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Simulation and Prediction of the Groundwater Level in the Surrounding Area of the Nebraska Management System Evaluation Area site in Central Nebraska.

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SIMULATION AND PREDICTION OF THE GROUNDWATER LEVEL IN THE SURROUNDING AREA OF THE NEBRASKA MANAGEMENT SYSTEM EVALUATION AREA SITE IN CENTRAL NEBRASKA

By

Cesar Augusto Gomez Pena

A THESIS

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SIMULATION AND PREDICTION OF THE GROUNDWATER LEVEL IN THE SURROUNDING AREA OF THE NEBRASKA MANAGEMENT SYSTEM EVALUATION AREA SITE IN CENTRAL NEBRASKA (MSEA)

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An efficient water budget is necessary to develop sustainable practices in irrigated lands and determine future trends. Despite a lack of detailed knowledge, climate change is found to profoundly influence groundwater resources through changes in groundwater recharge, groundwater elevation, and groundwater flow processes. Prediction of the groundwater level (GWL) under a changing climate is essential to improve agricultural management.

The goal of this research is to predict the GWL from 2056 to 2060 in the surrounding area of the MSEA. In order to achieve the target, the first research task is to develop a groundwater flow model and then simulate the model to match the historical GWL from 1991 to 2014. The School of Natural Resources (SNR) and the Nebraska Department of Natural Resources (DRN) provided historical groundwater level, soil lithology, and irrigation well data of the site. Visual MODFLOW Flex (version 2015.1) was used to develop the groundwater flow model. Results show that groundwater modeling fairly matched the historical groundwater pattern. The calibrated groundwater model was then applied to predict GWL in the area from 2057 to 2060 using future climate data. In this study, future climate data were obtained from a downscaled climate change predictions from the Community Climate System Model (CCSM4) that represents the worst climate scenario with a high greenhouse gas emission pathway. Future predictions

show an overall decreasing trend of GWL over the simulation period, with increases in non-irrigated seasons (winter season) and decreases in irrigated seasons. Nevertheless, the declining rate is higher than the recharge rate, which leads to an average decreased amount of 3.34 feet from the year 2056 to the year 2060.

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CHAPTER 1

PROJECT OVERVIEW AND OBJECTIVES

1. Project Overview

Groundwater is an important part of the water cycle and is one of the most valuable natural resources in the United States. For example, in Central Nebraska, groundwater is the main source of water for farming activities (i.e., irrigation). Irrigation has supported agricultural production, resulting in $50 billion in sales in 2012 **(U.S. Department of Agriculture, 2014).** Nonetheless, throughout the years, farming practices have been increasing the concentration of chemicals in shallow aquifers. Therefore, a good understanding of how groundwater moves through a shallow aquifer is required to assess the Best Management Practices (BMPs) to mitigate groundwater contamination **(McGuire and Kilpatrick, 1998).**

Climate change may be defined as the alteration of the composition of the Earth's atmosphere due to the growing greenhouse emission because of human activities. For instance, variations in precipitation and temperature during the year will have a direct impact on changes in groundwater level **(Darwin, 2010)**. Variations in the climate influence the groundwater system both directly (e.g., recharge due to precipitation and snow melt) and indirectly (e.g., through changes in groundwater uses). Both processes can be affected by human activates such as changes in land use. Changes in climate could also affect groundwater primarily through changes in irrigation demands due to variations of precipitation (**Taylor et al., 2012).**

In this work, we focus on simulation and prediction of the groundwater level in the proximity of the Nebraska Management Systems Evaluation Area Site (MSEA) in Central Nebraska. Several previous studies strived to determine the groundwater movement in this area. For instance, in 1992, the U.S. Geological Survey (USGS), the U.S Department of Agriculture (USDA) and the University of Nebraska-Lincoln (UNL) defined a hydrogeological system in the proximity of the MSEA site to aid the interpretation of groundwater sampling **(McGuire and Kilpatrick, 1998).** Furthermore, USGS conducted a study of the future groundwater availability in the high plains to provide a tool for water resources managers and stakeholders **(Peterson et al., 2016).** Both studies investigated the groundwater movement in shallow aquifers based on historical and measured data.

Groundwater models have been widely accepted and used as a tool for water-resources investigations. Although the configuration of the groundwater flow is complex to determine, some assumptions helped approximation. However, due to the lack of information and techniques, assumptions such as the uniform distribution of hydraulic conductivity, simplified boundary conditions, and groundwater recharge were necessary to simulate physical groundwater levels. For instance, **McGuire and Kilpatrick (1998)** arbitrarily divided the aquifer in half and assumed a constant hydraulic conductivity for both parts. In some cases, over-simplified assumptions could lead to non-realistic solutions especially if the model area is vast. Nevertheless, because groundwater flow models are mathematical simplifications of complex natural systems that limit their accuracy, it is crucial to know how practical these limitations are when using models and interpreting results **(Gannett et al., 2012).**

In this work, we developed a 3-D groundwater flow model in the surrounding area of the MSEA. Different from the previously modeling efforts, a realistic 3-D soil lithology model of the site was developed based on soil lithology data collected by SNR of UNL. Due to the lack of stream gauging near to the site, historical groundwater data from DNR were gathered to determine boundary water levels from 1991 to 2014. Monthly actual evapotranspiration and precipitation data were collected to assist in determining well-pumping rates **(Swenson, 2006)** in the study area. Comparisons between calibrated targets to historical groundwater levels indicate that the model reproduced acceptable groundwater levels. Therefore, the model was used to forecast groundwater levels from 2056 to 2060. Well pumping rates were determined by using predicted precipitation from the Weather System and Forecasting model (WRF), actual evapotranspiration and groundwater recharge from Hydrus-1D inverse modeling. Furthermore, boundary conditions were estimated by extrapolating historical river elevations. Results of this study show that groundwater will decreases 3.34 feet on average through the groundwater simulation (2056 to 2060).

The developed 3D groundwater model considers realistic data such as geospatial evapotranspiration data, historical precipitation detected by NOAA radar, historical groundwater elevations, soil lithology types, and distributed permeability of the aquifer whereas most available groundwater models assumed average values. Nevertheless, our model considers a spatial and temporal variation of input data. Therefore, the results of the model are highly positive and can likely predict groundwater level variations due to climate changes.

2. Objectives

The overall aims of this study include two particular but related scenarios:

1. Calibrate a groundwater model by comparing simulated data and historical groundwater data from 1991 to 2014.
2. Predict the groundwater flow for 2056 to 2060 based on future climate change data.

3. Thesis Organization

This thesis is organized into 4 chapters and their sub-chapters. Chapter 1 gives a general review or summary of this research and provides broad objectives. Chapter 2 provides a background review on groundwater flow, hydrogeological properties of the subsurface. Chapter 3 addresses the first aim, i.e. determination of the groundwater flow in Central Plate Nebraska. Chapter 4 addresses the second goal, i.e. prediction of the groundwater flow for 2056 to 2060 in Central Plate Nebraska. Chapter 5 provides general conclusions of the research.

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CHAPTER 2 BACKGROUND

1. Historical and recent studies of modeling groundwater flow in central Nebraska.

Previous studies have modeled groundwater flow in Central Nebraska. In the 1990’s, the U.S Geological Survey (USGS), the U.S Department of Agriculture (USDA) and the University of Nebraska-Lincoln (UNL) conducted a groundwater flow modeling study in the surrounding area of the Nebraska Management Systems Evaluation Area (MSEA) site. The main objective of their study was to understand how groundwater moves through the shallow aquifer to strengthen the effectiveness of the best management practices (BMPs) on reducing nitrate concentration in groundwater. The shallow aquifer is the principal source of water for most irrigation wells in Central Nebraska. The study area is 50 mi^2 where 75% is irrigated corn and 10% is irrigated soybeans. The hydrogeology of the site is mainly composed of sand and gravel and interbedded silt and clay soils **(McGuire and Kilpatrick, 1998).** They collected hydrological data such as precipitation, river stages and groundwater level and geological data such as soil lithology and hydraulic conductivity for every soil type. The model simulated two steady state periods, i.e. 1931 and 1991. The model did not consider transient simulation due to the variance over the time of the boundary conditions and pumping rate. Their results showed that the water entered the study area from western boundary and left the eastern boundary. Furthermore, the north boundary (Wood River) is not hydraulically linked to the aquifer **(McGuire and Kilpatrick, 1998).** Some oversimplified assumptions in the study, such as homogeneous hydraulic conductivity, simple type of boundary conditions and steady-state flow, could cause the results to deviate from real groundwater conditions.

In 2016, Peterson et al. developed a groundwater flow model of the Northern High Plains Aquifer in Colorado, Kansas, Nebraska, South Dakota, and Wyoming that covered roughly 175,000 square miles. This simulation strived to evaluate the future groundwater availability in various potential future conditions to support science-water resources management. This problem emerged due to the increasing droughts across the northern aquifer. This simulation had two periods. One period included the years before 1940 and the second term from 1940 to 2009 **(Peterson et al., 2016).** In this work, a groundwater conceptual model was developed using MODFLOW FLEX. Soil Water Balance (SWB) **(Westenbroek et al., 2010)** was applied to determine the hydrological data such as recharge from precipitation and irrigation pumping rate. The hydraulic conductivity of the high plains aquifer is composed of sand, loamy sand, gravel and some interbedded clay and silts. Precipitation and recharge increase from west to east **(Peterson et al., 2016).** Furthermore, they improved the groundwater conceptual modeling by adjusting more than 1300 parameters to match the historical groundwater data. The historical data contained groundwater level measurements from more than 343,000 wells and base flow from ten thousand streams. Mean calibrated recharge was smaller than estimated with the SWB; therefore, adjustment was conducted to improve the match of the groundwater calibration targets (**Peterson et al., 2016).** The model is by far the most comprehensive groundwater flow model in the area. This model covers the groundwater flow of the Northern High Plains Aquifer which comprise 62 million acres in the states of Colorado, Nebraska, South Dakota and Wyoming with a mesh resolution of 3281 ft. Therefore, this model works for regional evaluation of groundwater resources. Our study area is 50 square miles with a mesh resolution of 500 ft., which is six times finer than the mesh resolution of the regional model.

In 2007, the Cooperative Hydrology Study (COHYST) assisted NE Natural Resources Districts in the study of groundwater management. COHYST is a study of the surface water and groundwater resources and the effects of agricultural activities over the Platte River Basin of Nebraska. Furthermore, COHYST used a strategy where a simple groundwater model was first developed, and then additional details were added as needed. This groundwater modeling began with a conceptual model, which is a narrative description of the groundwater flow at the beginning of the simulation period. MODFLOW-2000 was the selected software. The model was constructed to investigate the effects of water management plans in a large-scale area of 10,400 square miles. The model was discretized into 206 rows and 300 columns where every cell measured 2640 ft. per side. Due to the large simulation area, the model will not accurately represent areas of a few square miles or less area. In addition, the model was designed to look at the effects of water management plans over scales of years to decades. It should not be viewed as capable of predicting effects through one year or less because it may not be sufficient to predict groundwater level under variations of precipitation and climate **(Peterson et al., 2007)**

2. Influence of Climate Change on Groundwater Flow

A key factor in developing a successful groundwater model is the accuracy of the hydrological data for input, such as precipitation, groundwater recharge, and actual evapotranspiration. Larger groundwater models depend on temporal and spatial climatological data to investigate the future climate changes on groundwater resources. Global climate models (GCMs) have been designed to predict changes in climate due to the increase of carbon and other greenhouse gases in the atmosphere. Nevertheless, there are uncertainties with this model that trigger the analysis of the average of multiple climate scenarios **(Crosbie et al., 2011)**. The effects of climate change and interaction between the unconfined aquifer and the atmosphere have been studied and modeled to determine the fluctuation of groundwater level **(Scibek and Allen, 2006).**

Researchers have been trying to quantify the impact of potential climate change on groundwater resources using hydrological models **(Bouraoui et al., 2009)**. For instance, **Jyrkama and Sikes (2007)** applied the Hydrological Evaluation of Landfill Performance model (HELP3) hydrological model to estimate potential groundwater recharge at a regional scale based on high spatial and temporal resolution. Actual evapotranspiration and potential groundwater recharge times-series have been predicted using results from a stochastic weather generator for three prominent locations in the north and south of Great Britain **(Herrera-Pantoja and Hiscock, 2008).** Notwithstanding, a common approach for most studies includes the following steps: (1) obtain data from GCMs, (2) downscaled climate data, (3) run future climate time series to estimate groundwater recharge and (4) use the new groundwater recharge to evaluate future climate scenarios **(Crosbie et al., 2010).**

Groundwater recharge can significantly vary over space and time due to its nonlinear nature. Therefore, estimating groundwater recharge is one of the most challenging tasks in the field of hydrology. With the help of inverse modeling, soil moisture data, potential evapotranspiration, and precipitation from automated weather data were used to estimate the spatial distribution of groundwater across Nebraska State **(Wang et al., 2016). Akbariyeh (2017)** used forecasted data from the Weather Research and Forecasting (WRF) to predict groundwater recharge in Nebraska. WRF is a regional climate change model that downscales the climate change predictions from the Community Climate System Models (CCSM4). CCSM4 is a global climate change model that simulated the Representative Concentration Pathways (RCP) 8.5 scenario which corresponds to the worst climate scenario with a high greenhouse gas emission pathway. Climate data from this model such as precipitation, land surface, temperature, leaf area index and soil moisture were used to determine groundwater recharge and actual evapotranspiration from the inverse modeling using Hydrus 1-D. Groundwater recharge and actual evapotranspiration are critical variables that will determine the future groundwater withdrawal and aquifer replenish. Therefore, a groundwater model coupled with regional scale climate data and climate scenario will be used to establish future fluctuation of groundwater level in the surrounded area of the Management Nebraska system Evaluation Area (MSEA).

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CHAPTER 3 SIMULATION OF THE GROUNDWATER LEVEL IN THE SURROUNDING AREA OF MSEA IN CENTRAL PLATTE NEBRASKA UNDER HISTORICAL DATA.

1. Overview

The goal of this chapter is to develop a groundwater flow model to simulate groundwater level (GWL) in the surrounding area of MSEA site. Historical groundwater level data were used to calibrate the model. The groundwater model was developed based on available data, including soil lithology information from forty-three test holes, historical groundwater level data, as well as irrigation well information within the research area. The focus aquifer of this study is the Shallow High Plains aquifer. The geological unit is mainly composed of sand and gravel with interbedded silt and clay zones. A three-dimensional distributed hydraulic conductivity field of the study area was developed using Rockworks 17 (Rockware). Results show that the distributed hydraulic conductivity of the site varies from 42 to 172 feet per day. The distributed hydraulic conductivity field of the site was then imported into Visual MODFLOW Flex V.2015 (Waterloo Hydrologic) to simulate the groundwater flow in the area.

The average groundwater recharge was assumed based on previously published studies **(Szilagyi et al., 2005 and Szilagyi et al., 2013),** where the recharge of the site ranged from 10 mm/yr to 30 mm/yr**.** For the study area, an average value of 20 mm/yr (or 0.80 in/yr) was established which is the mean value between 10 and 30 mm/yr. The upper and bottom boundary conditions for the site were defined based on the groundwater table and the base of the shallow aquifer, respectively. The northern boundary is the Wood River which is not hydraulically connected to the shallow aquifer, whereas the Platte River is the south boundary and was assumed to be a constant head boundary. A transient groundwater flow model was simulated from 1991 to 2014. Simulated groundwater levels were compared with available historical groundwater table data collected on the site. A generally acceptable agreement between simulated and historical groundwater levels suggested that the calibrated model can be used to examine future groundwater scenarios.

2. Model assumptions

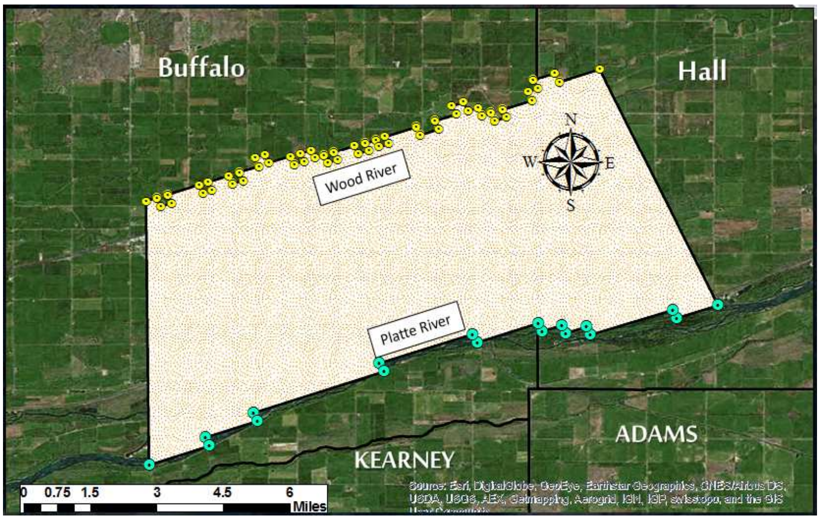
Model simulation includes using spatial and temporal data from various sources. Some assumptions were also made due to the lack of information:

- Due to the lack of detailed distribution of groundwater recharge (GR), the model assumes a constant recharge rate equal to 0.80 in/yr (see figure 3-13).
- Total porosity and effective porosity were assumed to be approximately similar to sand and gravel for which porosity ranges from 0.25 to 0.50 on average.
- When data is not available, pumping wells were assumed to have a fully screen case.
- All irrigation wells that penetrated the silt layer were assumed to be fully penetrated.
- The initial groundwater level was generated using monitoring wells assuming that the groundwater level did not change in the next sixty days.
- The amount of water pumped from the aquifer was assumed to be fully used by actual evapotranspiration.
- The water cycle for the soil was assumed vertical dominated. Therefore, water runoff was considered negligible.

3. Methods

3.1. Study Area.

The study area covers 50 square miles, and it is located between the Gibbon and Shelton Cities, bounded by the Wood River on the north and Platte River on the south. Figure 3-1 is the location of the study area.   This area is intensively cropped where 75% is irrigated corn, and 10% is irrigated soybeans. The ground surface elevation ranges from 2085 feet in the west to 1990 feet in the east. The thickness of the hydrological unit is 80 to 100 feet on average **(McGuire and Kilpatrick, 1998).** The geologic unit is composed of sand and gravel with interbedded silt and clay deposits in some areas **(McGuire and Kilpatrick, 1998).**



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 3-1. Location of the study area and its north and south boundaries.

3.2. Methods to Develop the 3-D Hydraulic Conductivity Model of the Study Area.

The Institute of Agriculture and School of Natural Resources of the University of Nebraska-Lincoln (UNL) maintains an interactive test hole map viewer which contains the stratigraphy and lithology of thousands of test holes in the state of Nebraska. Forty-three bore holes (Figure 3-2) were identified within the study area. Relevant information can be extracted from each test hole, including latitude, longitude, DEM elevation and soil type at different depths. The information was then inputted into Rockworks V.17 **(“RockWare, Inc.,” 2016)** to generate a 3-D soil lithology model. Figure 3-3 illustrates the information obtained from the UNL test hole database. Rockworks is the standard software in the petroleum, environmental, geotechnical, and mining industry for subsurface data visualization, with popular tools such as maps, cross sections, fence diagrams, solid models, and volumetrics (“Rockware, Inc.,” 2016). Figure 3-4. shows borehole distribution throughout the site.

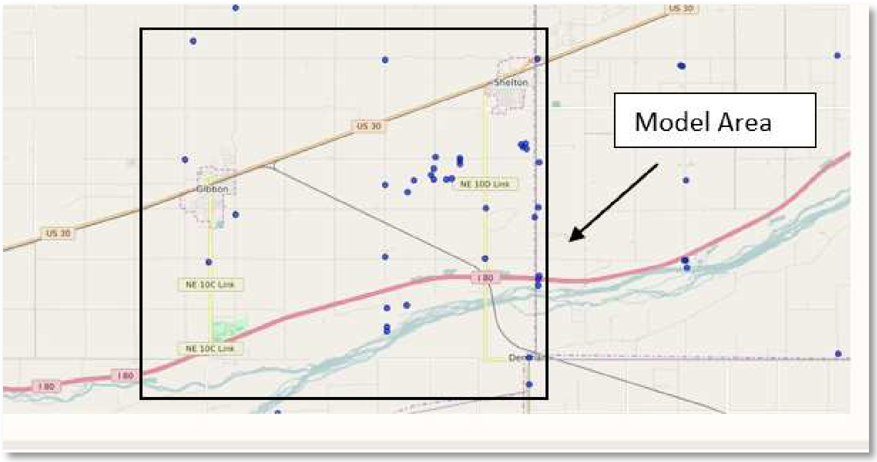
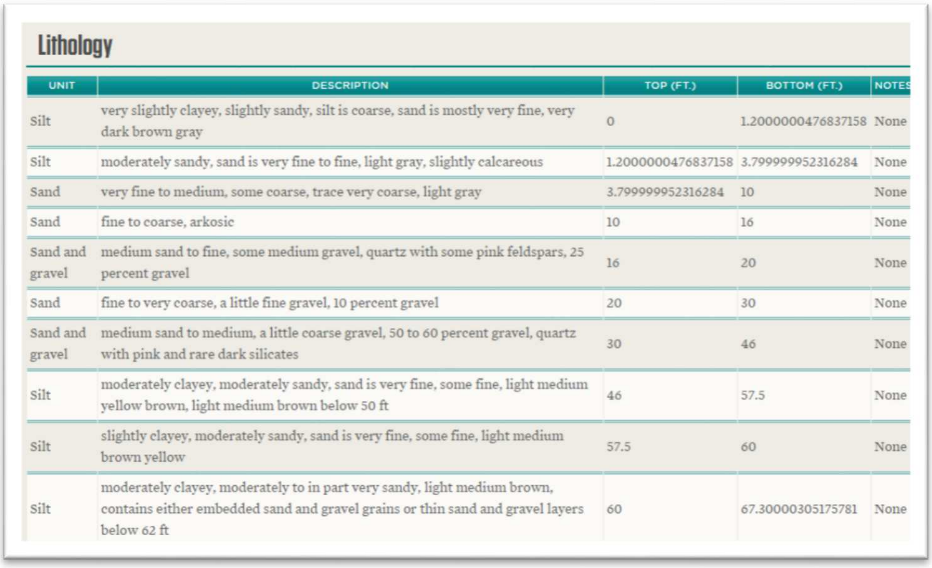


Figure 3-2. Location of the bore holes within the research area



Lithology

UNIT	DESCRIPTION	TOP (FT.)	BOTTOM (FT.)	NOTES
Silt	very slightly clayey, slightly sandy, silt is coarse, sand is mostly very fine, very dark brown gray	0	1.2000000476837158	None
Silt	moderately sandy, sand is very fine to fine, light gray, slightly calcareous	1.2000000476837158	3.799999952316284	None
Sand	very fine to medium, some coarse, trace very coarse, light gray	3.799999952316284	10	None
Sand	fine to coarse, arkosic	10	16	None
Sand and gravel	medium sand to fine, some medium gravel, quartz with some pink feldspars, 25 percent gravel	16	20	None
Sand	fine to very coarse, a little fine gravel, 10 percent gravel	20	30	None
Sand and gravel	medium sand to medium, a little coarse gravel, 50 to 60 percent gravel, quartz with pink and rare dark silicates	30	46	None
Silt	moderately clayey, moderately sandy, sand is very fine, some fine, light medium yellow brown, light medium brown below 50 ft	46	57.5	None
Silt	slightly clayey, moderately sandy, sand is very fine, some fine, light medium brown yellow	57.5	60	None
Silt	moderately clayey, moderately to in part very sandy, light medium brown, contains either embedded sand and gravel grains or thin sand and gravel layers below 62 ft	60	67.30000305175781	None

Figure 3-3. Sample of the soil lithology data from the School of Natural Resources

Figure 3-4. Borehole distribution within the site area.

As mentioned earlier, the geological unit is composed mainly of sand and gravel with some interbedded clay and silt. The investigated subsurface lithological well logs indicated that the area consists of six soil types, where 90% consists of sand, gravel, and sand and gravel and 10% consists of sandstone, clay, and topsoil. In this work, we used lithological modeling techniques that were based on litho blending solid tool provided by Rockworks V.17. The lithological modeling illustrates the complexity of the hydrostratigraphy framework of the study area and shows the spatial trend and variability of thickness and heterogeneity of the aquifer **(Ahmed, 2009).** The model resolution was 2000 ft. (X) x 2000 ft. (Y) x 0.5 ft. (Z). Therefore, the discretization in the X, Y, Z directions consisted of 29 x 25 x 313 nodes, respectively. A 3-D lithology model was created by employing a horizontal litho blending algorithm and smoothing the resulted solid to resemble the heterogeneity of aquifer. Figure 3-5 presents front and rear view of the lithological model created by Rockworks. As shown here, a silt layer constrained the bottom of the lithologic model, which is consistent with well log data.

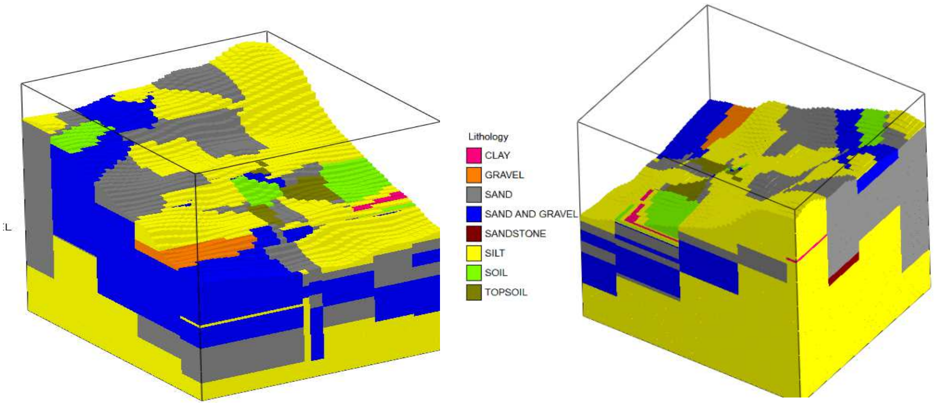


Figure 3-5. Front and rear view of the lithological model.

The lithological model produced by Rockworks includes the distributed hydraulic conductivity field of the study area. A hydraulic conductivity (K) value was first assigned to each node based on typical K values of the corresponding soil types **(Delleur, 2006).** Table 1 provides the K values used for each soil type.

Lithology	**Hydraulic Conductivity [ft. d^{-1}]**
Sand	41
Sand and Gravel	172
Clay	0.66
Gravel	328
Sandstone	0.10
Silt	0.15

Table 1. Typical hydraulic conductivity values for soils present on the site.

In this method, voxel node values were assigned horizontally until it found a region that has a voxel node with a different soil type. The final solid was smoothed to average the K values allocated to every voxel. Here, a "voxel" is a tridimensional cell that contains geospatial information and geological data. The resulting K field ranges from 42 ft./d for sand to 172 ft./d for gravel (Figure 3-6). Ultimately, this smoothed lithology was exported to ASCII XYZG values where XYZ describes the location and G represent the average hydraulic conductivity of the voxel. The Rock works Solid, Smoothing Filter tool, reads an existing solid model and averages the G-values based on a user declared "filter" size (Rockworks). Therefore, if the horizontal filter size is set up equal to "1", then each node will assign the average of itself and the eight nodes immediately surrounding it. Furthermore, if the vertical filter size is "1", then each node will be assigned the average of itself and the nine nodes immediately above and below it **("RockWare, Inc.," 2016).**

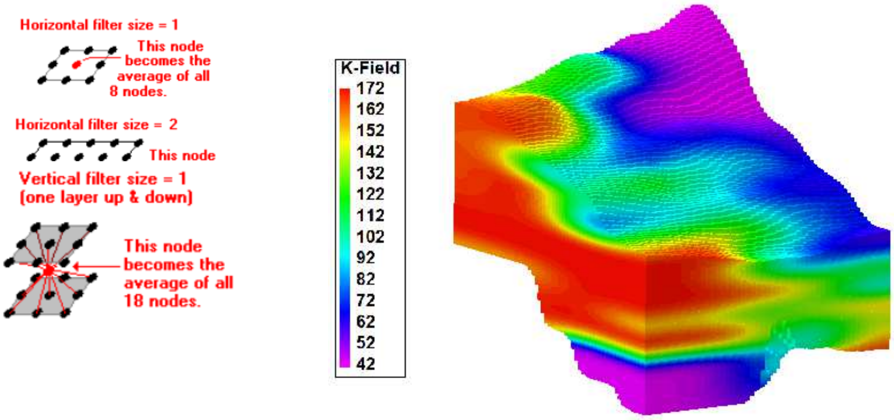


Figure 3-6. Solid smoothing filter tool approach and the distributed hydraulic conductivity field.

3.3. Groundwater Flow Model.

The U. S. Geological Survey's (USGS) MODFLOW **(McDonald, 2005)** is a modular, three-dimensional, finite-difference groundwater flow model which is widely applied in groundwater modeling. Visual MODFLOW Flex version 2015.1 was used to simulate the study area.

3.3.1. Defining a Modeling Domain and Hydraulic Conductivity Field

The first modeling step is to establish a groundwater conceptual model, which describes the groundwater occurrence and movement in the study area including physical characteristics (aquifer thickness, aquifer base elevation, groundwater flow rate), inflows and outflows from the aquifer and any change in storage over time **(Peterson et al., 2005)**.

The shallow aquifer is the principal hydrogeologic unit in this study. Therefore, it is necessary to define the top and bottom horizon of the aquifer. Two surfaces were obtained by the upper most voxel node from the soil lithology model generated and the higher voxel node of the silt layer. As this data is imported to MODFLOW Flex, the software automatically creates the solid hydrological unit between both ground and the silt layer. Figure 3-7 shows the imported soil surface, silt layer, and the solid zone formation. The upper surface elevation ranges from 2042 feet to 1993 feet above sea level and the bottom layer from 1973 feet to 1936 feet above sea level. The average thickness of the aquifer ranges from 80 feet to 100 feet.

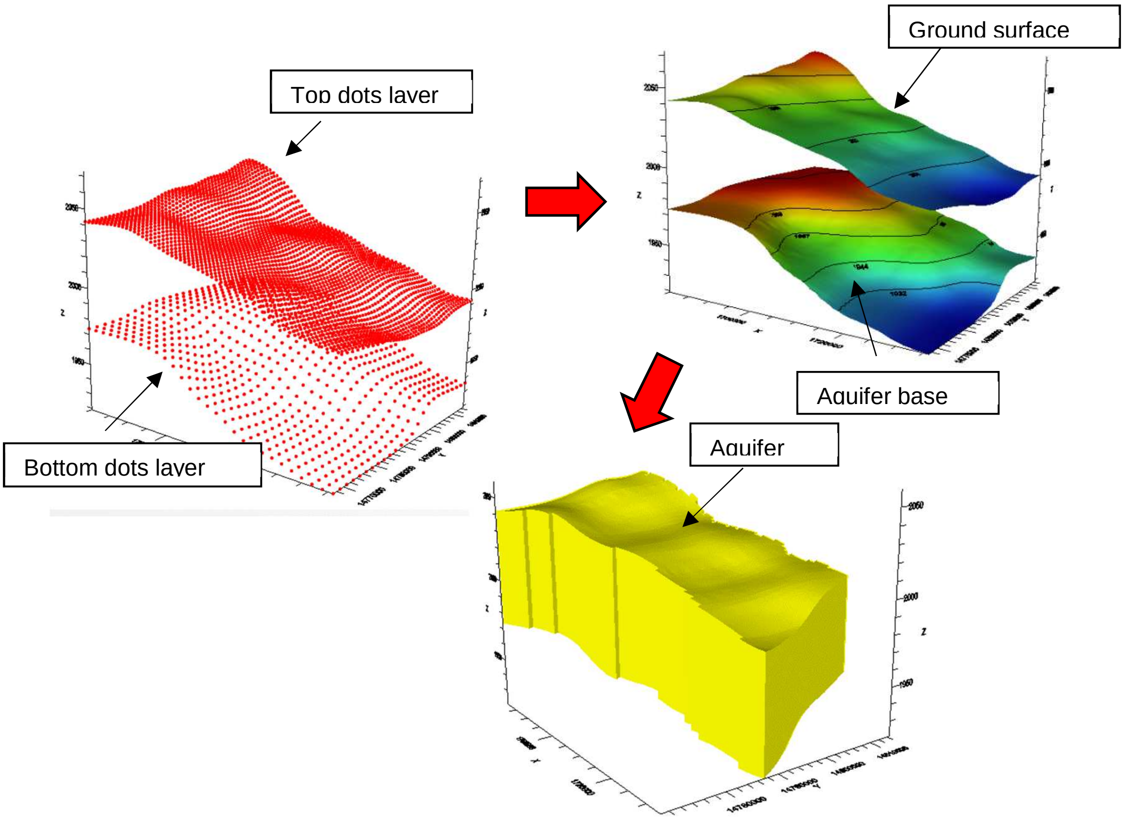


Figure 3-7. Imported point data, interpolated surfaces, and the zone of the geological formation.

Three essential parameters need to be defined prior to the translation of the conceptual modeling to numerical modeling, including conductivity, storage, and initial heads. The hydraulic conductivity model created by Rockworks was imported into Visual

MODFLOW Flex. Figure 3-8 shows the imported hydraulic conductivity field in MODFLOW.

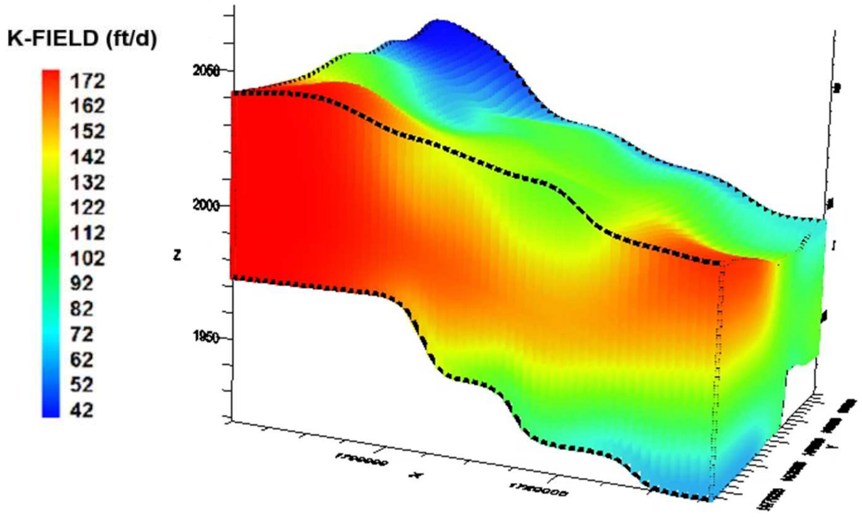


Figure 3-8. MODFLOW hydraulic conductivity field in feet per day.

The hydraulic conductivity is smaller on the north boundary (Blue section) than the south (Red section). This difference is because the soil type at the northern side mainly consists of sand whereas the southern border has more gravels. The total porosity of the geological formation ranges from 0.25 to 0.50 **(Delleur, 2006).** The average effective porosity is 0.15 and the average total porosity used was 0.35. The initial hydraulic heads used for the present study were defined according to the historical groundwater flow levels in the year 1991 as reported in a USGS report **(McGuire and Kilpatrick, 1998) (**Figure 3-9).

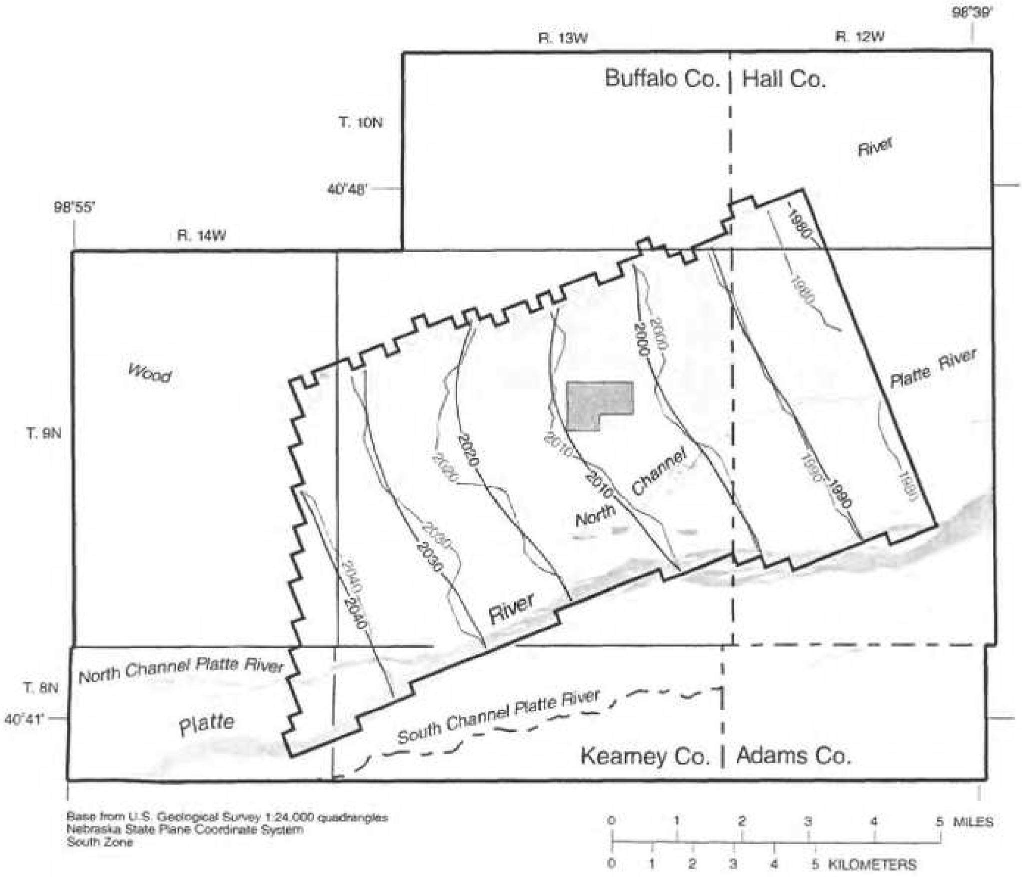


Figure 3-9. Simulated and observed groundwater table in the study area, 1991 (**McGuire and Kilpatrick, 1998**).

3.3.2. Defining Boundary Conditions

The upper boundary of the shallow unconfined aquifer is defined as a water table boundary. The monitored water table in the year 1991 was used as the initial value. The lower boundary of the model is a silt layer which was obtained from bore hole data. Therefore, a no flow boundary condition was defined on the bottom boundary of the model. The southern boundary is the Platte River, which is hydraulically linked to the aquifer and therefore it was assumed as a specific head boundary **(McGuire and Kilpatrick, 1998).** The northern limit of the study area is the wood river, which is not hydraulically connected to the aquifer **(McGuire and Kilpatrick, 1998).** Therefore, it was simulated as a general head boundary. The western and eastern boundary of the model were also simulated as general head boundaries (GHB) because the water enters from the west and leaves the study area from the east side. A GHB allows groundwater flow in or out of the model domain (depending on groundwater elevation changes along the boundary). GHB conditions can approximate the hydraulic responses of the limit to the groundwater conditions variations. Figure 3-10 illustrates the boundary conditions in a 2-D plane:

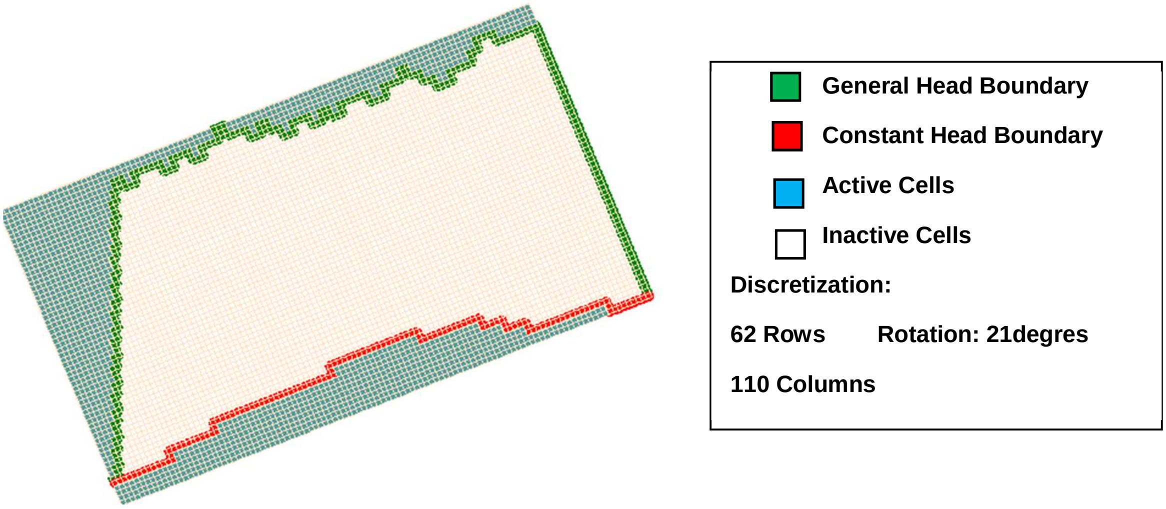


Figure 3-10. Boundary conditions in a 2-D plane for the site area.

The purpose of using the general head boundary condition is to avoid unnecessarily extending the model domain outward to meet the element influencing the head in the model. As a result, the General Head boundary condition is usually assigned along the outside edges (sides) of the simulation model domain **(MODFLOW, 2016)**. While a constant head boundary provides an infinite source of water, a general head boundary does not give an infinite amount of water. Figure 3-11 depicts the concept of general head boundary and relevant parameters. The boundary distance used was 100 feet. The conductance is a numerical parameter that represents the resistance to flow between the source and model domain. This variable was calculated according to **(MODFLOW, 2016):**

$$C = \frac{(LxW)K}{D}$$

Where,

- (LxW) is the surface area of the grid cell face exchanging flow with the external source/sink.
- K is the average hydraulic conductivity of the aquifer material separating the outer source/sink from the model grid. For the model, average hydraulic conductivity is roughly 90 ft./d.
- D is the distance from the external source/sink to the model grid.

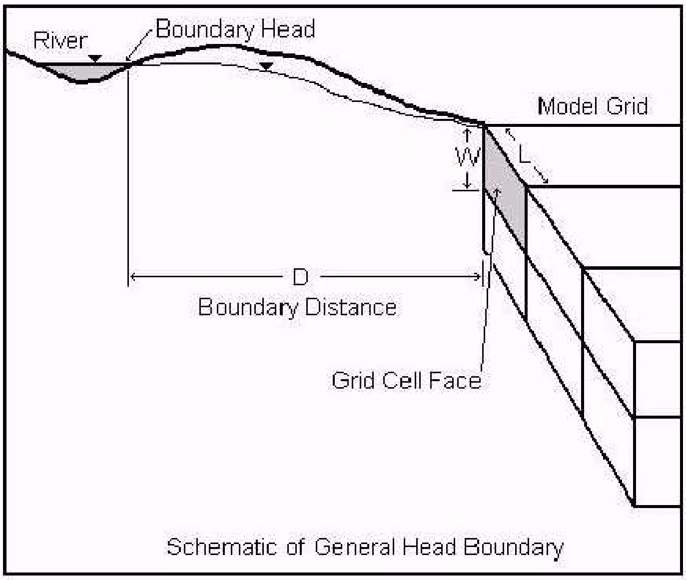


Figure 3-11. General head boundary schematics and its variables

To apply the general head boundary condition, a reference water level was needed. Similarly, to implement the specific head boundary condition, water head at the location of Platte River was necessary. Because no river stage was found close to the study area, groundwater head at the boundary was estimated by interpolating data from historical groundwater data. From the SNR database **(School of Natural Resources, 2017)**, groundwater monitoring wells were in the study area, which provides groundwater level data from year 1991 to year 2014. Interpolation was conducted based on the groundwater levels in each monitoring well from 1991 to 2014 to get an average yearly groundwater map. Time series data were generated for every boundary point. A total of 56 points were defined according to the numerical discretization for the upper boundary to serve as a reference water level to implement the general head boundary. 18 points were defined for the south boundary at the Platte River to implement a specific head boundary. Figure 3-12 shows the 18 points of the Platte River boundary and figure 3-13 shows an example interpolated groundwater elevation map in the model domain area in year 2000 and time series data at two selected locations in the boundary.

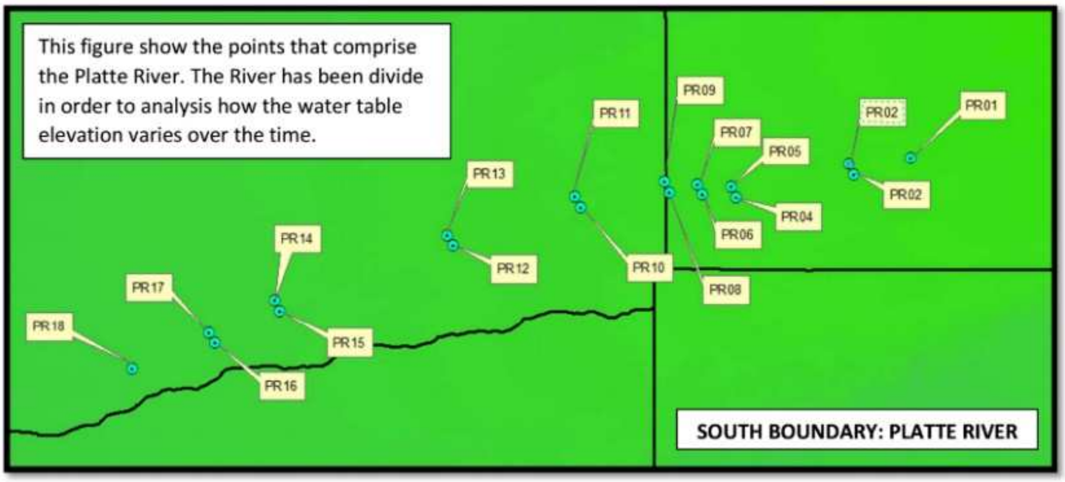
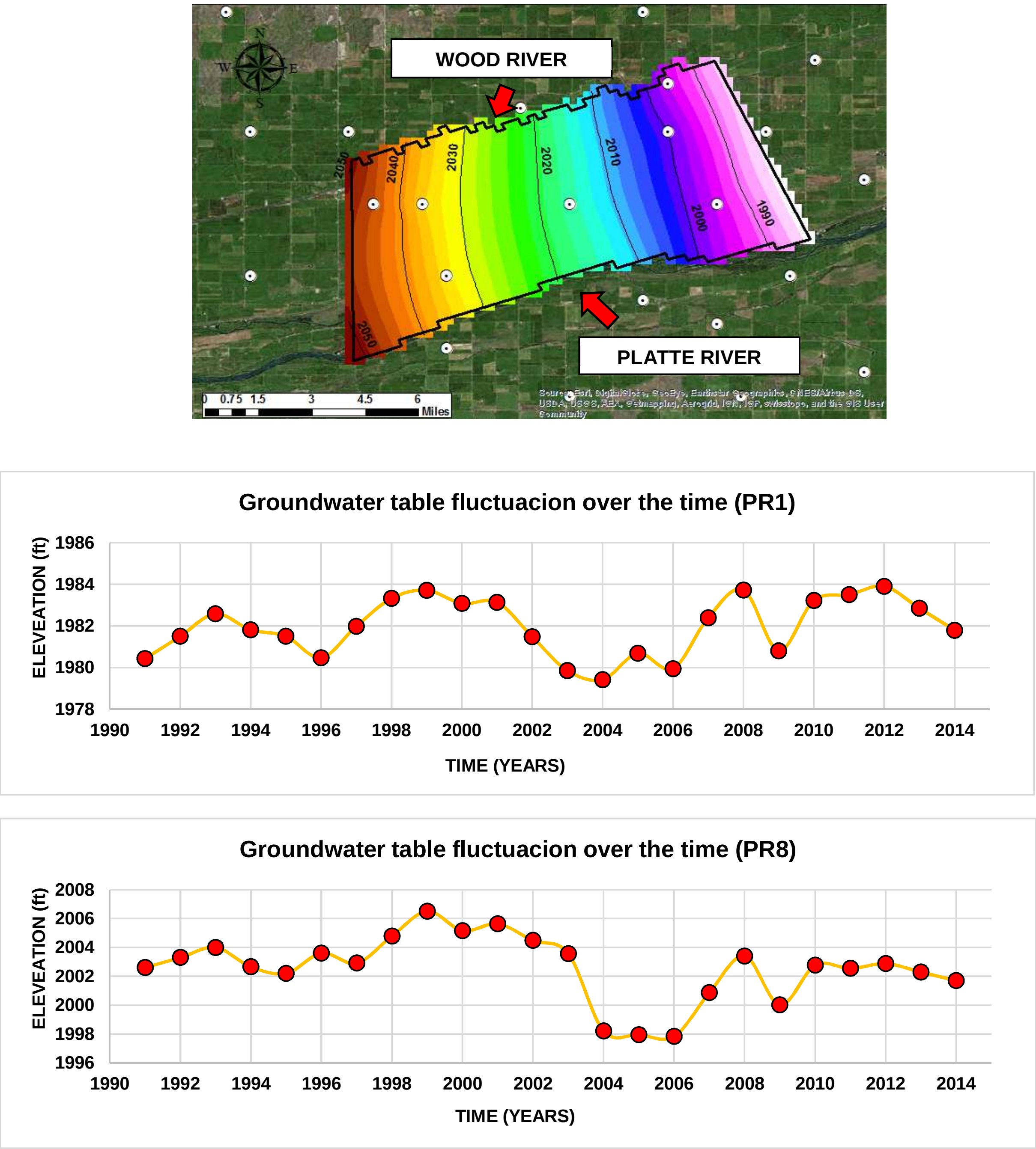


Figure 3-12. Platte River divided into eighteen points to simulate south boundary.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 3-13. Groundwater elevation variation for points PR1 and PR8 (Bluepoints) in the Platte River and interpolated groundwater map from monitoring wells (white points) for the 2000 year

3.3.3. Determination of Pumping Rate and Recharge

A study of the land use area showed that roughly 70% of the researched area is covered by cultivated crops **(McGuire and Kilpatrick, 1998),** including irrigated corn and irrigated soybeans. The groundwater recharge ranges from 10 to 30 in/year, where 20 mm/yr was used as the average of the range **(Szilagyi, 2003)**. Figure 3-14 shows the long-term estimate base annual groundwater recharge**.** Figure 3-15 is GIS data from the National Land Cover Database (NLCD 2011), which illustrates the land use distribution of the study area. The National Land Cover Database (NLCD) serves as the ultimate Landsat-based, 30-meter resolution, land cover database for the Nation. NLCD provides spatial reference and descriptive data for characteristics of the land surface such as thematic class (for example, urban, agriculture, and forest), percent impervious surface, and percent tree canopy cover **(USGS, 2017).** Many irrigation wells were located in the study area, and the pumping rates of these wells will impact groundwater flow in this area. Therefore, it is important to determine the pumping rate of irrigation wells when modeling groundwater flow in the area.

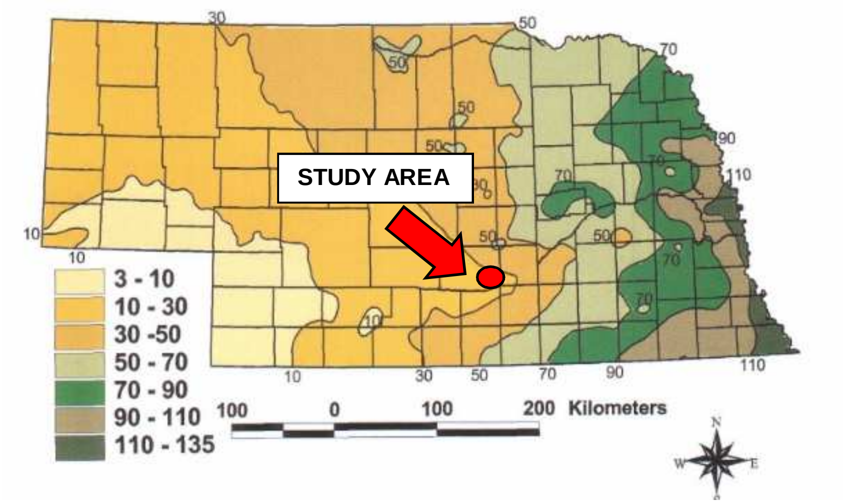


Figure 3-14. Estimate long-term base annual groundwater recharge in mm/yr **(Szilagyi, 2003).**

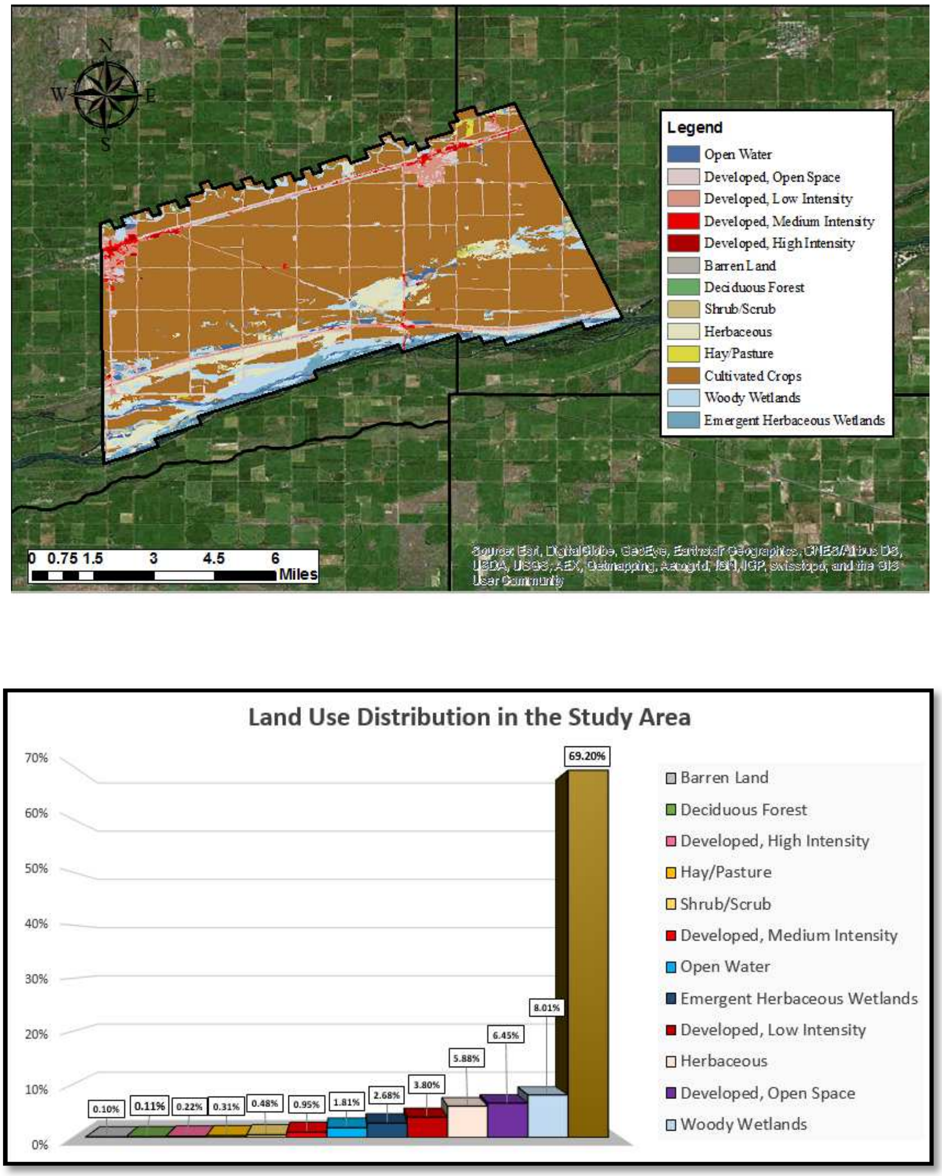


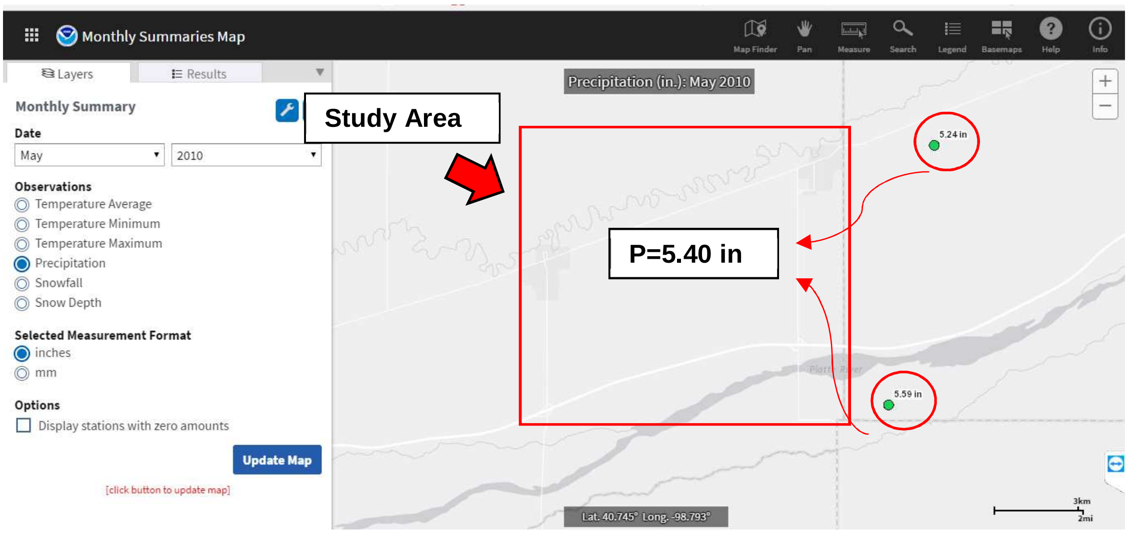
Figure 3-15. Soil land use and bar graph that shows the land use distribution over the research area.

According to the Nebraska Department of Natural Resources (NDNR), a total of 400 irrigation wells are in the area, where 258 irrigation wells pump the groundwater from the shallow aquifer, and approximately 142 wells pump water from the Ogallala aquifer. Figure 3-16 shows the density of wells within the study area **(NDNR, 2017).**

Figure 3-16. Irrigation well density in the study area

NDNR maintained a database which provides crucial information on all registered irrigation wells, including, well ID, well location (latitude, longitude), pumping start and end date, irrigated area, well depth and well elevation. However, there is no information about pumping rates and operational schedules of each irrigation well. Therefore, it is necessary to determine the amount of water that was pumped out for irrigation. Because all the pumps were for irrigational purposes, we assumed that plant transpiration and soil evaporation consumed all pumped water. If there was any over pumping, we assumed that extra pumped water infiltrated back to the subsurface. Therefore, the amount of water that was pumped out would be equal to the difference between the precipitation and actual evapotranspiration of the crop in the area. For wet days where the precipitation exceeded the actual evapotranspiration, it was assumed that there was no water extraction from the aquifer. Therefore, the pumping rate for that day was null. Whereas, for dry days where the actual evapotranspiration exceeded the precipitation, the difference between them became the water needed for plants to strive. Ultimately, water reaches the soil in the form of rainfall then the water diverted into infiltration and runoff. For our study runoff was assumed to be negligible because areas in high plains are flatter, as well as, soil is permeable.

In order to estimate the amount of water pumped out, actual ET and precipitation data of the study area were needed. The monthly precipitation data were obtained from the National Centers for Environmental Information (NOAA). NOAA implements an interactive map tool **(NOAA, 2017)** that shows the precipitation data captured by radar. Figure 3-17 is an example monthly average precipitation for May 2010. Occasionally for some months, no radar was available within the study area, the precipitation of the nearest radar station was used to approximate the precipitation of the study area. Also, if there were more the two radars near to the study area, the average of all radars was be assumed to be the precipitation of the site.



Monthly Summary

Date: May 2010

Observations
○ Temperature Average
○ Temperature Minimum
○ Temperature Maximum
● Precipitation
○ Snowfall
○ Snow Depth

Selected Measurement Format
● inches
○ mm

Options
☐ Display stations with zero amounts

Precipitation (in.): May 2010

Lat. 40.745° Long. -98.793°

Figure 3-17. Average monthly precipitation for May 2010.

ET accounts for the water transferred to the atmosphere by two processes known as transpiration and evaporation. Based on the advancement in remote sensing technology, the Google Earth Engine Evapotranspiration Flux (EEFLUX) calculates ET as a residual of the energy balance because evapotranspiration consumes energy during its process. Using thermal data images from LANDSAT and MODIS which are satellites program that capture imagery of the Earth. The EEFLUX package offers the estimation of actual evapotranspiration at a resolution of 30 m **(Irmak et al., 2012)**. In this work, ninety satellite images (LANDSAT 5 and LANDSAT 8) were downloaded, and the monthly average actual ET was calculated by averaging the spatial data of the site using software ArcMap 10.5. (ESRI Geographic Information System Company). Figure 3-18 shows an example of the downloaded digital image from EEFLUX in ArcMap 10.5 for August 2002.

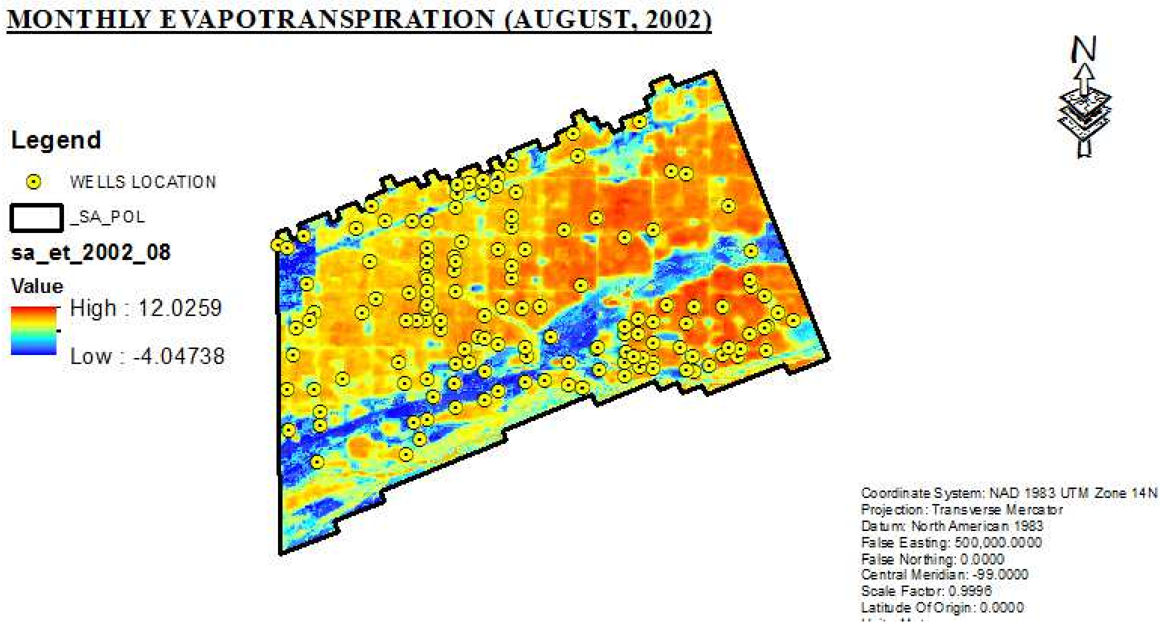


Figure 3-18. Actual evapotranspiration (mm/d) in the study area for August 2002.

Figure 3-19 shows the typical average daily ET during the growing season **(Dupon Pioneer, 2017)**. Figure 3-20 showed the monthly average actual ET estimated based on EEFLUX image data from 1991 to 2014, where ET ranges from 0.03 inches per day during the early growing season to 0.30 inches per day during the growing season. Comparing the observed actual ET from EEFLUX data and average seasonal actual ET data or Central Nebraska (Figure 3-20), actual evapotranspiration rates seem to be within acceptable ranges, and they can be used to estimate well pumping rates.

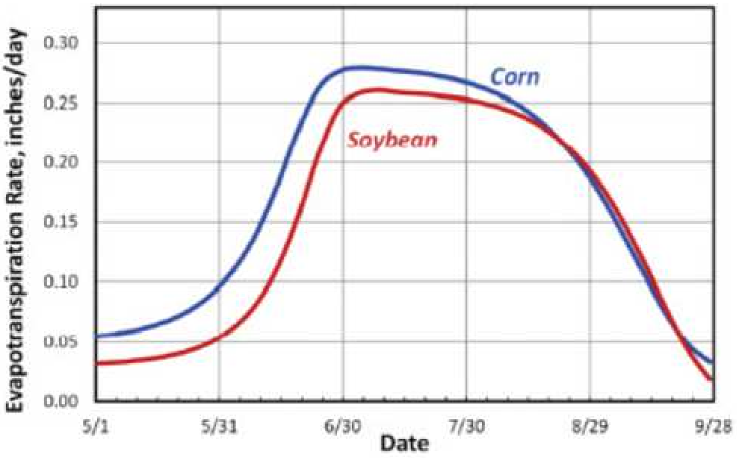


Figure 3-19. Average daily ETa for corn and soybeans in Central Nebraska **(Dupon Pioneer, 2017)**

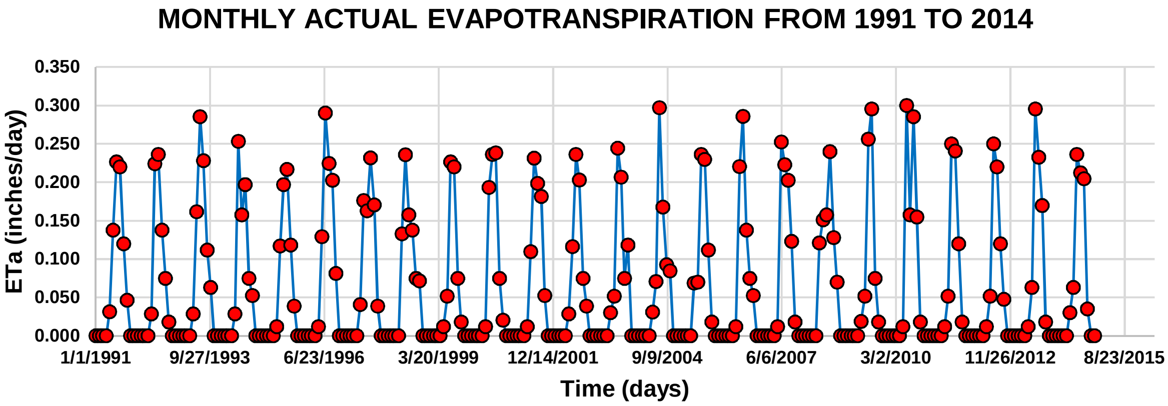


Figure 3-20. Average daily ET for research area calculated from EEFLUX.

Ultimately, to calculate the pumping rate for each well, it was necessary to multiply the irrigated area of each well with the difference between actual ET and precipitation, which provides a pumping rate in the unit of ft^3/d. Table 3 shows an example calculation of a well that irrigates 80 acres. The irrigation season began in May and ended in October for the research study.

1	2	3	4	5	6	7	8	9
MONTH	**ETa (mm/d)**	**ETa (in/d)**	**ET (in/M)**	**$P2_{ave}$ (in/M)**	**E-P (in/M)**	**E-P (ft/d)**	**Area(Ft^2) 80 acres**	**Rate (ft^3/d)**
1/1/1991	0.00	0.000	0.00	0.00	0.00	0.0000	3484800	0
2/1/1991	0.00	0.000	0.00	0.00	0.00	0.0000	3484800	0
3/1/1991	0.00	0.000	0.00	0.00	0.00	0.0000	3484800	0
4/1/1991	0.00	0.000	0.00	0.00	0.00	0.0000	3484800	0
5/1/1991	0.793	0.031	0.94	5.61	0.00	0.0000	3484800	0
6/1/1991	3.495	0.138	4.27	1.21	3.06	0.0082	3484800	-28624
7/1/1991	5.750	0.226	6.79	1.35	5.44	0.0151	3484800	-52672
8/1/1991	5.590	0.220	6.82	1.80	5.02	0.0135	3484800	-47049
9/1/1991	3.043	0.120	3.71	0.89	2.82	0.0076	3484800	-26454
10/1/1991	1.176	0.046	1.39	1.10	0.29	0.0008	3484800	-2797
11/1/1991	0.00	0.000	0.00	0.00	0.00	0.0000	3484800	0
12/1/1991	0.00	0.000	0.00	0.00	0.00	0.0000	3484800	0

Table 2. Pumping rate calculate based on actual evapotranspiration and precipitation for the year 1991.

Note:

Col 3 = Col 2 /25.4
Col 4 = Col 3 * #days in month
Col 6 = Col 4 – Col 5
Col 7 = Col 6 *# day in month / 12
Col 9 = Col 7* Col 8

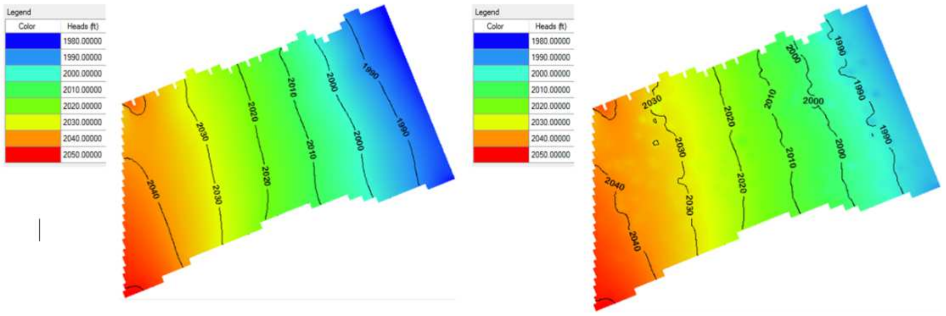
3.3.4. Numerical Engine Setup

The numerical model regularly spaced grid 62 rows and 110 columns using the finite difference grid approach. Each row and column represent 505 feet and 510 feet, respectively. Therefore, every cell represents an area of about 6 acres. The numerical grid was rotated 21-degrees in the counterclockwise direction to align the model with the rivers. The influence of the mesh size on the numerical simulation was examined. It was found that results were not influenced if mesh sizes were at or smaller than 500 ft. In the vertical discretization, the model uses the deformed grid type where the top and the bottom of the model layers follow the horizon elevation. The minimum elevation is 1920 feet, and the maximum elevation is 2060 feet. The vertical discretization is divided into three layers.

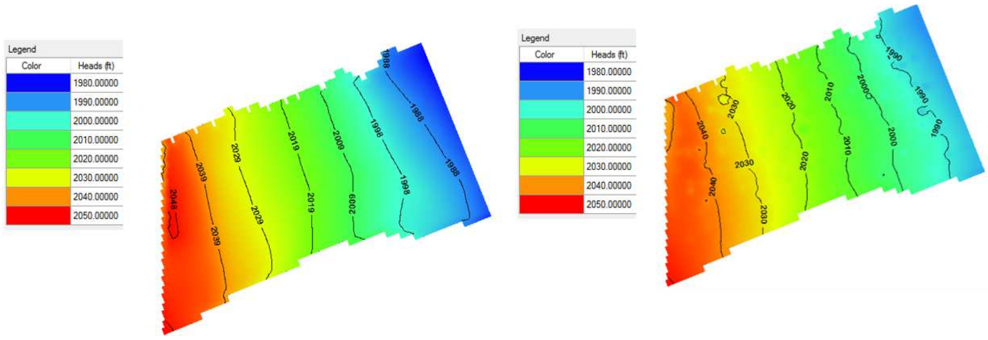
A transient model was defined where there is a total of 328 stress periods based on from the time-period of boundary conditions and time schedule for all pumping wells. MODFLOW NWT, a Newton-Raphson based numerical engine for MODFLOW-2005, was used to solve the present study. Due to its capacity to address asymmetric matrices **(McDonald, 2005)**, the numerical model can converge easily by using MODFLOW NWT.

4. Results and Discussion

In general, groundwater moved horizontally from the western boundary to the eastern boundary. During the simulation period, the water table fluctuated, with a higher water level declination in the irrigation season due to higher pumping rates. Over the years, there was a substantial decrease of the water table elevation. Furthermore, the more water level decrease was greater on the western side of the study area than the eastern side, which was due to the higher density of irrigation wells in the west part of the study area. Figure 3-21 shows the groundwater table for non-irrigation season (left side picture) and irrigation season (right side picture) every five years.


Legend
Color
Heads (ft)
1980.00000
1990.00000
2000.00000
2010.00000
2020.00000
2030.00000
2040.00000
2050.00000
2040
2030
2020
2010
2000
1990

(a)


Legend
Color
Heads (ft)
1980.00000
1990.00000
2000.00000
2010.00000
2020.00000
2030.00000
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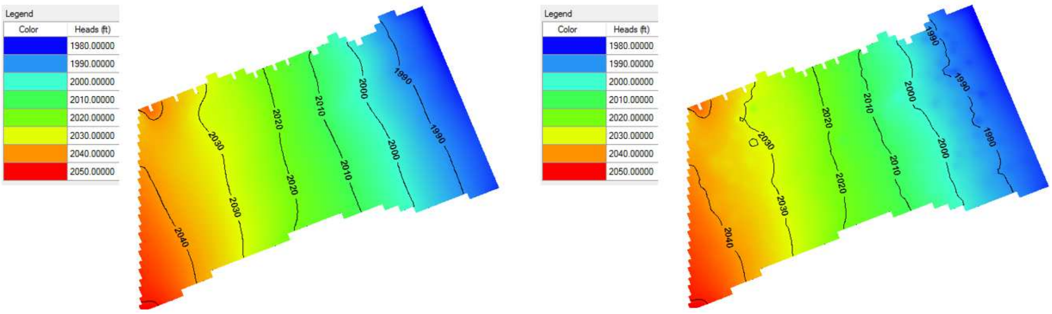
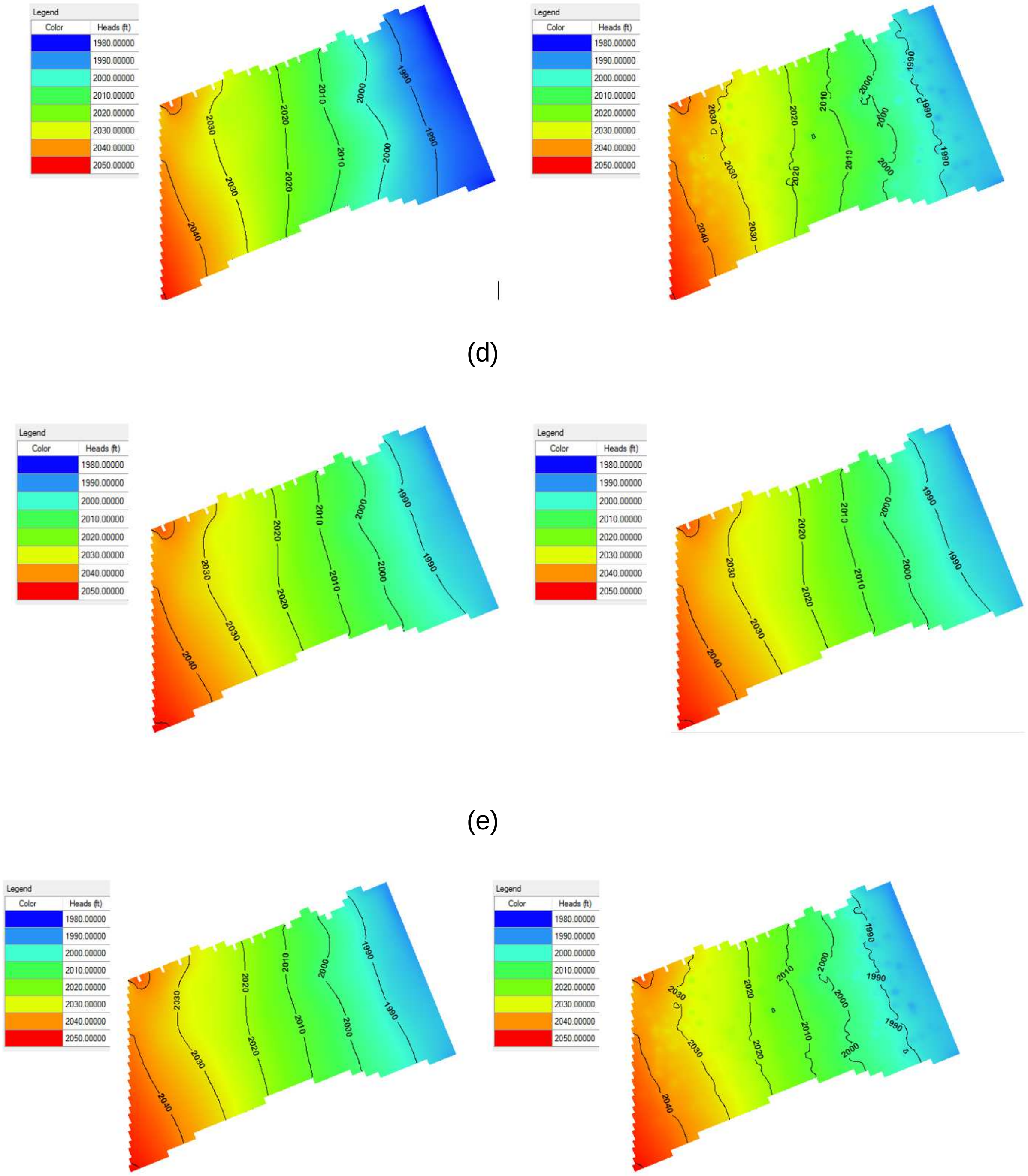
2048
2039
2029
2019
2009
1998
1988
2040
2030
2020
2010
2000
1990

(b)


Legend
Color
Heads (ft)
1980.00000
1990.00000
2000.00000
2010.00000
2020.00000
2030.00000
2040.00000
2050.00000
2040
2030
2020
2010
2000
1990

(c)



(d)

(e)

(f)

Figure 3-21. Groundwater table simulation for non-irrigation season (left picture-May) and irrigation season (right picture-August) for: (a) 1991, (b) 1995, (c) 2000, (d) 2005, (e) 2010 and (f) 2014

Figure 3-22 provides a time series of water table changes at the four corner points of the MSEA. In all four points, groundwater levels were up and down periodically. There was always a substantial increase of the groundwater table in non-irrigation seasons, and a decline in irrigation seasons (May-October). The declination of the water table in irrigation seasons can be attributed to the pumping rates, which were higher than the aquifer replenishment rates. During the non-growing season (from November to April), the groundwater level tended to rise due to the lack of pumping and contributions from precipitation and snowmelt that replenish the aquifer; whereas, during the growing season (from May to October), the groundwater table tended to decrease due to water pumping for irrigation. Comparing both seasons, groundwater declination cannot be fully compensated by groundwater recharge especially in areas where the hydraulic conductivity is higher. The groundwater elevation is decreasing slowly year by year, at an average rate of roughly 0.21 feet per year around the MSEA due to the significant amount of pumping rate.

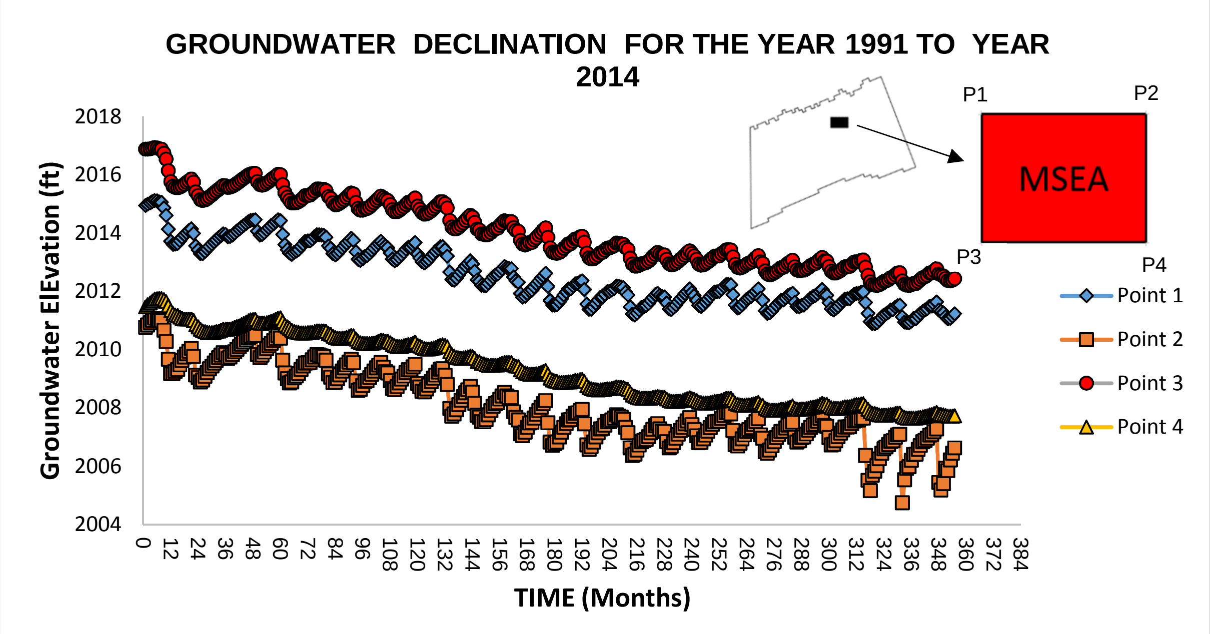
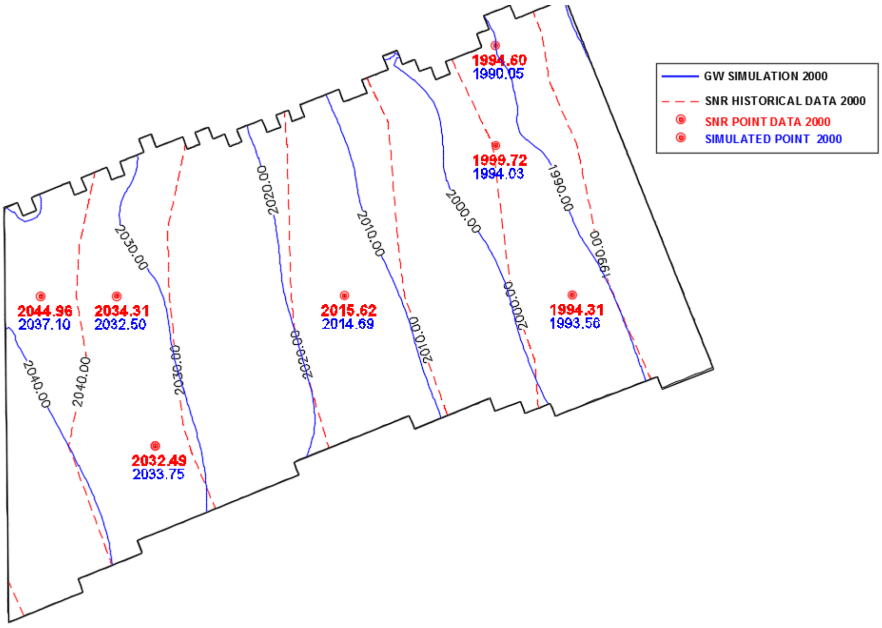


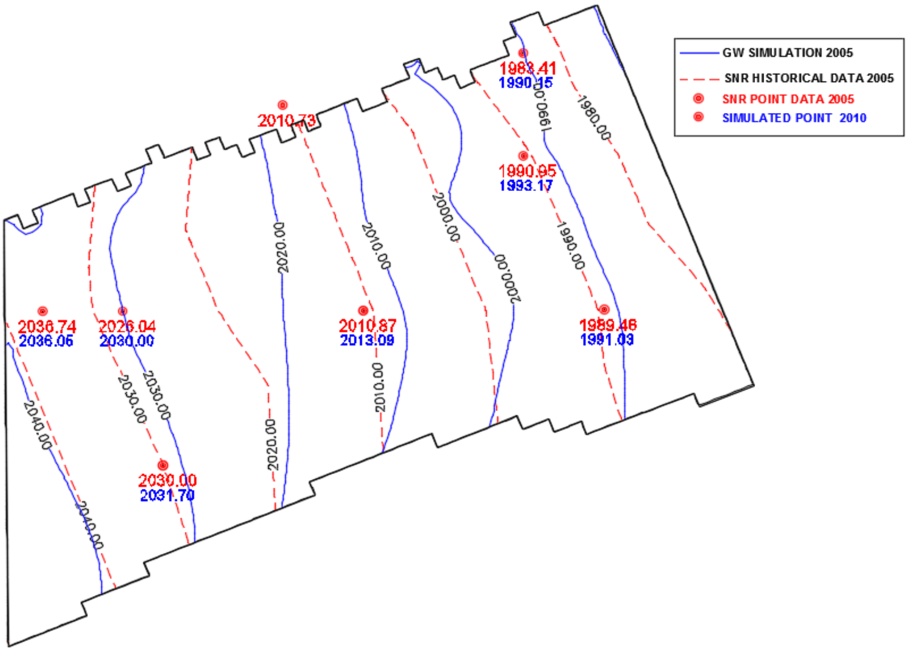
Figure 3-22. Location and groundwater table declination within the MSEA area.

Simulated groundwater tables were compared to observed groundwater tables of the study area from year 1991 to 2014, as shown in Figure 3-23. The simulated groundwater table follows a similar trend as the observed groundwater table, with a higher water table in the west. For some years, simulated water table contours were more curved than observed water table contours. This could be because only seven monitoring points were available to create the observed groundwater head contours, which will provide flatter curves. In the numerical simulation, 258 irrigated wells were included and much more detailed water head information was available. Figure 3-24 presents a comparison of water tables at the locations with monitoring wells for each year, which includes 155 data points. As shown in figure 3-24, most data are located close to the 1:1 line, indicating an acceptable agreement between simulated and observed water table levels. The comparison by points revealed that the maximum estimation error is roughly 4 ~5 feet. Given the limited information of the site and the uncertainties related to hydrogeological and pumping information, it can be considered the approach to calibrating the groundwater level acceptable. The model will be extended to predict the groundwater level under future scenarios.

(a)


GW SIMULATION 2000
SNR HISTORICAL DATA 2000
SNR POINT DATA 2000
SIMULATED POINT 2000
1994.60
1990.05
1999.72
1994.03
2044.96
2037.10
2034.31
2032.50
2015.62
2014.69
1994.31
1993.56
2032.49
2033.75
2040.00
2030.00
2020.00
2010.00
2000.00
1990.00

(b)


GW SIMULATION 2005
SNR HISTORICAL DATA 2005
SNR POINT DATA 2005
SIMULATED POINT 2010
1983.41
1990.15
2010.73
1990.95
1993.17
2036.74
2036.05
2026.04
2030.00
2010.87
2013.09
1989.46
1991.03
2030.00
2031.70
2040.00
2030.00
2020.00
2010.00
2000.00
1990.00
1980.00

(c)

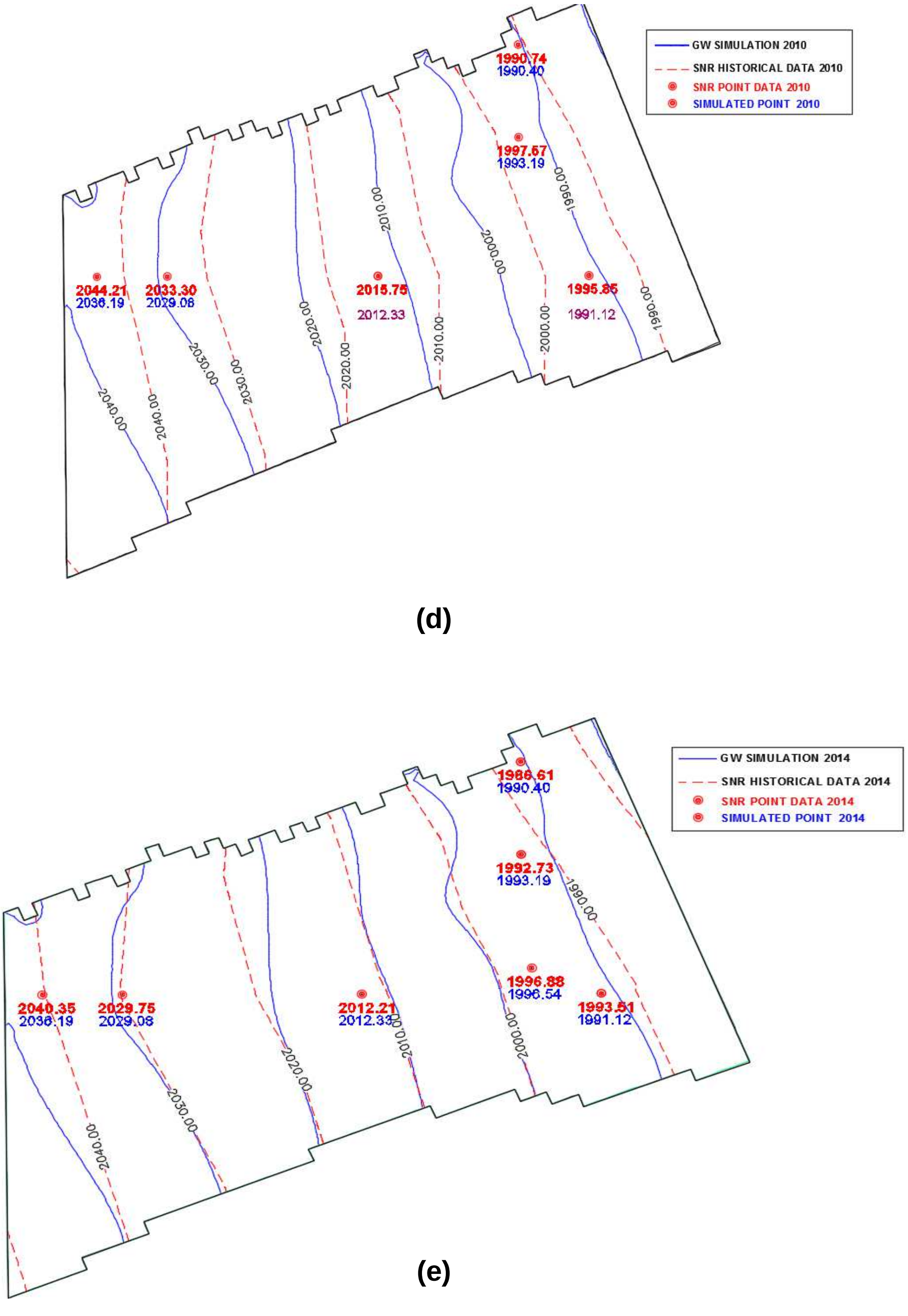


Figure 3-23. Comparison between observed and simulated groundwater table for May **(a)** 1995, **(b)** 2000, **(c)** 2005, **(d)** 2010 and **(e)** 2014

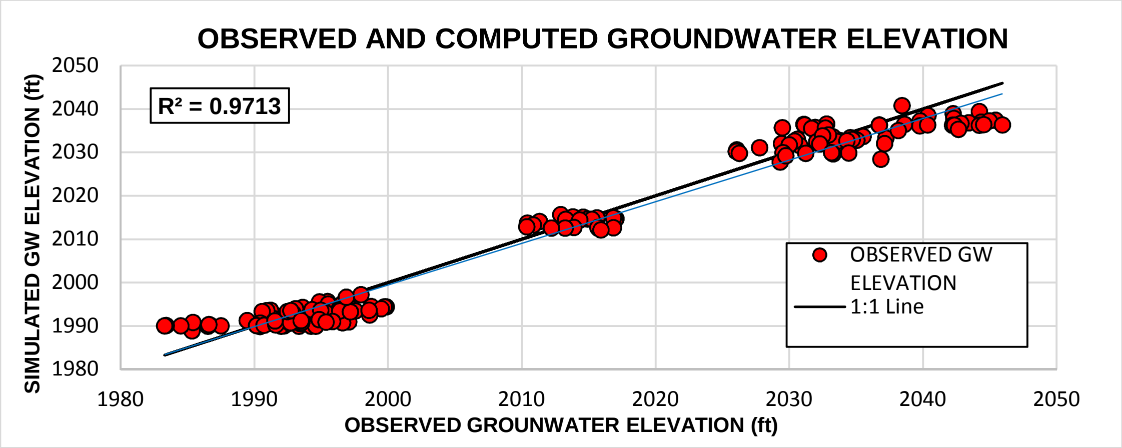


Figure 3-24. Comparison between observed and simulated groundwater table for all monitoring wells.

5. Conclusions

A model was developed to simulate the movement of the groundwater through the subsurface within the study area using Visual MODFLOW Flex V.2015. The study area covers approximately 50 square miles where 75% is irrigated corn and soybeans. A three-dimensional distributed hydraulic conductivity field was developed using 43 borehole data. The groundwater elevation map published in a previous study **(McGuire and Kilpatrick, 1998)** was used as the initial head for the simulation. The northern boundary along Wood River, as well as the eastern and western boundaries of the area, were assumed to be general head boundaries. Whereas, the Platte River is a source of water to the aquifer and was assumed to be a specific head boundary. Furthermore, the groundwater recharge ranges from 10 to 30 mm/year, and a 20 mm/yr was used as the average of the range (See figure 3-14). The model was discretized in 62 rows, and 110 columns where each cell represents 6 acres. River elevations and well pumping rates were defined by the variation of the groundwater elevation and evapotranspiration for EEFLUX, respectively.

Results show that the groundwater table simulation approaches to the historical groundwater data. Nevertheless, the simulated groundwater map varies with respect to the historical groundwater map because there is a lack of monitoring wells within the study area. The maximum difference between simulated and observed data was 5 feet. Consequently, the groundwater flow model will be used to predict groundwater elevation for different climatological scenarios.

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CHAPTER 4 PREDICTION OF THE GROUNDWATER LEVEL IN THE AREA SURROUNDING THE MSEA, CENTRAL PLATTE NEBRASKA UNDER FUTURE CLIMATE SCENARIO.

1. Overview

Understanding the impact of climate change on soil hydrological processes and groundwater resources is crucial to assess future agricultural activities **(Akbariyeh, 2017).** Consequently, an accurate description of how the groundwater table behaves under future climate conditions is a necessary task to consider. Furthermore, predictions of well capacity, groundwater recharge, precipitation and actual evapotranspiration are critical initial data for future groundwater table responses. Researchers have applied several techniques to forecast the groundwater table based on calibrated groundwater models. **Nayak et al. (2006)** employed an artificial neural network technique (ANN for short) in forecasting the groundwater level fluctuation in an unconfined coastal aquifer in India. An ANN is a complex web that consists of many simple neural cells which resemble the human brain, and it ANN does not require a mathematical model (Feng and Hong, 2008). Peterson et al. (2016) designed a transient groundwater flow model that provided a tool for groundwater resource managers to assess the status and availability of groundwater resources. They used the soil water balance model (SWB) to estimate groundwater recharge from precipitation and groundwater withdrawals from irrigation wells. Cheng et at (2002) proposed an empirical statistical model that could likely be used to predict variations in groundwater in response to different climate scenarios.

The present study applied geospatial information to determine climate variables that are linked with the groundwater flow. Precipitation, groundwater recharge, and actual evapotranspiration are essential variables to be used in the simulated aquifer. This research study intends to apply these variables to predict the groundwater table in the study area under a future climate scenario. The Weather Research and Forecasting (WRF) model were used to provide the downscaled climate data over the Central Platte Basin to predict variables such as precipitation, land use, and air temperature **(Akbariyeh, 2017).** In a separate study **(Akbariyeh, 2017)**, the groundwater recharge (GR) and actual evapotranspiration of the site during 2056-2060 were predicted using forecasted soil moisture data for the Central Platte Basin. Hydrus 1-D was employed in that study to conduct inverse modeling based on Richard's equation. The hydrostratigraphy properties remain constant for the forecasting modeling, as well as the types of boundary conditions. Future groundwater boundary data were simulated by applying Fourier Series Regression to the historical data. The groundwater flow model developed in Chapter 3 using Visual MODFLOW Flex V. 2015 was employed to forecast groundwater table from 2056 to 2060.

2. Model Assumptions

The model simulation make use of spatial and temporal data from various sources. However, some assumptions were also made due to the lack of information:

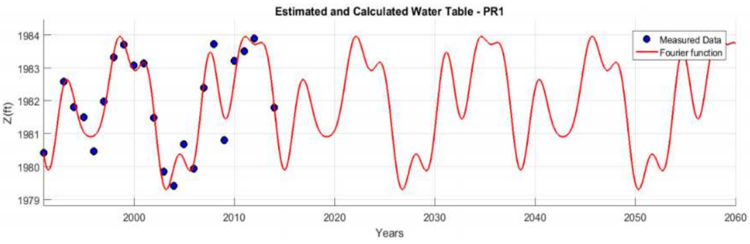
- The number of irrigation wells in the future is the same as in the historical period.
- Water heads for defining the specific head boundary condition and the reference water head for the general boundary condition under the future condition were assumed to follow a Fourier time series function of historical water levels.
- Well screens were assumed to be to the full depth of the well when data were not available.
- The amount of water pumped from the aquifer was assumed to be fully used by actual evapotranspiration.

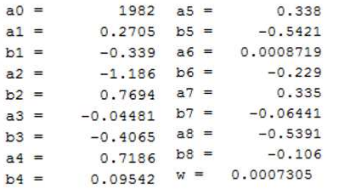
3. Methods

3.1. Boundary Conditions under Future Scenario

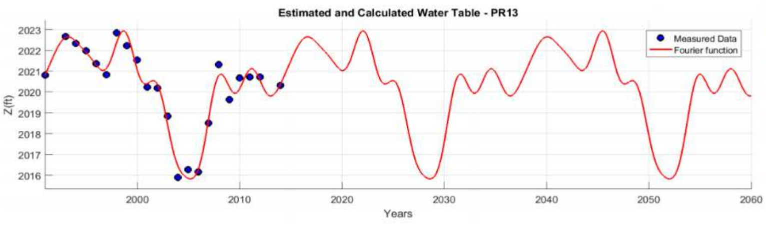
The same types of the boundary conditions were applied under future climate conditions. The northern boundary along the Wood River was assumed to be a general head boundary, as well as, the west and east sides of the model **(McGuire and Kilpatrick, 1998)**. Furthermore, the southern boundary is the Platte River, which is hydraulically connected to the aquifer. Therefore, the Platte River was modeled as a specific head boundary. In order to apply the general head boundary condition, a reference water level was needed. Similarly, to implement the specific head boundary condition at the Platte River, water head at the location of Platte River under future scenarios is required. As detailed in Chapter 3 for historical data, a time series of groundwater levels at the north and south boundaries were obtained by interpolating the groundwater levels in the monitoring wells in the area. For future conditions, Fourier series based curve was applied to the historical data points. Future boundary data from 2056 to 2060 were predicted by extending the Fourier regression equation. The curve fitting tool of the MATLAB (R2016a) was used for the regression. Figure 4-25 shows a Fourier series regression for three points along the Platte River.

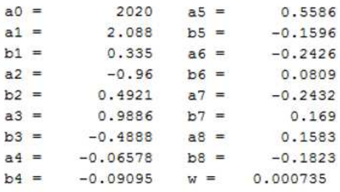
$$Z = a_0 + \sum_{i=1}^{8} a_i \cos(iwt) + b_i \sin(iwt)$$



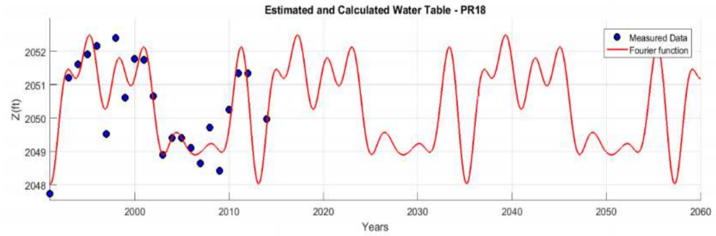


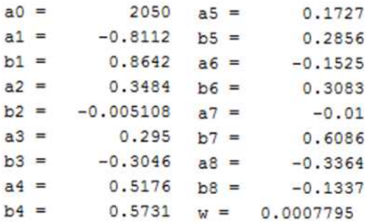
```
a0 =        1982   a5 =       0.338
a1 =      0.2705   b5 =     -0.5421
b1 =      -0.339   a6 =   0.0008719
a2 =      -1.186   b6 =      -0.229
b2 =      0.7694   a7 =       0.335
a3 =    -0.04481   b7 =    -0.06441
b3 =     -0.4065   a8 =     -0.5391
a4 =      0.7186   b8 =      -0.106
b4 =     0.09542   w =    0.0007305
```





```
a0 =        2020    a5 =      0.5586
a1 =       2.088    b5 =     -0.1596
b1 =       0.335    a6 =     -0.2426
a2 =       -0.96    b6 =      0.0809
b2 =      0.4921    a7 =     -0.2432
a3 =      0.9886    b7 =       0.169
b3 =     -0.4888    a8 =      0.1583
a4 =    -0.06578    b8 =     -0.1823
b4 =    -0.09095    w =     0.000735
```





```
a0 =        2050   a5 =      0.1727
a1 =     -0.8112   b5 =      0.2856
b1 =      0.8642   a6 =     -0.1525
a2 =      0.3484   b6 =      0.3083
b2 =   -0.005108   a7 =       -0.01
a3 =       0.295   b7 =      0.6086
b3 =     -0.3046   a8 =     -0.3364
a4 =      0.5176   b8 =     -0.1337
b4 =      0.5731   w =    0.0007795
```

Figure 4-25. Graphs showing historical groundwater data (Blue dots) and Fourier series curve for: (a) Platte River point PR01, (b) Platte River point PR13 and (c) Platte River point PR18.

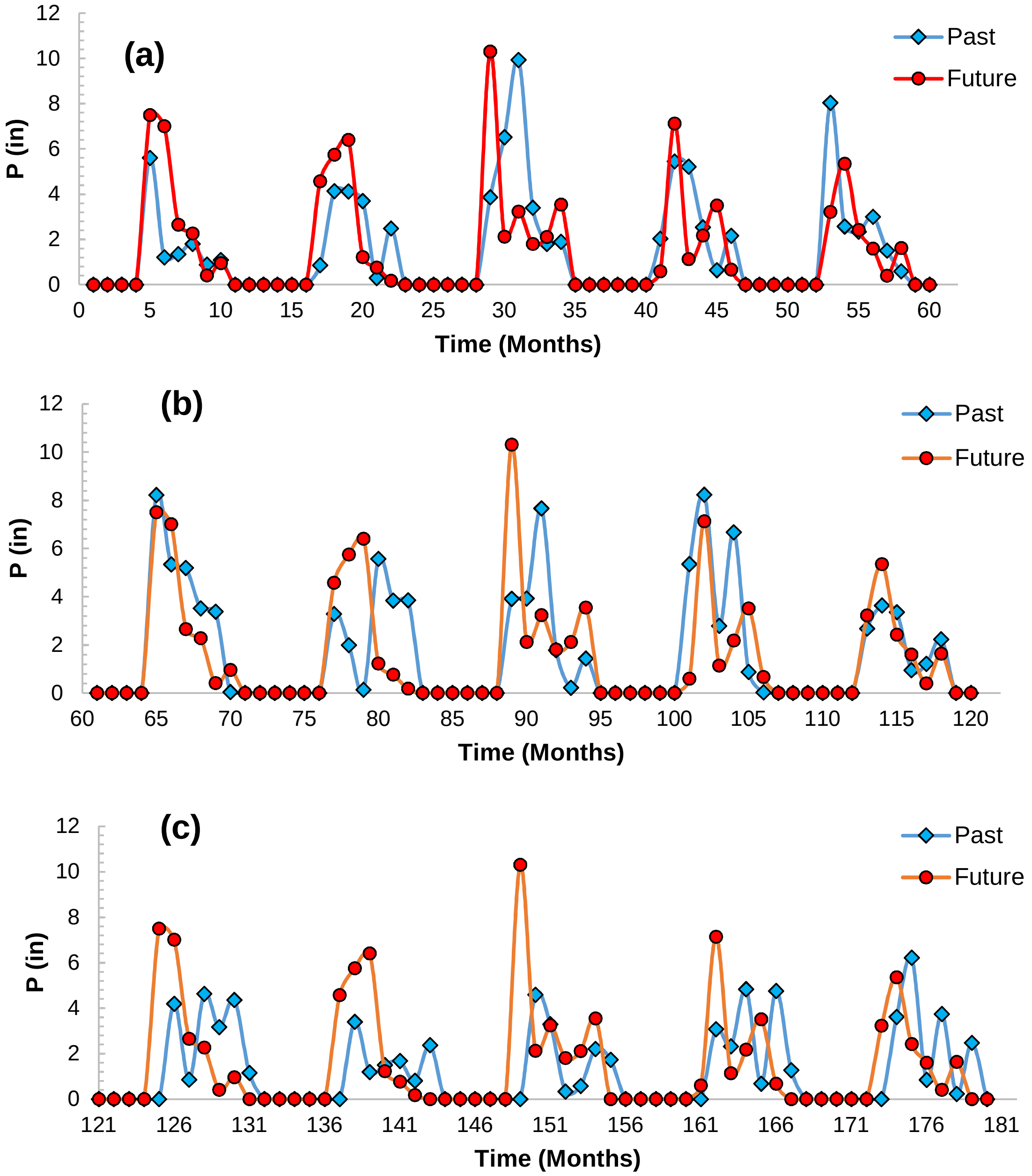
3.2. Determination of Future Pumping Rates

Because it is uncertain how many wells will be pumping in the future, the model assumes the same number of pumps located in the study area as in the historical period (1994 to 2014). Therefore, two hundred fifty-eight wells (258) active pumping wells will withdraw water for this future stress period (see Figure 3-16). The locations of pumping wells, as well as screen locations and irrigated areas, were kept same as the historical information from NDNR website. All the wells were assumed to pump during the growth season (from May to October).

As in the case of the historical period, we assumed that plant transpiration and evaporation consumed all pumped water because all pumps were for irrigational purposes. If there was any over pumping, it was assumed that extra pumped water infiltrated back to the subsurface. Therefore, the amount of water that was pumped out was equal to the difference between the precipitation and actual evapotranspiration of the crops in the area. For wet days where the precipitation exceeds the actual evapotranspiration, it was assumed that there was no water extraction from the aquifer. Therefore, the pumping rate for that day is null. Whereas, for dry days where the actual evapotranspiration exceeds the precipitation, the difference between them becomes the water needed for plants to strive.

3.3. Comparison between Future and Past Climate conditions.

Precipitation intensity from 1991 to 2014 and 2056 to 2060 are plotted at different time intervals. Forecasted rainfall (2056-2060) are compared every five years since 1991 until 2014 to get a better comparison between the past and future precipitation. Total precipitation from 1991 to 1995 during the growing season (from May to October) was approximated as 2314 mm which was slightly less than the total precipitation of 2353 mm from year 2056 to year 2060. Total precipitation during 1996-2000, 2001-2005, 2006-2010, 2011-2014 was roughly 2570 mm, 1929 mm, 2824 mm, and 1750 mm, respectively. It seems that the precipitation pattern from 2056 to 2060 is closer to the period of 1991-1995 than to any other period. Due to the variation of precipitation over time, irrigation water requirements and application times will be changed **(Akbariyeh, 2017).** Figure 4-26 shows the comparison between historical precipitation and future predicted rainfall.



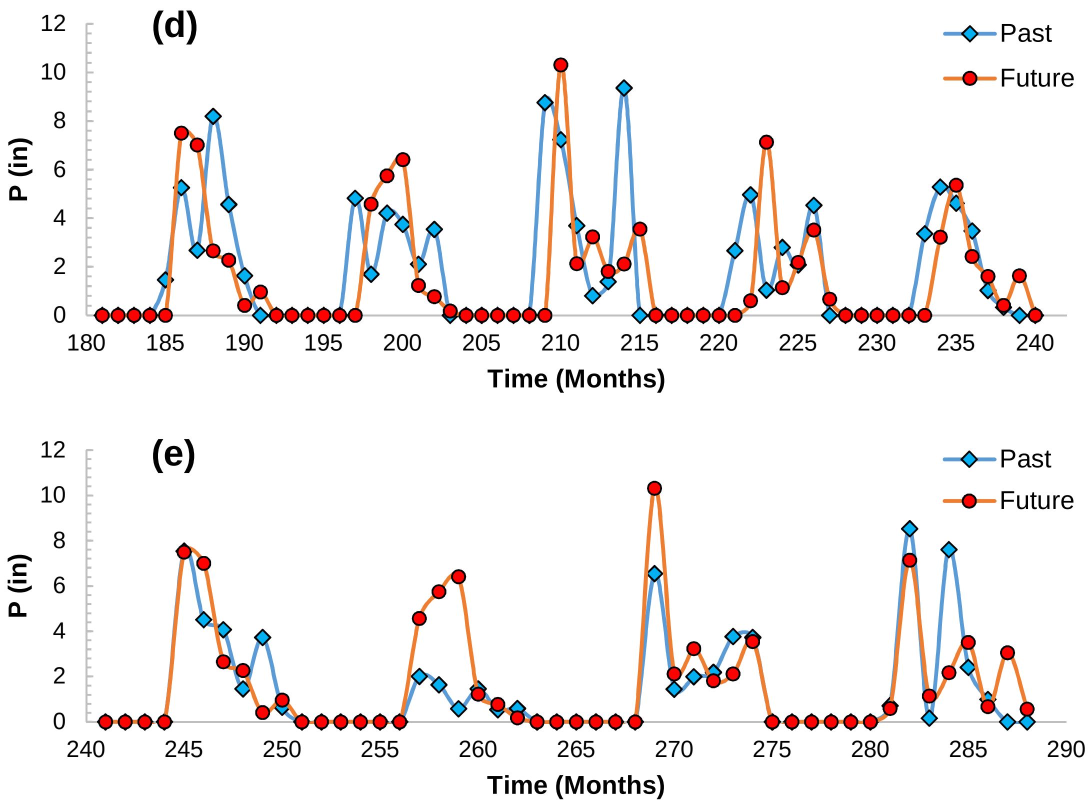
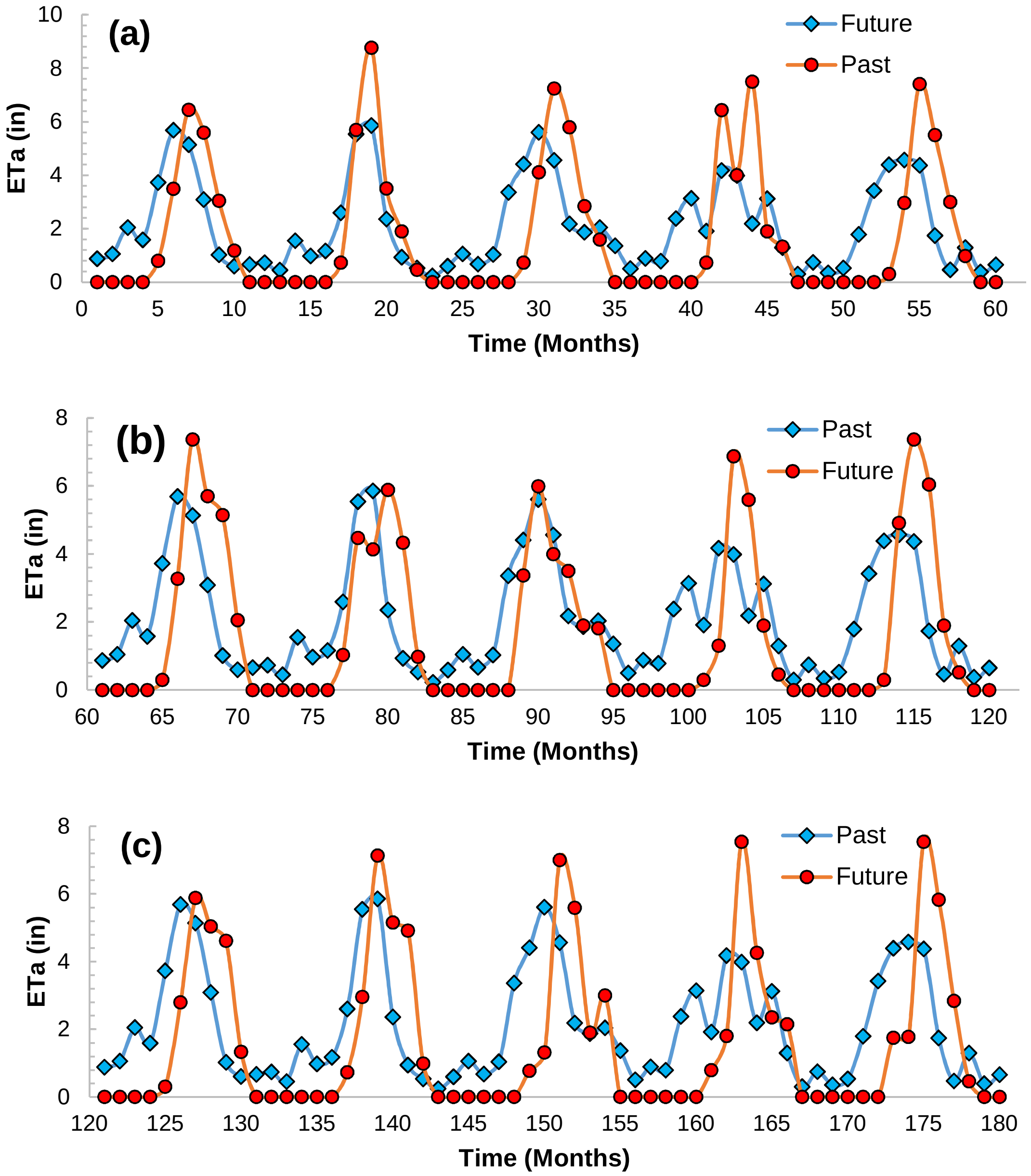


Figure 4-26. Comparison between historical precipitation and forecasted precipitation during growing season (May 1st to October 1st): **(a)** from years 1991 to 1995, **(b)** from year 1996 to 2000, **(c)** from year 2001 to 2005, **(d)** from year 2006 to 2010 and **(e)** from year 2011 to 2014

3.4. Comparison between historical, actual evapotranspiration and future actual evapotranspiration.

Future actual evapotranspiration (monthly from 2056 to 2060) was determined by Akbariyeh (2017) by applying the inverse modeling in Hydrus 1D. Briefly, by optimizing soil hydraulic properties, an inverse procedure was conducted to a vadose zone water flow model to best match the soil moisture data during 2057-2059. Then, the model was run for the last year (2060) to validate against the optimized soil hydraulic properties. In the model, the water flux that leaves the bottom boundary and upper boundaries are the groundwater recharge and actual evapotranspiration, respectively. Figure 4-27 shows the comparison between historical and forecasted actual evapotranspiration.



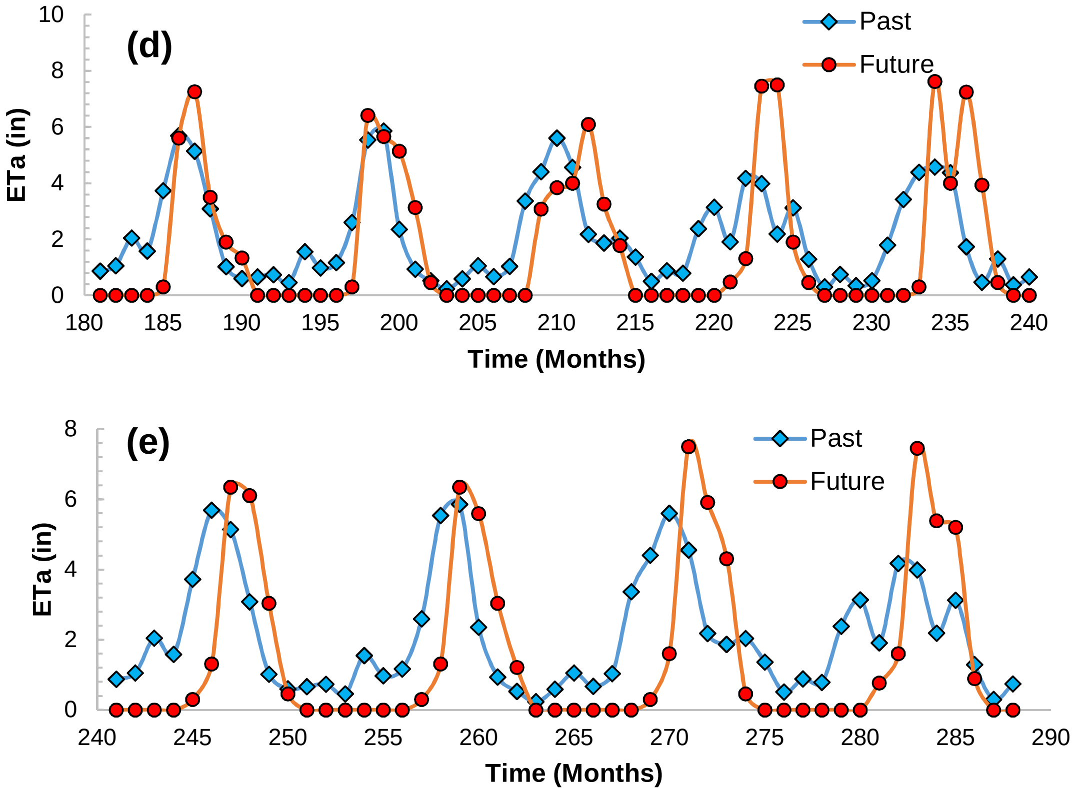


Figure 4-27. Comparison between historical actual evapotranspiration and forecasted actual evapotranspiration during growing season (May 1st to October 1st): **(a)** from years 1991 to 1995, **(b)** from year 1996 to 2000, **(c)** from year 2001 to 2005, **(d)** From year 2006 to 2010 and **(e)** from year 2011 to 2014

Total actual evapotranspiration (ETa) amounts from 1991 to 2014 and 2056 to 2060 were plotted at different time intervals. Forecasted ETa (2056-2060) were compared every five years from 1991 until 2014. Total ETa during the interval 1991 to 1995 was approximately 2691 mm during the growing season which is smaller compared to total ETa of 2317 mm during 2056 to 2060. Furthermore, total ETa during 1996-2000, 2001-2005, 2006-2010, 2011-2014 was roughly 2609 mm, 2551 mm, 2684 mm and 1949 mm, respectively. Actual evapotranspiration depends on the available soil moisture for the crops. Greater ETa in the past than in the future means that less water will be consumed.

Finally, to calculate the pumping rate for each well within the aquifer, it was necessary to multiply the irrigated area of each well with the difference between actual ET and precipitation, which provides a pumping rate in the unit of ft^3/d. Table 3 shows an example calculation of a well that irrigates 100 acres. The irrigation season began in May and ended in October for the research study

MONTH	ETa (mm/d)	ETa (in/d)	ETa (in/M)	P (in/M)	ETa-P (in/M)	E-P (ft/d)	Area(Ft^2)	Capacity (ft^3/d)
1/1/2056	0	0.000	0		0.00	0.0000	4356000	0
2/1/2056	0	0.000	0.00		0.00	0.0000	4356000	0
3/1/2056	0	0.000	0.00		0.00	0.0000	4356000	0
4/1/2056	0	0.000	0.00		0.00	0.0000	4356000	0
5/1/2056	0.793	0.031	0.94	5.61	0.00	0.0000	4356000	0
6/1/2056	3.495	0.138	4.27	1.21	3.06	0.0082	4356000	-35780
7/1/2056	5.750	0.226	6.79	1.35	5.44	0.0151	4356000	-65840
8/1/2056	5.590	0.220	6.82	1.80	5.02	0.0135	4356000	-58811
9/1/2056	3.043	0.120	3.71	0.89	2.82	0.0076	4356000	-33067
10/1/2056	1.176	0.046	1.39	1.10	0.29	0.0008	4356000	-3497
11/1/2056	0	0.000	0.00		0.00	0.0000	4356000	0
12/1/2056	0	0.000	0.00		0.00	0.0000	4356000	0

Table 3. Pumping rate calculate based on actual evapotranspiration and precipitation for the year 2056.

Excess precipitation (ETa-P) is defined as the difference between actual evapotranspiration and precipitation. Figure 4-28 shows the comparison between historical and future excess precipitation. The trend shows that historical excess precipitation is slightly higher than future excess precipitation which indicates that less water will be needed to supply water to irrigated lands.

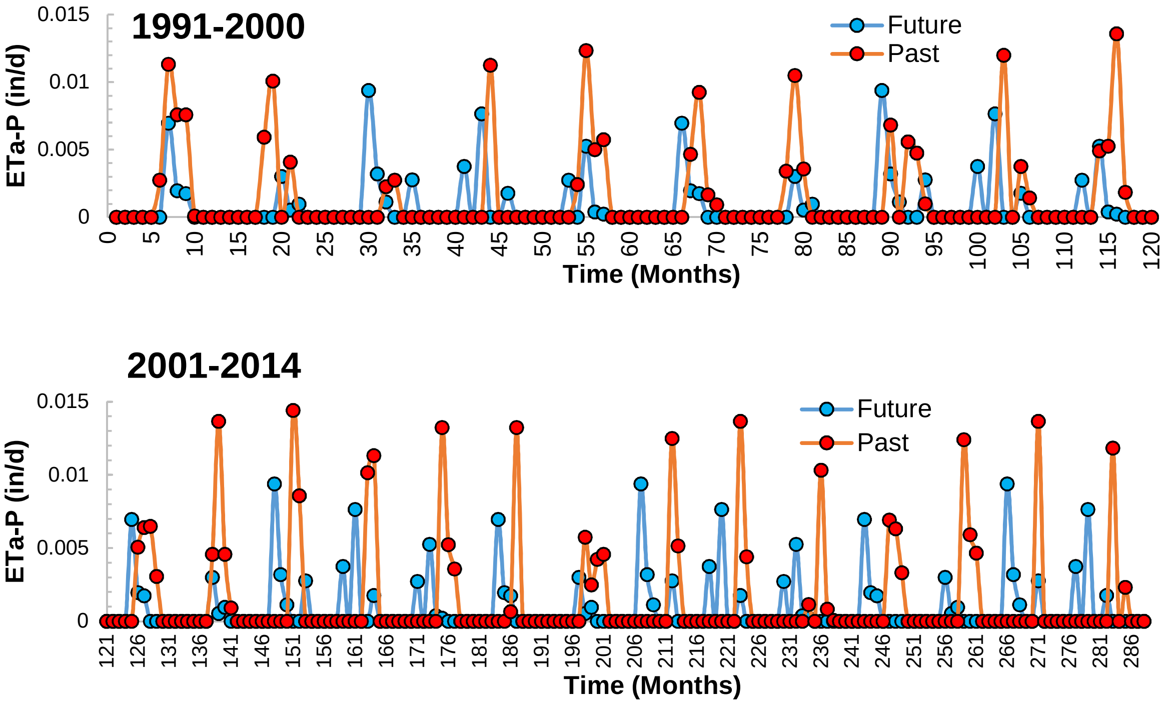


Figure 4-28. Monthly Comparison between the past and future actual evapotranspiration minus precipitation. (a) 1991-2000, (b) 2001-2014

3.5. Future Groundwater Recharge (GR)

In the model, the water flux that leaves the bottom boundary and upper boundary were the groundwater recharge and actual evapotranspiration, respectively. Figure 4-29 shows the comparison between future and historical GR recharge, respectively. The study area recharge ranges from 10 to 30 mm (See figure 3-14). Average GR in the future is smaller than the historical GR data **(Akbariyeh, 2017).** Future GR will decrease more than 50% probably due to the higher

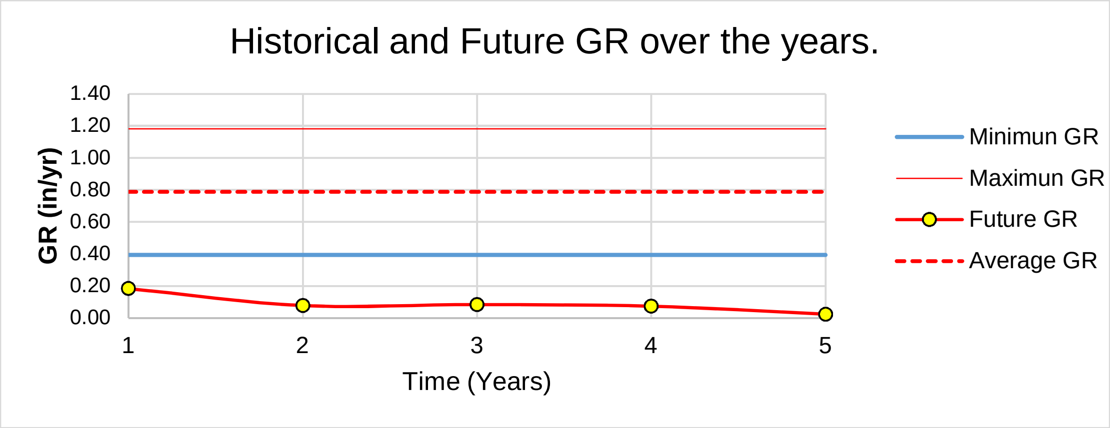


Figure 4-29. Comparison between historical and future groundwater recharge.

3.6 Numerical Modeling

The numerical model setup was the same as for modeling the historical period. The shallow groundwater system of the research area was simulated using distributed hydraulic conductivity, regularly spaced grid 62 rows and 110 columns using the finite difference grid approach. Each row and column represent 505 feet and 510 feet, respectively. The USGS MODFLOW-NWT, a Newton-Raphson formulation for improved simulation of unconfined groundwater-flow problems, was used.

4. Results and Discussion

Figure 4-30 provides a time series of the simulated groundwater table in the study area from year 2056 to year 2060. As was observed during the historical period, groundwater moves from the western side to the eastern side of the study area. During this time, the groundwater table has an imminent declination due to the influence of climate conditions (Precipitation, actual evapotranspiration, and GW withdrawal). Future precipitation is on average 47.5 cm/yr, which is slightly higher than the average historical precipitation of 44.1 cm/yr. Future ETa is roughly 463 mm/yr from year 2056 to year 2060, smaller than the historical actual evapotranspiration that was roughly 520 mm/yr on average for the period 1991 to 2014. Furthermore, predicted future GR (0.1 in/yr.) is significantly smaller than historical GR (0.8 in/yr.) All these factors together lead to a constant groundwater table declination during the future simulation period (2056-2060). Based on the simulation results, the groundwater declines approximately 0.66 ft/yr. Figure 4-31 provides a time series of water table changes at the four corner points of the MSEA. Groundwater levels showed a steady decline at the site as well. As during the historical period, groundwater levels show some level of declination and fluctuation. On average, the groundwater level in the area surrounding the MSEA decreases 0.66 ft per year which give a total 1 meter of decrease over the five years of simulation. Furthermore, the groundwater level declines on average 0.6 ft/yr in areas with mainly sandy aquifer near the Wood River, whereas areas consisting of gravel (Areas toward Platte River) could decline on average 2 ft/yr. Groundwater level declination is more evident at the southwest corner of the MSEA site than the other three points because the hydrogeology of the southwest corner of the MSEA contains more gravels than sands. Groundwater declination is higher in the future than in the past because future precipitation and future ETa are slightly higher compared to historical period. Nevertheless, future recharge rates are smaller than historical recharge which leads to the predicted decrease of groundwater levels during future. Ultimately, the influence of the uncertainties of all variables used for prediction could mislead the results from the original values, as well as, few historical monitoring well within the site.

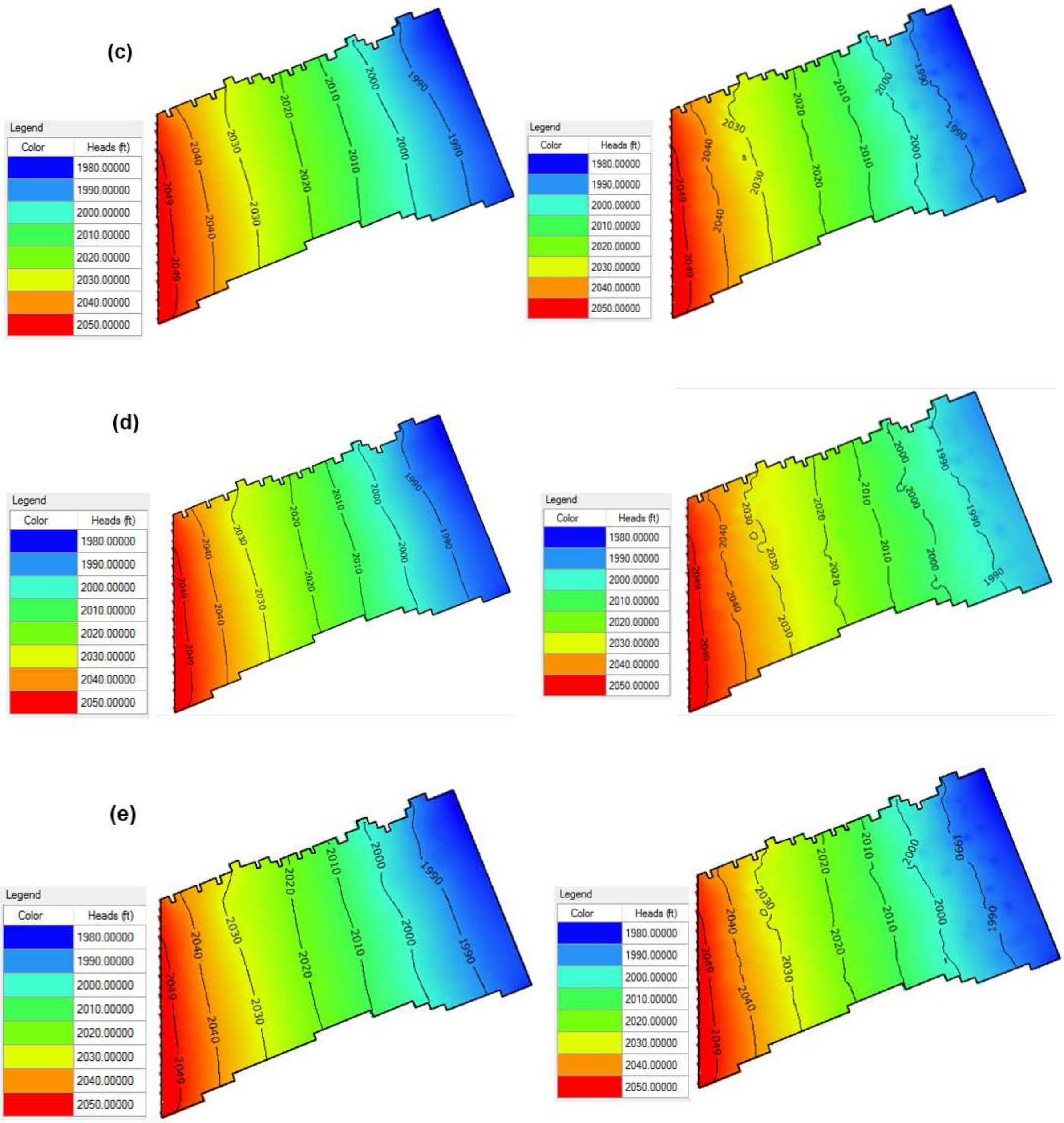


Figure 4-30. Groundwater table simulation for non-irrigation season (left picture-May, 1st) and irrigation season (right picture-August, 1st) for: **(a)** 2056, **(b)** 2057, **(c)** 2058, **(d)** 2059 and **(e)** 2060

Figure 4-32 shows a comparison between groundwater levels from 1993-1995 and Future GR from April-2057 to March-2060. A decrease of 0.5 meters is predicted in the next 40 years.

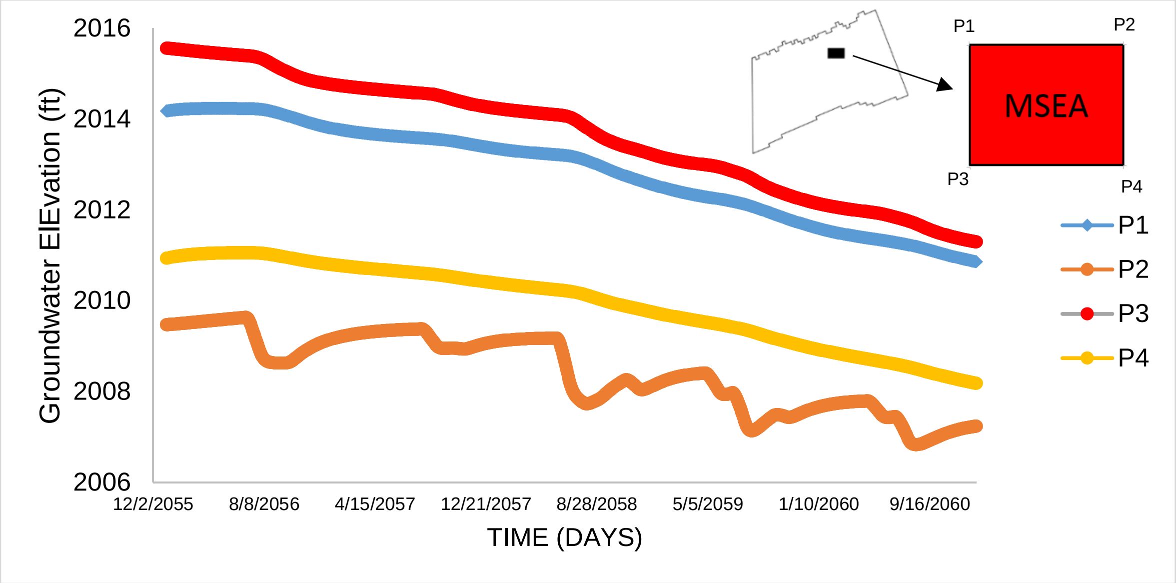


Figure 4-31. Groundwater table declination for fours corners of the Nebraska Management System Evaluation Area (MSEA).

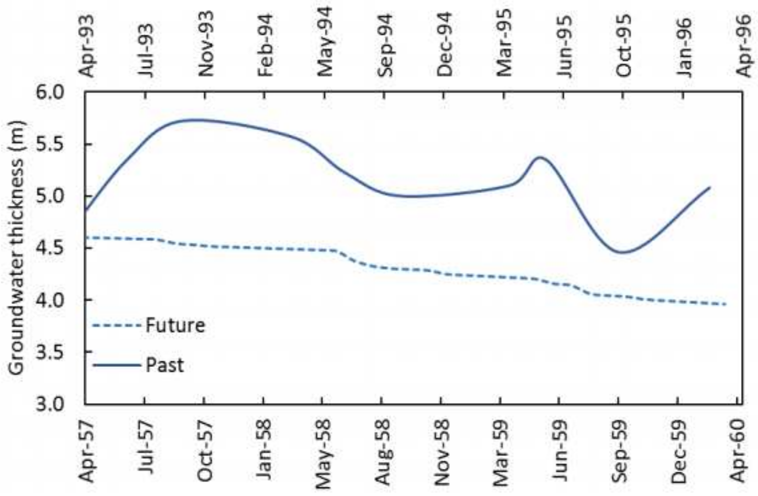


Figure 4-32. Mean groundwater thickness during April-1993 to March-1996 and April-2057 to March- 2060 **(Akbariyeh, 2017).**

5. Conclusions

The groundwater table surrounding the MSEA area under future climate scenarios was forecast using a groundwater flow model calibrated by historical groundwater level monitoring data. In this work, future precipitation data were obtained from downscaled climate data using the Weather Research and Forecasting (WRF) model **(Akbariyeh, 2017)**; the future groundwater recharge rate and actual evapotranspiration were estimated based on Hydrus 1D inverse modeling **(Akbariyeh, 2017),** and future pumping data were estimated based on the difference between precipitation and ETa. It was assumed that the amount of future irrigation wells was the same as the historical period due to the uncertainty of number of active future wells. The hydraulic conductivity distribution and boundary conditions were similar to the historical period. Well screens were assumed to be to the full depth of the well when data were not available.

Initial results show the groundwater declination is about 0.66 ft per year or a total of 1 meter on average for the entire simulation period which was five years. The forecasted data are 0.50 meters lower than the groundwater table from the 1990's which indicates that the groundwater level still declines from 2014 to 2055 (see figure 4-32).

Future precipitation was found to be similar to the historical precipitation. Nevertheless, future ETa is smaller than historical ETa for about 57 mm/yr, which indicates that there will be a lesser crop water use in the future. Future GR is likely to decrease more than 50% than historical GR **(Akbariyeh, 2017)**. Therefore, groundwater levels will decrease due to the higher reduction of future GR, but most importantly due to the difference between actual evapotranspiration and precipitation.

Groundwater declination is going to be greater in areas with higher hydraulic conductivity. For instance, simulated groundwater levels show that GW declination in gravel and sand areas are roughly 2 ft/yr and 0.66 in/yr, respectively. Ultimately, water-resources managers and stakeholders will need to assess the status of current agricultural practices to mitigate the groundwater declination by defining programs that strictly control groundwater withdrawals.

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CHAPTER 5: CONCLUSIONS

Groundwater is an important part of the water cycle and is one of the most valuable natural resources in the United States. For example, in Central Nebraska, groundwater is the main resource of water for farming activities (i.e., irrigation). Irrigation has supported agricultural production, resulting in $50 billion in sales in 2012 **(U.S. Department of Agriculture, 2014).** However, variations in the climate could influence the groundwater systems both directly by changes in recharge (i.e., recharge due to precipitation and snow melting) and indirectly through changes in groundwater uses.

In this research study, a 3-D groundwater flow model was developed to simulate groundwater levels (GWL) in the surrounding area of the MSEA site. The groundwater model was developed based on available data, including soil lithology information from forty-three test holes, precipitation and satellite ETa data as well as irrigation wells information within the research area. Historical groundwater level data were used to calibrate the model. The calibrated model was then applied to predict future groundwater levels in the area. Precipitation, groundwater recharge, and actual evapotranspiration are essential variables to be used in the simulated aquifer. This research study intends to apply these variables to predict the groundwater table in the study area under future climate scenario. Downscaled climate data over the Central Platte Basin were obtained from the Weather Research and Forecasting (WRF) model **(Akbariyeh, 2017).**

Specific conclusions for each chapter are as follows:

1. A 3D groundwater flow model, containing a realistic heterogeneous hydraulic conductivity field, was successfully developed and calibrated with historical groundwater level measurements in the area.
2. Comparison between historical data and simulated groundwater levels indicated that the model correctly reproduced groundwater levels during the 1991-2014

simulation period using appropriates inputs such as boundary conditions, groundwater recharge and pumping rates.

3. Groundwater declination was higher on the west side of the model than on the east side due to higher density of pump wells. Therefore, a larger groundwater declination was found on the west side of the study area. During the non-growing season (November to April), groundwater level tends to rise due to the lack of pumping and the contribution of precipitation and snowmelt that replenish the aquifer; whereas, during the growing season (May to October), groundwater table tends to decrease due to water pumped for irrigations. Comparing both seasons, groundwater declination cannot be fully compensated by groundwater recharge, especially in areas where the hydraulic conductivity is higher.
4. The future groundwater table showed a declination trend due to a significant reduction of the groundwater recharge. For this area, the excess precipitation is slightly smaller in future predictions than in the past under the assumption that the future density of pump wells remains constant since 2014.
5. Future groundwater level declination is impacted by the distribution of subsurface hydrogeology of the study area. South areas with mainly gravel show higher declination rates than north boundary areas with smaller hydraulic conductivity.

5.1 Recommendations for Future Research:

- The model considered an average groundwater recharge due to the lack of data for this area. Therefore, a study of how the groundwater recharge varies spatially will be helpful to improve the model.
- The 3D groundwater model can be coupled with a contaminant transport model to estimate transport of contaminant throughout the area by using appropriate inputs.

- Future studies can utilize the groundwater model to predict groundwater level in a different period by applying appropriate boundary conditions values, groundwater recharge, and pumping rate.
- The hydrogeology of the site was developed by using interpolation techniques for 43 boreholes. This can be improved by including additional monitoring wells in the study area.