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An Alternative Assessment of Groundwater Level Changes: An example application in Clay and Adams County, Nebraska

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Disclaimer: The following thesis was produced in the Environmental Studies Program as a student senior capstone project.

An Alternative Assessment of Groundwater Level Changes: An example application in Clay and Adams County, Nebraska

By

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and
Dr. Jesse Korus

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An Alternative Assessment of Groundwater Level Changes: An example application in Clay and Adams County, Nebraska

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Abstract

This study uses publicly available data (1934 to 2015) from several online sources relating to groundwater levels, bedrock depth, and annual precipitation from six wells located near Hastings, Nebraska. Traditionally, groundwater levels are presented in reports that show changes in terms of feet gained or lost. An alternative method employed in this study assesses variations in groundwater supply and availability using total saturated thickness of the groundwater system in terms of a percentage change in saturated thickness. This method represents groundwater resources in the context of the quantity available as opposed to the traditional method of changes in terms of feet gained or lost. Findings suggest that prior to predevelopment (before 1960's), percent change of saturated thickness remained negligible and during increased irrigation development (1960's-1980) there was a steady decrease in percent change of saturated thickness. After 1980 groundwater levels equilibrated and oscillated around a potentially new equilibrium that was responsive to changes in the amount of precipitation.

Keywords: Groundwater, aquifer, Nebraska, management, percent change, storage, precipitation

1. **Introduction**

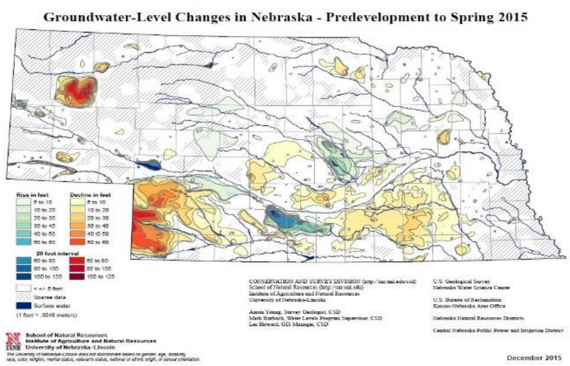


Figure 1 depicts the condition of groundwater saturated thickness in terms of feet lost. Image credit: CSD, 2015

In Nebraska, agriculture contributes one quarter of the state's economy (Foster et al., 2015). Groundwater systems provide a necessary resource that allows farmers to increase crop yields, promote economic development in rural areas, and allow farmers to continue producing in drought conditions (Foster et al., 2015). Changes in groundwater availability can be presented in a variety of ways. Data can be depicted using different colors on a map representing increases and decreases. For example, lowering groundwater levels on a map can be shown in red on maps in red (Figure 1). Changes in groundwater levels are presented as hydrographs in terms of changes in depth to groundwater over time (Figure 2. Both these approaches can alarm natural resource managers who in turn may implement groundwater management areas. Although both these methods are useful, they do not provide information about the changes in the amount of groundwater in storage. An alternative method of assessing changes in the groundwater system is to examine variations in terms of percent change in saturated thickness over time (Figure 2). This approach provides a visualization of the overall impact on the availability of the groundwater resources that is less dramatic than the traditional groundwater level method (Figure 2).

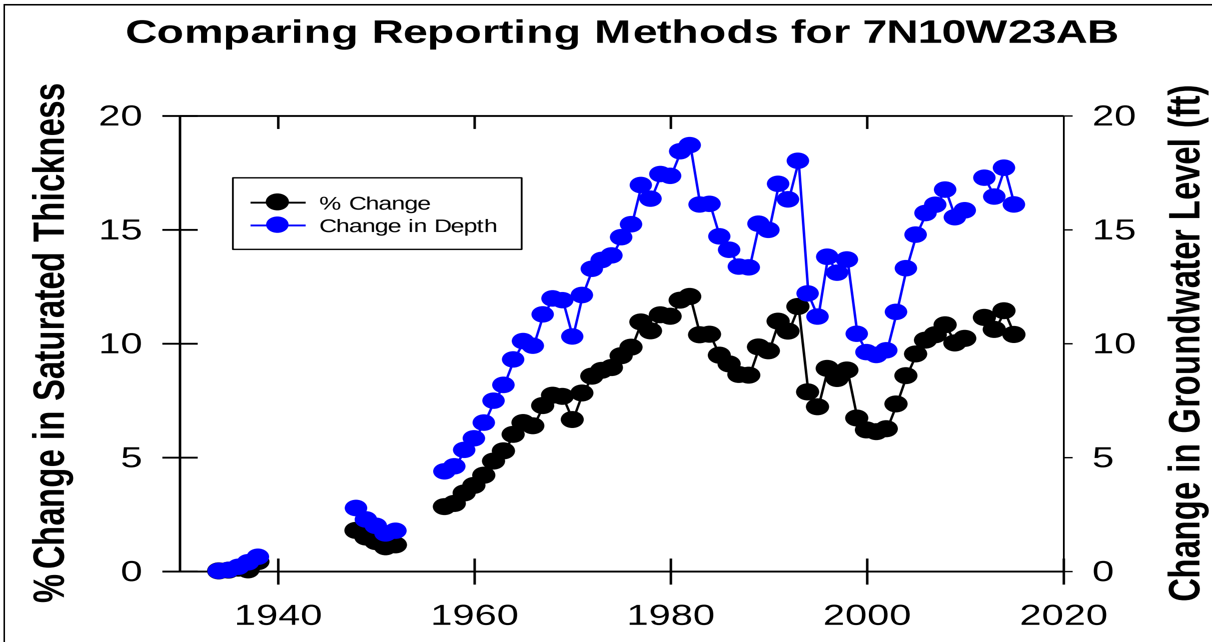


Figure 2 shows a comparison of the percent change in saturated thickness and change in depth to groundwater. A percent change looks less dramatic and gives a better representation of the available groundwater.

1.1 Background on Water Resources

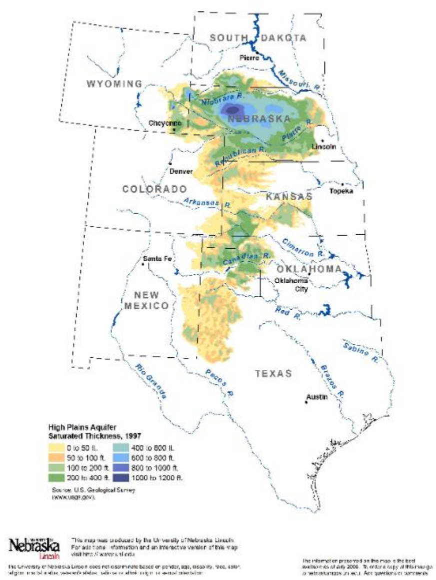


Figure 3 shows the location of the High Plains Aquifer. Image Credit: USGS, 1997

Global water data indicates that approximately 70 percent of the Earth's surface is covered in water. A little over 96 percent of the total water on earth is seawater (Shiklamanov, 1993). Of the remaining 4 percent of water on earth, 67 percent is captured in glaciers, ice caps, and permafrost (Shiklamanov, 1993). Groundwater, the world's largest and most evenly distributed source of freshwater available (Szilagyi & Jozsa, 2010), comprises 30 percent of the total volume of freshwater (Shiklamanov, 1993) Groundwater is stored in systems consisting of unconsolidated materials (sand and gravel), sedimentary and igneous rocks, and metamorphic rocks. Primary openings for groundwater is in the pore spaces within gravel, sand and silt in unconsolidated and consolidated sedimentary materials. Secondary openings, made up of fractures and voids, are common in igneous and metamorphic rocks (Heath, 1983).

In the United States, the Midwest contains the High Plains Aquifer (HPA) which occurs in eight states (Figure 3). The largest and deepest portions of this groundwater system occurs under Nebraska and underlies 64,400 square miles (Fleming et al., 2012). The HPA supports nearly fourteen million acres of irrigated farmland and twenty percent of the total annual crop harvest in Nebraska through the use of roughly five trillion gallons of water annually (Fleming et al., 2012).

Sustained drought and agricultural practices led to the dust bowl years of the 1930's. At that time, farmers started utilizing surface water and developing shallow wells to irrigate their crops. As technology improved during World War II, deeper wells were drilled that tapped into groundwater to irrigate crops (Fleming et al., 2012). Center-pivot irrigation was introduced in the 1950's. As the technology improved and center pivots became more widely available, the number that tapped into groundwater systems (aquifers) went significantly increased (Fleming et al., 2012). With the increased pivot use, the amount of groundwater in storage was reduces data and policy makers in Nebraska saw a need for more management of this important resource.

Nebraska's water institutions have evolved from a system of state-controlled water resources to a system of divided state and local control, and in some situations, both state and local entities share responsibility for management (Hoffman Babbitt et al., 2015). In 1975, the Nebraska Unicameral enacted the Ground Water Management Act that granted primary responsibility for groundwater management to 24 Natural Resource Districts (NRDs) (Stephenson, 1996). Since this act, 24 NRDs have become 23 after two combined. The purpose of groundwater management is to ensure and maintain a sustainable level in the groundwater resource.

Historically, documented declines in groundwater levels have led to the implementation of stringent regulations to ensure that the groundwater supply will be available to meet the needs of farmers (Hobza and Sibray, 2014). In Nebraska, groundwater is appropriated through Correlative Rights. This means that every landowner has an equal right to extract groundwater if it is seen as a beneficial use by the public management (UNL Water Team, 2016). The landowner must have a permit prior to drilling and they must register the new well with the Nebraska Department of Natural Resources once the drilling is complete (UNL Water Team, 2016). However, in times of drought, each landowner must make equal reductions in their consumption. Despite the correlative rights, certain areas of the state with groundwater storage issues have a set amount of water they are allowed to pump each year. These wells are monitored with meters to ensure compliance.

1.2 Background on Groundwater

Groundwater availability is the most significant issue that farmers face worldwide (Comis, 2008), as well as in Nebraska. As irrigation technology improved during the time of World War II, the number of irrigation wells increased from 1,500 in 1941 to over 8,000 in 1953; in fact, during the 1950's through the 1960's the average number of wells being drilled each year was around 2,000 in Nebraska (Fleming et al., 2012). As stated, the expansion of groundwater-based irrigation, which taps into the HPA, helps increase crop yields, promotes economic development in rural areas, and helps farmers cope with drought conditions (Foster et al., 2015). Sound agricultural practices are required to ensure an adequate and sustained food supply for the world population. These practices should include sustainable water management practices to ensure the longevity of groundwater supplies.

Groundwater levels are an important set of data used to estimate the total amount of water contained in a groundwater system. Large amounts of groundwater level data are available, ranging from present day to the time of predevelopment (i.e., before irrigation ~1950s). Monitoring of groundwater levels gives a direct indication of the total groundwater supply (Fulton et al., 2014). These water level data are compiled and analyzed in numerous ways across different agencies and individuals to monitor the overall health of the groundwater system. Different measurements are available from which the total saturated thickness can be calculated. This thickness represents the amount of subsurface geological material that contains water with the groundwater system from the top of the system (i.e, water table) to the base of the aquifer, referred to as bedrock. Water levels measured represent the depth from the surface to the water table.

The following hydrologic mass balance equation can describe the change in water volume of a groundwater system (Figure 4):

$$\Delta W/\Delta t = \Delta I/\Delta t - \Delta O/\Delta t$$

where ΔW equals the change in volume of water available in a groundwater system (i.e., change in saturated thickness), ΔI equals a change in input to the groundwater system, such as precipitation and snowmelt, ΔO equals the change in total outputs from sinks like irrigation and natural discharges, such as base flow seepage into surface waters, (Korus & Burbach, 2009), while Δt equals the change in time between measurements. These data show long- and short-term trends in groundwater fluctuations (Piggott et al., 1996).

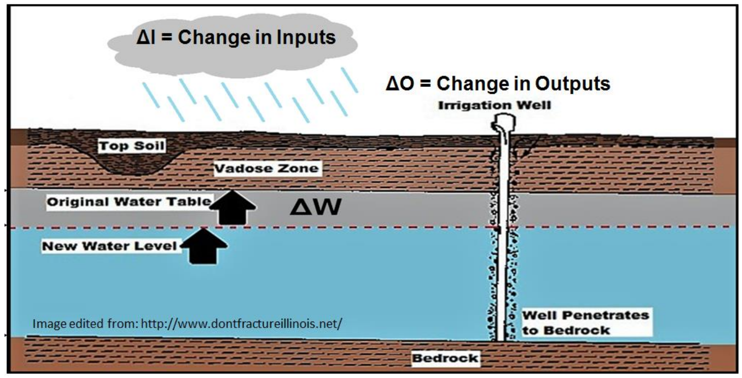


Figure 4 shows a side view of a well penetrating a groundwater system and reaching the bedrock with the hydrologic mass balance equation variables labeled.

According to the hydrologic mass balance, if the system has reached an equilibrium, the mass of water added to the system from precipitation must equal the mass of water leaving the system through irrigation and natural discharges (Korus & Burbach, 2009). At equilibrium water levels do not change. If the water level raises, there is more water entering the system than leaving. In the instance of a decline in water levels, there has to be either less water entering the system, more water leaving, or a combination of the two (Korus & Burbach, 2009). Equilibrium in groundwater resources is only reached when extraction is balanced by recharge (Alley et al., 1999).

As irrigation is only needed during the summer growing season, groundwater levels are lower in the fall from the summer extraction. Slight static water level variations can be seen on a yearly basis due to heterogeneous precipitation. Because of varying weather patterns, irrigation is used on an "as-needed" basis, leading to a need for water resource management to be able to adapt to different environmental conditions. As water is pumped from the groundwater system, water flows in horizontally and creates a cone of depression. As pumping ceases, groundwater levels recover, but is typically lower than the level it had prior to the irrigation season. Monitoring changes in the groundwater levels provides mechanism to assess the impact of irrigation on the system over time.

This case study will look at the historic changes in groundwater storage in Clay and Adams counties in south central Nebraska by looking at the change in annual spring time saturated thickness. This study is revisiting work initially conducted by Dr. Dave Gosselin in 1993. He was tasked with examining groundwater resources in the Groundwater Management Area that was implemented under the Little Blue NRD. The initial analysis concluded that the groundwater levels had stabilized from the predevelopment levels. It was found that the percent change in groundwater system thickness followed an s-curve, with the most recent data at the time showing a slow in growth. This present research is directed at analyzing changes in saturated thickness from predevelopment to present for six wells and then evaluating the relationship between precipitation and changes in saturated thickness.

2. **Methods**

Water levels are regularly taken by many different agencies across Nebraska. The Natural Resource Districts (NRDs), the Department of Natural Resources (DNR), the United States Geological Survey (USGS), and the University of Nebraska-Lincoln’s (UNL) Conservation and Survey Division (CSD) all take water level measurements at different locations across the Nebraska throughout the year. All of this information is compiled into a database that is maintained by the CSD. The DNR maintains a database that includes the geological logs, initial readings of static groundwater levels, and other documentation associated with well registration. These data are public record and can be accessed and assessed by anyone. These widely available data are utilized in many different ways, such as generating water reports for the state to show the overall health of the groundwater system as part of an annual ground-water level monitoring report.

In this study, a combination of these databases were used to obtain historical groundwater information in Clay and Adams Counties. Initially, the USGS database was used to determine the identification number associated with individual wells. This identification number was then searched in the CSD database to correlate a different well identification number that is utilized by the DNR. This number was then used to search the DNR database to determine the year that the well was drilled, the depth of the shale or bedrock layer of the groundwater system and the static water level at the time that the well was drilled. The well locations can be visualized in Figure 5. These data are important in order to be able to calculate the saturated thickness in that location of the HPA. This information was then stored and organized in a Microsoft Excel spreadsheet to show the change in saturated thickness over time.

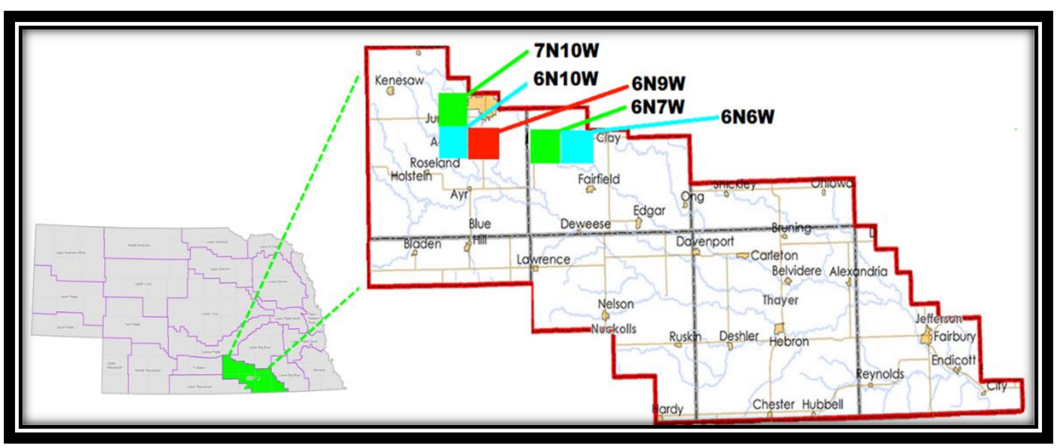


Figure 5 shows the area of study with townships containing wells highlighted. The map of Nebraska outlines the different NRDs.

As discussed, groundwater levels are regularly taken to estimate the amount of groundwater available. When a well is initially drilled, the holes occasionally reach all the way to the bedrock of shale underlying the groundwater system.

After a few days, once the water level has been given a chance to equilibrate, the water level is taken of the well. For this study it was necessary to use wells drilled to a depth that reaches bedrock. The depth to bedrock gives the total thickness of the geologic material available for groundwater, which will be shown as *B*, for bedrock. The water level taken upon development, *S*, gives the expected depth of the groundwater in the well. Once the levels were all gathered, the static water level, *W*, was subtracted from the groundwater system basement level to give the total saturated thickness at that exact point in the groundwater system.

Once this saturated thickness was determined for the levels upon development of the well, it was used as a baseline of comparison for as long as well water levels are taken.

Baseline Saturated Thickness (To) = B - S

Saturated Thickness at Time x (Tx) = B - W

With this baseline saturated thickness that has been calculated for each well, levels taken at different times were used to determine the amount of water in that well over a span of time. The point of this research was to find a collection of wells in the database that are drilled to the base of the groundwater system. This was crucial to the study because in order to graph the long term change in saturated thickness, it is absolutely necessary to know the total depth to the bedrock. The percent change of saturated thickness can be calculated by (Figure 6):

% Change of Saturated Thickness =
[To – Tx / To] x 100%

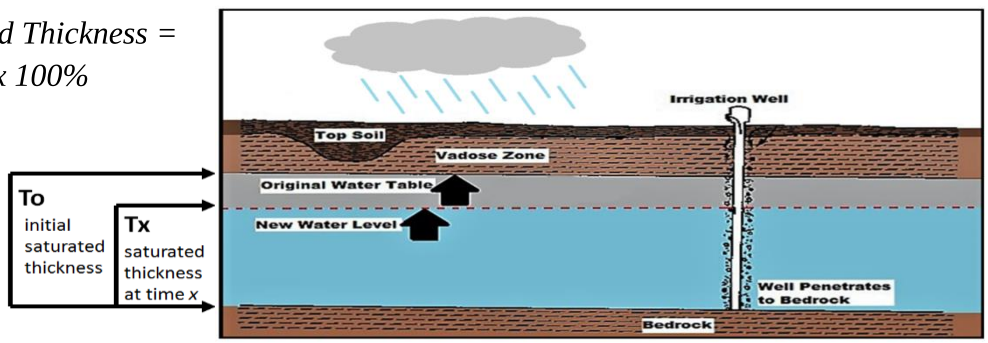


Figure 6 shows a cross section of a well with a visualization of the parameters taken for this study.

This formula was used to show the percentage of the saturated thickness that has been lost due to extraction. Traditional reports show how many feet are lost from the groundwater system over the time being examined. These reports provide information on relative changes in the static water level, but measures of these changes are only useful in context of aquifer storage. For example, ten feet of change equates to a larger percent loss in a groundwater system where the saturated thickness is one hundred feet than it does to a system that is five hundred feet thick. The method employed in this study provides a more useful measure of changes in the amount of water stored in the groundwater system.

Once the well information and static water level data was collected, precipitation data was be gathered from the National Oceanic and Atmospheric Administration (NOAA). For the purpose of this case study, total annual precipitation levels from Hastings, Nebraska was be used because it is relatively central to the area of study. These data were be plotted against the percent change in saturated thickness to look for trends and the groundwater level response to precipitation. Even though annual rain totals fluctuate, it was expected to have extended periods of both higher than average and lower than average amounts. The response in groundwater levels were also to be examined.

3. Results

For this study, six wells from the original Groundwater Management Area in Clay and Adams County, Nebraska were found that penetrate to bedrock. These individual well data were plotted on a line graph, known as a hydrograph. In Figure 7, data from three Adams County wells are plotted. Figure 8 presents similar data from Clay County. Precipitation data was then gathered from the NOAA website and plotted. Hastings data was used for precipitation in both counties because it was the nearest weather monitoring station to the area of study. In these data, the fluctuations of precipitation oscillates around a yearly average of 26.44 inches (NOAA, 2016).

In these static water level data sets, years of measurements are missing, showing gaps in Figures 7 and 8. Despite these missing values, trends can be seen in the data. The predevelopment stage of the wells had negligible loss in saturated thickness compared to the loss after development occurred. Once the period of development occurred, in the 1960's to the late 1970's, the percent change in loss of saturated thickness increased in five of the six wells. However, these data suggests that from the peak low saturated thickness in about 1980 until present, the groundwater system has reached the peak loss in saturated thickness. The variability in water levels cannot be attributed to one single cause, but a slight delay between saturated thicknesses can be seen as a delayed response to changes in precipitation.

It can be seen in Figure 7 and 8 that wells 7N10W23AB, 6N9W4BC, 6N6W9BD, 6N6W24AC, 6N7W23BB follow the same trajectory. Prior to development, before 1960, the percent change in saturated thickness is negligible. Once development occurs, the percent change increases as a loss in saturated thickness, occurring until 1980, when the saturated thickness is at its peak in change. After this 1980, the saturated thickness increases for approximately five years before decreasing for another five. Over the next decade, the percent change in saturated thickness decreases. After 2000, the percent change in saturated thickness increases again before the trajectory flattens out for the current data. In Adams County, well 6N10W23BB is an outlier, with minor fluctuations along the predevelopment level, but not major change in saturated thickness.

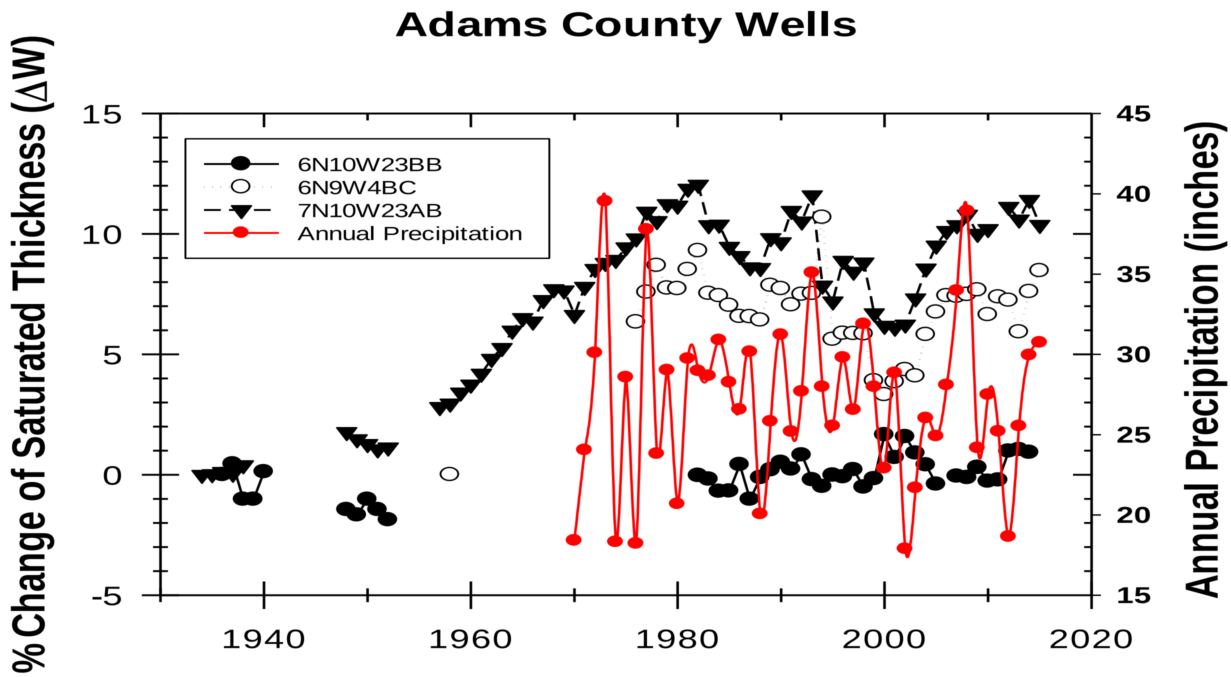


Figure 7 shows the percentage change in saturated thickness for wells in Adams County, Nebraska, plotted with the total annual precipitation represented as the red circles.

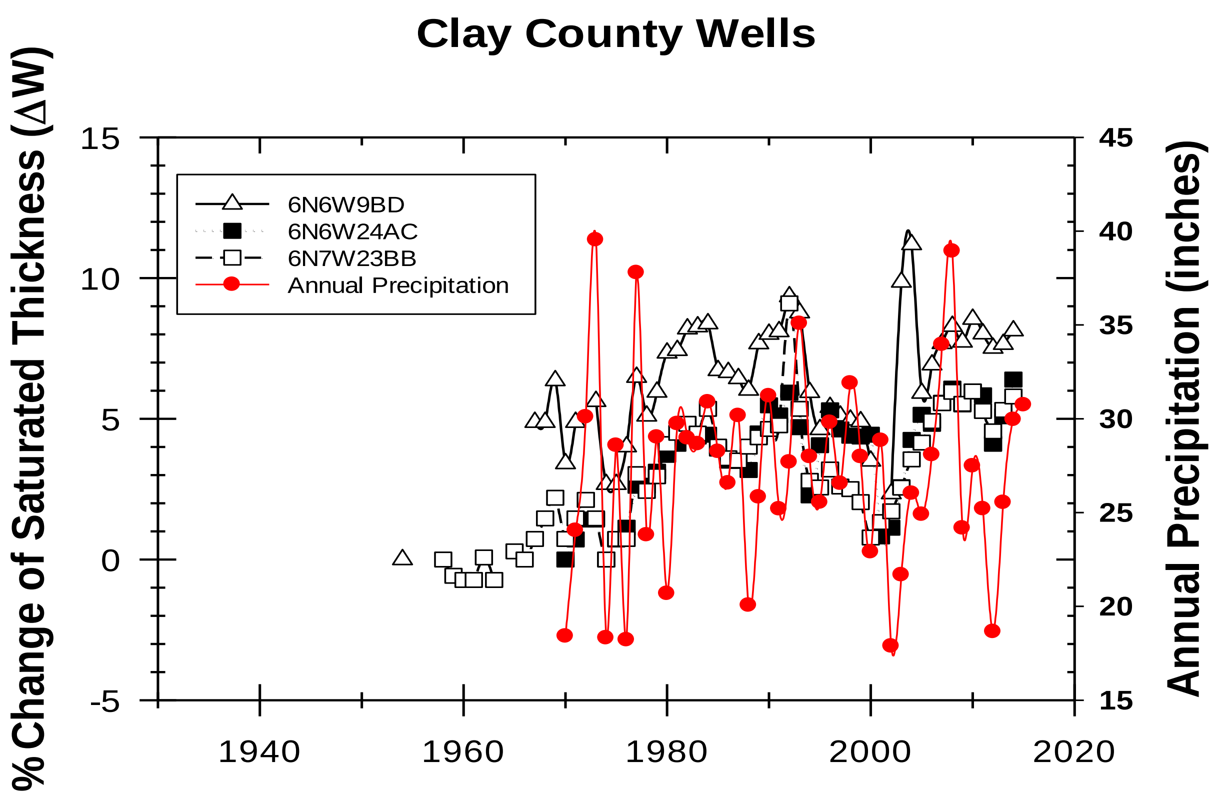


Figure 8 shows the percent change in saturated thickness for wells in Clay County, Nebraska, plotted with the total annual precipitation represented as the red circles.

4. Discussion

The comparison of these data resulted in visible trends. Of the six wells studied, five showed a drop in saturated thickness from predevelopment to 1980, when the peak loss appeared to take place. After 1980, saturated thickness went through periods of increases and decreases. The maximum percent change in saturated thickness occurred in well 7N10W23AB at a value of 11.61%, representing an eighteen foot drop in static water levels. However, once the five year average was calculated, the data flattened out, and the variance was a maximum of only 2% from the new equilibrium.

A five year running average was calculated and plotted for the groundwater and precipitation data (Figure 9). The five-year average graph shows less fluctuation and further supports the suggestion that groundwater levels have reached a new equilibrium that they oscillate around. It can be seen in Figure 9 that after 1980 the change in saturated thickness increases, then it decreases a little before it has another period of increase. Around 2005, the saturated thickness decreases again before starting to flatten out. If an average was taken and plotted along each set of data, the slope would be close to zero, meaning there is no net loss or gain in saturated thickness over this period of time.

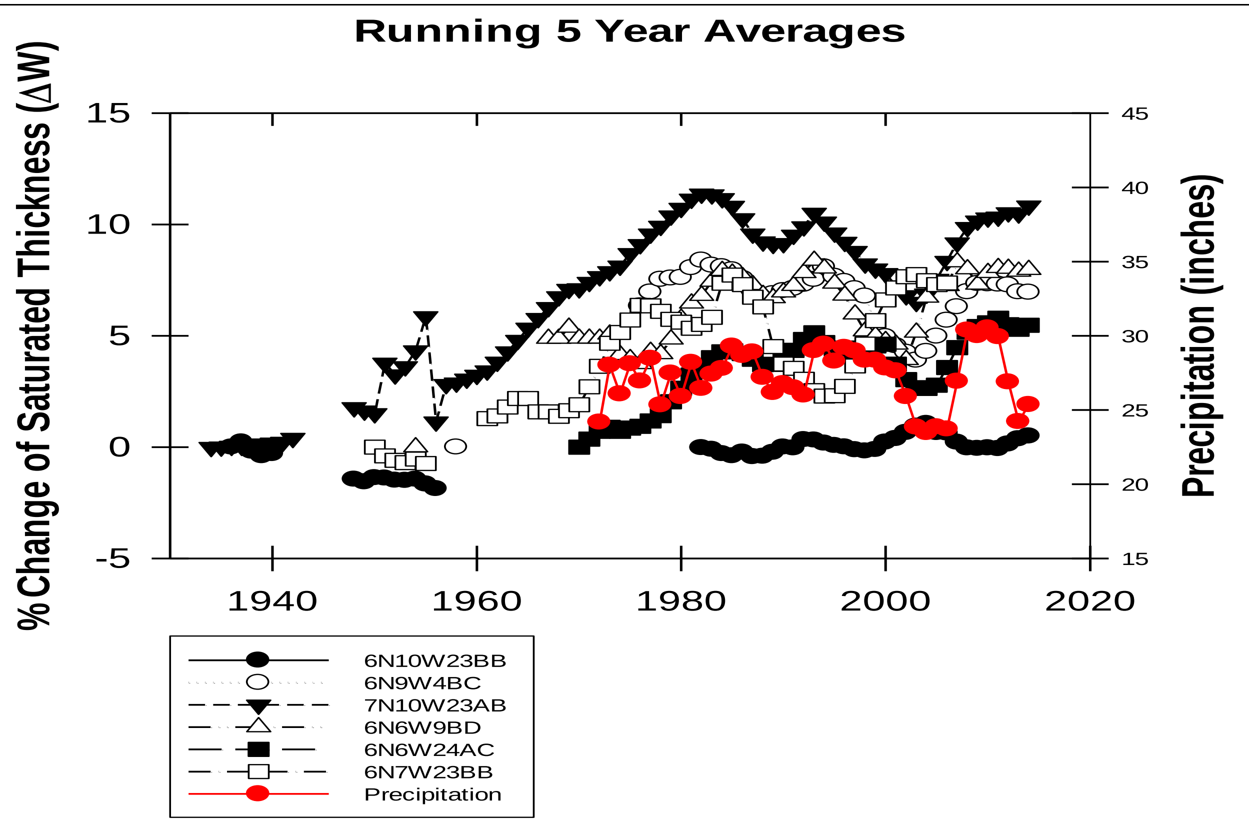


Figure 2 shows an annual running average of the previous five years data. The red plot shows average precipitation while the black plots represent the labeled wells. The average percent change thickness only slightly varies throughout a 25 year period.

The results in this study can be described by the hydrologic formula, where $\Delta W = \Delta I - \Delta O$. The change in storage, ΔW, is the static water level data. Because the amount of groundwater in storage does not remain constant, precipitation levels, pumping amounts, or a combination of both have not equilibrated. In this study, ΔI refers to a change in inputs, being precipitation. Figures 7, 8, and 9 show that precipitation fluctuates. The final variable, ΔO, is equal to a change in outputs. For this study, the only output factor considered is groundwater pumping for irrigation.

Given that there are only so many acres of irrigated cropland in the area, it was predicted that the graph of percentage change in saturated thickness would follow an s-curve. Prior to the expansion of groundwater irrigation, there would be a negligible amount of water extracted from the groundwater system, leaving the percentage of the saturated thickness lost very low, depicted as section 1 in Figure 10. As groundwater irrigation expanded in the 1960's and 1970's, the amount of groundwater utilization increased, leading to a rise in total use as well as the percentage change in saturated thickness. This portion of development would be expected to have the steepest slope of percentage lost, depicted as section 2 in Figure 10. As development of groundwater irrigation wells proceeded, there are only so many acres of irrigated cropland that can have irrigation wells. At this point in time, the wells being drilled would be replacing old wells and better groundwater management techniques would be implemented, so the curve of percentage change in saturated thickness was expected to taper off and potentially reach a new equilibrium, as is depicted in section 3 of Figure 10. The percent of saturated thickness was expected to be slightly static along this curve between years due to varying levels of precipitation, but overall, this was expected to be relatively consistent. Trends as described on the s-curve (figure 10) can be seen more clearly with the 5 year running average graph (Figure 9).

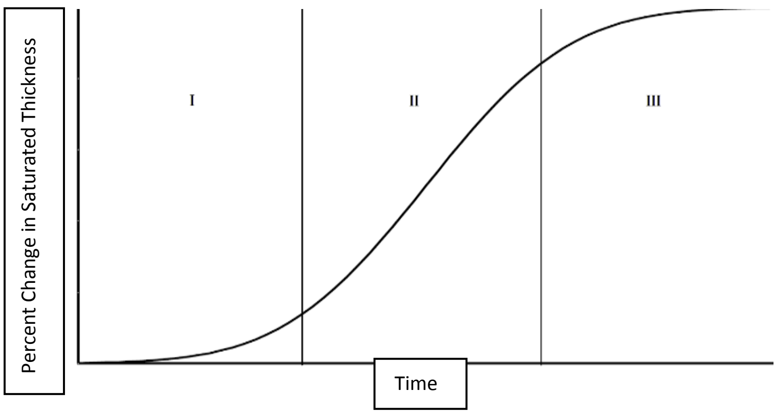


Figure 3 shows an example of an s-curve graph. The first section depicts predevelopment, the second section depicts the period of rapid development, and the third section depicts the predicted trajectory of groundwater level stabilization.

Although the plots in Figure 9 did taper off, it had more variance than initially expected due to responses of precipitation. The water levels response could be impacted by the timing of precipitation. Earlier rains occurring in the cooler spring would have less opportunity to evaporate or be taken up by plants, leading to a larger proportion finding its way into the groundwater system as recharge. In Figures 7, 8, and 9, the change of saturated thickness has an inverse relationship, where a low point on the change of saturated thickness reflects an increase in saturated thickness. In years with low precipitation, such as the early 2000s, groundwater levels had improved over the past ten to fifteen years. After the period of lower than average precipitation, the delayed response of decreasing saturated thickness can be seen just as precipitation starts to reflect its average annual value. This delayed response is due to recharge taking longer to reach the groundwater system than it does to change pumping rates. Pumping rates are a direct response to precipitation levels, where precipitation takes a few years to recharge the groundwater system.

These data presented suggest that the groundwater saturated thickness has reached a new equilibrium. Out of the six wells tested, the new equilibrium ranges from relatively no change to a maximum change of 11.61%. The groundwater is being used for beneficial purposes, such as agricultural production, and there are no substantial losses from the peak change in the 1980s. One of the major issues with groundwater management is determining what is considered a tolerable use of this resource. The difficult question is what is the percent change threshold where total saturated thickness becomes a problem? At what point do more strict management techniques need to be employed?

One potential method of determining this threshold would be to look at flow rates of adjacent streams to the area. Because surface water and groundwater are hydrologically connected, one would affect the other. In future studies it would be interesting to plot adjacent river streamflow, precipitation, and percent change in saturated thickness on a single graph for each individual well.

One of the six wells showed no significant loss in saturated thickness. This well is located in a valley and supplies the city of Hastings, Nebraska with their municipal water supply. The reason that this well in particular does not show any loss is because it is located in a valley. The gradient flow of the groundwater will recharge this area before any major losses can be observed. One factor that can be considered future studies is the location of wells in the groundwater flow system. It could be inferred that wells in lower surface elevation locations will have less fluctuation in saturated thickness.

This case study focuses on a narrow area relative to the HPA as an entire system. Although more well data would have to be analyzed before any major conclusion can be drawn, these data presented in this study suggest that there may be a similar trend across other areas of high agricultural output. This alternative method shows a better representation of the groundwater resources available. Limitations of such studies are finding wells that penetrate to bedrock. Groundwater system type would also have to be taken into consideration. A groundwater system consisting of unconsolidated gravel and sands would have a much faster recharge rate than a system consisting of metamorphic and igneous rock would. Future studies could look at other areas, such as Box Butte County, Nebraska, where saturated thickness shows a constant decrease. Areas like this may have not reached a new equilibrium. Future studies could also portray the percent change in saturated thickness as an inverse to show a direct relationship with precipitation. This would also make the graph easier for the general public to interpret, because a decrease in saturated thickness would be shown as a negative slope. This was not employed in this case study in order to compare results with the initial study.

5. Conclusion

The method employed in this case study, showing groundwater resources in terms of a percent change in saturated thickness as opposed to the traditional method of showing changes in feet gained or lost, gives a better representation of the state of groundwater systems. This method could be a great resource for groundwater managers worried about the results of the traditional method.

If a new equilibrium has been achieved, inputs and outputs of groundwater have remained steady since the early 1980's. This will take a little pressure off of groundwater managers as they continue to maintain a sustainable level of use.

The oscillations that occurred in the percent change in this study area after 1980 are a result of fluctuations in precipitation. More wells would need to be evaluated before a definitive answer on a new equilibrium could be given on the area of study. The trends presented in this case study are too localized relative to the total expanse of the HPA. A study of six wells gives a moderate representation of the area, but a larger concentration of wells located throughout this area would be needed to draw a full conclusion.

Literature Cited

Alley, W.M., T.E. Reilly, O.L. Franke. (1999) "Sustainability of Ground-Water Resources." U.S. Geological Survey Circular 11.86. USGS, Reston, VA.

Chen, Xunhong, James Goeke, Scott Summerside. (1999) "Hydraulic Properties and Uncertainty Analysis for an Unconfined Alluvial Aquifer" Ground Water 37:6:845-854.

Comis, Dan. (2008) "The Ogallala: Guaging, Protecting the Aquifer's Health" Agricultural Research 56:4:4-8.

CSD, Conservation and Survey Division at The University of Nebraska – Lincoln, historical water levels database, accessed online. http://snr.unl.edu/data/water/groundwater/NebGW_Levels.aspx

DNR, Nebraska Department of Natural Resources, Well Registration database, accessed online. http://data.dnr.nebraska.gov/wells/Menu.aspx

Fleming, Adonna, Leslie M. Delserone, Elaine Nowick. (2012) "The Ogallala Aquifer in Nebraska: Gray Literature (1891-2010)" Journal of Agricultural & Food Information 13:213-239.

Foster, T., N. Bronzovic, A.P. Butler. (2015) "Analysis of the Impacts of Well Yield and Groundwater Depth on Irrigated Agriculture." Journal of Hydrology 523:88-96.

Fulton, Allan, Toccoy Dudley, Kelly Staton. (2014) "Groundwater Level Monitoring: What Is It? How Is It Done? Why Do It?" University of California Agriculture & Natural Resources Cooperative Extension.

Heath, Ralph C. (1983) "Basic Ground-Water Hydrology" U.S. Geological Survey Water-Supply Paper 2220. 86 p.

Hobza, C.M., S.S. Sibray. (2014) "Hydrostatigraphic Interpretation of Test-Hole and Borehole Geophysical Data, Kimball, Cheyenne, and Deuel Counties, Nebraska, 2011-2012." U.S. Geological Survey Open-File Report 2014-1103. 45 p.

Hoffman Babbitt, Christina, Mark Burbach, Lisa Pennisi. (2015). "A Mixed-Methods Approach to Assessing Success in Transitioning Water Management Institutions: A Case Study of the Platte River Basin, Nebraska" Ecology and Society 20:1:785-795.

Korus, J.T., M.T. Burbach (2009) "Analysis of Aquifer Depletion criteria with implications for Groundwater Management." Great Plains Research 19:187-200.

Piggot, Andrew R., A. Ghosh Bobba, Kent S. Novakowski. (1996) "Regression and Inverse Analyses in Regional Ground-Water Monitoring" Journal of Water Resources Planning & Management 122:1:1-10.

Shiklomanov, Igor. (1993) "World fresh water resources" Water in Crisis: A Guide to the World's Fresh Water Resources. Oxford University Press, New York.

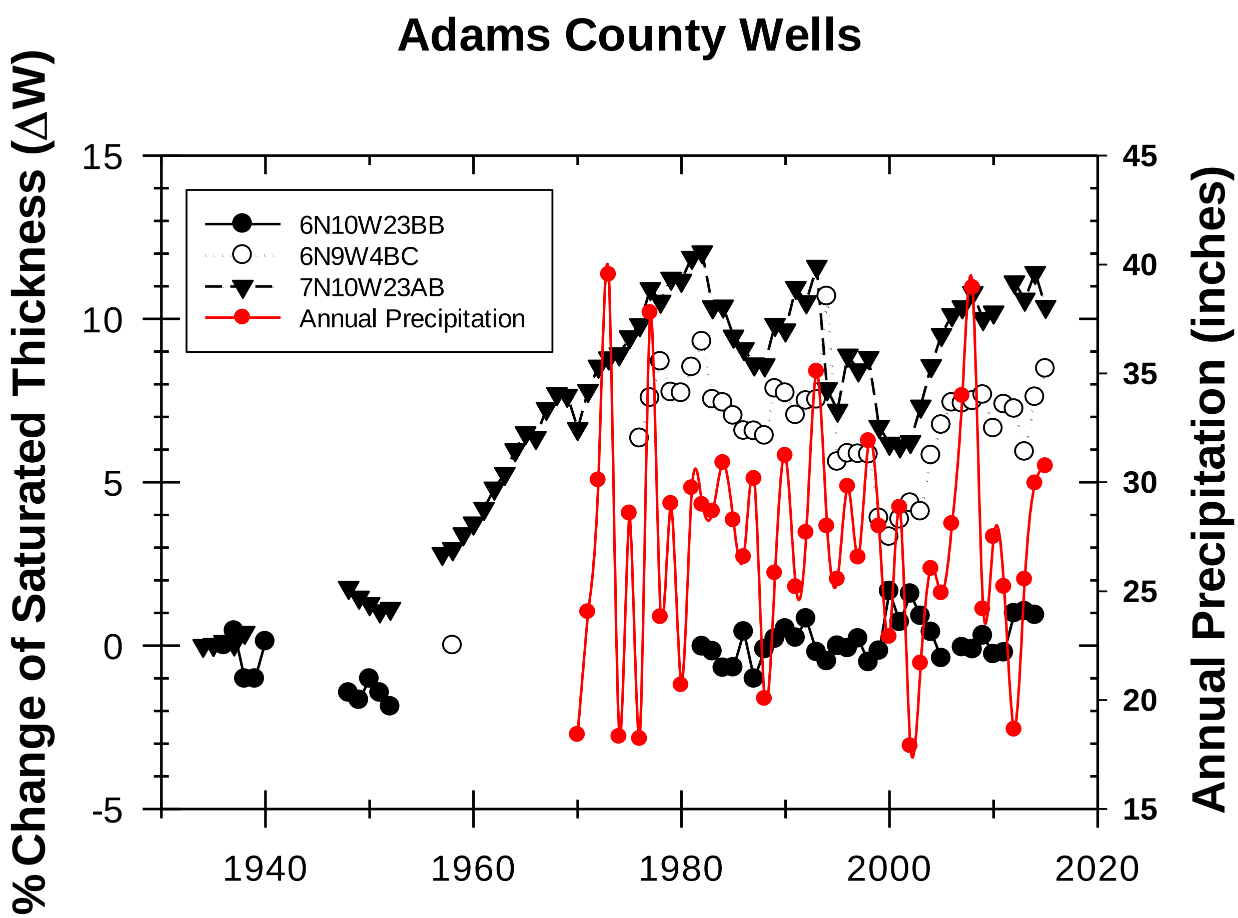
Stephenson, Kurt. (1996) “Groundwater Management in Nebraska: Governing the Commons Through Local Resource Districts” Natural Resources Journal 36:761-778.

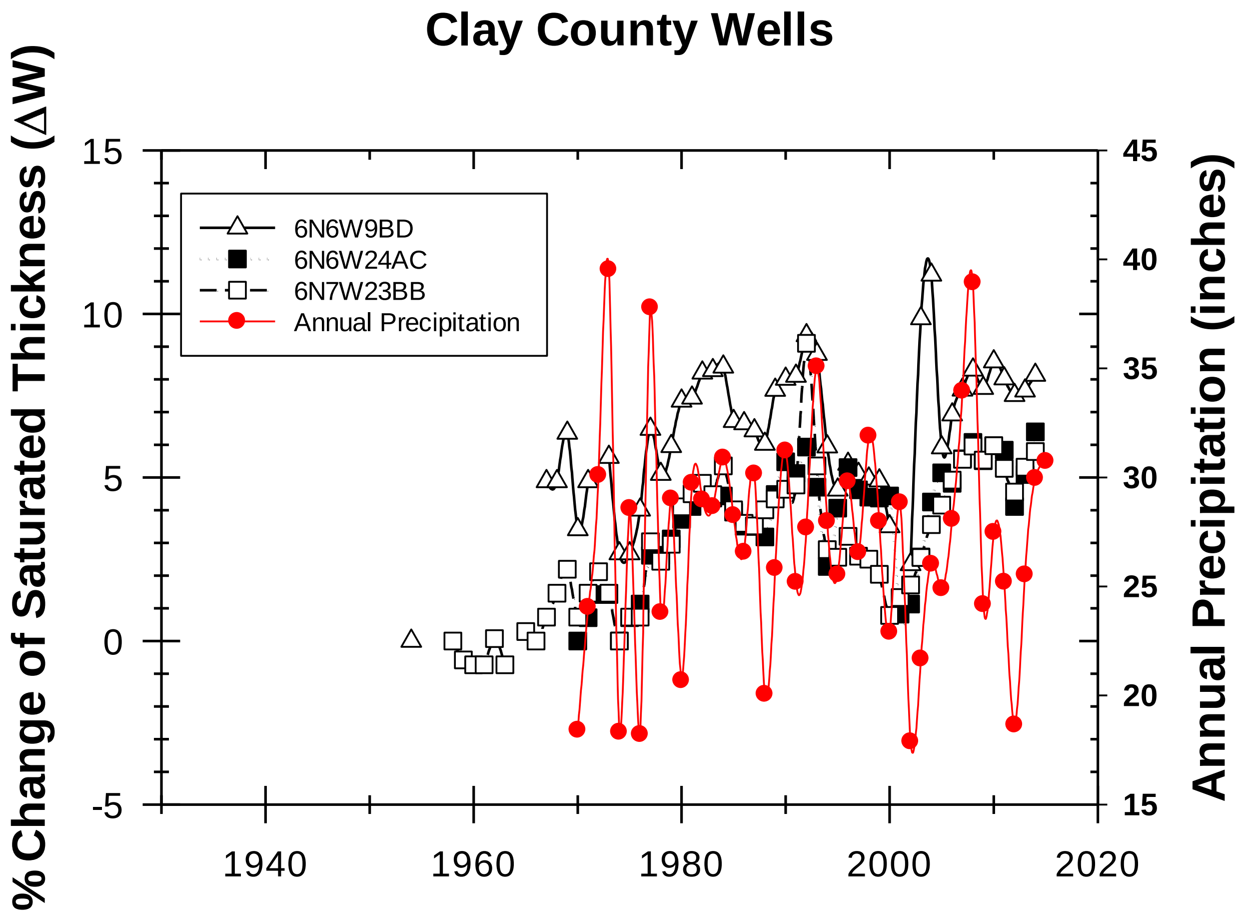
Szilagyi, Jozsef, Janos Jozsa. (2012) “MODIS-Aided State Wide Net Groundwater-Recharge Estimations in Nebraska” Groundwater 51:5:735-744.

UNL Water Team (2016) “Regulations & Policies” accessed online. http://water.unl.edu/cropswater/regulations

Appendix

Full sized graphs




Clay County Wells
% Change of Saturated Thickness (ΔW)
Annual Precipitation (inches)
6N6W9BD
6N6W24AC
6N7W23BB
Annual Precipitation
15
10
5
0
-5
45
40
35
30
25
20
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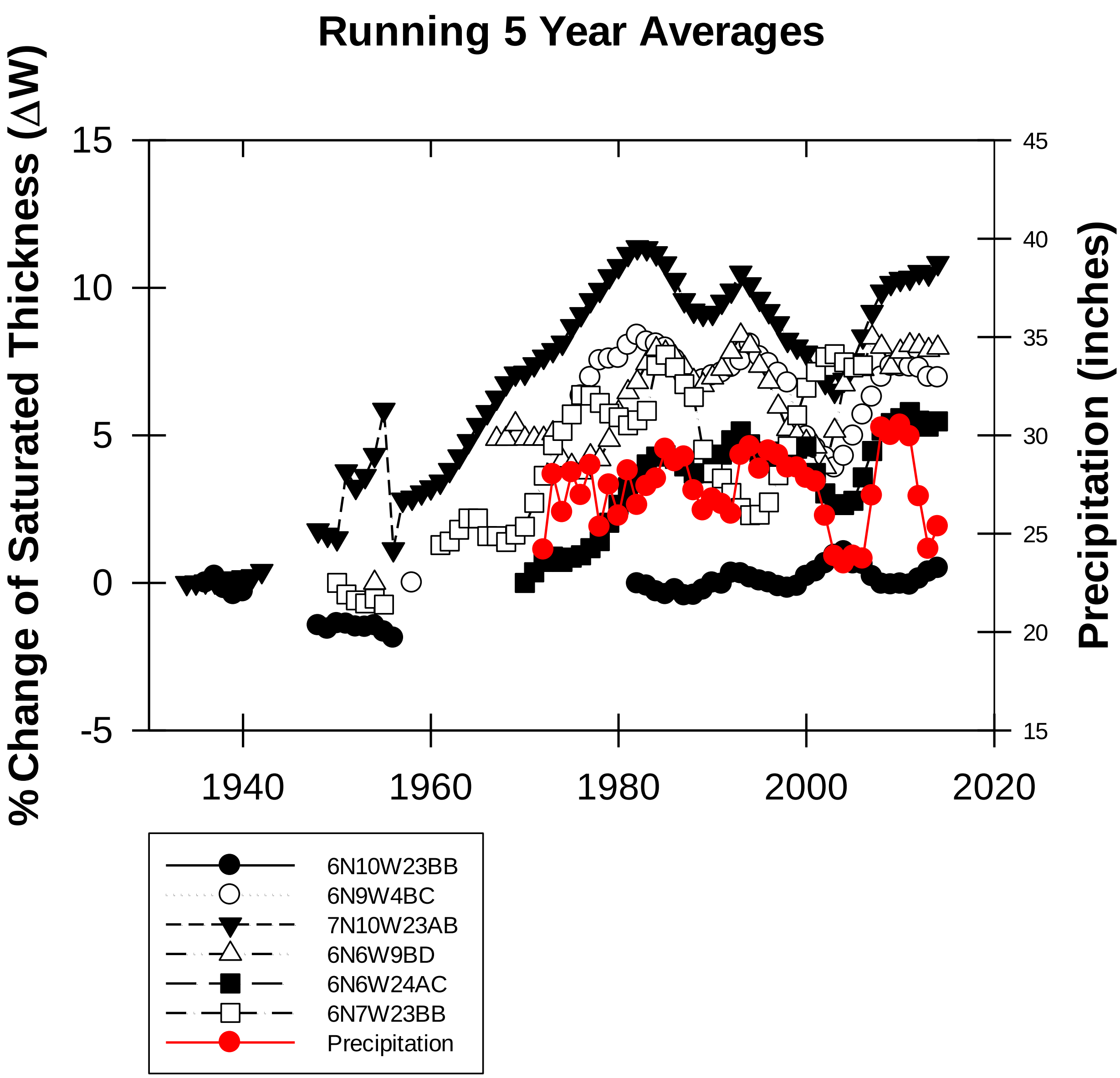
1940
1960
1980
2000
2020


Running 5 Year Averages
% Change of Saturated Thickness (ΔW)
Precipitation (inches)
15
10
5
0
-5
1940
1960
1980
2000
2020
45
40
35
30
25
20
15
6N10W23BB
6N9W4BC
7N10W23AB
6N6W9BD
6N6W24AC
6N7W23BB
Precipitation