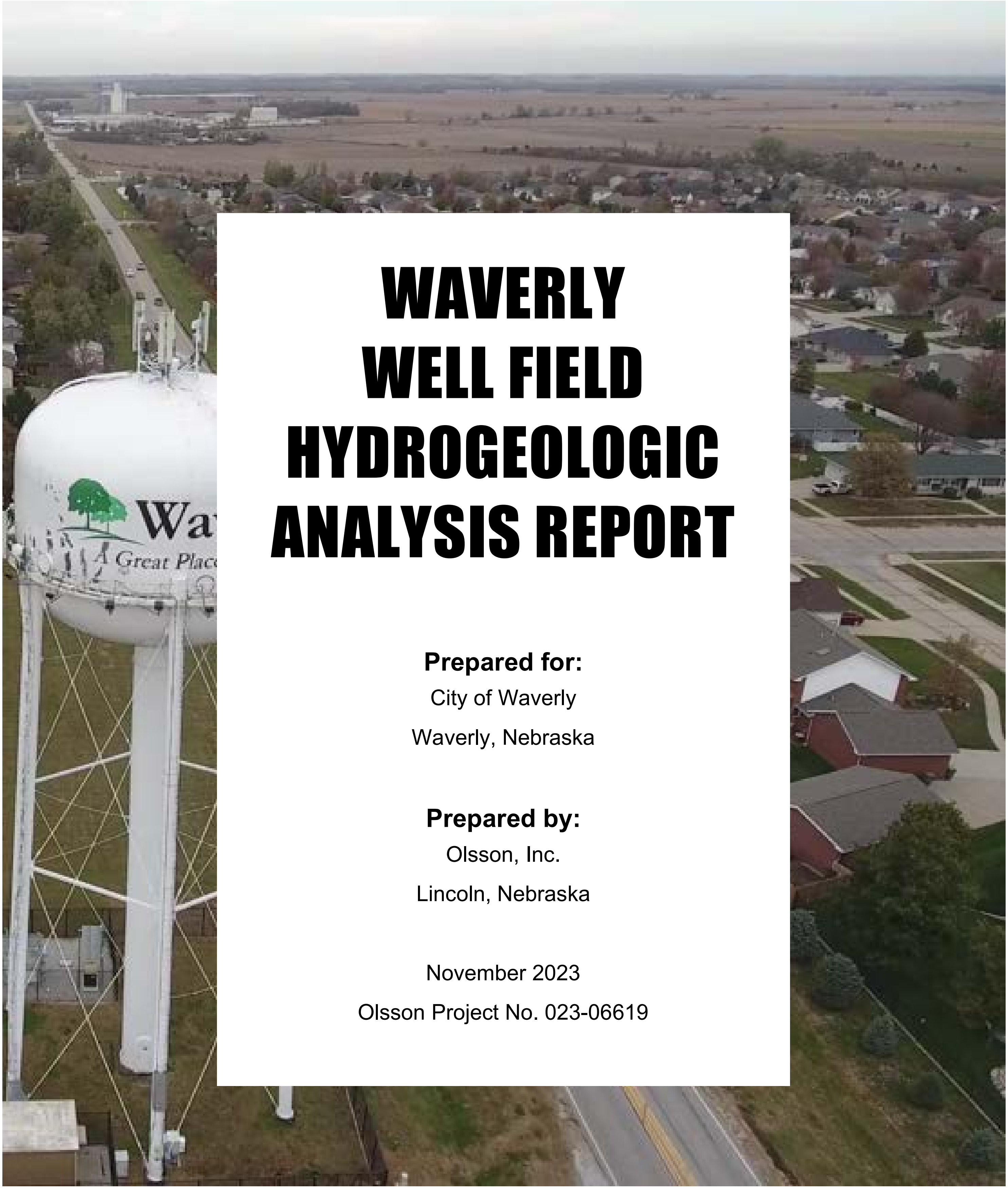

WAVERLY WELL FIELD HYDROGEOLOGIC ANALYSIS REPORT

Prepared for:

City of Waverly

Waverly, Nebraska

Prepared by:

Olsson, Inc.

Lincoln, Nebraska

November 2023

Olsson Project No. 023-06619

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SUMMARY

The City of Waverly (Waverly) has experienced recent water level declines in their municipal wellfield. With the expected increase in demand as the city's population expands, Waverly is looking to ensure that it can provide adequate water supply from its municipal wells to meet the projected water demand as well as mitigate any negative impacts that a lowering water table may have on the municipal water supply. This hydrogeologic analysis shows that the water level declines seen at the Waverly municipal wells is also seen in long-term monitoring wells in the immediate vicinity. It is the Olsson team's opinion that there are actions Waverly can take to maintain the water supply necessary for current and future water supply demands, mitigate the effects that a lowering water table may have on the current municipal well infrastructure, and to better schedule municipal well extraction to prevent pumping water levels from exceeding the shutoff water levels described in the Waverly Water Distribution Study (Olsson, 2023).

Groundwater levels recorded by the United States Geologic Survey mirror the water level declines that have been observed in the Waverly municipal wells in the past 5 to 7 years. This indicates that the water level declines are not solely attributable to the increase in municipal and industrial water demands from Waverly. Five of the seven currently active municipal wells are screened in the Dakota aquifer which is a semiconfined aquifer system, meaning that recharge to the aquifer system is affected by long-term trends in precipitation over many years as opposed to reflecting immediate responses to precipitation events. This implies that it will take several years of increased precipitation to alleviate the decline in water levels seen around Waverly. Additionally, a semiconfined aquifer leads to large levels of drawdown between the static and pumping water levels, which poses an issue to wells constructed with high water level shutoffs from a pump set closer to the surface. The Lower Platte Missouri Tributaries model was used to identify the modeled municipal and industrial water use of Waverly and project that use to increase by 2.5% into the future. The results of this modeling effort also point towards water level declines using what the Olsson team considered to be a representative climatic cycle of wet, normal, and years.

Olsson recommends that Waverly consider the three following actions to mitigate and manage water level declines with the projected increase in demand. The first being the development of a subregional groundwater model that would more accurately represent the hydrogeologic setting of the Waverly wellfield and would be a calibrated tool that Waverly could use to analyze the impacts of wells placed in various locations and alterations to the pumping regime on an actionable temporal and spatial scale. The second recommendation would be to redrill and reconstruct some municipal wells in the area to have shorter screens with pumps set lower in the well and pumping at a lower rate to prevent the pumping water level from reaching the shutoff water levels. And lastly, for Waverly to explore the possibility of drilling new municipal

wells with these same recommendations near Wells 7 and 9, to the east of Waverly towards Camp Creek, and lastly, to the south of Waverly's Wellhead Protection Area. Any combination of these three recommendations would make the Waverly wellfield more resilient to both regional water level declines and an increase in water supply demand.

1. INTRODUCTION

The hydrogeologic analysis described in this report was completed by Olsson under contract with the City of Waverly, Nebraska. This document was prepared solely for the City of Waverly, Nebraska in accordance with the contract between the City of Waverly, Nebraska and Olsson dated October 6th, 2023. This document is only intended to be relied upon by the City of Waverly, Nebraska personnel that will use this analysis for consideration when estimating the longevity of the local groundwater system. All data, drawings, documents, or information contained in this report have been prepared exclusively for the City of Waverly, Nebraska and may not be relied upon by any other person or entity without the prior written consent by the City of Waverly, Nebraska .

This report was initiated to assess and report on the hydrogeological resource in the region of the existing well field. Therefore, the primary objectives of this hydrogeologic analysis are to assess the groundwater resources in the area, the usage, the historic and future water levels, and use the Lower Platte Missouri Tributaries groundwater model to estimate future trends. This hydrogeologic analysis report will cover existing data on the hydrogeologic resource of the area, briefly explain the groundwater modeling process used for this report and present the results of that modeling effort.

2. HYDROGEOLOGIC REVIEW

To understand the hydrogeologic setting affecting the Waverly municipal wells, Olsson defined an area encapsulating Waverly's municipal wells and its surroundings, this area will henceforth be termed the study area. Olsson analyzed historic water level data and saturated thickness trends from the Lower Platte Missouri Triubutaries (LPMT) regional groundwater model in the primary hydrogeologic unit of the area, the High Plains Aquifer, to assess the hydrogeologic resource throughout the project area. Historical water level data from the United States Geological Survey (USGS) was gathered for nearby wells and was analyzed for information on historic trends of the hydrogeologic resource in the study area. Additional information on the current and future demand of the hydrogeologic resources in the area were provided by a previous Water Study for the City of Waverly from 2023 (Olsson, 2023).

2.1 Hydrogeologic Setting

The study area for this hydrogeologic assessment is located in southeastern Nebraska near the western edge of Lancaster County, centered around the Waverly municipal wells. The study area extends approximately 4 miles to the north and east, 6.5 miles to the south, and 5 miles to the west of Waverly. The study area is presented in blue in **Figure 2**. The study area contains both rolling hills and the Salt Creek stream valley (Korus et al., 2013) The elevation within the study area varies from 1,381 feet above sea level in the hills and down to 1,066 feet above sea level in the Salt Creek valley, see **Figure 3**.

There have been 11 municipal wells for Waverly, although only seven are currently active, these are described in **Table 1**. The study area is underlain by three different bedrock geologies, see **Figure 4**. The Shawnee and Wabunsee Formations underlay the alluvial deposits of the Salt Creek stream valley where Wells 4 & 5 are located, wells 4 & 5 are not screened in these bedrock formations, rather they are extracting water from the shallower alluvial deposits of the Quaternary Period (see **Figure 4**). Five of the seven Waverly municipal wells are underlain by the Dakota Group of the Cretaceous Period as the primary source of water for Waverly as shown in **Figure 4**. The Dakota Group, or Dakota aquifer, is a bedrock aquifer, differing from the alluvial deposits of the Salt Creek valley, in that the recharge of the Dakota aquifer is less directly affected by precipitation and surface water interactions as the alluvial deposits of the Salt Creek valley (Divine & Sibray, 2017). The Dakota Group consists of sandstones which have water bearing properties making them useful for extraction but are not as transmissive as the unconsolidated Quaternary deposits located farther east of Waverly (Divine & Sibray, 2017). Additionally, the Dakota aquifer varies between being an unconfined to a semiconfined aquifer system being partially confined by shale layers, which are generally considered to be aquitards (Divine & Sibray, 2017). In the well diagram figures (see **Appendix A**), shale layers can be seen above and throughout the screened intervals of Wells 8, 9, 10, and 11, which may be affect recharge timing and overall rates at these locations. Aquifer recharge rates in the Dakota aquifer varies spatially across its extent, with some parts of the aquifer being more or less confined by layers of shale and siltstones while other parts of the aquifer are more exposed to recharge from precipitation. The assumed recharge of the Dakota aquifer in the study area is not immediately supported by precipitation events as an unconsolidated and unconfined aquifer, rather the recharge in the study area is representative of longer term precipitation patterns over multiple years rather than monthly precipitation patterns. The annual precipitation for weather station Waverly 0.4 W, NE as reported by the High Plains Regional Climate Center (2023) is presented in **Figure 1**.

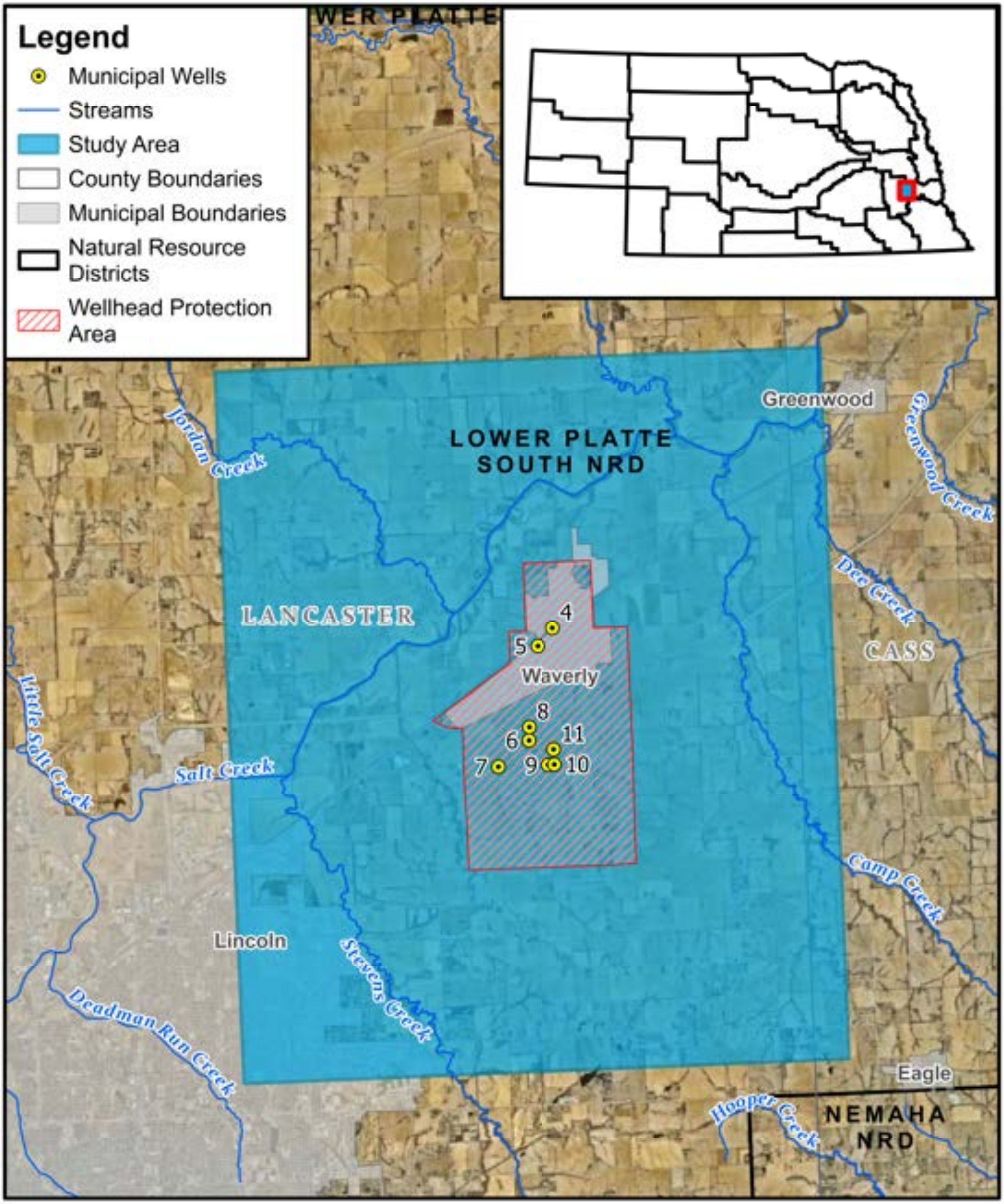
Table 1. Description of Waverly municipal wells and screened aquifer.

NDNR Well Registration Number	Colloquial Well Number	Well Depth (ft)	Aquifer Material
G-068617	4	59	Unconsolidated Quaternary alluvial deposits
G-070134	5	57	Unconsolidated Quaternary alluvial deposits
G-070533	6	172	Dakota aquifer
G-070534	7*	155	Dakota aquifer
G-114724	8	182	Dakota aquifer
G-136114	9	192	Dakota aquifer
G-175276	10	180	Dakota aquifer
G-175275	11	179	Dakota aquifer
**Well 7 is currently inactive but planned to be reconstructed within the next year.*			

Figure 1. Annual precipitation for Waverly 0.4 W, NE station (HPRCC, 2023).

While some information can be gleaned from the regional LPMT model regarding the hydrogeologic setting in the area, the cell size of a regional model is not calibrated with the intent to accurately reflect the hydrogeology of an area as small as the study area of this assessment. To further the understanding of the hydrogeologic setting, this hydrogeologic assessment employed both the NDNR Registered Well Database and coupled it with aerial electromagnetic (AEM) data gathered by the Lower Platte South NRD (LPSNRD) and the Eastern Nebraska Water Resources Assessment (ENWRA). The NDNR Registered Well Database provides the borehole logs for every registered well in the state, excluding municipal wells for public safety concerns. The borehole logs and well construction information were passed to Olsson by Waverly, and these logs were also added to the borehole and AEM comparisons. The boreholes give insight into the geologic stratification at a single point, being able to capture abrupt changes in geology vertically. A limitation of the NDNR borehole logs is that they cannot provide insight into the geology of an area that does not already have a registered well. AEM data provides measurements of resistivity to depths up to and sometimes exceeding 1,000 feet across very large areas. AEM provides data that is less vertically refined compared to the NDNR borehole logs as AEM data cannot accurately register the abrupt changes in geologic strata, although AEM data provides nearly continuous data across large areas, which allow for the assessment of lateral trends in geology. The relationship between resistivity and lithology is nonunique, nonlinear, and nonuniversal, making it difficult to explicitly identify specific lithologic targets using solely AEM data. Without the other, both the NDNR borehole logs and the AEM data are useful but have limitations to their applicability. Although, when used together, AEM data and NDNR borehole logs can provide insight into the water bearing properties of areas where there are not registered wells by comparing the relative resistivity values where borehole logs indicate good aquifer bearing materials to places where borehole logs are not available. Figures of the paired NDNR borehole logs and the AEM data from four separate surveys are presented in **Appendix B**. These figures depict cross-sectional AEM data plotted from the beginning of the flight line, following the flight path, with any NDNR registered well within 750 feet of the flightpath being plotted on the chart at the bottom of the figure. The NDNR registered wells are plotted using a translation table that converts the geologic descriptions transcribed by the well driller to a rating of 1 through 5, 1 being poor aquifer material, i.e. not very conductive nor transmissive such as layers of shale, and 5 being better aquifer material i.e. very conductive and transmissive materials such as unconsolidated Quaternary sand and gravel deposits. The interpretation of AEM data is inconsistent among existing surveys of the area, but generally decent to good aquifer material translates to resistivity values between 20 to greater than 55 ohm-meters (Ω-m).

A synthesis of the available hydrogeologic data shows that the Waverly area has significant lateral variability, resulting in clear differences in NDNR borehole logs from wells that are located near to one another. This hydrogeologic variability is not captured in the discretization of the LPMT regional groundwater model as will be expanded upon in **Section 3** of this assessment.



olsson

STUDY AREA LOCATION

HYDROGEOLOGIC ASSESSMENT
WAVERLY, NE

FIGURE 2

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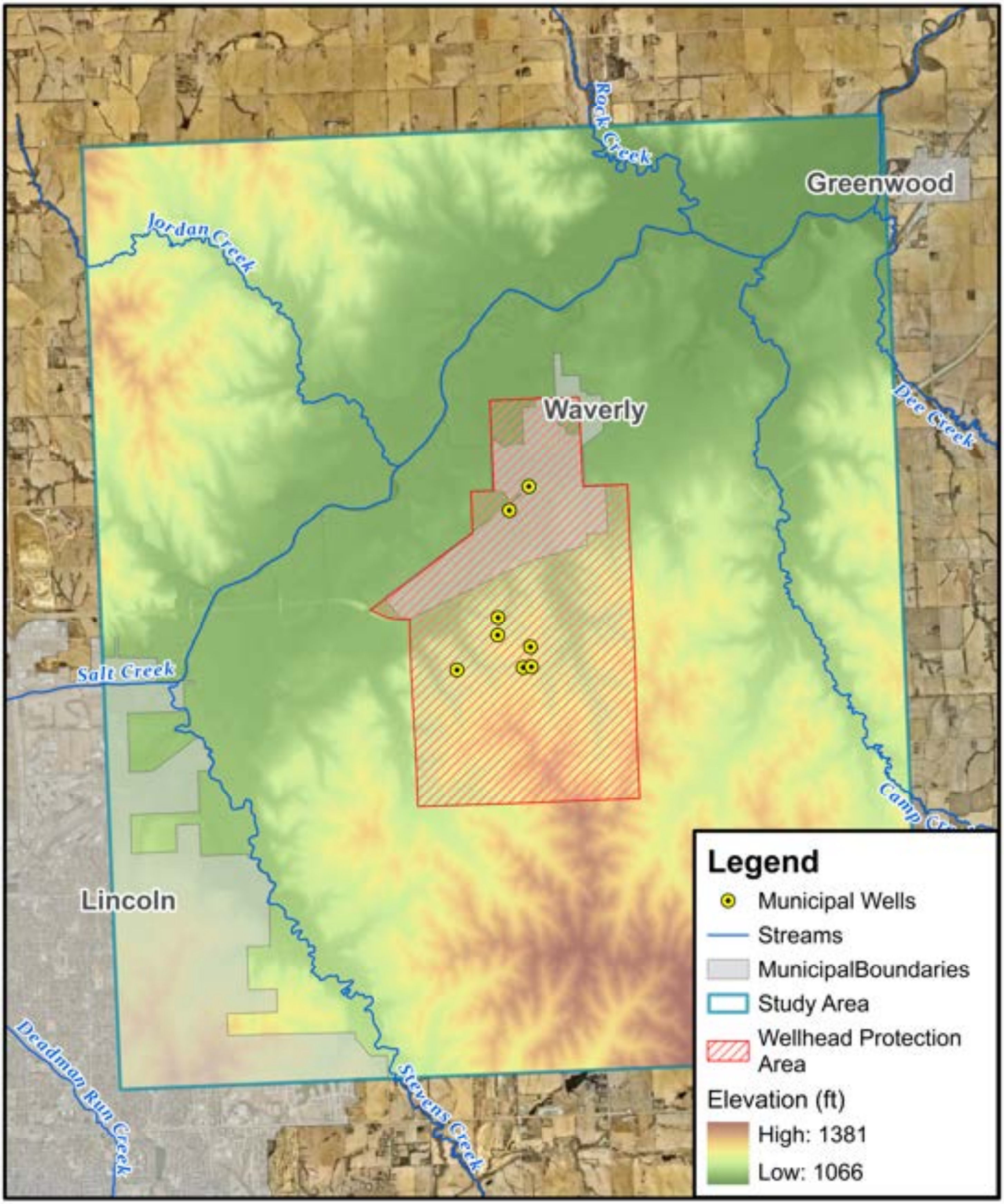

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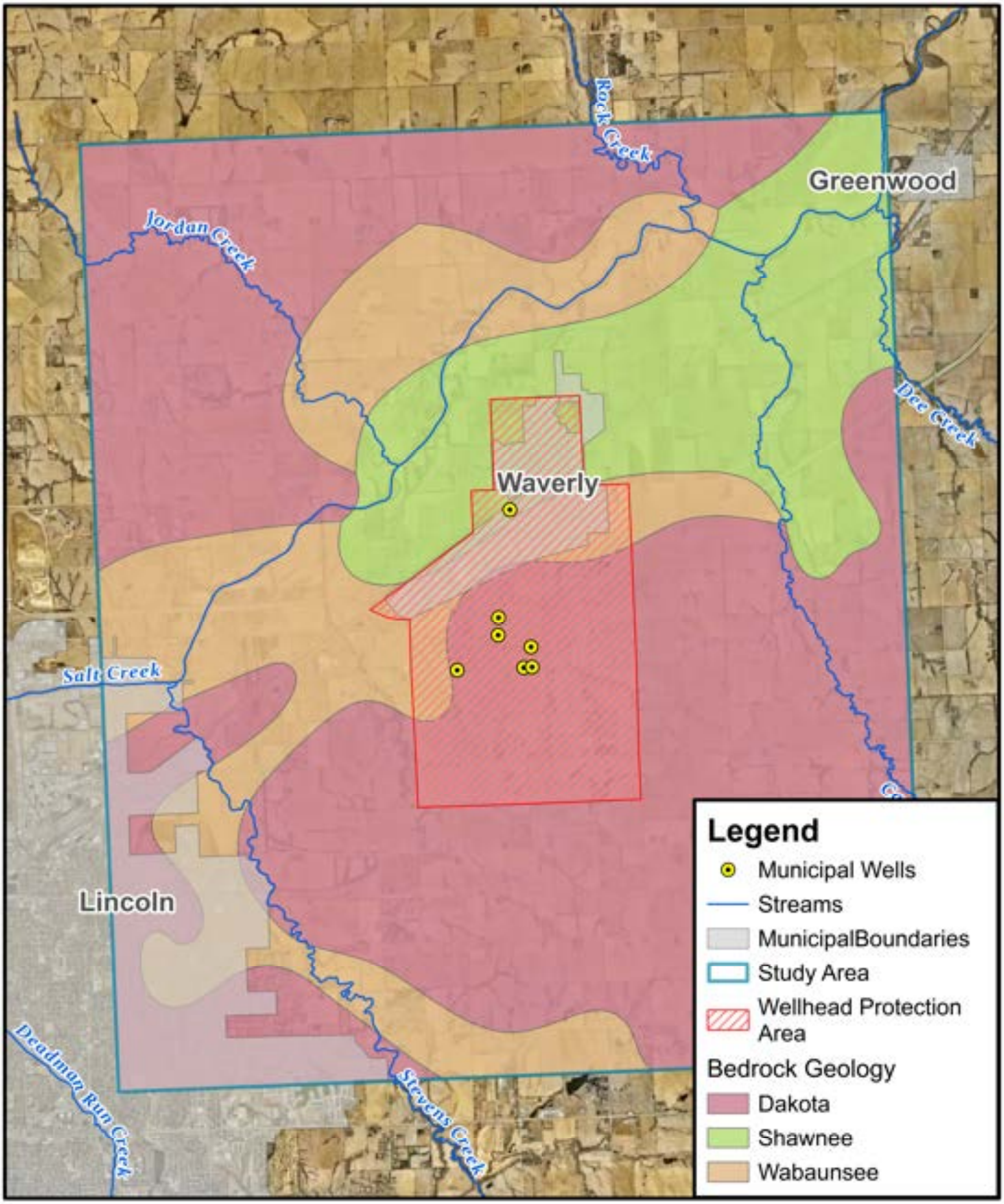
1 INCH = 1.5 MILES
NAD 1983 StatePlane Nebraska FIPS 2600 Feet

TOPOGRAPHY

HYDROGEOLOGIC ASSESSMENT
WAVERLY, NE

FIGURE

3



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1 INCH = 1.5 MILES
NAD 1983 StatePlane Nebraska FIPS 2600 Feet

BEDROCK GEOLOGY

HYDROGEOLOGIC ASSESSMENT
WAVERLY, NE

FIGURE 4

2.2 Municipal Water Extraction

As mentioned previously, Waverly currently has seven active municipal wells which supply a growing population of 4,532 people and is expected to reach 6,734 people by 2043 (Olsson, 2023). Waverly has an average quantity of water distributed of 591,265 gallons per day (gpd) with this quantity expected to increase with the increase in population (Olsson 2023). **Figure 5** displays the gallons pumped per month by Waverly's municipal wells over the previous 5 years (Olsson, 2023). The modeled extraction of Waverly's municipal wells is discussed in greater detail in **Section 3** of this assessment.

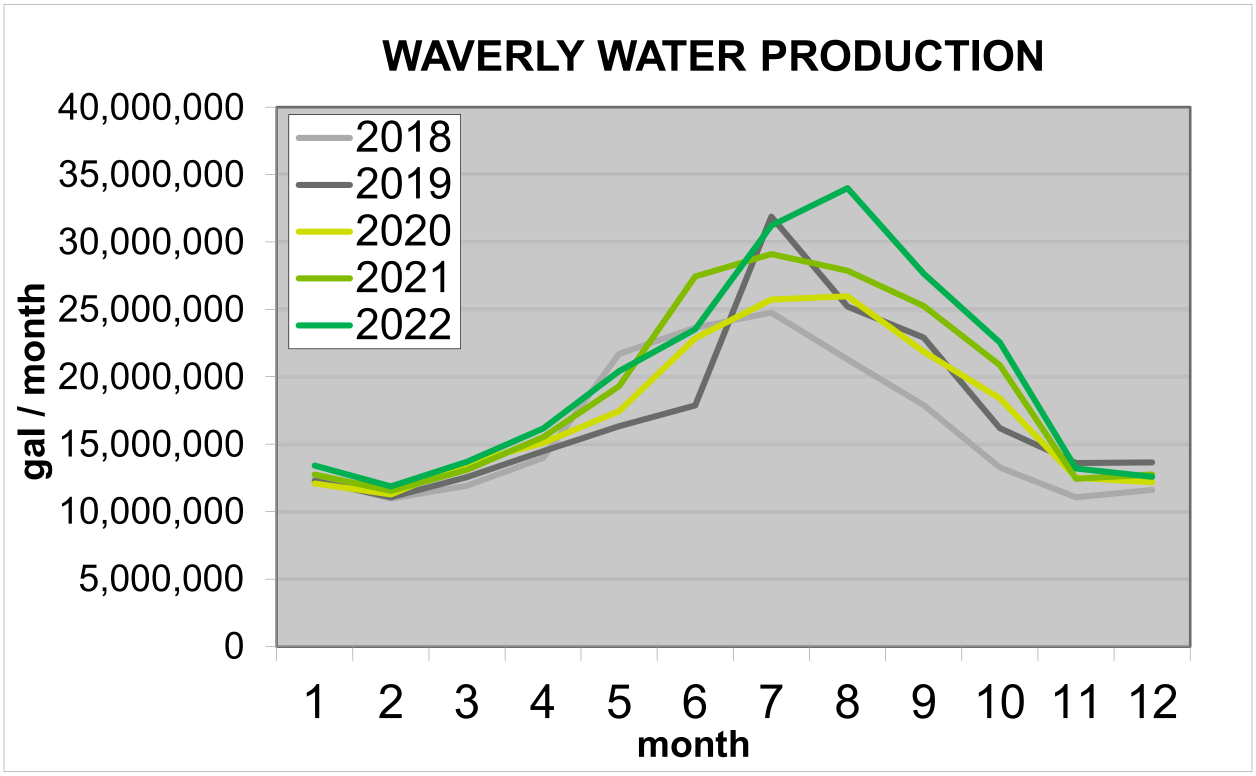
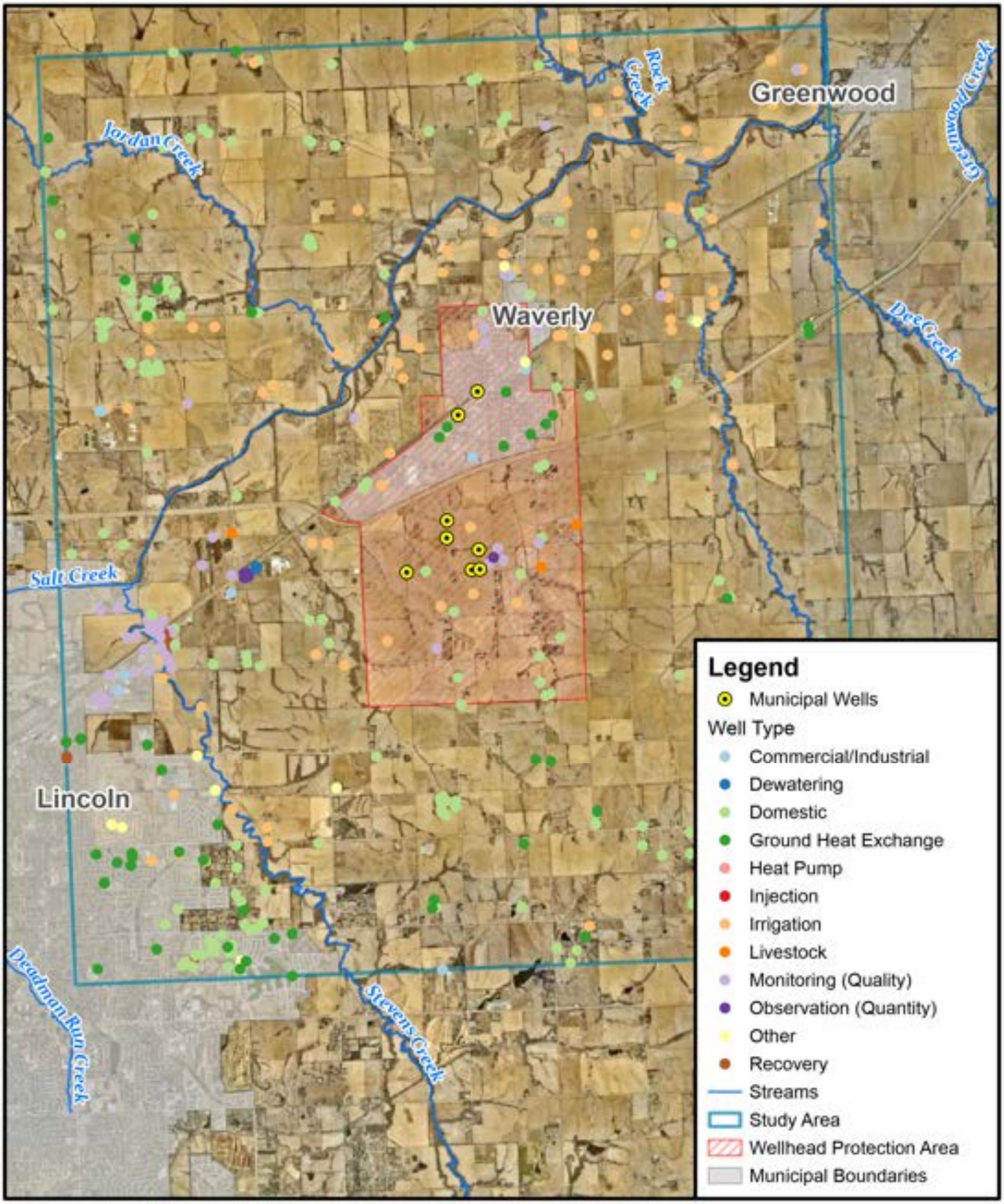


Figure 5. Monthly water production from Waverly's municipal wells from 2018 to 2023 (Olsson, 2023).

Municipal well production is not the only source of extraction in the study area, there are 495 other active wells in the study area, see **Figure 6**. Of the 495 active wells in the study area, there are 80 irrigation wells, 199 domestic wells, and 9 industrial wells (**Figure 6**).



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REGISTERED WELL LOCATIONS

HYDROGEOLOGIC ASSESSMENT
WAVERLY, NE

FIGURE

6

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2.3 Historical Water Level Data

Water level data for the Waverly municipal wells was passed to Olsson from Waverly, these measurements included both static water levels and pumping water levels for all of the active wells including the recently inactive Well 7. The 2023 Water Study also provided the shutoff water level for each of these wells, the point at which the well can no longer be active as the water level will be too low for the pump to extract water (Olsson, 2023). The pumping water level and the shutoff level for each of the wells are presented in **Figure 7**. If the pumping water level reaches the shutoff level, that well will need to be designated as inactive to preserve the pump in that well. **Figure 8** is similar to the previous figure, but it has the addition of the static water level for each of Waverly's municipal wells. In all of the wells besides Well 7, which has been inactive since 2021, there are recent declines in both the static and pumping water levels beginning in the late 2010s. Furthermore, the trend downwards are reflected in the most recent 2023 water level measurements. The large amounts of drawdown between the static and pumping water levels seen in **Figure 8** at Wells 6, through 12 are attributable to the semiconfined properties of the Dakota aquifer these wells are screened within. Wells 4 and 5 have much smaller differences between the static and pumping water levels because they are screened within the unconsolidated, unconfined Quaternary alluvial deposits.

Olsson gathered water level data from observation wells operated by the USGS at fourteen locations near Waverly, seen in **Figure 9**. These fourteen locations provide yearly data from the 1980s to present, with some wells being sampled seasonally. Water levels at all fourteen locations have fluctuated seasonally and annually, with current water levels similar to those observed in the 1980s, as seen in **Figure 10**. Recent water level declines can be seen at all fourteen locations since fall of 2016. These declines are emphasized in **Figure 11**, which displays the depth to water below ground surface (bgs) for all fourteen USGS monitoring locations near Waverly from 2012 to present. The water level declines seen in the USGS monitoring well locations surround Waverly are also reflected in the water level measurements of the Waverly municipal wells provided to Olsson.

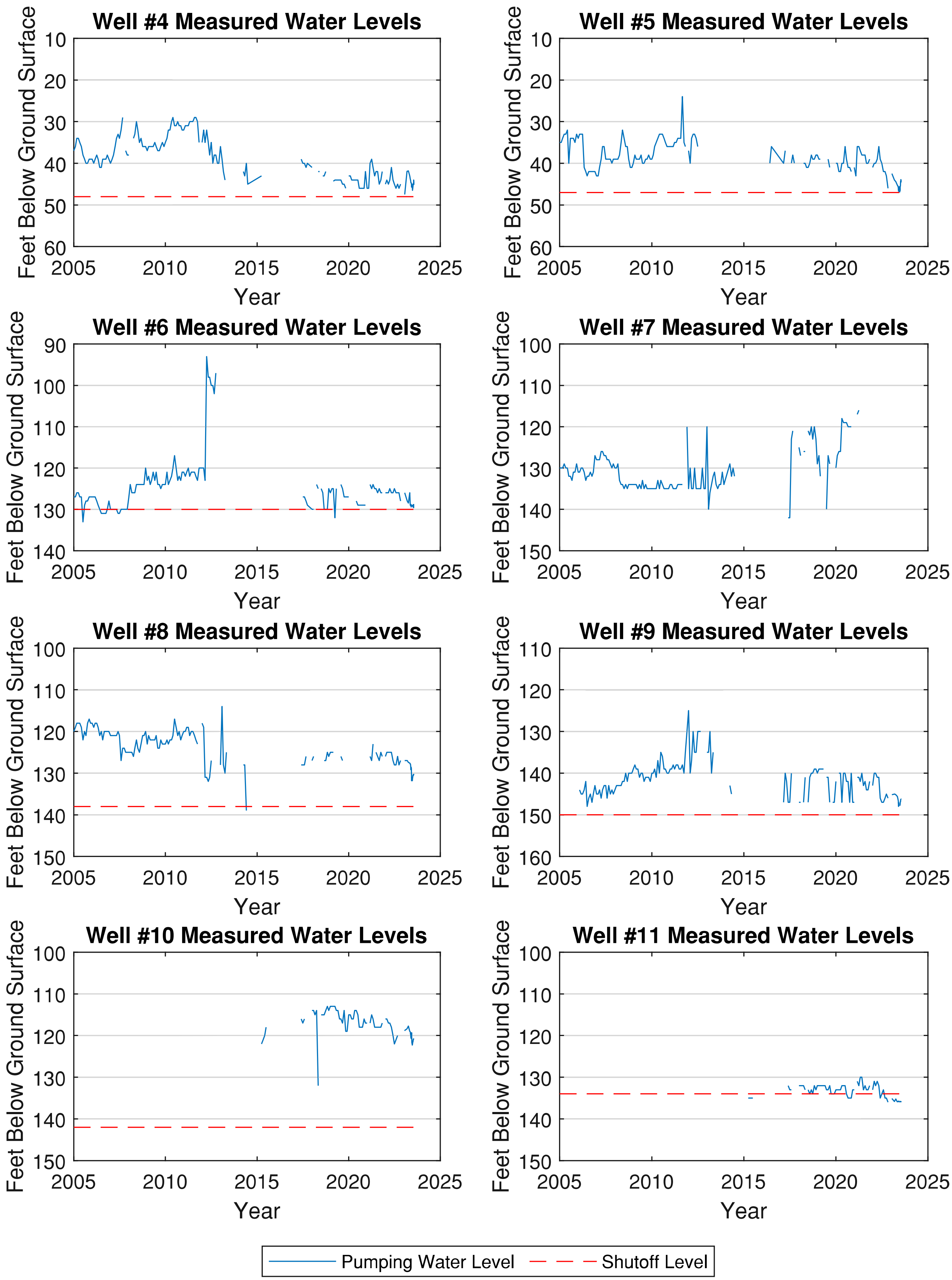


Figure 7. Waverly municipal wells pumping and shutoff water levels.

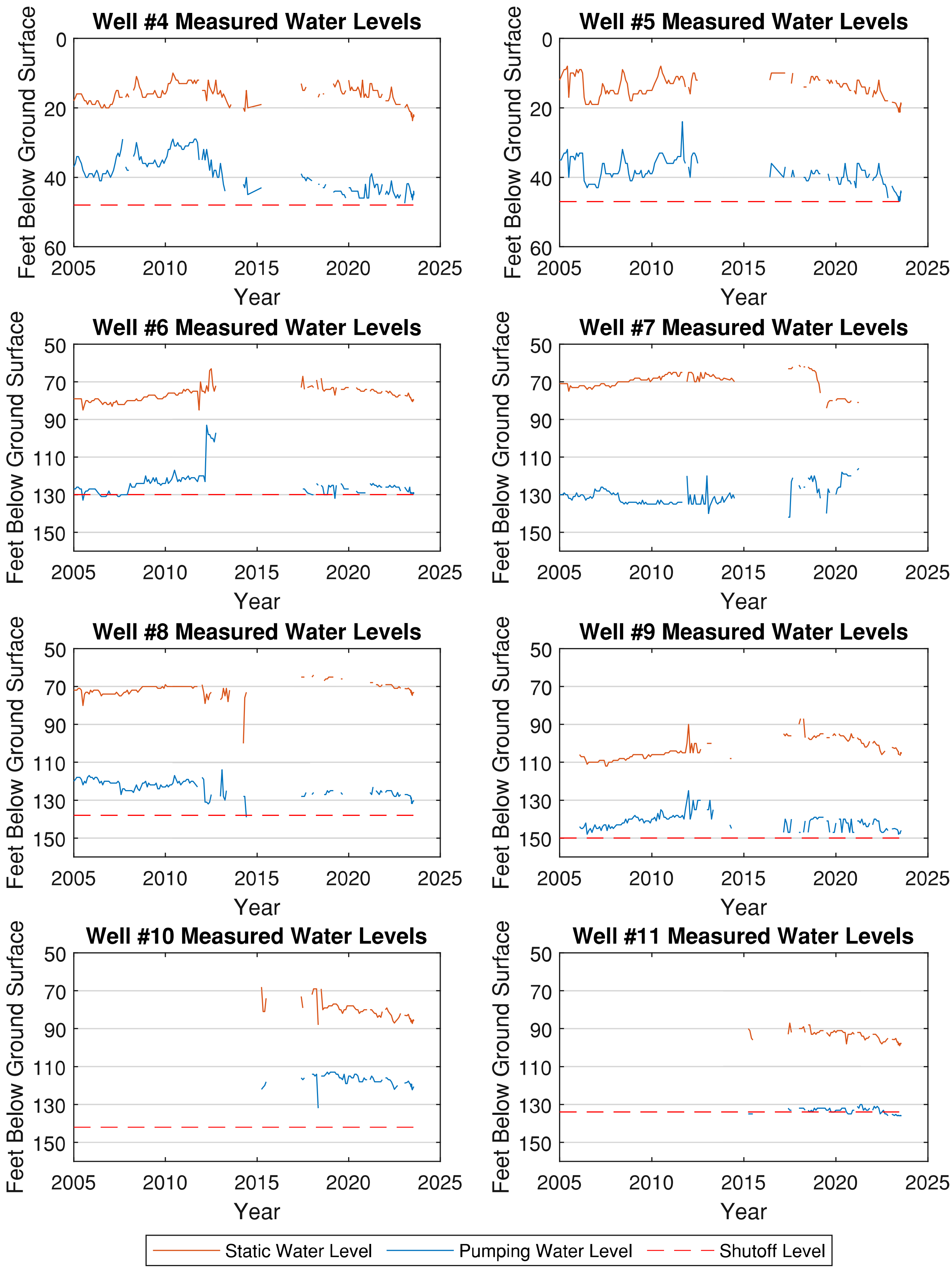
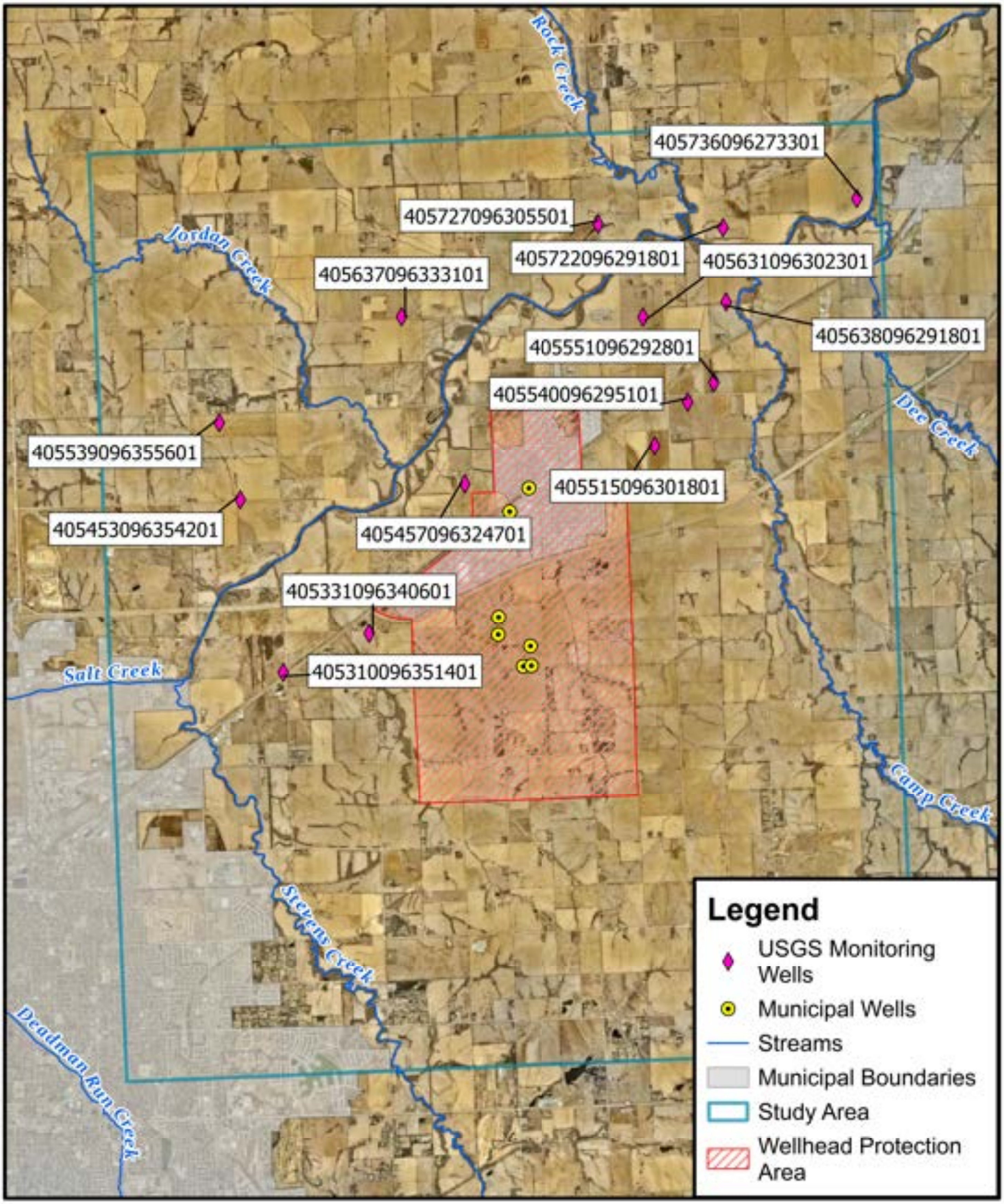


Figure 8. Waverly municipal wells static, pumping, and shutoff water levels.



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olsson

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1 INCH = 1.5 MILES

NAD 1983 StatePlane Nebraska FIPS 2600 Feet

USGS MONITORING WELL LOCATIONS
HYDROGEOLOGIC ASSESSMENT
WAVERLY, NE

FIGURE
9

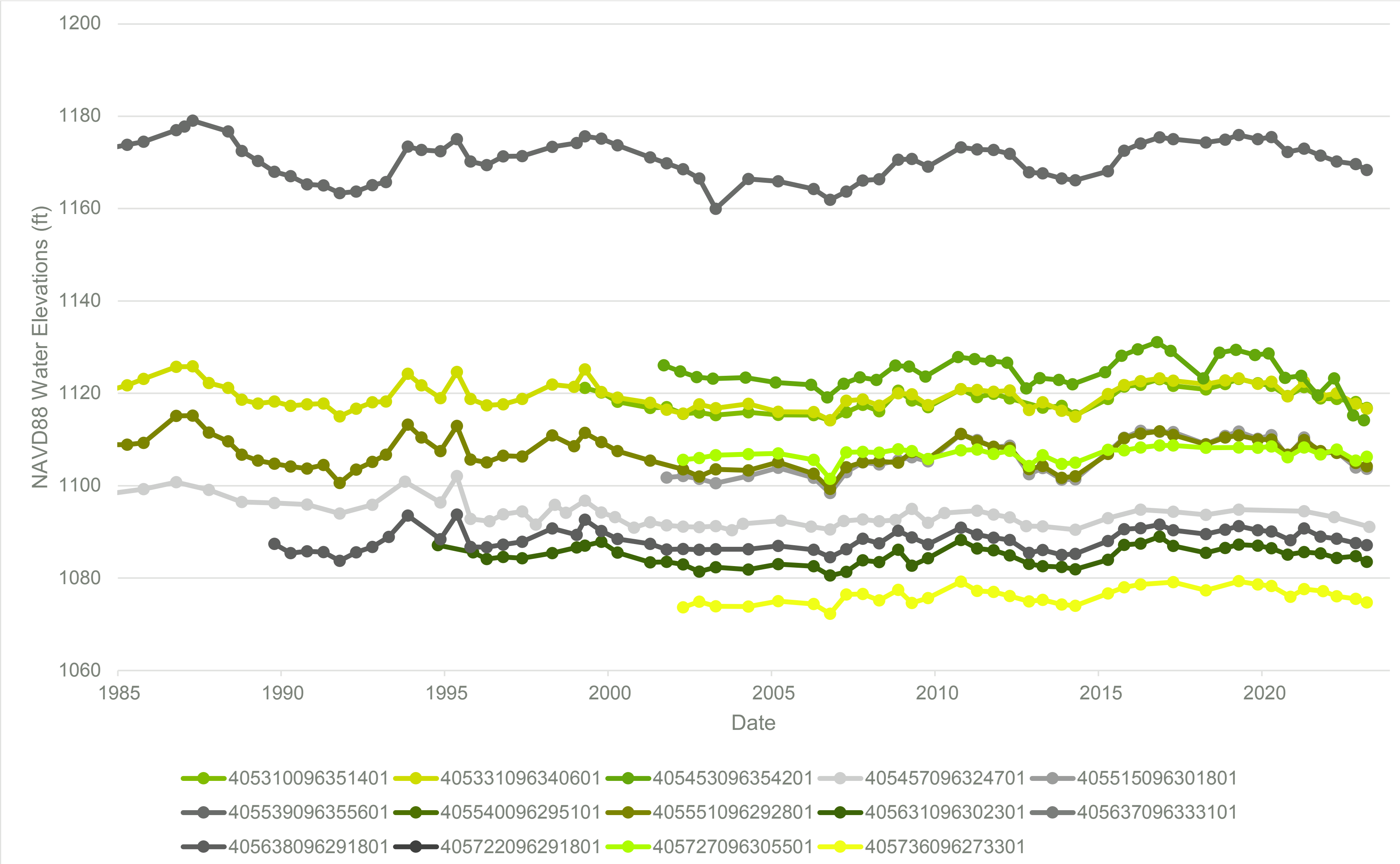

Figure 10. Water level elevations above NAVD88 for nearby USGS monitoring wells from 1985 to 2023.

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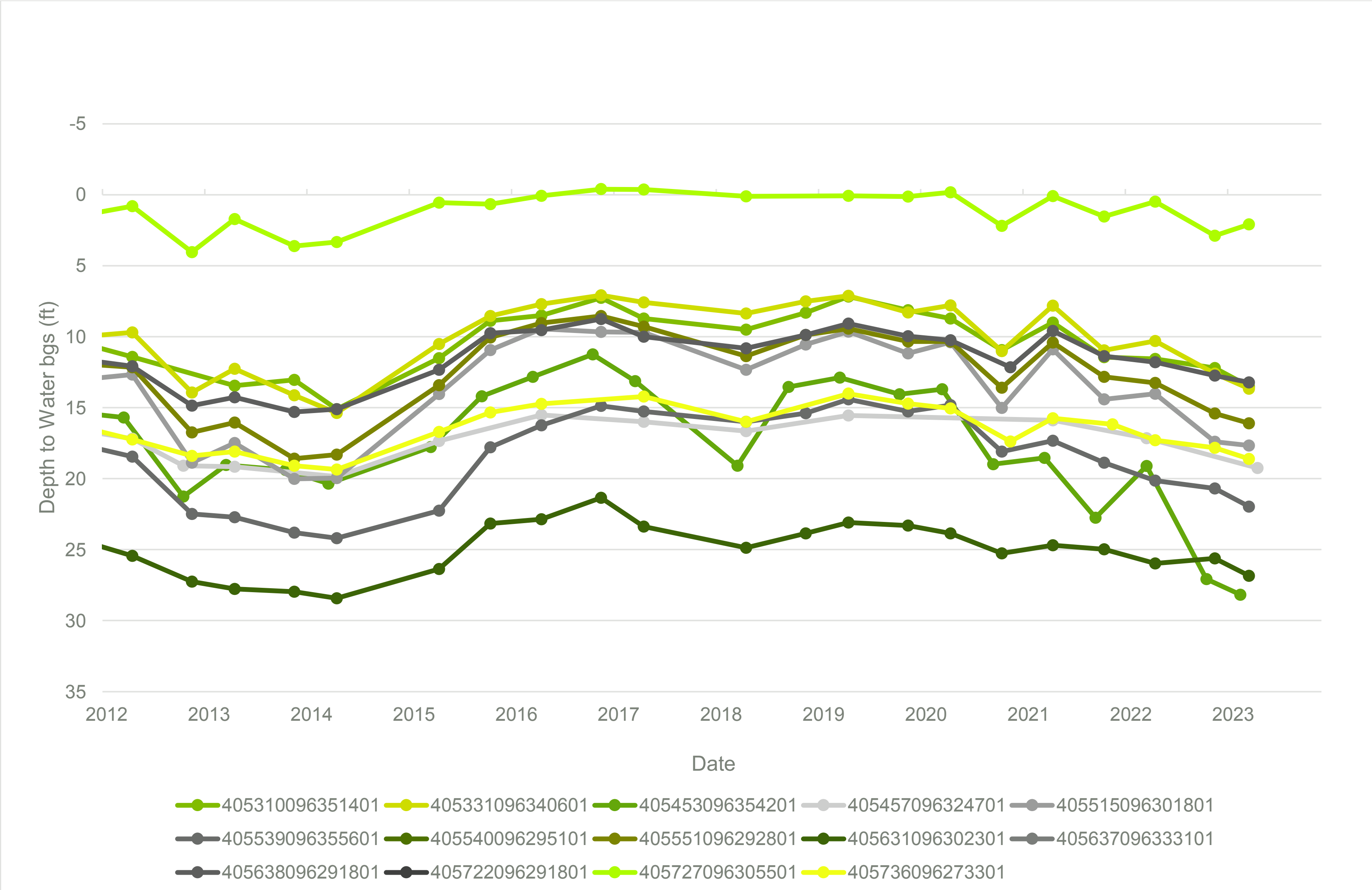

Figure 11. Depth to water below ground surface for nearby USGS monitoring wells from 2012 to 2023.

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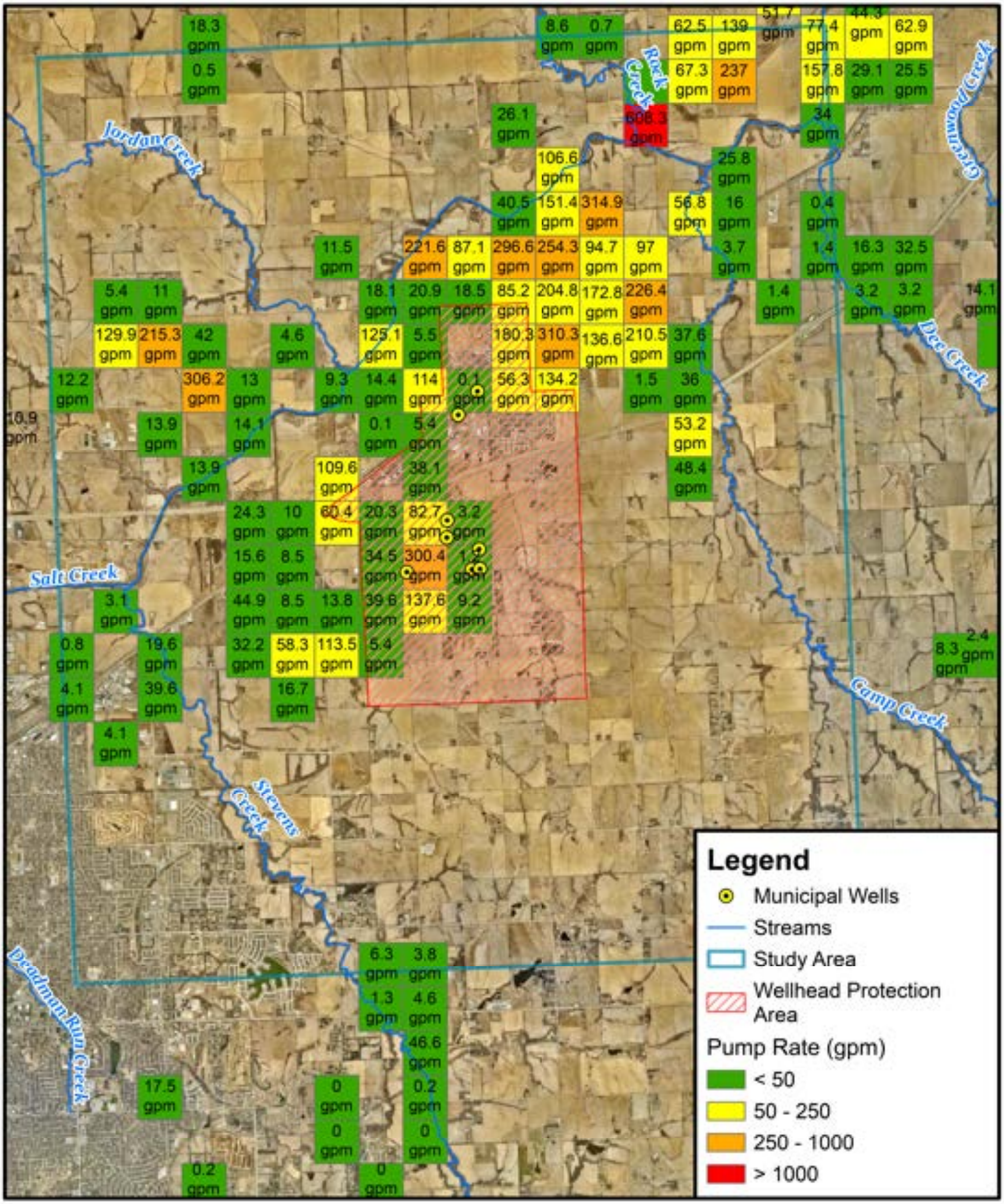
3. ASSESSMENT OF HISTORIC AND FUTURE WATER LEVELS

The Lower Platte Missouri Tributaries Groundwater model is a hydrogeological model designed to simulate and analyze groundwater flow in the Lower Platte and Missouri River tributaries region of Nebraska. The Lower Platte Missouri Tributaries Groundwater model was developed by the Nebraska Department of Natural Resources (NDNR) in collaboration with various stakeholders and consulting firms. The model was developed and calibrated by hydrogeologists, engineers, and experts in the field. It's a valuable tool for assessing and understanding the complex interactions between surface water and groundwater in this area, aiding in the management of water resources, and making informed decisions related to the regional groundwater resource.

3.1 Water Extraction from Regional Groundwater Model

The LPMT groundwater model contains pumping estimates for large capacity wells. Agricultural pumping was developed with a watershed model incorporating land use information and historical climatic conditions. The watershed model consist of four traditional components, which estimate the weather conditions, develop field-level estimates of the soil water balance, and scale these estimates regionally to develop recharge and pumping input files for the groundwater model. **Figure 12** is an example of the groundwater pumping in the Waverly area computed by the watershed model. Municipal and industrial pumping estimates were developed across Nebraska as part of the statewide municipal and industrial project. Estimates from this study are included in the LPMT model. **Figure 13** is an example of municipal and industrial pumping in the Waverly area.

The LPMT groundwater model served as a tool for projecting future water level changes within the vicinity of the Waverly well field. To achieve this, the calibration model spanning from 1960 to 2020 was used. Subsequently, an extension of the model was implemented to forecast groundwater conditions for an additional 25 years. This extension involved the replication of the last 8 years three times, with a unique occurrence of the year 2013 repeated a fourth time. This choice of the 8-year interval was deliberate, as it encapsulated the most contemporary land-use data and encompassed a spectrum of climatic variations, ranging from wet to dry, including typical years.



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1 INCH = 1.5 MILES

NAD 1983 2011 StatePlane Nebraska FIPS 2600 Ft US

JULY 2020 PUMP RATE AS MODELED IN LPMT

HYDROGEOLOGIC ASSESSMENT
WAVERLY, NE

FIGURE 12

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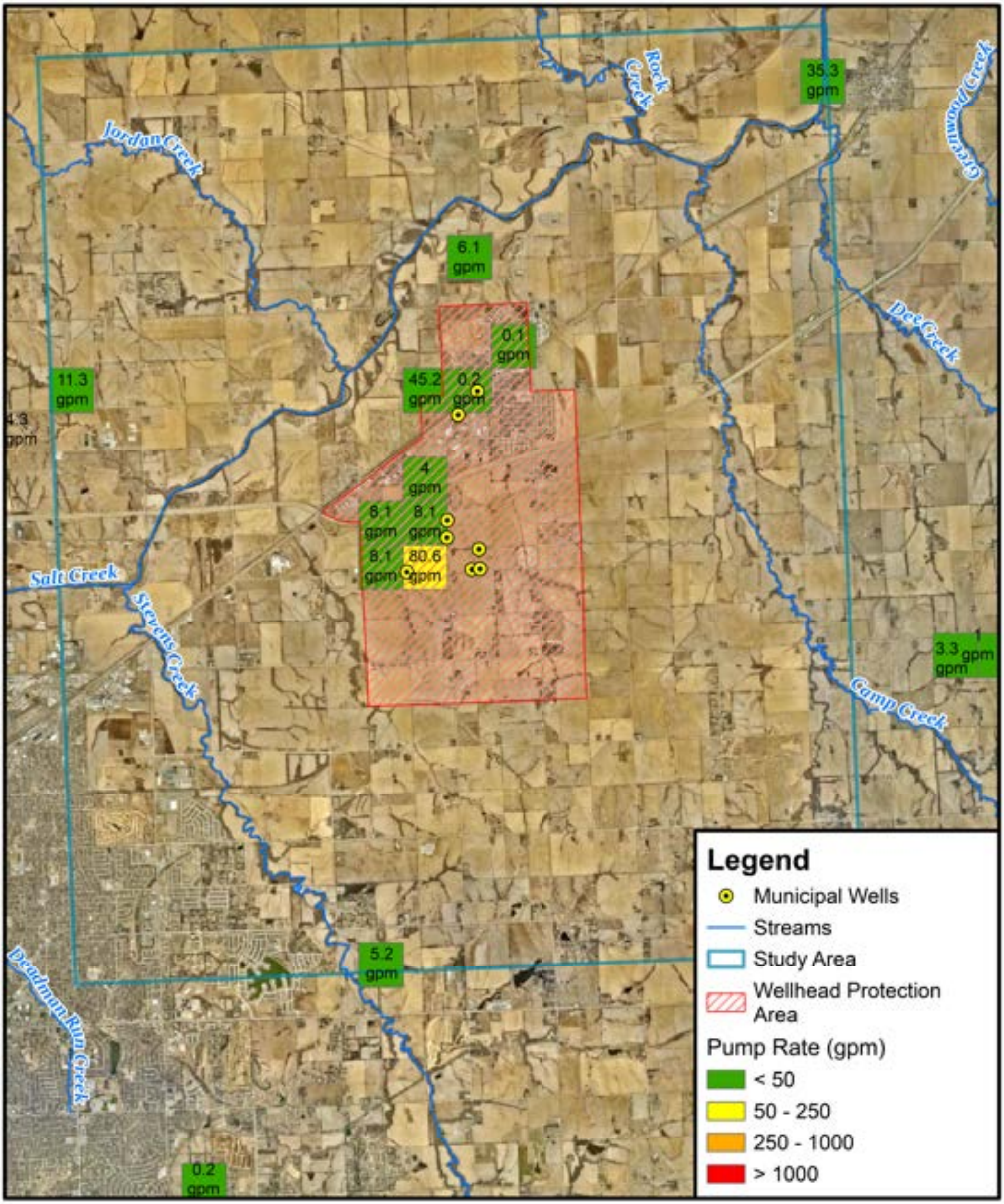

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0 1 Miles
1 INCH = 1.5 MILES
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DECEMBER 2020 PUMP RATE AS MODELED IN LPMT

HYDROGEOLOGIC ASSESSMENT
WAVERLY, NE

FIGURE 13

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The groundwater model cells containing pumping estimates for the Waverly wells were initially set to zero. Beginning in 2012, actual monthly pumping data, provided by Waverly, was incorporated into the grid cells that corresponded to each well, and this continued throughout the model's duration. Furthermore, future projections of pumping were generated using a similar methodology to extend the other model files. Notably, an additional step was introduced, involving an annual increase in pumping to align with the anticipated 2.5% growth rate.

3.2 Long Term Trends in Groundwater Levels

In **Figure 14**, the groundwater model's computed groundwater levels in the vicinity of the Waverly wells are shown. The observed trend from 2012 to 2022 is similar to the pattern seen in certain wells, specifically #6 and #9, where water levels initially rose in the early 2010s but gradually declined in more recent years. As a result of the input data furnished to the model, it projected ongoing drawdowns for the next 25 years. Furthermore, the seasonal fluctuations became more pronounced as a result of the projected demand increased over time.

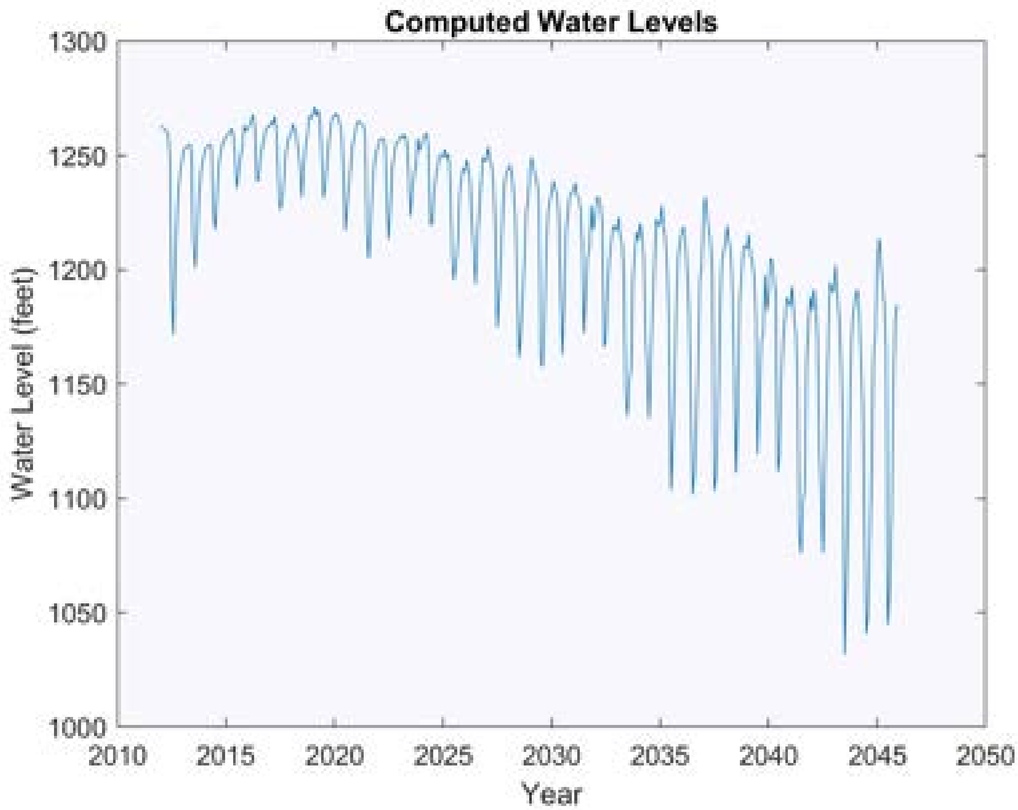

Figure 14. LPMT regional groundwater model computed groundwater levels near Waverly's municipal wells.

3.3 Limitations

Four primary limitations should be taken into consideration when interpreting the finding of this study and making decisions related to the management and conservation of water resources.

3.3.1 Data Availability

One of the primary limitation of this hydrogeologic study is the reliance on available data. The assessment heavily depends on bore log data, geophysical data, and water level data from nearby wells. The completeness, accuracy, spatial completeness, and representativeness of these datasets may vary, potentially introducing uncertainties into the analysis.

3.3.2 Inconsistencies in Bore Logs

Bore log data can be subject to inherent inconsistencies. Variability in the quality and detail of bore logs, as well as potential gaps in the recorded information, can limit the precision of lithological descriptions. Moreover, the rotary drilling methods employed to obtain this data are recognized to present inherent challenges. These include the risk of fines loss, strata mixing, and incomplete sample recovery, all of which collectively contribute to the difficulty in creating accurate bore logs. In addition, it is worth noting that variations in interpretations from one driller to another can further complicate the process of compiling consistent and reliable bore logs. This can affect the reliability of the interpretations based on these logs.

3.3.3 Nonuniqueness and Nonlinearity of Resistivity Data

The use of geophysical data to infer lithology introduces challenges. Resistivity measurements can exhibit nonuniqueness, nonlinearity, and nonuniversality in their relationship with lithology. As a result, it may be challenging to explicitly identify specific lithologic targets, and the interpretations derived from geophysical data should looked at with the previously mentioned limitations in mind.

3.3.4 Scale and Resolution of the Regional Model

The regional LPMT groundwater model, while valuable for understanding the broader water budget and trends, has limitations when applied to sub-regional assessments. The model’s scale and resolution may not be adequate for evaluating sub-regional aquifers with significant variability, potentially leading to oversimplification and an insufficient level of detail for localized hydrogeologic analysis. The LPMT groundwater model is characterized by a two-layer structured grid with cells measuring half a mile by half a mile. Notably, aquifer geometry, hydraulic properties, sources, and sinks are all specified on a cell-by-cell basis, and their variation cannot be represented at a finer resolution than that of the grid cells. Moreover, the model's computations are executed at a cell-by-cell level, which imposes a limitation on the resolution of the solutions and associated outputs, preventing them from achieving a finer level of detail. In an areas such as Waverly where the aquifer varies spatially in short distances, the large cell size of the regional model is a limitation.

4. RECOMMENDATIONS

Using the best available science of the LPMT regional model, nearby monitoring wells, AEM data, and information about the local water levels and well constructions has revealed that there have been declines in the water table in and around the study area. Based on the findings of this hydrogeologic assessment, there are three recommendations for potential action to understand and/or address the lowering water table affecting Waverly's municipal wells and wellfield.

4.1 Developing a Subregional Groundwater Model

The LPMT regional groundwater model is an extremely useful tool for understanding the hydrology and water budget of large spatial and temporal extents. Alternatively, the LPMT regional model lacks both the spatial and temporal resolutions to be actionable at a daily interval for an area as compact and geologically complicated as the study area. A subregional groundwater model would create a tool that would more accurately represent the geologic complexity of the study area and at a timescale more useful for scheduling municipal water extraction. Rather than generalizing the geologic strata for a single model cell covering a ½ mile by ½ mile area, a subregional model would make use of the borehole logs of the groundwater wells in the study area to recreate the stratigraphy at the exact locations of the wells. A subregional groundwater model would not physically address the lowering of the water table but would allow for management decisions to be made with a tool that is calibrated to the specific hydrogeology of the model domain and at a timescale that would be useful for municipal well scheduling. Additionally, the decision to create a subregional model would benefit the following two recommendations in both the planning and management of those recommendations.

4.2 Addressing Current Municipal Wells

Using the borehole logs and well construction information provided by Waverly, it appears that there is an opportunity to redrill, reconfigure the well construction to optimize the available aquifer, utilize existing water distribution infrastructure, and maintain adequate pumping water level elevations. This recommendation would be aimed at optimizing the wells currently screened in the Dakota aquifer which underlies five of the seven currently active Waverly municipal wells. By redrilling the wells screened in the Dakota aquifer to the full extent of the Dakota's water bearing materials, there could be some expansion of the saturated thickness available to the well. Additionally, although it is recommended that the redrilled wells have shorter screened intervals located at the bottom of the well, this could reduce the maximum pump rate of the well. This may not be an issue as the capacity of the Waverly wellfield is not a concern for the current water demand on the municipal wells, rather the declining water levels are the primary concern of the city. Should the shorter screened interval not affect the potential pump rate of the well, it would still be recommended certain wells be pumped at a lower rate than they are currently pumped if a VFD is available at the well. This would minimize the drawdown that could put the pumping water level closer to the shutoff water level for the pumps. The recommendation of reducing the pump rate would reduce drawdown as relatively compared to a higher pumping rate for all wells in both the unconsolidated alluvial deposits and the semiconfined Dakota aquifer. **Table 2** outlines the recommended actions to address each of Waverly's current municipal wells.

Table 2. Recommendations for addressing current municipal wells.

NDNR Well Registration Number	Colloquial Well Number	Recommendation and Reasoning
G-068617	4	Consider reducing the pumping rate to keep the pumping water level above the shutoff level. The screened interval is located in a favorable lithology and lowering the pump depth would not be advisable as the pump would be located within the screened interval.
G-070134	5	Consider reducing the pumping rate to keep the pumping water level above the shutoff level. The screened interval is located in a favorable lithology and lowering the pump depth would not be advisable as the pump would be located within the screened interval.
G-070533	6	Consider redrilling this well to reconfigure with a shorter screened interval with a top elevation at greater depth than current; set the pump above the lowered screened interval. The current pump depth is located within the screened interval and could jeopardize the condition of the well and aquifer.
G-070534	7	When this well is reconstructed, consider configuring with a shorter screened interval with a top elevation at greater depth than historical level. Set the pump above the lowered screened interval.
G-114724	8	No action at this time. The pumping water level currently sits approximately 10 feet above the shutoff water level for this well. Consider reducing the pumping rate if the difference between the pumping water level and shutoff level reduces.
G-136114	9	Consider redrilling this well to reconfigure with a shorter screened interval with a top elevation at greater depth than current, set the pump above the lowered screened interval. Additionally, consider alternative locations for redrilling. The marginal lithology and water levels at this location are not conducive to a resilient production well.
G-175276	10	No action at this time. The pumping water level currently sits approximately 20 feet above the shutoff water level for this well.
G-175275	11	Consider alternative locations for redrilling. The marginal lithology and water levels at this location are not conducive to a resilient production well.

Furthermore, as mentioned in **Section 2.1**, the Dakota aquifer in this study area, which underlies five of the seven currently active Waverly municipal wells, is an aquifer system that does not reflect immediate rises in groundwater levels in response to precipitation events in this area. This portion of eastern Nebraska has not received a high amount of precipitation since 2016, as shown in **Figure 1** (HPRCC, 2023). As seen in the trends in Waverly's municipal well groundwater levels in **Figures 7** and **8**, there was no significant jump in static water levels in 2016 in response to the high amount of precipitation seen during that period, but there has been an overall matching trend of drier years with less precipitation and declining water levels. This indicates that the relationship between precipitation and groundwater levels in the Dakota aquifer within the study area is representative of long-term trends as opposed to a more responsive and immediate relationship. This means that it will take several years with higher precipitation amounts than those seen in **Figure 1** to begin to relieve water declines in this area. Additionally, wetter years would lead to decrease demand on the aquifer in the area which would also help to relieve the water level declines.

The recommendation to redrill and reconfigure the construction of the Waverly municipal wells would make the Waverly municipal wellfield more resilient to the stress of more years of drought conditions by lowering the shutoff water levels for the municipal wells at the expense of the current pumping rates. Nonetheless, if current pumping rates can be lowered without compromising the wellfield's ability to meet the current water demand, there will be less risk of the pumping water levels reaching the shutoff levels listed in the Waverly Water Distribution Study (Olsson, 2023). This recommendation could benefit from a subregional groundwater model, as mentioned in **Section 4.1**, by increasing the confidence at which the groundwater levels in the area would be affected by various climatic conditions and the alterations to pumping regime.

4.3 Adding New Municipal Wells

Similarly to the recommendation to redrill and alter the well construction of the current municipal wells, adding one or more municipal wells to the current Waverly municipal wellfield following the general recommendation of having a shorter screened interval, as mentioned in **Section 4.2**, would provide additional relief regarding water level declines. Adding a municipal well or multiple municipal wells to the Waverly wellfield with a short screened interval in the Dakota aquifer and a pump set just above the screened interval will allow the Waverly water system to be able to pump at lower rates, similarly proposed in **Section 4.2,** without compromising the municipal water system's ability to respond to the current water demand. Furthermore, additional municipal wells would add to the overall capacity of the Waverly municipal water system and would alleviate some demand on the current wells regarding potential population growth and increased demand as projected in the Waverly Water Distribution Study (Olsson, 2023).

Siting new municipal well locations was not the initial nor primary focus of this hydrogeologic assessment, however information gleaned in this assessment can provide insight into locations for further hydrogeologic inquiry. Potential areas to gather information for a newly sited well include the area between Wells 7 and 9 located to the north of Alvo Road. The well diagrams in **Appendix A** display similar lithologies between Wells 7, 9, and 10 that could potentially allow for a deeply set, short screen in productive aquifer material, as well as the opportunity to utilize the existing water distribution infrastructure of the current municipal wellfield.

A second option would be to explore to the east of Waverly's municipal boundary towards Camp Creek. The USGS wells between Waverly and Camp Creek have shown downward trends in recent years similar to all other USGS wells in **Figures 10** and **11**, but they are not showing as drastic of changes as others around the Study Area. Furthermore, the figures with paired AEM and borehole data show productive lithologies and high conductivity values in this same area.

A final location that may be worthwhile to explore is to the south of the Waverly Wellhead Protection Area around Havelock Avenue centered between 134th and 148th St. This area is showing an area of high resistivity, which is typically indicative of good, coarse aquifer material. Although it should be noted that there is a lack of lithological data from nearby boreholes and a lack of long-term monitoring data nearby to know if the hydrogeology would support a municipal well here. These recommendations could benefit from a subregional groundwater model, as mentioned in **Section 4.1**, by allowing the potential locations of a new well or wells to be analyzed and be placed in locations where the drawdown of the well would have the least impact on current municipal wells while still being a productive extraction well.

5. REFERENCES

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