GROUNDWATER, CORN AND CATTLE: AN INVESTIGATION ON THE IMPLICATIONS OF FUTURE GROUNDWATER AVAILABILITY ON THE AGRICULTURAL INDUSTRY IN WESTERN KANSAS

by

PAUL J. BRUSS

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Approved by:

Major Professor
David R. Steward

Abstract

Kansas relies on groundwater for nearly 85 percent of the total water used each year, most of which is used for irrigation. Over the last 30 years, declining groundwater levels in some areas have put pressure on agricultural industries. Ongoing research on the usage of groundwater resources will be necessary to sustain agriculture.

In this study, two groundwater models were developed to investigate groundwater availability and use in western Kansas. The first model, called the Saturated Thickness Model (STM), investigated how groundwater resources will change over the next century. The second model, called the Change in Water Level Model (CWLM), was used to forecast water use trends for three agricultural districts in western Kansas by relating the change in groundwater levels over time to the volume of water pumped for irrigation. To understand how these changes would affect the agricultural industry, the research investigated historical trends in reported groundwater use, corn production and cattle in feedyards.

The results showed significant decreases in the modeled saturated thickness over the next 100 years in western Kansas. Modeled groundwater use matched reported groundwater use data relatively well. The model showed significant decreases in groundwater use over the next 100 years, with the largest decrease being in the southwest district. Overall, forecast water use trends were in agreement with current outlooks for each area. The results from the correlation analysis showed a negative relationship between groundwater use and irrigated corn production, indicating improved irrigation efficiency and crop species over the past 30 years. Further correlations showed the number of cattle on feed in a particular area increased with the amount of irrigated corn production in the same area. This implies the cattle feedyards tendency toward local source of grain.

As groundwater resources decline, corn production will decrease, and changes in the agricultural landscape will require adaptation. Feedyards will need to find new sources of corn grain or change to a less water dependent feed. Further research is needed to determine where corn grain will be produced in the next 100 years, and how corn grain will be transported to feedyards in southwest Kansas.

Table of Contents

List of Figures

List of Tables

Definitions

1. **Anisotrophy** - Anisotrophy in a set of data means that the data is directionally dependent. When interpolation is being used to estimate an unknown point, data points in a given direction may be more influential than data points in another direction. Kriging is able to address anisotrophy.

2. **ArcGIS** - ArcGIS is a software suite developed by ESRI that allows users to create, edit, view and analyze geographical data. More information on ArcGIS can be found at http://www.esri.com/software/arcgis/index.html.

3. **Autocorrelation** - Autocorrelation is the spatial correlation of data where the correlation is dependent on the distance and/or the direction separating the locations of data points.

4. **Geostatistical interpolation** - Geostatistical interpolation involves the use of both mathematical and statistical models, involving autocorrelation, to create a continuous surface from a sample of data points dispersed in different locations. The main advantage of geostatistical interpolation over deterministic methods such inverse distance weighting (IDW) is the ability to assess how well the interpolated values match the true values.

5. **Kriging** - Kriging is the primary geostatistical method used for spatial interpolation.

6. **lag size** - A lag is the vector between two data points. A lag has both a distance component and directional component. The lag size is the distance. The lag size is one of the parameters selected during the process of ordinary kriging. It has an affect on how the semivariogram operates.

7. **Number of neighbors** - The number of neighbors is one of the parameters selected during the process of ordinary kriging. It determines how many data points will be considered when estimating a given unknown point.

8. **Ordinary Kriging** - Ordinary Kriging is the most commonly used type of Kriging. In Ordinary Kriging, the trend is constant but unknown.

9. **Raster** - In ArcGIS, a raster is an image that consists of a grid of pixels whereby each pixel has information stored within it. Rasters can come in the forms such as aerial and satellite imagery or digital elevation models. Common formats for rasters are GRID, TIFF, JPEG, PNG and GIF.

10. **Saturated thickness** - Saturated thickness is the vertical depth of the aquifer between the water table and the bedrock floor.

11. **SciLab** - SciLab is an open source, interpreted, computer programming language that can be used for a wide range of scientific and engineering problems. More on SciLab can be found at www.scilab.org.

12. **Semivariogram** - A semivariogram is a function used in the kriging process to help determine spatial correlation of known points.

13. **Specific yield** - Specific yield is the amount of water that will drain from a volume of aquifer material due to gravity.

Acknowledgments

There are several people that I am in debt to for their part in helping me write and submit this thesis. First, I would like thank my advisor, Dr. David Steward, for initially sparking my interest in water resources, and for providing me with the opportunity to pursue it further. Second, I would like to thank my wife, Sarah, who made sacrifices to allow me to pursue graduate school, and has always been encouraging and supportive. Third, I would like to thank Dr. Michael Apley and Dr. Marcelus Caldas for taking the time to serving on my committee, review my thesis and supervise my final examination. Fourth, I would like to thank Xiaoying Yang and Rick Chubb for their help with ArcGIS and assistance with data. Lastly, I am sincerely thankful for the financial support that I received from the University Transportation Center and Kansas NSF-EPSCoR to conduct this research.

Dedication

This thesis is dedicated to my wife, Sarah, who has constantly been there for me throughout the entire journey of writing this thesis.

Chapter 1

Introduction

1.1 Overview

The state of Kansas has long had a rich agricultural heritage, known throughout history for its homesteaders and cow towns. Since settlement opened in 1854, Kansans have made a way of life despite difficulties, including limited resources, turning Kansas into a productive agricultural state. Today, this heritage continues through the efforts of Kansas farmers and ranchers who work to keep Kansas a key agricultural producer in the nation. According to the USDA's National Agricultural Statistics Service, in 2009 Kansas farmed the second largest area of cropland in the nation. In terms of individual crops, Kansas ranked 1st in production of grain sorghum, 2nd in wheat production, and 7th in corn production. The cattle industry has also maintained an important role in the state and national agricultural economy. In 2009, Kansas had the 3rd most cattle and calves in the nation, with a total of 6 million head of cattle as of January 1, 2010. Approximately 2.37 million cattle and calves were on feed. Cash receipts for cattle sales in Kansas in 2009 were approximately 5.5 billion dollars.[1] The success that the agricultural industry has seen for several years has not come without difficulty. To be able to produce reliable yields, farmers have often needed to rely on sources other than natural precipitation to water their crops. Since the advent of the center pivot irrigation system in the mid-1900s, western Kansas farmers have relied significantly on finite groundwater resources to grow important, though water intensive, crops like corn. Groundwater resources have since been in decline, raising concerns over the sustainability of agriculture in the region. This has led to a need for more research on how we use groundwater and how the resource's availability has changed over time. The purpose of this thesis is to investigate current and future groundwater availability and use in western Kansas, and to determine the relationships between groundwater resources and agriculture in the area.

This thesis is separated into five chapters, with the references and appendices at the end. Following this introductory Chapter, Chapter 2 provides background information on the Ogallala Aquifer, agriculture in western Kansas, and previous research related to the subject of this study. Chapter 3 discusses the methodology used to conduct the research for this project. In Chapter 4, the results of the research work are presented and discussed, and the implications of the results to broader society are considered. Lastly, Chapter 5 provides the conclusion for this thesis. Here, the aims of the thesis are reviewed, the results are summarized, and the broader impact of this research is discussed.

Chapter 2

Literature Review

2.1 The High Plains and Ogallala Aquifers

The High Plains Aquifer, which includes the Ogallala formation, is one of the largest aquifers in the world, reaching into eight states, and covering an area of approximately 450,000 km^2.[2] It is the largest source for groundwater use in the United States, making up 30 percent of total irrigation groundwater use in the US. Other than irrigation, the 2nd largest use of groundwater is for public supply. The High Plains Aquifer is the primary source of drinking water to 82 percent of the people that live within its borders.[3]

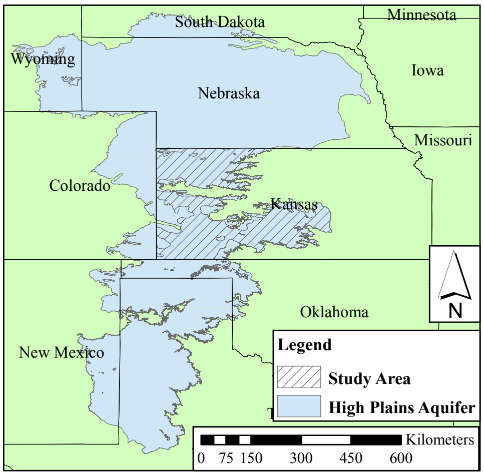


Figure 2.1: *Extent of the High Plains Aquifer in the Midwest United States.*

The Ogallala Aquifer, which makes up 80 percent of the High Plains Aquifer, is the primary groundwater resource in the state of Kansas.[3] The Ogallala Aquifer is considered fossil water because much of it was originally formed about 3.8 million year ago from river deposits from the Rocky Mountains. As a result, it is mostly a non-renewable source. The estimated recharge to the aquifer from precipitation is a mere 6.35 - 12.70 millimeters per year.[4]

The extent to which groundwater is available varies spatially throughout western Kansas. The saturated thickness, which is the vertical depth of the aquifer between the water table and the bedrock floor, varies as well. The saturated thickness gives indication to the volume of available groundwater underlying an area. According to research conducted by the Kansas Geological Survey, the saturated thickness of the Ogallala Aquifer in Kansas ranges anywhere from 0 to over 100 meters, with the greatest depth in areas of the southwest (see Figure 2.2).[5]

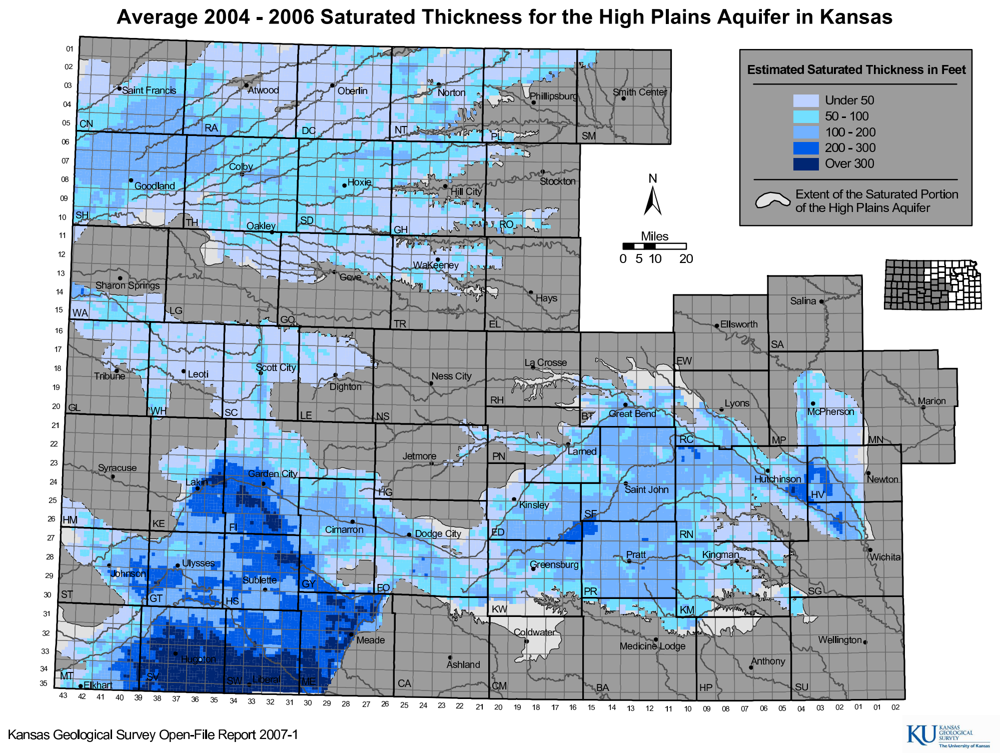


Figure 2.2: *KGS - Average saturated thickness from 2004 to 2006 (Source: OFR 2007-01).*

The state of Kansas relies on groundwater for 85 percent of its total water use. This includes municipal, industrial, agricultural, and rural domestic purposes.[4] This is remarkable in comparison to the United States average of 20 percent.[6] Of the total groundwater used in Kansas, 94 percent is used for irrigation.[4] The need for extensive irrigation is due to limited precipitation in western Kansas. Average annual precipitation in Kansas, shown in Figure 2.3, ranges from approximately 429 millimeters per year in the western part of the state to 1160 millimeters at the eastern border of the state.[7] For perspective, a rough estimate of the minimum water requirements for growing corn is approximately 610 to 760 millimeters of precipitation, depending on the climate (converted from 24 to 30 inches).[8,9]

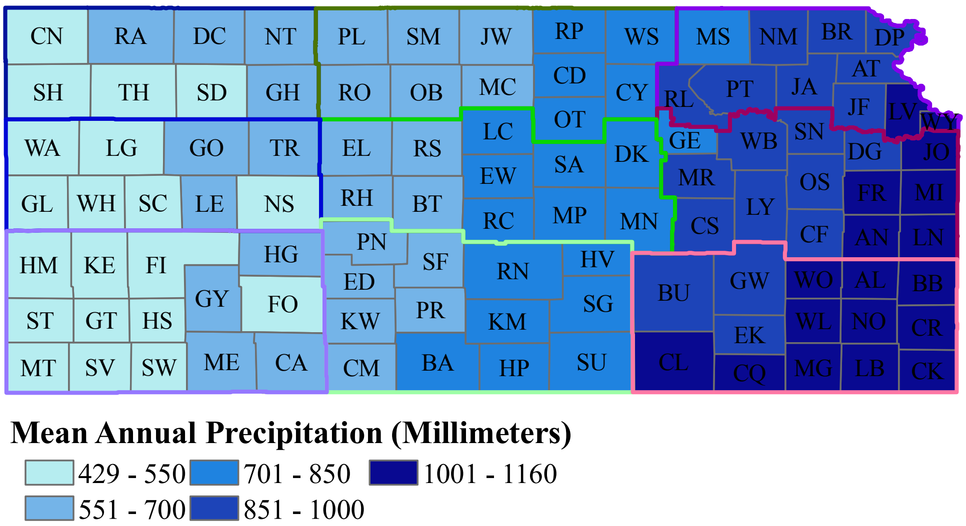


Figure 2.3: *Kansas Normal Annual Precipitation 1980-2009 (Data Source: KSRE Weather Data Library).*

Irrigation in the Ogallala region initially took off in the 1950s with the advent of the center pivot irrigation system. The Kansas Water Appropriation Act of 1945, the law that established the basic structure for administering and regulating water rights, was passed initially to develop the use of groundwater. Groundwater was seen as an unlimited supply. During the next 30 years, near exponential growth in the number of groundwater wells occurred throughout the Ogallala Aquifer. Soon, however, observed declines in the groundwater table led to concerns of groundwater mining, changing the outlook on groundwater resources. A shift from development toward regulation occurred soon after. In 1972, the

Groundwater Management District Act was passed and over the next 4 years, 5 Groundwater Management districts were formed, enabling key groundwater areas to be governed with limited local autonomy. In 1978, the Kansas Water Appropriation Act was amended continuing a shift toward regulation rather than development. By 1980, the Kansas Division of Water Resources (DWR) began requiring non-domestic water uses to be reported yearly. Today, according to reported groundwater use over the last 30 years, groundwater use has decreased or plateaued in many areas.[10] Conservation programs, irrigation efficiency, and large areas being closed off to new groundwater appropriations are positive ways that groundwater use has decreased. Increased pumping costs, decreasing yields and less productive parts of the aquifer have likely been the cause for decreasing groundwater use in some areas. Nonetheless, groundwater use today continues at a rate that is at risk of endangering future agriculture. In Figure 2.4, the total irrigation groundwater use is shown for 2009.

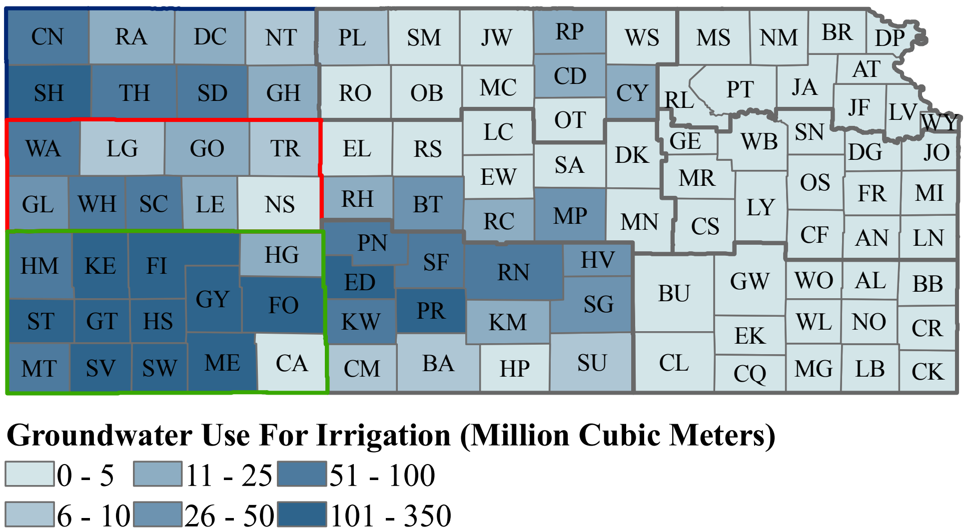


Figure 2.4: *2009 Irrigated Groundwater Use from WRIS database.*

For reference, 1 acre-feet is approximately 1233 cubic meters. As shown in the figure, groundwater use varies spatially throughout western Kansas. The extent of the Ogallala Aquifer is apparent in the location of groundwater use throughout western Kansas.

2.2 A Short Overview on Previous Research on Groundwater Availability

Government agencies and educational institutions concerned with the declining groundwater resources in the Ogallala have spent considerable effort over the last forty years in characterizing the aquifer, recording changes in water levels, and understanding how we use the resource. The United States Geological Survey (USGS) was one of the first agencies invested in understanding the changing Ogallala Aquifer at a regional scale. While the USGS's role covers a wide range of areas in water resources, geology, and climate (among others), its role in the study of groundwater has been crucial. USGS Professional Paper 1400-B, published by Gutentag (Gutentag et al., 1984) was one of the earliest and most important publications on the High Plains Aquifer as a whole. The paper is a comprehensive work, providing information on the geological and hydrological characteristics of the aquifer as well as describing the role the aquifer has played in our society. An important part of the paper describes the changes in saturated thickness that have occurred in the aquifer due to the development of irrigation. Since this publication, the USGS has continued to be involved in investigating the changes in the aquifer. The USGS works with other agencies to provide the infrastructure for monitoring groundwater, and they continue to release reports on work in the area. On of the most recent publications on the changing aquifer is in McGuire (2009).[6] In Figure 2.5, a map produced for this report shows the observed changes in saturated thickness throughout the High Plains Aquifer covering eight states from predevelopment to 2007 (including the Ogallala formation in Kansas).

At the state level, the Kansas Division of Water Resources (DWR)and Kansas Geological Survey (KGS) have also invested efforts to understand the changing Ogallala Aquifer in Kansas. While the DWR's role has been largely regulatory, it has played an important role in recording how Kansans use water. As required by the Kansas Water Appropriation Act, Kansans who use groundwater for purposes beyond domestic uses must report their water use annually. The DWR maintains an extensive record of this reported water use

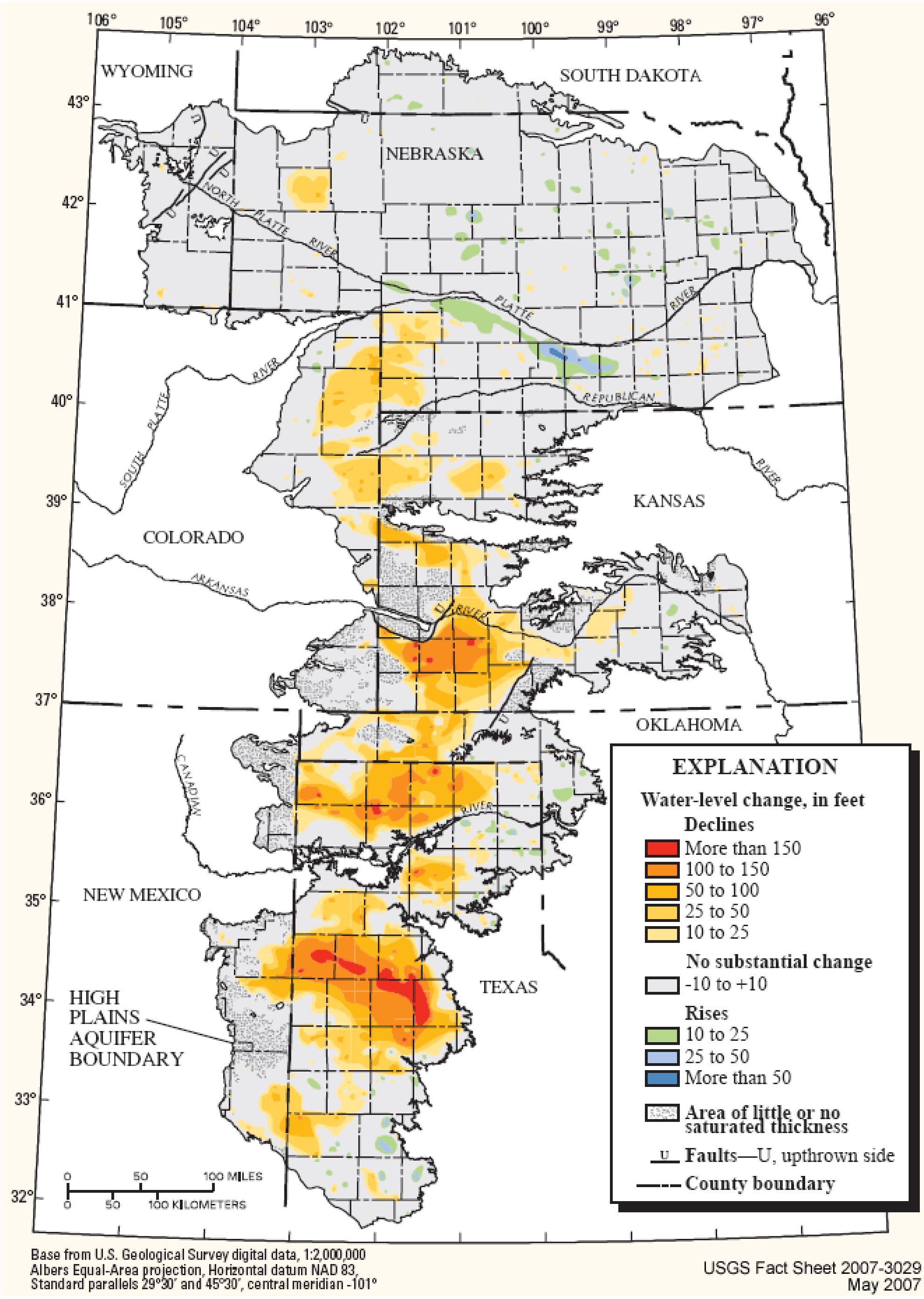


Figure 2.5: *Changes in saturated thickness from Predevelopment to 2007 published by the USGS in McGuire (2009).*

in a database called the Water Rights Information System, or WRIS. The WRIS database includes yearly water use reports for all points of diversion in the state, starting in 1958. Reliability of the data are checked for quality control but does vary depending on the time period it is reported, the individual user, and the location of the diversion point. For instance, water use reporting was not mandatory until 1980, and actual metering of water use didn't begin until 1992 starting in Groundwater Management District 3, and still isn't implemented in all areas of Kansas. Nonetheless, the data available in the WRIS database provide important information on the use of water in Kansas over time.

The Kansas Geological Survey has a similar role to the USGS but at the state level in Kansas. Along with research in geology, geophysics and energy in Kansas, the KGS investigates a wide variety of topics related to water resources and maintains several important water-related databases as well. The KGS is the home of the WIMAS, WWC5 and WIZARD databases. The WIMAS (Water Information Management and Analysis System) database maintains information on all current water rights connected to points of diversion throughout Kansas and is related to the DWR's WRIS database. The WWC5 (Water Well Completion Records) database maintains information on all available drilling logs connected to water wells in Kansas. Information from WWC5 has been used develop information regarding depth to bedrock and locations of productive saturated thickness. The WIZARD database is the home of groundwater level data produced from an extensive network of monitoring wells throughout Kansas. Accessible via the KGS's website, all three databases are available to the public.

The KGS is also a source of active research concerning the Ogallala Aquifer. To understand groundwater availability in Kansas over time, the KGS developed predevelopment and current saturated thickness maps. The term 'predevelopment' generally refers to the time before major irrigation use, around the 1940s and 1950s. In Figure 2.6, the predevelopment saturated thickness is mapped by the KGS. This map provides a good indicator of natural conditions of the aquifer prior to irrigation development (see Figure 2.2 for a map of current saturated thickness).

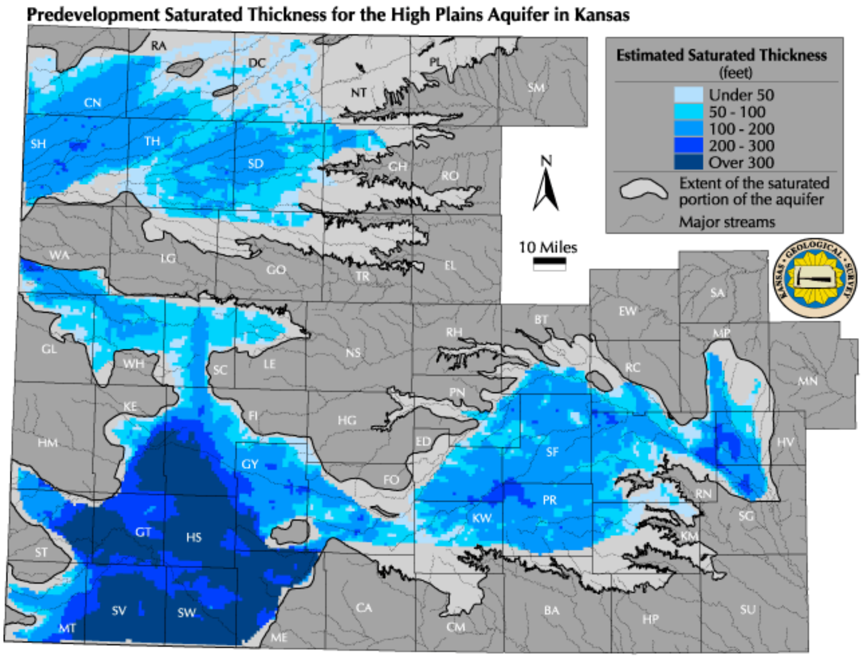


Figure 2.6: *KGS - Predevelopment saturated thickness (Source: KGS - High Plains Atlas).*

The KGS has also conducted research involving the mapping the of changes in saturated thickness over time, and projecting water level declines into the future to determine an estimated usable lifetime. Using historical decline rates projected into the future, and a minimum saturated thickness estimated to be the threshold for productive pumping for irrigation, maps were developed showing the estimated usable life of the aquifer. These maps, called the Estimated Usable Lifetime maps, were first created in 1998.[11] In Figure 2.7, the most recent Estimated Usable Lifetime is mapped using water level changes from 1996 to 2006.

The KGS has documented methods for mapping the groundwater level data that have been produced since 2002. In a series of open file reports, most recently in OFR 2007-32, the KGS documents statistical and geostatistical analysis conducted for groundwater levels throughout the Ogallala Aquifer. The primary method of interpolation in these reports by the KGS is Kriging.[12]

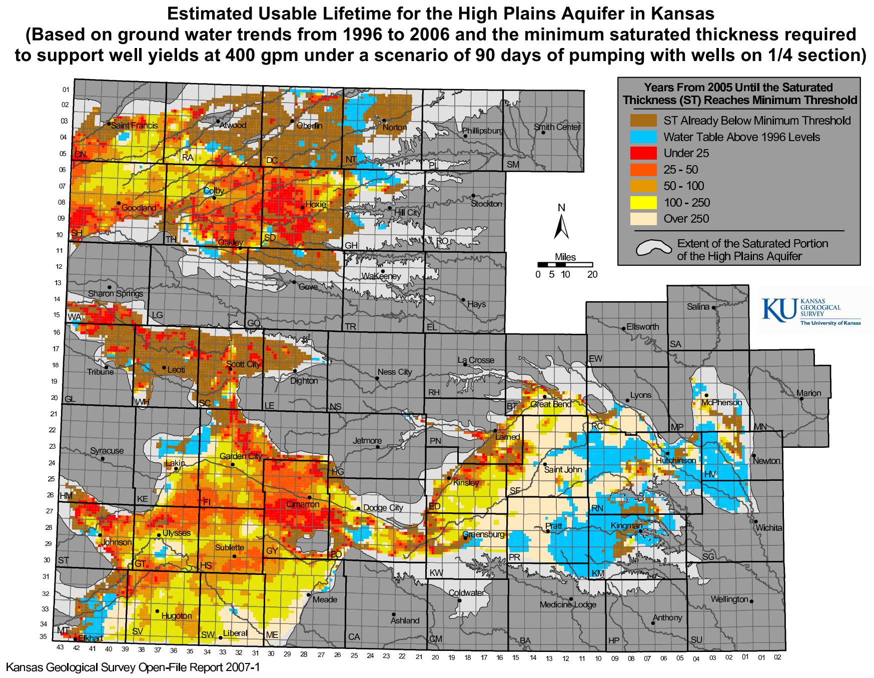


Figure 2.7: *KGS - Estimated Usable Lifetime based on 1996-2006 trends (Source: OFR 2007-01).*

Educational institutions including land grant universities like Kansas State University (K-State) have also played an active role in research. Benefiting from a variety of colleges focused on agriculture, science and engineering, considerable research has been conducted in efforts to understand groundwater in Kansas as well as understand and improve the agricultural industry that relies on it. Active Research relevant to this thesis that occurs at K-State includes groundwater modeling, GIS, agronomic and livestock research as well as political and economical research . K-State also maintains a network of research and extension sites and hosts its own weather data library.

2.3 Agriculture in Western Kansas

Agricultural production has long been the main industry in western Kansas. The primary crops produced are corn, wheat, sorghum and soybeans. In Kansas, wheat is the most widely planted crop, representing approximately 40 percent of harvested crop acreage, followed by corn, soybeans and then sorghum.[13] The top graph in Figure 2.8 shows the historical trend of planted area. In terms of production, however, for nearly a decade the Wheat State has

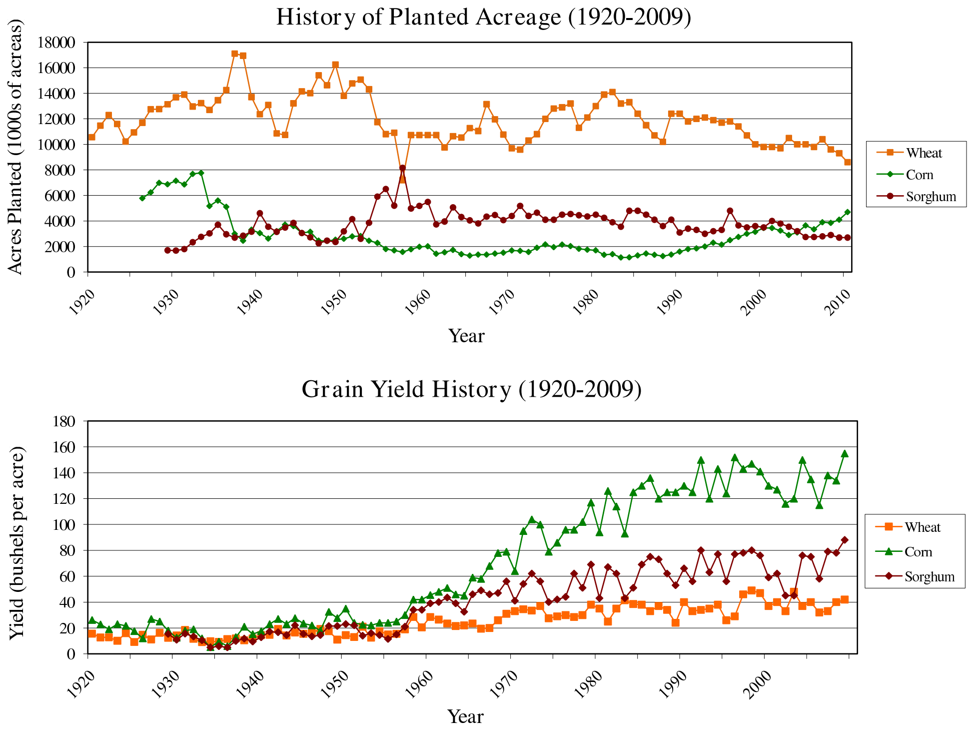


Figure 2.8: *Historical Harvested Acreage and Yield for main crops in Kansas (Data Source: NASS).*

actually produced more corn than any other crop. This is mostly due to significant increases in yield that have occurred over the last half century and a recent increase in planted area. The leading cause for increase in corn yield is the development of groundwater irrigation. In the bottom graph in Figure 2.8, the historical trend in crop yields are shown. The increase in yield that occurred over the last half century follows the approximate timing of the development of irrigation. Today, Kansas ranks 7th nationally in corn production.[13]

Depending on the availability of sufficient precipitation, corn in Kansas can be grown with or without the use of irrigation. In most areas of western Kansas, there is insufficient precipitation to grow a reliable corn crop year in and year out. Areas in the northern and northwestern parts of Kansas are the main exception. In figures 2.9 and 2.10, irrigated and

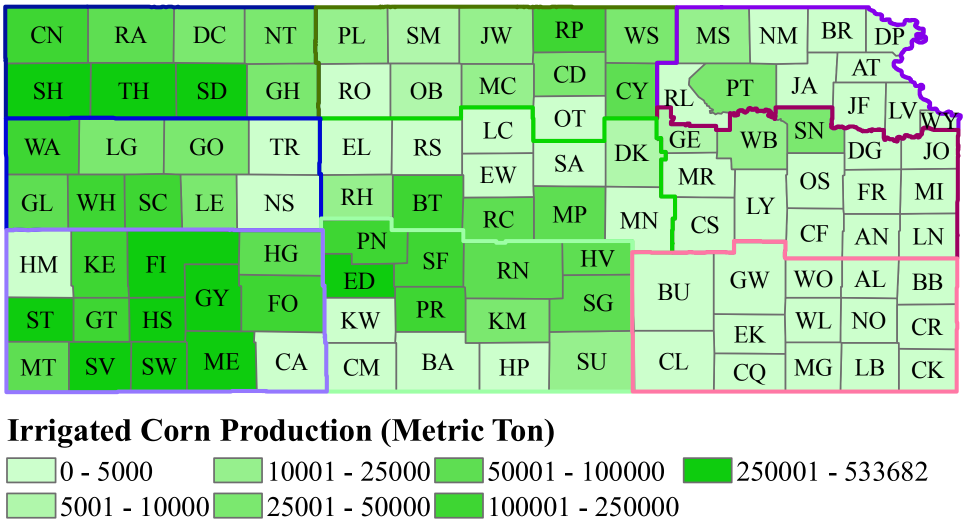


Figure 2.9: *2007 Irrigated Corn Production in Kansas (Data Source: NASS).*

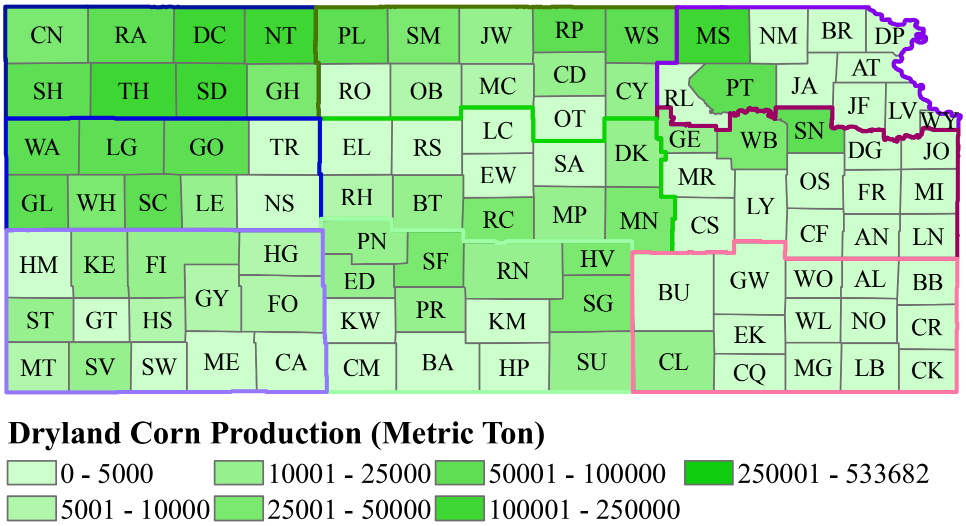


Figure 2.10: *2007 Dryland Corn Production in Kansas (Data Source: NASS).*

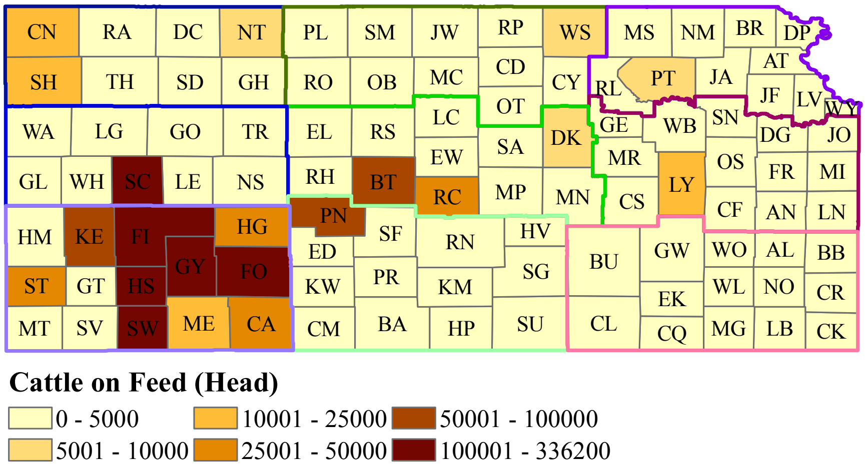


Figure 2.11: *Cattle on Feed as of January 1, 2008 (Data Source: NASS).*

dryland corn production on a county basis is shown for 2007. Production for 2007 is shown over more recent years due to greater data availability at the county level for the year. The similarities between Figures 2.9 and 2.4 clearly show the connection between irrigated corn production and groundwater irrigation throughout western Kansas.

The main market for corn in Kansas is feed grain for the livestock industry in Kansas. Corn is used as feed for many types of livestock in Kansas, including cattle, hogs and poultry. In Kansas, the production of cattle leads the livestock industry. The cattle industry has had a long history in Kansas, dating back to the cowtowns that grew after the civil war.[14] Today, Kansas is one of the leading cattle producers in the United States. As of January 1st, 2010, Kansas had about 6 million head of cattle and calves on farms.[13] Kansas is currently one of the top three states for total cattle and calves, cattle on feed, and beef production.[13] In Figure 2.11, total cattle on feed surveyed at the beginning of 2008 in each Kansas county is shown. The southwest has become the primary hub for the cattle industry in Kansas. According to the Kansas Livestock Association, the dry and moderate climate, access to local feed (see corn production), and competition of several large meat packing companies makes the southwest an ideal location for feeding cattle.[15] In 2009, the cattle industry represented 46% of all agricultural cash receipts in Kansas, totaling 5.5 billion dollars.[1]

2.4 Availability of State Agricultural Data

The National Agricultural Statistics Service (NASS) is the branch of the USDA that collects and maintains all kinds of agricultural data. The NASS has a local field office in Kansas that is in charge of data for the entire state. The Kansas field office divides the state into nine agricultural districts. These regions are labeled in Figure 2.12, and are included in the figures within this thesis for reference. These districts are used to aggregate data to regions for analysis.

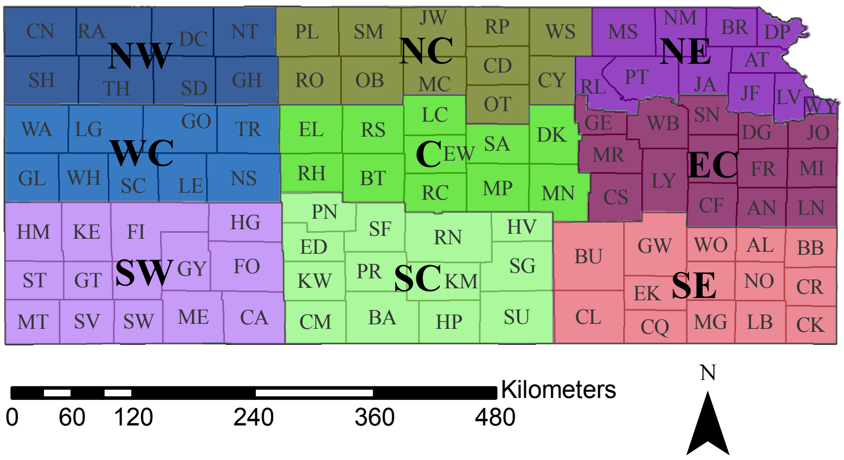


Figure 2.12: *NASS Agricultural Districts in Kansas.*

The Kansas office of the NASS has an extensive amount of agricultural data. Statistics for irrigated and dryland crops are available for most crops grown within the state. The resolution of crop data is available at county totals, agricultural district totals and state totals, but the availability of the data at different resolutions is variable. The time period of available data varies depending on the statistic, but most data are available from 1975 to present. Data are also available for most types of livestock in Kansas. Similarly to crop data, the availability and resolution of data are dependent on the statistic in question. Statistical data for Kansas agriculture are available at the website for the Kansas office of the NASS, at `http://www.nass.usda.gov/Statistics_by_State/Kansas/index.asp`.

2.5 Grain Transportation

An important aspect of agricultural industry in Kansas is the extensive transportation sector that supports it. The transportation sector plays a crucial role in the movement of crops and livestock. In regards to the cattle industry, transportation is needed to move cattle from pastures to feedlots and from feedlots to processing plants. Efficient transportation is also critical in moving significant amounts of feed from storage locations throughout the state to feed yards. According to a study conducted by the Kansas field office of NASS in partnership with the USDA and KDA in 2002, 100% of corn grain shipped to elevators arrived by truck. Also, nearly 80% of corn grain shipped from elevators was moved by truck, including an average of 93% of grain in the western districts.[16] Other options for transportation of grains are by rail or by barge. In the next couple chapters, we will look at the changes in groundwater availability, and the effects of decreasing groundwater resources on local irrigated corn production. Transportation will play an important role in moving corn grain resources to feedyards from areas where corn is still grown.

Chapter 3

Methodology

In this chapter, the methods used to conduct this research project are discussed. In the first section of the methodology, an initial groundwater elevation model developed by David Steward and Xiaoying Yang is discussed along with two modified versions of the model developed for the purpose of this project. The first adapted model enabled the groundwater model to output yearly data for saturated thickness and the second adapted model enabled it to output the change in groundwater level for five year increments. In the second section, the methods used to create saturated thickness maps of western Kansas are discussed. Saturated thickness maps are a helpful way of understanding the amount of groundwater available in an area. The methods include the use of ArcGIS software, specifically the use of Ordinary Kriging interpolation within the Geostatistical Analyst Package. In the third section, the methods used to forecast groundwater use are discussed. To calculate groundwater use data from the model, the change in groundwater level over time was related to the volume of water leaving the aquifer. The model water use data was then compared to water use data from the Water Rights Information System (WRIS) database, maintained by the Kansas Division of Water Resources. Lastly, in the fourth section, the methods for correlating groundwater use, corn production and cattle on feed data are explained. The main method for correlating these data involves the use of the least squares method.

3.1 Groundwater Models

Prior to the beginning of this research project, a groundwater model was developed by Drs. David Steward and Xiaoying Yang in 2008, using non-linear regression in SciLab to fit water level data at each individual well to a curve. To develop their model, historical water level data were used from over 2000 monitoring well sites from the Kansas Geological Survey's WIZARD Well Database (see Figure 3.1). Data at each monitoring well were fit to a curve

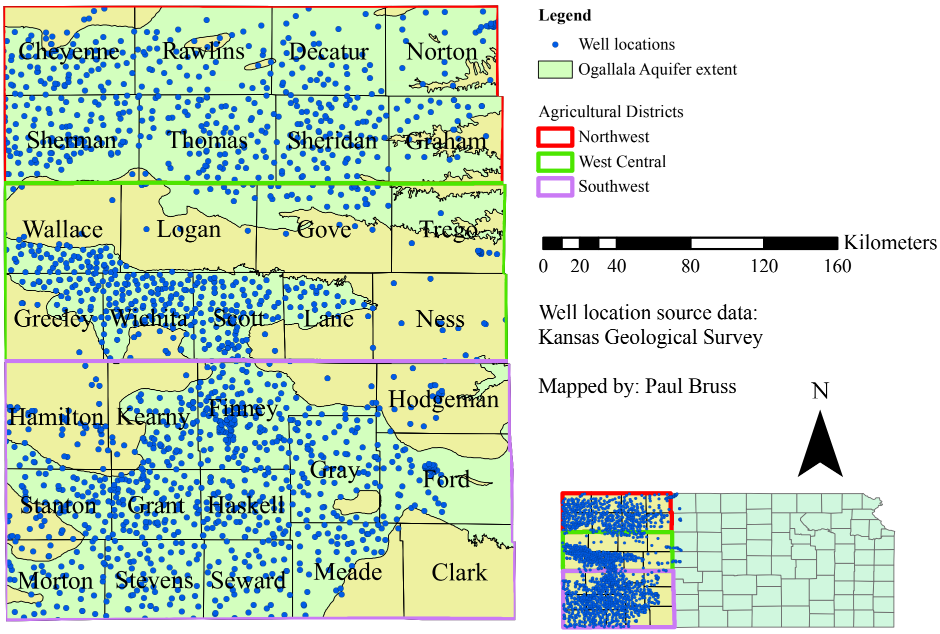


Figure 3.1: *Location of KGS monitoring wells.*

selected to match how water levels have historically behaved. The curve is defined by the general equation:

$$H = \frac{1}{1 + e^{\alpha_0 + \alpha_1 t}} \tag{3.1}$$

where α_0 and α_1 are unknown coefficients to be determined, t is a scaled time variable and H is a dimensionless ratio of the saturated thickness at a given time to the predevelopment saturated thickness,. H can also be defined defined as:

$$H = \frac{\phi_t - \phi_{bot}}{\phi_{pred} - \phi_{bot}} \tag{3.2}$$

where ϕ_t is the groundwater elevation at time t, ϕ_{pred} is the predevelopment groundwater elevation and ϕ_{bot} is the bedrock elevation.

A non-linear regression analysis was performed for each set of data at every monitoring well. Figure 3.2 shows the data fit to the curve. Results from the regression showed an average error of 1.8 meters. The curve fit to the data was then extrapolated into the future providing projected groundwater elevation data at each monitoring well location. The final output of the model was a comma-separated value (CSV) file showing yearly groundwater elevation for each monitoring well, projected out to a selected year. A journal article detailing the work related to this groundwater elevation model is currently in progress. For this thesis, all model data were projected out to 2110.

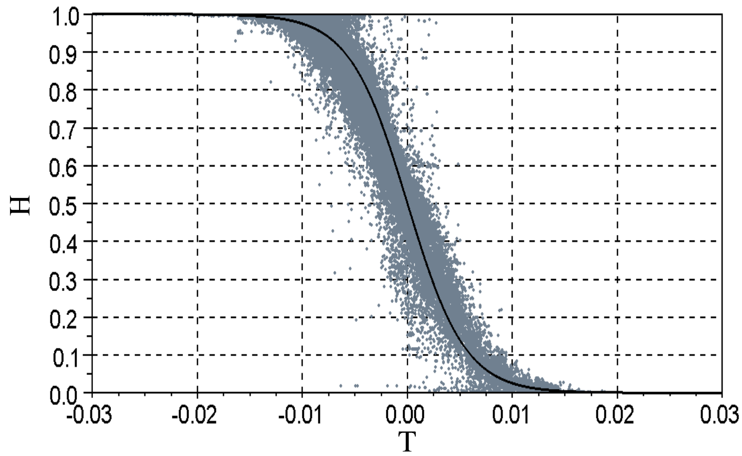


Figure 3.2: *KGS WIZARD well data fit to curve.*

Using the initial groundwater elevation model, two modified versions of the model were developed by the author for the purpose of this research project. The first adaptation was developed so that the model would output saturated thickness values instead of groundwater elevation at each well location. This was accomplished within the model SciLab script by subtracting the bedrock elevation from the groundwater elevation output data at each well location. For the purpose of this thesis, this adapted model will be referred to as the Saturated Thickness Model (STM). Using the Saturated Thickness Model data, an initial saturated thickness map for 1960 was developed for the Ogallala Aquifer as a starting point. Subsequent saturated thickness maps were later developed from the 1960 map, and will be discussed in greater detail in the next section.

The second adaptation was developed so that the model would output the change in groundwater elevation over 5 year increments. This was accomplished within the model script by subtracting from the output groundwater elevation for a given year the groundwater elevation from 5 years before (Example: 1970-1965). A negative sign was added to the output to represent the change of water level (from higher to lower groundwater elevation) as a positive value of water leaving the aquifer. In this thesis, this model will be referred to as the Change in Water Level Model (CWLM). The output of this adapted model was used for two purposes. First, using the Change in Water Level Model output in conjunction with the 1960 saturated thickness map, saturated thickness maps were created in 5-year increments from 1965 to 2110. The second purpose of this model was to forecast groundwater use into the future. This will be discussed in greater detail later.

3.2 Creating Saturated Thickness Maps in ArcGIS

Saturated thickness maps were created to give insight on how groundwater resources will change in the future. In this research project, saturated thickness maps were created in five year increments from 1960 to 2110. Using ArcGIS, the general process was to first create a beginning year saturated thickness raster surface for the year 1960 from the STM output data. Then, using CWLM output data from 1965 to 2110, several 'change in groundwater level' raster surfaces were created. To create a saturated thickness map for a given year, 1965 for example, the change in water level raster surface for the period 1960 to 1965 was subtracted from the 1960 saturated thickness raster surface. To create a saturated thickness map for 1970, the change in water level raster surface for the period 1965 to 1970 was subtracted from the newly created 1965 saturated thickness raster. Subsequent saturated thickness maps were created using this process from 1960 to 2110. More detailed steps for this process are explained next.

The first step was to create a beginning saturated thickness map for the year 1960. This was achieved using the output data from the STM and tools in ArcGIS. The tools used within ArcGIS are explained in further detail throughout Section 3.2. In the STM, saturated thickness data were created for each monitoring well location. To use the output data in ArcGIS, the CSV file was converted into a database (dbf) file using Microsoft Excel. Next, the saturated thickness data were given location data in ArcGIS. This was done by joining the model output dbf file to a point shapefile in ArcGIS containing the locations of all of the wells used to develop the model. A point shapefile with the STM data included was created by exporting the shapefile with the joined dbf table to a separate shapefile. Lastly, in preparation for the Ordinary Kriging process, the shapefile was projected using *USA Contiguous Albers Equal Area Conic projection*. (More detail on creating the point shapefile containing the model data can be found in Appendix A).

The next step was to use an interpolation method within ArcGIS to create a raster surface from the point data. Several methods were available within the ArcGIS's Geostatistical Analyst extension, including both deterministic and stochastic methods. The Kriging method was selected for the purposes of this research for a few different reasons. The first reason is that Kriging has the ability to provide statistical feedback in the form of prediction errors to help assess the accuracy of the interpolation. Second, Kriging takes into account both the distance and direction of the known points when predicting unknown points. This also allows for points in one direction relative to the unknown point to have greater influence if necessary. This is necessary when anisotrophy exists. The general Kriging method assumes the data results from stochastic and stationary processes. The Kriging method has been used to interpolate groundwater level data in several open file reports, including recently in OFR-2007-32.[12]

The Ordinary Kriging Method was selected over Universal and Simple Kriging methods based on a review of ArcGIS's documentation for the GeoStatistical Analyst tools.[17]. Within the Ordinary Kriging method, there were several parameters that could to be selected to define how the interpolation would work. Some options were selected manually while others were selected automatically through a built-in optimization process. The options selected manually included the order of trend removal, transformation of data, type of function to fit the empirical semivariogram, anisotropy, lag size and the number and minimum amount of neighbors. The order of the trend was determined through the use of the trend analysis tool within Geostatistical Analyst (see Appendix B); a 2^{nd} order trend was determined to best fit the data. Upon analysis of the auto-optimized semivariogram, it was determined that anisotrophy did exist within the data. Anisotrophy means that data points in a certain direction are more influential in determining the true value of an unknown point than data points in a different direction. Different lag sizes were selected in combination with a semivariogram model function to fit the data. To select the remainder of options, several trial runs were conducted using a variety of combinations of parameters. The criteria for selecting a final setup was determined by minimizing the Root Mean Square Error (RMS Error). The RMS Error indicates how close a predicted value is to the measured value. The smaller the RMS Error, the better the prediction. The RMS error is suggested in the Geostatistical Analyst documentation as a basic way to determine how well the model fits the observed data.[17] The final parameters selected manually for the 1960 saturated thickness map were the following:

- Order of Trend Removal: 2^{nd}
- Data Transformation: None
- Semivariogram Model: Spherical
- Anistropy: Yes
- Lag Size: 5000
- Number of Neighbors (minimum): 10(5)

After the interpolated surface was made, the prediction map was saved as a raster with a cell size of 100 x 100 meters. The 100 x 100 meters cell size was used in order to achieve sufficient resolution without drastically increasing the processing time in ArcGIS. To eliminate any artifacts from converting the prediction map to a raster, negative values for saturated thickness in the raster were set to zero using the raster calculator tool. Within the raster calculator tool, the following equation was used:

$$Raster2 = (Raster1 > 0) * Raster1 \tag{3.3}$$

In the equation, 'Raster1' was the filename of the raster being fixed, and 'Raster 2' was the name of the new file created. The output of this raster was saved as the new 1960 saturated thickness raster.

After creating the beginning saturated thickness raster for 1960, the change in groundwater level surfaces were created from CWLM data from 1965 to 2110. This was achieved in the same general process that the saturated thickness raster was created. The CWLM output data were converted from a CSV file to a dbf file, and joined to a point shapefile containing the locations of the wells (see Appendix A for more detail). A finalized point shapefile with the change in groundwater level data was created by exporting the shapefile with the joined dbf file to a new shapefile. Ordinary Kriging was used to create each surface. To determine the parameters for each surface, some parameters were kept consistent for all years, while other parameters were determined individually. Using the trend analysis tool, a 2^{nd} order trend was determined for all years (see Appendix B). Upon observation of the data, it was also determined that anisotrophy existed throughout the data. Finally, no transformations were used in the interpolation process. For the remaining parameters selected manually, minimizing the RMS Error was again the leading criteria. Appendix D shows the final parameters used for all of the change in groundwater level surfaces as well as the prediction errors that resulted from each interpolation. The prediction surfaces created by the Kriging tool were saved as rasters with a cell size of 100 by 100 meters. The cell size of 100 x 100 meters was selected to keep consistency with the saturated thickness raster.

To create the subsequent saturated thickness rasters, the Raster Math tool was used. As an example, to create a saturated thickness raster surface for 1965, the change in water level raster for 1960 to 1965 was subtracted from the 1960 saturated thickness raster. To create a saturated thickness raster surface for 1970, the change in water level raster for 1965 to 1970 was subtracted from the newly created 1965 saturated thickness surface. This method was used to create saturated thickness raster surfaces from 1965 to 2110. To make the process more efficient, the process was automated using code in the command prompt of ArcGIS that would run continuous iterations until all rasters were made. The code can be found in Appendix E.

Once all of the saturated thickness raster surfaces had been created, the Raster Processing Clip tool was used to crop the raster surfaces to the extent of the Ogallala Aquifer as defined by GIS data from the USGS's NAWQA GIS database.[18] This was done because there is little saturated thickness outside of the extent used to clip the raster surface, and it was the best way to avoid overestimation of groundwater saturated thickness in the raster data. An automated process was used to clip the surfaces. The code for the process can be found in Appendix F.

3.3 Calculating 5-Year Agricultural District Level Groundwater Use

In this section, 5-year values for groundwater use were forecasted at the agricultural district level from 1965 to 2110. 5-year totals were used in keeping with the increments used for the saturated thickness maps. The NASS agricultural districts were used for aggregating groundwater use for two reasons. The main reason was that the agricultural districts were later used for correlating groundwater use and corn and cattle data. The second reason is that the northwest, west central, and southwest agricultural districts helpfully separate the Ogallala Aquifer into three unique sections. One section of the Ogallala Aquifer is known to have limited resources available (west central district), another has a moderate amount (northwest district), and the third still has a significant amount of groundwater resources left (southwest district). Separating the aquifer into these three sections allowed for the observation of the aquifer at different stages of usable life individually.

The methods applied in this research to calculate groundwater use with the groundwater model required some theoretical background. The main concept behind extracting information on groundwater use from the groundwater model came from relating the change in groundwater level to the volume of water leaving the aquifer. This involves specific yield, which is the amount of water drained from a volume of aquifer under gravity. The basic equation for specific yield is:

$$S_y = \frac{V_{wd}}{V_{total}} \tag{3.4}$$

where V_{wd} is the amount of water drained from a unit volume of the aquifer and V_{total} is the total unit volume. If both volumes are divided by the same area, A, and the equation is rearranged to solve for water drained per area, it forms the following equation:

$$\frac{V_{wd}}{A} = S_y \frac{V_{total}}{A} \tag{3.5}$$

In this equation, V_{wd}/A is the volume of drained water per area and V_{total}/A is the total unit volume per unit area. As applied to this research, the volume of water drained per area is the linear amount of groundwater being pumped out of the aquifer per area, and total height is the change in groundwater level per area. This relationship was used to estimate groundwater use in the Ogallala Aquifer.

The next step was to use a raster multiplication tool in ArcGIS to multiply the change in groundwater level rasters used previously by a specific yield raster. The product of the two equaled the volume of water drained per unit area (unit area = each raster cell). The data for specific yield came from the USGS-NAWQA High Plains Regional Ground Water Study GIS data. These data were originally published under USGS Open File Report 98-414, as a shapefile. The specific yield data were converted to raster of 100 x 100 meters resolution using a Polygon to Raster Conversion tool within ArcGIS (see Appendix C). Again, the

100 x 100 meter resolution was kept consistent with the saturated thickness rasters and the change in water level rasters.

At this point, raster files of water drained per unit area had been created for each 5-year period from 1965 to 2110. The next step was to sum the groundwater use for each agriculture district. This was achieved by using the Zonal Statistics As Table tool in ArcGIS. The Zonal Statistics as Table tool calculates statistics (including a sum) for the raster cells contained within a specified area, and exports the statistics as a table. This tool was used to calculate the sum of groundwater use per unit area for each agriculture district. Within this tool, an agricultural district shapefile was used to delineate the districts, and for each five year period, the raster data of water drained per unit area were summed and output into a database file. This process was automated using a code implemented into the command line of ArcGIS (See Appendix G). Each table created (one for each 5-year period) contained the sum of groundwater use per unit area for each district. To get the total volume of groundwater use per agricultural district, the summed values were multiplied by the raster cell size (100 x 100 meters, or 10,000 m^2) in Microsoft Excel. A final table was made in Microsoft Excel containing the modeled groundwater use in each district from 1965 to 2110.

As a source of comparison, groundwater use data from the Kansas Division of Water Resources WRIS database were used by computing the total quantity of water pumped from the aquifer. The WRIS database was available through the Kansas State University GIS Commons as a dbf file. To use the WRIS database, the dbf file was imported into ArcGIS, and converted into a point shapefile. To convert the database file into a point shapefile, the *Add X Y Data* tool was used with the spatial data (latitude and longitude for each point of diversion) within the dbf file to locate the wells. The North American Datum 1983 geographic coordinate system was used when creating the shapefile. Since the WRIS database includes all kinds of reported water use, including surface and non-consumptive uses, steps were taken to filter out reported water use not for irrigation and not from groundwater sources. To do this, a definition query was created so that only points of diversion which were of groundwater source (Source = 'G'), and used for irrigation purposes (UMW_CODE = 'IRR') were included. To get the total groundwater use for each agricultural district for the same five year periods, the Summarize tool within the Attribute Table was used. Since the water use data were available at yearly intervals, the data were summarized for yearly intervals for each agricultural district. Each yearly summarization table was then used to create a table in Microsoft Excel summarizing the yearly groundwater use by agricultural district from 1958-2009. Finally, a second table was created summarizing groundwater use by agricultural district at five year increments from 1965 to 2010. Since the 2010 data were not yet available, the average of 2006 to 2009 was used to fill the 2010 data. The modeled groundwater use and reported groundwater use were compared using the least squares method to determine correlations between the two methods. Further explanation of the least squares method is given in the next section.

3.4 Developing Correlations Between Groundwater Use, Corn Production and Cattle on Feed

Correlations between groundwater use, corn production and cattle on feed were investigated to better understand how groundwater and agriculture in western Kansas are related. Groundwater use and irrigated area data from 1980 to 2009 in western Kansas were obtained from the WRIS database as described in the previous section. In this case, yearly data at the agricultural district level were used. The water use data that are reported in WRIS do not separate the water use by the crop type irrigated. Since corn is the most irrigated crop by acreage in Kansas, and also has the greatest water requirement of major crops grown in Kansas, it can assumed that majority of reported groundwater use for irrigation is for irrigating corn.[8,13] With this understanding, the reported groundwater use data are used representatively. Irrigated and dryland corn production and cattle on feed data were obtained from NASS for years 1980 to 2009 at the agricultural level. Yearly totals for cattle on feed were not available at the agricultural district level. Therefore, the data used for cattle on feed was a survey taken January 1st of each year. Precipitation data were collected from the Kansas Research and Extension Weather Data Library. The precipitation data were averaged by agricultural district. Overall, data were aggregated or obtained at the statistical district level because this provided the most complete dataset for all types of data. For correlation analysis, all nine districts were investigated so that areas with and without groundwater could be compared in the analysis. To investigate correlations between each set of data within each district, linear regression was performed using the least squares method. The least squares method is defined as

$$SSE(\hat{\beta}_0, \hat{\beta}_1) = \sum_{i=1}^{n} [y_i - (\hat{\beta}_0 + \hat{\beta}_1 x_i)]^2 \tag{3.6}$$

where for a dataset of n observations, (x_i, y_i) are the observed data points being correlated, and $\hat{\beta}_0$ and $\hat{\beta}_1$ are estimated parameters determined to minimize the Sum of Square Errors function, $SSE(\hat{\beta}_0, \hat{\beta}_1)$. The estimated best fit line, $\hat{y} = \hat{\beta}_1 x_i + \hat{\beta}_0$ is then used to determine how well the observed data x_i and y_i are correlated. A standard indicator for how well two datasets are correlated is the Coefficient of Determination, also known as the R^2 value. The R^2 value is the fraction of variation that is explained by the best fit line. It is defined by the equation:

$$R^2 = 1 - \frac{SSE}{SS_{total}} \tag{3.7}$$

Here, $SSE = \sum (y_i - \hat{y}_i)^2$ and $SS_{total} = \sum (y_i - \bar{y}_i)^2$ for n number of observations. y_i is the observed value, $\hat{y}_i$ is the estimated value, and $\bar{y}_i$ is the mean value for observation i. R^2 values range from 0 to 1, with 1 indicating that the data is perfectly correlated. Determining whether a R^2 value is significant or not depends on the data that is being correlated. One situation may require a value of R^2 to be 0.90 or higher to be significant, while another may only require 0.20 or less. Unable to find previous research that could suitably be used to create a criteria on, two limits were developed by the author as a way to quantify whether a R^2 value is significant. Two different kinds of correlations were made during this project; time-series and non-time-series (or correlations between distinct datasets). Determination of the limits for whether a R^2 value was significant was based on the level of noise that was anticipated to be in the data. Therefore, a higher limit was used for time-series correlations than for correlations between non-time-series. For time-series correlations, a R^2 value of 0.5 or higher was determined to be significant. For non-time-series correlations, a R^2 value of 0.3 or higher was determined to be significant. In this research project, correlations for the following combinations were made:

- Time-series correlations:
  - Groundwater Use vs. Time
  - Irrigated Area vs. Time
  - Groundwater Application vs. Time
  - Precipitation vs. Time
  - Irrigated Corn Production vs. Time
  - Irrigated Corn Yield vs. Time
  - Dryland Corn Production vs. Time
  - Dryland Corn Yield vs. Time
  - Cattle on Feed vs. Time
- Non-time-series correlations
  - Irrigated Corn Production vs. Groundwater Application
  - Dryland Corn Production vs. Precipitation
  - Dryland Corn Yield vs. Precipitation
  - Irrigated Corn Production vs. Dryland Corn Production
  - Cattle on Feed vs. Irrigated Corn Production
  - Cattle on Feed vs. Dryland Corn Production

The groundwater application dataset was created from the groundwater use and irrigated area data. Groundwater application was defined as the volume of water used per irrigated area, and was calculated simply be dividing the groundwater use data by the irrigated area data. When correlating the Irrigation vs. Groundwater Application, precipitation data was not included with the groundwater application data because it skewed the correlation in areas where there was very little groundwater irrigation occurring (eastern and parts of central Kansas). While it is understood that precipitation is an important part of irrigated crops, it was not helpful to include it when attempting to determine the relationship between irrigated corn production and groundwater use. In the next chapter, the results are presented and explained.

Chapter 4

Results and Discussion

In this chapter, the results of the research work are presented and discussed in three sections. The first section addresses the results from mapping the modeled saturated thickness from 1960 to 2110 within ArcGIS. In the second section, the results of the groundwater use model are discussed. Lastly, the results of correlation analysis are presented and discussed.

4.1 Modeling Saturated Thickness

In the next five pages, modeled saturated thickness of the Ogallala Aquifer in western Kansas from 1960 to 2110 is mapped. Saturated thickness is the depth from the top of the groundwater table to the bedrock floor of the aquifer. It provides significant insight on the volume of groundwater available in an aquifer at a given time. Maps of the saturated thickness are shown at 20 year increments from 1960 to 2100, with additional maps created for 2010 and 2110 to provide a saturated thickness map for the current year and a 100 year projection. For aid in the discussion, the saturated thickness is separated by 3 agricultural districts as described in Section 2.4. The northwest, west central and southwest districts are indicated by the red, green and violet outlines in the maps. Also, the legend is held consistent to allow for comparison between years. The results are shown next.

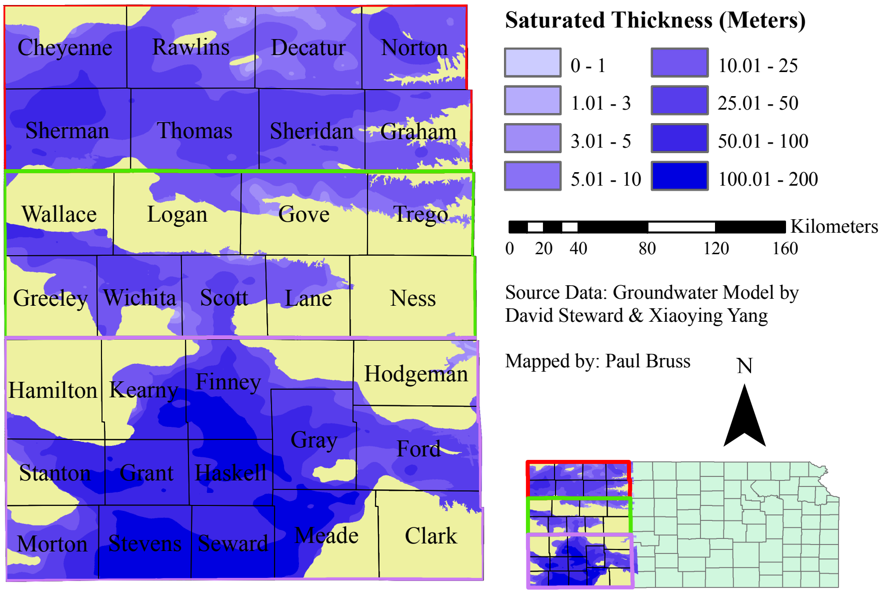


Figure 4.1: *Modeled Saturated Thickness for 1960.*

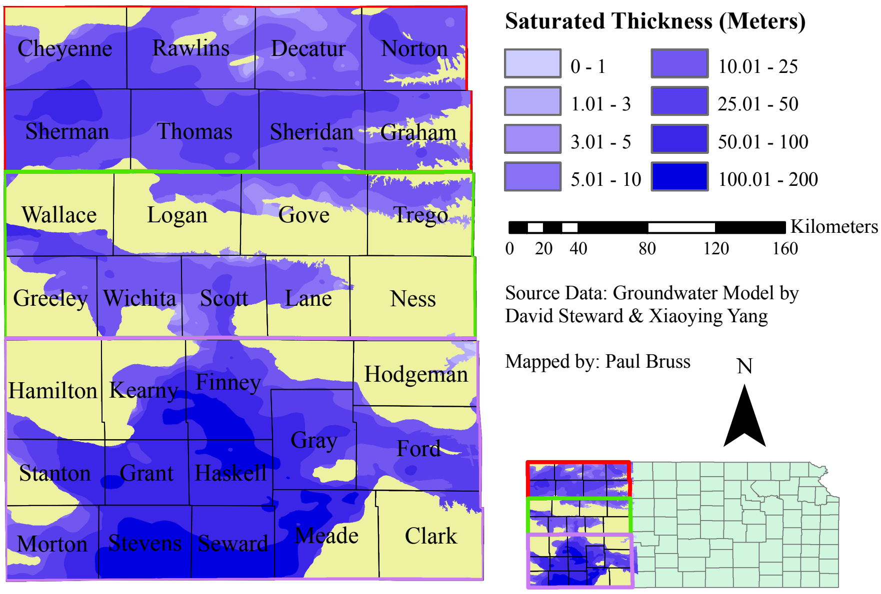


Figure 4.2: *Modeled Saturated Thickness for 1980.*

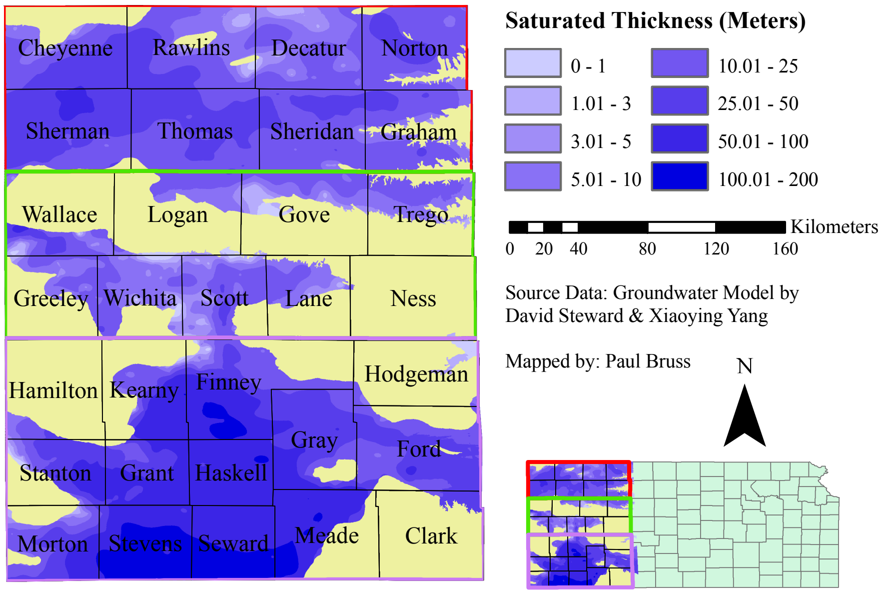


Figure 4.3: *Modeled Saturated Thickness for 2000.*

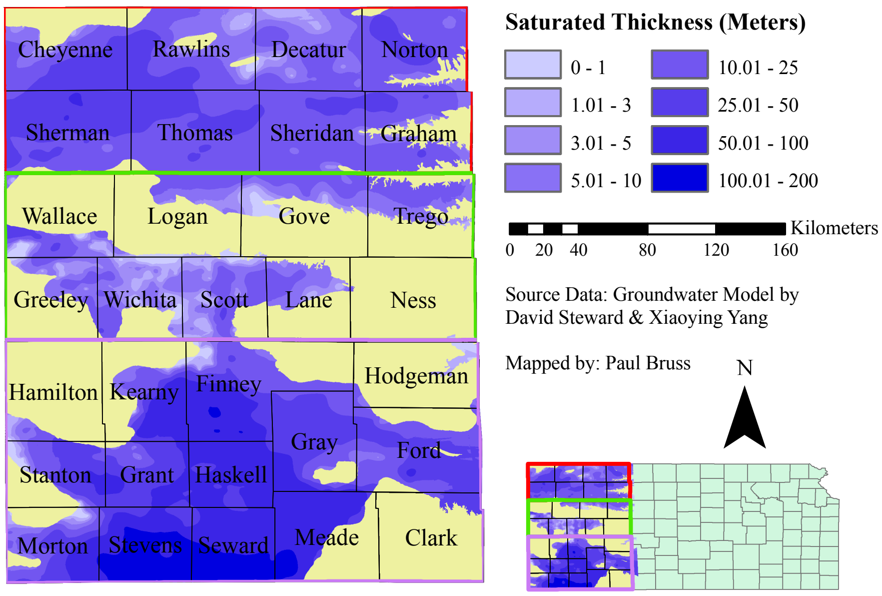


Figure 4.4: *Modeled Saturated Thickness for 2010.*

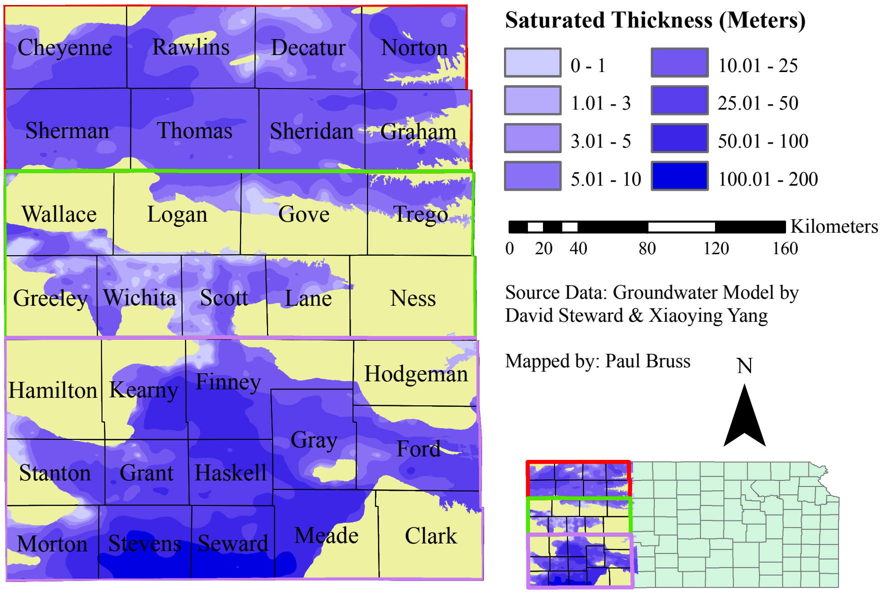


Figure 4.5: *Modeled Saturated Thickness for 2020.*

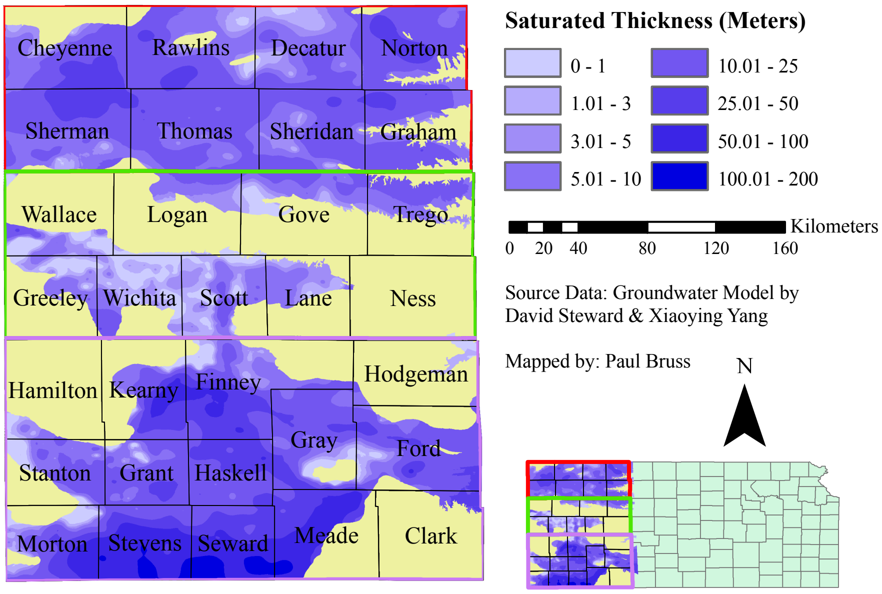


Figure 4.6: *Modeled Saturated Thickness for 2040.*

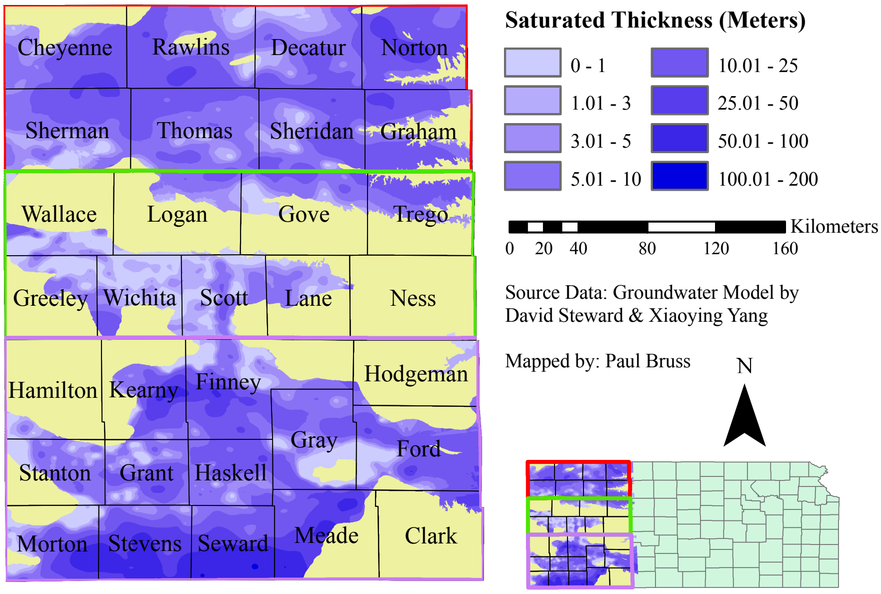


Figure 4.7: *Modeled Saturated Thickness for 2060.*

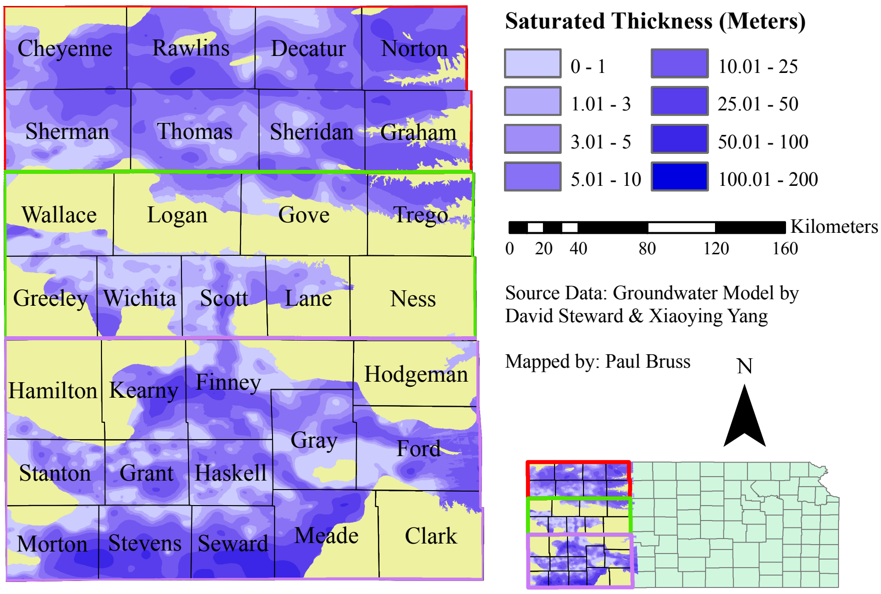


Figure 4.8: *Modeled Saturated Thickness for 2080.*

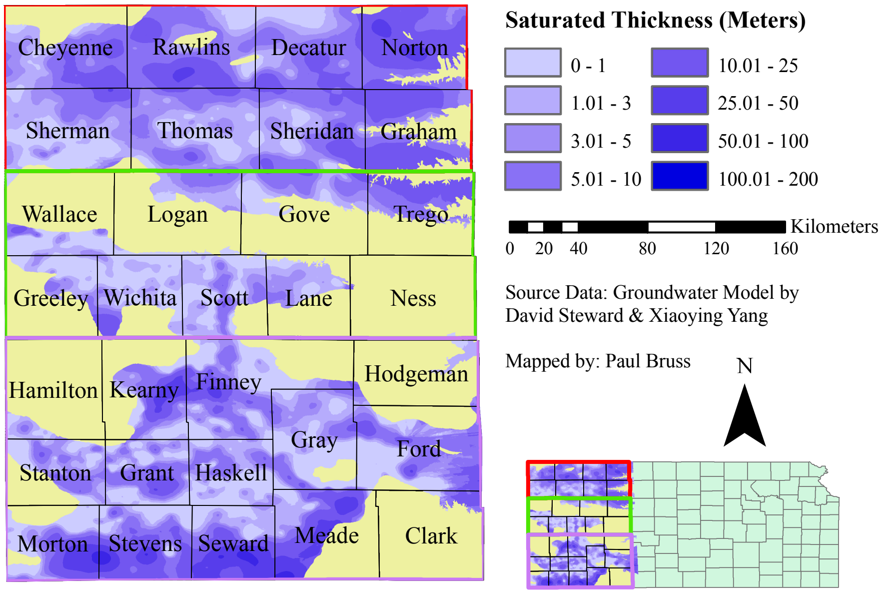


Figure 4.9: *Modeled Saturated Thickness for 2100.*

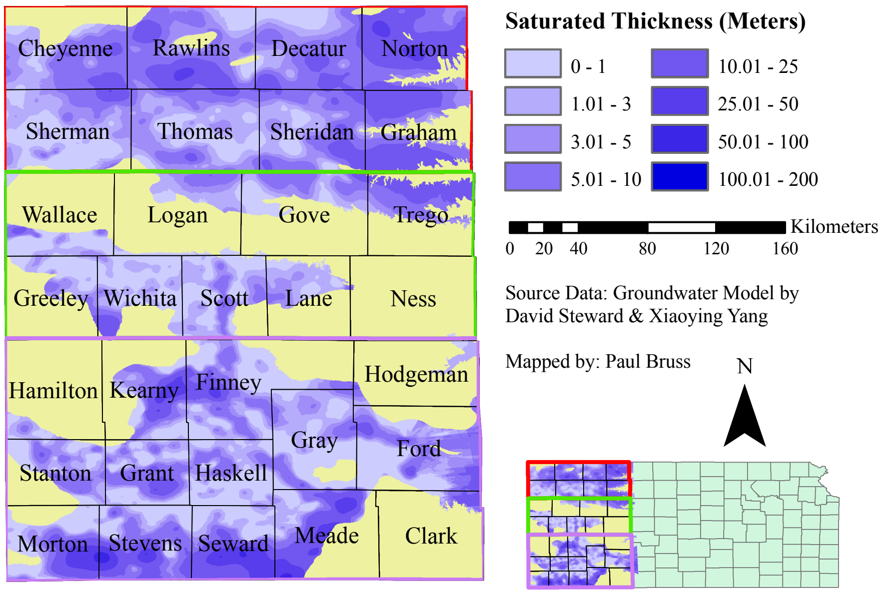


Figure 4.10: *Modeled Saturated Thickness for 2110.*

Year	Northwest	West Central	Southwest
1960	24.9	18.3	72.7
2010	19.6	8.5	51.6
2060	10.8	4.5	18.8
2110	6.6	3.2	6.7

Table 4.1: *Average modeled saturated thickness in meters in the northwest, west central and southwest districts in Kansas through time.*

The saturated thickness maps presented in Figures 4.1 to 4.10 show how the availability of groundwater varies both spatially and temporally. From the results, it can be seen that currently the deepest part of the aquifer is in the southwest agricultural district and that varying amounts of groundwater exist in the northwest and west central districts. The west central district shows the least amount of groundwater. From 1960 to present, the section of aquifer in the west central district saw the most significant change in saturated thickness. According to the KGS, the predevelopment saturated thickness in that area ranged from 15 to 61 meters (converted approximately from feet), with the majority of the area from 15 to 30 meters (see Figure 2.6). For the year 1960, the modeled data shows that the saturated thickness in west central Kansas was similar to predevelopment, however beginning to decrease. Using the Zonal Statistics tool in ArcGIS, the average thickness in the west central district for 1960 was calculated to be 18.3 meters. The model results show that by 2010, the average saturated thickness of the district had decreased to an average of 8.5 meters. This decrease was confirmed by the saturated thickness map released by the KGS in 2006, where most of the aquifer had decreased to less than 15 meters (see Figure 2.2). During this same period, the Ogallala Aquifer in northwest and southwest Kansas saw declines as well, but less significant in comparison to their total saturated thickness. In the northwest, from 1960-2010, the average saturated thickness decreased from 24.9 meters to 19.6 meters. In the southwest, for the same period, the average thickness decreased from 72.7 meters to 51.6 meters.

From 2010 to 2110, the model forecast that the aquifer in west central Kansas will continue to decline, although the rate of decline is less. Low saturated thickness, limited accessibility to remaining water, and costs of pumping water from greater depth are possible reasons that groundwater pumping rates can decrease, slowing water level decline. In this case, decreases in the rate of decline is likely due to the first two reasons. It is forecast that by 2110, the average thickness of the aquifer in west central Kansas will be 3.2 meters. In reality, the saturated thickness may not decline to this level. The equation used to model the groundwater assumes that ultimately the saturated thickness will decline to zero. It is more likely that the saturated thickness will reach an equilibrium where limited pumping will match any recharge that occurs.

During the same period, the model forecast that the most significant changes in the Ogallala Aquifer will occur in the northwest and southwest sections of the aquifer. The model projected that groundwater resources in both sections will be mostly exhausted by 2110. Average saturated thickness for the northwest and southwest in 2110 were predicted at 6.6 and 6.7 meters. Some areas in both the northwest and southwest will retain substantial saturated thickness levels. In the northwest, areas where greater thickness will still exist according to the model include the four northern counties, Cheyenne, Rawlins, Decatur and Norton. Parts of these counties may retain as much as 10 to 30 meters of saturated thickness in 2110. In the northwest, more precipitation occurs than in the other areas of western Kansas. Greater precipitation means less groundwater pumping, and greater recharge to the aquifer. This leads to lesser rates of decline. In the southwest, areas where greater saturated thickness will still exist includes the four southern counties Morton, Stevens, Seward and Meade as well as Kearny and Finney counties. Parts of these counties may retain as much as 40 to 60 meters of thickness. These areas will retain greater saturated thickness levels mostly because they had the greatest saturated thickness prior to development.

The implications of the decline in groundwater resources will be considerable, having an impact on the environment and the Kansas agricultural economy. These changes will change how, where and what crops will produced. The ability to grow corn in most parts of western

Kansas depends on the availability of groundwater for irrigation. Corn is the most produced crop in Kansas in terms of total production because of the farmer's ability to irrigate lands with groundwater resources. In the last section, the decrease in saturated thickness showed how groundwater resources continue to decline. In this section, the forecast changes in groundwater use due to declining groundwater resources are discussed.

4.2 Modeling Groundwater Use

In the previous section, changes in groundwater resources could be observed through the mapping of saturated thickness over time. In this section, by relating these changes in the Ogallala Aquifer's saturated thickness to the amount of water being drained from the aquifer, groundwater use was modeled. Groundwater use was modeled from 1965 to 2110 over 5-year periods using the process outlined in Section 3.3. The northwest, west central and southwest agricultural districts were used to aggregate groundwater use into regions for analysis. As a source for comparison, reported groundwater use from the Kansas Division of Water Resources WRIS database was quantified for 5-year periods from 1965 to 2010 using the same agricultural districts. Below, Figure 4.11 shows the modeled groundwater use from 1965 to 2010.

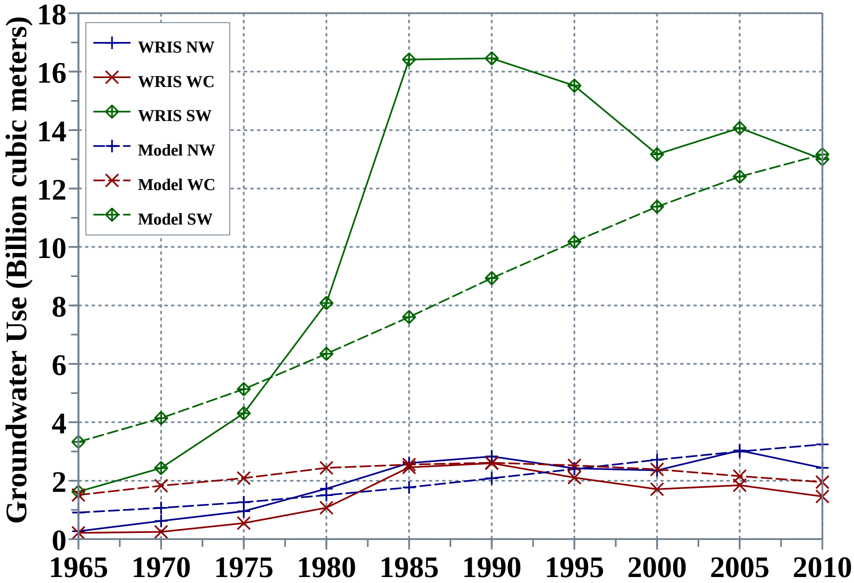
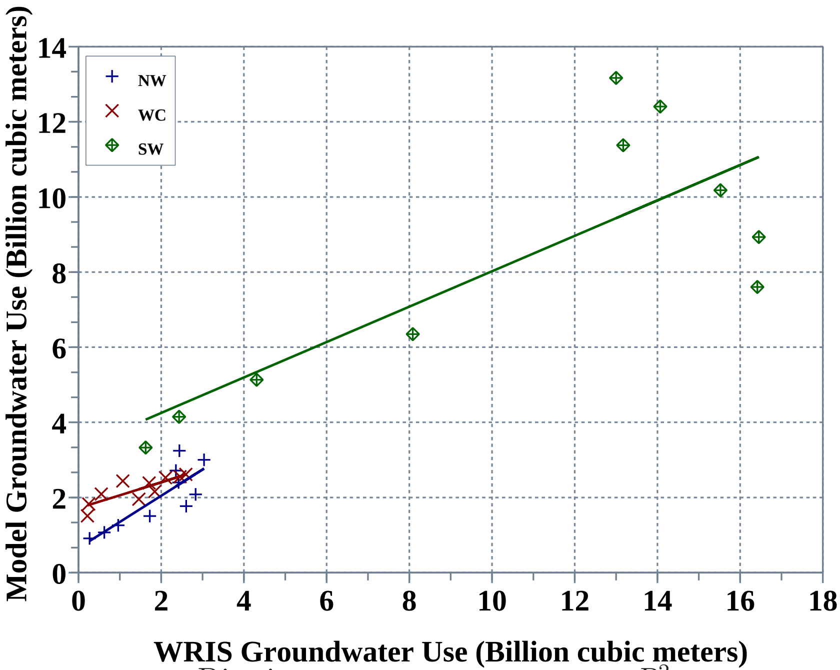


Figure 4.11: *Modeled vs. WRIS Groundwater Use, 1965 to 2010.*

In each line showing modeled and reported groundwater use, the data points for a given year represent the total groundwater used in a particular district for the five year period leading up to that year. The solid lines represent reported groundwater use and the dashed lines represent modeled groundwater use. Groundwater use for each agricultural district is distinguished by color and indicated in the legend. As an example, the data point on the solid green line in 1970 are the total reported groundwater used in the southwest district from 1965 to 1970. To quantify how well the modeled groundwater use matched the reported groundwater use, a basic correlation analysis was done between the two datasets. Results are shown in Figure 4.12.



District	c_0	c_1	R^2
NW	0.65469	0.69639	0.68305
WC	1.71414	0.34512	0.69548
SW	3.30643	0.47157	0.62493

Figure 4.12: *Correlation between Modeled and reported (WRIS) groundwater use.*

Statistics for each district are shown in the table below the graph. R^2 values ranged from .625 to .695. Optimal correlation of the two sets of data would be a 1:1 ratio represented by $c_0 = 0$ and $c_1 = 1.0$ ($y = c_0 + c_1 * x$), and where $R^2 = 1.0$, indicating that the model accounts for all variance. Though the correlation was not perfect, similarities in the trends

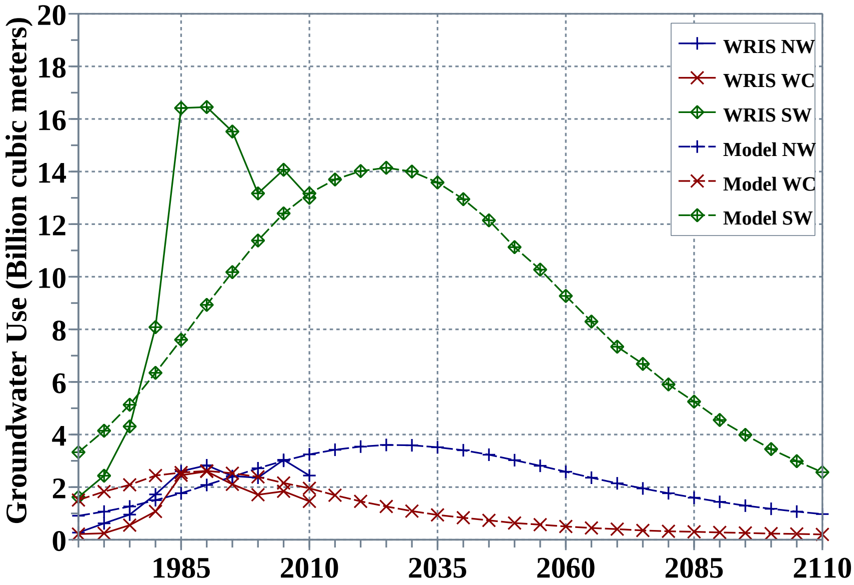


Figure 4.13: *Modeled Groundwater Use, 1965 to 2110.*

can be seen. Next, the modeled groundwater use was extrapolated out to 2110. The WRIS reported groundwater use is also included.

Figure 4.13 shows the projected groundwater use for the northwest, west central and southwest districts out to 2110 based on the modeled groundwater use along with the WRIS reported groundwater use. In the next 100 years, groundwater use in all three districts were forecast to decline significantly. The model forecast that groundwater use in the northwest and southwest districts would continue to increase for a few more decades while groundwater use in the west central district would continue to decline. The southwest district, shown in green, was forecast to have the greatest decrease in groundwater use over the next 100 years.

Upon an initial visual comparison, the modeled and reported groundwater use between 1965 and 2010 in the west central and northwest districts look similar, while the similarities between modeled and reported groundwater use in the southwest district seem less clear. In Figure 4.12, the results of the correlation analysis quantify the relationships between the modeled and reported groundwater use data for each of the three districts. R^2 values were in the range of approximately 0.624 to 0.695. Observation of the 6 green data-points in the top right of Figure 4.12 shows that the R^2 value for the southwest district, 0.62493, may be skewed, and the correlation less clear. It should be noted that the reported and modeled groundwater use data were determined in two significantly different ways. WRIS reported groundwater use is determined directly from water users either from metered pumps or other methods of estimation. The measurement method for reporting depends on the user, the location of the well and the time period of the report. Water use reporting did not become enforced until 1980 and water meters did not start becoming required until 1992 starting in the southwest. Some variance in the data may be explained by this. Prior to 1980, the modeled groundwater use appears to be greater than the reported amounts. Prior to 1980, enforcement of water use reporting was not as stringent, and so some water use may not be accounted for. This is likely why around 1980, there is major increase in water use.

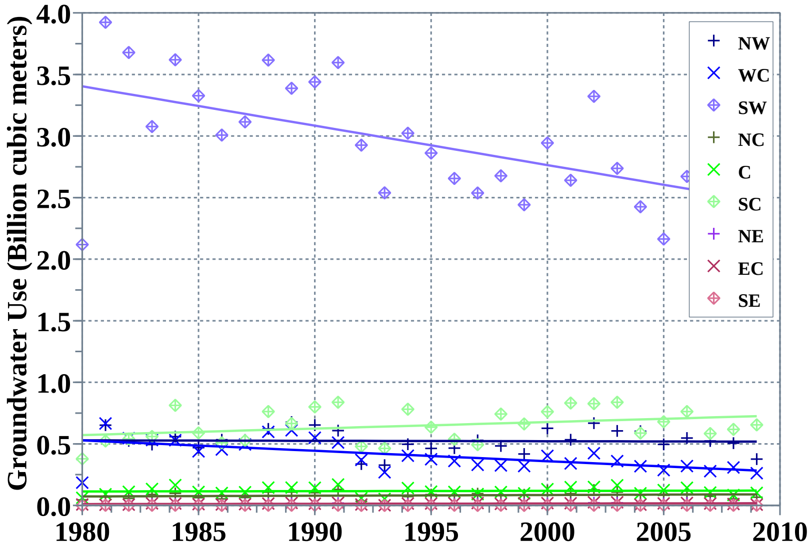
The modeled groundwater use is inferred from the physical changes in the modeled aquifer. There are limiting factors to the modeled groundwater use values. Limits to the accuracy of the modeled groundwater use include the accuracy of the interpolation method, the accuracy of the specific yield data used in the raster calculations, and the accuracy of the assumption made regarding the water balance. The groundwater use model assumes that all changes in groundwater levels are directly attributable to pumping for irrigation. Also, in the groundwater use model, the model limits groundwater to the extent defined by the KGS. If any Ogallala Aquifer groundwater exists outside this extent, it was not accounted for in the groundwater use model.

In Figure 4.13, the modeled groundwater use is extrapolated out to 2110. Modeled groundwater use in the west central section shows that water use has been in decline since approximately 1990. The reported groundwater use from WRIS confirms this finding. Modeled groundwater use in the west central district will continue to slowly decline out to 2110. Modeled groundwater use in the northwestern district shows that water use will continue to gradually increase until it peaks near 2030 and then begin to decline slowly. The reported groundwater use trend from 1965 to 2010 shows the same water use trend, although recent trends show that water use has steadied. The modeled groundwater use in the southwest is the area of most interest. The aquifer in the southwest agricultural district groundwater irrigates more than any other part of Kansas and produces the most corn in Kansas. In Figure 4.13, the model forecast groundwater use in the southwestern district to continue to increase until approximately 2025 and then begin to rapidly decline. This rapid decline would occur as less farmers would continue to pump groundwater. Causes for less pumping could include less productive wells or increased pumping costs. According to the model results, within 50 years, from 2025 to 2075, groundwater use in the southwest is forecast to reduce by 50 percent from 14 billion cubic meters of water to 7 billion cubic meters. By 2110, groundwater pumping will be reduced to approximately 2.5 billion cubic meters.

It should also be noted that in all three districts the reported groundwater use appear to have decreased or steadied before the model predicts it. There are several potential reasons for this. The most likely reason is that governing entities have in some areas stopped appropriating groundwater, which essentially prevents water use from increasing beyond a maximum total appropriation in each area. This is the case in GMD 3, located in the southwest agricultural district. A second reason is that, by choice, farmers may be using less water. Increases in irrigation efficiency, drought resistant crops, and enrollment in water conservation programs are all potential ways groundwater use may have decreased, A third reason could be that there is simply less groundwater available then previously thought.

4.3 Results of the Correlation Analysis

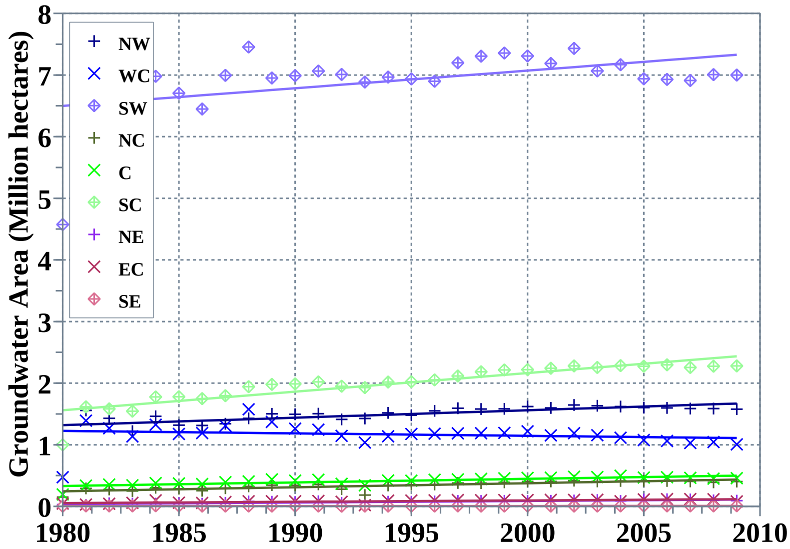
In this section, the results of the correlation analyses are presented and discussed. Groundwater use and precipitation, irrigated and dryland corn production, and cattle production data were investigated to determine the relationships that exist between them. The main goal of the the correlation analyses was to see whether current and future declining groundwater use would have an impact on corn production and cattle production. The time period for the analyses was from 1980 to 2009, chosen based on the availability of the data. Data were gathered for all nine agricultural districts to show differing trends in each district, including districts with and without groundwater. For each correlation, a graph shows the plotted data along with a best-fit line. Different colors distinguish between each agricultural district (colors also match Figure 2.12). First, trends over time were investigated for the different datasets. The results are shown in Figures 4.14 to 4.22.



District	c_0 [Gm^3]	c_1 [Gm^3/yr]	R^2 [−]
NW	1.22417	-0.00035	0.00105
WC	17.27956	-0.00846	0.38785
SW	66.71386	-0.03197	0.34772
NC	-1.09887	0.00059	0.03823
C	-0.36198	0.00024	0.00461
SC	-9.90078	0.00529	0.12364
NE	-0.45974	0.00024	0.14547
EC	-0.43281	0.00022	0.10369
SE	-0.01834	0.00001	0.06109

Figure 4.14: *Time series: groundwater use*

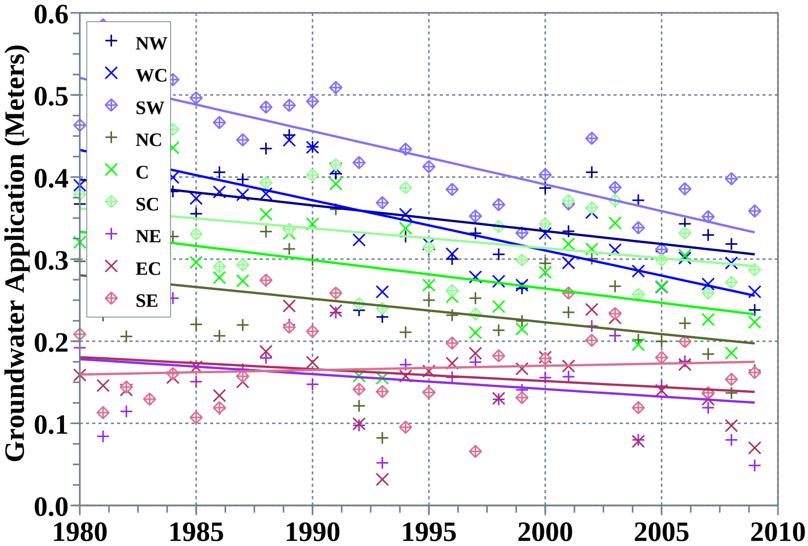
Groundwater use values in this analysis included water uses for all irrigated crops, not just corn. Given that corn has a high water requirement, and is the most widely produced irrigated crop in Kansas, the majority of the groundwater use was likely for corn production. Therefore, the groundwater use data were used as a useful indicator of irrigation for corn production. Figure 4.14 generally shows that groundwater use in the western districts (northwest, west central, and southwest districts) have been declining over the last 30 years, while the other six district's groundwater use has remained generally unchanged. While none



District	c_0 [Mhe]	c_1 [Mhe/yr]	R^2 [−]
NW	-22.66494	0.01211	0.57369
WC	9.13852	-0.00400	0.03905
SW	-50.10580	0.02859	0.24450
NC	-12.71150	0.00654	0.66928
C	-11.13649	0.00579	0.66399
SC	-58.26811	0.03022	0.80358
NE	-5.02246	0.00256	0.72936
EC	-4.29949	0.00220	0.54740
SE	-0.06265	0.00003	0.03255

Figure 4.15: *Time series: groundwater area*

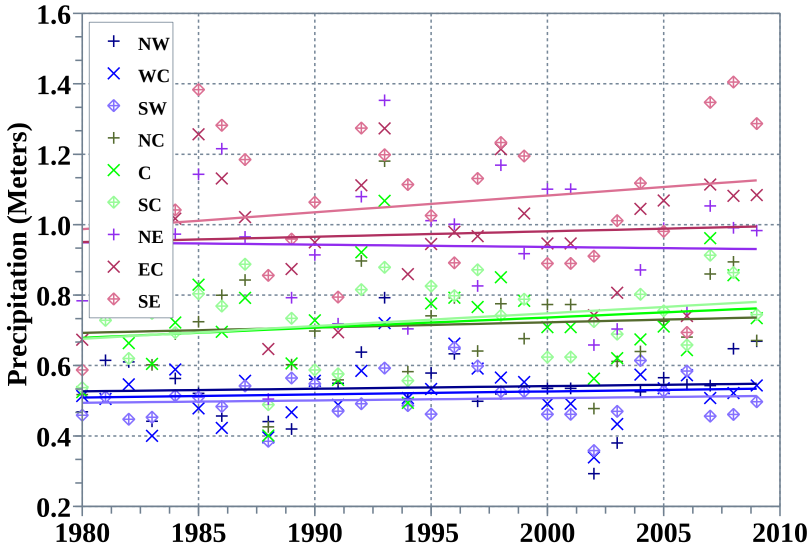
of the districts had R^2 values above 0.5, the values for the west central and southwest districts seem to standout from the other 7 districts and may still be significant. One reason for the low R^2 values in many of the districts can be explained by the lack of available groundwater use in those districts. Outside of northwest, west central and southwest agricultural districts, the only other part of the state with significant groundwater is the south central district. And a constant line over time will render near 0 R^2 values. Figure 4.15 shows the historical irrigated area in Kansas. Based on the figure, irrigated area has not changed significantly over the last 30 years, especially in areas of little groundwater resources. R^2 values were considerably higher, with most districts' trends being considered significant. The west central and southeast districts had likely had low R^2 values due to their near constant values over the last 30 years. Districts where irrigated area have increased significantly include the northwest and south central districts. Both had R^2 values above 0.5 and had the highest increases in irrigated area over the time period. The southwest district also showed increases in irrigated area, although the trend is less clear. These districts are all areas where there is still considerable groundwater available.



District	c_0 [m]	c_1 [m/yr]	R^2 [−]
NW	6.61320	-0.00314	0.21107
WC	12.54723	-0.00612	0.65423
SW	13.36463	-0.00649	0.66747
NC	5.95389	-0.00287	0.14065
C	7.20088	-0.00347	0.19544
SC	5.15288	-0.00242	0.13992
NE	3.79488	-0.00183	0.08812
EC	3.07093	-0.00146	0.05837
SE	-0.88942	0.00053	0.00830

Figure 4.16: *Time series: Groundwater application*

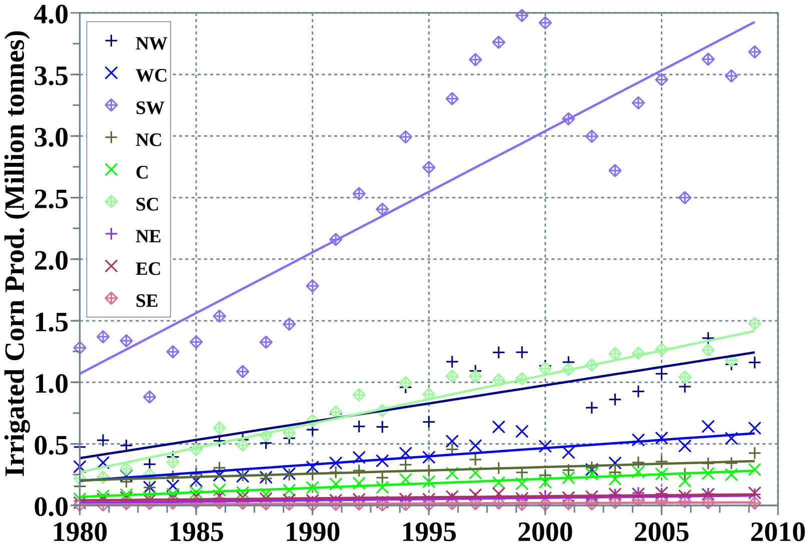
Figure 4.16 shows the historical trend of groundwater application over time. Groundwater application is the volume of groundwater used per irrigated area, measure in meters. In nearly all districts, a trend in decreasing groundwater application was found. The districts that produced the most significant results were the west central and southwest districts, with R^2 values of 0.654 and 0.667 respectively.



District	c_0 [m]	c_1 [m/yr]	R^2 [–]
NW	-0.95340	0.00075	0.00482
WC	-1.19115	0.00086	0.00949
SW	-0.82864	0.00067	0.00822
NC	-2.27775	0.00150	0.00804
C	-5.04583	0.00289	0.03158
SC	-6.47703	0.00361	0.07958
NE	2.25753	-0.00066	0.00098
EC	-2.07840	0.00153	0.00674
SE	-8.48542	0.00478	0.04403

Figure 4.17: *Time series: precipitation*

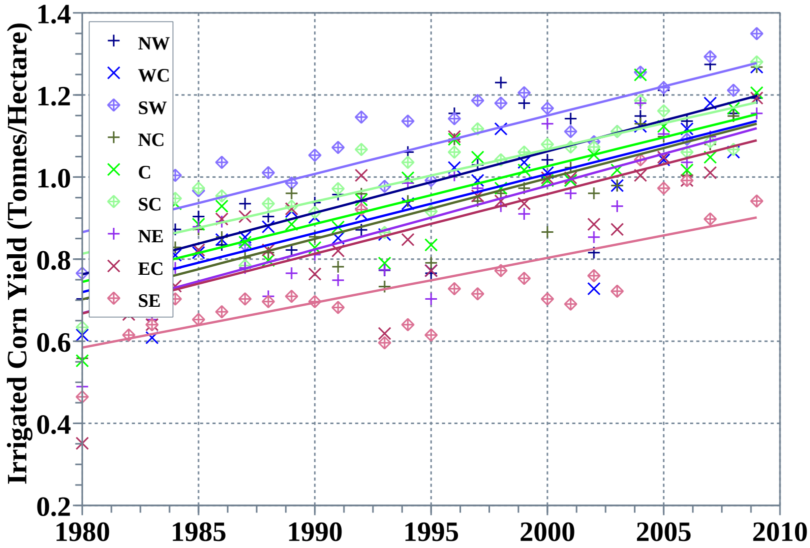
Figure 4.17 shows the results of correlating precipitation over time. The results indicate that there is no clear trend. This means that precipitation over the last 30 years has varied substantially, and neither a strong decreasing or increasing trend occurred.



District	c_0 [Mt]	c_1 [Mt/yr]	R^2 [−]
NW	-58.22301	0.02960	0.72172
WC	-26.12681	0.01330	0.63398
SW	-193.96170	0.09850	0.73833
NC	-10.42521	0.00537	0.45744
C	-14.45385	0.00733	0.82840
SC	-77.96904	0.03951	0.92849
NE	-4.01872	0.00204	0.55735
EC	-3.27405	0.00167	0.44586
SE	-1.08278	0.00055	0.24426

Figure 4.18: *Time series: irrigated corn production*

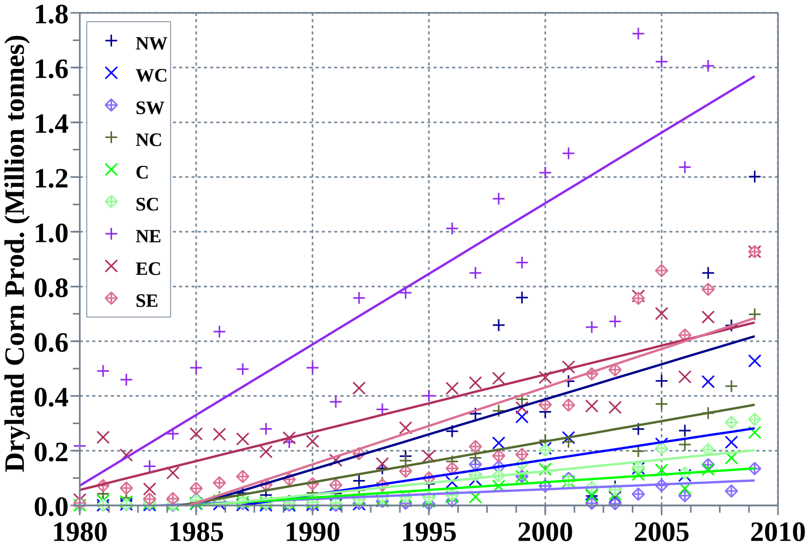
Figure 4.18 shows a clear trend of increasing irrigated corn production, particularly in the northwest, southwest and south central districts. The greatest increase in irrigated corn production over the past 30 years has occurred in the southwest district. R^2 values for all three of these districts were largely above 0.5. The west central district also significant increases in irrigated corn production, although at a lesser rate. As expected, most areas with little or no known groundwater resources did not see any significant trend in irrigated corn production.



District	c_0 [t/He]	c_1 [t/He/yr]	R^2 [−]
NW	-28.92524	0.01499	0.60007
WC	-27.74615	0.01438	0.65280
SW	-27.26159	0.01421	0.74099
NC	-28.51223	0.01475	0.69418
C	-27.14288	0.01408	0.68360
SC	-24.36270	0.01272	0.70605
NE	-30.08428	0.01553	0.65343
EC	-28.14623	0.01455	0.54716
SE	-21.06045	0.01093	0.50698

Figure 4.19: *Time series: irrigated corn yield*

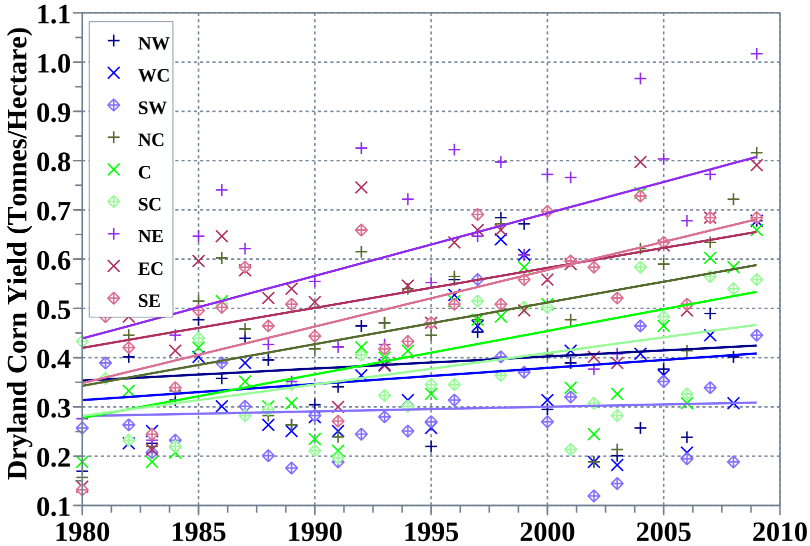
Figure 4.19 shows the trends in irrigated corn yield over time. The yield is defined as the amount of corn produced per unit area, in this case tonnes per hectare. An interesting note is that the trends for almost all districts are the same. The change in yield in 7 of the 9 districts is between .0140 and .0156 tonnes per hectare per year. This represents an increase in yield of 40% over the last 30 years and is due to increased water use efficiencies, technological improvements and better crop genetics. R^2 values for all 9 districts were above 0.5, indicating that their trends to be significant.



District	c_0 [Mt]	c_1 [Mt/yr]	R^2 [−]
NW	-50.86693	0.02563	0.54034
WC	-25.39269	0.01278	0.54227
SW	-7.07241	0.00357	0.38101
NC	-29.57709	0.01491	0.60599
C	-11.16847	0.00563	0.61928
SC	-16.92350	0.00852	0.68682
NE	-102.09278	0.05160	0.68524
EC	-41.70694	0.02109	0.70677
SE	-55.83446	0.02813	0.75016

Figure 4.20: *Time series: dryland corn production*

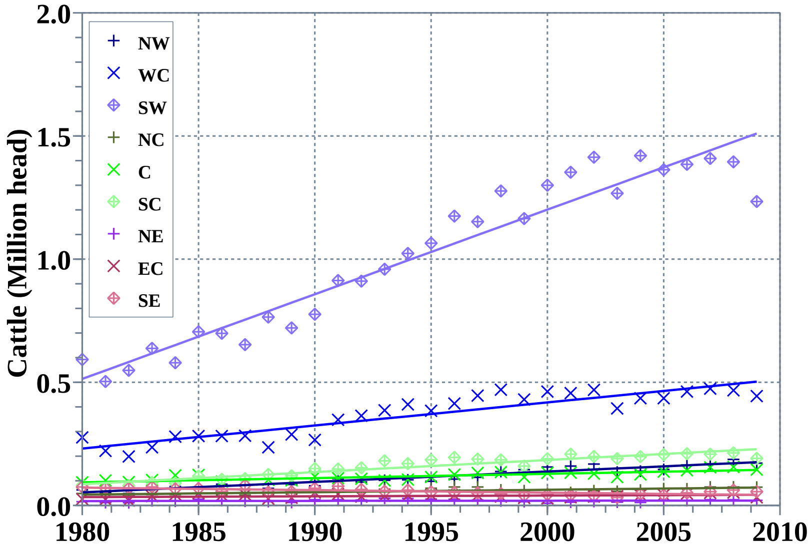
Dryland corn is grown without any irrigation. In Kansas, dryland corn production is more common in central and eastern Kansas where there is little or no groundwater and much more precipitation. Figure 4.20 shows generally more production in the eastern districts, with the greatest increasing trend in the northeast district. R^2 values indicated significant trends for all districts except for the southwest. This is likely due to the strong emphasis on irrigated corn production in that district.



District	c_0 [t/He]	c_1 [t/He/yr]	R^2 [−]
NW	-4.50008	0.00245	0.02279
WC	-6.15740	0.00327	0.04129
SW	-1.60487	0.00095	0.00653
NC	-16.39533	0.00845	0.19240
C	-17.20265	0.00883	0.28272
SC	-12.35087	0.00638	0.21869
NE	-24.74035	0.01272	0.29678
EC	-15.64841	0.00812	0.19929
SE	-22.37049	0.01147	0.47972

Figure 4.21: *Time series: dryland corn yield*

Figure 4.21 shows the results of the dryland yield trends over time. The results generally show that there is not a very clear trend in dryland yield. This is likely due to dryland corn yield's influence by precipitation, which also did not show a clear trend over time. R^2 values were highest in the eastern and central districts, though none met the criteria to be considered significant.



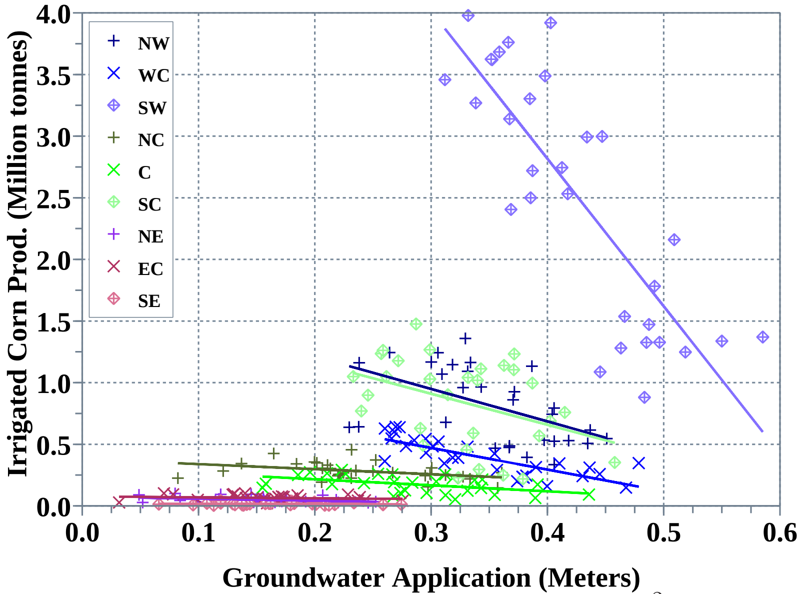
District	c_0 [Mhead]	c_1 [Mhead/yr]	R^2 [−]
NW	-8.30340	0.00422	0.88429
WC	-18.28755	0.00935	0.82771
SW	-67.52448	0.03436	0.92354
NC	-1.90355	0.00098	0.54264
C	-3.33835	0.00173	0.67299
SC	-9.61523	0.00490	0.87804
NE	-0.11395	0.00007	0.01184
EC	-0.58953	0.00031	0.10687
SE	2.07328	-0.00101	0.48465

Figure 4.22: *Time series: cattle*

The last time-series trend analysis shows trends in cattle on feed over the past 30 years. It should be noted that the data are a survey of cattle on feed as of January 1 for the year, and not a yearly total. Yearly totals of cattle on feed were not available at a resolution greater than the state level making the data unusable for this research. Nonetheless, the beginning of the year survey of cattle on feed is a good indicator for trends in cattle on feed over time. Figure 4.22 shows strong increasing trends in the southwest and west central districts, and a moderately increasing trend in south central district. R^2 values were particularly high for this analysis, particularly in the western districts and in the south central district. In the southwest district, a curtailment of increases over the last 5 years in the southwest district and decreases in the last 2 years indicates that the increasing trend may not occur.

The results from the time-series correlation analyses provided interesting and sometimes surprising results. Over the past 30 years, groundwater use in the western districts have generally been declining. Despite decrease in the volume of groundwater use, the amount of irrigated area in most districts except the west central district were either increasing or constant. Of particular interest is the southwest district, where the most groundwater use occurs. From 1980-2009, the southwest district simultaneously saw the greatest rate of decrease in groundwater application (see Figure 4.16) and greatest rate of increase in irrigated corn production (see Figure 4.18)of all of the agricultural districts. This change occurred in an area of Kansas that still has significant groundwater resources available and, as shown in Figure 4.17, did not see an increase in precipitation. This indicates increases in irrigation efficiency and likely improvements in more drought resistant corn species. Dryland crops also saw increases in production and yield without a noticeable trend in increasing precipitation. Noteworthy increases in dryland corn production occurred in the northwest and west central districts, while the southwest district saw the least increase in dryland corn production. As shown in Figure 4.22, trends in cattle on feed were generally increasing in western Kansas, as well as in the south central district. The large majority of cattle on feed are in the southwest and west central districts. Given the infrastructure and meat processing companies established there, it is unlikely to change.

The second set of the analyses involved correlating the sets of data between each other. The two relationships of greatest focus for the purpose of this thesis were the relationship between water resources, including groundwater use and precipitation, and corn production, and the relationship between corn production and cattle production. Several different comparisons were attempted, though only the analysis that provided useful and relevant information were included in the results shown. The results of this part of the analysis are

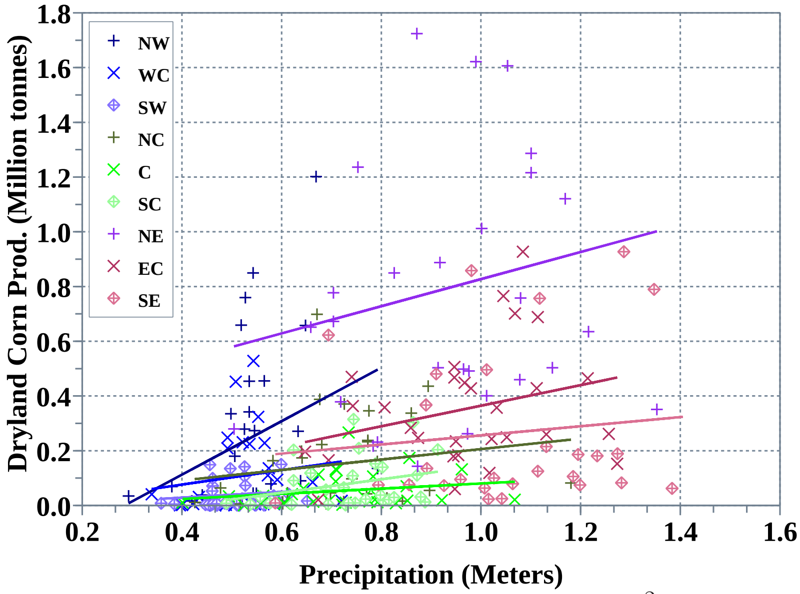


District	c_0 [Mt]	c_1 [Mt/m]	R^2 [−]
NW	1.73856	-2.63333	0.26675
WC	0.99860	-1.76102	0.63633
SW	7.60418	-11.96806	0.68715
NC	0.38029	-0.41204	0.15732
C	0.31370	-0.48820	0.22589
SC	1.66470	-2.51640	0.15757
NE	0.07375	-0.15571	0.12573
EC	0.07676	-0.07494	0.03385
SE	0.01780	-0.01296	0.00498

Figure 4.23: *Irrigated corn vs. groundwater application*

shown in Figures 4.23 to 4.28.

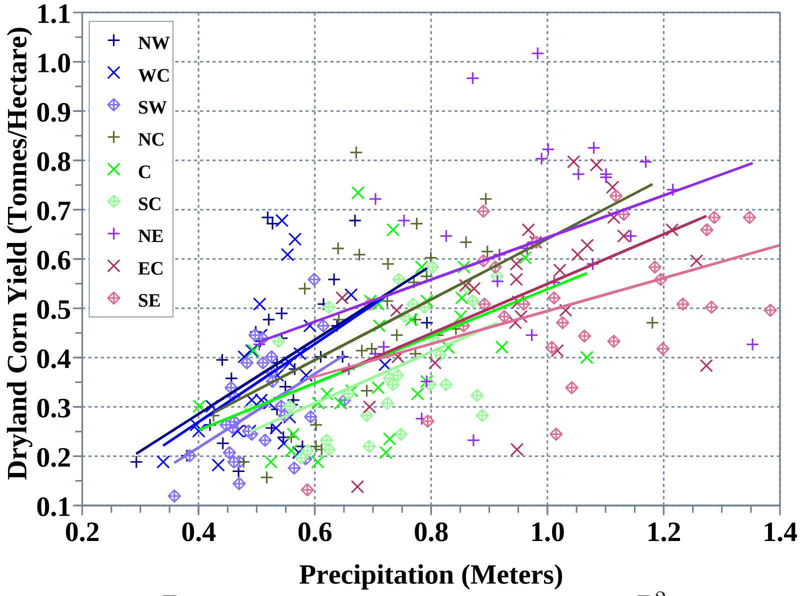
Figure 4.23 shows the relationship between irrigated corn production and groundwater application from 1980-2009. Interestingly, the relationship appears to show that for this period, greater corn production occurred with less groundwater use. This is contrary to what was expected. This relationship can likely be explained through greater irrigation efficiency and more drought resistant crop types. R^2 values, using the criteria of R^2 ==0.3 being significant, show significant trends in the west central and southwest districts.



District	c_0 [Mt]	c_1 [Mt/m]	R^2 [−]
NW	-0.27863	0.97758	0.09123
WC	-0.02934	0.26413	0.02067
SW	-0.01254	0.10309	0.01730
NC	0.01488	0.19129	0.02795
C	-0.01391	0.09404	0.04579
SC	-0.10005	0.24447	0.09265
NE	0.33155	0.49552	0.03049
EC	-0.01188	0.37631	0.08391
SE	0.08936	0.16668	0.01334

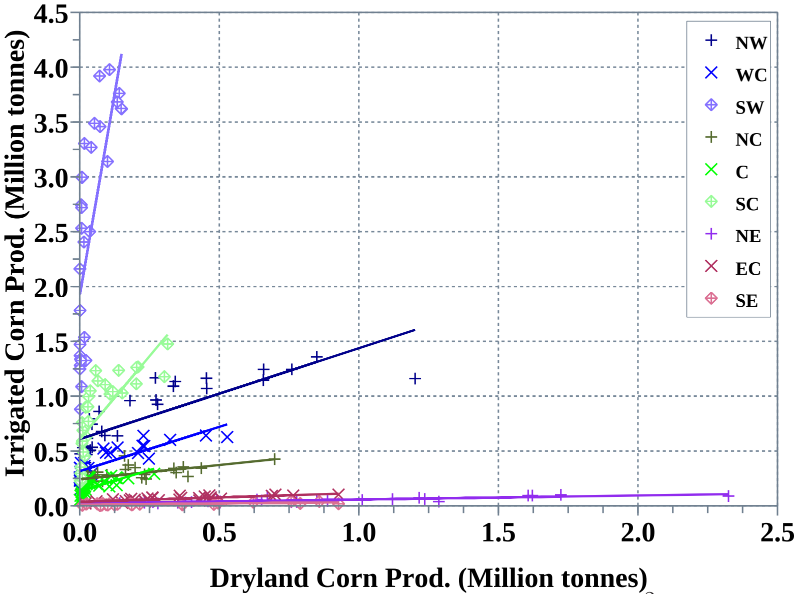
Figure 4.24: *Dryland corn production vs. precipitation*

Figures 4.24 and Figure 4.25 show the relationship between dryland corn production and yield, and precipitation. The correlation of dryland corn production and yield with precipitation is not particularly strong. R^2 values for the correlation between dryland corn production and precipitation, shown in Figure 4.24, were all less than 0.1. R^2 values for the correlation of dryland corn yield and precipitation were all less than 0.3. Though the trend is weak, both show a positive correlation.



District	c_0 [t/He]	c_1 [t/He/m]	R^2 [−]
NW	-0.01538	0.75227	0.24909
WC	-0.04743	0.79186	0.21634
SW	-0.08127	0.74717	0.21815
NC	0.02671	0.61404	0.28425
C	0.06222	0.47669	0.21819
SC	-0.00441	0.51994	0.23818
NE	0.21674	0.42685	0.16132
EC	0.04600	0.50352	0.28615
SE	0.16076	0.33376	0.20558

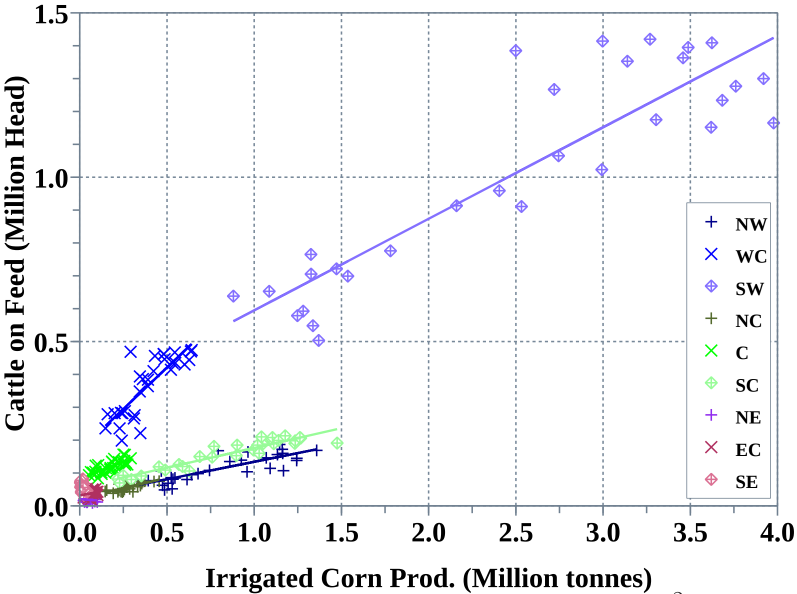
Figure 4.25: *Dryland corn yield vs. precipitation*



District	c_0 [Mt]	c_1 [Mt/Mt]	R^2 [−]
NW	0.60880	0.82844	0.68716
WC	0.31619	0.80901	0.66672
SW	1.91913	14.69401	0.54829
NC	0.24241	0.26033	0.39439
C	0.13445	0.76146	0.45642
SC	0.60624	3.03154	0.57817
NE	0.02059	0.03660	0.69683
EC	0.03657	0.07961	0.63451
SE	0.00942	0.02357	0.47174

Figure 4.26: *Irrigated corn production vs. dryland corn production*

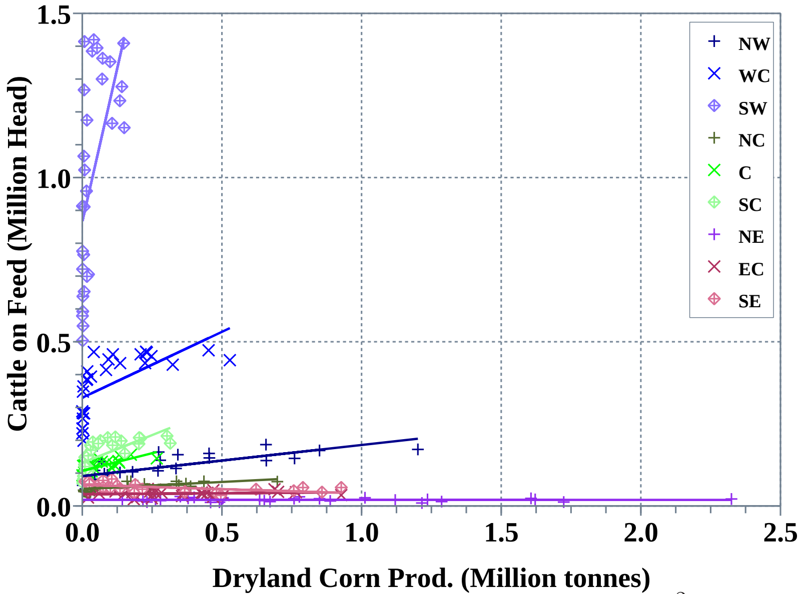
Figure 4.26 shows the relationship between irrigated corn production and dryland corn production. The results show that particular districts tend to display strong emphasis toward either irrigated or dryland production, depending on the amount of precipitation in an area and the availability of groundwater. A few districts, including the northwest, north central and west central show a greater balance between irrigated and dryland corn production within the district. R^2 values for all 9 districts were above 0.3, indicating the trends to be significant.



District	c_0	c_1	R^2
	[Mhead]	[Mhead/Mt]	[−]
NW	0.02798	0.10612	0.67868
WC	0.16847	0.50489	0.67262
SW	0.31641	0.27846	0.79696
NC	0.02342	0.12311	0.53562
C	0.08416	0.19679	0.56338
SC	0.05639	0.11988	0.88381
NE	0.02060	-0.03888	0.02826
EC	0.03224	0.08679	0.05159
SE	0.06491	-0.48825	0.12930

Figure 4.27: *Cattle on Feed vs. Irrigated Corn Production*

Figures 4.27 and 4.28 show the relationship between irrigated and dryland corn production with the number of cattle on feed at the beginning of the year in each district. Figure 4.27 generally shows that areas with more cattle on feed typically have greater amounts of irrigated corn production. R^2 values were significant in Figure 4.27 for all districts except the eastern districts. The eastern districts had very little cattle on feed and irrigated corn production. There is also a weak but positive trend between dryland corn production and the number of cattle on feed. Looking at the data as a whole in Figure 4.28, it shows



District	c_0 [Mhead]	c_1 [Mhead/Mt]	R^2 [−]
NW	0.09091	0.09469	0.54098
WC	0.32966	0.40128	0.41895
SW	0.86485	3.73531	0.36416
NC	0.05160	0.04305	0.38108
C	0.10714	0.21445	0.52666
SC	0.13097	0.33899	0.44464
NE	0.01886	-0.00024	0.00055
EC	0.03581	0.00579	0.02299
SE	0.06414	-0.02606	0.31276

Figure 4.28: *Cattle on Feed vs. Dryland Corn Production*

that where dryland corn production occurs, there is generally less cattle on feed. R^2 values in Figure 4.28 were generally significant, with exception to the northeast and east central districts.

The correlation between different datasets was different than anticipated. It was anticipated that a positive correlation would be developed between irrigated corn production and groundwater use, showing that greater irrigated corn production required more groundwater use. It was also anticipated that a positive correlation would exist between irrigated corn production and the number of cattle on feed. This relationship would show the clear connection between groundwater use, irrigated corn production, and the number of cattle on feed in an area. The results, however showed a negative relationship between groundwater use and irrigated corn production, and a positive relationship between irrigated corn production and cattle on feed. This relationship between groundwater use and irrigated corn production would likely have been positive had the same analysis been conducted using data prior to 1980, when the use of irrigation was still greatly expanding. After 1980, however, the irrigated area in most districts become fairly constant, and groundwater use was at a peak. The trend in groundwater use since 1980 has been toward greater efficiency, which caused the negative relationship. The relationship between irrigated corn production and groundwater use is shown in Figure 4.23. The correlation between irrigated corn production and cattle on feed did result in a positive correlation, shown in 4.27. The likely explanation of this relationship is the need for local corn grain at cattle feedyards. It is most economical for feedyards to get feed from as close a source as possible. And it is most economical for farmers who are close to feedyards to produce corn.

Looking at the results of the research conducted for this thesis as a whole, certain findings were made. It is clear from the modeled saturated thickness maps that in western Kansas, groundwater resources will decline significantly over the next 100 years. Similarly, the modeled groundwater use shows that the decline in groundwater resources will cause a decrease in groundwater use as well. The correlation between irrigated corn production and groundwater use does show that improvements in irrigation efficiency likely helped reduce groundwater use while still increasing production over the last 30 years. These improvements, however, will not increase efficiency of water use enough to avoid eventual exhausting of groundwater resources. The reduction of groundwater resources will reduce the ability to grow large amounts of corn in Kansas, in turn providing less cattle feed for the southwest Kansas cattle industry. In preparation for a future period when irrigation is no longer a reliable source of water for crops, changes will need to be made in the feed base for finishing cattle in western Kansas.

Chapter 5

Conclusions

The Ogallala Aquifer is the primary source of irrigation water for agriculture in western Kansas, and is of special importance in the production of corn grain. Over the last 30 years, declining groundwater levels have been a cause for concern over the sustainability of groundwater resources for future agriculture. In this thesis, current and future groundwater availability in western Kansas was investigated through the use of a groundwater model that projected the Ogallala Aquifer saturated thickness out to the year 2110. Changes in the saturated thickness were analyzed in sections delineated by the 3 western agricultural districts, as defined by the Kansas Agricultural Statistics Service. It was found that the saturated thickness across all 3 western districts was in decline and that significant decreases in saturated thickness would occur over the next 100 years. The greatest declines occurred in the southwest district, where the saturated thickness was projected to decline from an average of 51.6 meters to 6.7 meters over the next 100 years. The northwest and west central districts showed declines from 19.6 meters to 6.6 meters and from 8.5 to 3.2 meters respectively over the same time period. Areas where saturated thickness will remain after 2110 were found in the northwest and southwest parts of Kansas. These areas include parts of Cheyenne, Rawlins, Decatur and Norton in the northwest and Morton, Stevens and Seward in the southwest.

By relating the changes in saturated thickness to the volume of water leaving the aquifer, groundwater use was modeled out to 2110. The modeled groundwater use was compared to reported groundwater use from the Kansas Division of Water Resources from 1965 to 2010. The correlation resulted in R^2 values of 0.683, 0.695 and 0.624 for the northwest, west central and southwest districts respectively. The general trends of the model over the next 100 years showed significant declines in groundwater use. The model forecasted that by approximately 2080, groundwater use in the southwest district would be reduced by 50%. In the northwest and west central districts, groundwater use was projected to decline as well, although by lesser amounts.

With a greater understanding of future groundwater availability and use, correlations were made to quantify the relationships between groundwater use, irrigated corn production, and cattle on feed. Using agricultural data from the Kansas Agricultural Statistics Service from 1980 to 2009, the least squares method was applied to correlate the data. It was anticipated that a positive relationship would develop between the datasets. The results of the analysis, however, showed a negative relationship between groundwater use and irrigated corn production in all three western districts that overly the Ogallala. This meant that from 1980 to 2009, irrigated corn production was increasing with less groundwater applied. It was determined that the negative relationship was due to increases in irrigation efficiency and the lack of further development in irrigation since 1980. Increases in irrigation efficiency were confirmed by correlating groundwater application and the volume of groundwater use per area irrigated, with time. What can be concluded is that developments have been made over the past 30 years toward more efficient uses of our limited groundwater resources.

Also during the correlation analysis, a positive relationship was found between irrigated corn production and the number of cattle on feed. In the southwest district, where the largest amount of cattle on feed are, a positive relationship with a R^2 value of 0.8 was found. Strong correlations were also made in the west central and southwest districts, where there are significant amounts of cattle on feed as well. This shows the importance of having a local feed source to feedyards.

The findings in this thesis provide information that is beneficial for future planning in the agricultural industry. From the results of this thesis, it is clear that the availability of groundwater for irrigation will be significantly limited in the next 100 years. While improvements in irrigation efficiency are occurring and will help ease some of the burden of limited groundwater, ultimately irrigated crops like corn will no longer be grown reliably in areas dependent on irrigation. The livestock industry, especially the cattle industry in southwest Kansas, will need to locate new sources of corn grain for feed or switch to a less water dependent feed source. Meeting this need will require an understanding of where corn will be produced in the future and an understanding of the role transportation will have in supplying corn grain to feedyards. Further research is needed to determine how corn production in Kansas will change as a result to a decline in groundwater resources, and to identifying potential sources of corn grain outside the state. More research is also needed to determine how transportation will play a role in providing corn grain to Kansas feedyards.

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Appendix A

Creating the Point Shapefile populated with Model Data

As part of the methodology for developing saturated thickness maps and forecasting water use, a shapefile containing model data was created in ArcGIS. In this appendix, the term 'model data' will refer to data created from either the Saturated Thickness Model (STM) or the Change in Water Level Model (CWLM). This process was used in both parts of the methodology. The model data point shapefile was created so that the data could be interpolated into raster surfaces in ArcGIS. The steps are as follows:

1. Create and prepare model output data for use in ArcGIS.

    (a) Run the model to create output data in the form of a comma separated value (CSV) file.

    (b) Open the model data csv file in Microsoft Excel, and re-save the CSV file as a database (dbf) file for use in ArcGIS.

2. Get monitoring well locations from USGS in table format

    (a) Get information on the locations of monitoring wells related to the model output data by going to the groundwater section of the USGS's National Water Information System database, located http://waterdata.usgs.gov/nwis/gw, and downloading groundwater well locations in Kansas.

(b) Save the table as a dbf file in Microsoft Excel.

3. Use the table of monitoring well locations to create a point shapefile of well locations.

   (a) Open the ArcGIS and start a new map file (mxd file).

   (b) Open the table of monitoring well locations and use the *Add XY data* tool to give the data a spatial identity on the map.

      i. *X field: LONGITUDE; Y field: LATITUDE*

      ii. *Coordinates System: Geographic* → *North American Datum 1983*

4. Next, add the model data file to ArcGIS and join the table to the newly created point shapefile.

   (a) Right click on the shapefile, and select *Join and Relates* → *Join*

   (b) Join the *HydroID* in the well location shapefile to the *ID* in the model output data, and *Keep only Matching records.*

5. Save the file as a new shapefile by right-clicking on the shapefile and choose *Data* → *Export data*

Appendix B

Trend Analysis

Spatial trends in the model data were investigated prior to the Ordinary Kriging process using the ArcGIS Trend Analysis tool. A trend analysis is conducted because part of the Kriging interpolation process often involves removing a spatial trend in the data prior to interpolating the surface. The Trend Analysis tool plots the data in three dimensions (xy, xz and yz planes) to allow the user to see any trends that may exist. Further, different order polynomials can be fit to the data to see which order trends fit best.[17]

In this research, the trend analysis helped in making decisions on what order of trend should be removed for the data for all years. It was decided that a 2nd order polynomial trend fit best for all years. Below are the plotted data points for change in water level data for four different years. The red points are the locations of the monitoring wells. The green and blue points are change in water level values projected on their respective planes. The green and blue lines show the 2nd order polynomial fit to the data.

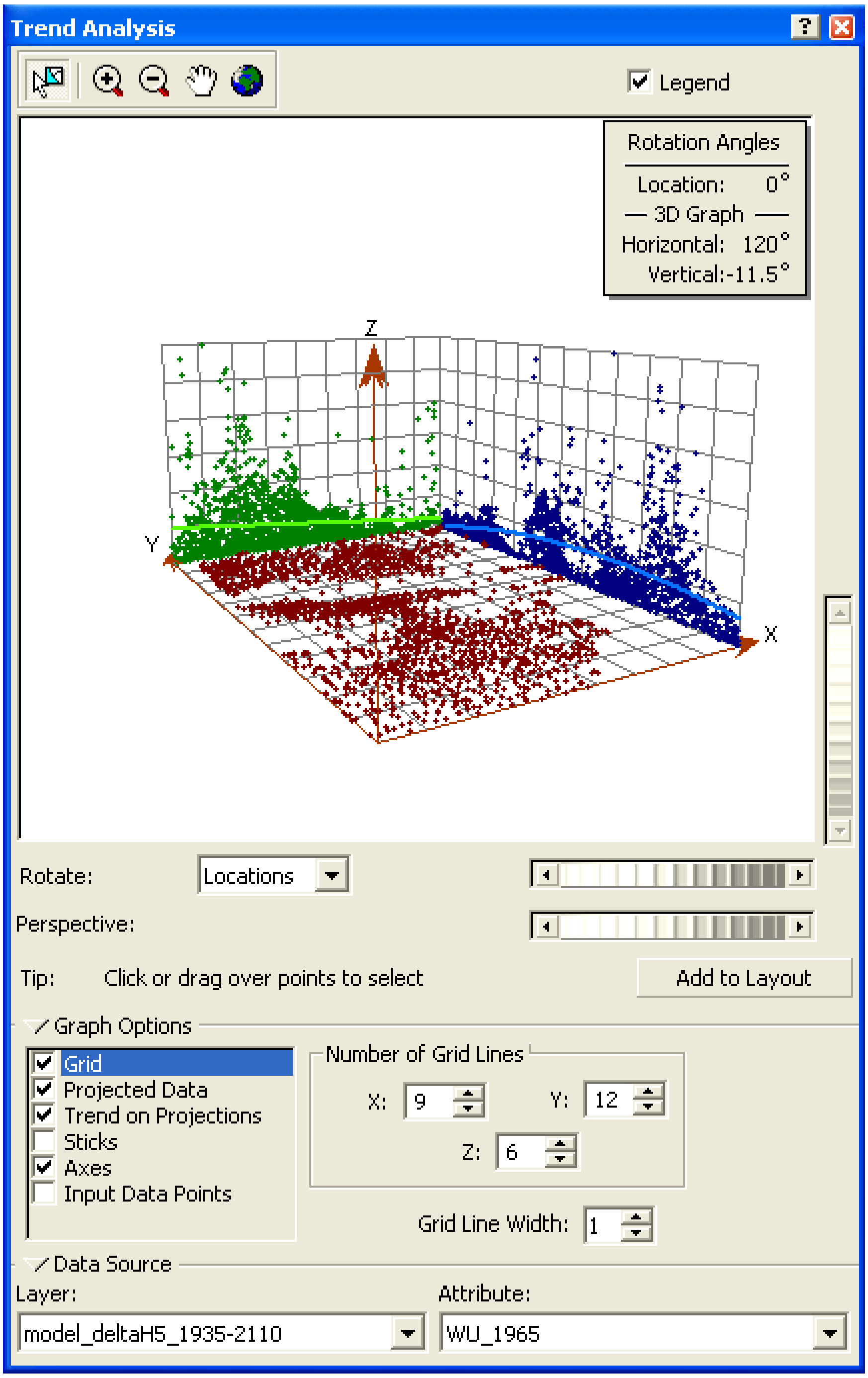

Figure B.1: *Trend Analysis of 1965 water level changes.*

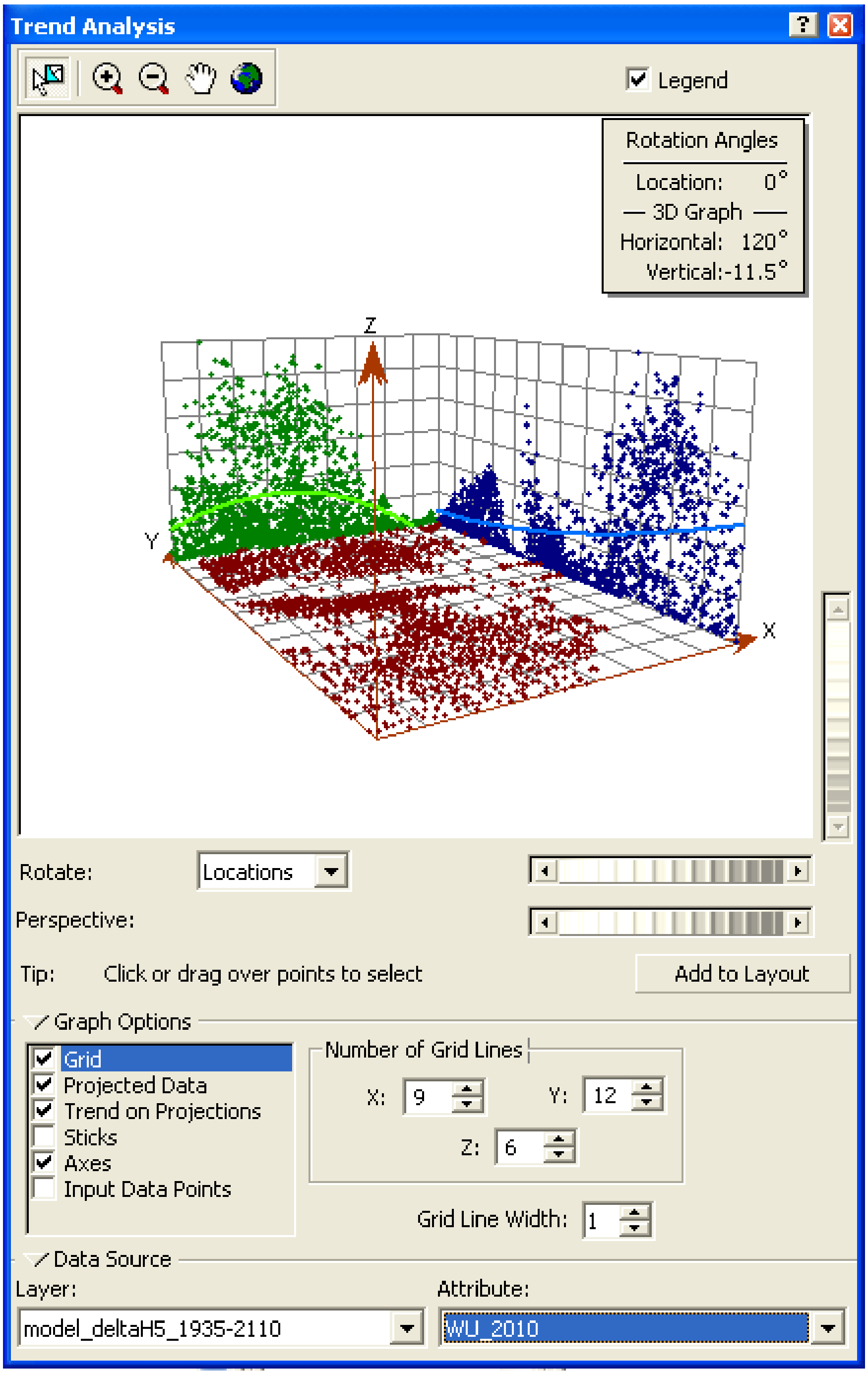

Figure B.2: *Trend Analysis of 2010 water level changes.*

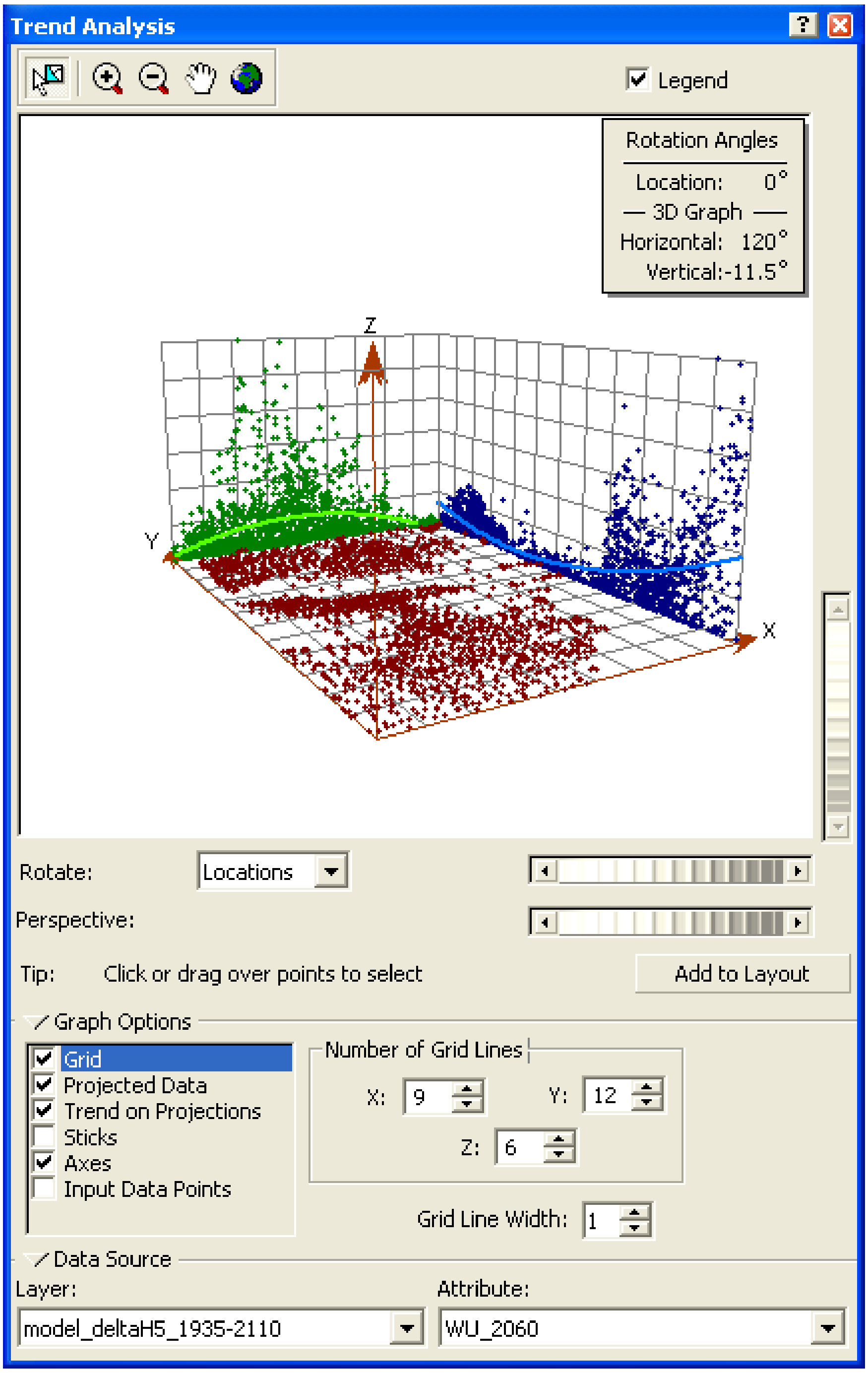

Figure B.3: *Trend Analysis of 2060 water level changes.*

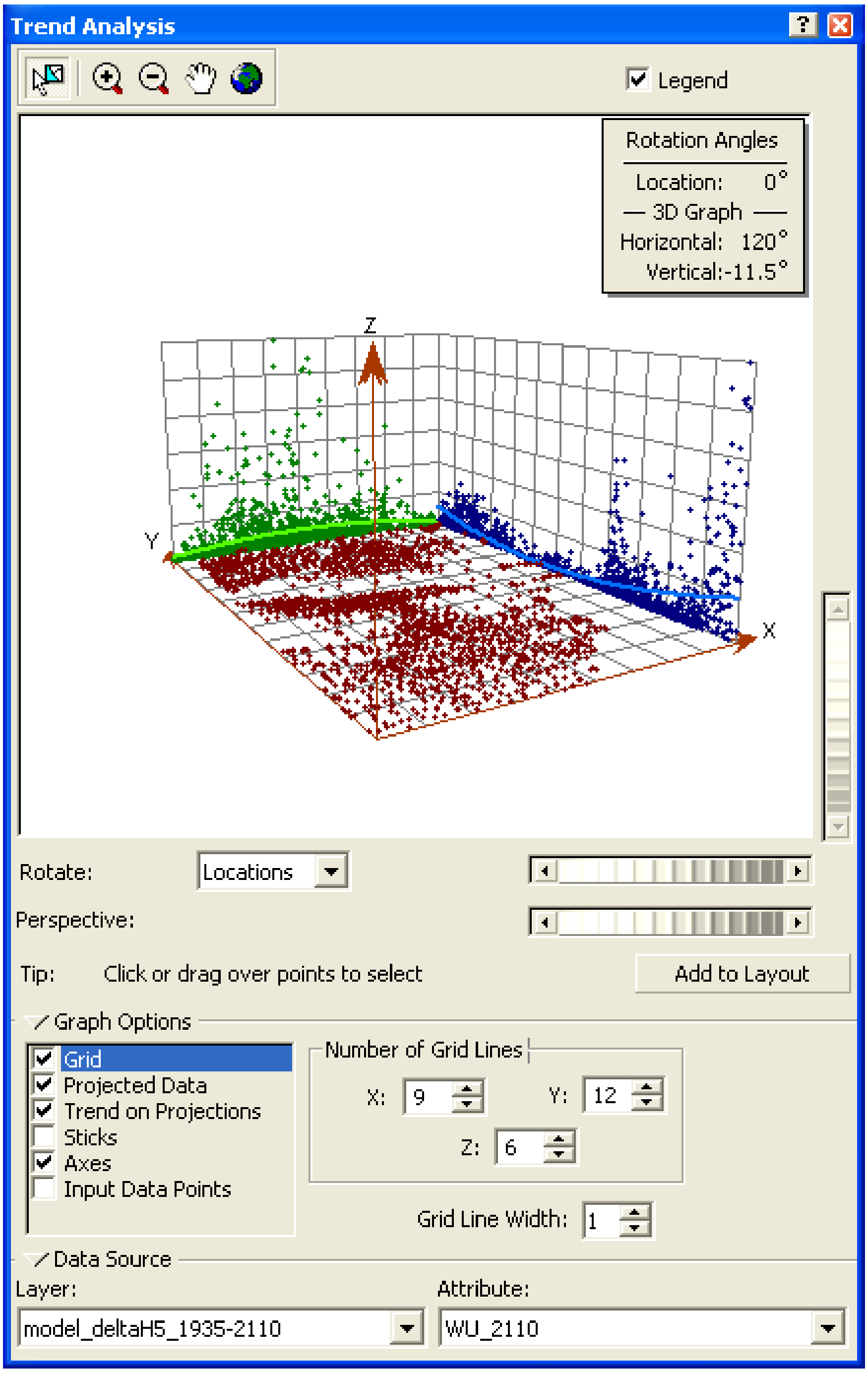

Figure B.4: *Trend Analysis of 2110 water level changes.*

Appendix C

Converting Specific Yield Shapefile to Raster

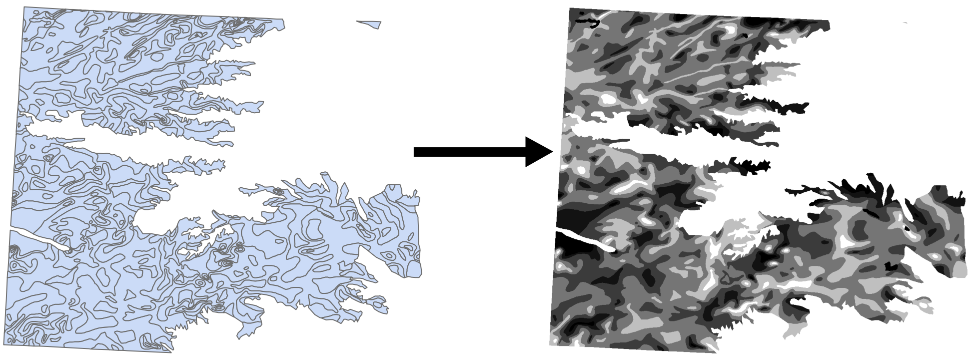

Figure C.1: *Conversion of specific yield shapefile to a raster file.*

To use the specific yield raster in Section 3.3, the file had to be downloaded from the USGS and converted from a shapefile to a raster. To do this, the following steps were taken:

1. Download specific yield file from the USGS-NAWQA High Plains Regional Ground Water Study website.

   (a) Go to http://co.water.usgs.gov/nawqa/hpgw/HPGW_home.html.

   (b) Select textitDATA from left side bar.

   (c) Select *Geographic Information System (GIS) digital data.*

(d) Select and download specific yield (OFR 98-414).

2. Open specific yield shapefile into ArcGIS.

3. Convert percentage value to decimal.

   (a) Add field (type = double) to attribute table in specific yield shapefile and name it SY (for specific yield)

   (b) Use the field calculator to populate the field equal to the *Minor1 / 100*.

   (c) Save edits.

4. Convert shapefile to raster (100 x 100 meters)

   (a) Within the Arc Toolbox, select the *Polygon to Raster* tool (*Conversion Tools* → *To Raster* → *Polygon to Raster*).

   (b) Select the following parameters

      i. Input Features = *Specific_Yield_KS*

      ii. Value Field = *SY*

      iii. Output Raster Dataset = *File name*

      iv. Cell Assignment Type = *CELL_CENTER*

      v. Priority Field (Optional) = NONE

      vi. Cellsize (Optional) = 100

Appendix D

Parameters Used for Ordinary Kriging of CWLM Data and Resulting Prediction Errors

In Tables D.1 through D.3 the final parameters are shown for the Ordinary Kriging of the CWLM data from 1965 to 2110. For all interpolations, the order of trend was always 2^{nd} order global polynomial interpolation, anisotrophy was always selected, there were no transformations of data, and the number of lags remained 12 (default). Parameters that were selected manually for each iteration of the Ordinary Kriging procedure include Model type, Lag size, and the number of neighbors (and minimum neighbors). The rest of the parameters were auto-optimized. The parameters are shown on the next few pages.

Yr	Model type	Range	Anisotropy	Minor range	Direction	Partial sill
1965	Exponential	71119.61755	Yes	67955.05151	295.8460255	0.625264675
1970	Exponential	73965.37042	Yes	66946.33822	294.424017	0.9341759
1975	Spherical	45117.17988	Yes	53844.41061	14.52580452	1.48937281
1980	Spherical	62568.93111	Yes	53944.58019	285.9737415	2.027296216
1985	Spherical	57205.67203	Yes	51212.61701	284.9031296	2.814161663
1990	Spherical	68176.94457	Yes	52959.48848	284.6571484	3.155519351
1995	Spherical	68197.69843	Yes	55946.76419	284.1766224	3.461748347
2000	Spherical	73892.59184	Yes	57310.35915	283.9655371	3.486569474
2005	Exponential	113549.9348	Yes	78327.25435	286.9913216	3.542886105
2010	Exponential	107989.6203	Yes	98053.90965	286.8340549	3.834467342
2015	Exponential	100752.7915	Yes	96690.3094	287.2752352	4.287364504
2020	Exponential	88899.52193	Yes	85772.15033	292.9155102	4.404097635
2025	Exponential	82972.88714	Yes	80041.2305	299.9570198	4.287931704
2030	Exponential	71119.61755	Yes	67871.38015	303.8151999	4.099037655
2035	Exponential	71119.61755	Yes	67810.07882	305.0700722	3.958997888
2040	Exponential	77046.25234	Yes	74041.65134	302.519743	3.696360777
2045	Exponential	77046.25234	Yes	73572.81058	298.8631802	3.426491024
2050	Spherical	41486.44357	Yes	38689.52847	292.4129572	2.409555162
2055	Exponential	79899.2548	Yes	75493.21804	289.3433418	2.655056609
2060	Exponential	79655.50421	Yes	72204.33485	286.2788839	2.319119507
2065	Exponential	79684.64398	Yes	72187.50979	283.8157158	1.97292413
2070	Spherical	41486.44357	Yes	38774.10683	283.2721224	1.182349966
2075	Spherical	17631.59925	Yes	14332.10936	86.73928833	0.525137907
2080	Exponential	17694.76099	Yes	14204.68184	81.01422691	0.567241721
2085	Spherical	11813.16898	Yes	7452.928873	69.35947609	0.372553818
2090	Exponential	11853.26959	Yes	8344.680519	75.00464821	0.351151024
2095	Spherical	11853.26959	Yes	7462.664099	70.78951073	0.262895582
2100	Spherical	11853.26959	Yes	7934.57729	72.86870289	0.210408037
2105	Spherical	11853.26959	Yes	7877.275251	73.73352718	0.167533295
2110	Spherical	11853.26959	Yes	8356.188436	76.79021168	0.129189247

Table D.1: *Ordinary Kriging Model type parameters.*

Yr	Variogram	No. of lags	Lag size	Nugget	Measurement Error
1965	Semivariogram	12	6000	0.181370721	0
1970	Semivariogram	12	6500	0.344757746	0
1975	Semivariogram	12	4000	0.537165075	0
1980	Semivariogram	12	5500	0.939651371	0
1985	Semivariogram	12	5000	0.998442559	0
1990	Semivariogram	12	6000	1.178948998	0
1995	Semivariogram	12	6000	1.172840149	0
2000	Semivariogram	12	6500	1.24397268	0
2005	Semivariogram	12	10000	1.318480993	0
2010	Semivariogram	12	9500	1.404062053	0
2015	Semivariogram	12	8500	1.199373111	0
2020	Semivariogram	12	7500	0.997443779	0
2025	Semivariogram	12	7000	0.93238809	0
2030	Semivariogram	12	6500	0.769952795	0
2035	Semivariogram	12	6500	0.728195147	0
2040	Semivariogram	12	6500	0.798716894	0
2045	Semivariogram	12	6500	0.753137525	0
2050	Semivariogram	12	3500	0.775956153	0
2055	Semivariogram	12	7000	0.698639821	0
2060	Semivariogram	12	7000	0.588924317	0
2065	Semivariogram	12	7000	0.508065216	0
2070	Semivariogram	12	3500	0.514554471	0
2075	Semivariogram	12	1500	0.403613623	0
2080	Semivariogram	12	1500	0.222158359	0
2085	Semivariogram	12	1500	0.199454805	0
2090	Semivariogram	12	1000	0.127802443	0
2095	Semivariogram	12	1000	0.131769039	0
2100	Semivariogram	12	1000	0.116221784	0
2105	Semivariogram	12	1000	0.101853426	0
2110	Semivariogram	12	1000	0.094133772	0

Table D.2: *Ordinary Kriging Variogram parameters.*

Year	Nghbrs.	Min. Nghbrs.	Sector Type	Angle	Mjr. semiaxis	Mnr. semiaxis
1965	10	5	Four and 45 degree	295.8460255	71119.61755	67955.05151
1970	10	5	Four and 45 degree	294.424017	73965.37042	66946.33822
1975	10	5	Four and 45 degree	14.52580452	45117.17988	53844.41061
1980	5	2	Four and 45 degree	285.9737415	62568.93111	53944.58019
1985	10	5	Four and 45 degree	284.9031296	57205.67203	51212.61701
1990	10	5	Four and 45 degree	284.6571484	68176.94457	52959.48848
1995	10	5	Four and 45 degree	284.1766224	68197.69843	55946.76419
2000	5	2	Four and 45 degree	283.9655371	73892.59184	57310.35915
2005	10	5	Four and 45 degree	286.9913216	113549.9348	78327.25435
2010	5	2	Four and 45 degree	286.8340549	107989.6203	98053.90965
2015	10	5	Four and 45 degree	287.2752352	100752.7915	96690.3094
2020	10	5	Four and 45 degree	292.9155102	88899.52193	85772.15033
2025	10	5	Four and 45 degree	299.9570198	82972.88714	80041.2305
2030	10	5	Four and 45 degree	303.8151999	71119.61755	67871.38015
2035	10	5	Four and 45 degree	305.0700722	71119.61755	67810.07882
2040	10	5	Four and 45 degree	302.519743	77046.25234	74041.65134
2045	5	2	Four and 45 degree	298.8631802	77046.25234	73572.81058
2050	5	2	Four and 45 degree	292.4129572	41486.44357	38689.52847
2055	5	2	Four and 45 degree	289.3433418	79899.2548	75493.21804
2060	5	2	Four and 45 degree	286.2788839	79655.50421	72204.33485
2065	5	2	Four and 45 degree	283.8157158	79684.64398	72187.50979
2070	5	2	Four and 45 degree	283.2721224	41486.44357	38774.10683
2075	10	5	Four and 45 degree	86.73928833	17631.59925	14332.10936
2080	10	5	Four and 45 degree	81.01422691	17694.76099	14204.68184
2085	10	5	Four and 45 degree	69.35947609	11813.16898	7452.928873
2090	10	5	Four and 45 degree	75.00464821	11853.26959	8344.680519
2095	10	5	Four and 45 degree	70.78951073	11853.26959	7462.664099
2100	10	5	Four and 45 degree	72.86870289	11853.26959	7934.57729
2105	10	5	Four and 45 degree	73.73352718	11853.26959	7877.275251
2110	10	5	Four and 45 degree	76.79021168	11853.26959	8356.188436

Table D.3: *Ordinary Kriging Neighborhood parameters.*

Yr	Mean	RMS	Avg. Std.	Mean Standardized:	RMS Standardized
1965	0.0005512	0.5085	0.5525	-0.0001591	0.9274
1970	0.0009175	0.6136	0.7335	0.00003351	0.8508
1975	-0.0009711	0.7531	0.8851	-0.002211	0.8692
1980	-0.001134	0.8995	1.122	-0.00222	0.816
1985	-0.001668	1.013	1.196	-0.002252	0.866
1990	-0.00213	1.078	1.277	-0.002524	0.8592
1995	-0.002643	1.108	1.283	-0.002739	0.8783
2000	-0.001771	1.125	1.309	-0.002144	0.8726
2005	-0.0003247	1.141	1.382	-0.0008297	0.8401
2010	-0.0009615	1.147	1.417	-0.001143	0.8232
2015	-0.0004307	1.132	1.359	-0.0004444	0.8516
2020	-0.0008916	1.114	1.302	-0.000648	0.8792
2025	-0.001397	1.101	1.281	-0.001112	0.8819
2030	-0.00143	1.089	1.231	-0.0012	0.9085
2035	-0.000688	1.082	1.203	-0.0008747	0.9199
2040	0.0002553	1.076	1.203	-0.0005033	0.9094
2045	0.001221	1.067	1.166	-0.00001041	0.93
2050	0.0005528	1.045	1.111	-0.0009285	0.9528
2055	0.001644	1.01	1.084	-0.0001671	0.9452
2060	0.002775	0.9634	1.004	0.0006712	0.9729
2065	0.003417	0.9078	0.9307	0.001169	0.988
2070	0.002336	0.8501	0.8699	0.0002056	0.9836
2075	0.003832	0.7884	0.8112	0.001984	0.9784
2080	0.005246	0.7286	0.744	0.003357	0.9998
2085	0.003256	0.6684	0.6701	0.001532	1.016
2090	0.004455	0.6121	0.6217	0.003589	1.01
2095	0.002464	0.5586	0.5531	0.0008344	1.029
2100	0.00302	0.5134	0.5048	0.002382	1.03
2105	0.002922	0.4709	0.4627	0.002973	1.027
2110	0.002233	0.4365	0.4262	0.002383	1.027

Table D.4: *Ordinary Kriging prediction errors.*

Table D.4 shows the prediction errors that resulted from the iterations of the Ordinary Kriging of the CWLM output data. The main criteria for selecting the parameters for the Ordinary Kriging was the RMS Error. The other errors were taken into consideration while investigating the interpolation process and are also shown.

Appendix E

Code for Creating Saturated Thickness Rasters

The following code was developed to automated the process of creating the saturated thickness rasters from 1965 to 2110. The code uses Raster Math Minus tool (3D Analyst Tools → Raster Math → Minus) to subtract the change in groundwater level over a period of time from a saturated thickness raster to create a new raster. The code was developed by figuring out which ArcGIS tool would accomplish the raster calculations needed, and then observing and replicating the code executed by the raster tool. Once the code was determined for one run of the tool, it was copied and edited to run multiple iterations, and pasted into the command line. In the code, the *satd_YEAR* is the saturated thickness raster, *deltah5_YEAR*

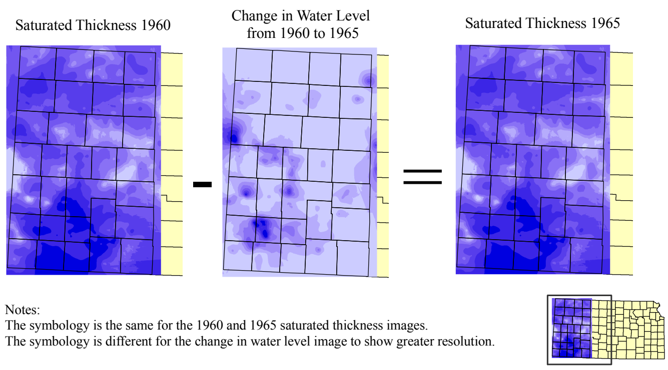

Figure E.1: *Creating 1965 saturated thickness raster from the 1960 saturated thickness raster and change in water level data.*

is the change in groundwater level raster subtracted from the saturated thickness raster to create the new saturated thickness raster. For example, the first run can be read "Minus from 1960 saturated thickness the 5-year change in groundwater levels from 1960 to 1965 and save as 1965 saturated thickness." The full code is as follows.

```
Minus_3d satd_1960 deltah5_1965 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_1965
Minus_3d satd_1965 deltah5_1970 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_1970
Minus_3d satd_1970 deltah5_1975 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_1975
Minus_3d satd_1975 deltah5_1980 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_1980
Minus_3d satd_1980 deltah5_1985 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_1985
Minus_3d satd_1985 deltah5_1990 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_1990
Minus_3d satd_1990 deltah5_1995 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_1995
Minus_3d satd_1995 deltah5_2000 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_2000
Minus_3d satd_2000 deltah5_2005 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_2005
Minus_3d satd_2005 deltah5_2010 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_2010
Minus_3d satd_2010 deltah5_2015 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\
satd_2015
```

Minus_3d satd_2015 deltah5_2020 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2020

Minus_3d satd_2020 deltah5_2025 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2025

Minus_3d satd_2025 deltah5_2030 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2030

Minus_3d satd_2030 deltah5_2035 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2035

Minus_3d satd_2035 deltah5_2040 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2040

Minus_3d satd_2040 deltah5_2045 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2045

Minus_3d satd_2045 deltah5_2050 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2050

Minus_3d satd_2050 deltah5_2055 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2055

Minus_3d satd_2055 deltah5_2060 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2060

Minus_3d satd_2060 deltah5_2065 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2065

Minus_3d satd_2065 deltah5_2070 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2070

Minus_3d satd_2070 deltah5_2075 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2075

Minus_3d satd_2075 deltah5_2080 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2080

Minus_3d satd_2080 deltah5_2085 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5 *satd_2085*

Minus_3d satd_2085 deltah5_2090 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ satd_2090

Minus_3d satd_2090 deltah5_2095 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ satd_2095

Minus_3d satd_2095 deltah5_2100 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ satd_2100

Minus_3d satd_2100 deltah5_2105 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ satd_2105

Minus_3d satd_2105 deltah5_2110 C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ satd_2110

Appendix F

Code for Clippling Saturated thickness raster to Aquifer Extent

The following code was developed to automated the process of clipping the saturated thickness rasters to the extent of the Ogallala Aquifer. This was done to limit the saturated thickness rasters to an area of known significant saturated thickness so as to not overestimate groundwater resources. The code uses the Raster Processing Clip tool (Data Management Tools → Raster → Raster Processing → Minus) to essentially limit the raster shape to the boundary of another polygon. The code was developed similarly as in Appendix E. Once the code was determined for one run of the tool, it was copied and edited to run multiple iterations, and pasted into the command line. In Figure F.1, a visual of what the code does during one iteration. For reference, files titled *satd_YEAR* are saturated thickness raster

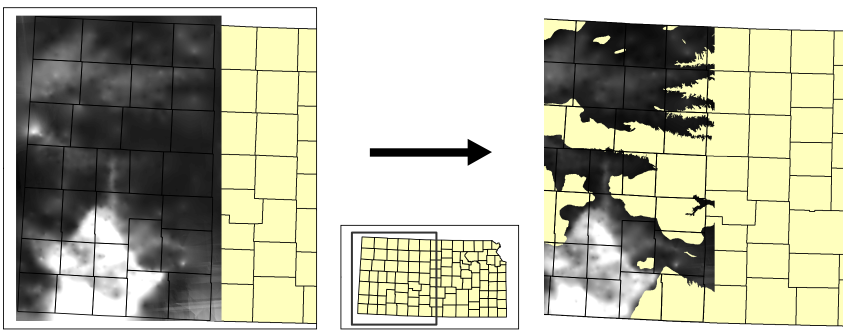

Figure F.1: *Clipping the saturated thickness raster to the extent of the Ogallala Aquifer.*

files, *High_Plains_Aquifer_Extent* is the aquifer extent clipped to, and *satd_YEAR_Aq* is the new clipped saturated thickness file. The full code is as follows.

Clip_management satd_1965 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_1965_Aq High_Plains_Aquifer_Extent # ClippingGeometry
Clip_management satd_1970 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_1970_Aq High_Plains_Aquifer_Extent # ClippingGeometry
Clip_management satd_1975 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_1975_Aq High_Plains_Aquifer_Extent # ClippingGeometry
Clip_management satd_1980 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_1980_Aq High_Plains_Aquifer_Extent # ClippingGeometry
Clip_management satd_1985 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_1985_Aq High_Plains_Aquifer_Extent # ClippingGeometry
Clip_management satd_1990 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_1990_Aq High_Plains_Aquifer_Extent # ClippingGeometry
Clip_management satd_1995 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_1995_Aq High_Plains_Aquifer_Extent # ClippingGeometry
Clip_management satd_2000 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2000_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2005 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2005_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2010 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2010_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2015 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2015_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2020 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2020_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2025 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2025_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2030 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2030_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2035 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2035_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2040 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2040_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2045 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2045_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2050 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2050_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2055 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2055_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2060 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2060_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2065 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2065_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2070 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2070_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2075 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2075_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2080 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2080_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2085 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2085_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2090 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2090_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2095 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2095_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2100 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2100_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2105 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2105_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Clip_management satd_2110 '-533229.125230168 -56005.0589967025 -111033.068229981 296851.472705933' C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\satd_2110_Aq High_Plains_Aquifer_Extent # ClippingGeometry

Appendix G

Code for Zonal Statistics of Model Groundwater Use

The following code was developed to automated the Zonal Statistics as Table code used to summarize modeled groundwater use. The Zonal Statistics as Table tool (Spatial Analyst Tools → Zonal → Zonal Statistics as Table) among other statistics provides the sum of the cell values of a raster, separated into zones. Using this tool, rasters of modeled groundwater use per unit area were summed by agricultural district. The code was developed similarly to Appendix E. Once the code was determined for one run of the tool, it was copied and edited to run multiple iterations, and pasted into the command line. For reference, files called *WU_YEAR* are water use raster files for a given year and *g_Statistics_Departments123 District WU_1965* are the agricultural districts the tool uses as zones to sum to. The full code is as follows.

```
ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_1965
C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu1965aq_zstat.dbf DATA
ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_1970
C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu1970aq_zstat.dbf DATA
ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_1975
C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu1975aq_zstat.dbf DATA
```

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_1980

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu1980aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_1985

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu1985aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_1990

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu1990aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_1995

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu1995aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2000

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2000aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2005

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2005aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2010

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2010aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2015

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2015aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2020

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2020aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2025

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2025aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2030

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2030aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2035

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2035aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2040

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2040aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2045

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2045aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2050

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2050aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2055

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2055aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2060

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2060aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2065

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2065aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2070

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2070aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2075

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2075aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2080

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2080aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2085

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2085aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2090

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2090aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2095

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2095aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2100

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2100aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2105

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2105aq_zstat.dbf DATA

ZonalStatisticsAsTable_sa Ag_Statistics_Departments123 District WU_2110

C:\DATA\RESEARCH\SatD_DeltaH\deltaH5\ZonalStats\wu2110aq_zstat.dbf DATA