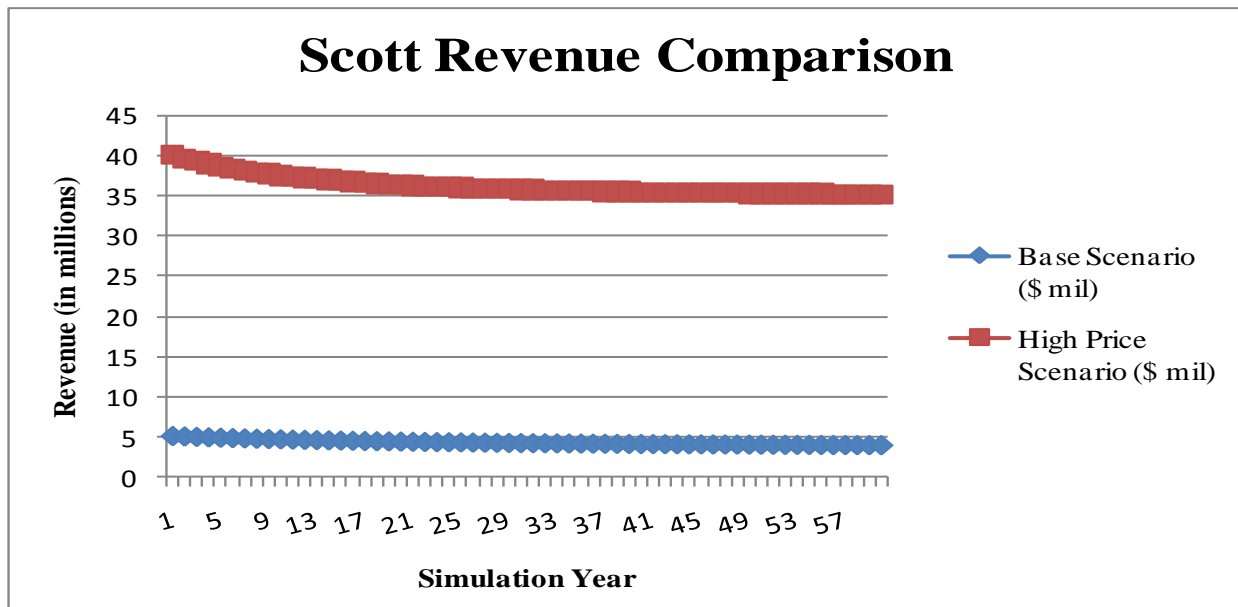


The two marginal cost of pumping plots are very similar save two items. First, the base scenario marginal cost of pumping increases at a decreasing rate throughout the simulation. This

forces the two plots to have a slightly dissimilar shape. The second difference is scale. Both plots start out at the base marginal cost of pumping (\$4.57), but the high price scenario ends slightly higher (\$4.99) than the base price scenario (\$4.9). Not surprisingly this is the closest (\$.09) the two scenarios come to each other in the three simulations. This is due to the relatively small difference in irrigated acres in the final year of the simulation and the higher total water of the base price scenario in the final years of the simulation.

The second point to consider is what effect the different price and cost structures will have on the net revenue. Figure 6.44 compares the two net revenues across the years of the simulation without a price adjustment.

**Figure 6.36 Scott Net Revenue Comparison**

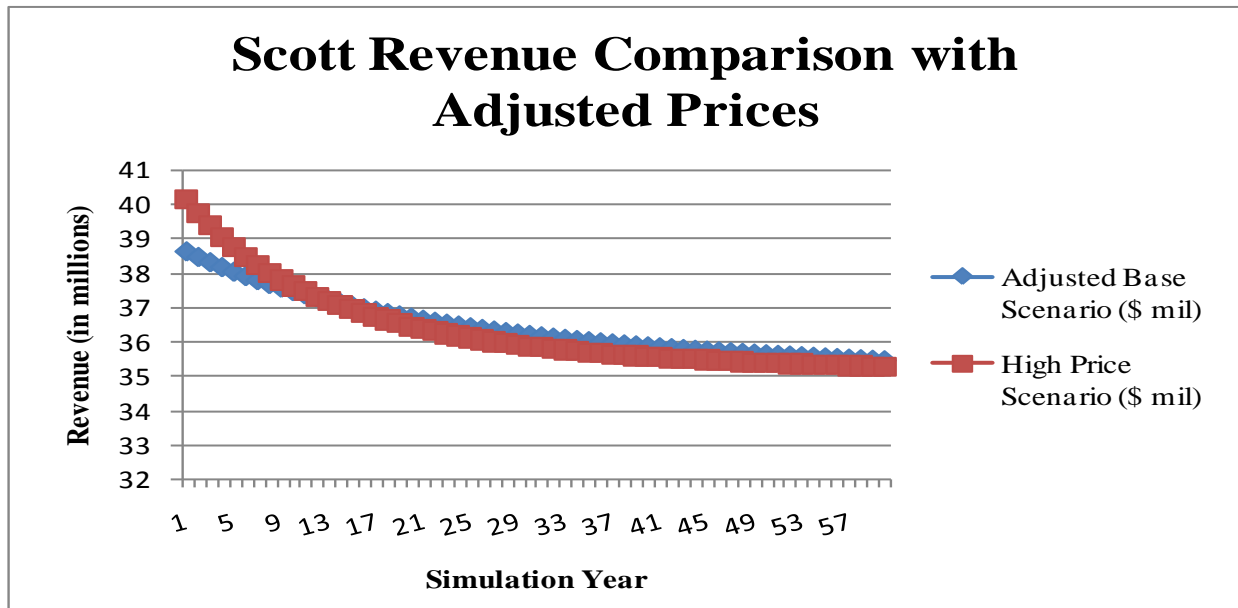


Throughout the simulation the high price net revenue remains larger than the base price net revenue. However, the difference between the two net revenues is decreasing over time. In the first year of the simulation the base price net revenue is \$5.16 million and the high price net revenue is \$40.13 million (an absolute difference of \$34.97 million). By the final year of the

simulation the base price net revenue is \$4.02 million and the high price net revenue is \$35.25 million (an absolute difference of \$31.23 million). The final evaluating tool is again the net present value of the two revenue streams. The net present value of the base price net revenue stream is \$87.6 million, and the net present value of the high price net revenue stream is \$706 million.

The next graph (Figure 6.45) shows the net revenue comparison with adjusted prices, as discussed before.

**Figure 6.37 Scott County Net Revenue Comparison, Adjusted Prices**



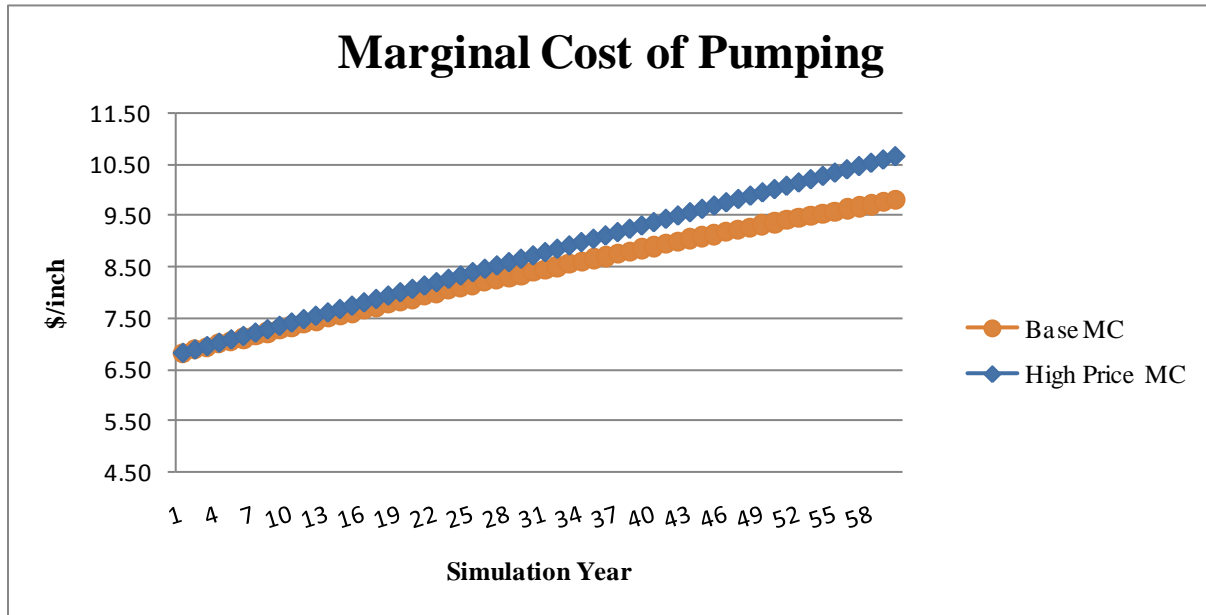
This scenario is fairly similar to Sheridan County in that during the initial years of the simulation the high price scenario is more profitable; however, over time the base price scenario becomes more profitable. It is slightly different than Sheridan County because the base price scenario first passes the high price scenario in year 12, after which it exceeds the high price profit stream by a peak of \$.36 million in year 31, and then the gap slowly lessens \$.22 million in the final year of the simulation. Additionally, the gap between the NPV values is much lower.

Assuming a 5% discount rate the NPV value of the adjusted base price scenario is \$ 703.08 million, only slightly less than the high price scenario NPV of \$ 706.22 million. Again, as the discount rate lessens the gap between the NPV values also decreases. If the discount rate falls below 2.2% the adjusted base price scenario becomes more profitable than the high price scenario. Finally, it should be noted that the extra saturated thickness (3.2 feet) from the base price scenario is not taken into account. Therefore, it would again be feasible that even under a high discount rate the base price scenario could be more profitable if the extra saturated thickness is taken into account.

### *Seward County Results*

The final county to consider is Seward County. It was previously established that that under the high price scenario Seward, the water rich county, had far more irrigated acres, high application rates, and total water use for all years of the simulation than the base price scenario. This would logically imply that the marginal cost of pumping would also be higher under the high price scenario. Figure 6.44 shows the marginal cost of pumping for the two price scenarios.

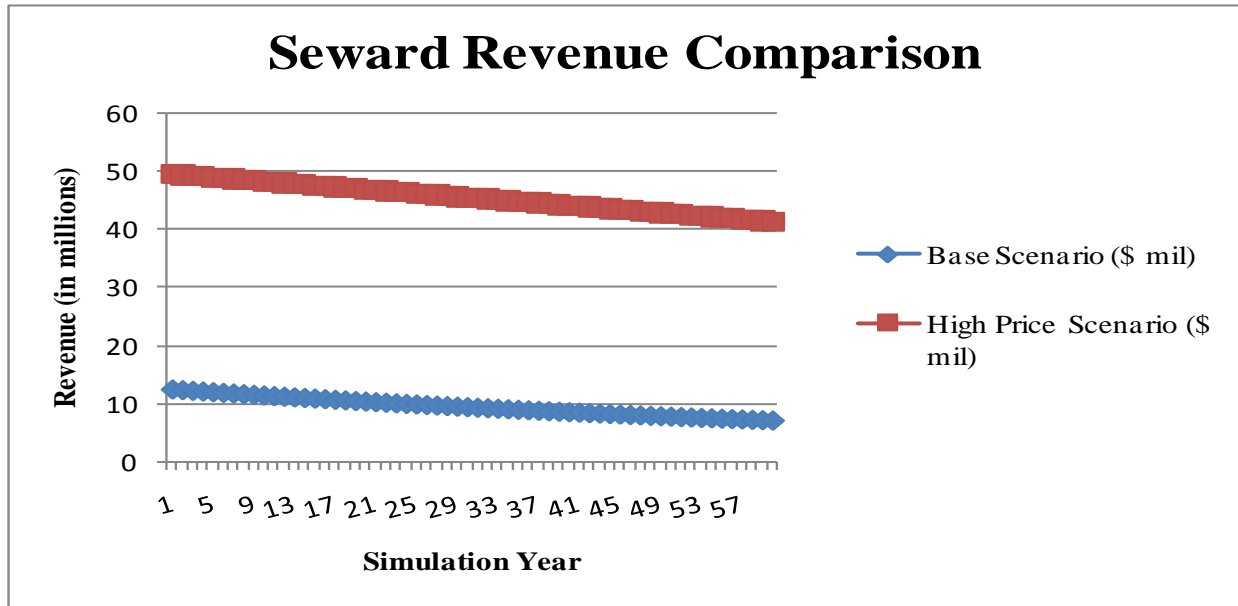
Figure 6.38 Marginal Cost of Pumping, Seward County



The two plots above both show the same almost linear increase in the marginal cost of pumping over time. The only real difference is the scale. Under the base price scenario the marginal cost of pumping starts at \$6.82 and finishes at \$9.78. Under the high price scenario the marginal cost of pumping starts at \$6.82 and finishes at \$10.65. The difference between the two scenarios in the final year is \$.87. This is by far the biggest difference observed, and is most directly correlated to the large increase in total water consumption increasing the lift (or decreasing the saturated thickness) in the high price scenario.

The next set of results to consider is the total net revenue differences between the two scenarios. Figure 6.48 displays the two scenario's net revenue across the simulation period.

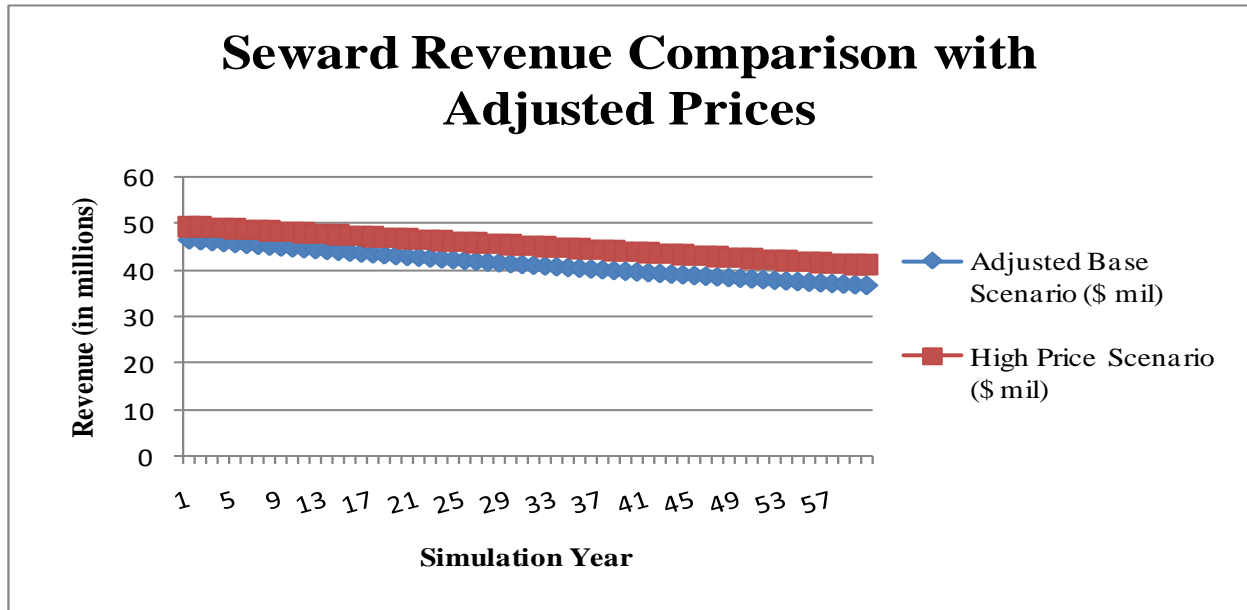
Figure 6.39 Seward Net Revenue Comparison



There is an almost linear decrease in net revenue each year in both scenarios. It is very clear that like the other counties the base price scenario revenue is much lower than the high price scenario revenue. In the first year of simulation the base price net revenue is \$12.36 million and the high price scenario's net revenue is \$49.47 million for an absolute difference of \$37.11 million. In the final year of the simulation the base price scenario's net revenue is \$7.04 million compared to the high price net revenue of \$41.26 million. This is an absolute difference of \$34.22 million; this also means that the absolute difference is decreasing over time. The final step is to find the net present value for the two income streams. Assuming a 5% discount rate, the net present value for the base price scenario's net revenue is \$201 million and the net present value for the high price scenario's net revenue stream is \$893 million.

The next Figure (6.49) shows the two net revenues with the price adjustment.

**Figure 6.40 Seward Net Revenue Comparison, Price Adjustment**



Again, there is an almost linear decrease in net revenue each year in both scenarios. Though it is clear that difference between the two scenarios has lessened, it is interesting that the adjusted base price scenario is never higher than the high price scenario (as seen with the other counties). In the first year of simulation the adjusted base scenario net revenue is \$46.69 million and the high price scenario's net revenue is \$49.47 million for an absolute difference of \$2.78 million. In the final year of the simulation the base scenario's net revenue is \$37.73 million compared to the high price net revenue of \$41.26 million. This is an absolute difference of \$3.53 million; this also means that the absolute difference is increasing over time unlike the other counties. The final step is to find the net present value for the two income streams. The net present value for the adjusted base scenario's net revenue, assuming a 5% discount rate, is \$825.62 million and the net present value for the high price scenario's net revenue stream is \$892.7 million. If the discount rate decreases the difference between the high price scenario and adjusted base price scenario will increase as well. Finally, it is also worth noting that the base price scenario's saturated thickness is 30.37 feet higher than the high price scenario. Therefore, it

is again feasible that base price scenario could be more profitable than the high price scenario if the additional saturated thickness is taken into account.

#### **6.4 Conclusion**

The main conclusions will be discussed in the next chapter. However, there are a few smaller items to be confirmed in this section. First, the hydrological results that were observed are consistent with the KGS predictions displayed in Figure 2.4. Additionally, the hydrological results also matched historical (or the known years of the simulation) to the extent that more water was used in the high price years.

Secondly, the models had a few troubles replicating the observed data; however, they largely performed well in replicating known acres; errors were quite small in terms of total crop percentage. This gives the model credibility and the modeler confidence that the acres will be close to correct as time progresses. Additionally, there were no outside of the norm results that would cast doubt on the fundamentals of the model.

Finally, the diversity of counties chosen helped to observe the differing effects of the price shock. Each county saw similar but uniquely different results for each phase of the model. It was particularly helpful to have a water rich, water average, and water poor county. This enabled the model to display results that give a full spectrum of the effects of a price shock.



## **Chapter 7: Conclusions and Implications**

There are numerous conclusions that can be drawn from this thesis. However, for the sake of brevity, there are several generalizations to discuss. The first obvious generalization is that the high price scenario results in a significant increase in irrigated production. This is an expected result that can be verified by historic data as shown in earlier chapter. In each of the case counties, the high price scenario immediately increased total irrigated production. There were some variances in the mix of irrigated crops, but the one constant is that irrigated acres increased from the base scenario. The amount of the increase depended significantly on the level of saturated thickness. The water rich county, Seward, saw both the largest initial increase and the largest absolute difference in the final year of the simulation. Conversely, the most water constrained county, Scott, saw the least initial increase in irrigated acres and the smallest absolute difference in the final year of the simulation.

The second main point is that high prices make it more profitable for farmers to apply more water in earlier years than later years. The total water consumption graphs were very telling in this regard. For Sheridan and Scott Counties the total water consumption dramatically increased in the first several years, so much so that the physical constraints for irrigation application per crop quickly became binding (particularly in Scott County). As a result it was observed that the base scenario had higher water consumption in the latter years of the simulations than the high price scenario did. After running the net present value of revenue streams, it appears that the aggressive initial water use induced by high prices may not be in farmers' long-term interests. In particular, the more measured water use trajectory from the base price scenario may provide a higher net present value of income, particularly if the value of the

ending stock of water in the aquifer is taken into account. This is more likely to be the case in Sheridan and Scott counties or if the discount rate is low.

The chief generalization is that the high price scenario significantly increased the rate of decline in saturated thickness. Regardless of the price scheme the saturated thickness in each of these counties will decrease so long as the rate of irrigation exceeds the recharge rate (which, as previously noted, is extremely small). Therefore, it stands reason that we should observe a decrease in the saturated thickness. So, the more interesting result is which pricing scenario decreases the saturated thickness more. In the three case counties shown the high price scenario unmistakably decreased the saturated thickness more than the base price scenario in both the short and long term. Additionally, the more saturated thickness that was initially available, the larger the decrease in overall saturated thickness. This is a result of significant increases in irrigated acres in areas where there was a lot of saturated thickness (Seward County in this thesis). In a water scarce county (such as Scott in this thesis) the saturated thickness will decrease more in a high price scenario than a base price scenario; however, the difference between the two rates will be much smaller than in a water-rich county.

Finally, the Positive Mathematical Programming (PMP) method proved to be very effective. As seen in the data section there was not a plethora of information (data) on this subject. Therefore, it was important that the method chosen for this study could use a minimal amount of data while still maintaining accuracy. The PMP method was able to take the minimal data, calibrate to it, and then effectively reproduce the observed results. Additionally, the production function was able to be incorporated into this process seamlessly while maintaining accuracy. This is one of the first times that the PMP method has been incorporated into an

applied groundwater management problem such as this, while also incorporating hydrological and agronomic information over time.

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## Appendix 1

```
1 clear all
2 clear function
3
4 file = 'C:\Users\Matt\Desktop\GRA\Thesis\Master.xls'
5 write = 'C:\Users\Matt\Desktop\GRA\Thesis\Thesis.xls'
6
7 %Master Code
8 % Note: This program requires that values are entered into Microsoft Excel
9 % 2003 (Excel 2007 will not work)
10
11 %Stage I Optimization
12 % Stage I and II find the profit maximizing level of crops given land constraints and profit levels per crop
13 %DEFINE PARAMETERS
14 % num_crops = size of crop vector
15 % xobs = Observed Crop Acres
16 % rev = Per Acre Revenue of Crop
17 % nirrc = Non-Irrigation Cost per acre
18 % irrc = Irrigation Cost per acre
19 % harvc = Harvest Cost per acre
20 % ac = Average Cost per Acre per Crop
21 % f = Average Profit per Acre per Crop
22 % WaU = Water Use per Crop
23 % A = ones([1,size(f)]) Needs to be Equal to the Number of Crops
24 % b = [Total Land Acre Constraint]
25 % lb= [0;0;...] Acres Used Must be Greater than Zero
26 % ub = Upper Bound of Crop Acres (Largest Amount of Possible Acres Per Crop) note that here is similar to a shadow price in that we add a small
epsilon (.01) to our base acres
27
28 %Equations
29 %[Wheat IRR, Wheat Dry, Corn IRR, Corn Dry, Sorghum IRR, Sorghum Dry, Soybeans IRR, Alfalfa IRR]
30 xobs = xlsread(file,'Scott', 'B2:I2')
31 num_crops = size(xobs,2)
32 price = xlsread(file,'Scott', 'B3:I3')
33 yield = xlsread(file,'Scott', 'B5:I5')
34 rev = price.*yield
35
36 nirrc = xlsread(file,'Scott', 'B8:I8')
37 irrc= xlsread(file,'Scott', 'B9:I9')
38 harvc= xlsread(file,'Scott', 'B12:I12')
39 ac = nirrc+irrc+harvc
40 f = rev-ac
41 WaU = xlsread(file,'Scott', 'B15:I15')
42 Ab = xlsread(file,'Scott','F34')
A = ones(size(f))
```

```

43 b = xlsread(file,'Scott', 'K2')
44 lb = [0;0;0;0;0;0;0]
45 epsilon = .01
46 ub = epsilon + xobs
47
48 %Stage II
49 [x,fval,exitflag,output,lambda] = linprog(-f,[],[],A,b,lb,ub)
50 display 'Upper Bound of Lambda'
51 lambda.upper
52 display 'Linear Inequality of Lambda'
53 lambda.ineqlin
54 display 'Gamma is the Slope of the Marginal Cost Function'
55 gamma = 2*(lambda.upper./xobs')
56 display 'Alpha is the Intercept of the Average Cost Function'
57 alpha = ac'-lambda.upper
58
59 %STAGE III verification
60 % Define Policy variables
61 T = xlsread(file,'Scott', 'B34');% time period for model
62 CT = 2.5; % 2.5 degree change in temperature (degrees fahrenheit) over T years. Set to zero for status quo scenario
63 CP = -.025; %-.025 Percent change in precipitation over T years. Set to zero for status quo scenario
64 CR = -.2; %-.20 Percent change in acquifer recharge over T years. Set to zero for status quo scenario
65 AR = .3; % Acreage reduction - used as a policy analysis variable. 100% of acreage reduction occurs at t = 0.Set to zero for status quo
scenario
66
67 % Define Hydrological variables
68 MIA0 = 24855*(1-AR); % Maximum Irrigated Acres in the sub basin at t = 0
69 BSA = 88500; % basin surface area (acres), used to calculate total annual recharge
70 RO = xlsread(file,'Scott', 'H34'); % annual Recharge (feet)at t = 0
71 Lift0 = xlsread(file,'Scott', 'C34'); % Depth to Water (feet) at t = 0
72 ST0 = xlsread(file,'Scott', 'D34'); % Saturated Thickness (feet) at t = 0
73 HC = xlsread(file,'Scott', 'G34'); % Hydraulic Conductivity (feet per day)
74 SY = xlsread(file,'Scott', 'E34'); % Specific Yield
75
76 % Define Pumping Plant variables
77 Days = xlsread(file,'Scott', 'K34'); % Days when well pumps; for max water availability
78 Acres = 126; % average acres under a center pivot
79 FP = 14.75; % Fuel Price of natural gas per MCF
80 PH = 46.2; % Pumping Head (feet) required to generate 20 psi at pivot point
81 EF = 58.6; % Energy efficiency for natural gass assuming a 75% pumping plant efficiency
82 TDH = PH + Lift0; % Total dynamic head (feet)
83 MC = (0.114*FP*TDH)/EF; %Marginal Cost of one acre inch of irrigation water
84 IE = xlsread(file,'Scott', 'N34'); % season long irrigation efficiency
85
86 %Define parameters for Irrigated Wheat

```



```

87  Wheat_Price = price(1); %Crop Price
88  Wheat_VE = xlsread(file,'Scott', 'B19'); % variable expenses not including irrigation fuel, seed, and fertilizer
89  Wheat_FaS = xlsread(file,'Scott', 'B20');%seed, and fertilizer expense at base yield
90  Wheat_HaH = xlsread(file,'Scott', 'B21');% Harvesting and Hauling expense per bushel
91  Wheat_Acres = xobs(1); % Acres in crop at t = 0
92  Wheat_FWY = xlsread(file,'Scott', 'B30'); % Fully Watered Yield
93  Wheat_BaseYield = yield(1);% Since FWY changes over time we need a base yield that stays constant to adjust budgets
94  Wheat_ET0 = xlsread(file,'Scott', 'B22'); % ET requirement for a fully watered yield at t = 0
95  %Wheat_B1 = xlsread(file,'Scott', 'B23'); % Change in ET per degrees fahrenheit increase
96  Wheat_GSP0 = xlsread(file,'Scott', 'B24'); % Growing Season Precipitation at t = 0
97  Wheat_EP = xlsread(file,'Scott', 'B25'); % Effectiveness of Precipitation
98  Wheat_CSM = xlsread(file,'Scott', 'B26'); % Change in soil moisture between planting and harvest
99  Wheat_NIR = xlsread(file,'Scott','B27'); % Net Irrigation Requirement
100 Wheat_GIR = xlsread(file, 'Scott','B28'); % Gross Irrigation Requirement
101 %Wheat_B2 = xlsread(file,'Scott', 'B29'); % the slope of the ET-Yield function;
102 Wheat_ObsWater = WaU(1)
103 Wheat_DY = yield(2); %Dryland Yield
104 Wheat_Dry_Profit = f(2)
105
106 %Define parameters for Irrigated Corn
107 Corn_Price = price(3); %Crop Price
108 Corn_VE = xlsread(file,'Scott', 'D19'); % variable expenses not including irrigation fuel, seed, and fertilizer
109 Corn_FaS = xlsread(file,'Scott', 'D20');%seed, and fertilizer expense at base yield
110 Corn_HaH = xlsread(file,'Scott', 'D21');% Harvesting and Hauling expense per bushel
111 Corn_Acres = xobs(3); % Acres in crop at t = 0
112 Corn_FWY = xlsread(file,'Scott', 'D30'); % Fully Watered Yield
113 Corn_BaseYield = yield(3);% Since FWY changes over time we need a base yield that stays constant to adjust budgets
114 Corn_ET0 = xlsread(file,'Scott', 'D22'); % ET requirement for a fully watered yield at t = 0
115 Corn_B1 = xlsread(file,'Scott', 'D23'); %Change in ET per degrees fahrenheit increase
116 Corn_GSP0 = xlsread(file,'Scott', 'D24'); % Growing Season Precipitation at t = 0
117 Corn_EP = xlsread(file,'Scott', 'D25'); % Effectiveness of Precipitation
118 Corn_CSM = xlsread(file,'Scott', 'D26'); % Change in soil moisture between planting and harvest
119 Corn_NIR = xlsread(file,'Scott','D27'); % Net Irrigation Requirement
120 Corn_GIR = xlsread(file, 'Scott','D28'); % Gross Irrigation Requirement
121 Corn_B2 = xlsread(file,'Scott', 'D29'); % the slope of the ET-Yield function;
122 Corn_ObsWater = WaU(3)
123 Corn_DY = yield(4); %Dryland Yield
124 Corn_Dry_Profit = f(4)
125
126 %Define parameters for Irrigated Sorghum
127 Sorghum_Price = price(5); %Crop Price
128 Sorghum_VE = xlsread(file,'Scott', 'F19'); % variable expenses not including irrigation fuel, seed, and fertilizer
129 Sorghum_FaS = xlsread(file,'Scott', 'F20');%seed, and fertilizer expense at base yield
130 Sorghum_HaH = xlsread(file,'Scott', 'F21');% Harvesting and Hauling expense per bushel

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131 Sorghum_Acres = xobs(5); % Acres in crop at t = 0
132 Sorghum_FWY = xlsread(file, 'Scott', 'F30'); % Fully Watered Yield
133 Sorghum_BaseYield = yield(5); % Since FWY changes over time we need a base yield that stays constant to adjust budgets
134 Sorghum_ET0 = xlsread(file, 'Scott', 'F22'); % ET requirement for a fully watered yield at t = 0
135 Sorghum_B1 = xlsread(file, 'Scott', 'F23'); % Change in ET per degrees fahrenheit increase
136 Sorghum_GSP0 = xlsread(file, 'Scott', 'F24'); % Growing Season Precipitation at t = 0
137 Sorghum_EP = xlsread(file, 'Scott', 'F25'); % Effectiveness of Precipitation
138 Sorghum_CSM = xlsread(file, 'Scott', 'F26'); % Change in soil moisture between planting and harvest
139 Sorghum_NIR = Sorghum_ET0 - Sorghum_EP*Sorghum_GSP0 - Sorghum_CSM; % Net Irrigation Requirement
140 Sorghum_GIR = Sorghum_NIR/IE; % Gross Irrigation Requirement
141 Sorghum_B2 = xlsread(file, 'Scott', 'F29'); % the slope of the ET-Yield function;
142 Sorghum_ObsWater = WaU(5)
143 Sorghum_DY = yield(6); % Dryland Yield
144 Sorghum_Dry_Profit = f(6)
145
146 % Define parameters for irrigated soybeans
147 Soy_Price = price(7); % Crop Price
148 Soy_VE = xlsread(file, 'Scott', 'H19'); % variable expenses not including irrigation fuel, seed, and fertilizer
149 Soy_FaS = xlsread(file, 'Scott', 'H20'); % seed, and fertilizer expense at base yield
150 Soy_HaH = xlsread(file, 'Scott', 'H21'); % Harvesting and Hauling expense per bushel
151 Soy_Acres = xobs(7); % Acres in crop at t = 0
152 Soy_FWY = xlsread(file, 'Scott', 'H30'); % Fully Watered Yield
153 Soy_BaseYield = yield(7); % Since FWY changes over time we need a base yield that stays constant to adjust budgets
154 Soy_ET0 = xlsread(file, 'Scott', 'H22'); % ET requirement for a fully watered yield at t = 0
155 Soy_B1 = xlsread(file, 'Scott', 'H23'); % Change in ET per degrees fahrenheit increase
156 Soy_GSP0 = xlsread(file, 'Scott', 'H24'); % Growing Season Precipitation at t = 0
157 Soy_EP = xlsread(file, 'Scott', 'H25'); % Effectiveness of Precipitation
158 Soy_CSM = xlsread(file, 'Scott', 'H26'); % Change in soil moisture between planting and harvest
159 Soy_NIR = Soy_ET0 - Soy_EP*Soy_GSP0 - Soy_CSM; % Net Irrigation Requirement
160 Soy_GIR = Soy_NIR/IE; % Gross Irrigation Requirement
161 Soy_B2 = xlsread(file, 'Scott', 'H29'); % the slope of the ET-Yield function;
162 Soy_ObsWater = WaU(7)
163 Soy_DY = 0; % Dryland Yield
164 Soy_Dry_Profit = 0
165
166 % Define parameters for Irrigated Alfalfa
167 Alfalfa_Price = price(8); % Crop Price
168 Alfalfa_VE = xlsread(file, 'Scott', 'I19'); % variable expenses not including irrigation fuel, seed, and fertilizer
169 Alfalfa_FaS = xlsread(file, 'Scott', 'I20'); % seed, and fertilizer expense at base yield
170 Alfalfa_HaH = xlsread(file, 'Scott', 'I21'); % Harvesting and Hauling expense per bushel
171 Alfalfa_Acres = xobs(8); % Acres in crop at t = 0
172 Alfalfa_FWY = xlsread(file, 'Scott', 'I30'); % Fully Watered Yield
173 Alfalfa_BaseYield = yield(8); % Since FWY changes over time we need a base yield that stays constant to adjust budgets
174 Alfalfa_ET0 = xlsread(file, 'Scott', 'I22'); % ET requirement for a fully watered yield at t = 0

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175 Alfalfa_B1 = xlsread(file,'Scott', 'I23'); %Change in ET per degrees fahrenheit increase
176 Alfalfa_GSP0 = xlsread(file,'Scott', 'I24'); % Growing Season Precipitation at t = 0
177 Alfalfa_EP = xlsread(file,'Scott', 'I25'); % Effectiveness of Precipitation
178 Alfalfa_CSM = xlsread(file,'Scott', 'I26'); % Change in soil moisture between planting and harvest
179 Alfalfa_NIR = xlsread(file,'Scott','I27'); % Net Irrigation Requirement
180 Alfalfa_GIR = xlsread(file, 'Scott','I28'); % Gross Irrigation Requirement
181 Alfalfa_B2 = xlsread(file,'Scott', 'I29'); % the slope of the ET-Yield function;
182 Alfalfa_ObsWater = WaU(8)
183 Alfalfa_DY = 0; %Dryland Yield
184 Alfalfa_Dry_Profit = 0
185
186 %Define parameters for Crop #4 = average non-irrigated acre
187 NIRR_Profit = 111.81; % Profit of average (based on crop mix) non-irrigated acre (Revenue - variable expenses)
188 NIRR_Acres = AR*MIA0; % Acres in crop at t = 0
189
190 % Create a matrix to store simulation output
191 Output = zeros(T,30);
192
193 % Define the nonlinear inequality constraint for maximum total water use
194 MWU = Corn_Acres*Corn_GIR + Corn_Acres*Corn_GIR + Corn_Acres*Corn_GIR;% Maximum Water Use
195
196 %Calibration Compensation
197 Wheat_delta = ((1-Wheat_ObsWater/Wheat_GIR)^((1-IE)/IE))*((Wheat_Price*(Wheat_FWY-Wheat_DY))/(IE*Wheat_GIR))-MC
198 Corn_delta = ((1-Corn_ObsWater/Corn_GIR)^((1-IE)/IE))*((Corn_Price*(Corn_FWY-Corn_DY))/(IE*Corn_GIR))-MC
199 Sorghum_delta = ((1-Sorghum_ObsWater/Sorghum_GIR)^((1-IE)/IE))*((Sorghum_Price*(Sorghum_FWY-Sorghum_DY))/(
(IE*Sorghum_GIR))-MC
200 Soy_delta = ((1-Soy_ObsWater/Soy_GIR)^((1-IE)/IE))*((Soy_Price*(Soy_FWY-Soy_DY))/(IE*Soy_GIR))-MC
201 Alfalfa_delta = ((1-Alfalfa_ObsWater/Alfalfa_GIR)^((1-IE)/IE))*((Alfalfa_Price*(Alfalfa_FWY-Alfalfa_DY))/(IE*Alfalfa_GIR))-MC
202
203 % Water Distribution
204 Wheat_Water0 = Wheat_GIR*(1-(((MC+Wheat_delta)*IE*Wheat_GIR)/(Wheat_Price*(Wheat_FWY-Wheat_DY)))^(IE/(1-IE)))
205 Corn_Water0 = Corn_GIR*(1-(((MC+Corn_delta)*IE*Corn_GIR)/(Corn_Price*(Corn_FWY-Corn_DY)))^(IE/(1-IE)))
206 Sorghum_Water0 = Sorghum_GIR*(1-(((MC+Sorghum_delta)*IE*Sorghum_GIR)/(Sorghum_Price*(Sorghum_FWY-Sorghum_DY)))
^(IE/(1-IE)))
207 Soy_Water0 = Soy_GIR*(1-(((MC+Soy_delta)*IE*Soy_GIR)/(Soy_Price*(Soy_FWY-Soy_DY)))^(IE/(1-IE)))
208 Alfalfa_Water0 = Alfalfa_GIR*(1-(((MC+Alfalfa_delta)*IE*Alfalfa_GIR)/(Alfalfa_Price*(Alfalfa_FWY-Alfalfa_DY)))^(IE/(1-IE)))
209 Water0 = [Wheat_Water0; 0; Corn_Water0; 0; Sorghum_Water0; 0; Soy_Water0; Alfalfa_Water0]
210
211 % Yield Calibration
212 Wheat_Yield = Wheat_DY + (Wheat_FWY - Wheat_DY)*(1 - (1 - (Wheat_Water0/Wheat_GIR)^(1/IE)))
213 Corn_Yield = Corn_DY + (Corn_FWY - Corn_DY)*(1 - (1 - (Corn_Water0/Corn_GIR)^(1/IE)))
214 Sorghum_Yield = Sorghum_DY + (Sorghum_FWY - Sorghum_DY)*(1 - (1 - (Sorghum_Water0/Sorghum_GIR)^(1/IE)))
215 Soy_Yield = Soy_DY + (Soy_FWY - Soy_DY)*(1 - (1 - (Soy_Water0/Soy_GIR)^(1/IE)))
216 Alfalfa_Yield = Alfalfa_DY + (Alfalfa_FWY - Alfalfa_DY)*(1 - (1 - (Alfalfa_Water0/Alfalfa_GIR)^(1/IE)))
217 yield_new = [Wheat_Yield; yield(2); Corn_Yield; yield(4); Sorghum_Yield; yield(6); Soy_Yield; Alfalfa_Yield]

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218
219 % Verification
220 rev_new = price'.*yield_new
221 H = diag(gamma)
222 G = -(rev_new - alpha)
223 [x1,fval1,exitflag1,output1,lambda1] = quadprog(H,G,[],[],A,b,lb, ones(num_crops,1)*b(1))
224 PreCheck = [x1 - xobs']
225 Check = abs(PreCheck)
226
227 %Stage IV Water Analysis
228 %DEFINE PARAMETERS
229 %Land and Water variables
230 % T = number of years to simulate
231 % WaU = Water Use per Crop
232 % H0 = Lift in Base pdt (feet above sea level) when t=0
233 % H(t) = Static Water Level (pdt) in time period t
234 % W0 = Total Water Use in time period 0
235 % R = Aquifer Recharge Rate (acre inches/acre)
236 % S = Specific Yield
237 % Ab = Land Area Above Aquifer (acres)
238 % HC = Hydraulic Conductivity (feet/day)
239 % ST0 = Saturated Thickness in time period 0 (feet)
240 % STt = Saturated Thickness in time period t (feet)
241 % Lift = Depth to Static Water Table (feet)
242 % Days = Average Length of Irrigation Season (days)
243 % maxpump = Maximum Pumping per Well per Growing Season (acre feet)
244 % wells = Number of Wells in the County
245 % W = Water Use Over All Crops
246 % STmin = Minimum Saturated Thickness to Support Irrigation
247 % Depletion = Rate of Aquifer Depletion
248 % GPM = Gallons Per Minute Pumped
249
250 % Starting Values
251 Airrigated = [1, 0, 1, 0, 1, 0, 1, 1]
252 Birrigated = xlsread(file, 'Scott','M2')
253 H= diag(gamma)
254 G = -[rev' - alpha]
255 T = xlsread(file,'Scott','B34')
256 %H0 = xlsread(file,'Scott','C34')
257 ST0 = xlsread(file,'Scott','D34')
258 S = xlsread(file,'Scott','E34')
259 Ab = xlsread(file,'Scott','F34')
260 HC = xlsread(file,'Scott','G34')
261 R = xlsread(file,'Scott','H34')

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262 %W0 = xlsread(file,'Scott','I34')
263 W0 = Water0'*x1/12
264 D = xlsread(file,'Scott','J34')
265 Days = xlsread(file,'Scott','K34')
266 wells= xlsread(file,'Scott','L34')
267 STmin = xlsread(file,'Scott','M34')
268 Lift0 = xlsread(file, 'Scott','C34')
269 MC0 = 0.114*FP*(PH + Lift0)/EF
270
271 %Equations
272 Prices = price'* ones(1,T)
273 Yields = yield' * ones(1,T)
274 W = W0 * ones(1,T)
275 Lift = Lift0 * ones(1,T)
276 maxpump = ones(1,T)
277 ST = ST0 * ones(1,T)
278 crop_acres = zeros(num_crops,T)
279 profit = zeros(num_crops,T)
280 doom = zeros (1,T)
281 flag = zeros(1,T)
282 Base_Cost0 = Water0*MC0
283 for t = 1:T
284     if t == 1
285         Depletion(t) = (W0/(S*Ab))-(R/(S*12))
286         Lift(t) = Lift0 + Depletion(t)
287         ST(t) = ST0 - Depletion(t)
288     else
289         Depletion(t) = (W(t-1)/(S*Ab))-(R/(S*12))
290         Lift(t) = Lift(t-1) + Depletion(t)
291         ST(t) = ST(t-1)-Depletion(t)
292     end
293     MC(t) = 0.114*FP*(PH + Lift(t))/EF
294     GPM(t)=-488.93+3.68*HC+8.75*ST(t)+.05*ST(t)^2
295     MAWA(t) = (GPM(t)*60*24*Days*12)/(7.48*43560*Acres)
296     Wheat_Water(t) = min(MAWA(t),Wheat_GIR*(1-(((MC(t)+Wheat_delta)*IE*Wheat_GIR)/(Wheat_Price*(Wheat_FWY-
Wheat_DY))))^(IE/(1-IE))))
297     Corn_Water(t) = min(MAWA(t),Corn_GIR*(1-(((MC(t)+Corn_delta)*IE*Corn_GIR)/(Corn_Price*(Corn_FWY-Corn_DY))))^(
IE/(1-IE))))
298     Sorghum_Water(t) = min(MAWA(t),Sorghum_GIR*(1-(((MC(t)+Sorghum_delta)*IE*Sorghum_GIR)/(Sorghum_Price*
(Sorghum_FWY-Sorghum_DY))))^(IE/(1-IE))))
299     Soy_Water(t) = min(MAWA(t),Soy_GIR*(1-(((MC(t)+Soy_delta)*IE*Soy_GIR)/(Soy_Price*(Soy_FWY-Soy_DY))))^(IE/(1-IE))))
300     Alfalfa_Water(t) = min(MAWA(t),Alfalfa_GIR*(1-(((MC(t)+Alfalfa_delta)*IE*Alfalfa_GIR)/(Alfalfa_Price*(Alfalfa_FWY-
Alfalfa_DY))))^(IE/(1-IE))))
301     Water(:,t) = [Wheat_Water(t); 0; Corn_Water(t); 0; Sorghum_Water(t); 0; Soy_Water(t); Alfalfa_Water(t)]
302     Base_Cost(:,t) = Water(:,t)*MC(t)
303     Wheat_Yield(t) = Wheat_DY + (Wheat_FWY - Wheat_DY)*(1 - (1 - (Wheat_Water(t)/Wheat_GIR)^(1/IE)))

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304     Corn_Yield(t) = Corn_DY + (Corn_FWY - Corn_DY)*(1 - (1 - (Corn_Water(t)/Corn_GIR)^(1/IE)))
305     Sorghum_Yield(t) = Sorghum_DY + (Sorghum_FWY - Sorghum_DY)*(1 - (1 - (Sorghum_Water(t)/Sorghum_GIR)^(1/IE)))
306     Soy_Yield(t) = Soy_DY + (Soy_FWY - Soy_DY)*(1 - (1 - (Soy_Water(t)/Soy_GIR)^(1/IE)))
307     Alfalfa_Yield(t) = Alfalfa_DY + (Alfalfa_FWY - Alfalfa_DY)*(1 - (1 - (Alfalfa_Water(t)/Alfalfa_GIR)^(1/IE)))
308     Wheat_Rev(t) = Wheat_Yield(t)*Wheat_Price
309     Corn_Rev(t) = Corn_Yield(t)*Corn_Price
310     Sorghum_Rev(t) = Sorghum_Yield(t)*Sorghum_Price
311     Soy_Rev(t) = Soy_Yield(t)*Soy_Price
312     Alfalfa_Rev(t) = Alfalfa_Yield(t)*Alfalfa_Price
313     Rev(:,t) = [Wheat_Rev(t); rev_new(2); Corn_Rev(t); rev_new(4); Sorghum_Rev(t); rev_new(6); Soy_Rev(t); Alfalfa_Rev(t)]
314     G = -(Rev(:,t) - alpha - ((Water(:,t).*MC(t))-Base_Cost0))
315     [x2,fval2,exitflag2,output2,lambda2] = quadprog(H,G,Airrigated,Birrigated,A,b,lb,ones(num_crops,1)*b(1))
316     flag(t) = exitflag2
317     if exitflag2 < 0
318         crop_acres(:,t) = 0
319         W(:,t) = 0
320         profit(:,t) = 0
321     Else
322         crop_acres(:,t) = x2
323         W(:,t) = (Water(:,t)*x2)/12
324         profit(:,t) = -fval2
325     End
326 End
327
328     xlswrite(write,crop_acres, 'Scott','G2:BN9')
329     xlswrite(write,Water, 'Scott','G12:BN19')
330     xlswrite(write,ST, 'Scott','G22:BN22')
331     xlswrite(write,Lift, 'Scott','G23:BN23')
332     xlswrite(write,Depletion, 'Scott','G24:BN24')
333     xlswrite(write,W, 'Scott','G25:BN25')
334     xlswrite(write,MAWA, 'Scott','G26:BN26')
335     xlswrite(write,MC, 'Scott','G27:BN27')
336     Total_Net_Rev = (Rev.*crop_acres)-(Base_Cost.*crop_acres)
337     xlswrite(write>Total_Net_Rev,'Net_Rev','B31:BI38')
338
339     %State V Price shock
340     Airrigated = [1, 0, 1, 0, 1, 0, 1, 1]
341     Birrigated = xlsread(file, 'Scott','M2')
342     H= diag(gamma)
343     G = -[rev' - alpha]
344     T = xlsread(file,'Scott','B34')
345     %H0 = xlsread(file,'Scott','C34')
346     ST0 = xlsread(file,'Scott','D34')
347     S = xlsread(file,'Scott','E34')

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348 Ab = xlsread(file,'Scott','F34')
349 HC = xlsread(file,'Scott','G34')
350 R = xlsread(file,'Scott','H34')
351 % W0 = xlsread(file,'Scott','I34')
352 W0 = Water0'*x1/12
353 D = xlsread(file,'Scott','J34')
354 Days = xlsread(file,'Scott','K34')
355 wells= xlsread(file,'Scott','L34')
356 STmin = xlsread(file,'Scott','M34')
357 Lift0 = xlsread(file, 'Scott','C34')
358 MC0 = 0.114*FP*(PH + Lift0)/EF
359
360 %Equations
361 Prices_new = [5.43; 5.43; 3.97; 3.97; 3.62; 3.62; 8.31; 111.33]* ones(1,T)
362 Yields = yield' * ones(1,T)
363 W = W0 * ones(1,T)
364 Lift = Lift0 * ones(1,T)
365 maxpump = ones(1,T)
366 ST = ST0 * ones(1,T)
367 crop_acres = zeros(num_crops,T)
368 profit = zeros(num_crops,T)
369 doom = zeros (1,T)
370 flag = zeros(1,T)
371 Base_Cost0 = Water0*MC0
372 for t = 1:T
373     if t == 1
374         Depletion(t) = (W0/(S*Ab))-(R/(S*12))
375         Lift(t) = Lift0 + Depletion(t)
376         ST(t) = ST0 - Depletion(t)
377     Else
378         Depletion(t) = (W(t-1)/(S*Ab))-(R/(S*12))
379         Lift(t) = Lift(t-1) + Depletion(t)
380         ST(t) = ST(t-1)-Depletion(t)
381     end
382     MC(t) = 0.114*FP*(PH + Lift(t))/EF
383     GPM(t)=-488.93+3.68*HC+8.75*ST(t)+.05*ST(t)^2
384     MAWA(t) = (GPM(t)*60*24*Days*12)/(7.48*43560*Acres)
385     Wheat_Water(t) = min(MAWA(t),Wheat_GIR*(1-(((MC(t)+Wheat_delta)*IE*Wheat_GIR)/(Prices_new(1)*(Wheat_FWY-
Wheat_DY))))^(IE/(1-IE))))
386     Corn_Water(t) = min(MAWA(t),Corn_GIR*(1-(((MC(t)+Corn_delta)*IE*Corn_GIR)/(Prices_new(3)*(Corn_FWY-Corn_DY)))
^(IE/(1-IE))))
387     Sorghum_Water(t) = min(MAWA(t),Sorghum_GIR*(1-(((MC(t)+Sorghum_delta)*IE*Sorghum_GIR)/(Prices_new(5)*
(Sorghum_FWY-Sorghum_DY))))^(IE/(1-IE))))
388     Soy_Water(t) = min(MAWA(t),Soy_GIR*(1-(((MC(t)+Soy_delta)*IE*Soy_GIR)/(Prices_new(7)*(Soy_FWY-Soy_DY)))
^(IE/(1-IE))))
389     Alfalfa_Water(t) = min(MAWA(t),Alfalfa_GIR*(1-(((MC(t)+Alfalfa_delta)*IE*Alfalfa_GIR)/(Prices_new(8)*(Alfalfa_FWY-

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Alfalfa_DY)))^(IE/(1-IE))))
390 Water(:,t) = [Wheat_Water(t); 0; Corn_Water(t); 0; Sorghum_Water(t); 0; Soy_Water(t); Alfalfa_Water(t)]
391 Base_Cost(:,t) = Water(:,t)*MC(t)
392 Wheat_Yield(t) = Wheat_DY + (Wheat_FWY - Wheat_DY)*(1 - (1 - (Wheat_Water(t)/Wheat_GIR)^(1/IE)))
393 Corn_Yield(t) = Corn_DY + (Corn_FWY - Corn_DY)*(1 - (1 - (Corn_Water(t)/Corn_GIR)^(1/IE)))
394 Sorghum_Yield(t) = Sorghum_DY + (Sorghum_FWY - Sorghum_DY)*(1 - (1 - (Sorghum_Water(t)/Sorghum_GIR)^(1/IE)))
395 Soy_Yield(t) = Soy_DY + (Soy_FWY - Soy_DY)*(1 - (1 - (Soy_Water(t)/Soy_GIR)^(1/IE)))
396 Alfalfa_Yield(t) = Alfalfa_DY + (Alfalfa_FWY - Alfalfa_DY)*(1 - (1 - (Alfalfa_Water(t)/Alfalfa_GIR)^(1/IE)))
397 Wheat_Rev_new(t) = Wheat_Yield(t)*Prices_new(1)
398 Corn_Rev_new(t) = Corn_Yield(t)*Prices_new(3)
399 Sorghum_Rev_new(t) = Sorghum_Yield(t)*Prices_new(5)
400 Soy_Rev_new(t) = Soy_Yield(t)*Prices_new(7)
401 Alfalfa_Rev_new(t) = Alfalfa_Yield(t)*Prices_new(8)
402 Rev_new(:,t) = [Wheat_Rev_new(t); (yield(2)*Prices_new(2)); Corn_Rev_new(t); (yield(4)*Prices_new(4)); Sorghum_Rev_new(t);
(yield(6)*Prices_new(6)); Soy_Rev_new(t); Alfalfa_Rev_new(t)]
403 G = -(Rev_new(:,t) - alpha - ((Water(:,t).*MC(t))-Base_Cost0))
404 [x2,fval2,exitflag2,output2,lambda2] = quadprog(H,G,Airrigated,Birrigated,A,b,lb,ones(num_crops,1)*b(1))
405 flag(t) = exitflag2
406 if exitflag2 < 0
407 crop_acres(:,t) = 0
408 W(:,t) = 0
409 profit(:,t) = 0
410 else
411 crop_acres(:,t) = x2
412 W(:,t) = (Water(:,t)*x2)/12
413 profit(:,t) = -fval2
414 end
415 End
416
417 xlswrite(write,crop_acres, 'Scott_shock','G2:BN9')
418 xlswrite(write,Water, 'Scott_shock','G12:BN19')
419 xlswrite(write,ST, 'Scott_shock','G22:BN22')
420 xlswrite(write,Lift, 'Scott_shock','G23:BN23')
421 xlswrite(write,Depletion, 'Scott_shock','G24:BN24')
422 xlswrite(write,W, 'Scott_shock','G25:BN25')
423 xlswrite(write,MAWA, 'Scott_shock','G26:BN26')
424 xlswrite(write,MC, 'Scott_shock','G27:BN27')
425 Total_Net_Rev = (Rev.*crop_acres)-(Base_Cost.*crop_acres)
426 xlswrite(write>Total_Net_Rev,'Net_Rev','B43:BI50')

```