THE IMPACT OF CLIMATE CHANGE ON THE EFFECTIVENESS OF WATER CONSERVATION POLICIES IN WESTERN KANSAS AND THE OGALLALA AQUIFER

by

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AN ABSTRACT OF A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree

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ABSTRACT

Water scarcity is already a critical issue in many regions across the world and in many places water supplies are likely to be further threatened by climate change (Bates *et al.*, 2008).

Climate change will affect water availability in these areas both directly and indirectly. The direct effects come about because increased temperature (accompanied by changes in wind, humidity, and solar radiation) may increase evaporative losses from surface water bodies, and also because reduced precipitation lowers the rate of water inflows. In the case of groundwater, these factors will reduce the rate of aquifer recharge (Bates *et al.*, 2008). The indirect effects arise from the biophysical impacts of climate change on vegetation, which are induced from rising temperatures, changing precipitation regimes, and increased atmospheric carbon dioxide levels. As a result of climate change, significant changes are expected in the hydrological cycle.

This research is focused in how climate change can affect crop, land, and water allocation over time. The specific issue of this research comes from the following question: Is climate change likely to have a significant impact on the effectiveness of different water conservation policies in the High Plains aquifer region?

This study is focused on the American High Plains, one of the most important water-scarce agricultural regions in North America. The study region for this research is a 31-county area overlying the Ogallala aquifer in western Kansas. This region encompasses approximately the western third of Kansas. Across these counties, the estimated remaining usable lifetime for aquifer water ranges from 50 to over 200 years (KGS), representing the range of water available in various parts of the aquifer.

A Positive Mathematical Programming (PMP) model (Howitt, 1995) was developed and calibrated to land- and water-use data in the thirty one county area for a base period of 2000-2008. The PMP simulation uses inputs of price conditions and the aquifer level in a given year to predict the acreages planted to each of the major crops and the water use by crop. Decision makers are assumed to maximize profits, given the limited availability of water and arable land. The major crops in the model include wheat, corn, sorghum, soybeans, and alfalfa; the vast majority of historical planted acreage in the case counties is comprised of these five crops. The model was run for each of the case regions after calibrating the PMP model to data from 2000-2008. Calibration ensures that the model predictions fall within a small tolerance of the base period observations. This step avoids the problem of over-specialization (where the model places all of the acreages under one or two of the most profitable crops), and gives realistic acres and water use figures with which to work.

The results suggest that the effects of the use of water conservation policies such as water use restriction and permanent conversion to dryland crops have positive effects on the trends of the different variables studied. With the implementation of these two policies, lower levels of total water use and higher levels of saturated thickness result but with a consequence of lower levels of net returns. However, the positive effects are lower in almost all cases if the effects of climate change on the same policies are taken into consideration. The scenarios of higher levels of temperature and lower precipitation levels projected for the region imply a greater demand for water for irrigated crops that results in lower levels of saturated thickness and simultaneously lower levels of net returns.

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DEDICATION

This dissertation is dedicated to my wife, Maria Angelica Santacruz de Garay, to my kids Elias Garay-Santacruz and Ezequiel Garay-Santacruz, and to the memory of my father Vicente Garay.

CHAPTER 1 – INTRODUCTION

1.1 MOTIVATION

Combating water scarcity is one of the major challenges facing the world in the 21st century. It is closely intertwined with the issues of food security, energy security, poverty reduction, economic growth, conflict reduction, adaptation to climate change and biodiversity loss.

Agriculture is and will continue to be the largest user of water worldwide. As the world population increases and patterns of food consumption change (for example, as people eat more meat), the risk of water scarcity will increase, unless water management is improved. Agriculture is the dominant water consumer worldwide (70%) and different types of agriculture place different demands on water resources (FAO 2011).

Water scarcity is usually due to a complex interaction of social, economic and environmental factors. It is rarely only the result of a lack of precipitation. Furthermore, if long term solutions to these problems are desired, responses to water scarcity requires the intervention of concerned parties as a whole, at local, and national and international levels.

Sustainable water use supports healthy ecosystems. However, the combination of climate change and other human forces threatens the continued viability of many ecosystems. In the face of this hydrological uncertainty that stems from different climate change scenarios, poorly planned solutions could increase the risks to ecosystems and the service they provide.

The consequences of water scarcity can be misleading. Such is the case with the decline of the Ogallala aquifer in the western United States, or the Edwards aquifer in the city of San Antonio, Texas. In most countries, groundwater is not well monitored, so that predicting when it reaches crisis levels is something that tends to escape us. Consequently, the risk of shortages is often perceived as a future issue or that only people involved in politics can handle.

As a result of climate change, significant changes are expected in the hydrological cycle. However, the prediction of changes in precipitation is one of the aspects of climate change that is most difficult to outline, thereby adding more uncertainty to water scarcity scenarios. Projections suggest that the tropics may become wetter or drier, depending on location. The subtropics are expected to become drier on average. In many places, the result of altered weather patterns that were previously predictable will be the uncertainty regarding the frequency of extreme weather events such as severe drought. The dry summer seasons in some areas will be drier and longer. Variations in snowpack in the mountains are a major cause of the lack of water security in many temperate regions of several countries, and in some areas have meant changes in both the frequency and volume of meltwater runoff (IPCC, 2007).

It is important to point out that the combination of climate variability and human activities causes the greatest impact on ecosystems, and leads to the greatest risks to water end users. Perhaps most important is that inadequate water management solutions in the face of climate change may increase risks. Many traditional solutions in water supply management (typical engineering solutions based on historical hydrological patterns whose relevance is increasingly dubious) simply postpone or worsen the risk.

1.2 CURRENT AQUIFER LEVELS

The Ogallala aquifer, which is part of the High Plains Aquifer System, is a large but shallow groundwater aquifer located beneath the Great Plains of the United States. One of the largest aquifers in the world, it covers an area of approximately 174,000 square miles in portions of the eight states of South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico and Texas.

But the Ogallala is not an underground lake. It is a spongy structure, whose formation started 20 million years ago due to the gradual landslide of gravel and sand from the Rockies. Most of its content is fossil water, stored from millions of years ago.

Until the 1940s, the aquifer remained largely unused and agriculture in the Great Plains depended on unreliable rainfall. Tillage for wheat cultivation on the plains loosened the fragile topsoil and erosion was increased by winds. Large dust storms during the drought of the 1930s, which inspired John Steinbeck to write The Grapes of Wrath, are a testimony to the ecological disaster unleashed by the cultivation of land unsuitable for agriculture. Two million people left their land and, to date, the rehabilitation of the region has not been completed, despite heavy investment in infrastructure and the introduction of improved soil management technologies (Konikow, 2013)

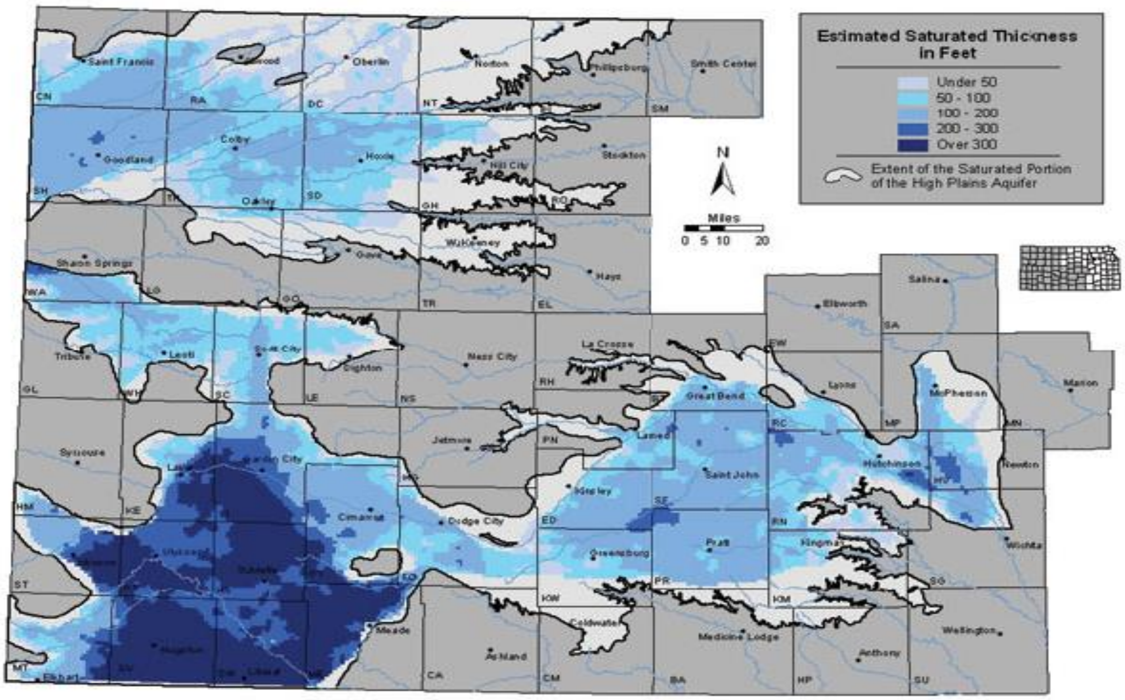
Figure 1.1. Regions and Location of the High Plains Aquifer

www.nrcs.usda.gov

After the Second World War intensive aquifer use began and today the Ogallala is used to irrigate more than 6.5 million hectares (over 16 million acres) devoted to corn, sorghum, soybeans and wheat. This allowed states like Nebraska, Kansas, Colorado, Oklahoma and Texas to compete in production with Illinois and Iowa (where rainfall is consistent). Essentially the Ogallala had replaced the natural climate.

Agricultural production on semi-arid land (such as the Great Plains) costs three to six times more than in temperate regions where rainfall is more regular or on gravity-irrigated land. The higher cost is due to the infrastructure, equipment and fossil fuel needed to draw irrigation water. To maintain current production levels, the US government provides four billion dollars annually to subsidize irrigation in the states above the Ogallala (Konikow, 2013).

Figure 1.2. Saturated Thickness for the High Plains aquifer in Kansas

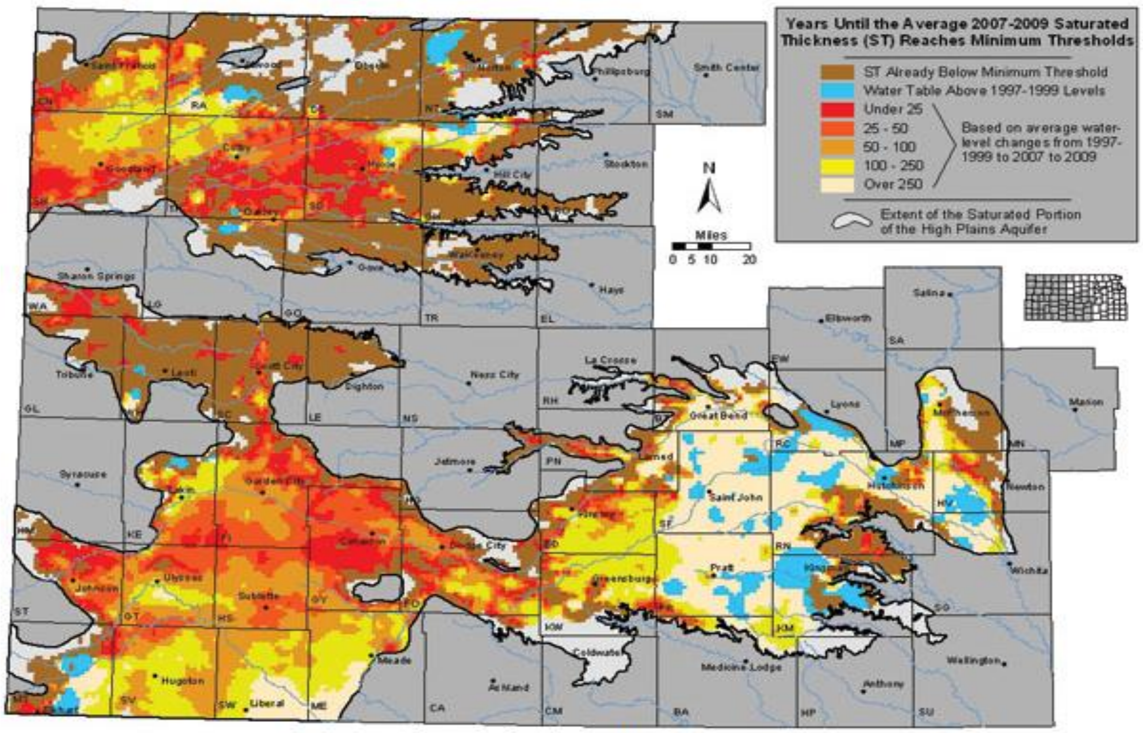


Source: Kansas Geological Survey

Agricultural water use competes with the demand from cities and industry on the plains. In addition, the Ogallala is contaminated with pesticides, fertilizer residues and waste from huge livestock-raising farms concentrated in the states above the aquifer.

In the case of fossil water, aquifer recharge is very slow. Therefore the extraction of water exceeds the natural recharge rate of the aquifer by 160 percent and the level of the mantle is falling rapidly. If this trend continues, some areas of the aquifer will cease to be productive aquifer within 50 years (KGS).

Figure 1.3. Estimated Usable Life



Source: Kansas Geological Survey

Depth to water in to Ogallala varies with the shape of the surface. The depth to water is greater where it under lies old canals and valleys. The Ogallala Formation consists mainly of thick sedimentary rocks in the deeper sections, transitioning to finer material toward the upper part (KGS).

Groundwater levels decrease when the irrigation extraction rate exceeds the rate of recharge. In some places, the water table has declined more than one meter per year at the time of maximum extraction. In extreme cases, wells had to be deepened in order to reach the declining water table.

The USGS estimates that the total water storage was about 2.925 billion acre-feet in 2005. This is a decline of nearly 253 million acre-feet, or 9%, since the substantial development of irrigation with groundwater began in the 1950s. According to Konikow (2013) the decline from 2001 to 2008, inclusive, is approximately 32 percent of the cumulative decline throughout the entire 20th century.

Water conservation practices, more efficient irrigation methods, and the area of reduced irrigation have helped to slow the depletion of aquifers, but levels generally continue to fall in areas that include southwestern Kansas.

1.3 GENERAL ISSUE

This study is motivated by the following question: how may climate change affect crop, land, water allocation, and water use over time?

Water scarcity is already a critical issue in many regions across the world and in many places water supplies are likely to be further threatened by climate change (Bates *et al.*, 2008). Increased water scarcity will exacerbate the existing conflicts over water allocation among municipal, industrial, agricultural, and environmental uses in these regions, many of which have rapidly growing populations with highly water-dependent industries.

Climate change will affect water availability in these areas both directly and indirectly. The direct effects come about because increased temperature (accompanied by changes in wind, humidity, and solar radiation) may increase evaporative losses from surface water bodies, and also because reduced precipitation lowers the rate of water inflows. In the case of groundwater, these factors will reduce the rate of aquifer recharge (Bates *et al.*, 2008). The indirect effects arise from the biophysical impacts of climate change on vegetation, which are induced from rising temperatures, changing precipitation regimes, and increased atmospheric carbon dioxide levels. Biophysical effects of climate change can be positive or negative depending on land uses in each region; climate change effects could also vary through time (Parry *et al.,* 2004). The biophysical impacts on crops will generate changes in the pattern of water use, ultimately affecting water availability.

The semi-arid regions are considered the most vulnerable areas that could be affected by water scarcity and climate change. In these areas, high temperatures, reduction in rainfall, and increases in rainfall variability could have considerable negative impacts on crop and livestock productivity (Antle, 2008). Because western Kansas is considered a semi-arid region, the impact of climate change on groundwater resources could be significant.

1.4 SPECIFIC PROBLEM

The specific issue of this research comes from the following question: Is climate change likely to have a significant impact on the effectiveness of different water conservation policies in the High Plains aquifer region?

The importance of water resources in agricultural industries has long been recognized. However, while water levels have been declining throughout the High Plains region, much of the focus from the water management perspective has been on selected 'hot spots' or intensive use areas, where there is a high density of irrigation wells and a localized depression in the water level. The prior appropriation legal framework in Kansas (and most other states in the Great

Plains and westward) provides a legal guarantee of water availability to holders of senior water rights. When this guarantee cannot be met in an area of rapid water level decline, the holder may file an impairment claim that forces the state's Chief Engineer to conduct an investigation and, if necessary, restrict the water use of holders of more junior water rights. Much of the water management effort in Kansas and similar states is to slow down the rate of decline in these intensive areas to prevent legally complicated impairment claims. For instance, the state of Kansas is implementing conservation programs which offer incentives to encourage irrigators to sell or lease out their water rights.

The possible influence of climate change on these policies has received little attention in the literature. Further, climate scientists predict that higher temperatures in Kansas could increase evaporation, resulting in less soil moisture. All these impacts could result in greater use of water for irrigation from the Ogallala Aquifer (Golden *et al.*, 2008). Moreover, climate models predict that the weather in the Ogallala aquifer region will become more volatile. There may be higher average temperatures and somewhat less annual rainfall. These changes would increase water use and accelerate the rate of aquifer depletion. Given the specialized and vertically linked nature of the regional economy, increased water scarcity could hamper already challenging rural economic development efforts.

Additionally, an important aspect that should be considered when analyzing the potential impacts of climate change is the level of data aggregation. Climate models often use data at a very coarse spatial resolution, which makes it problematic to study the impact of climate change using regional models (Antle, 2008). In general, uniform changes in climate generate spatially heterogeneous impacts on producers due to varying water resources and land characteristics. In most cases, researchers model the representative land unit at highly aggregated levels. This approach ignores any spatial variability within each spatial unit, masking distributional issues that may be important for water policy. Moreover, if many of the model relationships are highly nonlinear the model's prediction error may increase. Even if one is only interested in aggregate measures at the regional scale, a more accurate prediction may be obtained by constructing many versions of the model – with each version parameterized to a small but distinct spatial unit—then aggregating the results.

Policy makers have little information on the impacts of climate change on water use given alternative water conservation policies. Similarly, many of the studies on crop choice and water use patterns have not considered the impacts of the climate change on the supply and demand of water. Therefore, there is need for an empirical model that can relate water conservation policies, climate change, and crop and land allocation to water use.

To clarify, by use of the term "effectiveness", this research seeks to determine whether the results obtained after the implementation of water conservation policies without considering the effects of climate change and the results obtained when these policies include the effects of climate change are consistent in regard to water use, saturated thickness and net return during the study period (fifty years). For this study, scenarios of climate change and aquifer depletion are considered, but not the effects of technological changes. Neither is population growth taken into account, since the majority of water demand in the study region is for agricultural irrigation.

1.5 RESEARCH OBJECTIVES

The general objective of this research is to study the possible impact of climate change on groundwater availability, land use patterns, and irrigated crop income in the Ogallala aquifer region and the interaction of climate change with water conservation policies. The following are specific objectives of this research:

- Determine the level of spatial aggregation that can give the most accurate predictions of land and water use.
- Project future land-use and water-use patterns under a status-quo scenario that assumes no climate change and current conservation policy.
- Estimate the impact of specific water conservation policies under an unchanged regional climate.
- Identify and quantify any changes on land-use and water-use patterns under alternative water policies due to changing climatic conditions.

CHAPTER 2 – LITERATURE REVIEW

The literature review is organized in two sections. The first section covers climate change issues, and the second section reviews some of the work that has been completed on aggregation problems.

2.1 CLIMATE CHANGE

Research has been conducted on the possible socioeconomic impacts of climate change. The literature suggests that climate change impacts can be analyzed at the regional or global level, and also by different sectors. This dissertation can be classified as a regional study. Therefore the literature related to climate change in this work will focus on research developed to study regional impacts of climate change, and most specifically, on agriculture and the water resource sector. These works normally use econometric and mathematical programming techniques to analyze agricultural productivity and land/water allocation under different climate change scenarios.

Connor *et al*. (2009) studied climate change on irrigated agriculture and its economic implications on the Murray Darling Basin located in Australia. The geographic area of analysis was considered the most productive agricultural region of that country. The authors considered three different climate change scenarios to carry out a sensitivity analysis. The authors ran the simulations with a mathematical programming model using the Danzig (1955) two-stage approach. In the first stage, the level of long-run capital investment to be used in the next 20-30 years was modeled. This was considered a long term variable. The second stage was subject to the first and it represented the annual quantity of water-use decisions and acreage fallowed in the short run. They modeled three climate scenarios, which they named mild, moderate, and severe scenarios. In each scenario, the authors assumed temperature increases of 1°C, 2°C and 4°C. The scenarios respectively generated 13, 38, and 63 percent reductions in basin water inflows, and at the same time crop evapo-transpiration increased by 4, 8, and 15 percent. The rainfall and runoff for the first two scenarios were taken from the Intergovernmental Panel on Climate Change (IPCC) 2030 projection for Southern Australia, while the third scenario is based in the IPCC 2070 projection for the same area of analysis. The authors found that under more severe climate scenarios, producers will incur higher costs in terms of investment in new technology to achieve irrigation efficiency. Also, they found that the most severe climate change scenarios resulted in a greater reduction of irrigated area.

Golden *et al.* (2008) implemented a dynamic simulation technique to model the possible impact of climate change in a small portion of Sheridan County located in northwest Kansas. There are two methodological aspects presented in this paper that are particularly relevant for this research: first, the way climate change scenarios are introduced into the dynamic simulation model, and second, the way the climate change scenarios were formulated. The climate change scenario used in their paper, taken from Hall (2008), is appropriate for the Great Plains area and was based on analysis by the Intergovernmental Panel on Climate Change (IPCC) report. Specifically, the climate change scenario suggested a mean increase in temperature of 2.5°F and a 2.5% reduction in precipitation over the next 50 years. Also, they considered a 20% reduction in groundwater recharge in the next 50 year period. The authors found that saturated thickness and water use declined the most under the higher temperature and lower precipitation scenario.

Another interesting result is that the producers' profit would be significantly affected because of the limitation on pumping capacity which would negatively affect crop yield.

Deschenes and Greenstone (2007) introduced a new method to model climate change and its economic impacts. They measured the impact of climate change in U.S. agriculture using random variation in temperature and precipitation. Deschenes and Greenstone critique the hedonic approach, which is a very common method used to study climate change, because it generates very sensitive parameters and may yield misleading projections. To Deschenes and Greenstone, the hedonic approach is inappropriate to study the impact of climate change. For this reason, they developed a new technique that used random year-to-year variation in temperature and precipitation to measure the impact of climate change on agricultural profit and yield. The authors used climate change scenarios from two different sources. The first set of climate scenarios came from the IPCC. These scenarios assume incremental increases of 5^0 F in temperature and 8 percent in precipitation, both of which are assumed to be uniform across the U.S. The second source of climate scenario is the Hadley Centre's Second Coupled Ocean-Atmosphere General Circulation Model. In general, Deschenes and Greenstone (2007) found that climate change would increase annual profits in the U.S. agricultural sector and that the effect on yields of most crops would be insignificant. On a state-by-state basis, they found positive impacts on profits and yields in some and negative impacts in others. Even the state-level negative or positive impacts are not large and depend on the regional characteristics. Their results are consistent with other works where the assumptions are that both mean temperature and precipitation will increase.

Hurd and Coonrod (2007) studied the implications of climate change on water resources in New Mexico and its possible socioeconomics impacts. They used three climate change scenarios selected from the IPCC (2007) for two different time periods. These climate scenarios reflect the range of outcomes projected for the region of New Mexico by 2030 and by 2080. At the same time they considered socioeconomic scenarios based on Smith and Wagner (2006). These scenarios include population and income growth trends for New Mexico based on the U.S census and the New Mexico Bureau of Business and Economic Research (NM BBER, 2004). Once the climate change and socioeconomic scenarios were constructed, the authors estimated water availability using a hydrologic model called WATBAL (Yates, 1996), which combined climatic and hydrologic processes. They used the Rio Grande Hydro-Economic Model (RGHE) to estimate water use and allocation as well as changes in economic welfare under different climate change scenarios. Hurd and Coonrod (2007) found that climate change generated negative impacts on all sectors considered in the study. The negative consequences were exacerbated under the most severe climate change scenarios. The most important finding of this paper for our study is that regions with high water resource dependency are very vulnerable to climatic changes due to its subsequent impact on water supply.

Lobell *et al.*, (2006) investigated the possible impact of climate change on perennial crop yields in California. They point out that the greater part of research on the effect of climate change is concentrated on annual crops. The main motivation for their research was that the perennial crops industry is very important for California and since this industrial system is relatively inflexible, the impacts of possible climate change may be greater than for conventional agricultural annual crops. For the analysis, the authors considered six major perennial crops in

California: wine grapes, almonds, table grapes, oranges, walnuts, and avocados. They estimated the effects of change in temperature and precipitation on the yield of each crop using multiple linear regression models. This study did not take in consideration the possibility of adaption to climate change by farmers. The authors evaluated how perennial crop yields responded to change in expected temperature and precipitation. Lobell *et al.* (2006) found that climate change scenarios implying higher temperatures would reduce yields for most of the perennial crops. Crop prices and consequently producer and consumer welfare would also be affected. The authors also pointed out that while climate change is only one of the several factors that would influence future perennial crops yields, it is important to isolate its possible implications.

Another study related to the impact of climate change in a water dependent region was developed by Chen *et al.,* (2001). They studied the possible impacts of climate change on water supply and demand and its economic implications in the San Antonio Texas Edwards Aquifer region. The authors separately estimated the effects of an increase in mean temperature and a decrease in rainfall on the aquifer rate of recharge (supply) and on water demand. In addition to the status-quo scenario (no climate change), they estimated four alternative scenarios for comparison. The scenarios are based on the climate projections of the Canadian Climate Center Model (CCC) and the Hadley Climate Center Model (HAD). To estimate the effects of change in temperature and precipitation on the rate of recharge they chose a log-linear regression based on a likelihood ratio test. Chen *et al.* (2001) found a considerable reduction in the aquifer rate of recharge under the four scenarios. Results related to crop yield and water demand are also reported. While water demand for irrigated crops increased, the yield of irrigated and non-irrigated crops decreased under all scenarios considered in the research. Their results are consistent with most of the research that considers an increase in mean temperature and a decrease in precipitation.

Lawrence and Maidment (1998) studied the potential implication of climate change on water resource availability for the Edwards Aquifer in central Texas. They evaluated the implications of several combinations of precipitation and temperature reported by six climate models using a combination of a rainfall-runoff model and a groundwater model. These climate models projected that atmospheric concentrations of carbon dioxide would increase, generating a warmer climate in the study region. More precipitation could offset the warmer temperatures, but such a change is not expected in the study region. Higher temperatures would result in greater evaporation and consequently the aquifer will decline. The climate data set used in their research was developed by the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) (Kittel et al.1995) for the time period from January 1895 to December 1993. To generate the VEMAP data set, observations of minimum and maximum temperature from 5,500 stations were collected. Considering that the demand of water in the study region is projected to increase continuously, the results reported by the combination of their rainfall-runoff model indicate that the most severe climate scenarios will lead to even greater stress on the Edwards Aquifer.

Mendelsohn *et al.,* (1994) used the “Ricardian” approach to examine the impact of climate change on land price and farm profits in three thousand counties in the United States. They argued that the “Production function approach”, which represents one of the most traditional methods to study the impact of climate change in agriculture, generates biased estimators. Specifically this bias comes from the fact that this method does not account for farmers' adaptation in response to changing economic and environmental conditions. Since this approach does not permit complete adaptation, generally it overestimates the impacts of climate change. The authors developed a new method that can correct the bias mentioned above using economic data to represent land value. This new approach, denoted the *Ricardian approach*, evaluates the impact of climate change on the net rent or value of farmland instead of analyzing the impact on yields of specific crops. For this analysis, the author estimated several regressions where the independent variables were climate, soil and socioeconomic variables. The dependent variable was land value. These regressions can be divided in two groups: the first set of regression included only climate variables, while the second set additionally included urban, soil, and other environmental variables. The data used in their paper are from different sources. The agricultural data were from the County and City Data Book (U. S. Bureau of the Census, 1998), and the soils data were from the National Resource Inventory (NRI). The basic climate data were from National Climatic Data Center which included information on precipitation and temperature from 1951 to 1980. The climate change scenario used for their paper is based on the Intergovernmental Panel on Climate Change (1990) and the National Academy of Sciences Panel on Greenhouse Warming (1992). As noted above, the scenario implies a 5^{o} F increase in mean temperature and an 8 percent increase in precipitation. They weighted the counties in two different ways. For the first group of regressions, cropland weights were used. The idea in this method was that "counties with a large fraction of cropland should provide a better reading on price determination". Other aspects such as cities or forests were not considered in this study. For the second group of regressions, crop-revenue weights were used. This approach emphasized "the aggregate value of crop revenue in each county". They found that under cropland weights the value of land suffered a considerable loss. This is because a warm climate is not attractive for agriculture. When they considered crop-revenue weights, they found that the net impact of climate warming is positive. An important insight from this paper is that depending on the variable considered to study the impact of climate change in agricultural sector, different conclusions can be obtained. In some cases the implications can be positive and in others cases they can be negative.

In sum, the findings from the literature on the regional implication of climate change on water resource and agricultural sectors are consistent. In scenarios where the temperature increases and the precipitation level decreases water resources are negatively affected. This tendency is exacerbated under extreme climate change scenarios. Another interesting finding is that changes in temperature and precipitation have an ambiguous effect on farm resources and profits. Depending on the characteristics of a given region, water use may rise while in others areas it may fall.

2.2 AGGREGATION

Because the study of climate change normally requires coarse data resolution, the level of data aggregation is not a minor issue to be considered. This section reviews the literature related to the aggregation problem.

A pioneering empirical study about the aggregation problem was developed by Grunfeld and Griliches (1960). They reported and analyzed two econometric results to compare the goodness of fit of micro and macro data. In the first study, the authors used the sum of expenditures on plant and equipment, and maintenance and repairs as a dependent variable. The stock of plant and equipment and the market value of firms, both at the beginning of the year, were the independent variables in a least-squares regression model. The data of eight large firms from 1935 to 1954 were used in this paper. The research compared “the multiple coefficients of determination (R^2)” found for each of the eight firms with the aggregate coefficient of determination obtained by combining (aggregating) the data from all eight firms. In this particular study, Grunfeld and Griliches (1960) found that to explain aggregate investment behavior, the results obtained from aggregating the variables and then computing the regression were better than the results computed from aggregating the results from individual firm regressions.

In the second part of the paper, the authors estimated a demand function where the annual consumption of fertilizer was the dependent variable while the “real” price of fertilizer (the price paid per plant nutrient unit divided by an index of prices received for crops) and lagged fertilizer consumption were the independent variables. The authors estimated a log-linear fertilizer demand function for the nine Census regions (New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, and Pacific) during 1932-56. The coefficients of multiple determinations in each of the nine regions were compared with two “composite” aggregate coefficients. Because the micro-equations were not linear, the authors aggregated the data in two ways. First, they aggregated the variables linearly and then took the logarithms of the sums. The second method of aggregation used in the paper was adding the logarithms of all the variables and using the sum of these as macro variables. For this part of the paper, the authors found that both the macro level and the micro level models presented very similar results. They concluded that if the objective of the research was to analyze aggregate U.S. fertilizer consumption, a disaggregate model at the regional level would not be necessary.

For both investigations mentioned above, Grunfeld and Griliches (1960) assumed that the information necessary to specify the micro level model is imperfect and sometimes incomplete. Hence, the misspecification problem is often times unavoidable. Instead of coefficient errors, they focused on the quality of prediction which they called “degree of explanation”. The tools used for this analysis were the correlation coefficient and the variance. They suggested that the macro level model would be preferred to a micro model if the specification and measurement errors were reduced by aggregating. They suggested that the most appropriate model for aggregate data could be the macro level model, especially if the micro level model is incorrectly specified. According to the case study reported in their paper, the authors concluded by saying that “aggregation is not necessarily bad if one is interested in the aggregates”.

Willmott *et al.* (1985) estimated several statistical measures to determine the predictive accuracy of geophysical models. In the set of different measures they emphasized the approaches based on the difference between the elements and values of a model predicted and observed. These measures include the root-mean-square error (RMSE), the systematic root-mean-square error (RMSEs), the unsystematic root-mean-square error (RMSEu), and the index of agreement (d2). They also presented additional indices such as the mean absolute error (MAE) and a modified version of the index of agreement (d1). The authors explained that difference or error measures are gaining relevancy in the literature compared to the correlation measure. This is because the correlation measures are inconsistent in estimating model accuracy. Willmott *et* *al.*(1985) also argued that bootstrapping can be used to evaluate both the confidence and significance associated with each of the difference indices. To demonstrate their arguments, the authors compared and evaluated two models that estimated wind velocity in the South Atlantic Bight (SAB). They showed that if the different measures mentioned above are used in combination with the correct statistics and data-display graphics, the performance of models can be accurately evaluated.

An important contribution on the analysis of aggregation problem, specifically on the prediction problem, was developed by Pesaran *et al.* (1989). They presented a specific test of consistent aggregation that compared macro and micro models under the assumption that the micro model is correctly specified. The method used by the authors to discriminate between models at different levels of aggregation was based on minimizing the variance of predicting the aggregate dependent variable. Specifically, the authors estimated disaggregate and aggregate employment demand functions for the UK economy from 1956 to 1984. The data set considered for their research was from the Cambridge Growth Project Databank. The estimations were developed for two different levels of aggregation: aggregation over 23 manufacturing industries and aggregation over all 40 industries of the economy. The specifications used were log-linear dynamic functions where the dependent variable was the log of the man-hours employed for each industry, and the independent variables were the time trend, the log of output of each industry, and the log of average real wage rate per man-hour employed for each industry. For the aggregate employment functions the authors used the sum of the logarithms of industry employment instead of the logarithm of the sum of industry employment usually used for this type of specification.

The authors compared the goodness-of-fit of both micro and macro equations. The estimations for the whole economy (40 industries) showed that the disaggregate model had a slightly better fit than the aggregate model, while the results for the 23 manufacturing industries suggested a better performance of the aggregate model. The different predictions of the aggregate dependent variable provided by the models can arise from two different sources: an error in the macro equation or a misspecification in the micro equation. Since the authors assumed that the micro model was correctly specified, the error in the macro equation was considered to be the source of the problem. The authors showed that the aggregate and disaggregate models would give the same prediction of the aggregate dependent variables in absence of aggregation bias.

Park and Garcia (1994) evaluated the appropriate level of aggregation to estimate acreage response models in agricultural economics. They evaluated the advantages and disadvantages of using aggregate data versus disaggregate data in a linear econometric model. The analysis was focused on the performance of the aggregate dependent variable. The authors made the comparisons by modeling acreage response at the state level and sub-state (or crop reporting district level) of Illinois for corn and soybeans acreages. For the sub-state level, they estimated equations for nine crop reporting districts using data from 1960 to 1988. The dependent variable used in the state and sub-state equations was the harvested acreage of corn and soybeans while the independent variables varied for each crop. For the corn acreage equations the independent variables were the relative conditional expected price of corn, relative futures price of soybeans, effective diversion payment for corn, income risk, and a dummy variable for the 1983 PIK program. On the other hand, for the soybean acreage equations the explanatory variables were the relative conditional expected price of corn and the relative future price of soybeans. The estimation technique used in their research was a system of seemingly unrelated regression (SUR). To make the results comparable, the aggregate explanatory variables were constructed adding the crop reporting district level at the state level so a direct comparison of coefficients across levels of aggregation was possible.

Park and Garcia (1994) found that the difference between acreage response at the state level and district level was minimal. Both the state level equations and the district level equation fit relatively well, but they found some unexpected signs on the estimated coefficients in the district level estimation. Thus the state level model produced coefficients that were more consistent with the expected signs. In addition, they used Zellner's F-test and Pesaran, Pierse, and Kumar's test, to test for aggregation errors in the state level equations. They also used Ramsey's RESET test to check for misspecification error in the crop reporting district equations. The tests for aggregation errors suggested that the state-level acreage equations were subject to aggregation bias while the tests employed to check for misspecification errors found this problem in the soybean equations but not in corn equations. They conclude the analyses suggesting that both aggregate and disaggregate models are subject to problems and their individual use would depend on the research purpose.

Wu and Adams (2002) estimated and compared eight statistical models using data from two different sources. They obtained data from the National Resources Inventory and also from the United State Department of Agriculture's (USDA's) National Agricultural Statistics Service (NASS). The study area was the Corn Belt (Iowa, Illinois, Indiana, Ohio, and Missouri). The eight models compared in their research have different levels of data aggregation. They divided the models by data source and by region. Five models were estimated and compared using data from the National Resources Inventory. The aggregation levels of the data in these five models were as follows: field, county, state and regional levels. The three remaining models were estimated using the National Agricultural Statistics Service (NASS) data, and the levels of aggregations considered were: county, state and regional levels. These data are the most similar to that used in this dissertation. Wu and Adams (2002) used county crop acreage (corn and soybeans) data to estimate a model at the county level of aggregation. The data for the state and regional models were constructed by aggregating the county level data to the state level and then to the regional or multi-state level. The results of the models estimated with county and state level data were aggregated to the regional or multi-state level for comparison purposes. The statistical measures used to evaluate the models were the root-mean-square error (RMSE) and the Theil's *U*-statistic. In addition to these two measures, they used the statistical properties of the parameters estimated and their corresponding elasticities to evaluate the models.

For the three models estimated using the NASS data and considering the Theil's *U*-statistic and the RMSE results, Wu and Adams (2002) found that the county model fit better than the state model, but the regional model performed better than the others. The regional or multi-state model performed better than models using disaggregate NASS data as well as in those estimated using NRI data. Regarding the statistical properties of the explanatory variables of each model, they found that models estimated with the most disaggregate data present more statistically significant variables. In agreement with Grunfeld and Griliches (1960), Wu and Adams (2002) concluded that depending on the research focus, "aggregation is not necessarily bad", and that the error-minimizing level of aggregation would depend on the type of crops.

Antle *et al.* (2007) developed a study analyzing soil carbon sequestration in the central United States (North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Michigan, Wisconsin, Illinois, Indiana, Ohio, Oklahoma, Texas, Arkansas, Louisiana, Kentucky, Tennessee, Mississippi, Alabama). To simulate the economic model, the authors integrated the results obtained from the estimation of "econometric production models" and a "biophysical simulation model". Two important findings are relevant for this dissertation. First, they found that considering a large region, the average rate of carbon sequestration predicted by the aggregate model was very similar to the carbon rate predicted by the disaggregate model. However, they also found that the macro models did not accurately predict the carbon rate at disaggregate levels (county level). In particular, they found that average carbon rates generated large prediction errors for a small scale region. To solve this issue the authors suggested that the policy analysis should not be realized at coarse levels of aggregation.

In summary, the literature on aggregation problems suggests that the ideal level aggregation will depend on several factors. There are pros and cons in using either aggregate or disaggregate models. The tradeoff between specification or measurement error in micro models and aggregation problems in macro models normally will be an issue to think about. The final choice will be subject to the research objective, data availability, and especially the size of the geographic area under analysis.

CHAPTER 3 – MODEL, STUDY REGION AND DATA SOURCES

The goal of the first part of this dissertation is to determine the level of data aggregation that can give us the most accurate prediction of observed aggregates. To do that, a Positive Mathematical Programming (PMP) model (Howitt, 1995; Clark, 2008) is employed that is calibrated to the data at varying levels of aggregation. In the first step of this approach, the model simulates crop choices and water at three levels of data aggregation (county, crop reporting district and state aggregation). Separate versions of the model are calibrated to observed crop allocations and water use in the "base year" (the average from 2000 to 2008) in each spatial unit at each of the three levels of data aggregation. This process allows comparisons of the following approaches: (a) running a model with county-level data and aggregating the results to the state level, (b) running a model with data aggregated to the multi-county crop reporting district level and then aggregating the results to the state level and (c) running the models on state-level aggregate data.

Comparing the results and analyzing their prediction errors for the individual observed years within the calibration base period (2000-08) allows us to test for aggregation bias. The proposed measures that this study uses to evaluate which of the simulation models better fits the actual data are the root-mean-square simulation error and root mean squared percent simulation error.

Once I determine the appropriate level of data aggregation for our research, a separate version of the model will be calibrated to the observed crop allocation and water use at the chosen aggregation level for the base year (average from 2000 to 2008). Then, combinations of two water conservation policies scenarios and two climate scenarios are simulated over a 50-year time horizon and these are compared with a status-quo scenario. The status-quo scenario represents the current situation without any exogenous constraints. The two conservation policies chosen for this study are: the Water Use Restriction policy, specifically defined as a mandatory annual or multi-year limit that reduces the amount of water pumped, and a Voluntary Permanent Conversion to Non-Irrigated Production policy.

To simulate the potential impacts of climate change, I use scenarios reported in the 2007 Intergovernmental Panel on Climate Change, Fourth Assessment Report (AR-4)[1]. The model is exercised over different climate scenarios, higher temperatures and lower precipitation levels, to project the trends in water use, crop acreages, and irrigated crop income.

First, each policy scenario is compared with the status-quo scenario to isolate the impact of each policy. Second, climate change scenarios are compared with the status-quo scenario that assumes climate change does not exist; this comparison reveals the possible impact of climate change on groundwater resources. Finally, the third category of comparisons interacts the two policy scenarios and the status-quo scenario with climate change. The purpose of the last category of comparison is to analyze the way that climate change alters the impacts of the conservation policies.

3.1 ANNUAL DECISION MODEL

[1] Details about the scenarios are found in the Study Region (3.6) and Data section (3.7).

The model chosen for this research is the PMP model developed by Clark (2008) for irrigated agriculture in western Kansas. The model in Clark (2008) predicts land and water allocation for eight crops (irrigated wheat, non-irrigated wheat, irrigated corn, non-irrigated corn, irrigated sorghum, non-irrigated sorghum, irrigated soybean, and irrigated alfalfa).

The land and water allocation problem is represented by the following expected profit maximization problem[2]:

$$max \sum_i P_i \, Y_i(w_i) x_i - C_i\big(w_i, x_i; \alpha_i, \gamma_{i,} \delta_i\big) x_i \qquad (3.1)$$

s.t. $\sum_i x_i \leq X$

where X = size of the farm,

$Y_i(w_i)$ = production function for crop i,

P_i= expected output price for crop i,

x_i= land area planted to crop i,

w_i = irrigation water use on crop i,

$C_i\big(w_i, x_i; \alpha_i, \gamma_{i,} \delta_i\big)$ = cost function for crop i, and

$\alpha_i, \gamma_{i,} \delta_i$ = parameters of the cost function.

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[2] More details of the model can be found in Clark (2008).

A core element of the optimization model in this dissertation is a set of water response functions, which predict the yield of various crops as a function of water use and weather variables. These functions are specified following the nonlinear plateau form derived from biophysical relationships by Martin *et al.* (1984). This production function has two important characteristics that matter for my research. First, it has properties that are consistent with agronomic and hydrologic principles. Second, it includes a flexible water response function that allows me to model climate change scenarios.

Following Martin *et al.* (1984) the production function can be expressed as:

$$Y_i(w_i) = DY_i + (FWY_i - DY_i)\left[1 - \left(1 - \frac{w_i}{GIR_i}\right)\right]^{\frac{1}{WUE}} \qquad (3.2)$$

where WUE ∈ (0, 1) = water use efficiency or irrigation application efficiency,

DY_i = lower bound of dry-land yield for crop *i*,

FWY_i = upper bound of fully watered yield for crop *i*,

GIR_i = gross irrigation requirement for crop *i*.

The first derivative with respect to water gives us the marginal product of the function written as:

$$\frac{\partial Y_i}{\partial w_i} = \frac{(FWY_i - DY_i)}{WUE * GIR_i} * \left(1 - \frac{w_i}{GIR_i}\right)^{\frac{1-WUE}{WUE}} \qquad (3.3)$$

where $Y_i(w_{i0}) = Y_{i0}$ $\qquad i = 1, \dots, I$ (3.4)

The cost function is linear in both land allocations and water use, and it is specified considering both the PMP literature and the groundwater literature. It can be expressed as follows:

$$C_i(w_i, x_i; \alpha_i, \gamma_i, \delta_i) = (w_i - w_{i0})\delta_i + \alpha_i + \left({}^1\!/_2\right)\gamma_i x_i, \qquad (3.5)$$

where w_{i0} is a base level of water use. When $w_i = w_{i0}$ we get the following equation:

$$C_i(w_{i0}, x_i; \alpha_i, \gamma_i, \delta_i) = \alpha_i + \left({}^1\!/_2\right)\gamma_i x_i \qquad (3.6)$$

The above functional forms are structured to solve the calibration problem as described in the next section. The term $(w_i - w_{i0})\delta_i$ captures the increase in costs due to water use in excess of the base period amounts.

Plugging equation (11) into (7) we get the following Lagrangian function:

$$\mathcal{L} = \sum_i P_i\, Y_i(w_i)x_i - \left[(w_i - w_{i0})\delta_i + \alpha_i + \left({}^1\!/_2\right)\gamma_i x_i\right]x_i - \lambda \sum_i x_i, \qquad (3.7)$$

where λ is the Lagrange multiplier. Taking derivatives with respect to land and water gives the following first order conditions,

$$x_i\colon P_i Y_i(w_i) - \left(w_i - w_{i,0}\right)\delta_i - \alpha_i - \gamma_i x_i - \lambda = 0, \qquad \forall i \qquad (3.8)$$

$$w_i\colon P_i Y_i'(w_i)x_i - \delta_i x_i = 0, \qquad \forall i \qquad (3.9)$$

3.2 MODEL CALIBRATION

In the PMP method, the unknown parameters in the objective function are calibrated to observed data on water and land use, ensuring that the model solutions fall within a small tolerance of observed patterns. This calibration procedure is in contrast to traditional approaches, in which arbitrary constraints are added to limit crop acreages or water use to a band around observed values. Such approaches reduce the flexibility of the model to predict changes in cropping patterns arising from exogenous shocks in weather and/or prices (Howitt, 1995). The self-calibration feature of PMP has made it a popular approach for policy modeling. The cost parameters $(\alpha_i, \gamma_i, \delta_i)$ also are obtained from the calibration process and represent part of the necessary input for the simulation.

In a properly calibrated model, the observed land allocations, $x_0 = (x_{10}, \dots x_{I0})$, and water levels used to irrigate crops, $w_0 = \ (w_{10}, \dots, w_{I0})$, must be equal to the solution of the first order condition of the previous section represented by equations (3.8) and (3.9). Following the same logic, the observed cost per acre of each crop, C_{i0}, must be equal to the per-acre cost function for each crop evaluated at x_{i0} and w_{i0}. This relationship can be expressed as:

$$C_i(w_{i0}, x_{i0};\ \alpha_i, \gamma_i, \delta_i) = \ C_{i0} \qquad (3.10)$$

These conditions form the basis to calculate the cost parameters. To do so, a modified version of the optimization problem in (3.1) is created where the observed production and costs, $Y_{i,0}$ and C_{i0}, replace the production and cost functions, respectively, and a calibration constraint is added for each crop:

$$\max_{\{x_i\}} \sum_i P_i Y_{i,0} x_i - C_{i,0} x_i \quad (3.11)$$

s.t. $\sum_i x_i \leq X$ and,

$$x_i \leq x_{i,0} + \varepsilon, \qquad i = 1, \dots, I$$

where ε is a small positive scalar,

$$Y_i(w_i) = Y_{i,0}, \text{ and } C_i(w_{i0}, x_{i0};\ \alpha_i, \gamma_i, \delta_i) = C_{i0}$$

The associated Lagrangian function is:

$$\mathcal{L} = \sum_i \left[P_i Y_{i,0} x_i - C_{i,0} x_i\right] + \lambda\,[b - \sum_i x_i] + \sum_i \mu_i \left[x_{i,0} + \varepsilon - x_i\right] \quad (3.12)$$

where μ_i is the multiplier on the calibration constraint. The first order conditions are:

F.O.C.

$$x_i{:}\ P_i Y_{i,0} - C_{i,0} - \lambda - \mu_i = 0, \qquad \forall_i \quad (3.13)$$

$$\lambda{:}\ b - \sum_i x_i = 0 \quad (3.14)$$

$$\mu_i{:}\ x_{i,0} + \varepsilon - x_i = 0, \quad (3.15)$$

The Lagrangian expressed in equation (3.12) can be calculated because the parameters of interest are known. The solution to this problem will be within a small tolerance (ε) of the observed acreages x_0. To represent both the observed acreage of crop *i* and the resulting solutions the calibration problem, x_0 will be used.

Assuming that the cost function is calibrated properly, the first order condition of the farmer's problem specified in equation (3.8) will be satisfied at $x_{i,0}$ and $w_{i,0}$. Since $f_i(w_{i,0}) = Y_{i,0}$, equation (3.8) is transformed to:

$$\alpha_i + \gamma_i x_{i,0} = P_i Y_{i,0} - \lambda \qquad (3.16)$$

Rearranging equation (19) gives:

$$C_{i,0} + \mu_i = P_i Y_{i,0} - \lambda \qquad (3.17)$$

Plugging equation (23) into equation (22), we obtain:

$$\alpha_i + \gamma_i x_{i,0} = C_{i,0} + \mu_i \qquad (3.18)$$

Assuming that the per-acre cost function is calibrated appropriately, it must be equal to the actual cost, $C_{i,0}$ evaluated at $x_{i,0}$ and $w_{i,0}$. Under this assumption, equation (3.6) is expressed as:

$$\alpha_i + \frac{1}{2}\gamma_i x_{i,0} = C_{i,0} \qquad (3.19)$$

Solving system of equations (3.18) and (3.19) obtains:

$$\gamma_i = 2\mu_i / x_{i,0} \qquad (3.20)$$

$$\alpha_i = C_{i,0} - \mu_i \qquad (3.21)$$

Thus, if the calibration problem is programmed and solved in a computer to reveal the values of μ_i, these results can be combined with the observed data on costs and acreages to obtain the cost parameters α_i and γ_i. The remaining parameter, δ_i, can be obtained using equation (3.9). If the calibration process is conducted properly, equation (3.3) will hold when it is evaluated at $x_{i,0}$ and $w_{i,0}$. Plugging equation (3.3) into equation (3.9), we get:

$$\delta_i = \frac{P_i(FWY_i - DY_i)}{(WUE)(GIR_i)} \left(1 - \frac{w_{i,0}}{GIR_i}\right)^{\frac{1-WUE}{WUE}} \qquad (3.22)$$

The parameters α and γ are estimated for all crops (irrigated and non-irrigated crop), while the parameter δ is estimated for irrigated crops only.

3.3 DYNAMIC SIMULATION MODELS

Once the parameters are obtained from the calibration exercise, the simulation process begins. In this step, new constraints are incorporated in the annual decision problem represented in equation (3.1). These constraints are related to water availability over time. The model simulated for a period of t = 1… 50 years can be represented as follows:

$$\max \sum_i P_i Y_i \left(w_{i,t}\right) x_{i,t} - \left[C_i\left(w_{i,t}, x_{i,t}; \hat{\alpha}_i, \hat{\gamma}_i, \hat{\delta}_i\right) + k_t w_{i,t}\right] x_{i,t}$$

$$\text{s.t.} \sum_{i=1}^{I} x_{i,t} \leq X$$

$$\sum_{i \in Q} x_{i,t} \leq X_a \qquad (3.23)$$

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

where Q = set of indices of irrigated crops,

m_t = maximum irrigation pumping given aquifer conditions and legally authorized water use in year t

X_a = legally authorized irrigated acreage,

k_t = extra cost of pumping per year,

$P_{i,t}$ = expected output price per crop and per year.

$\hat{\alpha}_i, \hat{\gamma}_i, \hat{\delta}_i$ = cost parameters obtained from the calibration process,

In the simulation model, a new term represented by $k_t w_{i,t}$ is incorporated to account for pumping costs. This term must have an inverse relationship with the aquifer level. Also, two new constraints are added to indicate that the number of irrigated acres is legally limited and that water use in each period is constrained by aquifer levels at that time.

Additionally, a number of equations of motion are used to update the hydrologic situation over time. The actual aquifer conditions in each period will determine the pumping cost (k_t) and the maximum water pumping level.

An important equation in the updating process of the dynamic simulation model is related to the total water pumped from the aquifer for irrigation purposes, denoted *WPI*. An important assumption to point out is that this variable does not include water consumed for domestic, industrial, and municipal purposes which are considered constant in the model. Water pumped for irrigation in year *t* is computed as:

$$WPI_t = \sum_i x_{i,t} w_{i,t} / 12 \qquad (3.24)$$

Because the right hand side of the equation is measured in acre-inches, it must be divided by 12 to convert the expression to acre-feet.

WPI is closely related to the rate of depletion of the aquifer. Gisser and Sanchez (1980) developed the following equation to compute depletion:

$$Depletion_t = \frac{WPI_t}{S*(LA)} - \frac{R_t}{12S} \qquad (3.25)$$

where $Depletion_t$ is the distance by which the water table falls during year t (in feet), S represents the aquifer's specific yield, *LA* represents the land area above the aquifer measured in acres, and R_t is the aquifer rate of recharge measured in inches/year. Depletion, in turn, determines the change in saturated thickness (*ST*) and pumping lift (*Lift*). The aquifer's saturated thickness (*ST*) is the difference between the saturated thickness of the previous year and the amount of depletion during year *t*:

$$ST_t = ST_{t-1} - Depletion_t \qquad (3.26)$$

Because there is a one-to-one relationship between the saturated thickness of the aquifer and the pumping lift (distance from the land surface to the water table, also known as depth to water), depletion can be related to the change in lift in the same manner:

$$Lift_t = Lift_{t-1} + Depletion_t \qquad (3.27)$$

The final equation of motion that is included in the simulation process is related to the well pumping capacity. This equation shows the amount of water that could be pumped per unit of time given a specific level of saturated thickness. It represents the water availability constraint. This relationship was developed by Golden *et al.* (2008) for the western Kansas region:

$$GPM_t = -488.93 + 3.68 * HC + 8.75 * ST_t + 0.05 * ST_t^2 \qquad (3.28)$$

where *GPM* represents the well capacity that is measured as gallons pumped per minute and *HC* represents the hydraulic conductivity measured in feet per day.

The maximum allowable water application can be determined from equation (3.28). This equation is a conversion of the GPM_t value. It is transformed from gallons pumped per minute to the maximum amount of water that can be used for irrigation over an irrigation season on a given sized field, m_t:

$$m_t = \frac{(GPM_t * 60 * 24 * Days)}{(7.48 * 43560 * Acres)} \tag{3.29}$$

Days is the duration of the irrigation season in days, and *Acres* is the representative size of a field irrigated from a single well. The *Days* value will vary between counties, and the *Acres* value assumed in this dissertation is 126 acres for each county. This value is representative of the size of an irrigated field in western Kansas.

To calculate the marginal cost of pumping, the updated value of $Lift_t$ is needed. The formula that will be used comes from irrigation engineering (Rogers, 1999):

$$MC_t = \frac{0.114 * FP * (PH + Lift_t)}{EF} \tag{3.30}$$

where *FP* is fuel price of natural gas, *PH* represents the Pumping Head measured in feet, and *EF* represents the energy efficiency of natural gas. The value of the pumping cost (k_t) expressed in equation (29) is computed from the result of (36) as:

$$k_t = MC_t - MC_0 \tag{3.31}$$

3.4 CONSERVATION POLICIES SCENARIOS

The two conservation policies chosen for this dissertation are: the Water Use Restriction policy, specifically defined as a mandatory annual or multi-year limit that reduces the amount of water pumped, and a Voluntary Permanent Conversion to Non-Irrigated Production policy.

The objective of the Water Use Restriction policy is to reduce the amount of water pumped for irrigation from each well. This policy can be implemented by changing the value of maximum irrigation pumping given aquifer conditions and legally authorized, represented by m_t in equation (3.23). This restriction represents the upper bound on water use for agricultural irrigation.

The Voluntary Permanent Conversion to Non-Irrigated Production is a long- run policy which consists of an incentive-based program where landholders receive compensation if they produce non-irrigated crops instead of irrigated crops. To model this policy, it is necessary to modify the value of X_a in equation (3.23) which represents the legally authorized irrigated acres.

3.5 CLIMATE CHANGE SCENARIOS

As mentioned before, the possible direct effect of climate change on groundwater comes from changes in temperatures and changes in precipitation patterns. These factors will reduce the rate of aquifer recharge, reducing the level of water availability over time. First, to model climate change scenarios, the aquifer rate of recharge is specified as a function of time (Golden, 2008). The recharge equation can be written as:

$$R_t = R_0\left[1 - \beta\left({}^{t}/_{T}\right)\right] \quad (3.31)$$

where β represents the proportional change in recharge from the beginning to the end of the simulation period.[3]

From previous equations we can observe that a reduction in the rate of recharge would accelerate aquifer depletion and would subsequently affect the saturated thickness. From several studies it is well known that the saturated thickness affects well capacity and crop decisions.

The second aspect that should be considered to model climate change scenarios is the implications on the production function that come from changes in mean temperature. Water use efficiency (WUE), which represents the irrigation efficiency of fully watered yield, can be defined as the ratio between the net irrigation requirement and the gross irrigation requirement:

$$WUE = \frac{NIR}{GIR} \qquad (3.33)$$

The Net Irrigation Requirement is a function of the evapo-transpiration requirements for a fully water yield. The relationship between yield and evapo-transpiration for crops grown in the Great Plains is assumed to be linear (Martin, *el.*,1984). Evapo-transpiration (ET) represents the sum of evaporation and plant transpiration. The Net Irrigation Requirement can be defined as:

$$NIR_{i,t} = ET_{FWY_i} - GSP_t * EP - \Delta SM \qquad (3.34)$$

where *GSP* represents precipitation in the growing season considered available for crop

[3] The value of β is obtained from Hall *et al.,* (2008)

production. ET_{FWY} represents the evapo-transpiration requirement of a fully water crop. EP represents the effective precipitation and it is defined in the National Engineering Handbook as "the part of rainfall that can be used to meet the evapo-transpiration of growing crops." The difference in soil moisture between planting and harvesting is represented by ΔSM.

In order to model the effects of change in temperature in the net irrigation requirement, the dynamic equation is redefined as:

$$NIR_{i,t} = \left(ET_{FWY} + \lambda_i * \Delta Temp * \frac{t}{T}\right) - \left(GSP_0 + \Delta GSP * \frac{t}{T}\right) * EP - \Delta SM \quad (3.35)$$

where λ is the parameter that captures the impact temperature change ($\Delta Temp$)will have on ET_{FWY} . This parameter, λ, is estimated by an OLS regression of evapo-transpiration on temperature. The change in growing season precipitation due to climate change is captured in ΔGSP.

The changes in the net irrigation requirement will affect the gross irrigation requirement. By (39), this effect can be calculated by:

$$GIR_{i,t} = \frac{NIR_{i,t}}{WUE} \quad (3.36)$$

The production function expressed in equation (3.2) is transformed to a dynamic production function:

$$Y_{i,t}(w_{i,t}) = DY_{i,t} + (FWY_i - DY_{i,t})\left[1 - \left(1 - \frac{w_{i,t}}{GIR_{i,t}}\right)\right]^{\frac{1}{WUE}} \quad (3.37)$$

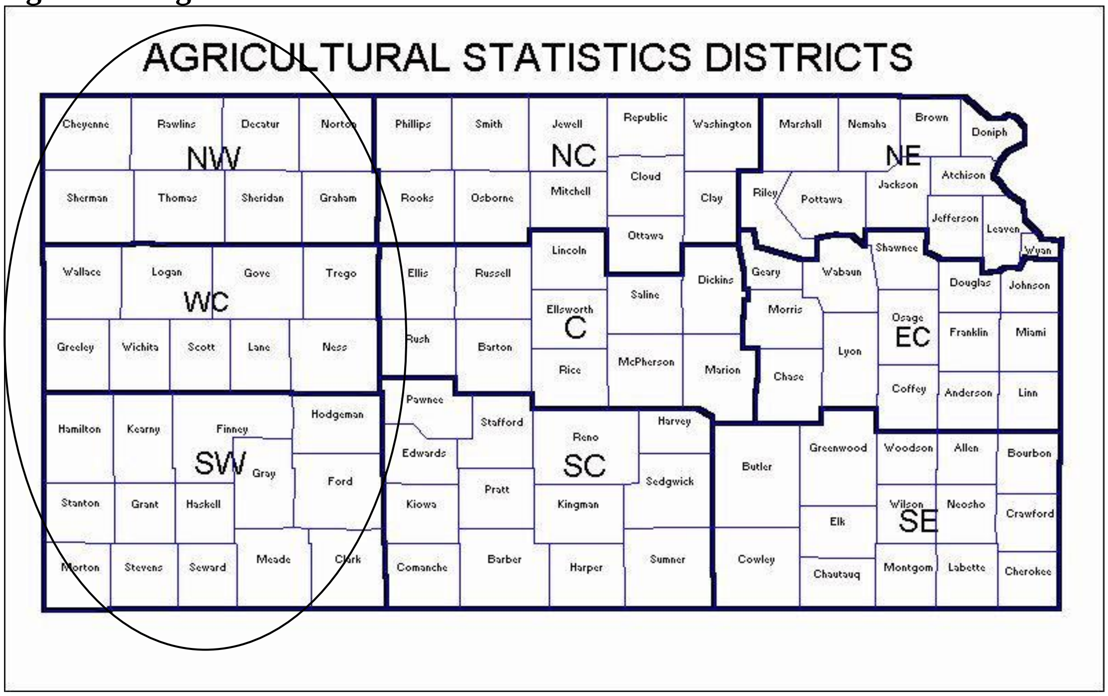
where $Y_{i,t}(w_{i,t})$, changes from year to year through the changes in $GIR_{i,t}$.

3.6 STUDY REGION

This study focus on the American High Plains, one of the most important water-scarce agricultural regions in North America. The region overlies the Ogallala aquifer, spanning portions of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. It underlies 111.6 million acres. The Ogallala aquifer contributes to the development of agricultural industries in the High Plains including irrigated crops, cattle feeding, and meat processing. After reliable technology to withdraw groundwater for irrigation became available, and considering the profitability of irrigated crops, planted areas of irrigated crops grew rapidly in the mid-Twentieth century. Given the low rate of natural recharge to the aquifer, the natural consequence of this expanded irrigation has been a steady decline of its water volume over the past several decades (Peterson and Ding, 2005). Historically, the portion of the aquifer in Kansas has experienced one of the highest levels of depletion. For instance, the area-weighted average water-level declined 14.0 feet in the U.S. from 1950 to 2007, while for the same period of time the water level change in Kansas was 22.7 feet (McGuire, 2009).

The study region for this dissertation is a 31-county area overlying the Ogallala aquifer in western Kansas. This region encompasses approximately the western third of Kansas. Following the boundaries of the USDA-NASS crop reporting districts, this region can be subdivided into three multicounty areas (including the northwest, west central, and southwestern Kansas crop reporting districts). These boundaries yield the intermediate “district” level of aggregation. The study region can be observed in the figure 4.

Figure 3.1. Agricultural Statistics Districts



Source: KASS

The study region lies in the central portion of the High Plains and reflects the variation in water availability across the aquifer. Across these counties, the estimated remaining usable lifetime ranges from 50 to over 200 years (KGS), representing the range of irrigated area available over the aquifer.

3.7 DATA SOURCES

This research uses county- level data from a variety of public sources. Crop acres and yields from 2002 to 2008, for the thirty-one counties located in the northwest, west-central and southwest crop reporting districts of Kansas, are from the National Agriculture Statistics Service (NASS). The base period for the calibration and simulation models is calculated as the average of the nine-year period 2000-08.

The data for cropping patterns (Table 3.1) was taken from the National Agriculture Statistics Service (NASS) website. The average over this nine year period was computed as the base values.

Tabla 3.1. Crop Production Parmeters

Parameter	Wheat		Corn		Sorghum		Soybeans	Alfalfa
	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Irrigated
Price								
Baseline Scenario	4.89	4.89	3.63	3.63	3.23	3.23	7.62	116.65
Yield (Average)								
Northwest	46.48	31.36	166.20	43.73	90.56	43.03	49.22	4.33
Southwest	47.58	31.68	178.78	44.79	93.96	47.10	42.51	5.43
West Central	46.07	31.95	154.41	51.43	88.83	50.02	31.94	4.01
Acres (Total)								
Northwest	73,241.2	1,017,545.1	253,835.0	297,095.4	19,729.9	245,171.5	41,752.7	43,180.3
Southwest	352,823.6	1,265,940.3	706,426.0	125,609.4	94,052.9	1,068,854.8	91,690.6	186,207.3
West Central	80,747.3	1,125,588.8	129,202.3	164,796.0	26,651.6	413,036.0	21,394.2	21,325.0
Revenue ($/Acre)								
Northwest	227.10	153.23	602.81	158.60	292.37	138.92	374.97	504.67
Southwest	232.43	154.77	648.42	162.46	303.33	152.04	323.81	633.77
West Central	225.07	156.07	560.03	186.52	286.77	161.47	243.31	467.86
Share of Planted Cropland (%)								
Northwest	3.68	51.09	12.75	14.92	0.99	12.31	2.10	2.17
Southwest	9.07	32.53	18.15	3.23	2.42	27.47	2.36	4.78
West Central	4.07	56.77	6.52	8.31	1.34	20.83	1.08	1.08

Source: National Agricultural Statistic Service (NASS): www.usda.nass.gov

There are several important notes to make about this table. The first important observation is the different crop patterns in each region. Northwest region is a wheat dominated region; whet comprises 54.77% of crop acres. Corn is a second with 27.67%, followed by sorghum (13.3%), soybeans (2.10%) and alfalfa (2.17%). It is also important to notice that all of the irrigated acres for the Northwest Kansas region encompass only 21.69% of total crop acres. Within the irrigated portion of acres, corn is the dominant crop with 59% of irrigated acreage.

Irrigated corn and alfalfa are by far the two highest gross income crops, although they only account for 15% of the total crop acres. Moreover, the two lowest gross income crops, dryland wheat and sorghum, make up 63.4% of crop acres. This is most likely due to variances in land fertility (whet and sorghum can grow on very marginal land), as well as cultural factors.

The West Central region is much less diversified than Northwest area. In fact 60.84% of West Central's total crop allocation is dedicated to wheat, although only 4.07% of that share is irrigated wheat. Overall, only 14.09% of crop acres in West Central Kansas are irrigated. Additionally, 97.84% of the total crop acres are in wheat, corn, or sorghum. The majority of that percentage (85.91%) is dryland production. The low levels of irrigation are due to that fact that West Central Kansas has very low levels of saturated thickness and annual rainfall. Therefore this region is somewhat limited to low water input crops. This makes West Central Kansas a particularly interesting county to study. Because the effects of aquifer decline may already be occurring, the climate change may have very little effect.

The Southwest region also has many distinct characteristics from Northwest and West Central Kansas. The first noticeable item is that this region is a heavily irrigated region with irrigated crops accounting for 37% of crop acres. This is expected as Southwest region has a high amount of saturated thickness, allowing many producers to take advantage of irrigation to raise higher-revenue crops. Additionally, Southwest region is a more diverse area with 7.14 of crop acres coming from soybeans and alfalfa. Like Northwest and West Central Kansas, whet is still the primary crop with 41.6% of crop acres. Irrigated corn comprises about 49.36% of the total irrigated acres. It would be expected that both corn and alfalfa are more prominent in Southwest region given the large amount of beef stockyards and dairy cattle operations in that area.

The three study region offers a different perspective on crop patterns and irrigated use. This will make for a diverse study of the effect of climate change on water use, saturated thickness and land allocation.

The aquifer level data are from the Kansas Geological Survey (Table 3.2). The variables from the KGS are lift, saturated thickness, and specific yield, land area above aquifer, hydraulic conductivity, and the annual recharge rate. The source for the number of wells is the Water Information Management and Analysis System (WIMAS).

Table 3.2. Hydrological Parameters

Parameter	Unit	Symbol	Northwest Range		Southwest Range		West Central Range	
			Max	Min	Max	Min	Max	Min
Base Lift pdt *(a)	feet	Lift	152	101	292	50	166	87
Base Saturated Thickness in ft *(a)	feet	ST	143	49	322	29	98	41
Specific Yield *(a)	--	s	0.1799	0.147	0.205	0.133	0.193	0.123
Land Area Above Aquifer (acres) *(a)	acres	A	687962	423495	739419	246248	495920	123902
Hydrolic Conductivity (ft/day) * (a)	feet/day	HC	87.32	42.46	99.81	47	90.2	45.54
Recharge Rate (acre inches/acre) * (a)	inches/year	R	1.07	0.5	1.33	0.5	0.8	0.5
Depth * (a)	feet	D	152.48	100.685	292.355	50.385	3535.23	87.02
Wells *(1) (b)	--	--	885	193	1811	53	886	124
Required Minimum Saturated Thickness	feet	Stimin	30	30	30	30	30	30

*See county level data in appendix 1a, 1b, and 1c
Source: a) Kansas Geological Survey Section Level Database (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: Ab = Wo/ ((s*D) + (R/12)) where Wo is total water use.

Here again it is important to notice the differences and similarities between the three study region. A very important point is that it is used range of data. Since each region has several counties, the table above shows the minimum and maximum range for each variable per region.

As explained previously, each region is composed of several counties, which allows the observation of some important characteristics. For example, in Southwest region, it is found both the county with the least lift and the county with the most lift (distance between the land surface and aquifer) are found in the Southwest region, which demonstrates the heterogeneity of counties in the region regarding water availability. This is one reason why this study uses county level data.

Regarding saturated thickness, the same characteristic can be observed in Southwest Kansas, where the counties with the highest and lowest levels are found. The Northwest Kansas region is the one with the most uniform levels of lift: the range between the maximum and the minimum level is 51 feet, and it also has the highest minimum saturated thickness level (49 feet). As for the rate of recharge, the low occurs in West Central Kansas, largely because rainfall levels are lower in that region than the other two. Northwest Kansas could be considered an average region in terms of aquifer statistics.

West Central Kansas is a very distinct region in terms of water resources. This region has on average the lowest levels of saturated thickness: the maximum level reached in some counties is 98 feet, while there are counties that measure only 41 feet. It should be noted that the minimum level of saturated thickness required for irrigation operations is 30 feet. This indicates that the irrigation potential of this region is very limited. Another important factor is the low rate of aquifer recharge. Interestingly the number of wells is fairly high in relation to the supply of groundwater. This region has a promising level of lift which makes it very attractive for irrigation .These features make this region an interesting case study.

Finally, the Southwest region of Kansas, the area with the highest average level of water in the aquifer, and at the same time a high level of aquifer recharge and a high level of hydraulic conductivity. Because of all the aforementioned features, irrigated crops are the most common in this region. Given the high level of groundwater, although the effects of climate change might stimulate more demand that could be met in the short and medium term, in the long run this region could be the one that suffers the greatest impact for failing to ration water.

Crop prices and the costs variables are from Kansas State University Extension budgets. The expected values of crop prices are used in the model. Cost variables in the model are irrigation costs, fertilizer and seed costs, harvest and hauling cost, and other variable expenses Table 3.3).

Tabla 3.3. Production Cost ($/Acre) (Average)

Parameter	Wheat		Corn		Sorghum		Soybeans	Alfalfa
	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Irrigated
Irrigation								
Northwest	8.56	0.00	82.51	0.00	55.84	0.00	21.29	43.47
Southwest	8.56	0.00	82.51	0.00	55.84	0.00	21.29	43.47
West Central	8.56	0.00	82.51	0.00	55.84	0.00	21.29	43.47
Variable Expenses								
Northwest	87.99	0.00	159.22	0.00	121.56	0.00	86.69	197.80
Southwest	87.99	0.00	168.73	0.00	121.56	0.00	86.69	197.80
West Central	87.99	0.00	170.31	0.00	121.56	0.00	86.69	197.80
Fertilizer and seed								
Northwest	62.10	0.00	177.32	0.00	99.63	0.00	54.56	54.65
Southwest	62.10	0.00	178.70	0.00	99.63	0.00	54.56	54.65
West Central	62.10	0.00	158.47	0.00	99.63	0.00	54.56	54.65
Harvesting and Huling								
Northwest	17.35	0.00	15.45	0.00	22.50	0.00	23.44	55.57
Southwest	19.97	0.00	35.62	0.00	28.22	0.00	23.01	79.76
West Central	19.35	0.00	40.13	0.00	26.80	0.00	20.37	57.55

Source: Kansas State University Extension Budgets

Another important group of data is the agronomic data, which are obtained from several sources. Agronomic variables required for the model include actual irrigation water use, irrigation required for fully watered yield, precipitation levels, gross and net irrigation requirements, fully watered yield, and dry land yield. These data were obtained from the Water

Information Management and Analysis System, NOAA National climatic Data Center, Kansas Weather Data Library, The National Engineering Handbook, Stone *et al.(2006)*; and O'Brien *et al.* (2008) (Table 3.4).

Table 3.4. Agronomic Data

Parameter	Alfalfa Irrigated	Corn Irrigated	Sorghum Irrigated	Soybeans Irrigated	Wheat Irrigated
Water Use (acre inches/acre) (a)					
Northwest	13.80	14.63	9.90	13.43	7.56
Southwest	16.67	16.93	10.77	15.07	8.37
West Central	14.36	13.69	9.13	11.20	7.11
ET Required for FWY (b)					
Northwest	28.00	24.51	20.40	23.74	15.19
Southwest	29.09	25.95	20.40	23.89	15.96
West Central	31.38	24.64	20.40	23.70	15.00
Growing Season Precip (inches) (c)					
Northwest	17.07	14.07	12.05	14.07	8.61
Southwest	16.07	12.83	11.18	12.83	8.90
West Central	16.44	13.25	11.56	13.25	9.03
Gross Irrigation Requirement (inches/acre) (d)					
Northwest	16.39	15.58	11.82	14.33	8.81
Southwest	19.27	18.59	12.79	16.09	9.87
West Central	21.21	16.04	12.30	14.72	8.11
Net Irritation Requirement (inches/acre) (d)					
Northwest	11.98	11.13	8.80	10.36	6.61
Southwest	13.94	13.66	9.56	11.61	7.13
West Central	15.91	11.99	9.23	11.04	6.05
Fully Watered Yield (FWY) (e)					
Northwest	5,69 (bu/acre)	177,50 (bu/acre)	103,43 (bu/acre)	53,55 (bu/acre)	50,19 (bu/acre)
Southwest	7,10 (bu/acre)	198,16 (bu/acre)	107,95 (bu/acre)	46,40 (bu/acre)	51,93 (bu/acre)
West Central	6,84 (bu/acre)	180,46 (bu/acre)	110,28 (bu/acre)	47,77 (bu/acre)	49,58 (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. allNote: 1)The variable "Total Water Use" is derived from the formula W0,i = WaUi*Acresiwhere Wo,i is the water use by crop, WaUi is Water Use per crop, and Acersi is acres by crop2) Net Irrigation Requirement (NIR) is calculated from the formula: ET0-(EP*GSP0)-CSMwhere ET0 is base ET required for FWY, EP is Effectiveness of Precipitation, GSP0 is base growing season precipitation, and CSM is change in soild moisture3) Gross Irrigation Requirement is calculate from the formula: NIR/IE, where IE is season long irrigation efficiency (.75 for this study)

Among the three regions, the one where more irrigated acre inches per acre are used for alfalfa, corn, sorghum, soybeans and wheat is the Southwest. This is in part because the region receives the least growing season precipitation. Additionally, it has the highest ET requirement for fully watered yield for all crops except for alfalfa. This region has the greatest water supply of all three study areas.

As for the other regions, variations between different crops can be observed. For example Northwest Kansas has the lowest water use for irrigated alfalfa, but the second lowest for all other crops. Additionally this region has the lowest Gross and Net Irrigation Requirement for almost all crops; the only one for which it is second is for irrigated wheat, although by very little. At the same time, Northwest Kansas has the highest level of Growing Season Precipitation for almost all crops except for irrigated wheat.

Climate change scenarios reported by the Intergovernmental Panel on Climate Change (IPCC) (Fourth Assessment Report (AR-4), Working Group II, Chapter 2) will be used. Specifically, the trends in temperature and precipitation of different seasons calculated for 32 world regions based on the coupled atmosphere-ocean general circulation model (AOGCM), and the Pre-Third Assessment Report (TAR) projections will be used. The emissions scenario considered in the previous models is named A2 (Table 3.5).

Table 3.5. Crop Parameter

Variable	Descriptions	Alfalfa	Corn		Sorghum		Soybeans	Wheat	
		Irrigated	Dryland	Irrigated	Dryland	Irrigated	Irrigated	Dryland	Irrigated
b_1	Slope of Yield- ET Function (bushels/inch of water)	7.8		13.30		9.40	3.80		10.20
λ	Change in Evapotranspiration (inch of water per Fo)	0.5		0.53		0.43	0.47		0.50
EP	Effective Precipitation	0.88	0.03	0.88	0.03	0.88	0.88	0.03	0.88
Climate change Scenario									
$\Delta Temp$	Total Change in Temperature (F^0)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
ΔGSP	Total Change in Growing Season Precipitation (inch of water)	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%
β	Proportional Change in Recharge	0.20	0.20	.020	0.20	0.20	.021	0.20	0.20

CHAPTER 4 – RESULTS ANALYSIS OF SPATIAL AGREGATION

Water scarcity is already a critical issue across much of the world, and it will become an even greater concern in the semi-arid region of the eight U.S. states overlying the Ogallala aquifer. The Ogallala aquifer is one of the largest water resources in the world, underlying 111.6 million acres including portions of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming (U.S. Geological Survey, 2006). This area represents one of the most important agricultural regions in the nation.

The Ogallala aquifer contributes to the development of agricultural industries including irrigated crops, cattle feeding, and meat processing. After reliable technology became available to withdraw groundwater for irrigation in the mid Twentieth Century, the acreage of irrigated crops increased dramatically. As the Ogallala aquifer is the principal source of water for irrigation in the High Plains region, a natural consequence of a high use of this resource for irrigation is a decline of water level availability. The area-weighted average water-level declined 14.0 feet from 1950 to 2007 (McGuire, 2009). Historically, the portion of the aquifer in Kansas has experienced one of the highest levels of depletion. For instance, for the period between 1950 and 2007 the water level change in the portion of the aquifer in Kansas declined 22.7 feet.

While there is an extensive literature developing economic simulation models of irrigated land and water use (see Brouwer and Hofkes (2008) and Harou et al. (2009) for recent reviews), little attention has been paid to the appropriate level of aggregation for these models. In most cases, researchers model the representative land unit in a relatively large region. This approach ignores any spatial variability within the region, which masks distributional issues that may be important for policy and, if many of the model relationships are highly nonlinear, may increase the model's prediction error. In particular, even if one is only interested in aggregate measures at the regional scale, a more accurate prediction may be obtained by constructing many versions of the model – with each version calibrated to a distinct spatial unit—and then aggregating the results.

4.1 METHOD AND PROCEDURE

The main objective of this section is to determine the level of data aggregation that can give us the most accurate prediction of observed aggregates. To do so, an analysis of the results of a Positive Mathematical Programming (PMP) model calibrated to data at varying levels of aggregation is performed. In the first step of this approach, crop choices and water use at three level of data aggregation (county, crop reporting district and state aggregation) are simulated by a Positive Mathematical Programming (PMP) model (Howitt, 1995; Clark, 2008). A separate version of this model calibrates the observed crop allocation and water use in the base year (average from 2000 to 2008) to the three levels of data aggregation for comparison. This allows us to compare the approaches of (a) running a model with county-level data and aggregating the results to the state level, (b) running a model with data aggregated to multi-county crop reporting districts and then aggregating the results with a further step to the state level and (c) running the models on state-level aggregate data.

Comparing the results and analyzing their prediction errors for the observed years following the calibration year (2000-08), allows us to test for aggregation bias. The measures that this research uses to evaluate which of the simulation models fit better with the actual situation are the root-mean-square simulation error and root mean square percent simulation error. The preliminary results suggest that the more disaggregated the data used in the calibration and simulation processes, the model fits better with the reality.

Several measures can be calculated to assess a model's prediction accuracy. Willmott et al. (1985) mentioned different measures that can be estimated to determinate both model accuracy and precision. In the set of different measures they emphasize the approaches based in the difference between the elements and values of a model predicted and observed. These measures include the root-mean-square error (RMSE), the systematic root-mean-square error (RMSEs), the unsystematic root-mean-square error (RMSEu), and the index of agreement (d2). They also present additional indices such as the mean absolute error (MAE) and a modified version of the index of agreement (d1). They also argued that bootstrapping can be used to evaluate both the confidence and significance associated with each of the difference indices. They showed that if the difference measures mentioned above are used in combination with the correct statistics and data-display graphics the evaluation of the performance of models can be accomplished.

Let Y denote some endogenous variable of interest that is simulated by the model. This analysis calculates and reports the root-mean-square simulation error using the following formula (Pindyck and Rubinfeld, 1998):

$$rms\ error = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(Y_t^S - Y_t^a)^2} \qquad (4.1)$$

where Y_t^S = simulated value of Y_t

Y_t^a = actual value

T = number of periods in the simulation

The root-mean-square-simulation error (RMSE) measures the differences between the values predicted by a simulation model and the actual value of the studied variable. The RMSE is measured in the same units as the data, and is representative of the size of a typical error.

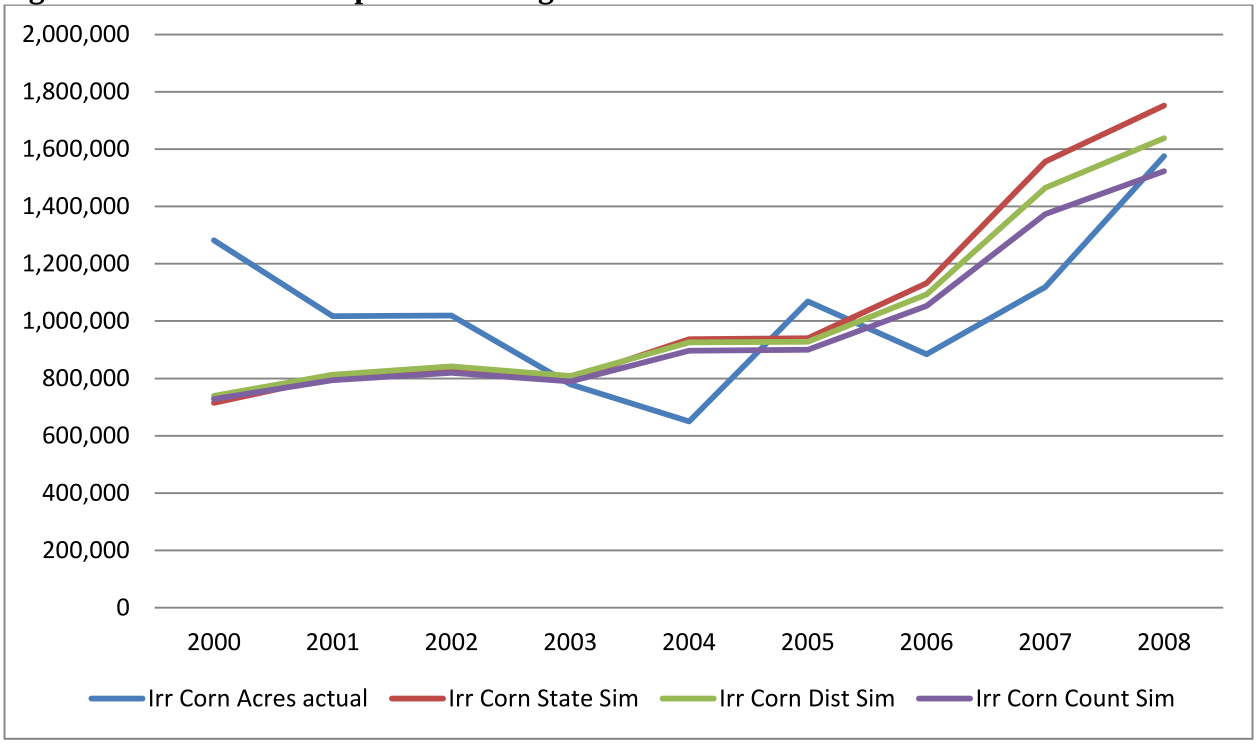
Additionally, the root-mean-square percent simulation error (RMSPE) is calculated following:

$$rms\ percent\ error = \sqrt{\frac{1}{T}\sum_{t=1}\left(\frac{Y_t^s - Y_t^a}{Y_t^a}\right)^2} \qquad (4.2)$$

The root-mean-square percent error provides the same properties as the root-mean-squares error, but expressed as percent.

The models calibrate and simulate crop allocation and water use for eight different crops. As the main objective of this section is to evaluate which of the three simulation models fits better with the actual value of the variables. In this case irrigated corn acreage is selected for comparison purposes. The following graph shows the simulation results obtained from the three models and the actual value of the irrigated corn from 2000 to 2008.

Figure 4.1. Observed and predicted irrigated corn acres western Kansas



The blue line reflects the actual value of irrigated corn acreage corresponding to the 31-county region obtained from the National Agriculture Statistics Service (NASS) for the period of 2000 to 2008. The red line represents the simulated results of irrigated corn using the most aggregated data. This model is called state level simulation. The green line reflects the result obtained from the model that used the district level aggregation. The value was obtained adding the irrigate corn acreages from each district. This model represents the first level of data aggregation and it is called district simulation model. Finally, the purple line represent the results of the third model called county level simulation. The value of this line is the summation of irrigate corn acreages obtained in the simulation for each of the thirty-one counties.

To make a more precise evaluation about the fit of three models, the root-mean-square simulation errors and root-mean-square-percent simulation error are presented in the following table.

Table 4.1: Model Prediction Errors for Region-Level Irrigated Corn Acreage, 2000-08

Model	RMSE (acres)	RMSPE (percent)
State Level Aggregation	294,911	28.37
District Level Aggregation	264,777	25.83
County Level	254,129	24.28

The root-mean-square-simulation-error (RMSE) is a measure of the differences between values predicted by a simulation model and the actual values observed from the variables modeled. It is a measure of precision. The results of RMSE presented in the above table show that the model that used the lowest level of data aggregation fits better with the actual value of the variable than the others two models. In the same sense, the district level aggregation model fits better than the state level model. These results are consistent with the second measure of precision represented by the root-mean-square percent error. Both the RMSE and the RMSPE are consistent with the expected results under the argument that the more aggregated the data, the probability of getting sample errors are higher.

4.2 SUMMARY AND CONCLUSION

The main objective of this chapter was to determinate the level of data aggregation that can give us a better fit of a simulation model to actual value of the variable studied. This chapter analyzed the data aggregation issue using a Positive Mathematical Programming (PMP) model constructed by Clark (2008). The data to calibrate and simulate the models were obtained from NASS, Kansas State Research and Extension, the Kansas Geological Survey, the Water Information Management and Analysis System, and Kansas Weather Data Library.

The models were calibrated with data aggregated to the county, crop reporting district, and region level for comparison. This allowed us to compare the approaches of running disaggregated models and then aggregating the results, and running the models on aggregate data. To analyze the results, the root-mean-square simulation error for each model was calculated. For simplicity, just the irrigate corn acreages was chosen as variable of comparison.

The results of the tests suggest that model that is simulated with most disaggregated data gives us the smallest value of the RMS simulation error, and the smallest percentage error, implying that for this specific variable (irrigated corn acreages) the data aggregation can generate a substantial difference between the values predicted by the model and the values actually observed. Consistent with this result, a graphical analysis shows that the results obtained from models run with disaggregated data follow more closely the actual value pattern of the selected crop.

CHAPTER 5 – RESULTS ANALYSIS OF WATER CONSERVATION POLICIES AND CLIMATE CHANGE SCENARIO

5.1 STATUS-QUO WITH CURRENT CONSERVATION POLICY AND CLIMATE CHANGE SCENARIO

In this chapter, the results of the two scenarios are reported and analyzed. First, the results of the base scenario are shown, which do not take into account any water conservation policy (current situation) and it is assumed that there is no climate change. Subsequently, changes are made to the levels of temperature and precipitation. These changes are reported by the Intergovernmental Panel on Climate Change (IPCC). Finally the two scenarios (Current Situation vs Climate Change) are compared in order to check the potential impacts of climate change on the studied variables (Total Water Use, Saturated Thickness, Net Returns).

5.1.1 SIMULATION UNDER STATUS-QUO SCENARIO

This section will discuss the potential impacts on the hydrological variables (total water use, saturated thickness) and the effect on net returns assuming no climate change.

5.1.1.1 TOTAL WATER USE

As previously explained, the study area is comprised of 31 counties in Western Kansas, which are put into three groups based on the USDA-NASS crop reporting districts. The three main regions are: Northwest, Southwest and West Central Kansas. The results related to the total water use in the three regions are reported in table 5.1.

Table 5.1. Total Water Use - Status Quo Scenario (Acres Feet)

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Cumulative
Northwest	433,523	434,986	435,612	428,684	418,817	412,789	21,411,312
Southwest	1,795,041	1,772,976	1,750,551	1,712,650	1,635,876	1,546,799	85,409,354
West Central	297,723	266,343	240,505	224,114	213,361	202,420	11,899,451

In the baseline scenario, total water use is projected to decline over the 50 year simulation (2009-2058) in the three study regions. The highest percentage reduction is in West Central Kansas, where the reduction from year 1 to year 50 is approximately 32%, followed by Southwest with a reduction of 14% and finally Northwest Kansas with a drop of 5%. However, since Southwest Kansas is currently the area with the greatest water supply, it is the area that suffers the biggest drop in terms of volume.

Figure 5.1. Total Water Use - West Central Kansas Status Quo Scenario

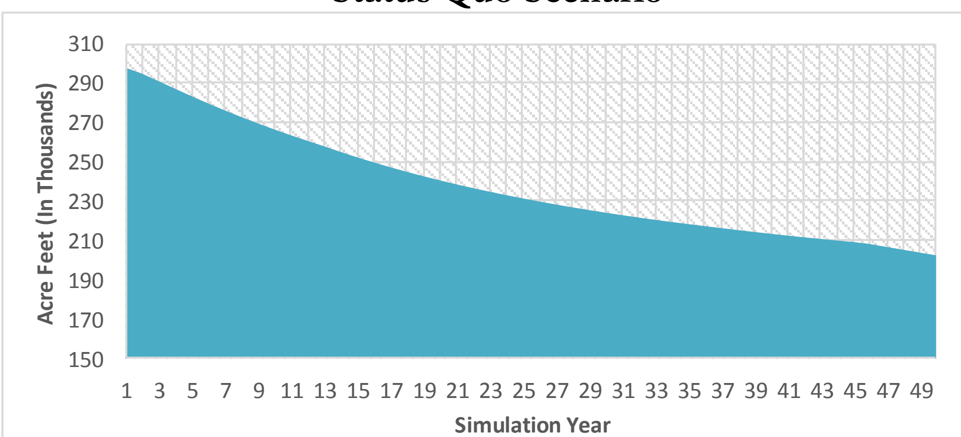


Figure 5.1 shows the trend of reduction in total water use in West Central Kansas, which starts at 298 thousand acre feet in year 1 and reaches approximately 202 thousand acre feet in year 50, for a reduction of 95 thousand acre feet during the simulation period. Furthermore, we

can see that the decrease occurs steadily throughout the period of simulation and more strongly in the 25 years.

Figure 5.2 shows the changes in total water use in the Northwest Kansas region. Unlike the West Central and Southwest regions, in this area the total water use increases during the first 20 years of the simulation, then later begins to fall slightly between the 20th and 28th years to suffer a heavy drop over the last 30 years of the simulation. The reduction in total water use in the study area was approximately 21 thousand acre feet during the 50 years of the simulation.

Figure 5.2. Total Water Use - Northwest Kansas Status Quo Scenario

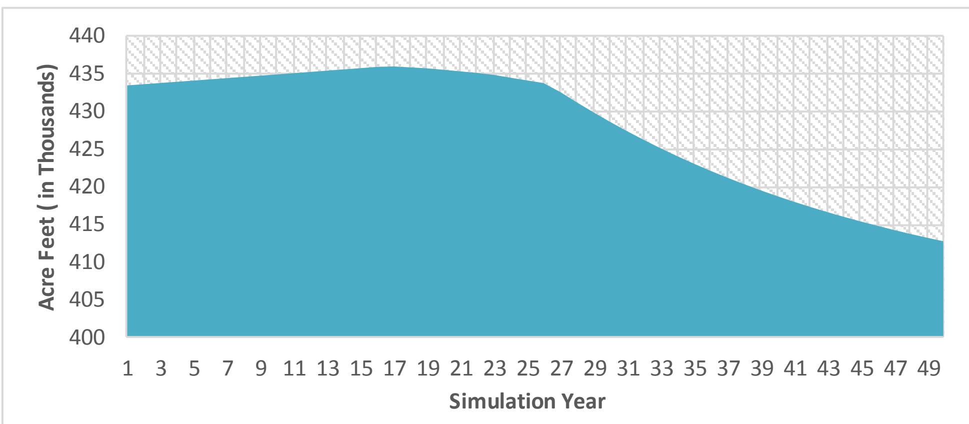
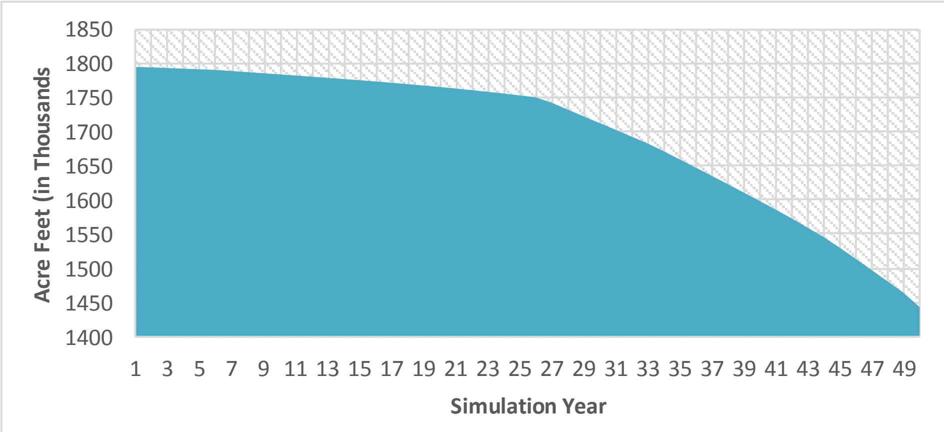


Figure 5.3 shows the changes in total water use in Southwest Kansas. In this region a decreasing trend can be observed throughout the study period, but with a change of slope in year 28.During the early years the decrease is slight; for example in the first 30 years the decline was 82 thousand acre feet, while the decrease in the last 20 years was 166 thousand acre feet. This gives a total reduction of 248 thousand acre feet over the study period.

Figure 5.3. Total Water Use - Southwest Kansas Status Quo Scenario



5.1.1.2 WEIGHTED AVERAGE SATURATED THICKNESS

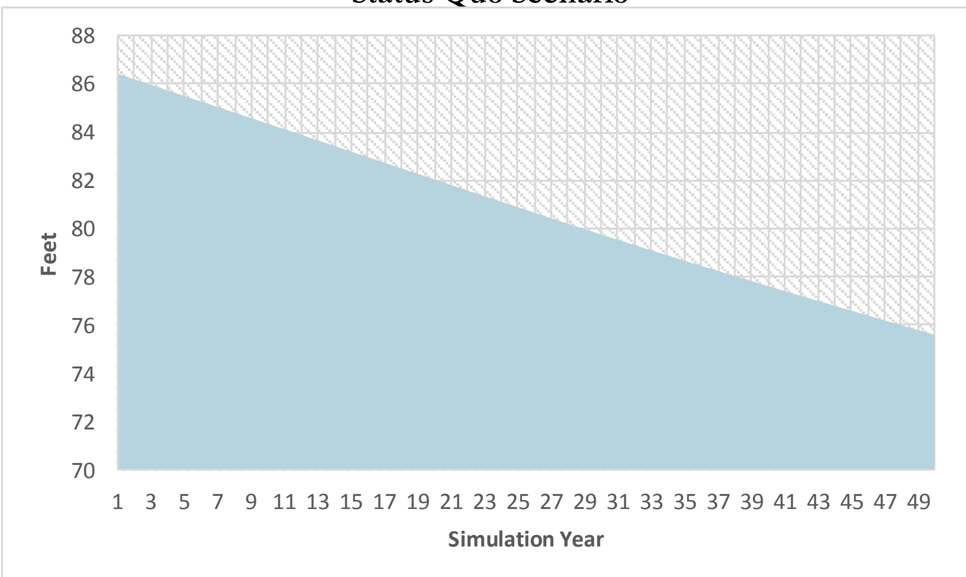
This section will discuss the trends of saturated thickness. Table 5.2 shows the levels of this variable during the 50 years of the study. As can be seen, a decrease occurs in the three study areas. The largest decrease occurs in the Southwest region, where the total reduction is 37%. In the West Central and Northwest regions the rates of decline are similar, at 14% and 12.5% respectively.

Table 5.2. Weighted Average Saturated Thickness - Status Quo Scenario (Feet)

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Percentage Change
Northwest	86	84	82	80	78	76	(12.52)
Southwest	179	166	152	138	124	112	(37.38)
West Central	53	51	49	48	47	46	(14.16)

In Figure 5.4 the trend of a steady decline in Northwest Kansas can be observed. This decrease starting in the first years is related to increased water use in the same period. In this region the average drop is 11 feet during the 50 years of the study.

Figure 5.4. Average Saturated Thickness - Northwest Kansas Status Quo Scenario



Figures 5.5 and 5.6 show the levels in the Southwest and West Central Kansas regions respectively. In both cases there is a decreasing trend, however in West Central a greater decline in the early years is observed. The average decrease is 67 feet and 7 feet respectively.

Figure 5.5. Average Saturated Thickness - Southwest Kansas Status Quo Scenario

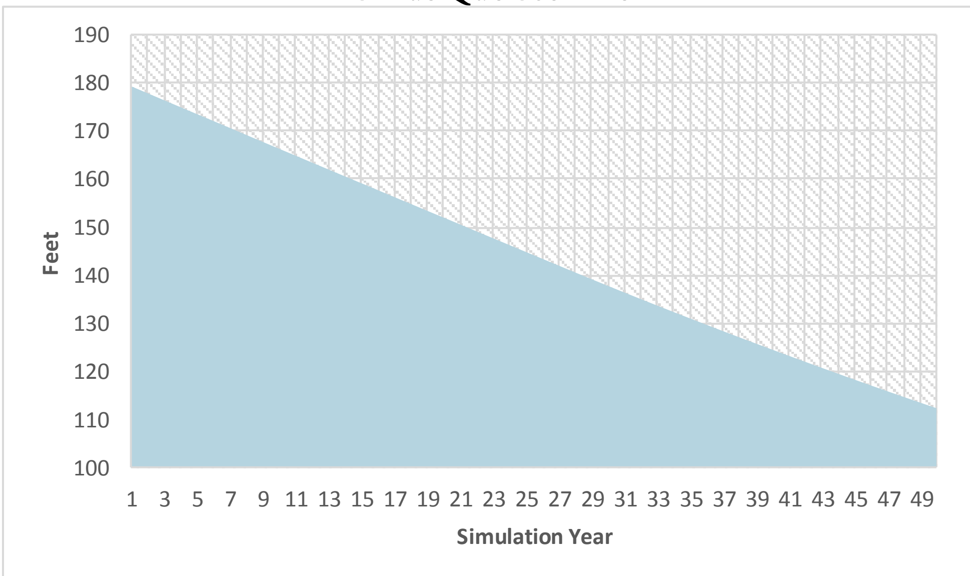
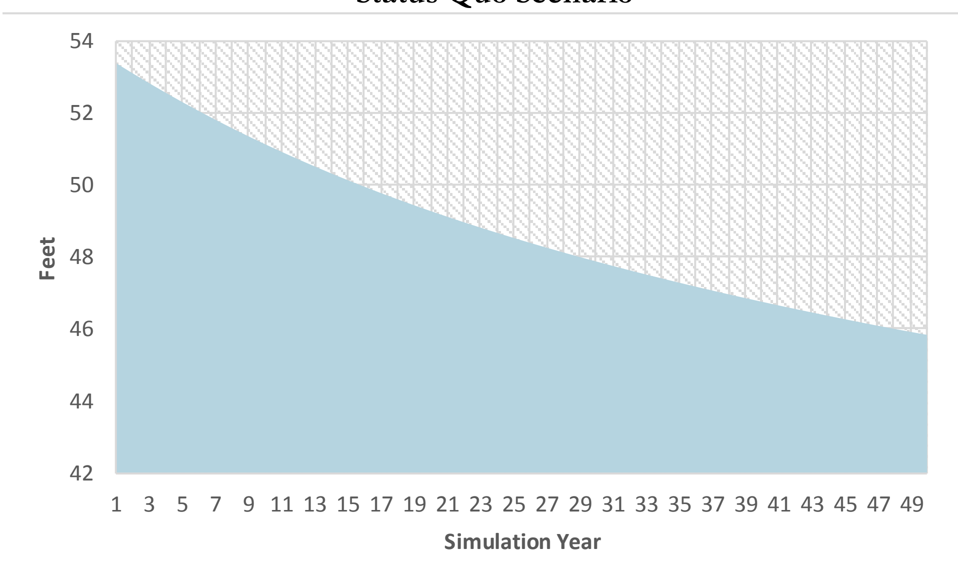


Figure 5.6. Average Saturated Thickness - West Central Kansas Status Quo Scenario



5.1.2 SIMULATION STATUS QUO SCENARIO VS CLIMATE CHANGE SCENARIO

This section discusses the effects of climate change and compares the results with the status quo scenario. The climate change scenario used in this analysis is based on estimates provided by North (2008) for the Great Plains area.[4] North (2008) based his analysis on the 2007 assessment by the International Panel on Climate Change (IPCC) which made use of more than 20 General Climate Models. The 2007 IPCC assessment is reported by Carter et al. (2007). This aggregation suggests a 2.5 degree Fahrenheit elevation in mean temperature and a 2.5% reduction in mean summertime precipitation over the next 50 years. Noah, Stuntz, and Abrams (2008) suggest that in the Ogallala Aquifer region, groundwater recharge may decrease by 20%, which is used as a proxy for the proportional change in recharge (β). As reflected in the preceding equations, these changes are assumed to occur in a linear fashion over the 50 year modeling horizon.

5.1.2.1 TOTAL WATER USE

Table 5.3 reflects the effects of climate change and compares them to the status scenario.

[4] North (2008) provided a range estimate. The center point of that range is used in this analysis.

Table 5.3. Total Water Use (Acres Feet) - Status Quo and Climate Change Scenarios

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Cumulative
Northwest							
Status Quo	433,523	434,986	435,612	428,684	418,817	412,789	21,411,312
Climate Change	433,523	438,586	442,639	433,453	425,720	418,060	21,670,562
% Change*	(0.00)	0.83	1.61	1.11	1.65	1.28	1.21
Southwest							
Status Quo	1,795,041	1,772,976	1,750,551	1,712,650	1,635,876	1,546,799	85,409,354
Climate Change	1,795,041	1,810,838	1,809,749	1,770,974	1,668,689	1,520,376	87,356,953
% Change*	-	2.14	3.38	3.41	2.01	(1.71)	2.28
West Central							
Status Quo	297,723	266,343	240,505	224,114	213,361	202,420	11,899,451
Climate Change	297,723	264,790	236,415	217,308	202,457	182,185	11,550,661
% Change*	-	(0.58)	(1.70)	(3.04)	(5.11)	(10.00)	(2.93)

*** Percent changes from status quo scenario**

Figure 5.7. Total Water Use - Northwest Kansas
Status Quo and Climate Change Scenarios

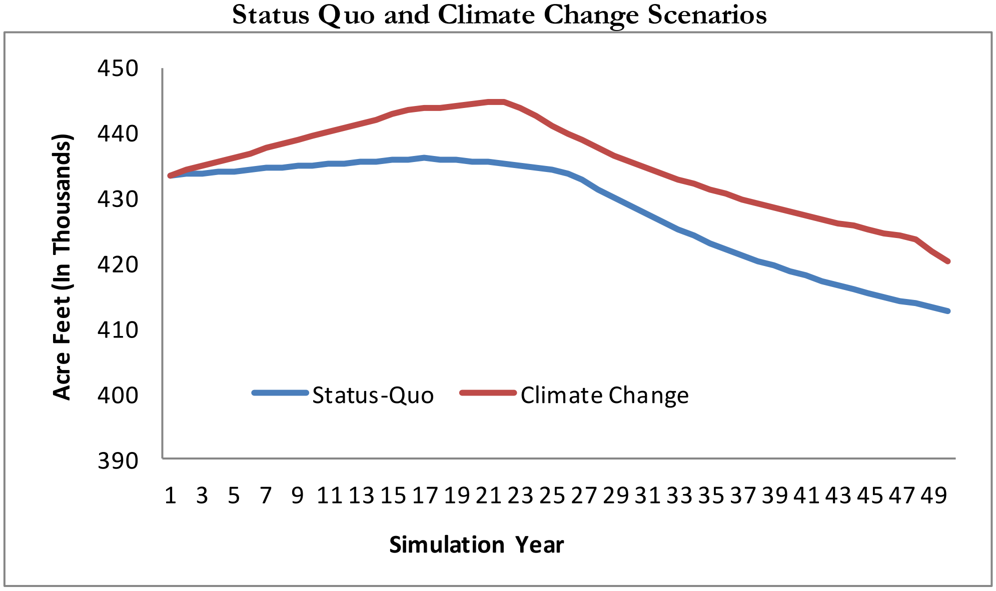


Figure 5.7 shows the trends in water use in Northwest Kansas during the 50 years considered for simulation. It can be noted that they begin at the same level in year one, but until year 20 the water use increased significantly more in the climate change scenario compared to the status quo. It later changes slope and begins to decrease until the last year of the simulation,

but always stays at higher levels than the status quo scenario. This reflects that given the drop in precipitation levels and the temperature increase, there is a greater demand for water to maintain production levels.

Figure 5.8 shows the trend of water use in both scenarios in the Southwest Kansas region, and as in the Northwest, water use is higher under the climate change scenario throughout almost all 50 years of simulation, due to the same aforementioned reasons. In both cases the water levels allow even greater use in the first years, but the slope of the curve representing the scenario with climate change is greater starting from the point of inflection, so that the drop is greater and even intersects the curve representing water use in status quo in year 44. Higher water use in the early years depletes water stocks so much that less water is actually extracted in the final years. This occurs because costs of extraction are higher and because the pumping constraints become binding.

Figure 5.8. **Total Water Use - Southwest Kansas Status Quo and Climate Change Scenarios**

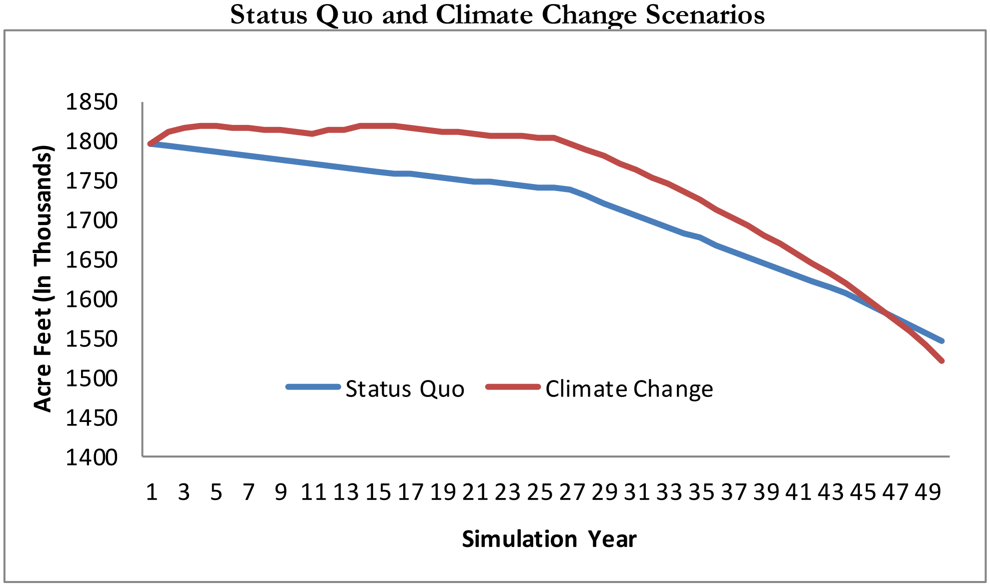
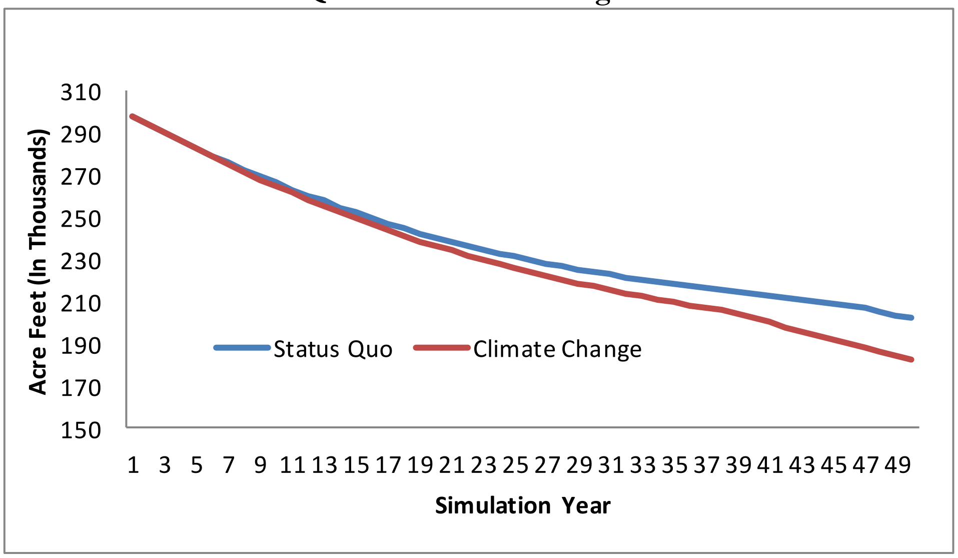


Figure 5.9 reflects the trends of water use under the climate change and status quo scenarios in the West Central Kansas region. Unlike the above mentioned regions, in the early years of the simulation water use has very similar levels in both scenarios, but starting in year 10 the water use under the climate change scenario is below that of the status quo scenario. This is explained by the fact that in this region practically all available water is currently being used.

Figure 5.9. **Total Water Use - West Central Kansas Status Quo and Climate Change Scenarios**



5.1.2.2 WEIGHTED AVERAGE SATURATED THICKNESS

Saturated thickness levels vary over all the territory above the aquifer. There are areas with levels higher than 300 feet and others with levels under 50 feet. These levels may even vary from one county to a neighboring county or even between adjacent farms. This characteristic implies that usage levels and water availability depend on the location of the farmer and if the farm is large, they can even vary within its own boundaries. The availability of water often becomes in itself a restriction that determines the type of crops in the region. Table 5.4 shows the trends in weighted average saturated thicknesses across counties in the three study regions (Northwest, Southwest and West Central Kansas) under the status quo scenario and the scenario that takes climate change into account.

Table 5.4. Weighted Average Saturated Thickness (Feet) - Status Quo and Climate Chage Scenarios

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Percentage Change
Northwest							
Status Quo	86	84	82	80	78	76	(12.52)
Climate Change	86	84	82	79	76	73	(15.12)
% Change *	-	(0.11)	(0.48)	(1.08)	(1.89)	(2.97)	
Southwest							
Status Quo	179	166	152	138	124	112	(37.38)
Climate Change	179	166	150	134	119	106	(40.87)
% Change *	-	(0.09)	(1.37)	(2.74)	(4.23)	(5.57)	
West Central							
Status Quo	53	51	49	48	47	46	(14.16)
Climate Change	53	51	49	48	46	45	(15.66)
% Change *	0.00	(0.09)	(0.32)	(0.71)	(1.23)	(1.75)	

*** Percent changes from status quo scenario**

Currently, saturated thickness levels in most of the aquifer are decreasing, and this can be observed in the three regions studied under the two scenarios. The decreasing trend occurs in the three regions at varying degrees as the availability of water is different in the three regions. We can also observe that under the climate change scenario the decrease is greater from year 20 onward in all three regions, and this is related to the fact that higher temperatures and lower precipitation levels affect the rate of aquifer recharge, while water demand is higher in order to maintain irrigation levels.

Figure 5.10. Weighted Average Saturated Thickness - Northwest Kansas Status Quo and Climate Chage Scenarios

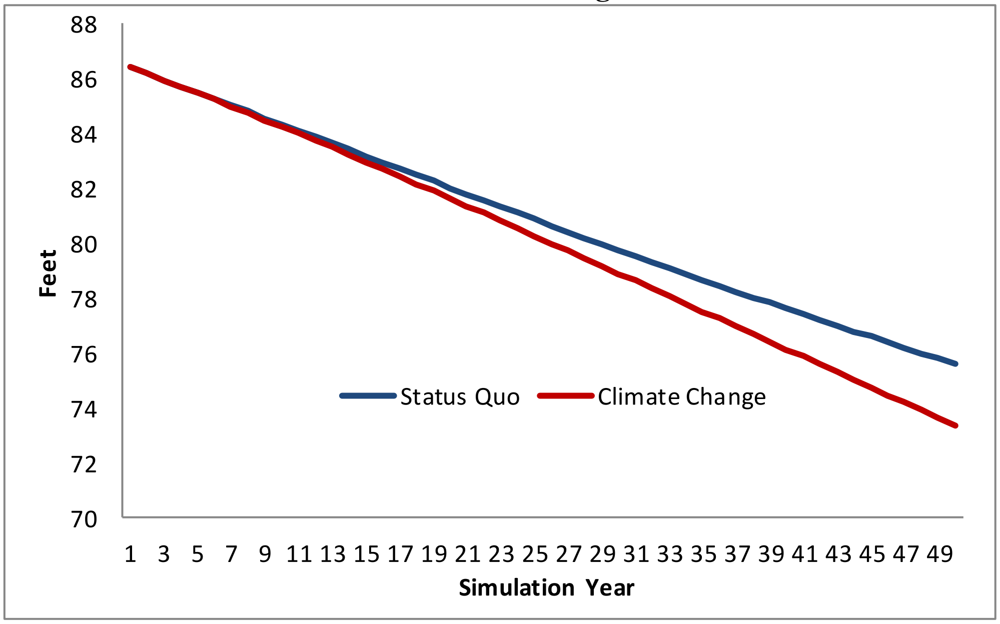


Figure 5.10 has only one large difference and that is the eventual ending saturated thickness. Both scenarios start at 86 acre feet of weighted average saturated thickness, but the higher water use in the initial periods under the climate change scenario drive the saturated thickness down more quickly. However, over time the status quo scenario begins to use more water than the climate change scenario. This results in relatively close saturated thickness levels in the final year of the simulation. Under the status quo scenario the final saturated thickness level is in average 76 acre feet. The climate change scenario results in average 73 acre feet. It is expected that the climate change scenario will result in a lower saturated thickness; however, it is interesting that over the 50 year simulation the final absolute difference is around 3 acre feet.

These results are consistent with what the Kansas Geological Survey (KGS) reported in terms of useable life. The KGS had reported that while many counties in Northwest Kansas 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 50 years of simulation there are still some irrigated producers, but the total value of irrigation has significantly fallen.

Figure 5.11. Weighted Average Saturated Thickness - Southwest Kansas Status Quo and Climate Chage Scenarios

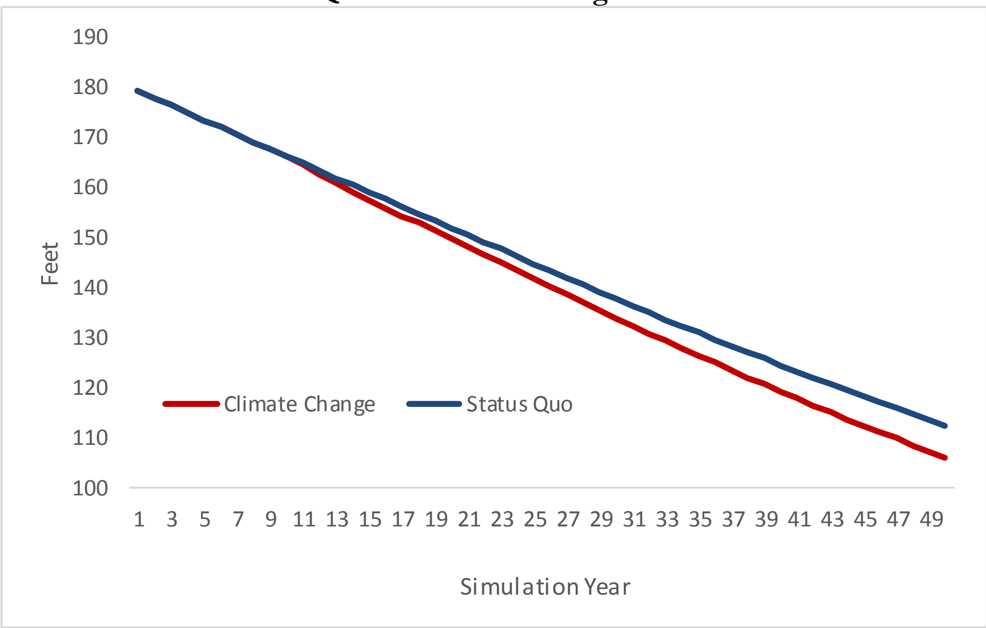
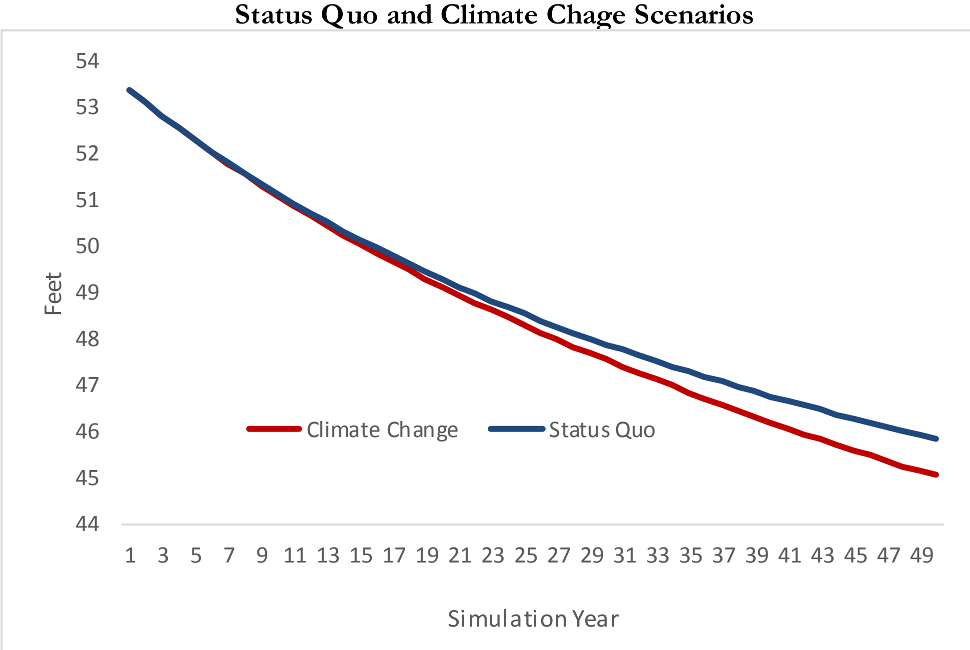


Figure 5.11 displays the levels of saturated thickness for the status quo and climate change scenarios in Southwest Kansas. In this case the graph shows an almost linear decrease in the level of saturated thickness. Additionally it is clear that high water use for the climate change scenario in each year decreases the saturated thickness much more than the status quo scenario. Each scenario starts with a weighted average saturated thickness level of 179 acre feet. By the end of the simulation the weighted average saturated thickness level is 112 and 106 acre feet for the status quo and climate change scenarios respectively. The absolute difference between the

two scenarios in the final year (5.57 acre feet) is the highest observed difference of any region. These results are expected and also consistent with the KGS which predicted that the majority of the counties in this region would have anywhere from 100 to over 250 years of irrigation left. Clearly, even under climate change scenario after 50 years there are still plenty of irrigated years left.

Figure 5.12 displays the changes in the weighted average saturated thicknesses for the two scenarios across time in west central Kansas.

Figure 5.12. Weighted Average Saturated Thickness - West Central Kansas Status Quo and Climate Chage Scenarios



Here again the two curves have a fairly similar shape. However, the initially higher water use in the climate change scenario increases the rate at which the saturated thickness declines in that scenario. Nevertheless, as also observed in the others two regions, as the time progresses it becomes obvious that the status quo scenario beings to use more water and the saturated thickness decreases quicker under this scenario. Both scenarios start with a weighted average saturated thickness level of 53 acre feet, but by the final year of simulation the status quo scenario has a saturated thickness level of 46 acre feet and the climate change scenario's saturated thickness level is 45 acre feet. The absolute difference between the two scenarios (1 acre feet), may seem fairly small, but translates into several more years of usable aquifer life. These results reflect that the amount of irrigated life is extremely limited in this region.

5.1.2.3 NET RETURNS

Table 5.5. Weighted Average Net Return Per Acre ($/cropland acre) - Status Quo and Climate Change

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Percentage Change
Northwest							
Status Quo	123.38	123.38	123.29	122.33	120.88	119.87	(2.84)
Climate Change	123.38	123.09	122.62	120.61	118.71	117.03	(5.15)
% Change*	-	(0.24)	(0.54)	(1.40)	(1.80)	(2.37)	
Southwest							
Status Quo	180.29	177.88	175.47	172.84	169.51	165.98	(7.94)
Climate Change	180.29	177.18	173.88	170.14	165.69	161.38	(10.49)
% Change*	-	(0.39)	(0.91)	(1.56)	(2.25)	(2.77)	
West Central							
Status Quo	92.88	90.69	88.80	87.54	86.68	85.93	(7.49)
Climate Change	92.88	90.21	87.78	86.00	84.57	82.95	(10.69)
% Change*	-	(0.53)	(1.15)	(1.76)	(2.43)	(3.47)	

*** Persent changes from status quo scenario**

Table 5.5 shows the trend of net returns over fifty years. We observe that climate change has negative impact on net returns.. It can be observed that there is a decrease in net return in the three regions. The Status Quo scenario shows that the greatest reductions in net return occur in West Central Kansas and Southwest Kansas with 7.49% and 7.94% respectively, while in Northwest Kansas under the Status Quo scenario the reduction in net return between the first year and the fiftieth year was 2.84%. By including the effects of climate change, this reduction is greater in the three regions. Under the of climate change scenario, reductions in net return in the Northwest, Southwest, and West Central regions are 5.15%, 10.49% and 10.69% respectively. The above table reflects only the productive income from the land actually farmed. For the three regions, the net returns are slightly below baseline levels because the need of more water will imply higher pumping cost under climate change scenario. The impact of climate change in the net returns occurs gradually over the simulation years.

5.2 IMPACT OF SPECIFIC WATER CONSERVATION POLICIES UNDER UNCHANGED REGIONAL CLIMATE: WATER USE RESTRICTION AND PERMANENT CONVERSION TO DRYLAND PRODUCTION

5.2.1 TOTAL WATER USE

In this section we consider two policies that were derived from water conservation policy surveys to experts in Kansas and Texas. The policies considered are:

1- Water Use Restriction: A mandatory annual reduction in pumping rates on each well

2- A Permanent Conversion to Dryland Production: Permanent cessation of irrigation on selected irrigated fields

The simulation results of these policies are compared to the status quo scenario. It must be emphasized that for both the status quo scenario and for both policies together, climate change is not considered. In both cases the objective is to try to see the effects of these policies on total water use in the three study regions, separate from the effects of climate change.

Table 5.6. Total Water Use (Acres Feet) - Status Quo and Policies Scenarios

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Cumulative
Northwest							
Status Quo	433,523	434,986	435,612	428,684	418,817	412,789	21,411,312
Permanent Conv.	392,703	365,391	366,512	365,985	360,905	356,003	18,259,550
% Change *	(9.42)	(16.00)	(15.86)	(14.63)	(13.83)	(13.76)	
Restrict Policy	382,858	380,895	376,932	370,373	353,157	335,947	18,394,441
% Change *	(11.69)	(12.44)	(13.47)	(13.60)	(15.68)	(18.62)	
Southwest							
Status Quo	1,795,041	1,772,976	1,750,551	1,712,650	1,635,876	1,546,799	85,409,354
Permanent Conv.	1,677,083	1,562,235	1,558,646	1,554,573	1,515,802	1,471,397	77,365,762
% Change *	(6.57)	(11.89)	(10.96)	(9.23)	(7.34)	(4.87)	
Restrict Policy	1,523,628	1,458,129	1,378,447	1,299,386	1,223,728	1,146,759	66,796,661
% Change *	(15.12)	(17.76)	(21.26)	(24.13)	(25.19)	(25.86)	
West Central							
Status Quo	297,723	266,343	240,505	224,114	213,361	202,420	11,899,451
Permanent Conv.	258,298	225,178	211,712	201,310	192,779	186,686	10,460,063
% Change *	(13.24)	(15.46)	(11.97)	(10.18)	(9.65)	(7.77)	
Restrict Policy	232,010	220,637	207,713	194,379	180,724	170,028	10,016,268
% Change *	(22.07)	(17.16)	(13.63)	(13.27)	(15.30)	(16.00)	

*** Percent changes from status quo scenario**

The water use restriction scenario considers a mandatory pumping limit on each well in each study site. Specifically, pumping on each well must be reduced by 1% annually, using base (2000-08) pumping as the starting point in year 1. In the model this is implemented as an additional constraint on pumping. This new legal constraint accompanies an existing physical constraint that accounts for the effect of aquifer decline. The physical constraint reflects the fact that, as the saturated thickness of the aquifer is reduced, the associated decline in well yields will limit how much water can be pumped from a single well in a fixed-length irrigation season.

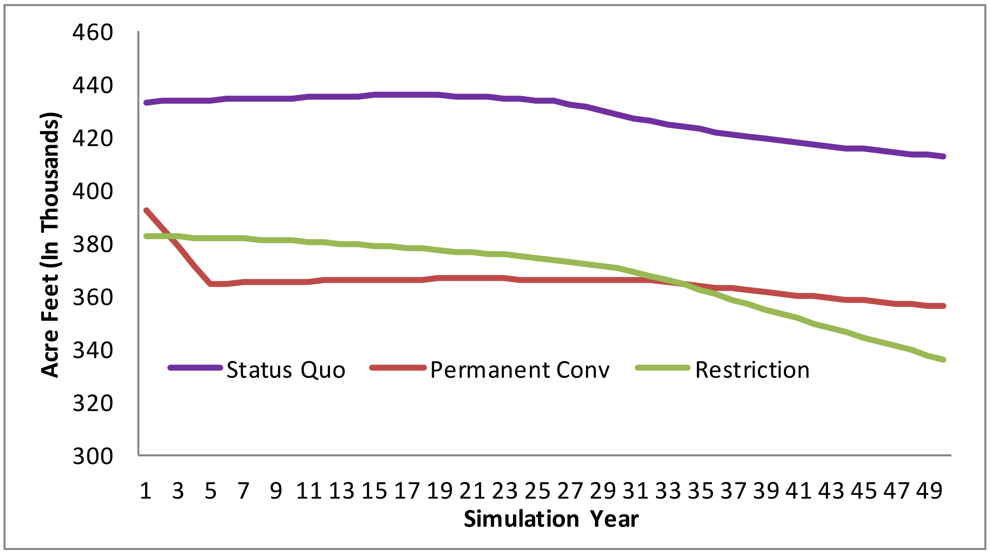
This policy affects all projected quantities in the same direction in all three regions. In particular, relative to the baseline, water use is reduced (Table 5.6). The effects are the strongest in Southwest Kansas, where cumulative water use is reduced by 22% from the baseline scenario.

The permanent conversion to dryland production is a scenario in which irrigated lands enrolled are removed from production for the entire 50-year period. In this scenario 10% of initial irrigated acreage is assumed to be enrolled and is incrementally removed from irrigated production in simulation years 1-5. At the same time, this scenario assumes that there is no requirement for the enrolled lands to be converted to a non-crop use, so that they can be used for nonirrigated crop production immediately.

Permanent Conversion policy generates distinct impacts across the three study regions. Water use is reduced in the early years of the simulation (Table 5.6) when the program takes irrigated lands out of production.

Figure 5.13 shows changes in water use under both scenarios and the status quo in Northwest Kansas. As can be seen, and as previously explained, in both cases there is a notable reduction of water use. However, unlike in the Southwest (Figure 5.14) and West Central regions (Figure 15), there is a sharp decline in the early years which is higher under the scenario of permanent conversion and then remains constant until the end of the simulation period. Meanwhile, under the of water restriction scenario, the decrease in water use tends to be greater from year 30 onward and this drop is greater than in the other scenario starting from year 33, ending up below the permanent conversion scenario in year 50. However, the total reduction over 50 years is very similar in both scenarios and gives a cumulative reduction of approximately 14% in both scenarios compared to the status quo.

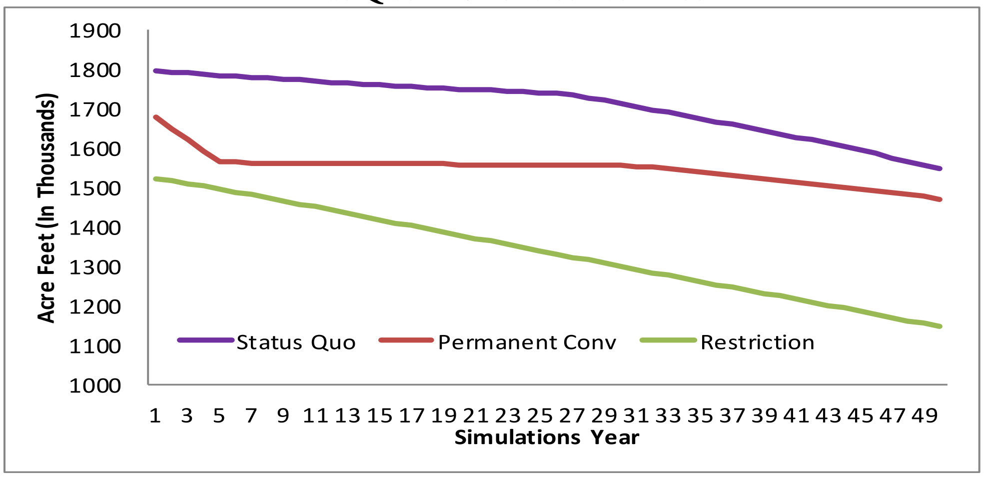
Figure 5.13. Total Water Use - Northwest Kansas
Status Quo and Policies Scenarios



Figures 5.14 and 5.15, show the pattern of water use for Southwest and West Central Kansas respectively. As shown, reductions in water use occur under both scenarios in both regions. However, in the Southwest under the scenario of permanent conversion, the drop is pronounced in the early years but then water use remains almost constant until the end of the period, while under the water restriction scenario it falls steadily from the first year to the last. In this region, the policy that restricts water use the most is the water use restriction policy with a cumulative reduction of approximately 22%, while under the permanent conversion policy the cumulative reduction is 9.5%.

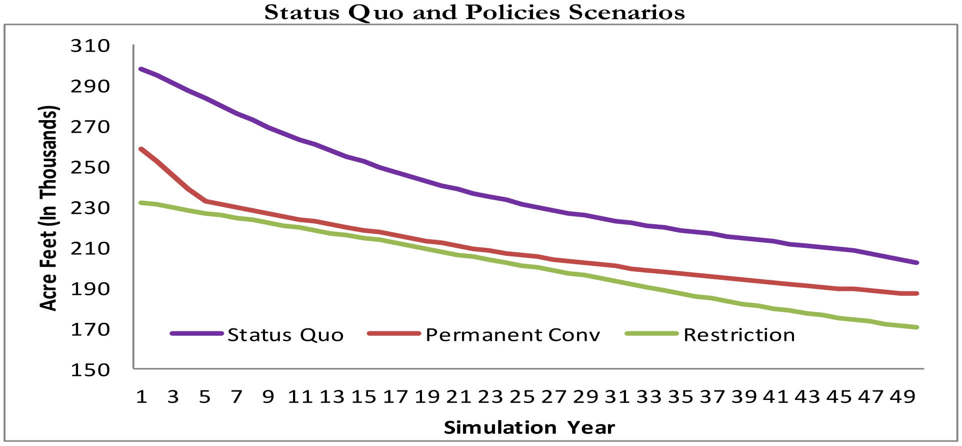
In the case of West Central Kansas, reductions that occur under both policies in cumulative terms are more similar, with a reduction of 12% under the permanent conversion scenario and 16% under the water restriction scenario. In this region, water use virtually equals the maximum potential level of use, with higher levels possibly available in certain counties.

Figure 5.14. Total Water Use - Southwest Kansas
Status Quo and Policies Scenarios



As shown in Figure 15, in West Central Kansas between years 10 and 30, the levels of water use are very similar under both scenarios, but then the reduction under the water restriction scenario is higher than in the permanent conversion scenario.

Figure 5.15. Total Water Use - West Central Kansas
Status Quo and Policies Scenarios



5.2.2 WEIGHTED AVERAGE SATURATED THICKNESS

The results obtained in relation to the weighted average saturated thickness are consistent with the levels of water use in each region under both scenarios.

Table 5.7. Weighted Average Saturated Thickness (Feet) - Status Quo and Policies Scenarios

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Percentage Change
Northwest							
Status Quo	86	84	82	80	78	76	(12.52)
Permanent Conv.	86	85	84	82	81	80	(7.81)
% Change *	(0.04)	0.71	2.01	3.17	4.26	5.35	
RestrictPolicy	86	85	83	82	80	79	(8.22)
% Change *	(0.00)	0.71	1.60	2.59	3.64	4.92	
Southwest							
Status Quo	179	166	152	138	124	112	(37.38)
Permanent Conv.	179	167	156	144	132	120	(32.76)
% Change *	(0.09)	0.61	2.62	4.35	5.84	7.27	
Restrict Policy	179	169	159	149	140	132	(26.17)
% Change *	(0.00)	1.80	4.55	8.35	12.81	17.89	
West Central							
Status Quo	53	51	49	48	47	46	(14.16)
Permanent Conv.	53	52	51	50	49	49	(8.31)
% Change *	(0.02)	1.81	3.54	4.80	5.85	6.79	
Restrict Policy	53	52	51	50	50	50	(7.21)
% Change *	(0.00)	2.17	3.90	5.28	6.64	8.09	

*** Persent changes from status quo scenario**

We can see that in the three study regions, the ending level of average saturated thicknesses increases, and this happens because the levels of water use are reduced with the implementation of the restriction policies in the three regions. In considering the water restriction scenario, the greatest effect can be observed in Southwest Kansas, where average saturated thickness at the end of the period was 18% higher than that of the status quo. This is consistent with the reduction of water use in that region under the same scenario which was 22% compared to the status quo scenario. As a result, planted acreage in Southwest Kansas shifts from irrigated corn to less profitable (and less water intensive) irrigated crops such as sorghum and wheat.

Under the permanent conversion scenario the same effect can be observed, where levels of average saturated thicknesses increase in the three study regions. In the Southwest and West Central Kansas regions, the increase in the average saturated thicknesses is higher under the water restriction scenario, but in Northwest Kansas average saturated thicknesses are slightly higher under the permanent conversion scenario.

Figure 5.16. Weighted Average Saturated Thickness - Northwest Kansas Status Quo and Policies Scenarios

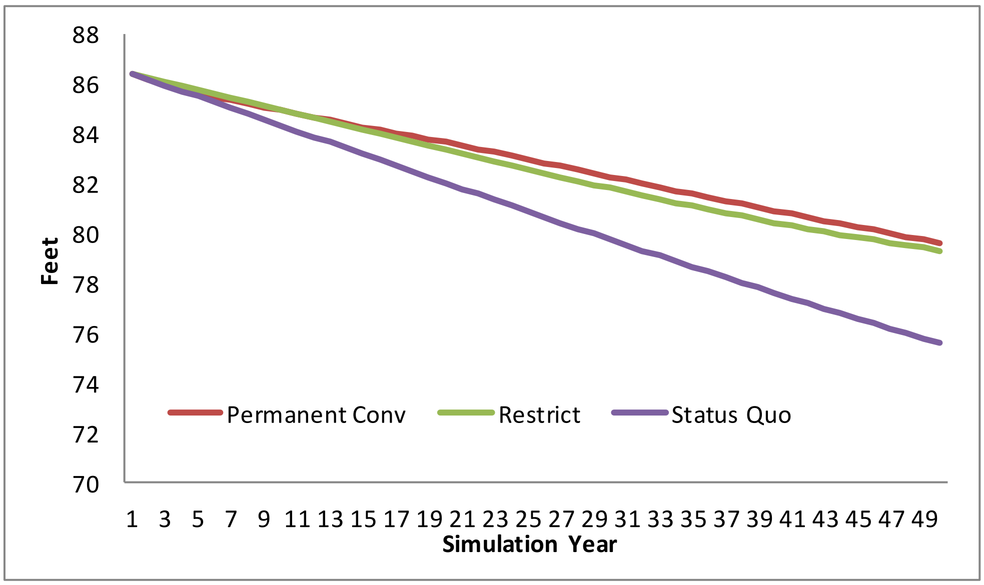


Figure 5.16 shows the effect of both policies on the average saturated thicknesses in Northwest Kansas. It can be seen that both policy scenarios and the status quo scenario start at an average of 86 feet, and at the end of the study period the level of average saturated thicknesses was 76 feet in the status quo scenario, while under the permanent conversion scenario it was 80 feet and for the water restriction scenario it was 79 feet. These levels are higher than the status quo by 5.35% and 4.92% respectively.

Figure 5.17 compares the trends of average saturated thicknesses under both scenarios and compares them with the status quo in the of Southwest Kansas region. The difference in Northwest Kansas is that in this region the implementation of the water restriction policy generates better results than the permanent conversion policy. At the end of the period, under the water restriction scenario the average saturated thicknesses level is 17.89% more than the status quo, while under the permanent conversion scenario the level is 7.27% more than the status quo.

Figure 5.17. Weighted Average Saturated Thickness - Southwest Kansas Status Quo and Policies Scenarios

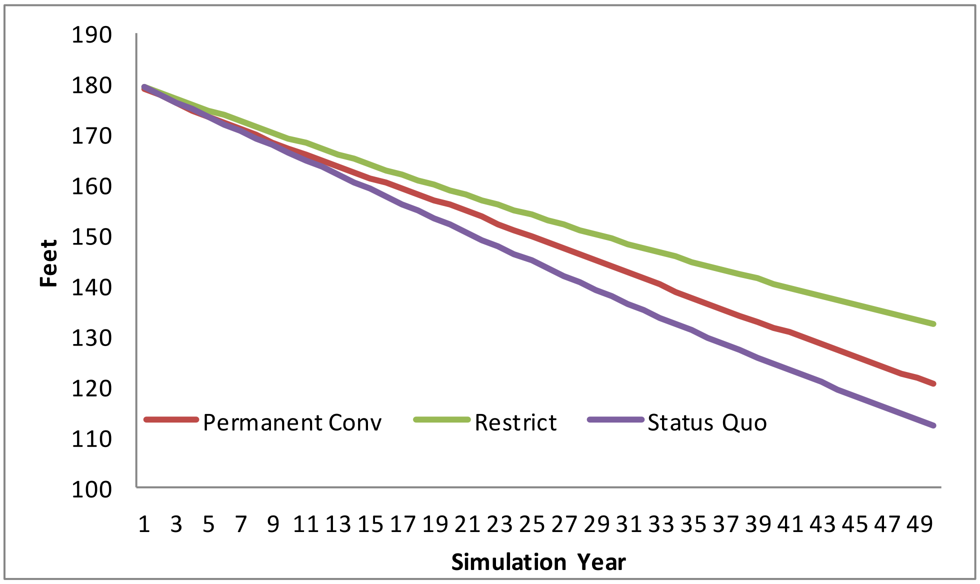
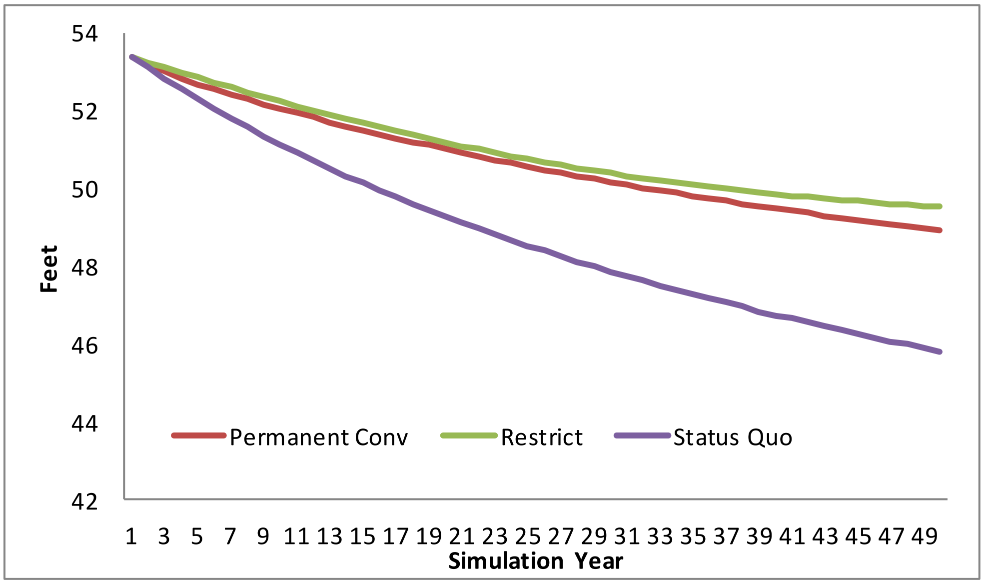


Figure 5.18 displays the results in West Central Kansas. The results obtained under the water restriction scenario are better than those of the permanent conversion scenario. However, the difference between these two scenarios at the end of the period is very small. Compared with the status quo scenario, water restriction and permanent conversion have levels 8% and 7% higher respectively, versus the status quo. These results are due to the reduction of water use under both scenarios.

Figure 5.18. Weighted Average Saturated Thickness - West Central Kansas Status Quo and Policies Scenarios



5.2.3 NET RETURN

This section analyzes the results regarding the net present value of the stream of net returns in the three study regions under permanent conversion and water restriction scenarios for comparison with the values obtained by the status quo (Table 5.8).

Table 5.8. Weighted Average Net Return Per Acre ($/cropland acre) - Status Quo and Policies Scenarios

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Porcentage Change
Northwest							
Status Quo	123.38	123.38	123.29	122.33	120.88	119.87	(2.84)
Permanent Conv.	122.42	120.76	121.42	121.16	120.15	119.05	(2.76)
% Change *	(0.78)	(2.12)	(1.52)	(0.95)	(0.61)	(0.69)	
Restriction Policy	121.17	120.83	120.08	118.92	116.47	113.92	(5.99)
% Change *	(1.79)	(2.07)	(2.60)	(2.79)	(3.65)	(4.97)	
Southwest							
Status Quo	180.29	177.88	175.47	172.84	169.51	165.98	(7.94)
Permanent Conv.	179.09	174.61	174.22	172.52	169.89	167.44	(6.51)
% Change *	(0.66)	(1.84)	(0.71)	(0.18)	0.22	0.88	
Restriction Policy	170.52	165.79	160.64	155.80	151.35	147.04	(13.77)
% Change *	(5.42)	(6.80)	(8.45)	(9.86)	(10.71)	(11.41)	
West Central							
Status Quo	92.88	90.69	88.80	87.54	86.68	85.93	(7.49)
Permanent Conv.	91.96	89.64	89.03	88.03	87.30	86.77	(5.65)
% Change *	(0.99)	(1.16)	0.26	0.56	0.72	0.98	
Restriction Policy	89.16	88.31	87.27	86.16	84.87	83.79	(6.01)
% Change *	(4.01)	(2.62)	(1.72)	(1.59)	(2.09)	(2.48)	

*** Precent changes from status quo scenario**

The table above shows the results on net return under the three scenarios (status quo, permanent conversion and water use restriction policy) in which the effects of climate change are not accounted for. As shown, in the three scenarios a decrease in net return occurs in all three regions during the simulation period. It's clear that the greatest impact in the three regions occurs under the Water Use Restriction policy. The greatest impact is felt in Southwest Kansas (13.77%), largely because this region is the one with the greatest water supply and this policy would have a greater impact on earnings during the period of the simulation. But on the other hand it should be noted that the same policy would yield a lesser loss compared to the Status Quo in West Central Kansas, but slightly higher when compared to Permanent Conversion (5.65%). This is largely due to the scarcity of water in the region.

In northwest Kansas, effects on the net return during the simulation are reduced. Under the Permanent Conversion policy, a reduction of 2.76% would result and under the Water Use

Restriction policy, a reduction of 5.99%. On the other hand, if no policy were applied, the reduction of revenue at the end of the simulation period would be 2.84%.

Different results can be observed depending on the agronomic characteristics and water availability in each region. It must be taken into account that each region is composed of several counties which themselves have different hydrological characteristics, so that a policy can have different impacts even among farmers who are in the same county and between counties that are in the same study region. The cost of this policy is assumed to be borne entirely by farmers in the simulations. In considering the permanent conversion policy, it can be seen that the effects in the three regions are similar but at different levels.

5.3 IMPACT OF SPECIFIC POLICIES DUE TO CHANGING CLIMATE CONDITIONS: WATER USE RESTRICTION AND PERMANENT CONVERSION TO DRYLAND PRODUCTION

In this section, the effects of climate change are incorporate in each of the policies, in order to analyze the role of climate change on the effects of the conservation policies discussed in the previous section. Assumptions about changes in temperature and precipitation used in Section 4.3.3 to measure the impacts of climate change are used in this section and are incorporated into both policies.

5.3.1 TOTAL WATER USE

The results are very interesting and relevant. The first thing to note is that the trending patterns over the simulation period are very similar; however the levels of water use are considerably different. First, the impact by climate change on each of the policies and in each region will be analyzed.

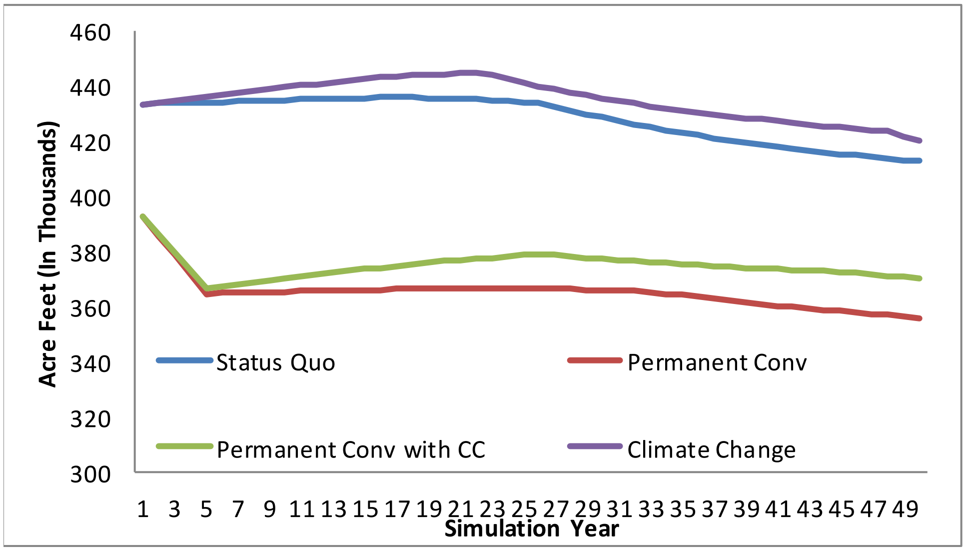
Table 5.9. Total Water Use (Acres Feet) - Status Quo and Policies with Climate Change Scenarios

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Cumulative
Northwest							
Status Quo	433,523	434,986	435,612	428,684	418,817	412,789	21,411,312
Climate Change	433,523	438,586	442,639	433,453	425,720	418,060	21,670,562
% Change *	(0.00)	0.83	1.61	1.11	1.65	1.28	1.21
Permanent Conv.	392,703	365,391	366,512	365,985	360,905	356,003	18,259,550
% Change *	(9.42)	(16.00)	(15.86)	(14.63)	(13.83)	(13.76)	(14.72)
Permanent Conv. Climate Change	392,703	370,163	376,451	377,298	373,789	370,305	18,733,691
% Change *	(9.42)	(14.90)	(13.58)	(11.99)	(10.75)	(10.29)	(12.51)
Restrict Policy	382,858	380,895	376,932	370,373	353,157	335,947	18,394,441
% Change *	(11.69)	(12.44)	(13.47)	(13.60)	(15.68)	(18.62)	(14.09)
Restrict Policy with Climate Change	382,858	385,465	385,351	374,566	354,019	329,732	18,556,873
% Change *	(11.69)	(11.38)	(11.54)	(12.62)	(15.47)	(20.12)	(13.33)
Southwest							-
Status Quo	1,795,041	1,772,976	1,750,551	1,712,650	1,635,876	1,546,799	85,409,354
Climate Change	1,795,041	1,810,838	1,809,749	1,770,974	1,668,689	1,520,376	87,356,953
% Change *	-	2.14	3.38	3.41	2.01	(1.71)	2.28
Permanent Conv.	1,677,083	1,562,235	1,558,646	1,554,573	1,515,802	1,471,397	77,365,762
% Change *	(6.57)	(11.89)	(10.96)	(9.23)	(7.34)	(4.87)	(9.42)
Permanent Conv. Climate Change	1,677,083	1,576,966	1,599,175	1,609,962	1,561,558	1,478,958	79,032,679
% Change *	(6.57)	(11.06)	(8.65)	(6.00)	(4.54)	(4.39)	(7.47)
Restrict Policy	1,523,628	1,458,129	1,378,447	1,299,386	1,223,728	1,146,759	66,796,661
% Change *	(15.12)	(17.76)	(21.26)	(24.13)	(25.19)	(25.86)	(21.79)
Restrict Policy with Climate Change	1,523,628	1,458,071	1,384,961	1,302,787	1,208,041	1,100,582	66,553,980
% Change *	(15.12)	(17.76)	(20.88)	(23.93)	(26.15)	(28.85)	(22.08)
West Central							
Status Quo	297,723	266,343	240,505	224,114	213,361	202,420	11,899,451
Climate Change	297,723	264,790	236,415	217,308	202,457	182,185	11,550,661
% Change *	-	(0.58)	(1.70)	(3.04)	(5.11)	(10.00)	(2.93)
Permanent Conv.	258,298	225,178	211,712	201,310	192,779	186,686	10,460,063
% Change *	(13.24)	(15.46)	(11.97)	(10.18)	(9.65)	(7.77)	(12.10)
Permanent Conv. Climate Change	258,298	225,645	211,724	199,147	189,228	177,923	10,371,586
% Change *	(13.24)	(15.28)	(11.97)	(11.14)	(11.31)	(12.10)	(12.84)
Restrict Policy	232,010	220,637	207,713	194,379	180,724	170,028	10,016,268
% Change *	(22.07)	(17.16)	(13.63)	(13.27)	(15.30)	(16.00)	(15.83)
Restrict Policy with Climate Change	232,010	220,246	206,319	191,118	174,696	160,374	9,856,263
% Change *	(22.07)	(17.31)	(14.21)	(14.72)	(18.12)	(20.77)	(17.17)

*** Persent changes from status quo scenario**

Figure 5.19 shows the trending pattern of water use under four scenarios in Northwest Kansas: status quo, climate change, permanent conversion and permanent conversion with climate change. As can be observed, the level of water use with climate change is greater than that observed under the status quo (this situation was previously compared). In the case of the permanent conversion scenario without climate change, the cumulative level of water use is reduced by approximately 15% in the 50 years of the simulation (Table 5.9). However, if the effect of climate change on the permanent conversion policy is included, reduction of water use is about 12% compared to the Status Quo scenario, a difference of 3%. If the scenarios that incorporate climate change (status quo vs. permanent conversion with climate change) are compared, the difference is reduced to 2%. In both cases the levels of water use are higher than those without climate change.

Figure 5.19. Total Water Use - Northwest Kansas
Status Quo and Policies with Climate Change Scenarios



The reduction of water use with climate change and without taking climate change into account in the first five years are very similar, but from year six onward, demand for water because of the effects of climate change is higher and remains so until the end of the simulation.

Figure 5.20. Total Water Use - Southwest Kansas
Status Quo and Policies with Climate Change Scenarios

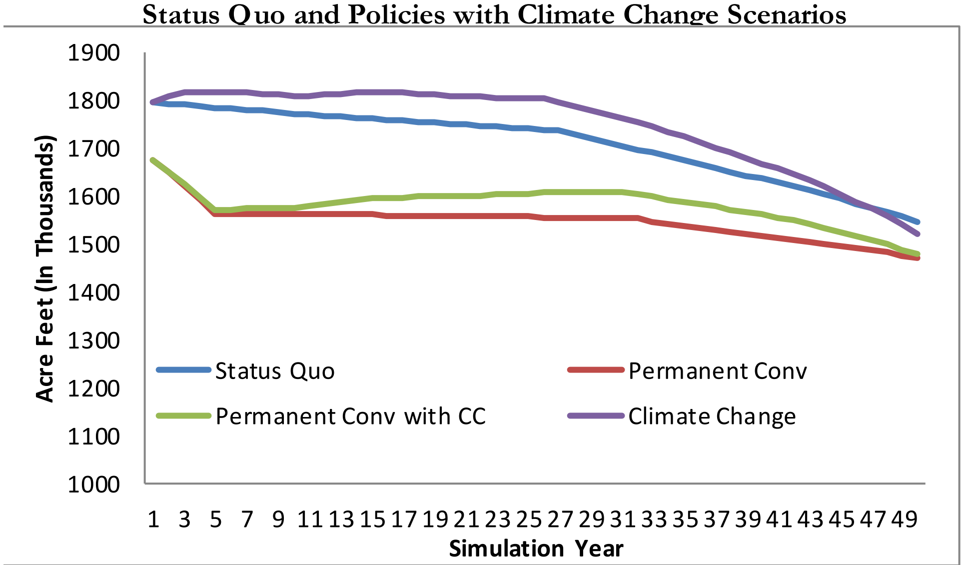
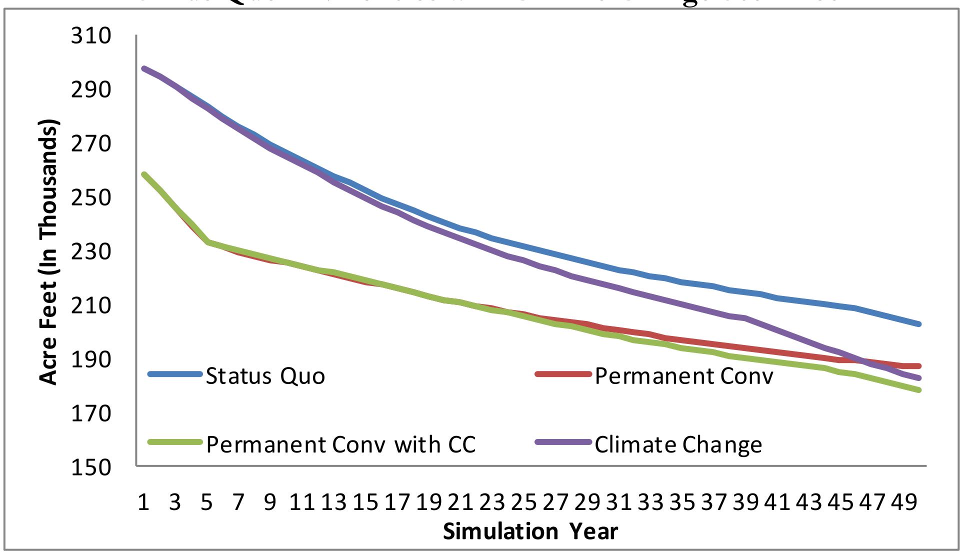


Figure 5.20 shows what happens in Southwest Kansas resulting from the permanent conversion policy with and without climate change. The cumulative reduction of water use in relation to the status quo in this region is approximately 9% (Table 5.9) if the effects of climate change are not considered. But observing climate change scenarios it can be seen that the reduction of water use diminishes to 7%. This means that 2% more will be used than what is believed would be used with the application of this policy. But if the climate change and permanent conversion scenarios are compared, the reduction is 9%. An important factor to point out is that in the last years of the simulation, the levels of water use under the scenarios of permanent conversion with and without climate change are very similar. At the same time, it should be noted that throughout the entire simulation period, water use is higher under the scenario of permanent conversion with climate change.

Figure 5.21 shows the effects of climate change on the permanent conversion policy in West Central Kansas. As can be seen, the results in this region are slightly different, which is due to the characteristics of the aquifer in the region. As was already explained, if the status quo and climate change scenarios are compared, starting in year 20, the scenario with climate change results in less water use, which is because the levels of water use in the region in many counties are approaching maximum potential use and the transition from irrigated crops to dryland crops is in process. The decreases in water use under the permanent conversion policy with and without the effects of climate change are very similar and are at about 12% at the end of the period.

Figure 5.21. Total Water Use - West Central Kansas

Status Quo and Policies with Climate Change Scenarios



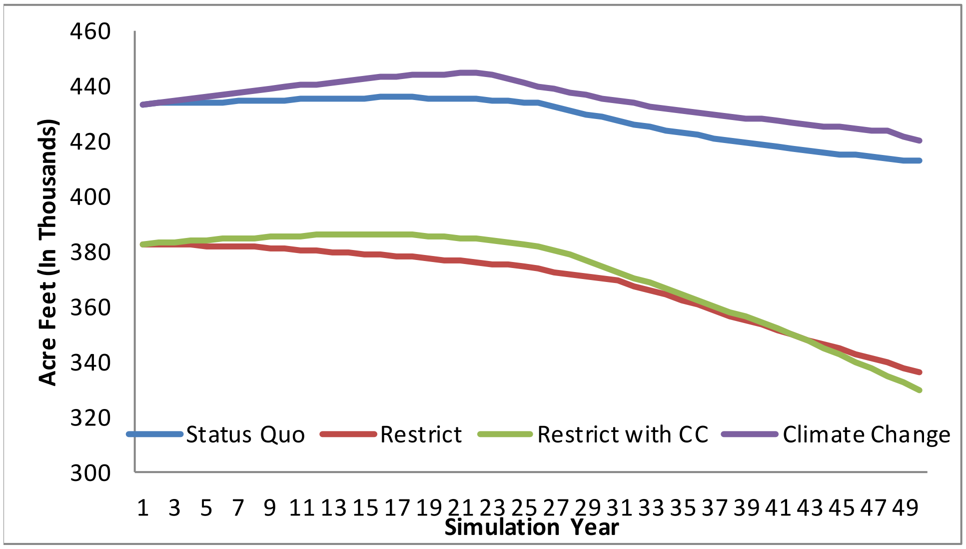
Next, the pattern of water use in the case of the water use restriction policy in the three study regions will be analyzed (Table 5.9).

Figure 5.22 shows the trends of water use in Northwest Kansas accounting for the effects of the water use restriction policy with and without climate change. As can be seen, the levels of water use in the early years of the implementation of the policy are greater if the effect of climate change is included. However, in the last five years of the simulation the scenario of water restriction with climate change intersects with the scenario without climate change. This is because in the first years, more water is used because of the effects of reduced rainfall and increased temperatures. Reduction of water use under the water use restriction scenario without climate change is 14% compared to the Status Quo, whereas if climate change is incorporated this amount is reduced to 13%.

The levels of water use are greater despite the restrictions if the effects of climate change in this region are taken into account.

Figure 5.22. Total Water Use - Northwest Kansas

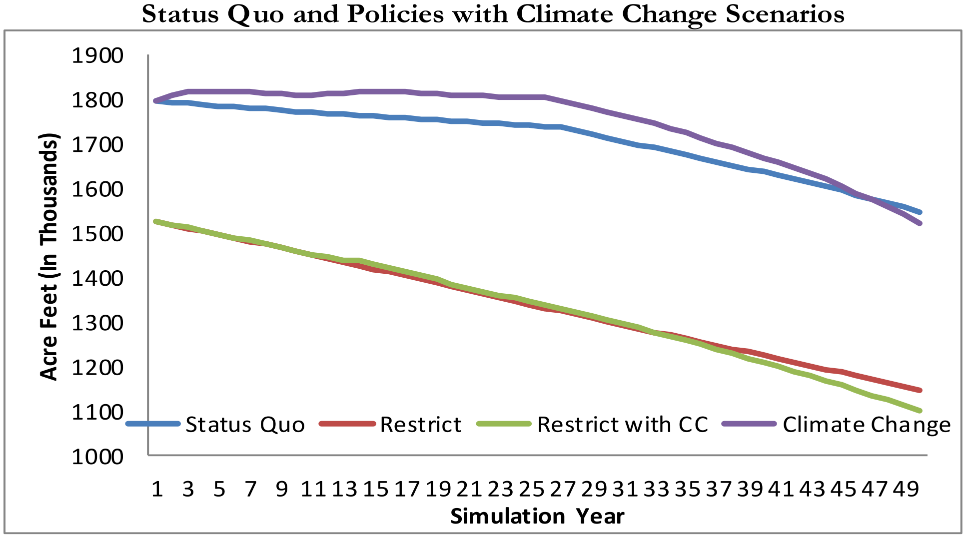
Status Quo and Policies with Climate Change Scenarios



Figures 5.23 and 5.24 display how climate change impacts the results of the implementation of the policy of water use restriction in Southwest and West Central Kansas. It can be seen that in both cases the effect is less than that observed in the Northwest. At the end of the period the reduction of water use under the water use restriction scenario compared with status quo is 22 % (Table 5.9) in the Southwest. If the effects of climate change are included, a very similar result is produced. In this region, the implementation of the policy is not strongly affected by climate change in terms of water use, which is largely due to greater availability of water.

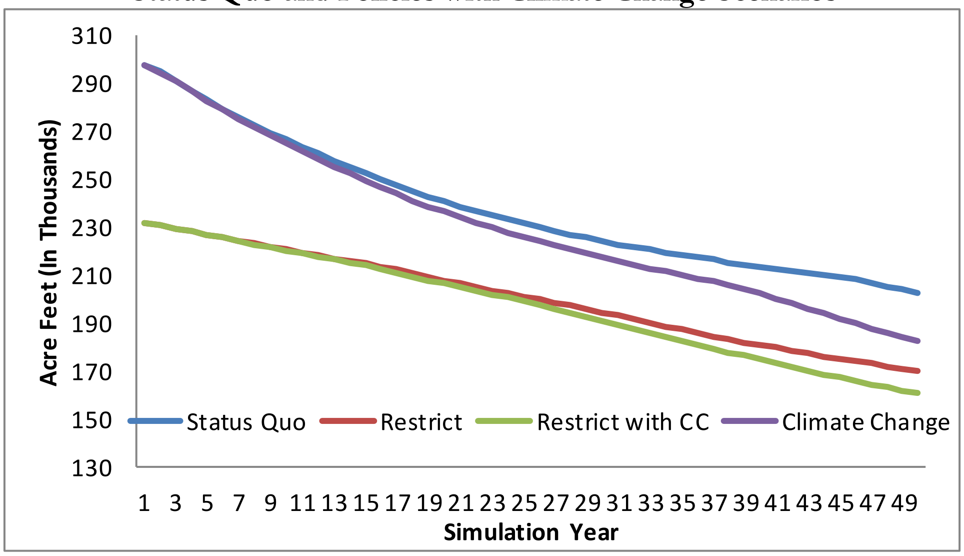
Looking at what happens in West Central Kansas, it can be seen that the reduction of water use is greater if the effects of climate change are included, because given the scarcity of water in the region, farmers change over sooner to dryland crops instead of irrigated crops. It should be remembered that this region is using practically the entire available supply of water and would be the first region to be affected by low water levels in the aquifer.

Figure 5.23. Total Water Use - Southwest Kansas
Status Quo and Policies with Climate Change Scenarios



The reduction in the level of water use comparing the status quo scenario with the water use restriction scenario without climate change is 16% (Table 5.9), whereas if we compare the climate change scenario with that of water use restriction with climate change, the reduction in water use is 14.5%.

Figure 5.24. Total Water Use - West Central Kansas
Status Quo and Policies with Climate Change Scenarios



5.3.2 WEIGHTED AVERAGE SATURATED THINCKNESS

This section analyzes the effects of applying climate change to the permanent conversion and water use restriction policies on the weighted average saturated thickness in the three study regions. Table 5.10 shows in detail the impacts on this variable compared with the status quo scenario. The tendency at the moment of including the effects of climate change are the same, but significant level changes occur in the studied variables.

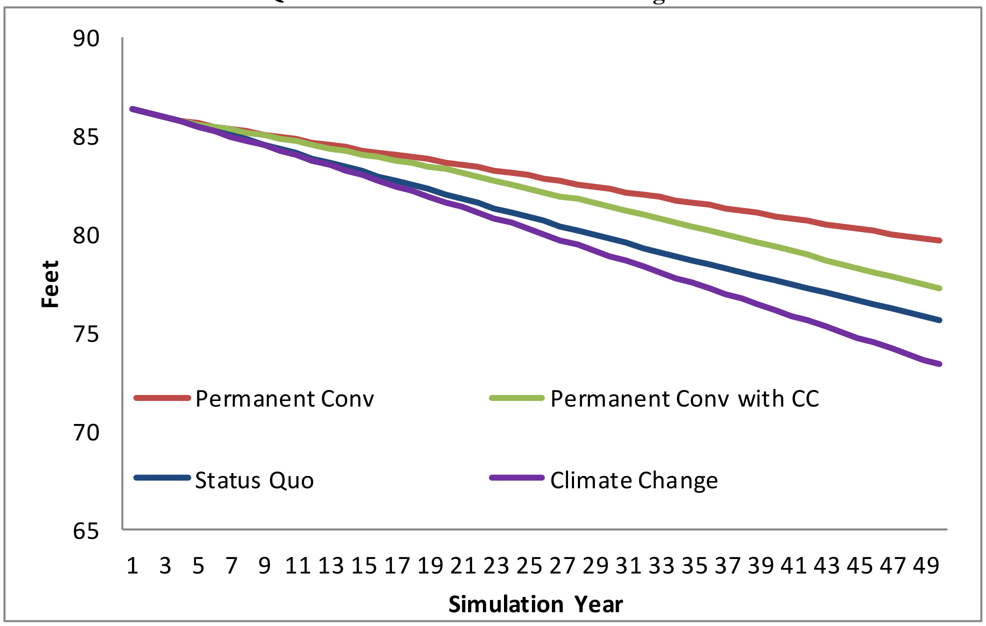
Table 5.10. Weighted Average Saturated Thickness (Feet) - Status Quo and Policies with Climate Change Scenarios

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Percentage Change
Northwest							
Status Quo	86	84	82	80	78	76	(12.52)
Climate Change	86	84	82	79	76	73	(15.12)
% Change *	-	(0.11)	(0.48)	(1.08)	(1.89)	(2.97)	
Permanent Conv.	86	85	84	82	81	80	(7.81)
% Change *	(0.04)	0.71	2.01	3.17	4.26	5.35	
Permanent Conv. Climate Change	86	85	83	81	79	77	(10.61)
% Change *	(0.04)	0.60	1.52	2.02	2.22	2.15	
Restrict Policy	86	85	83	82	80	79	(8.22)
% Change *	(0.00)	0.71	1.60	2.59	3.64	4.92	
Restrict Policy with Climate Change	86	85	83	81	79	77	(8.88)
% Change *	(0.00)	0.60	1.12	1.51	1.85	2.28	
Southwest							
Status Quo	179	166	152	138	124	112	(37.38)
Climate Change	179	166	150	134	119	106	(40.87)
% Change *	-	(0.09)	(1.37)	(2.74)	(4.23)	(5.57)	
Permanent Conv.	179	167	156	144	132	120	(32.76)
% Change *	(0.09)	0.61	2.62	4.35	5.84	7.27	
Permanent Conv. Climate Change	179	166	154	140	126	113	(36.94)
% Change *	(0.09)	(0.09)	1.19	1.36	1.04	0.61	
Restrict Policy	179	169	159	149	140	132	(26.17)
% Change *	(0.00)	1.80	4.55	8.35	12.81	17.89	
Restrict Policy with Climate Change	179	169	157	146	135	126	(29.71)
% Change *	(0.00)	1.74	3.27	5.75	8.68	12.24	
West Central							
Status Quo	53	51	49	48	47	46	(14.16)
Climate Change	53	51	49	48	46	45	(15.66)
% Change *	0.00	(0.09)	(0.32)	(0.71)	(1.23)	(1.75)	
Permanent Conv.	53	52	51	50	49	49	(8.31)
% Change *	(0.02)	1.81	3.54	4.80	5.85	6.79	
Permanent Conv. Climate Change	53	52	51	50	49	48	(10.83)
% Change *	(0.02)	1.69	3.04	3.68	3.93	3.86	
Restrict Policy	53	52	51	50	50	50	(7.21)
% Change *	(0.00)	2.17	3.90	5.28	6.64	8.09	
Restrict Policy with Climate Change	53	52	51	50	49	48	(7.52)
% Change *	(0.00)	2.06	3.44	4.23	4.81	5.31	

*** Present changes from status quo scenario**

Figure 5.25 shows an analysis of the changes that occur in the results of the implementation of the policy of permanent conversion with climate change on the weighted average saturated thicknesses in Northwest Kansas. In comparing the status quo and permanent conversion scenarios, a difference of 4 feet can be observed at end of the period (Table 5.10). But if climate change is taken into account, the difference is clearly reduced to only 1 foot at the end of the period. This is due to higher levels of water use under the climate change scenario. It is easy to see that due to the effects of climate change, the results of the implementation of the permanent conversion policy are lower than expected, and lower than those achieved if climate change is not accounted for.

Figure 5.25. Weighted Average Saturated Thickness - Northwest Kansas
Status Quo and Policies with Climate Change Scenarios



In regard to Southwest Kansas, the effects of climate change are even higher (Figure 5.26). The lowest level of weighted average saturated thicknesses occurs under the scenario of Climate Change, whereby at the end of the period the level is nearly 6 feet less than the status quo scenario. It is easily observed that upon implementing the permanent conversion policy, there is a higher level than that of status quo at 8 feet. However, upon including climate change it can be seen that the effect of the policy is reduced to only 1 foot above the status quo, denoting a loss of overall effectiveness of the policy of permanent conversion. Compared with the climate change scenario, the permanent conversion scenario with climate change results in a difference of 7 feet, but at lower levels of saturated thicknesses.

Figure 5.26. Weighted Average Saturated Thickness - Southwest Kansas

Status Quo and Policies with Climate Change Scenarios

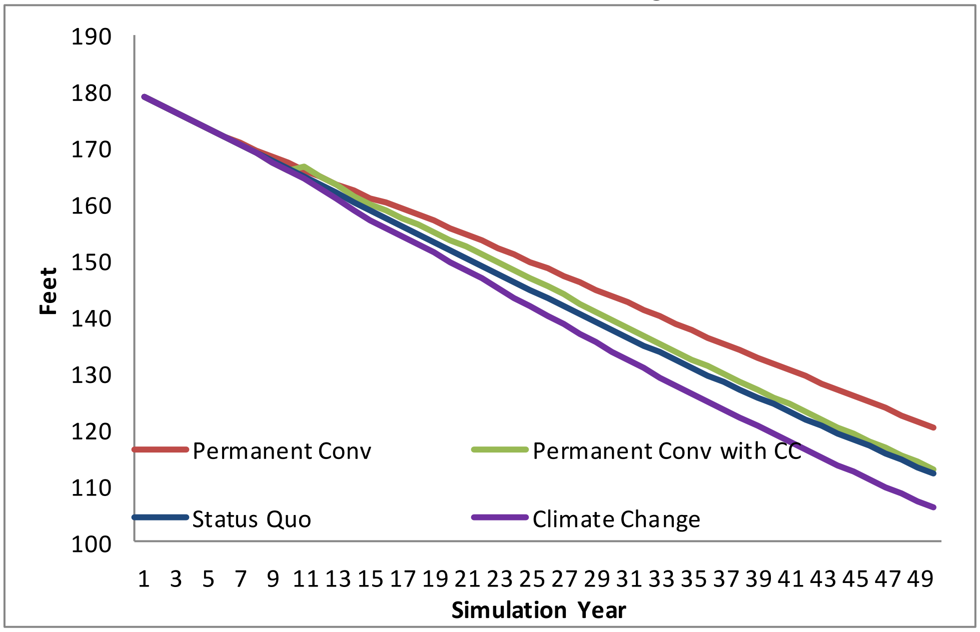
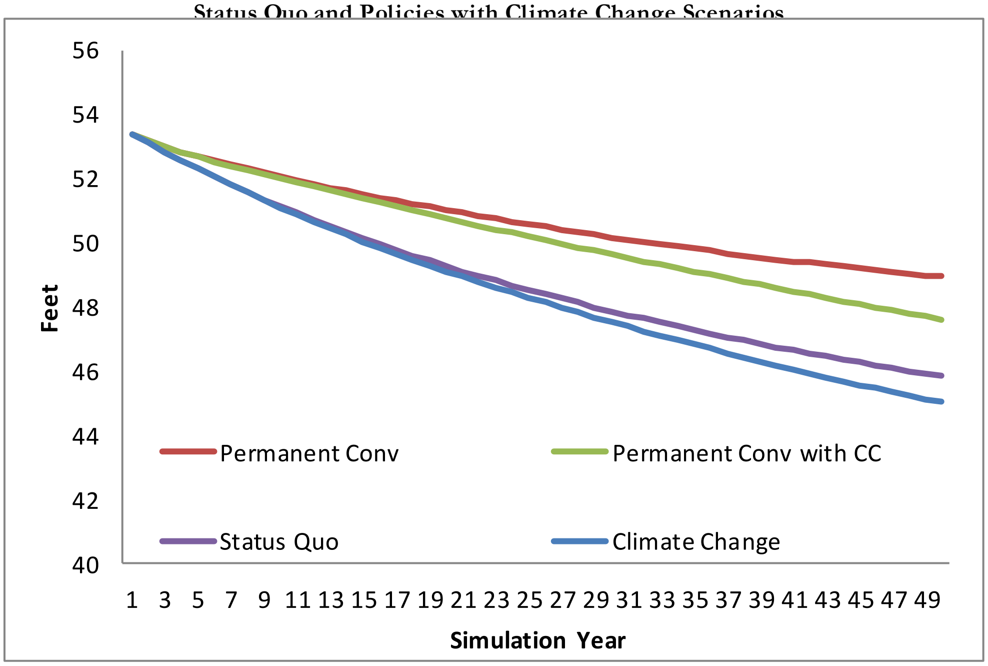


Figure 5.27 shows the results for West Central Kansas. In this region the results are more similar to those in Northwest Kansas. The implementation of the permanent conversion policy yields a higher level than status quo by 3 feet, but if climate change is included, and if this is compared with the scenario of permanent conversion with climate change, this difference is reduced to 2 feet. If permanent conversion with climate change is compared with the Climate Change scenario, the difference is 3 feet, but the levels of weighted average saturated thicknesses are less than those expected after the implementation of the policy.

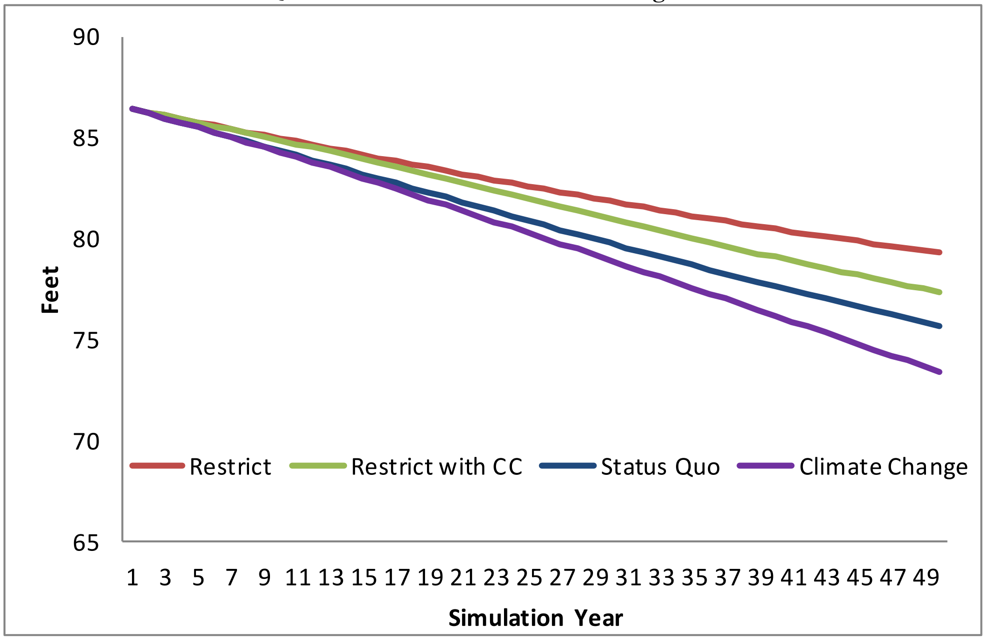
Figure 5.27. Weighted Average Saturated Thickness - West Central Kansas

Status Quo and Policies with Climate Change Scenarios



Next, the effects of including climate change upon applying the water use restriction policy are analyzed. The effects are very similar to those obtained by introducing changes in temperature and precipitation upon implementing the permanent conversion policy. For example in the case of Northwest Kansas (Figure 5.28), it can be noted that when climate change is in effect, the results expected after the implementation of the policy of water use restriction are not achieved. Without the effects of climate change, the level is 4 feet higher than status quo on average (Table 5.9), but if climate change is included this difference is reduced to 1 foot, a result much lower than expected. The difference is 4 feet when the scenario of climate change is compared with permanent conversion with climate change. This difference is equal to that obtained by comparing the status quo scenario with the scenario of climate change without permanent conversion, but the levels are different. In the case of the climate change scenario, the results from the implementation of the policy are not as large as expected.

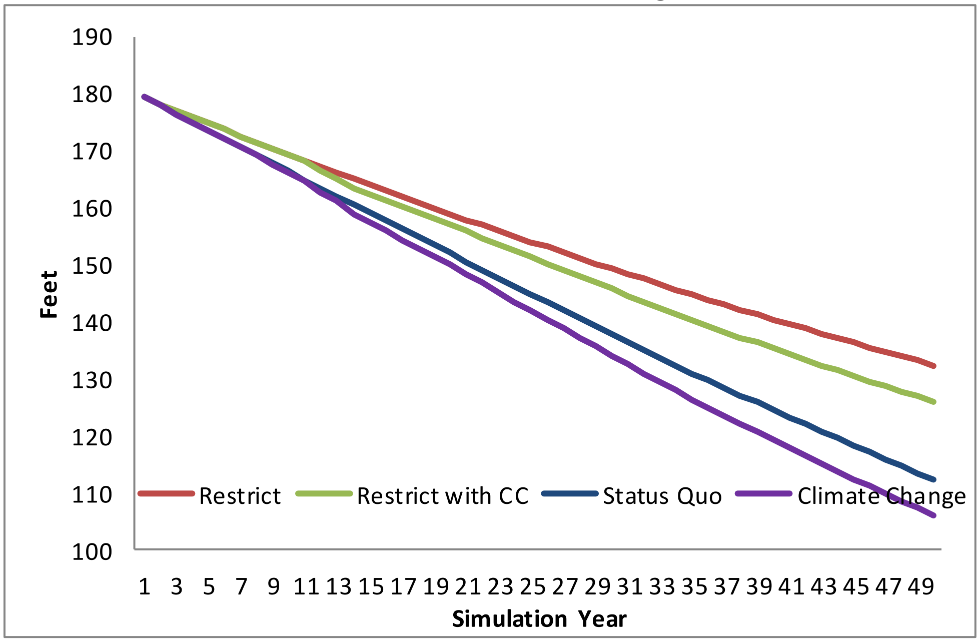
Figure 5.28. Weighted Average Saturated Thickness - Northwest Kansas
Status Quo and Policies with Climate Change Scenarios



The same can be observed for the other study regions. The Southwest Kansas (Figure 5.29) trend is very similar to that of the Northwest. Of course different levels are obtained due to the difference in accessibility of the aquifer in both areas. When the scenario of climate change without water restriction is compared to the status quo scenario, an average level of 20 feet results at the end of the period, but if climate change is applied and the scenario is compared with the status quo, this difference is reduced to 14 feet. Comparing the two scenarios with climate change, the difference is also 20 feet, but with lower than expected levels.

Figure 5.29. Weighted Average Saturated Thickness - Southwest Kansas

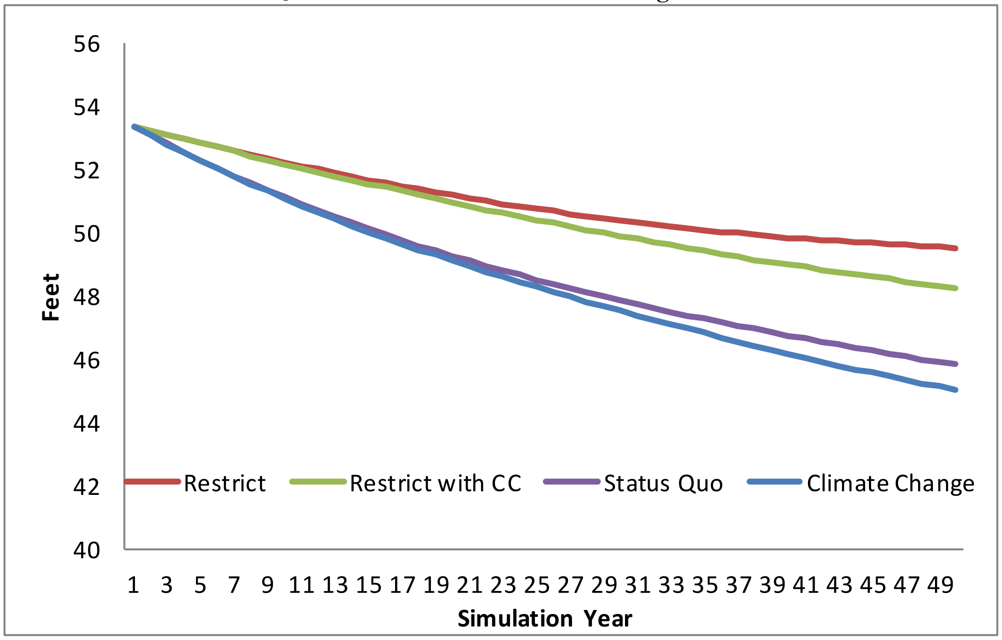
Status Quo and Policies with Climate Change Scenarios



In the case of West Central Kansas (Figure 5.30), the effects are very similar to the other regions. The implementation of the water restriction policy compared to the status quo scenario results in a higher level of weighted average saturated thicknesses by 4 feet. With climate change accounted for, this difference is reduced to 5 feet at the end of the simulation period when compared with the status quo. There is a difference of 3 feet if the water restriction policy is compared with the climate change scenario. In both cases the level of saturated thicknesses is overestimated if the effects of climate change are not accounted for.

It must be remembered that the results are aggregations of counties that are in the same region; in many cases, individual results may differ from one county to another despite being in the same region. This is due to the characteristics of the geographical distribution of the aquifer.

Figure 5.30. Weighted Average Saturated Thickness - West Central Kansas
Status Quo and Policies with Climate Change Scenarios



5.3.3 NET RETURN

This section discusses the related results and the variations experienced by the net return in the three study regions under the scenarios of permanent conversion and water restriction when the effects of climate change are included (Table 5.11).The results can be compared to the Status Quo scenario as well as the climate change scenario.

Table 5.11. Weighted Average Net Return Per Acre ($/cropland acre) - Status Quo and Policies with Climate Change

Zone	Year 01	Year 10	Year 20	Year 30	Year 40	Year 50	Porcentage change
Northwest							
Status Quo	123.38	123.38	123.29	122.33	120.88	119.87	(2.84)
Climate Change	123.38	123.09	122.62	120.61	118.71	117.03	(5.15)
% Change *	-	(0.24)	(0.54)	(1.40)	(1.80)	(2.37)	
Permanent Conv.	122.42	120.76	121.42	121.16	120.15	119.05	(2.76)
% Change *	(0.78)	(2.12)	(1.52)	(0.95)	(0.61)	(0.69)	
Permanent Conv. Climate Change	122.42	120.53	120.91	119.83	117.97	116.40	(4.92)
% Change *	(0.78)	(2.31)	(1.93)	(2.04)	(2.41)	(2.90)	
Restriction Policy	121.17	120.83	120.08	118.92	116.47	113.92	(5.99)
% Change *	(1.79)	(2.07)	(2.60)	(2.79)	(3.65)	(4.97)	
Restriction Policy with Climate Change	121.17	120.52	119.27	116.77	113.23	109.33	(9.77)
% Change *	(1.79)	(2.32)	(3.26)	(4.54)	(6.33)	(8.79)	
Southwest							
Status Quo	180.29	177.88	175.47	172.84	169.51	165.98	(7.94)
Climate Change	180.29	177.18	173.88	170.14	165.69	161.38	(10.49)
% Change *	-	(0.39)	(0.91)	(1.56)	(2.25)	(2.77)	
Permanent Conv.	179.09	174.61	174.22	172.52	169.89	167.44	(6.51)
% Change *	(0.66)	(1.84)	(0.71)	(0.18)	0.22	0.88	
Permanent Conv. Climate Change	179.09	174.03	172.79	170.17	166.37	162.90	(9.04)
% Change *	(0.66)	(2.17)	(1.53)	(1.54)	(1.85)	(1.86)	
Restriction Policy	170.52	165.79	160.64	155.80	151.35	147.04	(13.77)
% Change *	(5.42)	(6.80)	(8.45)	(9.86)	(10.71)	(11.41)	
Restriction Policy with Climate Change	170.52	164.51	157.92	151.80	145.97	140.69	(17.50)
% Change *	(5.42)	(7.52)	(10.00)	(12.17)	(13.88)	(15.24)	
West Central							
Status Quo	92.88	90.69	88.80	87.54	86.68	85.93	(7.49)
Climate Change	92.88	90.21	87.78	86.00	84.57	82.95	(10.69)
% Change *	-	(0.53)	(1.15)	(1.76)	(2.43)	(3.47)	
Permanent Conv.	91.96	89.64	89.03	88.03	87.30	86.77	(5.65)
% Change *	(0.99)	(1.16)	0.26	0.56	0.72	0.98	
Permanent Conv. Climate Change	91.96	89.24	88.14	86.63	85.43	84.26	(8.38)
% Change *	(0.99)	(1.60)	(0.74)	(1.04)	(1.44)	(1.94)	
Restriction Policy	89.16	88.31	87.27	86.16	84.87	83.79	(6.01)
% Change *	(4.01)	(2.62)	(1.72)	(1.59)	(2.09)	(2.48)	
Restriction Policy with Climate Change	89.16	87.88	86.38	84.76	83.02	81.56	(8.52)
% Change *	(4.01)	(3.10)	(2.73)	(3.18)	(4.22)	(5.08)	

*** Percent changes from status quo scenario**

The table above shows the trend of net return under all scenarios used in this research study. Interesting and different results can be observed in each region. Under the climate change scenario, the reduction in the net return is higher than the status quo in all regions. In Northwest Kansas, if the Permanent Conversion policy is applied including the effects of climate change, it could generate a smaller reduction of net return (4.92%) than if the Restriction policy (9.77%) is applied. Moreover, applying the permanent conversion policy would lead to a smaller reduction than if no policy were implemented, considering the base scenario that includes climate change effects (5.15%)

In Southwest Kansas, the results of the implementation of both policies including the effects of climate change are very similar to those of Northwest Kansas. The reduction in net return under the permanent conversion scenario including climate change would be 9.04%. This result, when compared to the implementation of the Restriction policy that includes climate change (17.50%) indicates a lower reduction of net return, as well as when compared to the base scenario including climate change (10.49%).

Results in West Central Kansas are different from those obtained in the other regions. In this region, the implementation of either of the two policies considered in this study would yield a lower reduction in net return compared to the baseline scenario that incorporates climate change. In addition, the reductions that would occur with the implementation of both policies are very similar (permanent conversion with climate change 8.38% and restriction policy with climate change 8.52%).

CHAPTER 6 – CONCLUSIONS, IMPLICATIONS AND FUTURE RESEARCH

6.1 CONCLUSIONS AND IMPLICATIONS

Many interesting conclusions can be drawn from this study. The shortage of water and the downward trend in Ogallala aquifer levels instigated the need for a lot of interdisciplinary research. Much of the research seeks to determine the effects the increased demand for water and for irrigated crops would have on the water table, due to their increased prices and profitability. Other studies show that the recharge rate of the aquifer is less than the rate of use, so the useful life of the aquifer is being reduced considerably. This increased use of the aquifer, although it might sound paradoxical, has been associated with improved technology and cost reductions resulting from it. Over the years, irrigation technology has improved considerably in terms of its efficiency and this has caused a greater extraction of water at lower costs for crop irrigation, generating better returns and good crop prices. In order to achieve greater sustainability of the aquifer, several water conservation policies have been designed which in some way or another seek to reduce water use and thus achieve greater useful life of the aquifer.

However, very few studies have addressed the effects that climate change could have on the results of the aforementioned policies. The research presented in this paper shows how the effects of climate change correspond to aquifer levels and how this impacts production figures. At the same time it allows for the observation that the implications of applying water conservation policies give rise to different results when the climatic variables are entered into the model. As mentioned previously, climate change can have direct and indirect effects on the demand and supply of water.

Some general conclusions are listed below, followed by some more specific ones. First of all, it should be mentioned that in this study, possible technological changes or changes in prices were not accounted for. Moreover, since the parameters are obtained from a calibration process, there are no confidence intervals throughout the course of the projections.

One of the first conclusions that can be drawn from this study is that as time passes, and if the level of water use continues at current rates, which is simulated under the status quo scenario in this research paper, the level of water use falls over time because the water supply diminishes. This situation is exacerbated by the effects of climate change. Given that the temperature increases and lower rainfall levels projected for the region generate increased demand for water in the early years, this, in addition to a low rate of replenishment, makes the levels of saturated thickness of the aquifer lower in the three study regions, such that the aquifer's lifetime is considerably reduced. At the same time, the net return is lower under the climate change scenario.

Another important conclusion follows from the results obtained when water conservation policies are applied, which correspond with the expected results. In the case of both policies, whether water use restriction or permanent conversion, it is evident that water use is reduced, there are higher levels of saturated thickness and lower levels of net returns in the three study regions. The final levels are different in each region due to the initial values of the studied variables. These values are determined by the hydrological conditions of the aquifer which are different between regions and even within each region.

Finally, when considering climate change and taking into account changes in temperature and precipitation in different scenarios, it can be observed that the trends remain generally as expected, but the magnitudes in all variables are different. Water use is still less than the status quo but is not reduced to the degree expected, because the new levels of temperature and precipitation bring about changes in water demand, which run counter to the effects generated in the water supply, since lower levels of rainfall negatively affect the rate of replenishment. For this reason, the level of saturated thickness in each region is lower whenever climatic variables are included in the policy scenarios, and the net return is even lower.

These results indicate that if the effects of climate change were not taken into account in the models used to simulate the effects of water conservation policies, inaccurate results would be obtained, and that different scenarios of water conservation policies may be overestimating the effects of implementing these policies. At the same time, since the type of crop in the region is subject to the supply of water from the aquifer, farmers could be affected more rapidly than expected, which implies a greater need for measures to adapt to climate change.

The more specific conclusions are as follows. If the effects of climate change are not taken into account, the results are less accurate and can lead to the application of the wrong policies. In relation to water use in the Northwest region, if the effects of climate change are not considered, it is notable that the implementation of the permanent conversion policy results in less water use than if the restriction policy is applied. However, if the same policies are considered, but the effects of climate change are included, the restriction policy yields a lower level of water use than permanent conversion.

Conversely, in the Southwest region, in both cases--both including and excluding the effects of climate change--the policy under which lower water use would result at the end of the study is the restriction policy.

West Central Kansas produces very different results. As this region has the smallest water supply, a lower water level occurs under the climate change scenario, which is largely because all of the available water is being used. In this region, under the restriction policy (both with and without climate change) the level of water use would be lower at the end of the simulation period.

In regard to Saturated Thickness, levels at the end of the simulation period are lower under the climate change scenario than under the status quo. This is because with climate change, the increased demand for water leads to greater water use at least in the first years, which is only reduced toward the end of the period. Interesting outcomes can be observed upon analyzing the results of the implementation of both policies.

In Northwest Kansas, if the effects of climate change are excluded, the policy under which the highest levels of saturated thickness would be obtained is permanent conversion. However, by incorporating the scenarios of climate change in both policies, it's clear that under both conversion and permanent restriction policies, the results at the end of the period would be the same. Therefore it would be irrelevant which policy were applied.

In West Central Kansas, without considering climate change, the opposite of Northwest Kansas occurs. Without accounting for climate change, the application of the restriction policy would give higher levels of saturated thickness at the end of the study period. However as in the

Northwest region, if climate change effects are included, the levels obtained at the end of the period are the same.

In the Southwest region, the only difference that exists between the implementation of both policies, including the effects of climate change, are the final levels, but both with or without climate change, the highest levels of saturated thickness are obtained under the restriction policy.

In regard to net return, the Northwest region yields different levels because of the effects of climate change, but the policy under which the smallest reduction of net return is obtained at the end of the period is permanent conversion.

Southwest Kansas returns results similar to those obtained in Northwest Kansas, where both with and without the effects of climate change, the policy that would yield a smaller reduction in net return at the end of the period would be permanent conversion. However, when considering climate change under both policies, the difference in favor of permanent conversion is minimal. Unlike the other two regions, both policies would lead to a lesser reduction in the net return at the end of the period, so that the application of either would be beneficial in this region.

From the above, it can be concluded that the non-inclusion of the effects of climate change on the policy scenarios could generate incorrect values in the studied variables, as well as resulting in misapplication of water conservation policies. In addition, the results of the policies are largely determined by the hydrological and agronomic conditions of each region, so that a policy may have different results in different regions. Further, the results of this study were reported at the crop reporting district level, but there is also substantial variation across counties within each district. For example, within the Northwest district the percent changes in water use under the climate changes scenario varies from 0.13% to -0.41%, with an average variation of -0.07 These results underscore the importance of considering spatial differences prior to implementation of policies.

6.2 FUTURE RESEARCH

For the purposes of this research study, only county level data were considered, and the results were aggregated from three regions. Given that aquifer levels and characteristics may vary from one county to another and even between neighboring counties, it would be interesting for future studies to use micro level data that can give more accurate results, and compare them with those obtained in this study .

Since the aim of this study is to observe the trends of the variables on a long term basis, the climate data used represent the average changes that would be expected to occur in rainfall and temperature levels in the next 50 years in this region. However, if the objective were to observe how these climatic variations can have effects on short term variability, these variations could be incorporated in the model and this would reveal short term outcomes and allow measures to adapt to climate change in the next few years to be proposed.

This study employs a calibration method to determine the parameters of the model, such that the model's prediction exactly fits the calibration base year. The advantage of this approach is that it can be applied even in a data sparse environment when time series of all relevant variables are not available. When sufficient data are available, an alternative approach would be to estimate the parameters econometrically, which would allow the researcher to quantify confidence intervals around the projections due to parameter uncertainty.

This research does not include population growth and technological changes, although the model allows for the inclusion of these variables so that in future research they could be considered.

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APPENDIX

Appendix 1a. Hydrological Parameter in the North West

Parameter	Unit	Symbol	North West							
			Chyenne	Decatur	Graham	Morton	Rawlins	Sheriran	Sherman	Thomas
Base Lift pdt	feet	Lift	152.0	109.0	101.0	136.0	136.0	112.0	146.0	129.0
Base Saturated Thickness in ft	feet	ST	94.0	49.0	88.0	141.0	65.0	72.0	143.0	90.0
Specific Yield	--	s	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2
Land Area Above Aquifer (acres)	acres	A	423495.0	572810.0	471769.0	466849.0	685286.0	566674.0	673882.0	687962.0
Hydrolic Conductivity (ft/day)	feet/day	HC	64.1	58.5	61.8	42.5	57.3	68.5	84.0	87.3
Recharge Rate (acre inches/acre)	inches/year	R	0.6	0.8	1.1	0.6	0.7	0.8	0.5	0.5
Depth	feet	D	152.5	108.5	100.7	135.7	135.8	111.5	145.9	128.7
Wells	--	--	583.0	237.0	193.0	375.0	239.0	708.0	885.0	797.0
Required Minimum Saturated Thickness	feet	Stimin	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0

Appendix 1b. Hydrological Parameter in the South West

Parameter	Unit	Symbol	South West													
			Clark	Finney	Ford	Grant	Gray	Hamilton	Haskell	Hodgeman	Kearny	Meade	Norton	Seward	Stanton	Stevens
Base Lift pdt	feet	Lift	128.0	121.0	104.0	233.0	134.0	173.0	292.0	50.0	144.0	152.0	78.0	189.0	225.0	185.0
Base Saturated Thickness in ft	feet	ST	193.0	183.0	87.0	199.0	139.0	72.0	227.0	29.0	174.0	315.0	75.0	315.0	131.0	322.0
Specific Yield	--	s	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2
Land Area Above Aquifer (acres)	acres	A	246248.0	739419.0	690005.0	368115.0	552663.0	608044.0	369061.0	301920.0	543046.0	612964.0	543112.0	410811.0	437037.0	466497.0
Hydrolic Conductivity (ft/day)	feet/day	HC	86.5	80.0	81.6	55.4	99.8	48.9	81.6	81.7	88.1	78.2	47.0	74.0	58.5	65.7
Recharge Rate (acre inches/acre)	inches/year	R	1.3	0.9	1.1	0.7	1.0	0.5	0.9	0.9	0.7	1.1	1.0	1.0	0.5	0.9
Depth	feet	D	120.6	121.4	104.3	233.0	134.2	172.7	292.4	50.4	144.0	152.2	78.5	189.5	224.9	185.3
Wells	--	--	53.0	1811.0	864.0	692.0	1525.0	256.0	986.0	408.0	848.0	609.0	205.0	566.0	750.0	753.0
Required Minimum Saturated Thickness	feet	Stimin	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0

Appendix 1c. Hydrological Parameter in the West Central

Parameter	Unit	Symbol	West Central								
			Gove	Greeley	Lane	Logan	Ness	Scott	Trego	Wallace	Wichita
Base Lift pdt	feet	Lift	87.0	147.0	89.0	117.0	89.0	112.0	87.0	166.0	125.0
Base Saturated Thickness in ft	feet	ST	50.0	41.0	47.0	68.0	47.0	46.0	50.0	98.0	50.0
Specific Yield	--	s	0.1	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.2
Land Area Above Aquifer (acres)	acres	A	293433.0	495920.0	391288.0	329797.0	123902.0	462980.0	293433.0	338669.0	460293.0
Hydrolic Conductivity (ft/day)	feet/day	HC	45.5	66.3	70.2	46.0	90.2	66.7	47.7	77.6	71.8
Recharge Rate (acre inches/acre)	inches/year	R	0.7	0.5	0.6	0.5	0.8	0.6	0.7	0.5	0.5
Depth	feet	D	87.3	146.8	88.6	117.0	87.0	112.1	89.0	3535.2	125.1
Wells	--	--	353.0	282.0	245.0	124.0	125.0	792.0	353.0	539.0	886.0
Required Minimum Saturated Thickness	feet	Stimin	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0