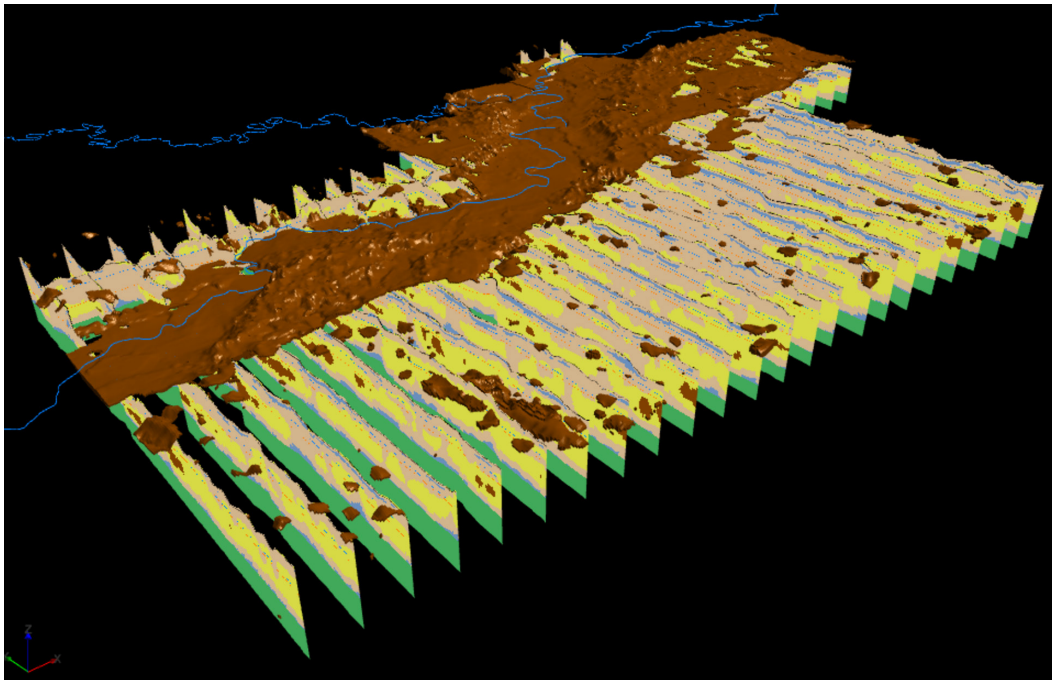
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Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Areas along South Loup River Within Lower Loup Natural Resources District



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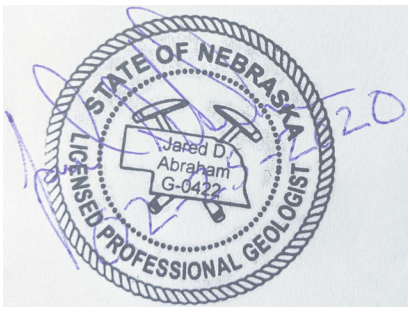
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Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled "*Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Areas along South Loup River Within Lower Loup Natural Resources District*". The Lower Loup Natural Resources District (LLNRD) commissioned a subsurface study to increase understanding of the hydrogeology within the District. AGF entered into an agreement with the Lower Loup Natural Resources District to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the LLNRD project area, and to recommend future work to enhance groundwater management activities.

The scope of work for this project was as follows:

1. SCOPE OF WORK

1.1 AGF began project planning upon signing of the project between the parties. This work included flight plans, database development, and review of hydrogeologic and geologic work for the area. The LLNRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies to AGF.

1.2 At the conclusion of the design process, the maximum line length for the LLNRD 2019 AEM survey area was about 14 miles in length in the east-west direction and about 10 miles in the north-south direction. An AEM survey utilizing the SkyTEM304M system was flown over the LLNRD as a flight block. These flights were provided as preliminary AEM inversions on October 20 to 26, 2019 and the final AEM data and inversions are included as a product attached to this data report.

1.4 Approximately 612.4 line-miles (992.1 line-kilometers) were acquired over the LLNRD AEM survey area on October 19-25, 2019. Status reports of the flying were provided to the Contract Representative of LLNRD on a daily basis, including the areas flown, production rates, and flight plan for the following day. The Kearney Airport was used during these flights for refueling and landings including overnight storage.

1.5 AGF processed and conducted quality assurance and quality control (QA/QC) procedures on all data collected from the acquisition system. AGF delivered preliminary data and inversions on October 26, 2019.

1.6 After final processing, 548.6 line-miles (888.7 line-km) of data were retained for the final inversions for the LLNRD AEM survey area. This amounts to a data retention of 89.6%. This high rate is the result of careful flight line planning and design. The final inverted georeferenced data are delivered to the LLNRD with this report. After inversion, AGF derived 2D sections, 3D electrical models, and interpreted geologic and hydrogeologic surfaces of the surveyed area.

1.7 AGF is providing a hydrogeologic framework report that includes maps of aquifer(s), maps of aquifer materials relationships to current test holes and production groundwater wells, estimates of water storage capacity, and maps of estimated potential recharge areas in the block flight areas. This report, as mentioned above, also includes all data (acquired, processed, developed) files. The report is delivered in PDF digital format and the data in ASCII and native formats.

2. KEY FINDINGS

2.1 **Boreholes** - Information from boreholes was used to analyze the AEM inversion results. These included CSD information on seven (7) boreholes containing lithology and stratigraphic information, and three (3) holes contained geophysical information. NE-DNR wells totaled 509 registered well records containing usable lithology information.

2.2 **Digitizing Interpreted Geological Contacts** - Characterization and interpretation of the subsurface was performed in cross-section and in derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), and Cretaceous Pierre Shale (***Kp***). The interpretive process benefited from the use of CSD and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary/Tertiary aquifer material mapping are included in the appendices as well as interpretative surface grids.

2.3 **Resistivity/Lithology Relationship** - Assessment of the sediment character in both the Quaternary and Tertiary Ogallala aquifer was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in survey area. A numerically robust assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-25 ohm-m), and aquifer (25-40 ohm-m), including coarse sand-rich intervals (>40 ohm-m) was determined. This allowed for the characterization of the ranges of resistivities present in the major geologic units described in this report.

2.4 **Hydrogeological Framework of the Buffalo County AEM Survey Area** - The AEM reveals considerable variability in the ***Q*** and ***To*** deposits across the AEM survey area. The subsurface distribution of materials can be generally characterized into two parts. The ***Q*** which covers the entire surface of the survey area including the South Loup River Valley and the upland areas north and south of the river. The ***Q*** aquifer within the South Loup River Valley of the AEM survey area is predominantly composed of unconsolidated aquifer and coarse aquifer materials composed of alluvial sediments. The ***Q*** also has nearly continuous areas of marginal and non-aquifer material layers in the near surface on the tablelands. ***Q*** materials lie upon ***To*** across the survey area. The ***To*** has a heterogeneous mix of aquifer materials which is the primary aquifer where there is aquifer and coarse aquifer materials. The ***To*** also has marginal and non-aquifer material deposits that can act as groundwater flow boundaries creating isolated aquifers and barriers to groundwater flow. The entire survey area has ***To*** non-aquifer and marginal aquifer layer lying on the ***Kp*** bedrock surface. The bedrock is eroded and has a shallow paleochannels cut into it.

2.5 **Estimation of Aquifer Volume and Water in Storage in the Buffalo County AEM Survey Area -** The unsaturated ***Q*** aquifer materials shows the non-aquifer material has an estimated volume(***If Saturated***) of 322,539 acre-ft and contains 129,015 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 2,202,678 acre-ft and contains 770,937 acre-ft, aquifer material has an estimated volume of 764,293 acre-ft and contains an estimated volume of 152,858 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 959,632 acre-ft for a total of 239,908 acre-ft of groundwater in storage. The amount of groundwater in storage for all ***Q*** material groups is 1,292,718 acre-ft.

The saturated Quaternary (***Q***) non-aquifer material has an estimated volume of 29,199 acre-ft and contains 11,679 acre-ft of groundwater in storage. The saturated marginal aquifer material has an estimated volume of 2,131,881 acre-ft and contains 746,158 acre-ft. The saturated aquifer material has an estimated volume of 1,761,880 acre-ft and contains an estimated volume of 352,376 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 1,100,334 acre-ft for a total of 275,083 acre-ft of groundwater in storage. The amount of groundwater in storage for all aquifer material groups is 1,385,296 acre-ft. Non-aquifer materials in the Buffalo County AEM survey area will yield approximately 233 acre-ft, marginal aquifer materials will yield approximately 37,307 acre-ft, aquifer materials will yield 77,522 acre-ft, and the coarse aquifer material will yield approximately 52,265 acre-ft. A total of 129,787 acre-ft is available from the combined aquifer and coarse aquifer materials.

The saturated ***To*** aquifer materials shows the non-aquifer material has an estimated volume of 760,848 acre-ft and contains 304,339 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 3,958,652 acre-ft and contains 1,385,528 acre-ft, aquifer material has an estimated volume of 4,344,496 acre-ft and contains an estimated volume of 868,899 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 1,112,992 acre-ft for a total of 278,248 acre-ft of groundwater in storage. The amount of groundwater in storage for all ***To*** material groups is 2,837,014 acre-ft.

2.6 Groundwater Declines, Water Quality, and the AEM Hydrogeologic Framework in the Buffalo County AEM Survey Area - The groundwater declines seen in Buffalo County AEM survey area are long term and related to the hydrogeology, recharge and land use. The AEM survey identified the areas of aquifer materials that will transmit the most, and the least, amounts of water within the subsurface and indicated pathways from the surface down to the groundwater system (recharge). The declines are directly related to the non-aquifer and marginal aquifer near surface layers on the tablelands. They limit the amount of recharge going to the aquifer system. There are also isolated aquifers in the subsurface. The LLNRD would benefit from building a water budget for the area based the hydrogeology, water use, land use, recharge, weather changes, and other factors.

Water quality samples for nitrate were compared to the AEM hydrogeologic framework. It was found that the water quality in the survey area was very good. The overlying ***Q*** near surface non-aquifer and marginal aquifer material layers reduce recharge that carry nitrates down to the water table. Two wells had values of 8.2 and 10.2 mg/l that are anomalies when compared to the aquifer materials in which they are completed in and appear to be point source pollution locations.

2.7 Potential Recharge Zones within the Lower Loup 2019 AEM Survey Area - Each AEM flight line was interpreted for aquifer material for the first model layer (10 ft), the second model layer (~20 ft) and the fifth model layer (~50 ft). Areas of coarse aquifer and aquifer material will have the highest potential to transmit the largest amount of water to the groundwater system. The marginal aquifer material has the lowest potential to transmit some water downward and the non-aquifer material will transmit minimal to no water to the groundwater aquifer. Maps have been created that show broad areas along the South Loup River and some tributaries to be the best areas for recharge at all 3 model depths. The worst areas of recharge are the tablelands because of thick layers of non-aquifer and marginal aquifer materials present at those locations.

2.8 Evaluating Potential Locations for Managed Aquifer Recharge (MAR) areas in the Buffalo County AEM Survey Area - The northeast corner of the survey area is an example of using the AEM hydrogeologic framework to look for potential MAR sites. There appears to be enough unsaturated aquifer and coarse aquifer material to provide storage space. These materials are thick and have high rates of recharge. They are a reasonable distance from the river. The stored water can move naturally back to the river by base flow or can be pumped when there is a need. All areas with MAR potential have not been identified by this survey.

2.9 Using AEM Results to Understand the Effect of Groundwater Management and Regulations - The Groundwater Management Plan and regulations were briefly compared to the results of the AEM hydrogeologic framework. The hydrogeology has a role in understanding this plan. The information provided by LLNRD on flowmeter locations, 2019 average groundwater use, and land use provides insight to how effective groundwater management may be across the area which continues to show declines. This information has not been evaluated for the local impacts which can affect the annual average declines reported by the District. The data on groundwater level changes show that the geology is one of the controls. No definitive conclusion was reached on how to evaluate the management plan, but the hydrogeology was linked to the water use and crop use. A full water budget needs to be developed to fully understand the effects of groundwater management.

3. Recommendations

Recommendations provided to the LLNRD in this section are based on the interpretation and understanding gained from the addition of the AEM data to existing information and from discussions with the LLNRD about their management challenges.

3.1 **Additional AEM Mapping** - The aquifer maps provided in this report represent the detailed hydrogeologic framework developed for the Buffalo County AEM survey area. The interpretations match well with the CSD and NE-DNR boreholes. No additional high resolution AEM information is needed within Buffalo County Area to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or “block flights” be collected to develop detailed frameworks in other areas of the District.

Other management areas or potential management areas should be mapped in detail to provide information on the hydrogeologic framework which provides detail on recharge, groundwater movement, etc. This could potentially be done in cooperation with the neighboring NRDs to get details on the continuous aquifer system that is shared in the area. The line spacing for the block flights should be on the order of 0.25 mile (1,320 ft).

For example, the detailed hydrogeologic frameworks presented in this report have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield. It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of the LLNRD. This will supply the LLNRD with information on groundwater flow, aquifer sustainability, depletion to streams, well interference, groundwater withdrawal, and other management considerations. Locating MAR sites is an activity the LLNRD is pursuing and AEM data is a primary component. Evaluating a water budget is another component of understanding integrated management, water quality and quantity management efforts.

3.2 **Update the Water Table map** - The groundwater data used in the analyses presented in this report use the 1995 water table map. Additional closely spaced water level measurement locations would improve the water table map. The transition from the flood plain to areas out of the flood plain into the tablelands would be a good addition to the network.

3.3 **Siting new test holes and production wells** – The AEM framework maps and profiles provided in this report provide insight on the 3D relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the LLNRD area was used in building the framework maps and profiles. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in optimal locations.

The location of new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution.

3.4 **Aquifer testing and borehole logging** - Aquifer tests are recommended to improve estimates of aquifer characteristics. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics is highly recommended. The few test holes with geophysical logs in the LLNRD survey area were inadequate. They were too few in number and none were calibrated. The borehole geophysical logs provided for this investigation demonstrate that additional calibrated and verified geophysical logs are required in the LLNRD.

Examples of additional logging would be borehole flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailed aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR). This is a quick and effective way to characterize porosity and water content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth. This is very cost effective when compared to traditional aquifer tests.

3.5 **Recharge Zones** - The LLNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. The block flights of AEM data acquisition provide the most detailed information for understanding recharge throughout the Buffalo County area. It is recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

It is recommended that additional focused high resolution AEM data be collected and interpreted along the streams utilizing closely spaced flight lines using an AEM system that has near-surface resolution. This will enhance the results of previous groundwater surface water interaction locations. By identifying these locations with precise placement of the sediment

packages along the stream, rather than large stream reaches as seen in other studies, a more thorough understanding of gaining and losing reaches of the streams can be made.

3.6 **Managed Aquifer Recharge**- An area which lies out of the flood plain in the northeast corner of the survey area may have potential for managed aquifer recharge. There appears to be enough unsaturated aquifer material and coarse aquifer material to provide storage space. These materials are thick and have high rates of recharge. They are a reasonable distance from the river. The stored water can move naturally back to the river by base flow or can be pumped when there is a need. A detailed analysis of the AEM data needs to be done to determine if there are other viable opportunities for the LLNRD.

3.7 **Build a Water Budget to Understand the Effectiveness of Groundwater Quantity Management** – Buffalo County has long term groundwater management declines. Future changes in management would benefit from a thorough understanding of the water budget. Significant data has already been collected such as the hydrogeologic framework, surface water measurements, groundwater level measurements, crop use, some flowmeter readings, etc. What needs to be completed is an evaluation and analysis of all of this information into a water budget. Doing a complete water budget is recommended for the survey area.

4. Deliverables

In summary, the following are included as deliverables:

- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz
- Borehole as ASCII *.xyz
- Interpretations as ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView FLT grid files – surface, topo, etc
- 3D fence diagrams of the LLNRD 2019 survey lines.
- 3D voxel models as ASCII *.xyz for the LLNRD AEM survey areas
- KMZs for the LLRND AEM survey flight lines

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List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
$A*m^2$	Ampere meter squared
AEM	Airborne Electromagnetic
AGF	Aqua Geo Frameworks, LLC
ASCII	American Standard Code for Information Interchange
cm	Centimeter
CSD	Conservation and Survey Division
COHYST	Platte River Cooperative Hydrology Study
dB/dt	Change in amplitude of magnetic field with time
DEM	Digital Elevation Model
DOI	Depth of Investigation
DGPS	Differential global positioning system
ENWRA	Eastern Nebraska Water Resources Assessment
ft	Feet
Fm	Geological Formation
FT	Fourier Transform
GIS	Geographic Information System
gpm	Gallons per minute
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
Km/km	Kilometers
KMZ/kmz	Keyhole Markup language Zipped file
Kp	Cretaceous Pierre Shale
LCI	Laterally-Constrained Inversion
m	Meters
MAG	Magnetic (data); Magnetometer (instrument)
MAR	Managed Aquifer Recharge
MCG	Minimum curvature gridding
MCL	Maximum Contaminant Level
mg/L	Milligrams per liter
µS/cm	Micro-Siemens per centimeter
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NE	Nebraska
NED	National Elevation Dataset
NE-DEE	Nebraska Department of Environment and Energy
NE-DNR	Nebraska Department of Natural Resources
NMR	Nuclear Magnetic Resonance
NRD	Natural Resources Districts
NRCS	National Resources Conservation Service
nT	Nano-Tesla
OM	Geosoft Oasis montaj
Ohm-m	Ohm-meter
PA	Profile Analyst
PFC	Primary Field Compensation

PLNI	Power Line Noise Intensity
Q	Quaternary
QA/QC	Quality Assurance/Quality Control
RMF	Residual Magnetic Field
Rx	Receiver
SC	Specific Capacity
SCI	Spatially-Constrained Inversion
SPCS	State Plane Coordinate System
STD	Standard Deviation
Sy	Specific yield
TDEM	Time-Domain Electromagnetic
TDS	Total dissolved solids
TEM	Time-Domain Electromagnetic
To	Tertiary Ogallala Group
Tx	Transmitter
UNL	University of Nebraska Lincoln
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
XYZ	ASCII file type
yr	year

Disclaimer: AGF conducted this project using the current standards of the geophysical industry and used in-house quality control standards to produce this geophysical survey and products. The geophysical methods and procedures described in this report are applicable to the particular project objectives, and these methods have been successfully applied by AGF to investigations and projects of similar size and nature. However, field or subsurface conditions may differ from those anticipated, and the resultant data may not achieve the project objectives. AGF's services were performed consistent with the professional skill and care ordinarily provided by professional geologists under the same or similar circumstances. No other warranty or representation, either expressed or implied, is made by AGF in connection with its services unless in writing and signed by an authorized representative of AGF

1 Introduction

1.1 Purpose of Current Project

Sound management of groundwater and surface water in central Nebraska has become increasingly important in recent years. There are expanding pressures placed on the resource by the ever growing and dynamic demands for: agricultural production, population growth and urbanization, potential contamination from natural and anthropogenic sources, industrial and commercial needs; along with ever present changing climate. The combination of these stresses on water resources has increased the need for detailed hydrogeologic frameworks of the subsurface. Uses of data from this survey will be utilized to develop a greater understanding of the recharge rates based on the mapped aquifer materials in the subsurface along the South Loup River within the survey area. Identifying potential areas for Managed Aquifer Recharge (MAR) for storage of groundwater to increase current supplies of groundwater to replace depletions from current uses or improve supply for future development is a priority for LLNRD. MAR can also provide off stream storage of excess water during flood events. This data can be used to enhance the hydrogeologic framework for groundwater modeling for testing management scenarios such as MAR at a local level where borehole resolution is not sufficient or of limited use. The dense flight line data of this study are excellent for local groundwater models by providing a high-resolution framework to build the model. Detailed subsurface information for groundwater management strategies and policies implemented to address water quantity and quality concerns is another effort that can be improved with a better understanding of recharge, and its relationship with the underlying aquifers. The mapping of the subsurface related to groundwater flow and hydrologic connection between different aquifers and streams is also important in understanding water quality and quantity. Geographic regions that are identified as major contributors to recharge could be areas targeted for enhanced promotion of best management practices (BMP) to reduce or eliminate future contamination events. Where AEM data exist as dense flight lines determination of groundwater in storage and specific yield provides a base for making management decisions and determining water budgets.

The 2019 Lower Loup Natural Resources District (LLNRD) survey continues to build upon the previous AEM survey efforts within the LLNRD. A location map showing cities in the LLNRD is presented in Figure 1-1. In 2016 AGF flew an AEM survey over areas of interest near Columbus, Nebraska and Management Area 28 for Managed Aquifer Recharge, groundwater availability and groundwater quality (AGF, 2017a). The current AEM survey area that was mapped in 2019 covers selected areas in Buffalo County, Nebraska. This report describes the hydrogeologic conditions assessed by using data collected from this LLNRD 2019 AEM survey. Additional data was also used from previous reports and studies as part of the process of creating this report. These reports include the Hydrogeologic Framework of Selected Areas in Lower Loup Natural Resources District (AGF, 2017a) and the Hydrogeologic Framework of Selected Areas in the Twin Platte and Central Platte Natural Resources Districts, Nebraska (AGF,2017b). Other background information includes analysis of historic groundwater levels, geologic descriptions from University of Nebraska-Lincoln Conservation and Survey Division (CSD) test holes, drillers logs obtained

from registered wells at the Nebraska Department of Natural Resources (NE-DNR), and a study by JEO (2018) on recharge of the Ravenna State Lake.

The AEM survey data were collected along lines spaced approximately 820 feet apart. This AEM survey was planned by LLNRD and AGF for the development of a 3D hydrogeologic framework of this project area and to recommend future work to enhance groundwater management activities. This work was supported by the Natural Resources Commission Water Sustainability Fund and the LLNRD.

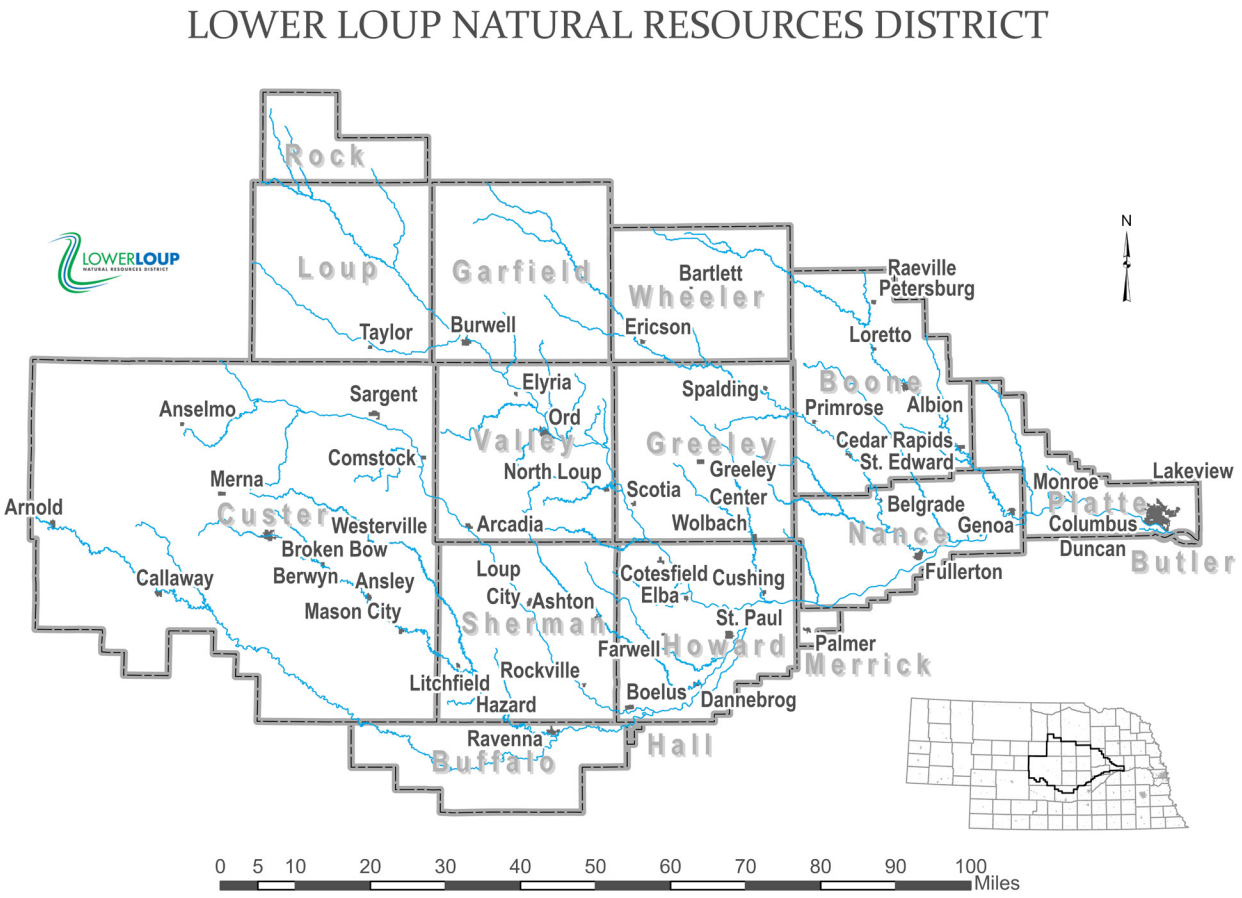


Figure 1-1. Map of the LLNRD in eastern Nebraska (modified from https://www.llnrd.org/assets/site/images/llnrdmap.jpg).

The labeled "As-Flown" flight lines are presented in Figure 1-2 and are also included as a Google Earth kmz in Appendix 3-Deliverables \KMZs\Flight Lines. AEM data acquisition is discussed in detail in Section 4. The main AEM flight area was near Pleasanton and Ravenna, Nebraska in the southern part of the District.

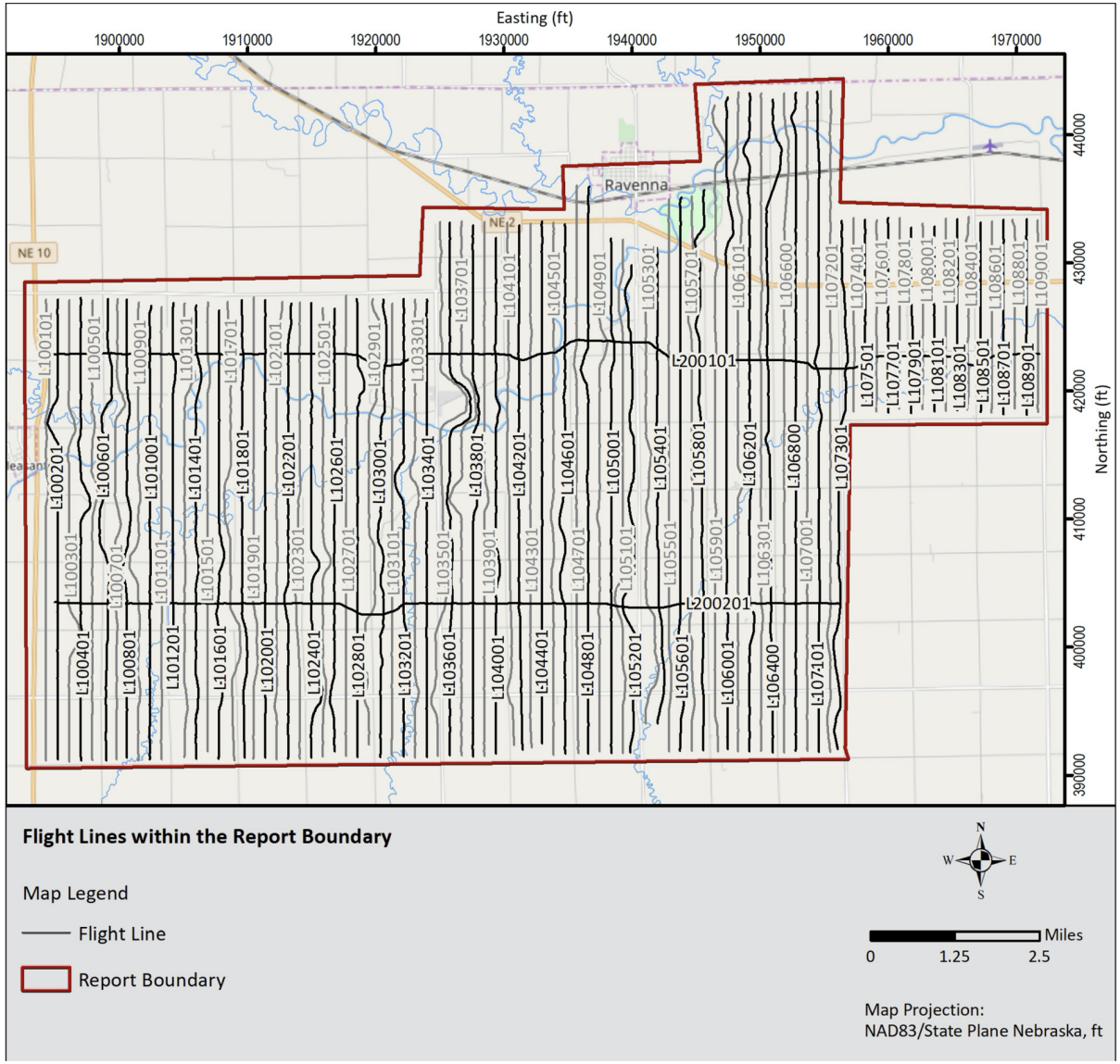


Figure 1-2. Map of the LLNRD AEM survey area including labeled as-flown flight lines.

1.2 Background

On January 1, 2002, the LLNRD declared the entire District a Phase I water quality management area for nitrogen management (LLNRD, 2017). This determination was based on studies by LLNRD and the Nebraska Department of Environment and Energy (NE-DEE). The conclusions from these studies indicated that the aquifers appeared to be contaminated to varying degrees with nitrate/nitrogen and the causes were likely related to fertilizer application and irrigation practices. The report also concluded that the most affected region, with some of the highest nitrate/nitrogen concentrations in the groundwater, occur in the eastern area of the district in parts of Platte and Nance counties. Based on this information, Area 28 was declared a Phase III water quality area 2 years later in 2004 (LLNRD, 2017).

Use of AEM technology to map and evaluate groundwater resources has gained momentum over the last 20 years in the United States and abroad. The state of Nebraska has been on the forefront of implementing AEM for water resources management over the last decade with projects across the state in a variety of geologic settings. In recent years, the Lower Loup Natural Resources District has coordinated efforts between local area Natural Resources Districts (NRDs), Conservation and Survey Division (CSD), the U.S. Geological Survey (USGS), and Aqua Geo Frameworks, LLC (AGF) in support of several projects designed to characterize the hydrogeology across the state. For purposes of this project, LLNRD and CSD are cooperating with AGF because of the shared borders and common groundwater management efforts between NRDs.

In addition to the AEM and Magnetic Total Field data acquired during this investigation, multiple resources were used to develop the presented hydrogeologic framework and subsequent recommendations for potential recharge areas and well locations. Data and findings from previous studies, along with geologic descriptions and geophysical data were utilized to develop the hydrogeologic framework presented herein.

1.3 Description of the LLNRD 2019 AEM Project Area

The area of interest is along the South Platte River within Buffalo County in the LLNRD AEM survey area and encompasses approximately 108.6 square miles (Figure 1-3). This area lies in its entirety within Buffalo County. Precipitation and irrigation runoff within the survey area is within the South Loup River basin and the area sits in a distinct groundwater region; namely, the East Central Dissected Plains (Pederson et al., 1986). The towns of Pleasanton and Ravenna lie within the LLNRD 2019 AEM survey area.

The entire LLNRD is under Phase 1 water quality controls for nitrogen management (LLNRD,2019a).

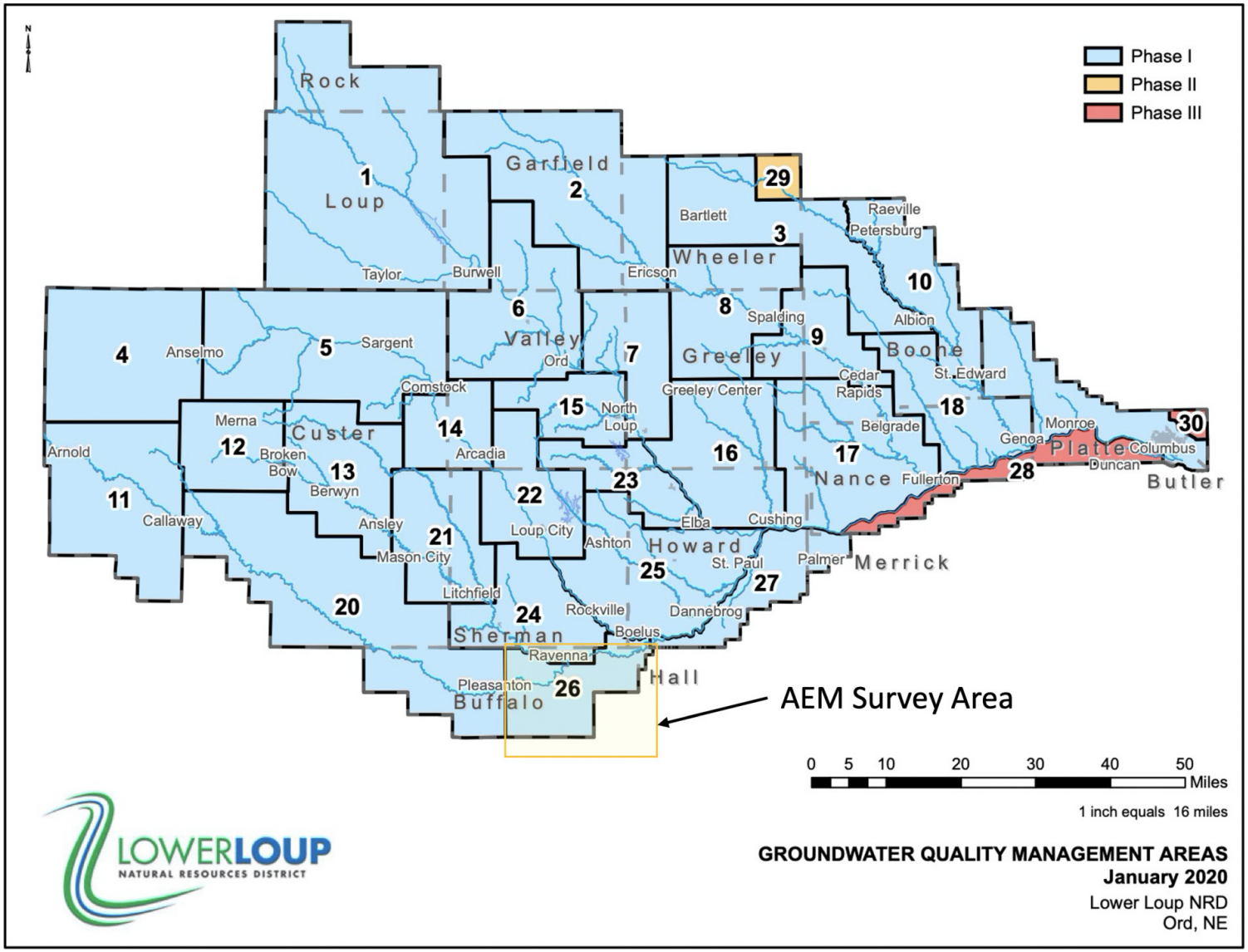


Figure 1-3. Map of the LLNRD Groundwater Quality Management Areas (modified from https://www.llnrd.org/assets/site/images/llnrdmap.jpg (LLNRD, 2019a)).

2 Project Area Hydrogeology

The AEM survey's objective was to map the geology and related hydrogeology of Quaternary (***Q***) and Tertiary Ogallala (***To***) deposits and the primary underlying bedrock Cretaceous Pierre Shale (***Kp***) that serves as an aquiclude. Background geology and hydrogeology for the project area are discussed in more detail in Gutentag et al (1984) and Carney (2008) and additional authors found in the following text. The following narrative is based primarily on the findings from these reports. For more detailed information the reader is directed to the Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report, 2006 (Cannia et al., 2006). This report presents a brief overview of the geology and hydrogeology of the project area pertinent to the AEM investigation and interpretation analysis.

2.1 Geologic Setting

The geology and hydrogeology of the LLNRD 2019 AEM Survey Area and surrounding areas have been studied extensively for over a century with the most recent studies focusing on understanding the hydrogeology of the area related to water quantity, groundwater-surface water interaction, surface water flow analysis and groundwater quality. The following sections will include only a brief overview of the geology and hydrogeology of the project area pertinent to the AEM investigation and interpretation analysis. For a more detailed review, the reader is encouraged to explore the background of the region using the references listed. The following narrative is based primarily on the findings from these reports.

2.1.1 Physiography and Regional Geologic Setting

The project area is in east-central Nebraska near the towns of Pleasanton and Ravenna within the Dissected Plains and Valleys topographic regions of Nebraska (CSD, 1951). Bedrock geology in the project area is comprised of consolidated marine and consolidated to semi-consolidated non-marine sedimentary rocks as presented in Figure 2-1 (from Burchett, 1986). These deposits are not deformed by folding and faulting. The Quaternary (***Q***) sediments are made up alluvial and eolian materials. The Tertiary Ogallala Group ***To*** is directly below the ***Q*** and both geologic units are in contact with each other and present across the survey area.

2.1.2 Surficial Geology

The complex Quaternary (***Q***) geology in central Nebraska consists of sequences of clay, silt, till, sand, and gravel overlying bedrock units. These materials are capped by loess deposits in many locations and sand dunes in others with alluvial deposits along the streams and South Loup River.

CSD test holes and drillers logs obtained from NE-DNR indicate loess, sand dune, and alluvium deposits in the project area. These ***Q*** lie upon the ***To*** unit that lies upon the Cretaceous Pierre Shale (***Kp***) bedrock. The ***Q*** deposits and ***To*** deposits contain aquifer materials that are used as water supply. The ***Kp*** is not an aquifer in the study area.

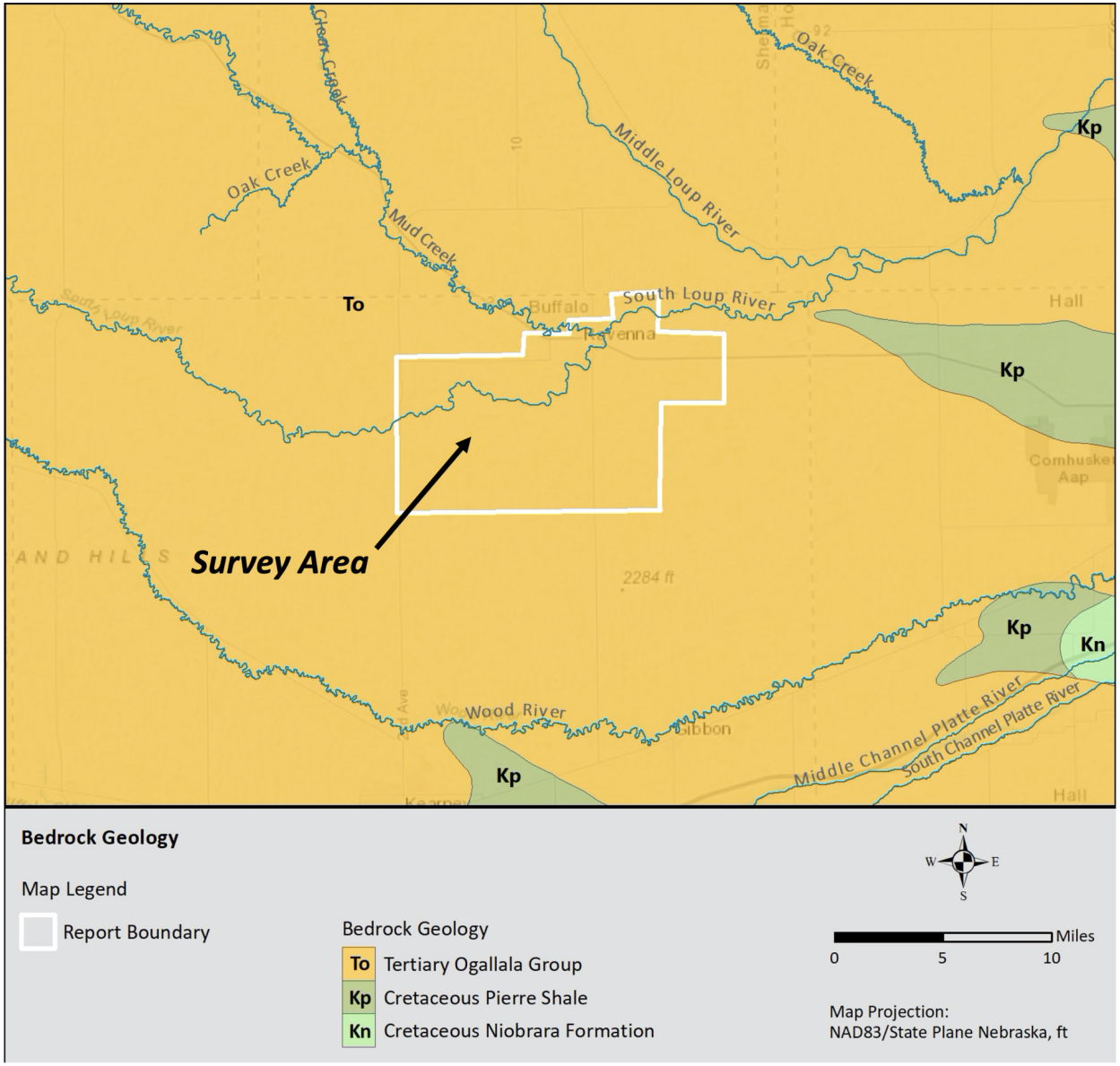


Figure 2-1. Bedrock map of the AEM survey area, modified from Burchett (1986).

2.1.3 Tertiary Geology

The Tertiary deposits survey area are Miocene Ogallala Group (***To***). The ***To*** is made up of predominantly fluvial material comprised of unconsolidated to semi-consolidated irregularly distributed beds of silt, clay, sand, and gravel (Souders, 2000). Some members of the ***To*** contain partially cemented friable sands or sandstone (Condra and Reed, 1959). The ***To*** is relative of similar thickness across the area and rests unconformably on underlying Cretaceous strata (Burchett, 1986). The ***To*** can serve as an aquifer and is saturated across the survey area.

2.1.4 Cretaceous Geology

The ***Kp*** deposits within the survey area are continuous and thick. The Upper Cretaceous bedrock formations are ***Kp*** and these formations are comprised of shale (Gutentag et al., 1984). The ***Kp*** acts as bedrock and confining unit to ***To*** deposits. None of the ***Kp*** yield beneficial amounts of potable groundwater within the survey boundaries.

2.2 LLNRD AEM Survey Area Hydrogeologic Characteristics in the Quaternary and Tertiary Ogallala System

The topography of the survey area (U.S. Geological Survey, 2020) in Figure 2-2 shows the main stem of the South Loup River along with the tributaries Mud Creek, Sweet Creek, Beaver Creek, and Cedar Creek. These streams are incised into the tableland which are the uplands extending out from the river valley to the north and south. The elevation of the ground surface varies from 2,290 to 1,940 feet from west to east. The overall elevation of the water table within the survey area (Figure 2-3) is based on the CSD 1995 water table map (NE-CSD, 1995). The 1995 CSD water table was chosen based on the most stable period of record and average precipitations during the same period. The 2019 static water table map provided by LLNRD was not used because of the instability of the period of record and abnormally high precipitation. In 2019 the annual precipitation was 43.73 inches compared to 1995 which was 23.66 inches (High Plains Climate Center, 2020). The water table map generally follows a similar slope to the land surface and slopes from west to east varying from 2,130 to 1,945 feet. Groundwater locally can be hydrologically connected to the South Loup River and its tributaries. Groundwater levels are located at shallower depths in the alluvial valleys and at deeper depths below the uplands. Water levels change with the seasons and typically reach maximum depths from groundwater pumping and usage during the crop growing months. Groundwater levels typically return to shallower, pre-stress levels in the March to June timeframe. Annual depths of drawdown and recharge of aquifers depends on the type of aquifer (e.g. confined or unconfined), proximity of the aquifer to the land surface, and the magnitude of stress exhibited on the system during the pumping season, combined with the amount of recharge available to the aquifer. Groundwater in confined to semi confined aquifers typically exhibits more drawdown than groundwater in unconfined systems that are present in alluvial settings. The groundwater system for the LLNRD 2019 AEM survey area is generally under unconfined conditions. However, under the tablelands, semi confined to confined conditions may exist

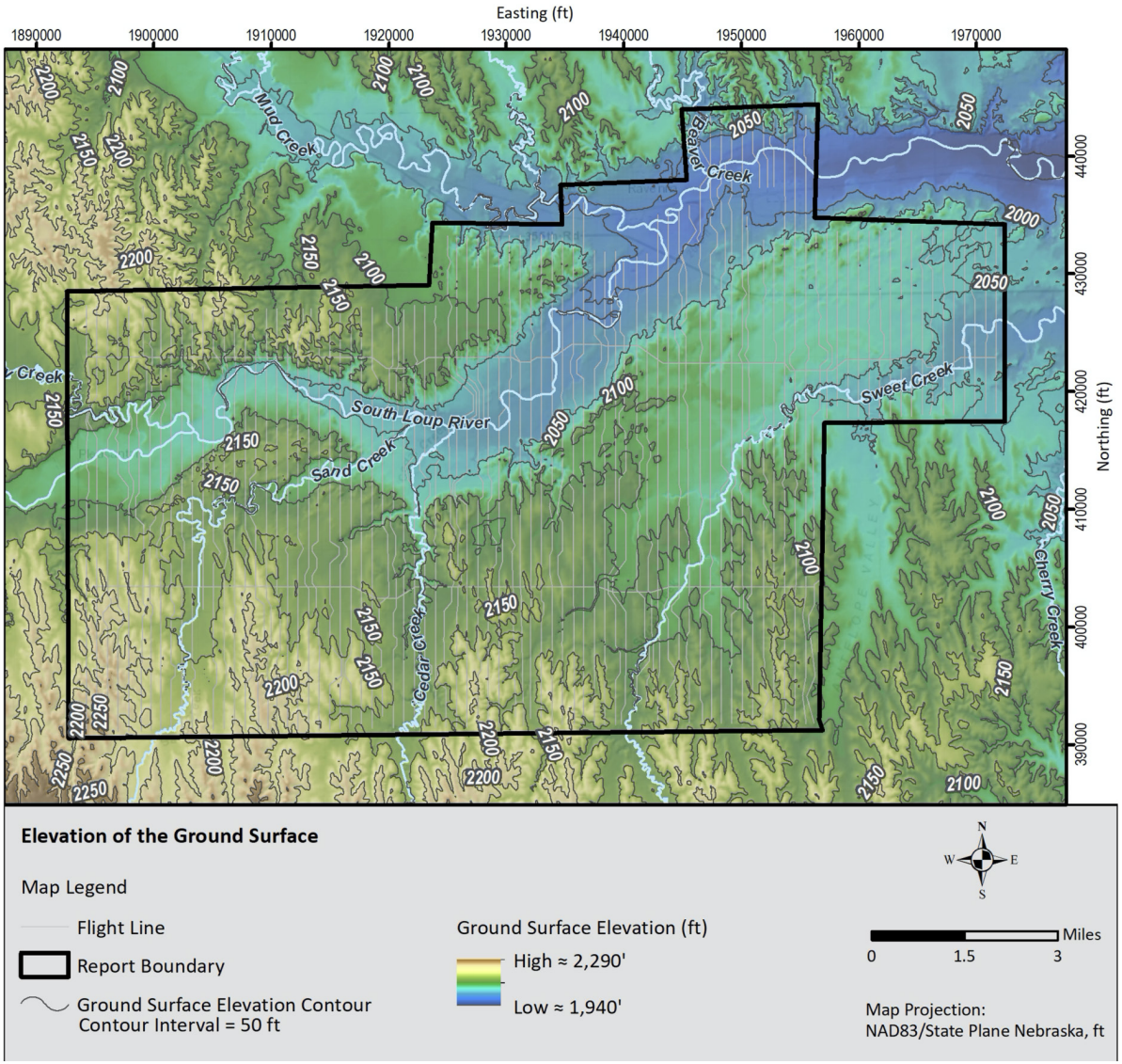


Figure 2-2. Map of elevation of the ground surface (U.S. Geological Survey, 2020). The elevation of the ground surface varies from 2,290 to 1,940 feet from west to east and is referenced to NAVD88 (feet)

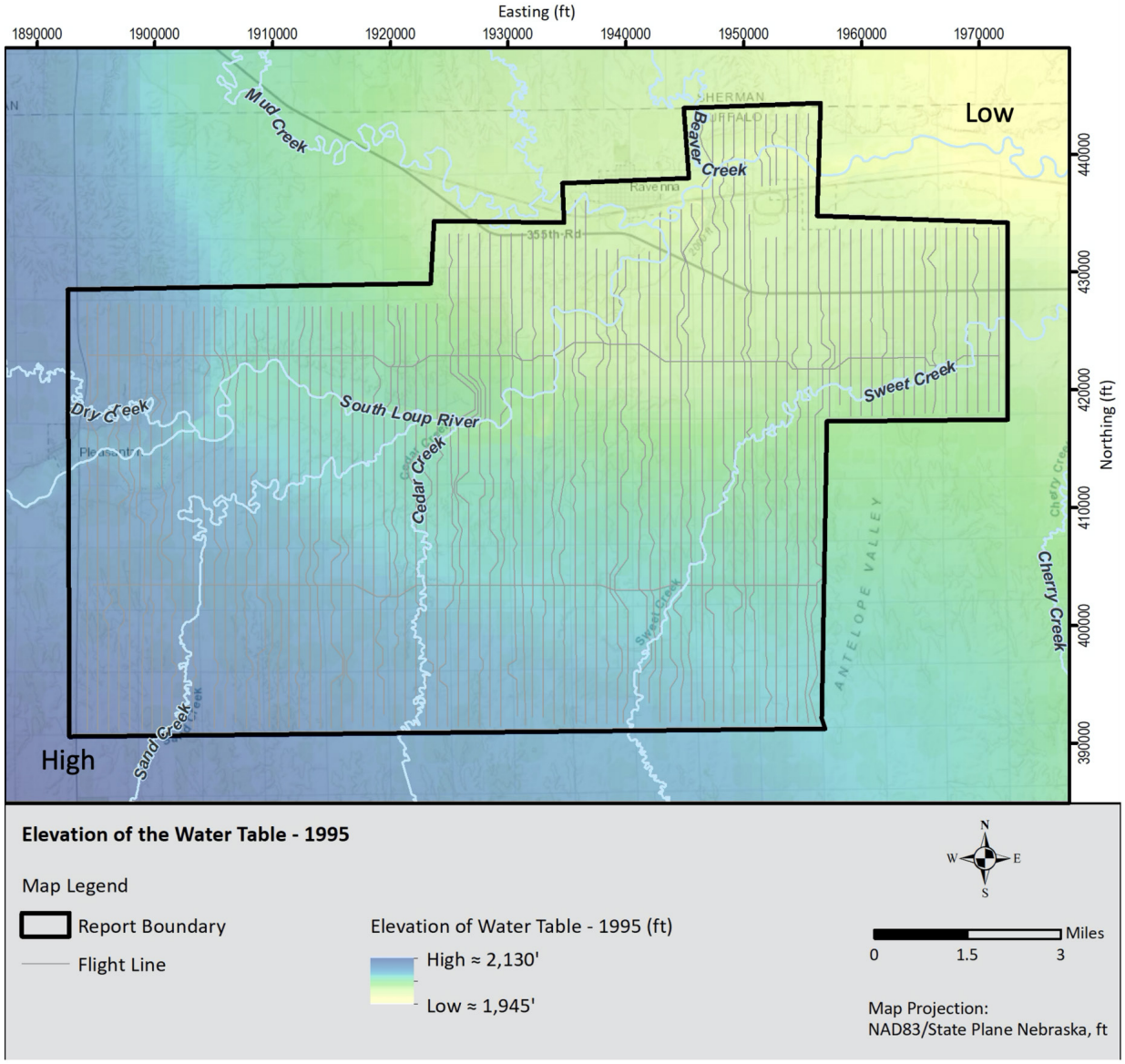


Figure 2-3. Map of Conservation and Survey 1995 Water Table. Groundwater elevation is similar to ground surface elevation. (NE-CSD, 1995).

The principal hydrogeologic unit within the AEM survey area is ***To*** alluvial materials based on review of borehole logs (NE-DNR, 2020). The ***To*** alluvial deposits underlie alluvial, till and loess deposits in the uplands survey area. Saturated ***To*** deposits in central Nebraska are a complex mixture of unconsolidated, saturated sand, and gravel deposits. The ***Q*** can also supply water to wells but there are fewer number of wells completed in the ***Q*** than in the ***To***.

There are also wells completed in both the ***Q*** and ***To***. The saturated ***Q*** and ***To*** deposits can be confined to unconfined, deep to shallow, and/or regional and local, and can be locally can be hydraulically connected with each other and surface water.

2.2.1 Connectivity to Surface Water

Groundwater flow connectivity to surface water features is largely undocumented. However, Peterson and Strauch (2007) report stream flow measurements at 531 sites conducted in November, 2006 in the Elkhorn and Loup River basins and selected streams in the Niobrara and Platte River basins in north-central Nebraska. Most of these sites were located throughout the Elkhorn and Loup River basins. There are 9 sites within the 25 sites shown on Figure 2-4 that make measurements of the South Loup River in the AEM survey area. Results at three sites 140, 138 and 133 below the confluence of the South Loup River and Mud Creek showed stream flow increasing from 126 to 161 cubic ft per second (CFS) in a downstream direction indicating surface water discharge to the South Loup River increased along that section. However, a more detailed review and analysis of the 25 sites near the project area (which was not a part of the scope of work for this project) would provide a more detailed explanation of these results. It is recognized that there is a strong groundwater-surface water connection along the rivers and streams in the project area.

Groundwater and surface water interactions were studied on the South Loup River in the AEM survey area (Figure 2-5) and reported on in USGS Scientific investigations Report 2018-5093 (Hobza and Schepers, 2018). Detailed analysis of surface water flow measurements and temperature studies shows that the influence of groundwater level change affects stream flow. Mostly by irrigation wells pumping and then shutting off after the growing season. The report cites the increase in surface water flow can be as much 1.5 cubic feet per second by focused groundwater discharge. During irrigation season some segments of the South Loup River can see declines in shallow groundwater levels below the level of the stream which shows a strong local connection to the ***Q*** and ***To*** deposits.

Locally, ***Q*** and ***To*** deposits are hydrologically connected to shallower aquifers and streams. The deeper aquifers can discharge into the shallow groundwater system or into the streams. The reverse is also true. Detailed studies are not available for precise estimates of groundwater-surface water relationships or where they occur.

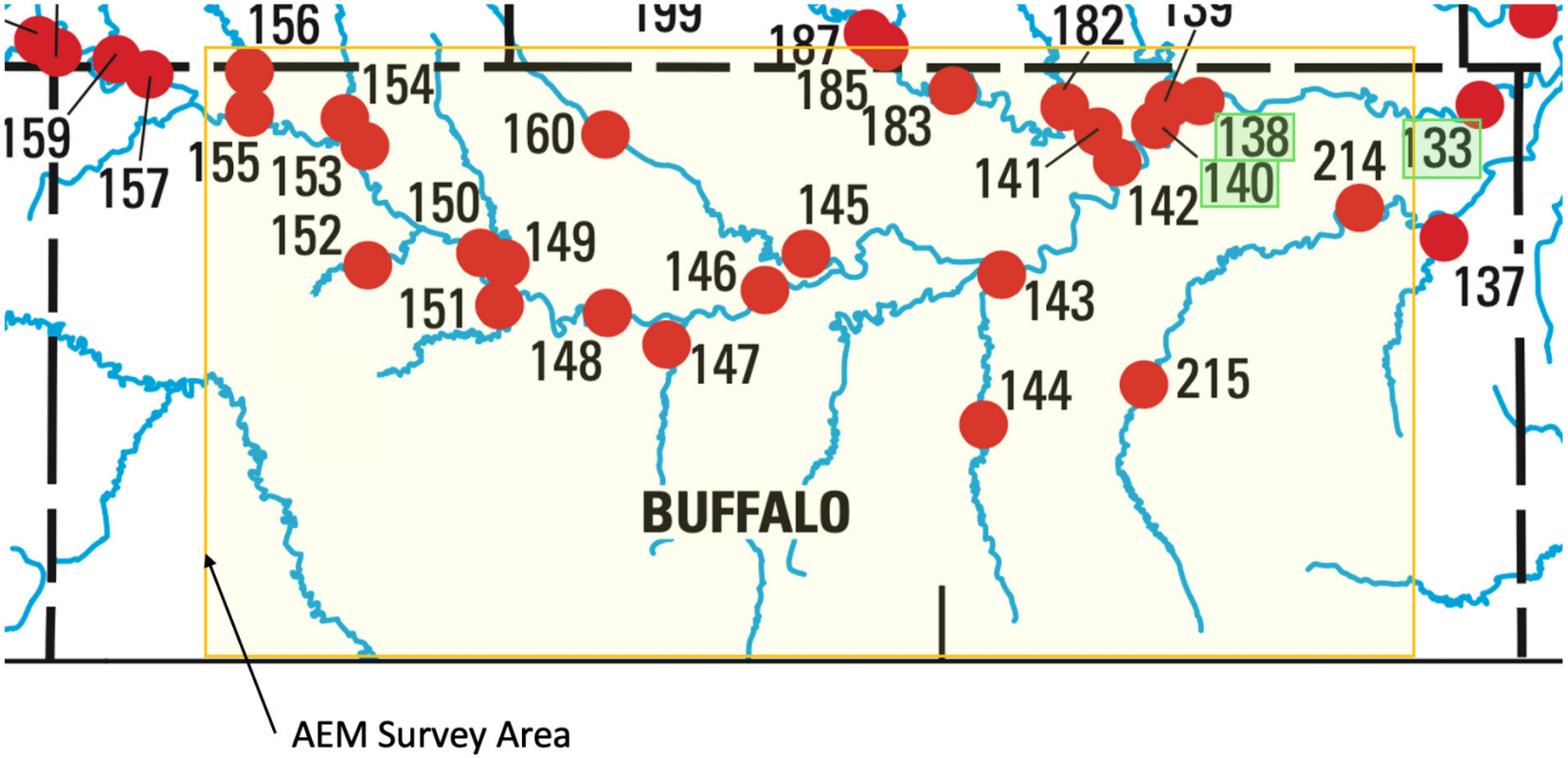


Figure 2-4. Map of stream flow measurement locations made during November 2006. Three sites 140, 138, and 133 below the confluence of the South Loup River and Mud Creek showed stream flow increasing. Modified from USGS data series report 332 (Peterson and Strauch, 2007).

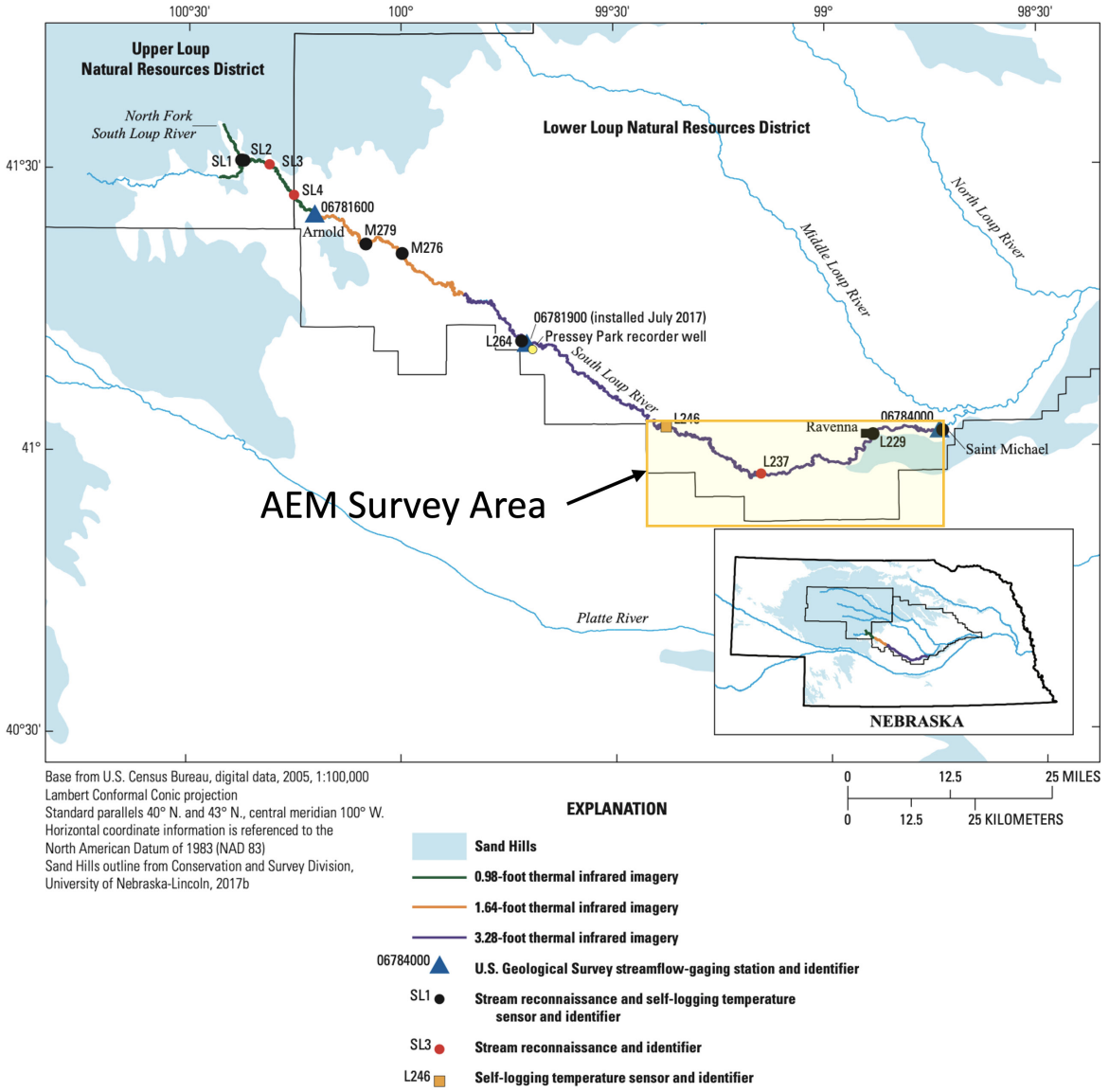


Figure 2-5. Map of stream flow and heat measurement locations made by USGS from SIR 2018-5093. These measurements show strong groundwater- surface water interaction in the AEM survey area. Modified from USGS SIR 2018-5093 (Hobza and Schepers, 2018).

2.2.2 Water Quality

U.S. Geological Survey Water Supply Paper 2245 provides an historic overview of water quality in the state of Nebraska (Engberg, 1984). Of interest is the map of Total Dissolved Solids (TDS) for the state which shows that the ***Q*** overall groundwater quality for TDS in the survey area ranges from 251 to 750 milligrams per liter (mg/L) and the ***To*** can be >750 mg/L. Electrical conductivity at two of the locations are in the flight path and reported readings of 406.2 and 500.2 µS/cm. The other 2 locations are west of the flight area, but still in the county, and reported TDS values of 520.0 mg/L and 703.2 mg/L. These readings were collected on 10/8/2019. This is important to the AEM survey results because concentrations of TDS above 1500 mg/L can affect the bulk resistivity values impacting the interpretations of the geological materials.

The Lower Loup NRD has been monitoring groundwater quality across the district with a network of monitoring wells since the late 1970s. One of the primary pollutants of concern is nitrate because of its steady rise in concentration to levels above the U.S. Environmental Protection Area (EPA) Maximum Contaminant Level (MCL) of 10 mg/L in certain areas of the district. Further discussion of nitrates in the study area can be found in Section 5.3.6 of this report.

3 Additional Background Information

Various sources of background information were used to interpret the AEM data, which is discussed in Section 5.

3.1 Borehole Data

Borehole data for this project consisted of a combination of lithologic, stratigraphic, and downhole geophysical logs. The borehole information was gathered from two sources: 1) CSD Nebraska Statewide Test Hole Database (UNL, 2020), which contains information from boreholes drilled between 1930 and 2019 by the CSD and other cooperating agencies, and 2) the Nebraska Department of Natural Resources (NE-DNR) Registered Well Database (NE-DNR, 2020).

Seven CSD boreholes are within the LLNRD AEM survey area that containing lithology and stratigraphic information are presented in Figure 3-1. Three CSD holes contained geophysical logs including 36-A-54, 37-A-54, and 38-A-54.

509 NE-DNR registered wells in the LLNRD AEM survey area containing lithology information are presented in Figure 3-2. 240 of these entries also contain information on yield, screen length, and water levels. Of the 240 wells, five were completed in Quaternary, 26 were completed in both the Quaternary and the Tertiary Ogallala Group, and 209 were completed in the Tertiary Ogallala Group.

The borehole utilized in this study are included in Appendix_3_Deliverables/Boreholes as ARC shapefiles databases.

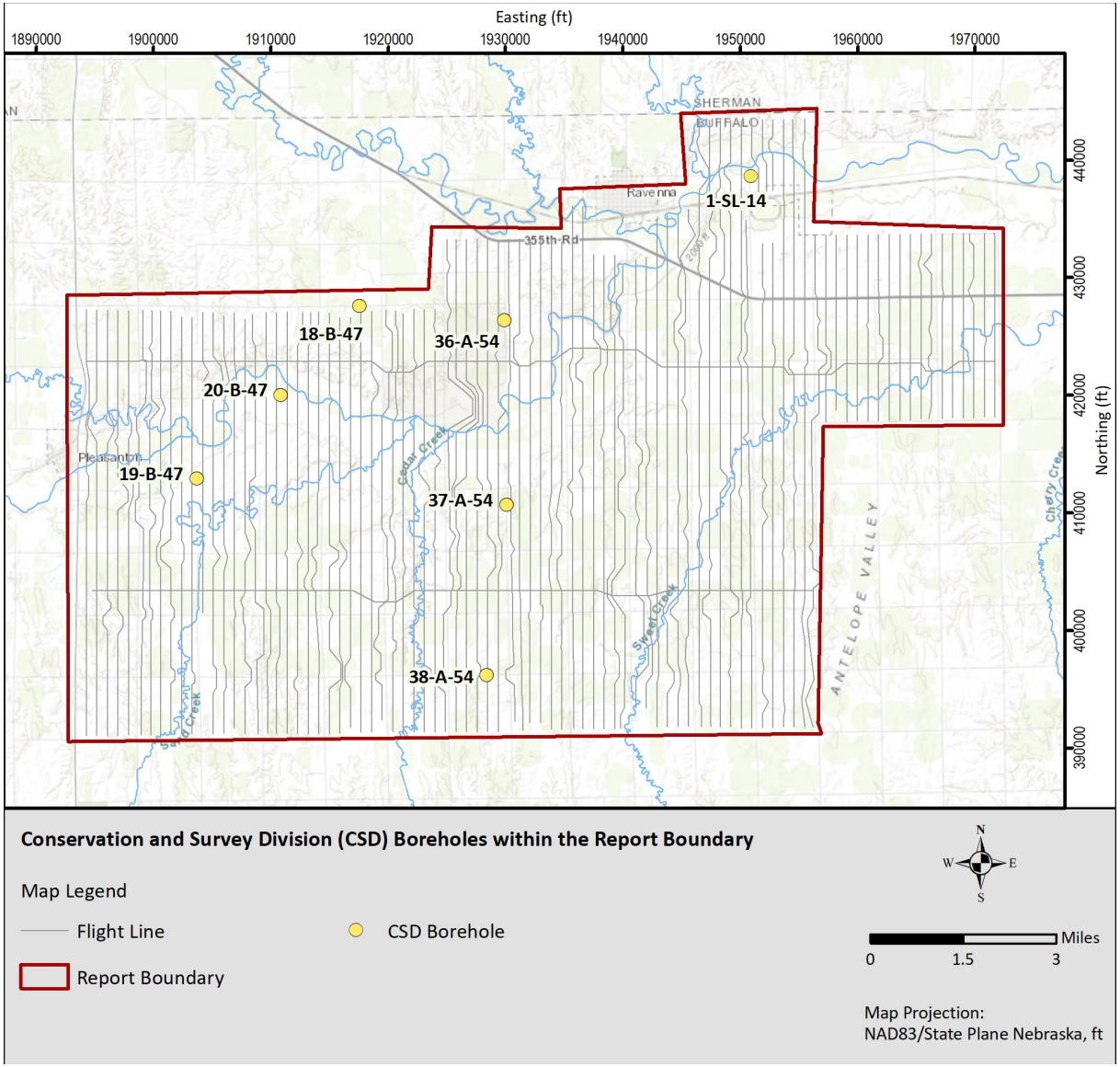


Figure 3-1. Locations of the Nebraska Conservation Survey Division (CSD) boreholes used in this study (UNL, 2020) of the LLNRD AEM survey area. The grey lines are the AEM flight lines.

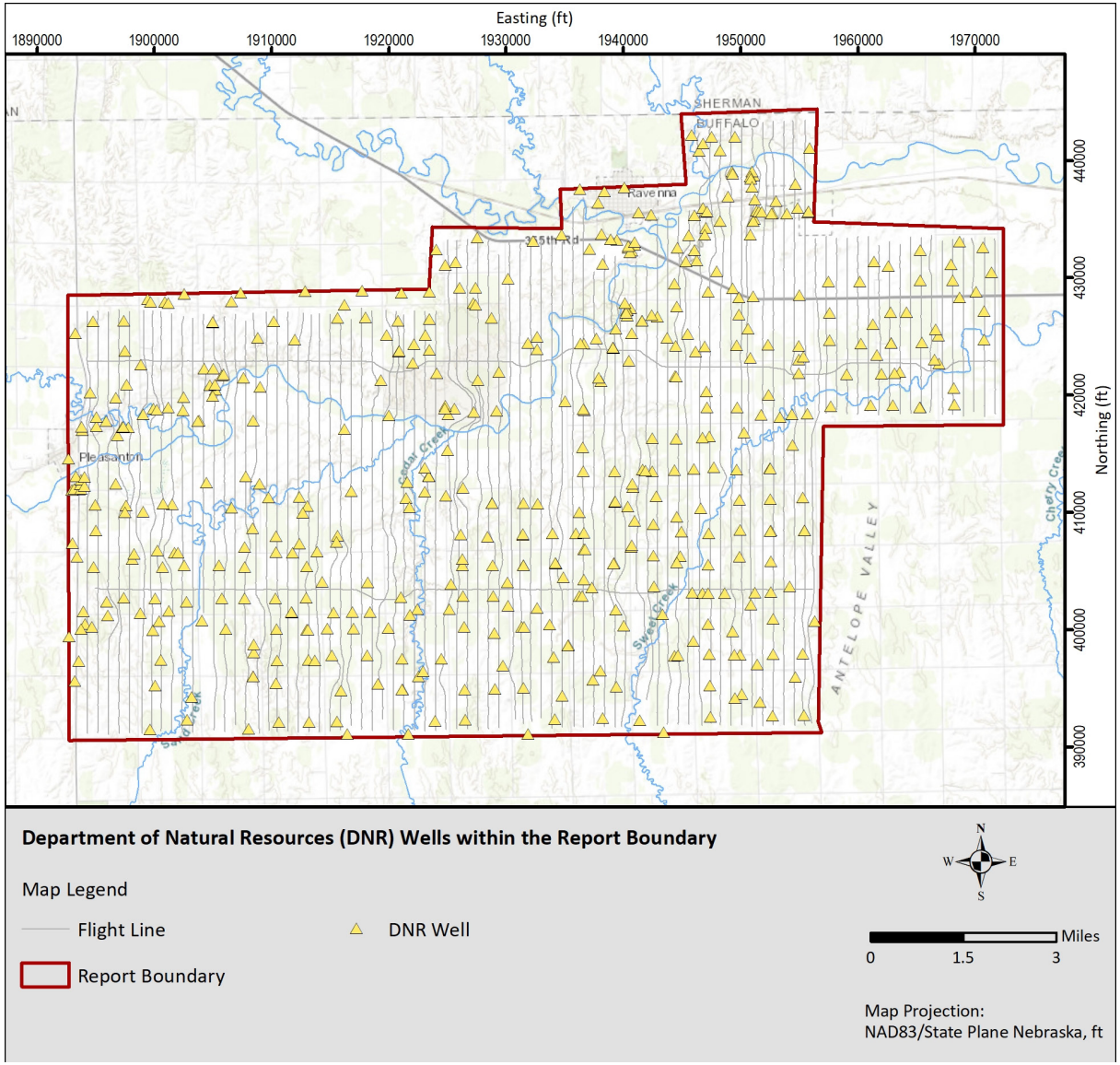


Figure 3-2. Locations of the Nebraska Department of Natural Resources (DNR) boreholes used in this study (NE-DNR, 2020) of the LLNRD AEM survey area. The grey lines are the AEM flight lines.

4 Geophysical Methodology, Acquisition and Processing

4.1 Geophysical Methodology

Airborne Transient Electromagnetic (TEM) or airborne Time-Domain Electromagnetic (TDEM), or generally AEM, investigations provide characterization of electrical properties of earth materials from the land surface downward using electromagnetic induction. Figure 4-1 gives a conceptual illustration of the airborne TEM method.

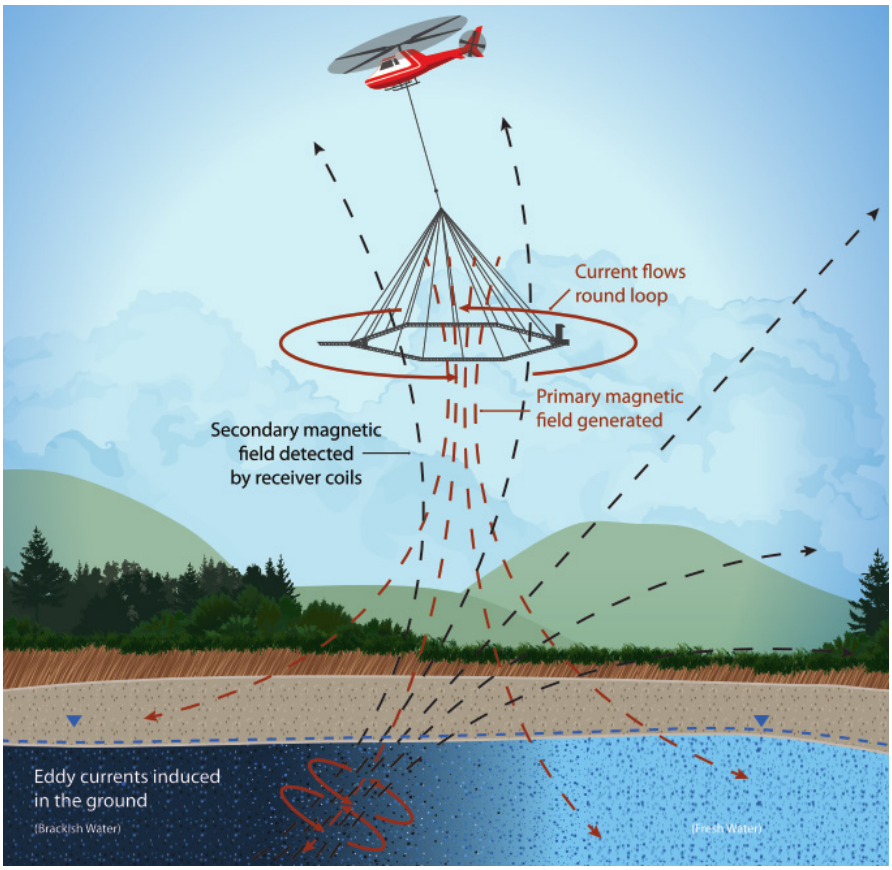
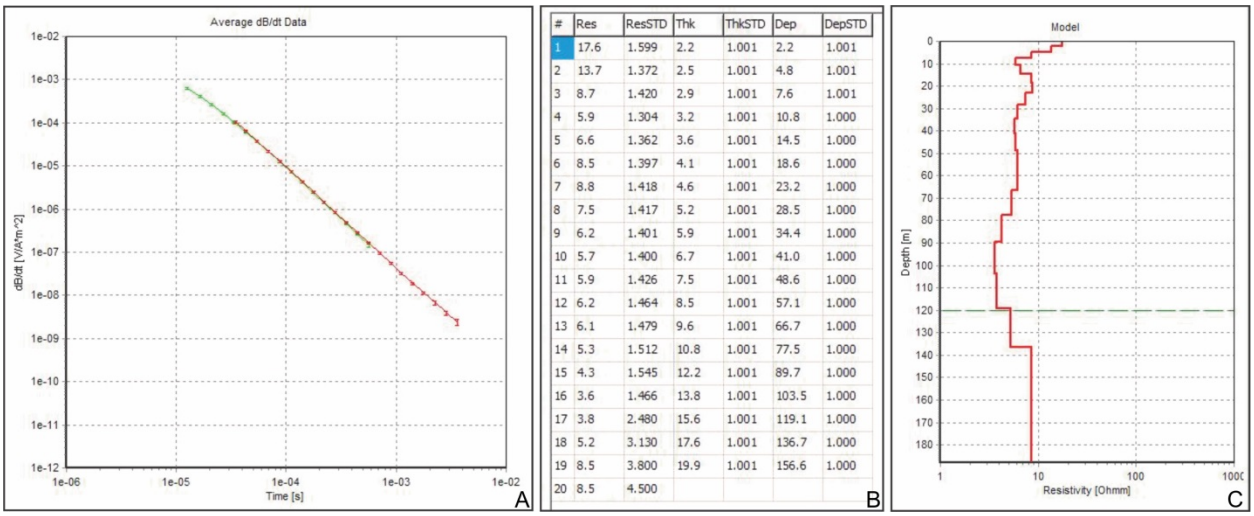


Figure 4-1. Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015).

To collect TEM data, an electrical current is sent through a large loop of wire consisting of multiple turns which generates an electromagnetic (EM) field. This is called the transmitter (Tx) coil. After the EM field produced by the Tx coil is stable, it is switched off as abruptly as possible. The EM field dissipates and decays with time, traveling deeper and spreading wider into the subsurface. The rate of dissipation is dependent on the electrical properties of the subsurface (controlled by the material composition of the geology including the amount of mineralogical clay, the water content, the presence of dissolved solids, the metallic mineralization, and the percentage of void space). At the moment of turnoff, a secondary time-varying EM field, which also begins to decay, is generated within the subsurface. The decaying secondary EM field generates a current in a receiver (Rx) coil, per Ampere's Law. This current is measured at several different moments in time (each moment being within a time band called a "gate"). From the induced current, the time rate of decay of the magnetic field, B, is determined (dB/dt). When

compiled in time, these measurements constitute a “sounding” at that location. Each TEM measurement produces an EM sounding at one point on the surface.

The sounding curves are numerically inverted to produce a model of subsurface resistivity as a function of depth. Inversion relates the measured geophysical data to probable physical earth properties. Figure 4-2 shows an example of a dual-moment TEM dB/dt sounding curve and the corresponding inverted electrical resistivity model.



#	Res	ResSTD	Thk	ThkSTD	Dep	DepSTD
1	17.6	1.599	2.2	1.001	2.2	1.001
2	13.7	1.372	2.5	1.001	4.8	1.001
3	8.7	1.420	2.9	1.001	7.6	1.001
4	5.9	1.304	3.2	1.001	10.8	1.000
5	6.6	1.362	3.6	1.001	14.5	1.000
6	8.5	1.397	4.1	1.001	18.6	1.000
7	8.8	1.418	4.6	1.001	23.2	1.000
8	7.5	1.417	5.2	1.001	28.5	1.000
9	6.2	1.401	5.9	1.001	34.4	1.000
10	5.7	1.400	6.7	1.001	41.0	1.000
11	5.9	1.426	7.5	1.001	48.6	1.000
12	6.2	1.464	8.5	1.001	57.1	1.000
13	6.1	1.479	9.6	1.001	66.7	1.000
14	5.3	1.512	10.8	1.001	77.5	1.000
15	4.3	1.545	12.2	1.001	89.7	1.000
16	3.6	1.466	13.8	1.001	103.5	1.000
17	3.8	2.480	15.6	1.001	119.1	1.000
18	5.2	3.130	17.6	1.001	136.7	1.000
19	8.5	3.800	19.9	1.001	156.6	1.000
20	8.5	4.500				

B

Figure 4-2. A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model.

4.2 Flight Planning/Utility Mapping

The primary source of noise in geophysical electromagnetic surveys are other electromagnetic devices that are part of typical municipal utility infrastructure. These include, for example, power lines, railroads, pipelines, and water pumps. Prior to AEM data acquisition in the LLNRD, three types of utilities (pipelines, railroads, and power lines) were located. Power line locations in Google Earth “kmz” format that were then converted to a Geographic Information Systems (GIS) Arc shapefile format. Some areas did not have coverage available for power line locations and were mapped by inspection from Google Earth imagery.

A GIS Arc shapefile of railroads in Nebraska was downloaded from the United States Department of Agriculture’s Natural Resource Conservation Service (US Dept Agriculture, 2020) and a shapefile of the pipelines in Nebraska was obtained. Maps of the utilities were exported in GeoTIFF and Google Earth kmz formats and were used during data processing and interpretation.

The locations of the flight lines were converted from a regularly spaced grid to one with flight lines optimized in order to avoid electromagnetic coupling with the previously mentioned utilities. This was done by moving along each flight line in Google Earth to inspect the path for visible power lines, radio towers, railroads, highways and roads, confined feeding operations and buildings, and any other obstructions that needed to be avoided during flight.

At the conclusion of the design process (Figure 1-2), the maximum line length for the LLNRD AEM survey area was about 15 miles in length in the east-west direction and a minimum of about 3 miles in the north-south direction and were separated by about 0.15 miles (250 m)..

4.3 AEM Survey Instrumentation

AEM data were acquired using the SkyTEM304M (304M) airborne electromagnetic system (SkyTem Airborne Surveys Worldwide, 2019). The 304M is a rigid frame, dual-magnetic moment (Low and High) TEM system. The area of the 304M Tx coil is 342 m^2 and the coil contains four (4) turns of wire. A peak current of nine (9) amps is passed through one turn of wire in the Tx for Low Moment measurements and a peak current of 112 amps is passed through the four turns of wire for High Moment measurements. This results in peak Tx Low and High magnetic moments of ~3,000 Ampere-meter-squared ($A*m^2$) and ~150,000 $A*m^2$, respectively.

The SkyTEM304M system utilizes an offset Rx positioned slightly behind the Tx resulting in a 'null' position which is a location where the intensity of the primary field from the system transmitter is minimized. This is desirable as to minimize the amplitude of the primary field at the Rx to maximize the sensitivity of the Rx to the secondary fields. The SkyTEM304M multi-turn Rx coil has an effective area of 105 m^2. In addition to the Tx and Rx that constitute the TEM instrument, the SkyTEM304M is also equipped with a Total Field magnetometer (MAG) and data acquisition systems for both instruments. The SkyTEM304M also includes two each of laser altimeters, inclinometers/tilt meters, and differential global positioning system (DGPS) receivers. Positional data from the frame mounted DGPS receivers are recorded by the AEM data acquisition system. The magnetometer includes a third DGPS receiver whose positional data is recorded by the magnetometer data acquisition system. Figure 4-3 gives a simple illustration of the SkyTEM304M frame and instrument locations. The image is viewed along the +z axis looking at the horizontal x-y plane. The axes for the image are labeled with distance in meters. The magnetometer is located on a boom off the front of the frame (right side of image). The Tx coil is located around the octagonal frame and the Rx Coil is located at the back of the frame (left side of image).

The coordinate system used by the 304M defines the +x direction as the direction of flight, the +y direction is defined 90 degrees to the right and the +z direction is downward. The center of the transmitter loop, mounted to the octagonal SkyTEM frame is used as the origin in reference to instrumentation positions. Table 4-1 lists the positions of the instruments (in feet) and Table 4-2 lists the corners of the transmitter loop in feet (whereas units of meters are presented in Figure 4-3).

The DGPS and magnetometer mounted on the frame of the SkyTEM304M require the use of base stations, which are located on the ground and are positioned in an area with low cultural noise. Data from the magnetometer and DGPS base stations were downloaded each day after the end of the day's AEM flights. The DGPS and magnetometer base stations were placed at the Universal Transverse Mercator (UTM) coordinate system location listed in Table 4-3. The horizontal geodetic reference used is North American Datum of 1983 (NAD83 in feet). All elevations are from USGS's National Elevation Dataset, referenced to the North American Vertical Datum of 1988; with feet as the unit of measurement.

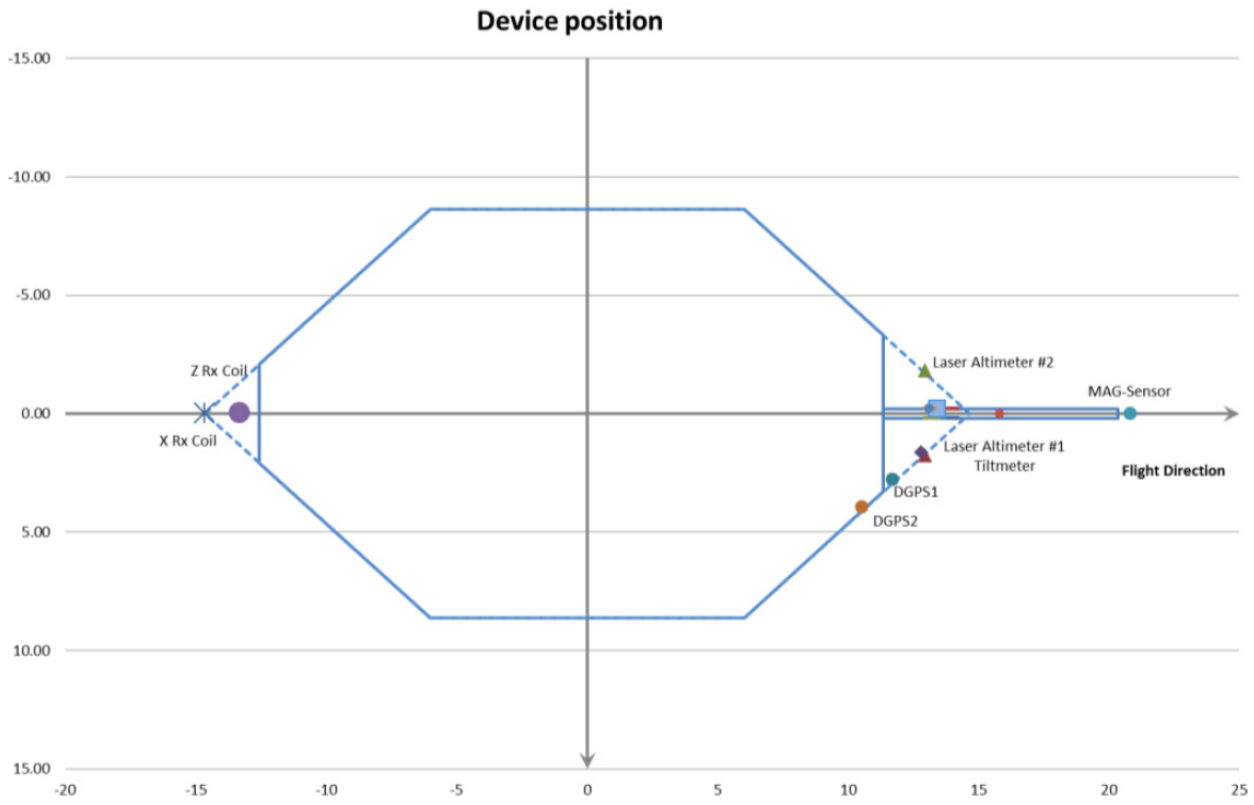


Figure 4-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1.



Figure 4-4. Photos of the SkyTEM304M system in suspension beneath the helicopter.

For this project, the 304M was flown at an average speed of 51 mi/hr (82.4 kilometers/hr) at an average flight height of 104 ft (31.7 m) above the land surface, using the sling-load cargo system of a Eurocopter Astar 350 B3 helicopter. Figure 4-4 displays a couple of images of the 304M in operation.

Table 4-1: Positions of instruments on the SkyTEM304M frame, using the center of the frame as the origin, in feet.

	DGPS 1	DGPS 2	Inclinometer 1	Inclinometer 2	Altimeter 1	Altimeter 2	Magnetic Sensor	Rx Coil
X	39.08	34.15	42.36	42.36	42.44	42.44	67.24	-43.46
Y	9.15	12.96	5.38	-5.38	5.87	-5.87	0.00	0.00
Z	-0.52	-0.52	-0.39	-0.39	-0.39	-0.39	-1.71	-6.56

Table 4-2: Positions of corners of the SkyTEM304M transmitter coil, using the center of the frame as the origin in feet.

Tx Corners	1	2	3	4	5	6	7	8
X	-41.46	-20.17	18.83	36.51	36.51	18.83	-20.17	-41.46
Y	-6.99	-28.18	-28.18	-10.46	10.46	28.18	28.18	6.99

Table 4-3: Locations of DGPS and magnetic field base station instruments.

Instrument	Easting (ft)	Northing (ft)	Zone
DGPS Base Station – Kearney Airport	1915928	324074	NESP83ft
Magnetometer Base Station – Kearney Airport	1913679	323874	NESP83ft

4.4 Data Acquisition

All SkyTEM systems are calibrated to a ground test site in Lyngby, Denmark prior to being used for production work (HydroGeophysics Group Aarhus University, 2010; HydroGeophysics Group Aarhus University, 2011; Foged et al., 2013). The calibration process involves acquiring data with the system hovering at different altitudes, from 16 ft to 164 ft, over the Lyngby site. Acquired data are processed and a scale factor (time and amplitude) is applied so that the inversion process produces the model that approximates the known geology at Lyngby.

For this survey, AEM data acquisition and the GPS and magnetic field base stations were based out of the Kearney Airport. Calibration test flights were flown to ensure that the equipment was operating within technical specifications. Survey set-up procedures included measurement of the transmitter waveforms, verification that the receiver was properly located in a null position, and verification that all positioning instruments were functioning properly. A high-altitude test, used to verify system performance, was flown prior to the beginning of the survey's production flights. In the field, quality control of the operational parameters for the EM and magnetic field sensors including current levels, positioning sensor dropouts, acquisition speed, and system orientation were conducted with proprietary SkyTEM software following each flight.

Approximately 612.4 line-miles (992.1 line-kilometers) were acquired over the LLNRD AEM survey area on October 19-25, 2019 (Figure 4-5). Several airports including the Kearney Airport were used during these flights for refueling and landings including overnight storage.

4.4.1 Primary Field Compensation

A standard SkyTEM data acquisition procedure involves review of acquired raw data by SkyTEM in Denmark for Primary Field Compensation (PFC) prior to continued data processing by AGF (Schamper et al., 2014). The primary field of the transmitter affects the recorded early time gates, which in the case of the Low Moment, are helpful in resolving the near surface resistivity structure of the ground. The Low Moment uses a saw tooth waveform which is calculated and then used in the PFC correction to correct the early time gates.

4.4.2 Automatic Processing

The AEM data collected by the 304M were processed using Aarhus Workbench version 5.2.0.0 (at Aarhus Geosoftware (http://www.aarhusgeosoftware.dk/aarhus-workbench-ib3ao) described in HydroGeophysics Group, Aarhus University (2011).

Automatic processing algorithms provided within the Workbench program are initially applied to the AEM data. DGPS locations were filtered using a stepwise, second-order polynomial filter of nine seconds with a beat time of 0.5 seconds, based on flight acquisition parameters. The AEM data are corrected for tilt deviations from level and so filters were also applied to both of the tilt meter readings with a median filter of three seconds and an average filter of two seconds. The altitude data were corrected using a series of two polynomial filters. The lengths of both eighth-order polynomial filters were set to 15 seconds with shift lengths of 12 seconds. The lower and upper thresholds were 1 and 100 meters, respectively.

Trapezoidal spatial averaging filters were next applied to the AEM data. The times used to define the trapezoidal filters for the Low Moment were $1.0x10^{-5}$ sec, $1.0x10^{-4}$ sec, and $1.0x10^{-3}$ sec with widths of 4, 7, and 18 seconds. The times used to define the trapezoid for the High Moment were $1.0x10^{-4}$ sec, $1.0x10^{-3}$ sec, and $1.0x10^{-2}$ sec with widths of 10, 20, and 36 seconds. The trapezoid sounding distance was set to 1.0 seconds and the left/right setting, which requires the trapezoid to be complete on both sides, was turned on. The spike factor and minimum number of gates were both set to 25 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

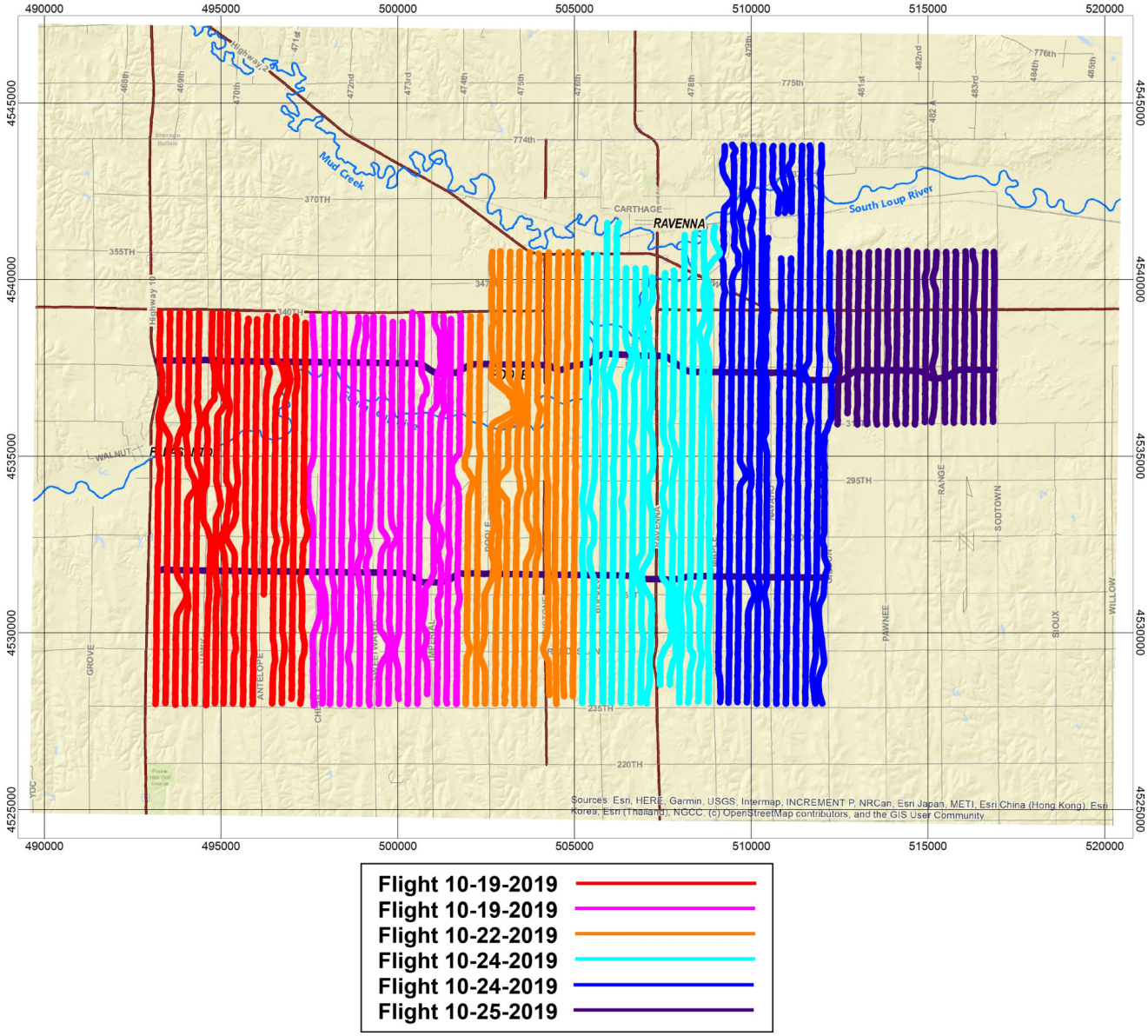


Figure 4-5. LLNRD 2019 AEM flight lines grouped by acquisition date. Projection is NAD83 State Plane Nebraska Feet.

4.4.3 Manual Processing and Laterally-Constrained Inversions

After the implementation of the automatic filtering, the AEM data were manually examined using a sliding two-minute time window. The data were examined for possible electromagnetic coupling with surface and buried utilities and metal, as well as for late time-gate noise. Data affected by these were removed. Examples of locating areas of EM coupling with pipelines or power lines and recognizing and removing coupled AEM data in Aarhus Workbench are shown in Figure 4-6 and Figure 4-7, respectively. Examples of two inversions, one without EM coupling and the other with EM coupling, are shown in Figure 4-8. Areas were also cut out where the system height was flown greater than 200 feet above the ground surface which caused a decrease in the signal level. This problem was encountered at several locations along the Loup River due to the tall cottonwood trees.

The AEM data were then inverted using a Laterally-Constrained Inversion (LCI) algorithm (Christensen et al., 2009; HydroGeophysics Group Aarhus University, 2011). The profile and depth slices were examined, and any remaining electromagnetic couplings were masked out of the data set.

After final processing, 548.6 line-miles (888.7 line-km) of data were retained for the final inversions for the LLNRD AEM survey area. This amounts to a data retention of 89.6%. This high rate is the result of careful flight line planning and design. In Figure 4-9 are flight lines with blue colors representing data retained for inversion and red lines representing data removed due to infrastructure and late time noise.

4.4.4 Power Line Noise Intensity (PLNI)

The Power Line Noise Intensity (PLNI) channel assists in identifying possible sources of noise from power lines. Pipelines, unless they are cathodically-protected, are not mapped by the PLNI. The PLNI is produced by performing a spectral frequency content analysis on the raw received Z-component SkyTEM data. For every Low Moment data block, a Fourier Transform (FT) is performed on the latest usable time gate data. The FT is evaluated at the local power line transmission frequency (60 Hz) yielding the amplitude spectral density of the local power line noise. The PLNI data for the LLNRD 2019 AEM survey area are presented in Figure 4-10.

4.4.5 Magnetic Field Data

As discussed above, the SkyTEM 304M includes a Total Field magnetometer. The magnetic Total Field data can yield information about infrastructure as well as geology. Figure 4-11 shows the magnetic Total Field intensity data for the LLNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF) creating the Residual Magnetic Field (RMF). These data are used in decoupling efforts.

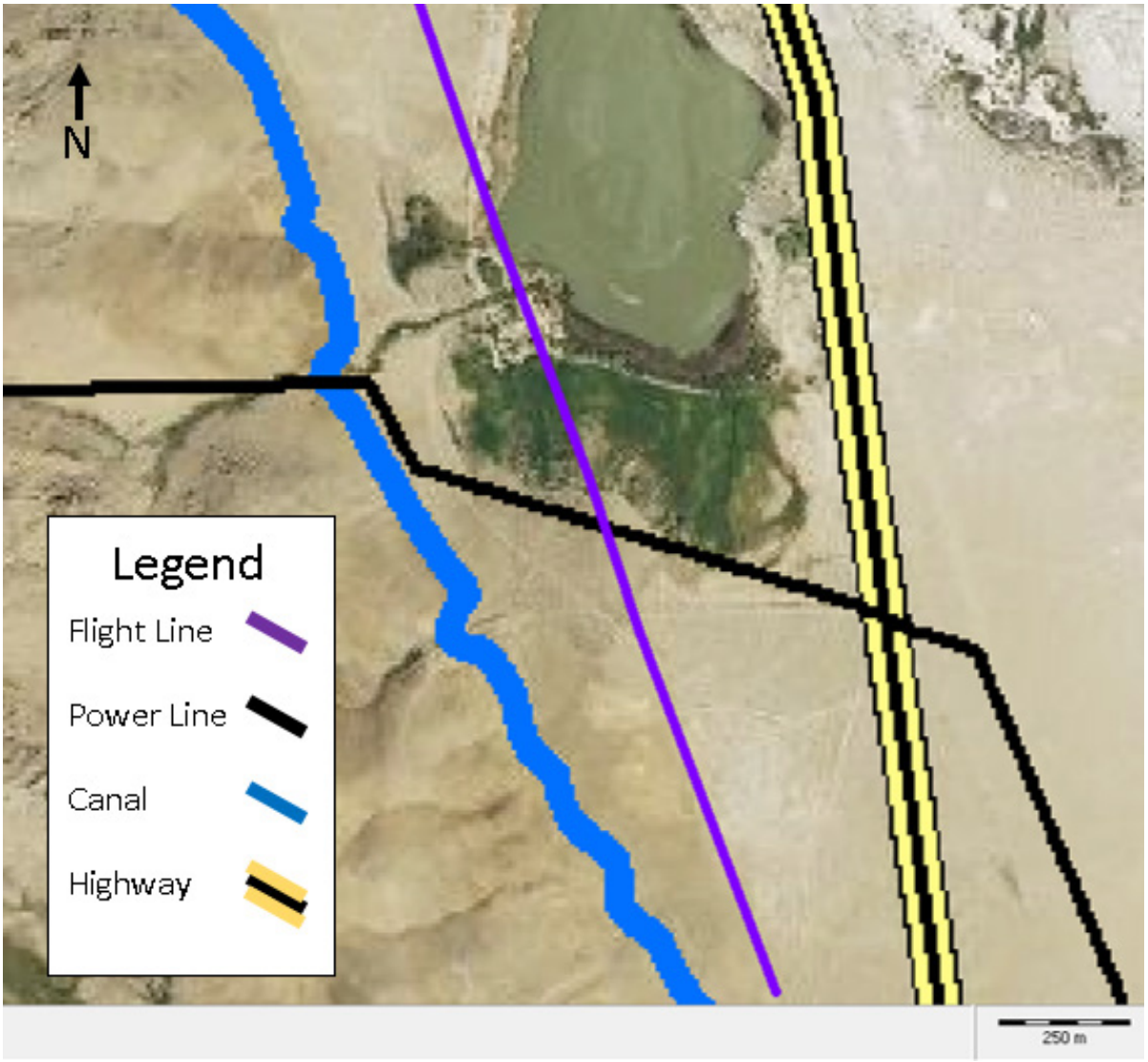


Figure 4-6. Example locations of electromagnetic coupling with pipelines or power lines.

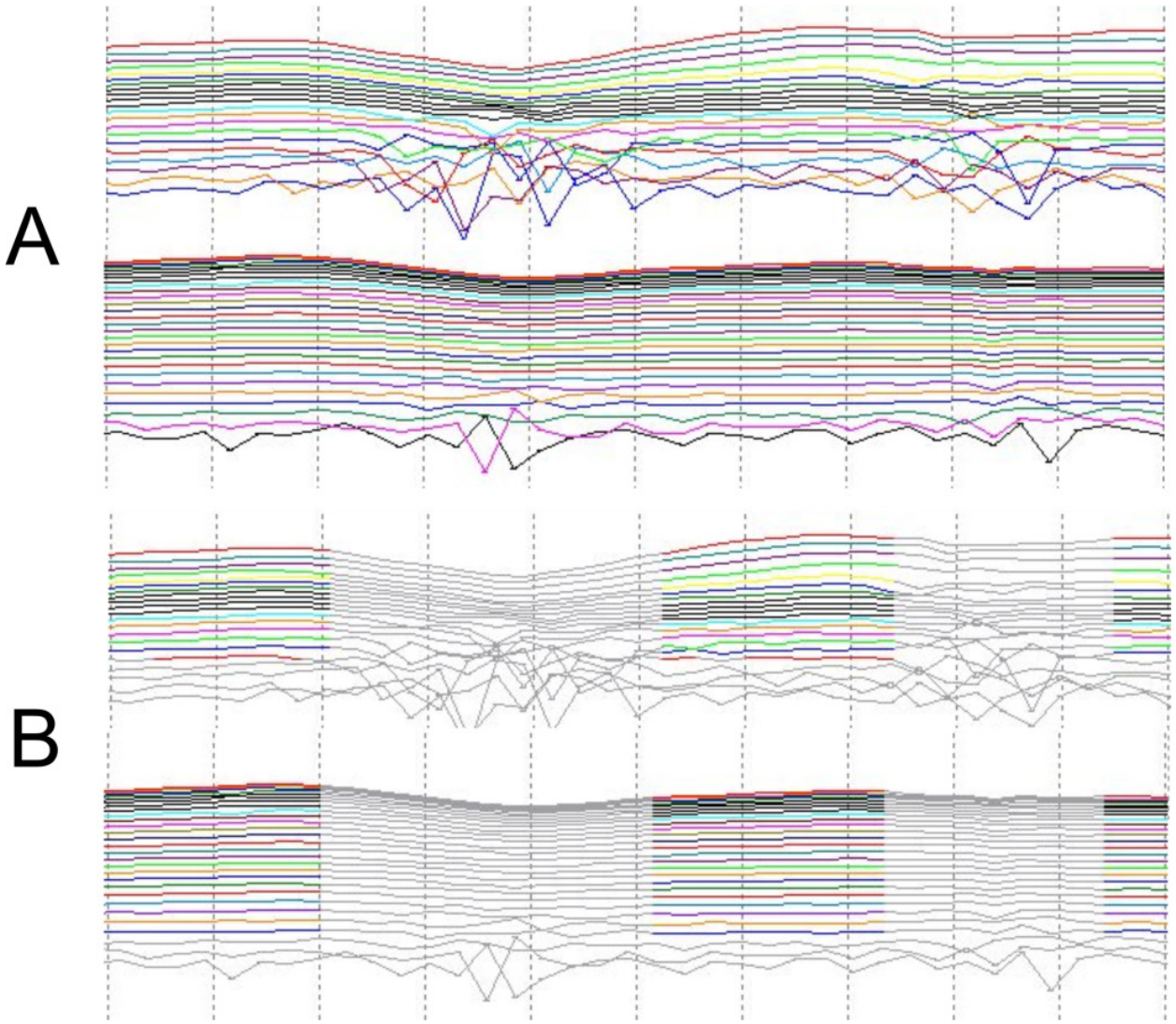


Figure 4-7. Example of AEM data affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

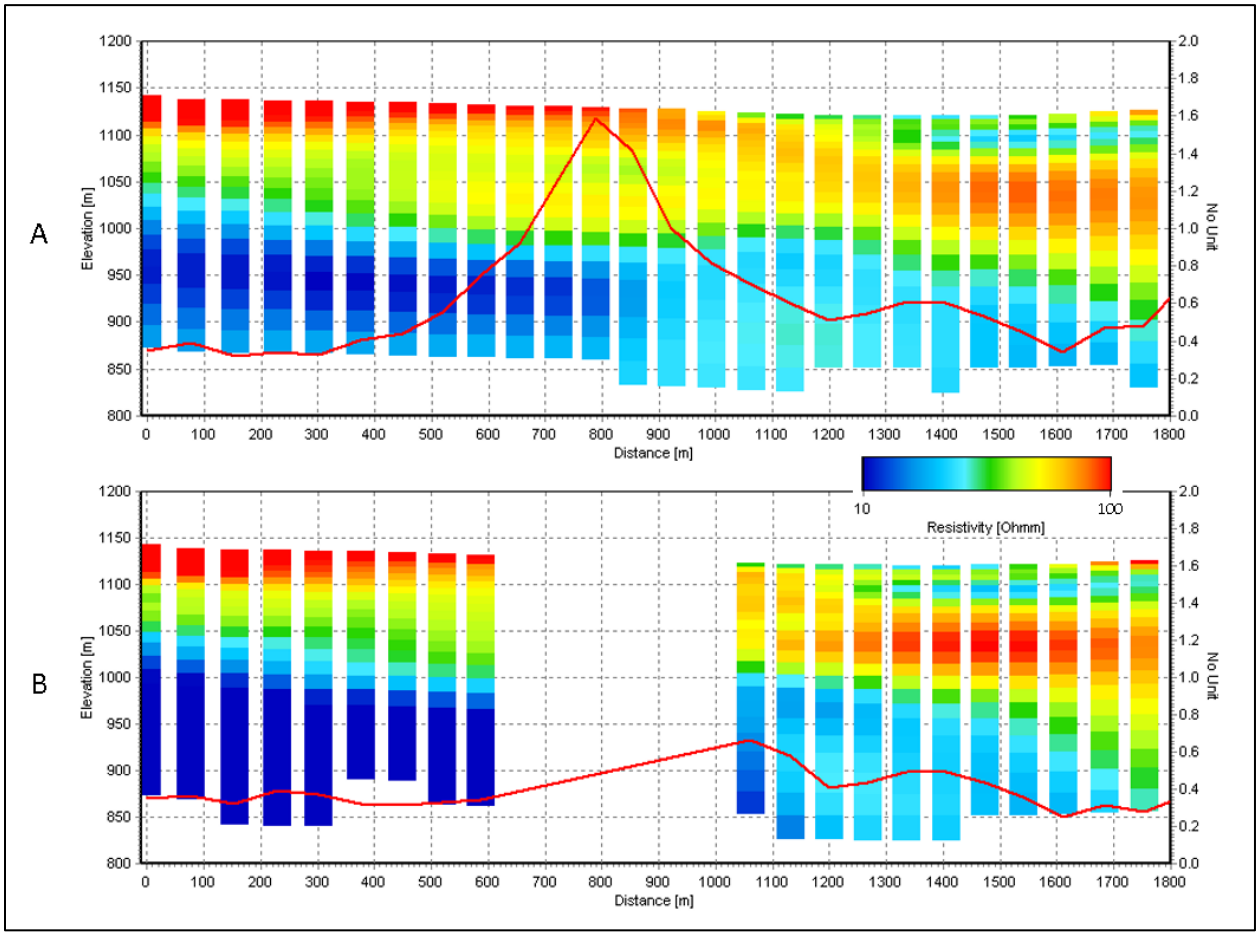


Figure 4-8. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

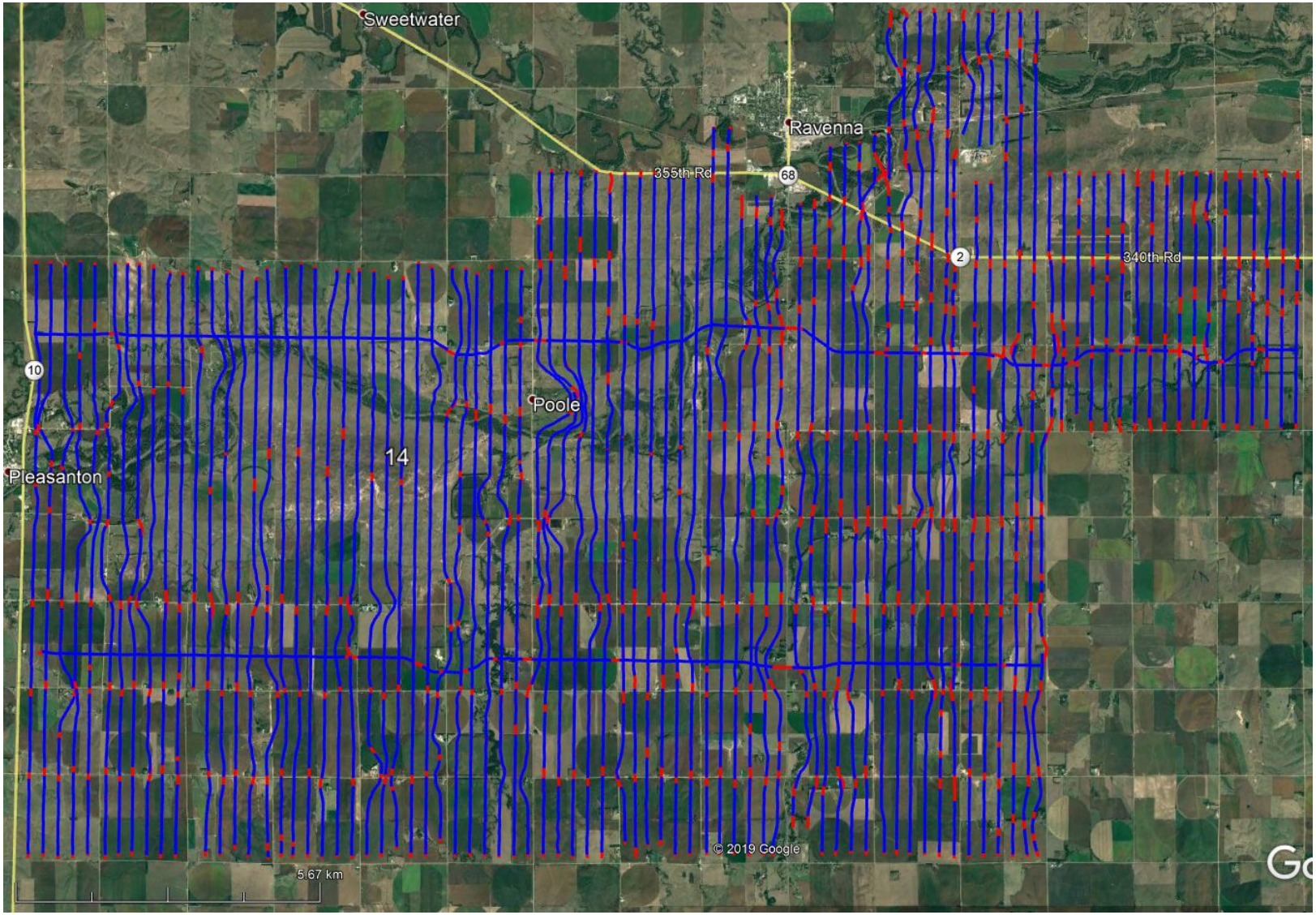


Figure 4-9. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LLNRD AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix_3_Deliverables\KMZ.

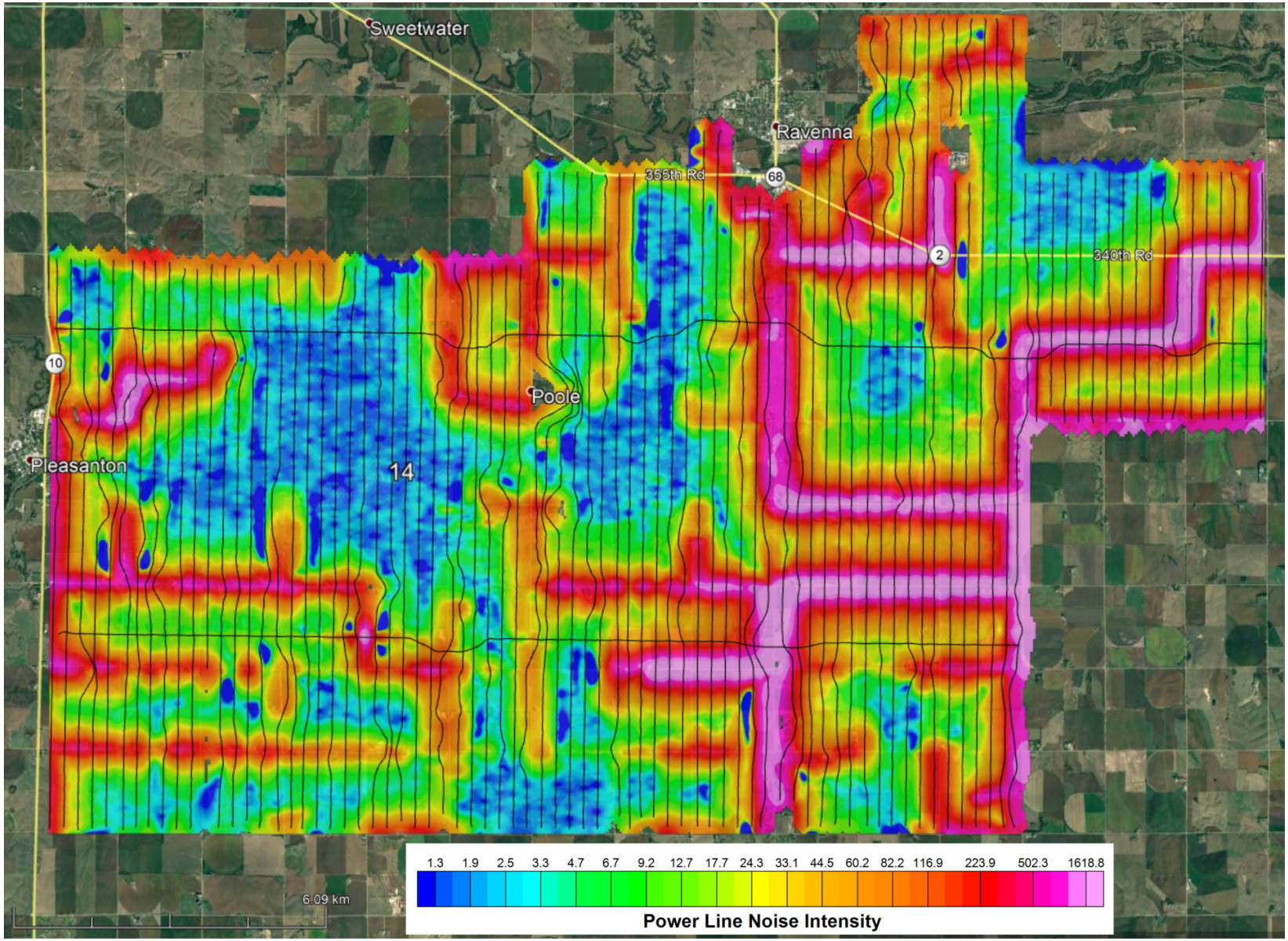


Figure 4-10. Power Line Noise Intensity (PLNI) map of the LLNRD AEM survey area.

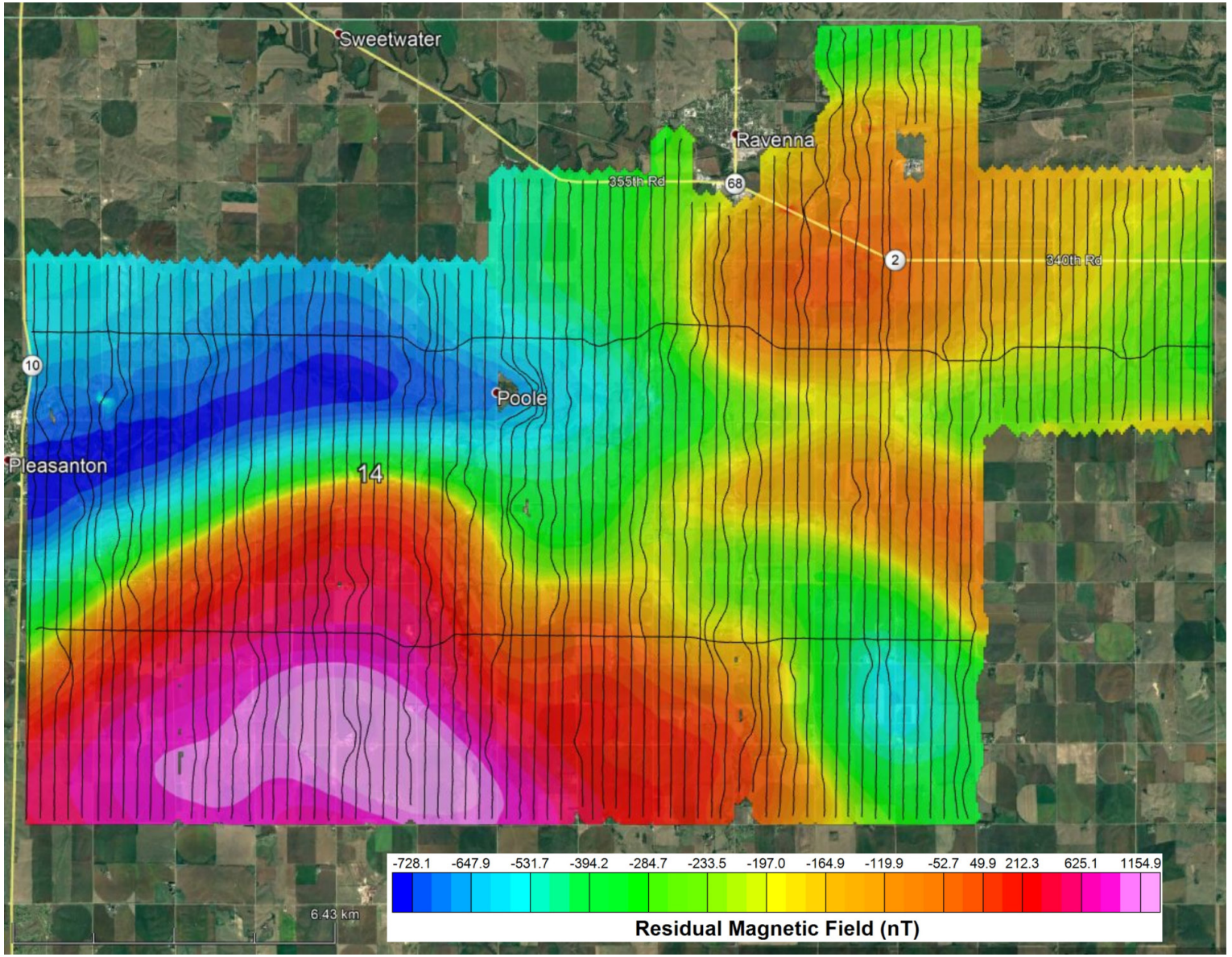


Figure 4-11. Map of the Residual Magnetic Field (nT) of the LLNRD AEM survey area.

4.5 Spatially-Constrained Inversion

Following the initial decoupling and LCI analysis, Spatially-Constrained Inversions (SCI) were performed. SCIs use EM data along, and across, flight lines within user-specified distance criteria (Viezzoli et al., 2008). The LLNRD AEM data were inverted using SCI smooth models with 40 layers, each with a starting resistivity of 10 Ohm-m (equivalent to a 10 ohm-m halfspace). The thicknesses of the first layers of the models were about 10 ft with the thicknesses of the consecutive layers increasing by a factor of about 1.04. The depths to the bottoms of the 39th layers were set to 1,067 ft, with thicknesses up to about 58 ft. The thicknesses of the layers increase with depth (Table 4-4 and Figure 4-12) as the resolution of the technique decreases. The spatial reference distance, ***s***, for the constraints were set to 328 ft with power laws of 0.75. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.4 and 1.4, respectively, for all layers.

In addition to the recovered resistivity models the SCIs also produce data residual error values (single sounding error residuals) and Depth of Investigation (DOI) estimates. The data residuals compare the measured data with the response of the individual inverted models (Christensen et al., 2009). The DOI provides a general estimate of the depth to which the AEM data are sensitive to changes in the resistivity distribution at depth (Christiansen and Auken, 2012). Two DOI's are calculated: an "Upper" DOI at a cumulative sensitivity of 1.2 and a "Lower" DOI set at a cumulative sensitivity of 0.6. A more detailed discussion on the DOI can be found in Asch et al. (2015).

Table 4-4: Thickness and depth to bottom for each layer in the Spatially Constrained Inversion (SCI) AEM earth models. The thickness of the model layers increase with depth as the resolution of the AEM technique decreases.

Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)	Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)
1	9.8	9.8	3.0	3.0	21	343.4	24.9	104.7	7.6
2	20.0	10.2	6.1	3.1	22	369.6	26.2	112.7	8.0
3	30.8	10.8	9.4	3.3	23	397.2	27.6	121.1	8.4
4	42.3	11.5	12.9	3.5	24	426.1	28.9	129.9	8.8
5	54.1	11.8	16.5	3.6	25	456.3	30.2	139.1	9.2
6	66.6	12.5	20.3	3.8	26	487.8	31.5	148.7	9.6
7	79.7	13.1	24.3	4.0	27	520.9	33.1	158.8	10.1
8	93.5	13.8	28.5	4.2	28	555.7	34.8	169.4	10.6
9	107.9	14.4	32.9	4.4	29	592.1	36.4	180.5	11.1
10	123.0	15.1	37.5	4.6	30	630.2	38.1	192.1	11.6
11	138.7	15.7	42.3	4.8	31	670.2	40.0	204.3	12.2
12	155.1	16.4	47.3	5.0	32	712.2	42.0	217.1	12.8
13	172.5	17.4	52.6	5.3	33	756.1	44.0	230.5	13.4
14	190.6	18.0	58.1	5.5	34	802.1	45.9	244.5	14.0
15	209.6	19.0	63.9	5.8	35	850.3	48.2	259.2	14.7
16	229.3	19.7	69.9	6.0	36	900.8	50.5	274.6	15.4
17	250.0	20.7	76.2	6.3	37	953.7	52.8	290.7	16.1
18	271.6	21.7	82.8	6.6	38	1009.1	55.4	307.6	16.9
19	294.6	23.0	89.8	7.0	39	1067.2	58.1	325.3	17.7
20	318.5	24.0	97.1	7.3					

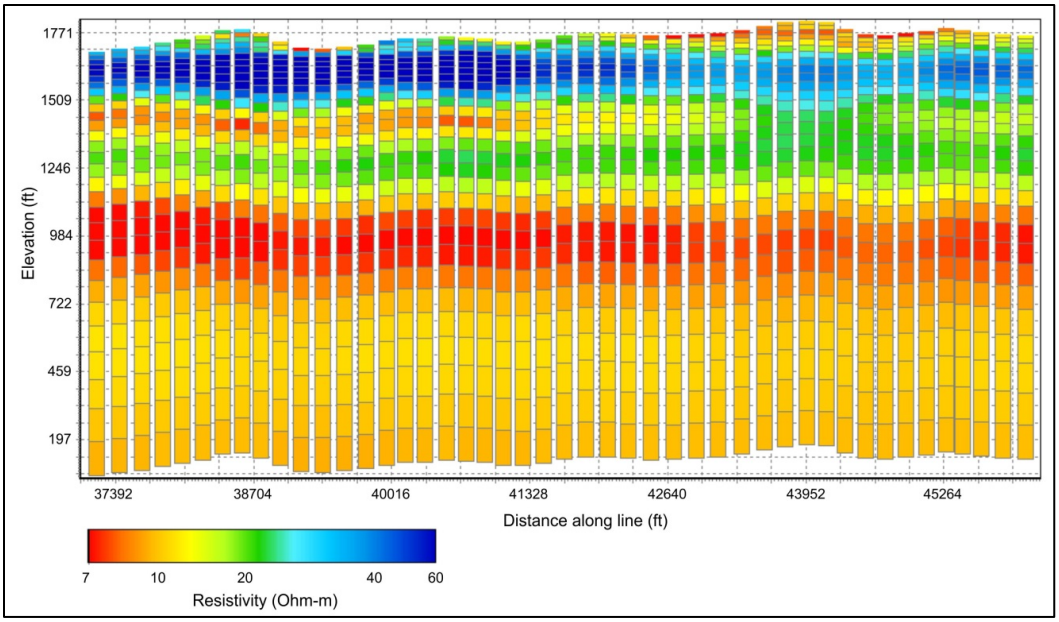


Figure 4-12. An example of an AEM profile illustrating increasing model layer thicknesses with depth.

Figure 4-13 presents a histogram of the LLNRD SCI inversion data/model residuals. Maps of data residuals for the LLNRD AEM study area are presented in Figure 4-14.

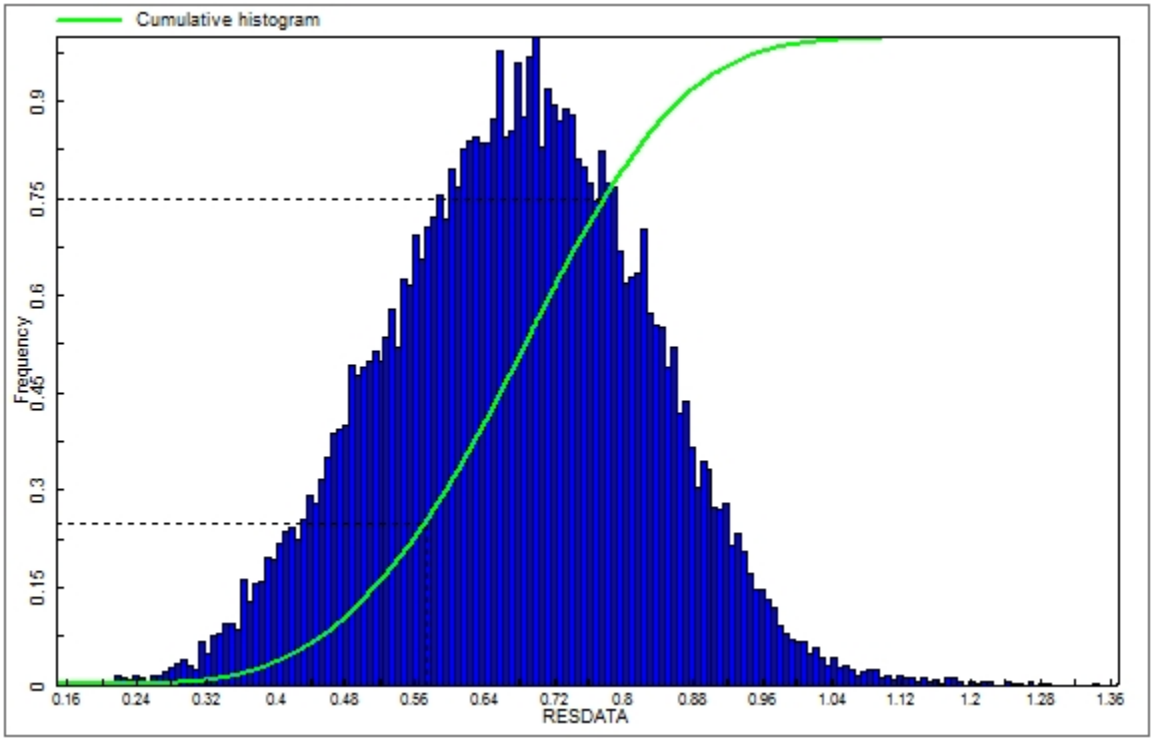


Figure 4-13. Data/model residual histogram for the LLNRD SCI inversion results.

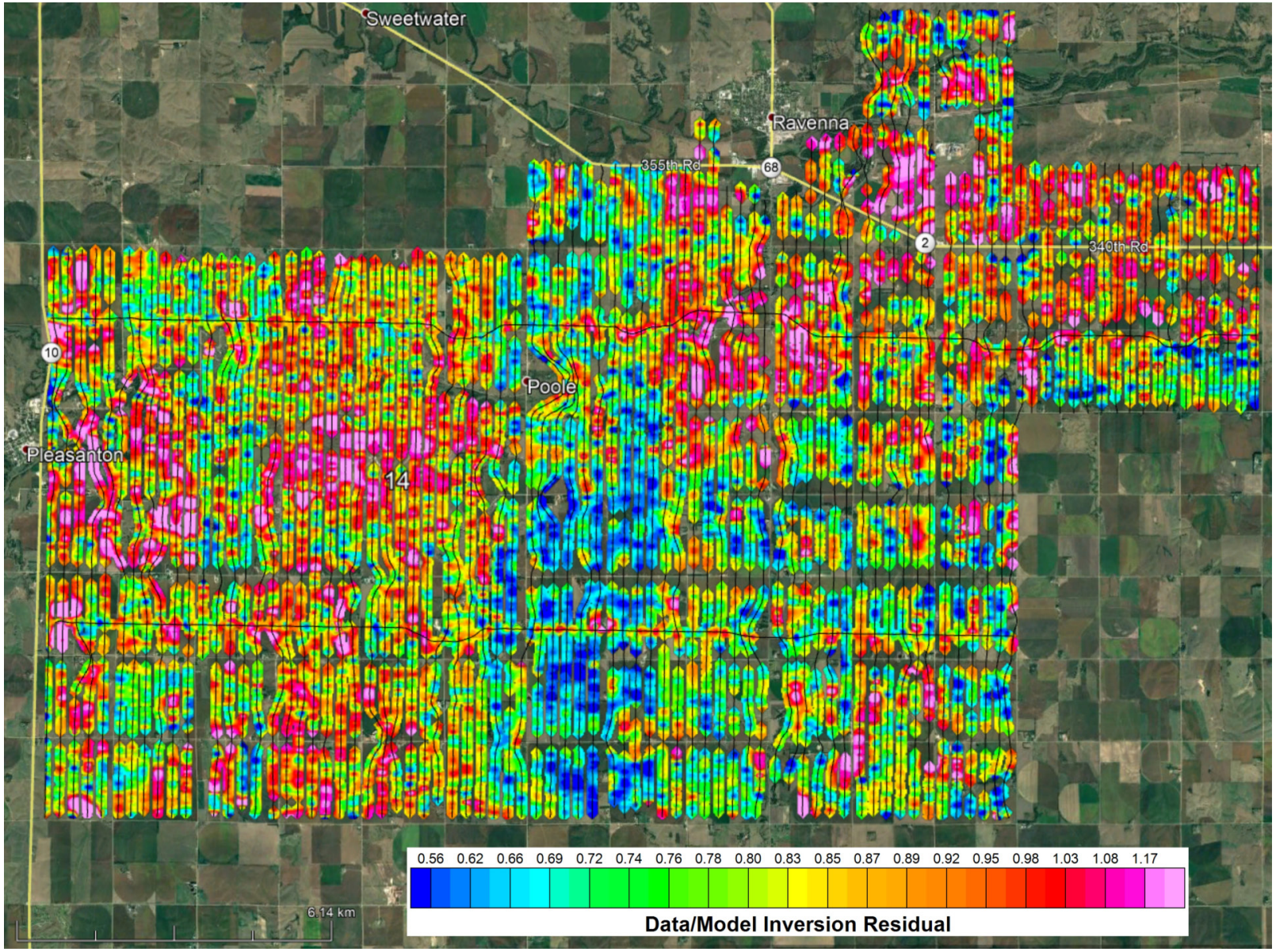


Figure 4-14. Map of data/model residuals for the LLNRD SCI inversion results.

5 AEM Results and Interpretation

This section provides the details on the process involved in the interpretation of the LLNRD 2019 AEM data and inversion results.

5.1 Interpretive Process

5.1.1 Merging AEM Flight Lines

After the inversion process several short lines were combined to form continuous lines within the survey area. The short lines are the results of lines that were broken up in areas that needed to be avoided due to flight regulations and or safety concerns. The resultant continuous lines allow for improved viewing and interpretation of the AEM inversions results. Table 5-1 lists the original flown lines and the merging that was implemented.

Table 5-1. Flight lines Merged within the LLNRD 2019 AEM Survey Area

Original Source Lines	Direction	New Merged Line
L106401	North-South	106400
L106402	North-South	
L106602	North-South	106600
L106701	North-South	
L106801	North-South	106800
L106901	North-South	

5.1.2 Construction of the Project Digital Elevation Model

To ensure that the elevation used in the project is constant for all the data sources (i.e. boreholes and AEM) a Digital Elevation Model (DEM) was constructed for the LLNRD survey. The data was downloaded from the National Elevation dataset (NED) located at the National Map Website (U.S. Geological Survey, 2020) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates are North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88). The 100 ft grid cell size was used throughout the project and resulting products. Figure 5-1 is a map of the DEM showing a vertical relief of 350 ft with a minimum elevation of 1,940 ft and a maximum elevation of 2,290 ft. This DEM was used to reference all elevations within the AEM and borehole datasets.

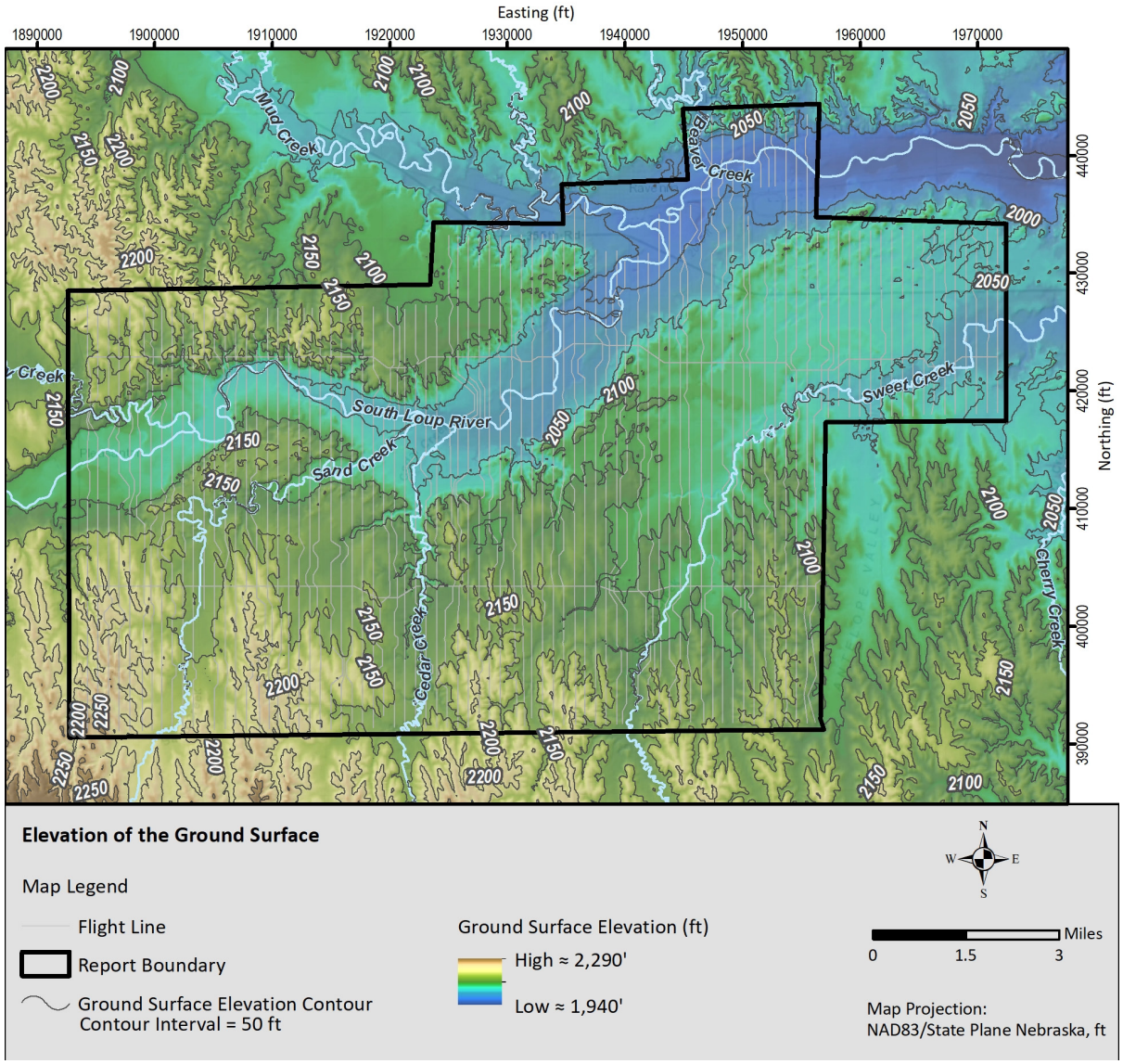


Figure 5-1. Map of the Digital Elevation Model for the 2020 LLNRD AEM Survey Area. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2020). The elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88) (feet).

5.1.3 Create Interpretative 2D Profiles

After final combination of the AEM data, characterization of the subsurface was performed in cross-section format using Datamine Discover Profile Analyst (**Datamine, 2020**). During interpretation, the horizontal and vertical scale of the profiles were adjusted to facilitate viewing. The color scale of the resistivity data was also adjusted to illuminate subtle differences in the resistivity structure within the inverted AEM resistivity data related to the area being interpreted. The first step in the interpretation is digitizing the contacts between the geologic units including: Quaternary (*Q*), Tertiary Ogallala Group (*To*), and the Cretaceous Pierre Shale (*Kp*). The interpreted geological units included the *Q*, *To*, and *Kp* from the upper surface to the DOI. The interpretive process benefited from the use of CSD and NE-DNR borehole logs which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (**Burchett, 1986**), but may differ due to the final interpretation of the AEM.

The interpretation began with picking the *Kp* contact and then finally the *To* interface.

The interpretation of the *Kp* included examining the AEM profile section for a low electrical resistivity layer that was also indicated in the borehole logs as the base of aquifer. Many of the CSD as well as the NE-DNR borehole logs stop at the *Kp* due to that stratigraphic unit not being considered an aquifer since it is composed predominantly of shale containing clay minerals. Many of the CSD boreholes have stratigraphic calls that assist in the location of the *Kp*. For the profiles, the clipping distance from the flight line was set independently for the CSD boreholes and the NE-DNR boreholes. Typically, the CSD clipping distance was set to ½ mile or 2,640 ft and the NE-DNR boreholes was set to a quarter mile or 1,320 ft. The inversion DOI was also inspected during interpretation of the profiles, but was always below the top of the *Kp* in the LLNRD 2019 flight area.

The interpretation of the *To* included examination of the CSD and NE-DNR boreholes and comparison with the AEM resistivities. Unlike the *Kp/To* surface there is not a strong resistivity contrast between the *Q* and the *To*. The borehole information is critical in the determination of an estimated top of the *To*. The following characteristics were used to locate the top of the *To*: 1) *To* indicated on the CSD borehole stratigraphic logs; 2) indication of sandstone, siltstone, or shale in the CSD borehole lithology logs; 3) indication of sandstone, siltstone, shale in the NE-DNR lithology logs; and 4) a generally lower electrical resistivity than the overlying *Q* alluvial deposits. Patterns in the resistivity were also used to match the difference in the *Q* and the *To*. It should be noted that the top of the *To* as interpreted is an estimate. This is due to the challenge of both the lithology interpretation of drill cuttings of the *To* and the low electrical resistivity contrast. Throughout this report the *To* will be shown as a dashed line and care needs to be exercised in the use of the interpreted top of To surfaces.

Figure 5-2 is an approximately 7-mile-long north-south line, L101201, which crosses the South Loup River. The line is on the western side of the LLNRD 2019 survey area. There is a single CSD test hole along the line, *19-B-47*, at which the AEM and the CSD test hole both indicate the *Kp* at depth as a low electrical resistive unit. *19-B-47* also indicates the *To* and that section is composed of both sandstone and sand. Several NE-DNR registered wells are also in the area and indicate sandstone. The high

resistivity zone along the South Loup River indicates the sand associated with the alluvial river deposits. On the south side of the line the loess is also indicated as low electrical resistivity near the surface. Just north of the river, a zone of low resistivity material is indicated by clay in the NE-DNR registered wells. Slight differences in the elevation of the top of the CSD and NE-DNR test holes and registered wells indicates that the holes and wells are slightly off line as they are projected on to the profile if within ½ a mile (2,640 feet) for the CSD test holes and ¼ of a mile (1,320 feet) for NE-DNR registered test holes. The white areas within the profiles are zones that were cut from the AEM data due to EM-coupling.

Figure 5-3 is an approximately 8-mile-long north-south line, L103901, that is east of Poole in the approximate middle of the LLNRD 2019 AEM survey area and crosses the South Loup River. There are three CSD test holes along the line, from north to south, *36-A-54*, *37-A-54*, and *38-A-54*. The AEM and the CSD test holes both indicate that the ***Kp*** is present at depth as a low electrical resistivity unit. Along this line the ***Kp*** has approximately 50 feet of relief. Several of the NE-DNR registered wells also indicate the top of the ***Kp*** due to their depth extent and the ***Kp*** not being an aquifer. The CSD test holes also indicate the ***To*** and that section is composed of both sandstone and sand with some silt. Several NE-DNR registered wells are also along the flight line and indicate sandstone. There is approximately 100 feet of relief in the ***To*** along this line. The high resistivity zone along the South Loup River indicates the sand associated with the alluvial river deposits. On the south side of the line the loess is also indicated as low electrical resistivities near the surface.

Figure 5-4 is a 3-mile-long north south line, L107701, that is on the east side of the LLNRD survey area. While there are no CSD test holes along this flight line, there are several NE-DNR registered wells along this line. The registered wells indicate the presence of the ***Kp*** due to the extent of the drilling with one well indicating shale at the base. The NE-DNR registered wells do indicate a few zones of sandstone related to the ***To***. Along the southern end of the line there is a low resistivity zone that is related to clay that is indicated by two of the NE-DNR registered wells. That zone does also extend to the middle portion of the flight line and is indicated by two more NE-DNR wells as silty clay and clay. The northern portion of the flight line have higher resistivities indicating sand rich materials within the ***Q*** section.

Figure 5-5 is a 12-mile east-west line, L200201, located in the southern part of the LLNRD 2019 survey area below the South Loup River. This line is characterized by the low electrical resistivity ***Kp*** and is also indicated by the extent of drilling by the NE-DNR registered test wells. There is an area in the ***Kp*** that shows approximately 50 feet of relief associated with a paleo drainage that was eroded into the ***Kp***. The ***To*** surface is indicated by the sandstones found in the NE-DNR registered wells. The interpreted surface is not solely based on this east-west line but the many north south lines that cut across the area. The ***To*** is noticeably more resistive on the western end of the line. The ***Q*** section is dominated by a topographically draped layer of low electrically resistive material related to loess.

The above examples illustrate the interpretive process that was used on the profiles provided within this report. Each flight line 2D profile is included in Appendix 1 – 2D Profiles.

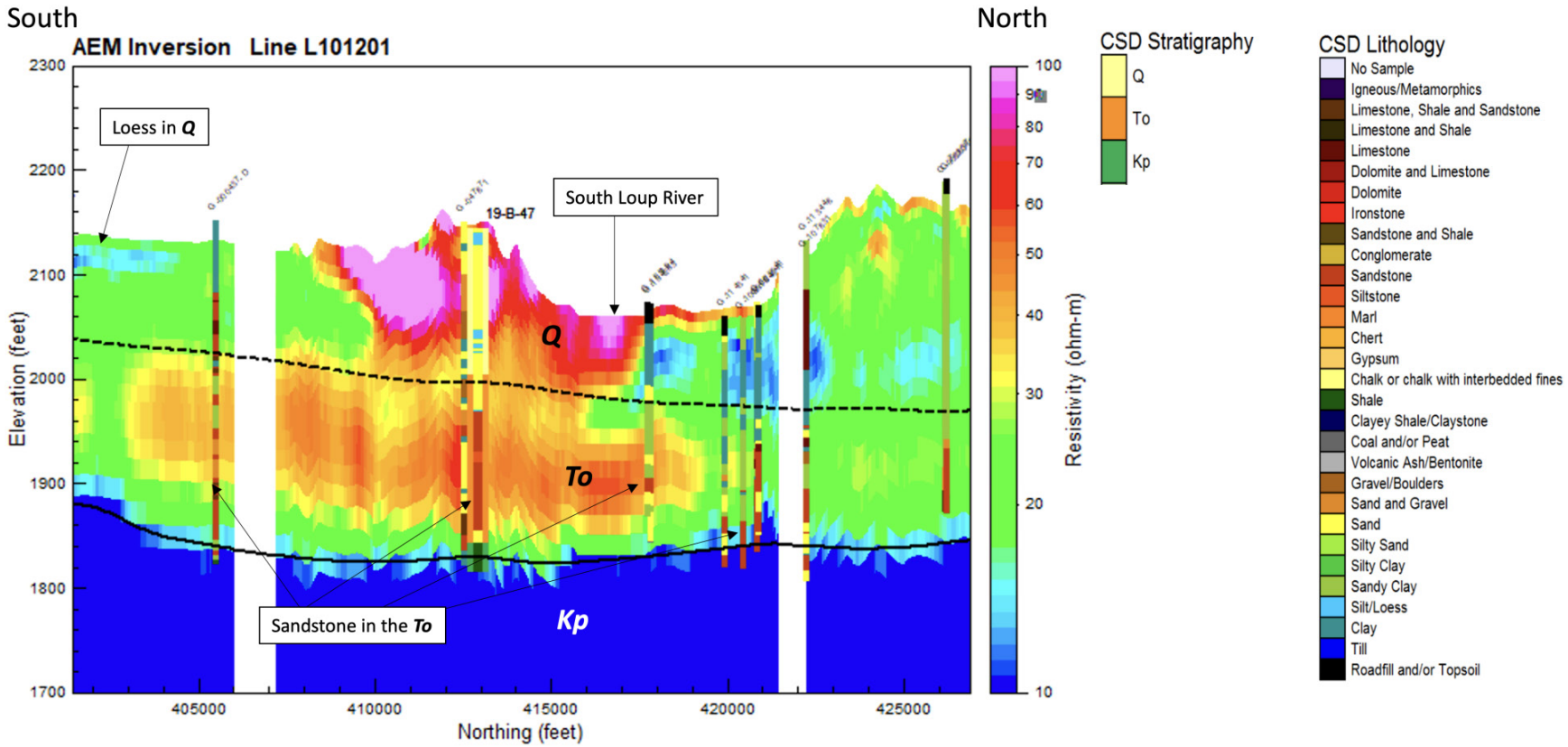


Figure 5-2. 7-mile north-south line L101201. CSD within ½ a mile and Nebraska DNR within ¼ of a mile borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by stratigraphic names. *Q*= Quaternary, *To* = Tertiary Ogallala Group, and *Kp* = Cretaceous Pierre Shale

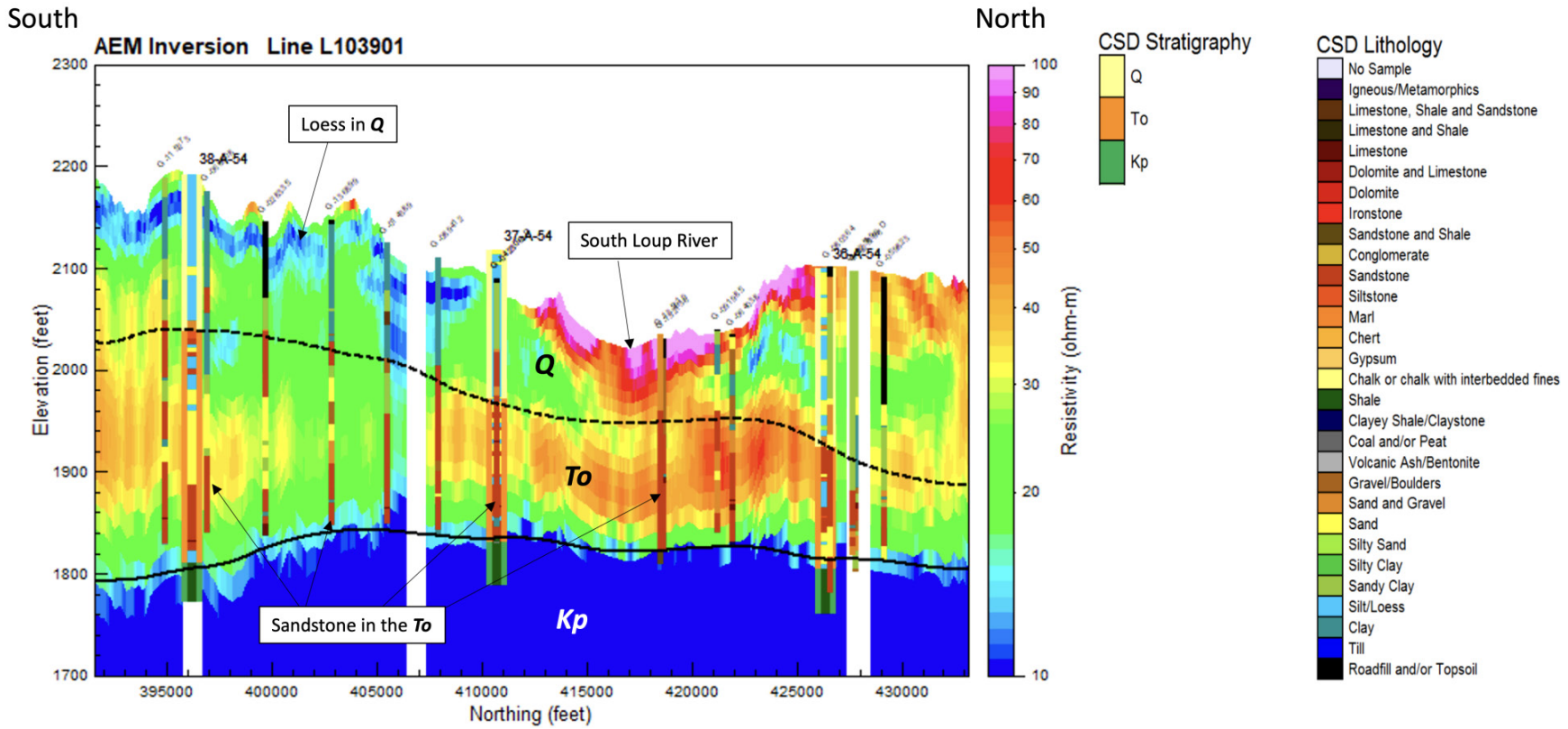


Figure 5-3. 8-mile north-south line L103901. CSD within ½ a mile and Nebraska DNR within ¼ of a mile borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by stratigraphic names. *Q*= Quaternary, *To* = Tertiary Ogallala Group, and *Kp* = Cretaceous Pierre Shale

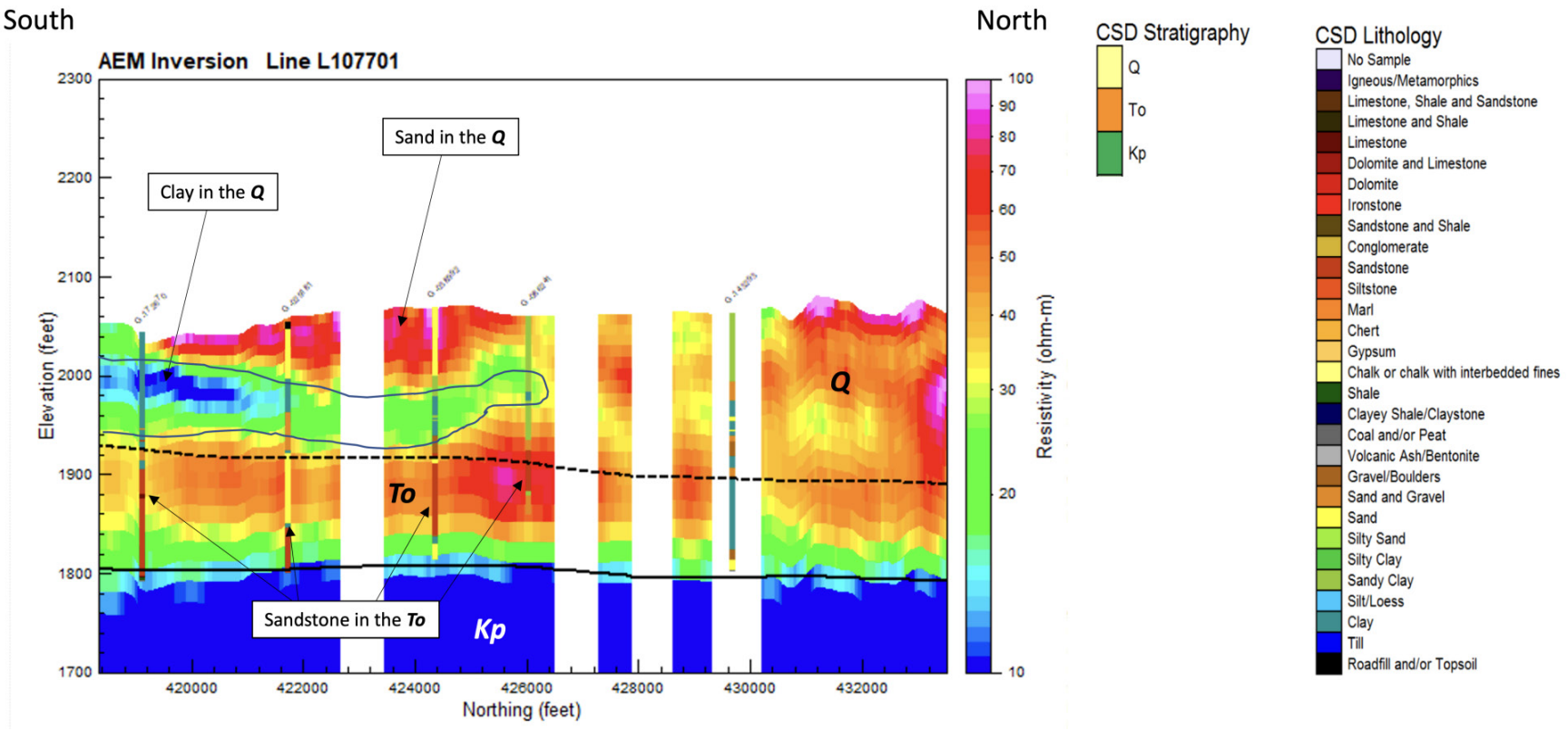


Figure 5-4. 3-mile north-south line L107701. Nebraska DNR within ¼ of a mile borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by stratigraphic names. *Q*= Quaternary, *To* = Tertiary Ogallala Group, and *Kp* = Cretaceous Pierre Shale

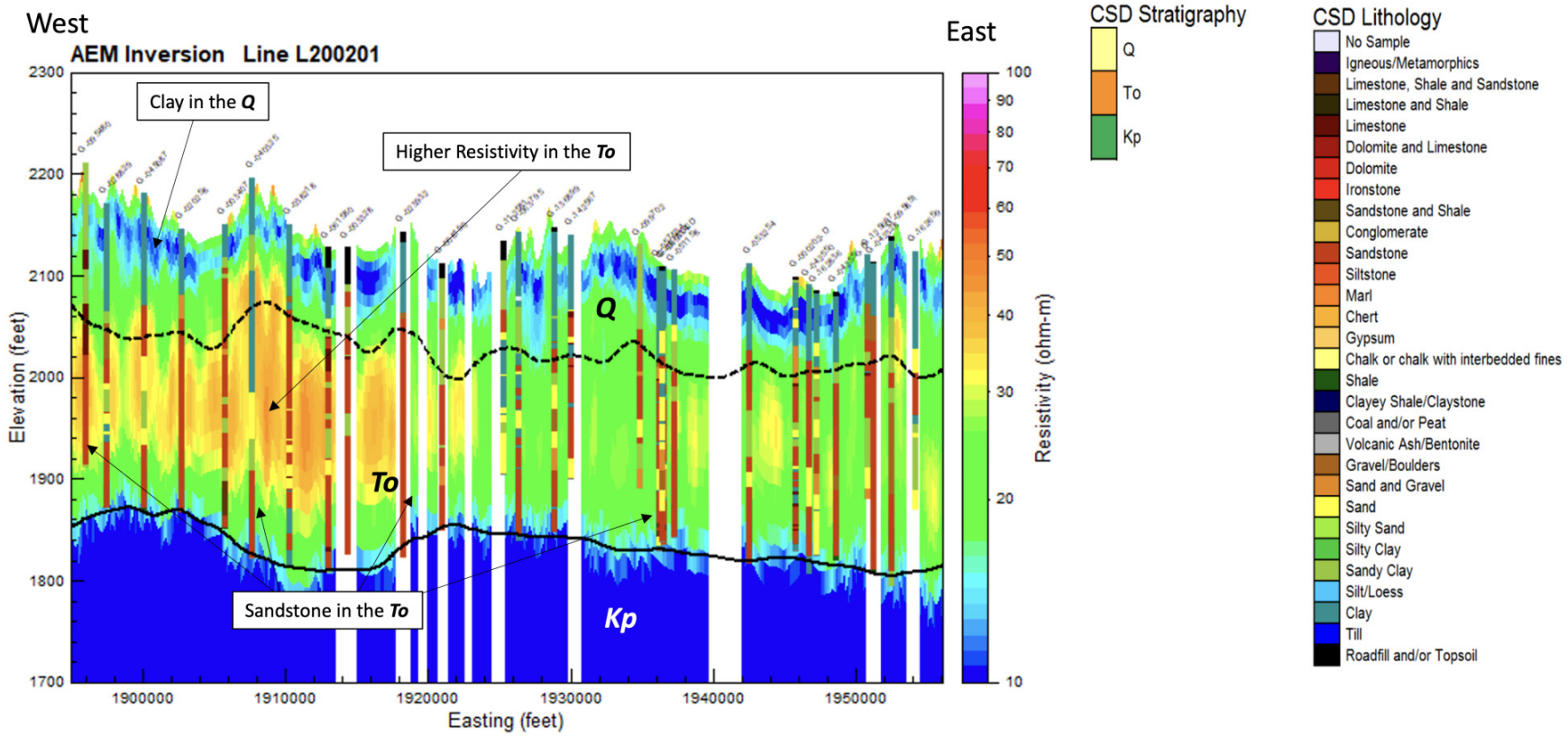


Figure 5-5. 12-mile east-west line L200201. Nebraska DNR within ¼ of a mile borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by stratigraphic names. *Q*= Quaternary, *To* = Tertiary Ogallala Group, and *Kp* = Cretaceous Pierre Shale.

5.1.4 Create Interpretative Surface Grids

For the LLNRD 2019 AEM project survey area geologic units' top elevation, geologic unit thickness, and geologic unit saturated thickness grids were produced. To create these grids, data such as a ground surface digital elevation model (DEM), water table elevation, Conservation and Survey Division (CSD) boreholes, and AEM interpreted point data of the survey area were imported and processed in ESRI's ArcMap along with the Spatial and Geostatistical Analyst extensions.

Raster grids of the elevation of the top of the Ogallala Formation ***(To)*** and Cretaceous Pierre ***(Kp)*** for the LLNRD survey area were produced. To create the grids, ~ 6,400 data points with top elevation values were extracted from the AEM interpretation and input into a database. Additionally, 6 CSD boreholes with depth to top of geologic units were added to the database and the database was input into ESRI's ArcMap for processing. The CSD borehole data provided control in areas between flight lines. The elevation point data were interpolated into a continuous surface using the kriging geostatistical model and exported to a 100 ft cell size grid. Figure 5-6 and Figure 5-7 are maps of top elevation of ***To*** and ***Kp***, respectively, within the LLNRD AEM survey area.

Quaternary deposits (***Q***)and ***To*** thicknesses were calculated for the LLNRD AEM survey area using the top of elevation grids with ArcMap's raster calculator. For the ***Q*** thickness grid, the elevation of the top of ***To*** was subtracted from the DEM. For the ***To*** thickness, the elevation of the top of ***Kp*** was subtracted from the elevation of the top of ***To***. The grids produced for the LLNRD AEM survey area were calculated using the 100 ft cell size. Figure 5-8 and Figure 5-9 are maps of ***Q*** and ***To*** thickness within the LLNRD AEM survey area, respectively.

To assist in the approximation of the saturated materials along the surveyed AEM flight lines, the 1995 CSD statewide water table (Nebraska CSD, 1995) was utilized. It should be noted that this inclusion provides only a generalized characterization of the saturated thickness of the aquifer as the CSD's dataset is two decades old at the time of the LLNRD AEM survey and local conditions likely deviate in areas with variable topography. The water table in the LLNRD 2019 survey area is close to the surface in some locations. To this end, a topographic correction was required to ensure that the water table height was below the surface topography. The original water table contour lines were gridded at a 1,000 ft cell size using the Oasis Montaj Minimum Curvature Grid and a blanking distance of 5,000 ft. The cells were set 'to extend beyond' to 50. The resulting grid was then re-gridded at a 100 ft cell size and compared with the DEM (Figure 5-1) of the LLNRD AEM survey area. In areas where the water table was greater than the topography, the water table was set to an elevation of the topography. The grid was then clipped to a buffered boundary around the AEM survey area (Figure 5-10). Saturated thickness of ***Q*** was calculated for the LLNRD AEM survey area by subtracting the 100 ft cell size top elevation of ***To*** grid from the 100 ft cell size 1995 CSD water table grid using ArcMap's raster calculator. The ***To*** was found to be fully saturated, so no specific saturated thickness grid was calculated for ***To.*** Figure 5-11 is a map of ***Q*** saturated thickness. Figure 5-12, Figure 5-13, and Figure 5-14 are maps of ***Q*** saturated thickness, ***To*** thickness, and ***Q*** saturated thickness plus ***To*** thickness with NE-DNR well points displaying estimated specific capacity within the LLNRD AEM survey area, respectively.

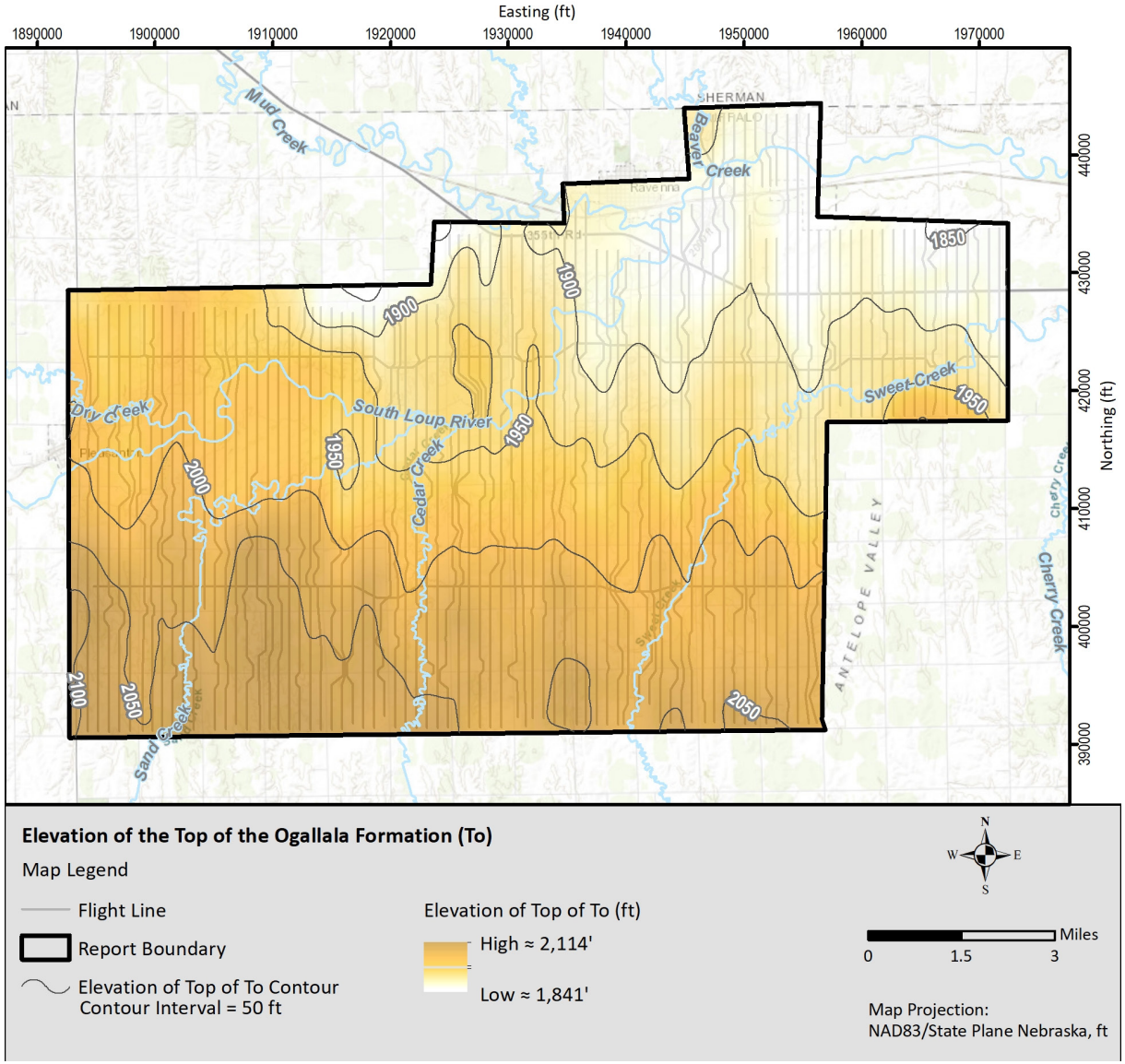


Figure 5-6. Map of the elevation of the top of the Ogallala Formation (*To*) within the LLNRD AEM survey area. The elevation values are referenced to NAVD 88 (feet).

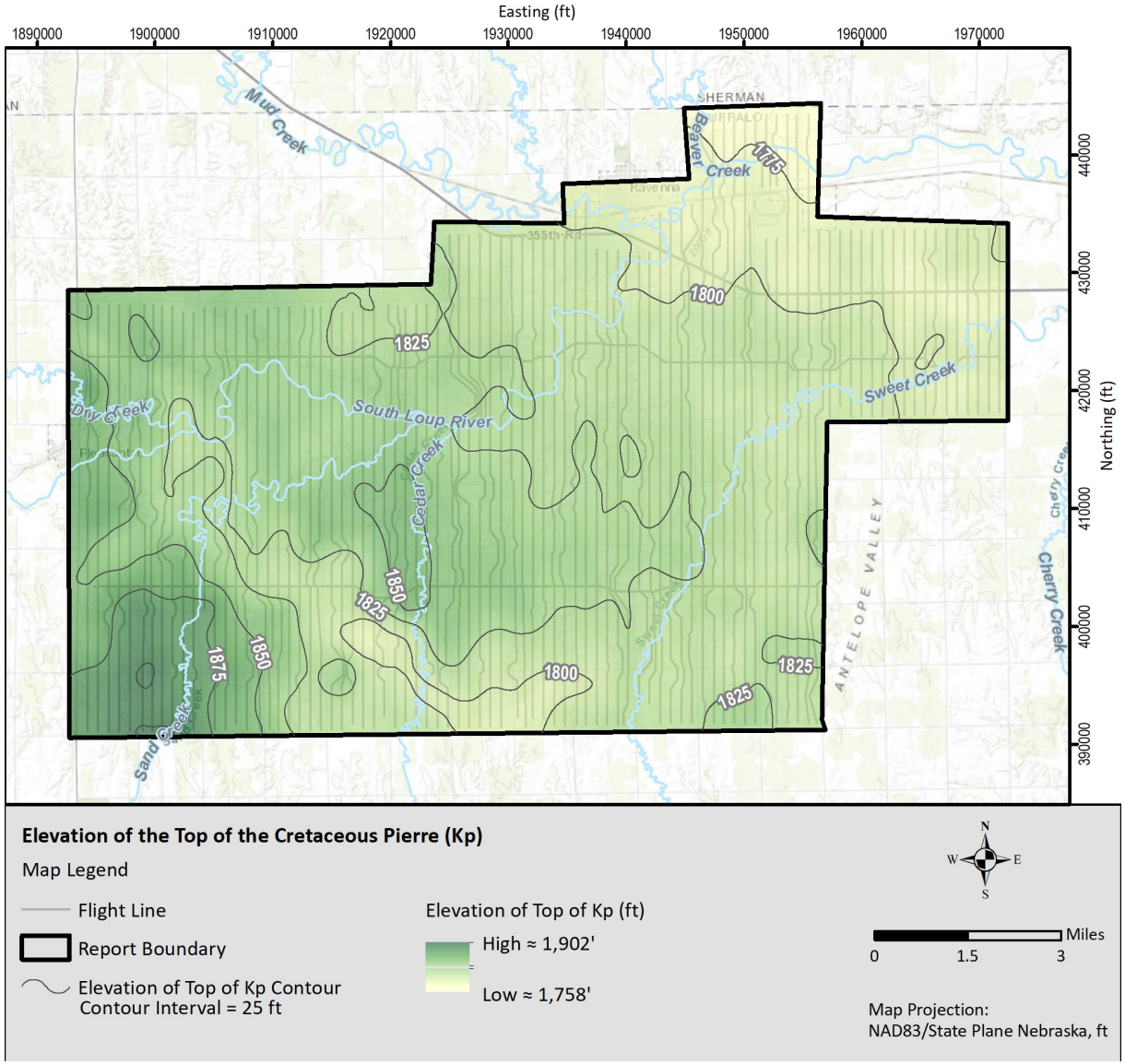


Figure 5-7. Map of the elevation of the top of the Cretaceous Pierre (*Kp*) within the LLNRD AEM survey area. The elevation values are referenced to NAVD 88 (feet).

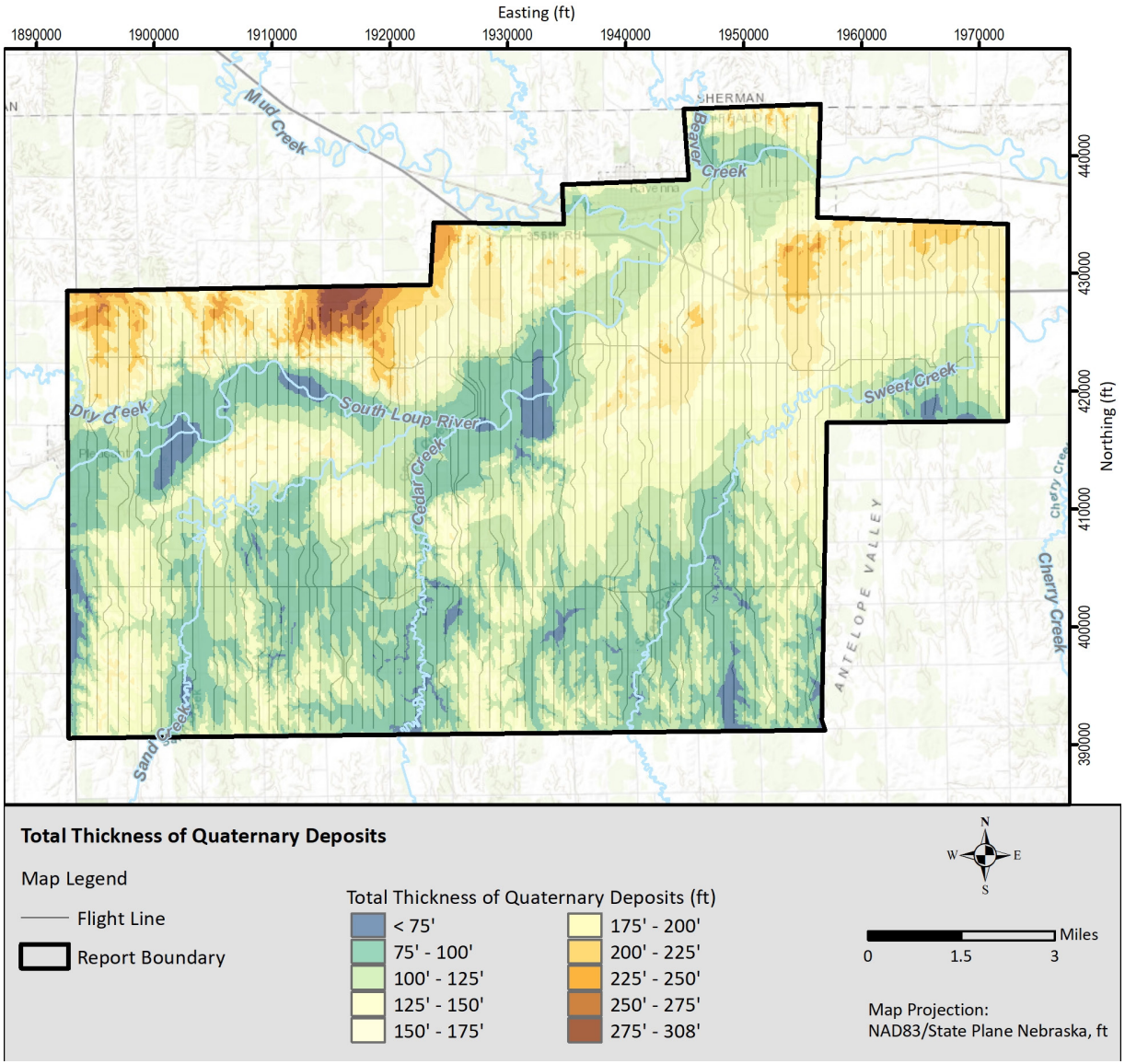


Figure 5-8. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the LLNRD AEM survey area.

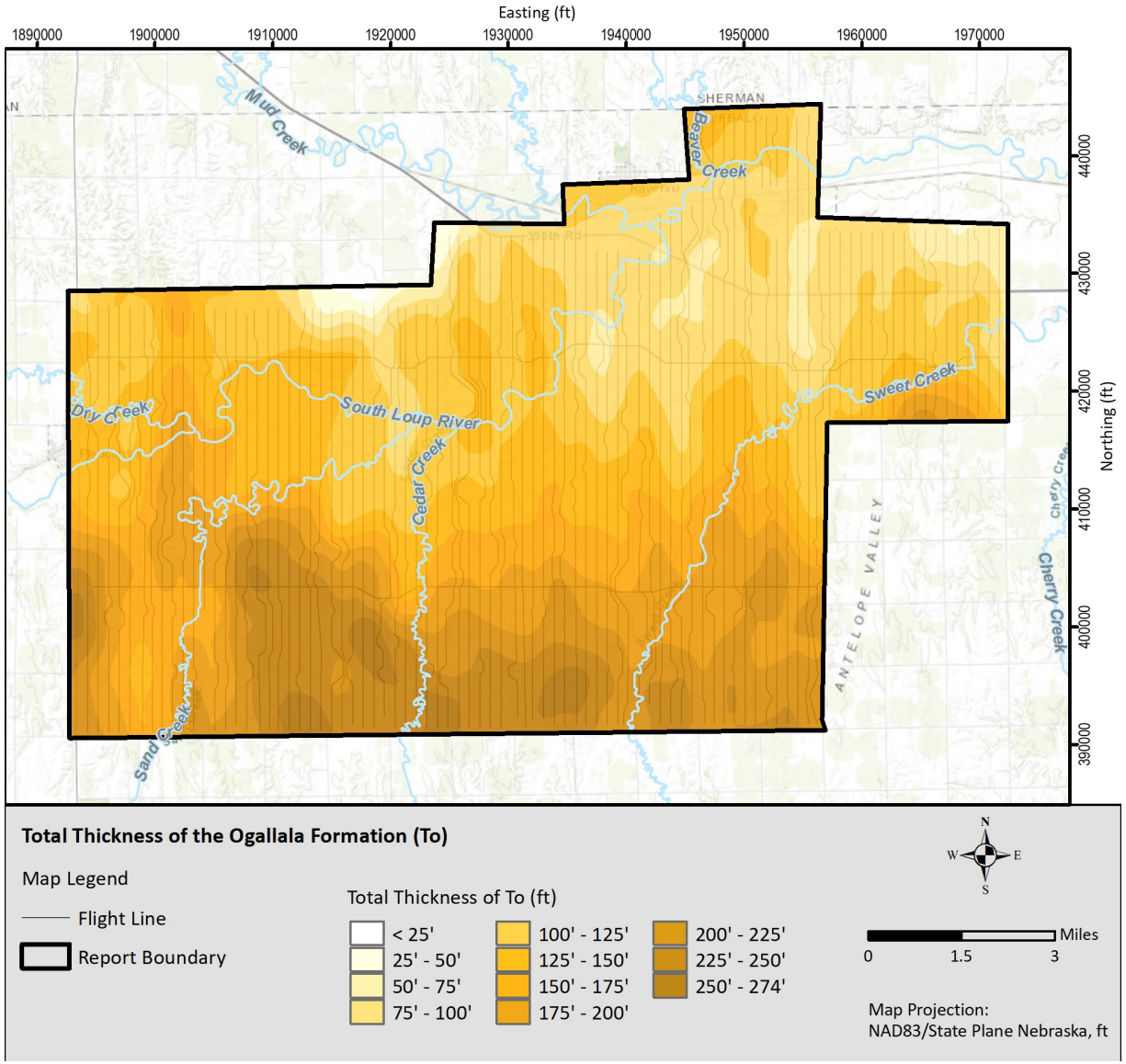


Figure 5-9. Map of the thickness (in feet) of Ogallala Formation (*To*) within the LLNRD AEM survey area.

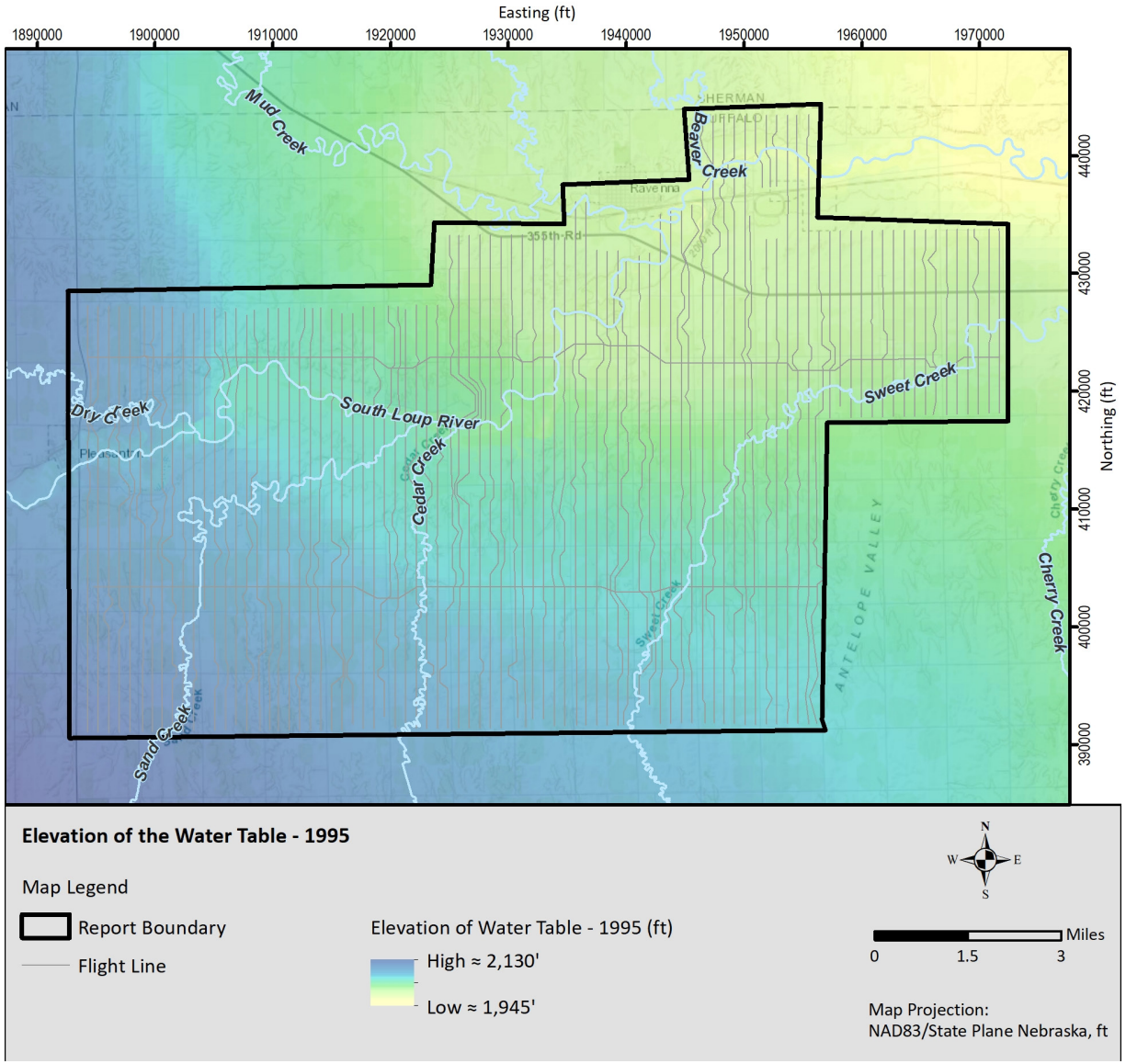


Figure 5-10. Map of the elevation (in feet) of the 1995 CSD water table within the LLNRD AEM survey area. The elevation values are referenced to NAVD 88 (feet).

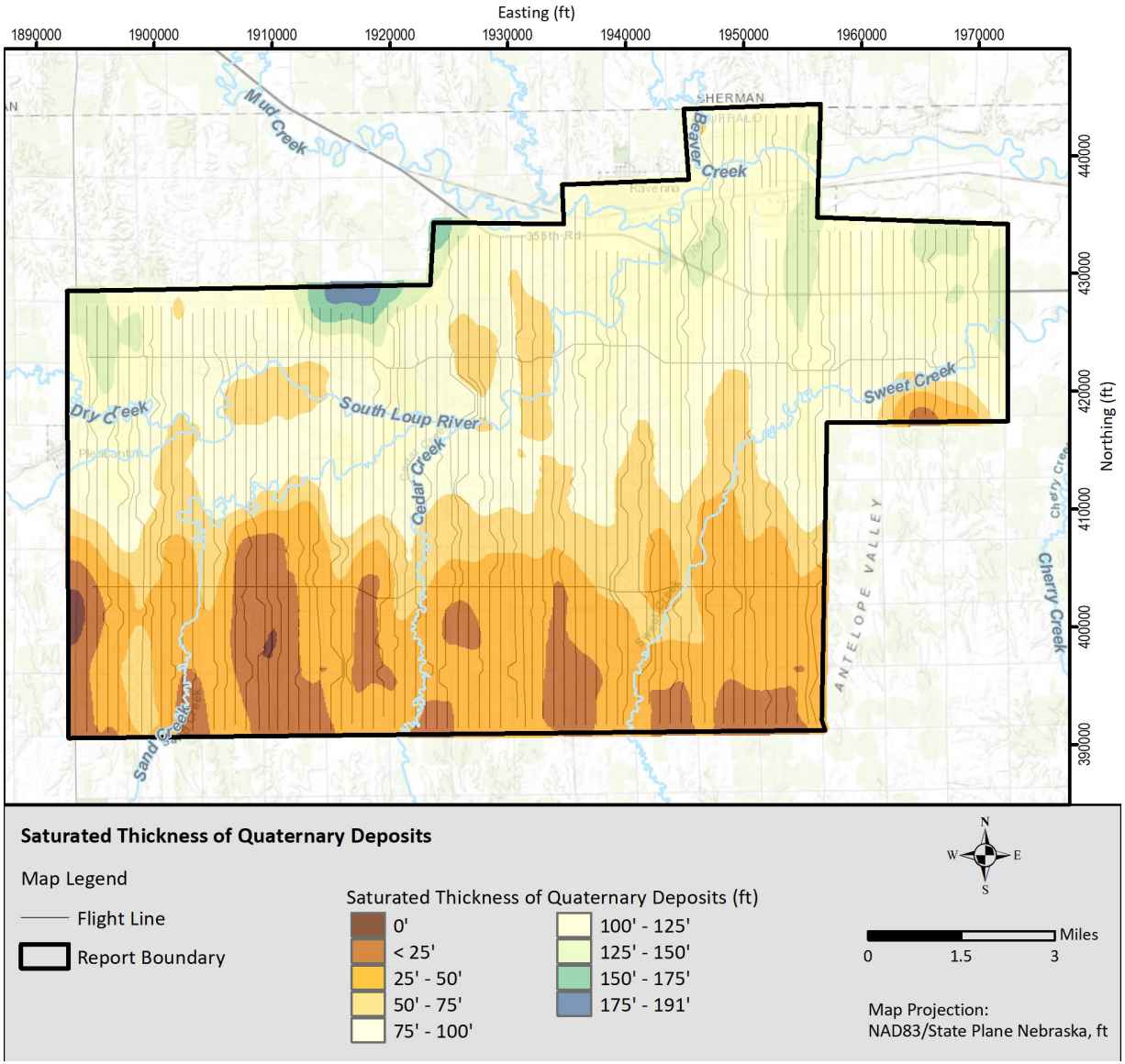


Figure 5-11. Map of the saturated thickness of Quaternary (*Q*) materials within the LLNRD AEM survey area. Flight lines are indicated by the gray lines.

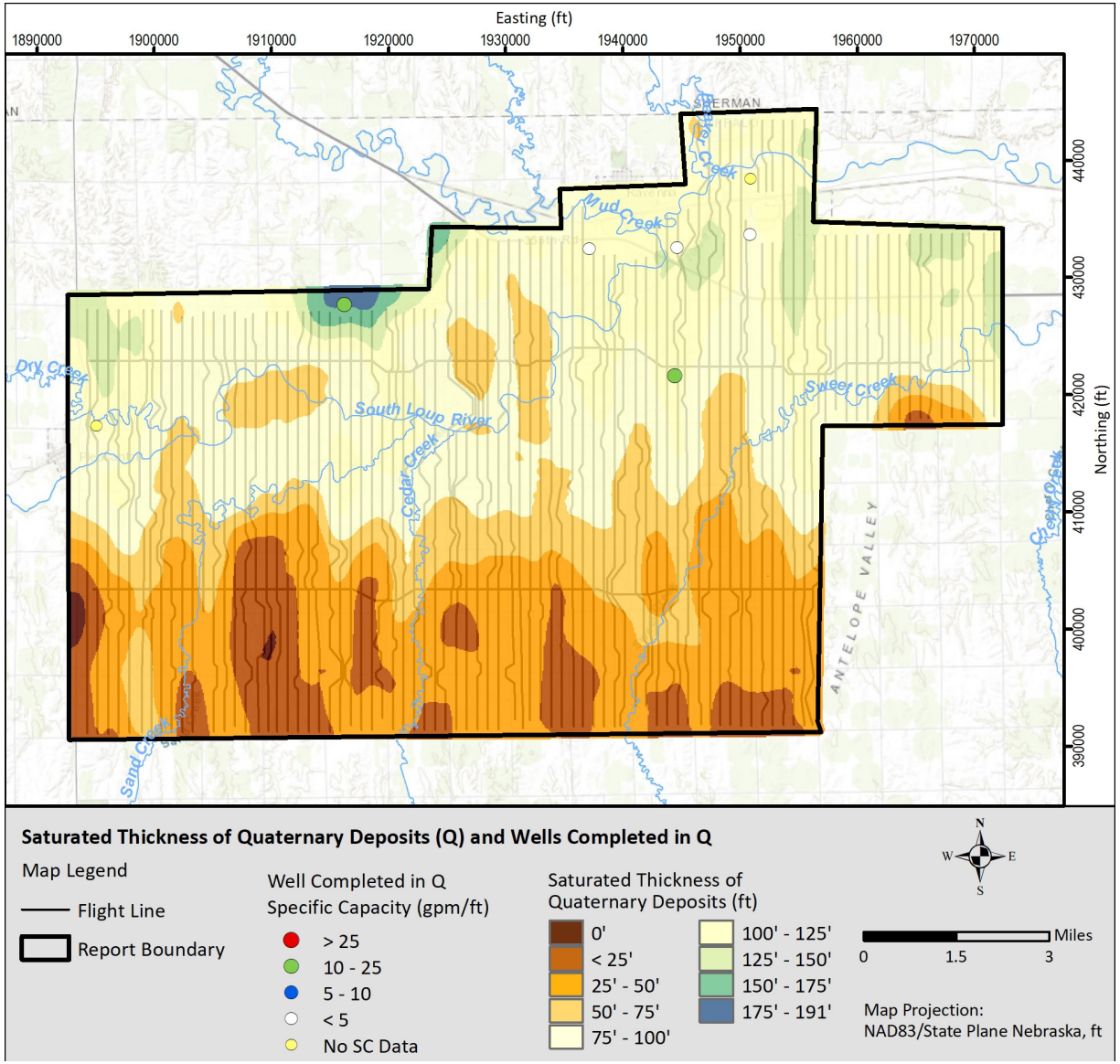


Figure 5-12. Map of the saturated thickness of Quaternary (*Q*) materials with well points displaying estimated specific capacity within the LLNRD AEM survey area. Flight lines are indicated by the gray lines.

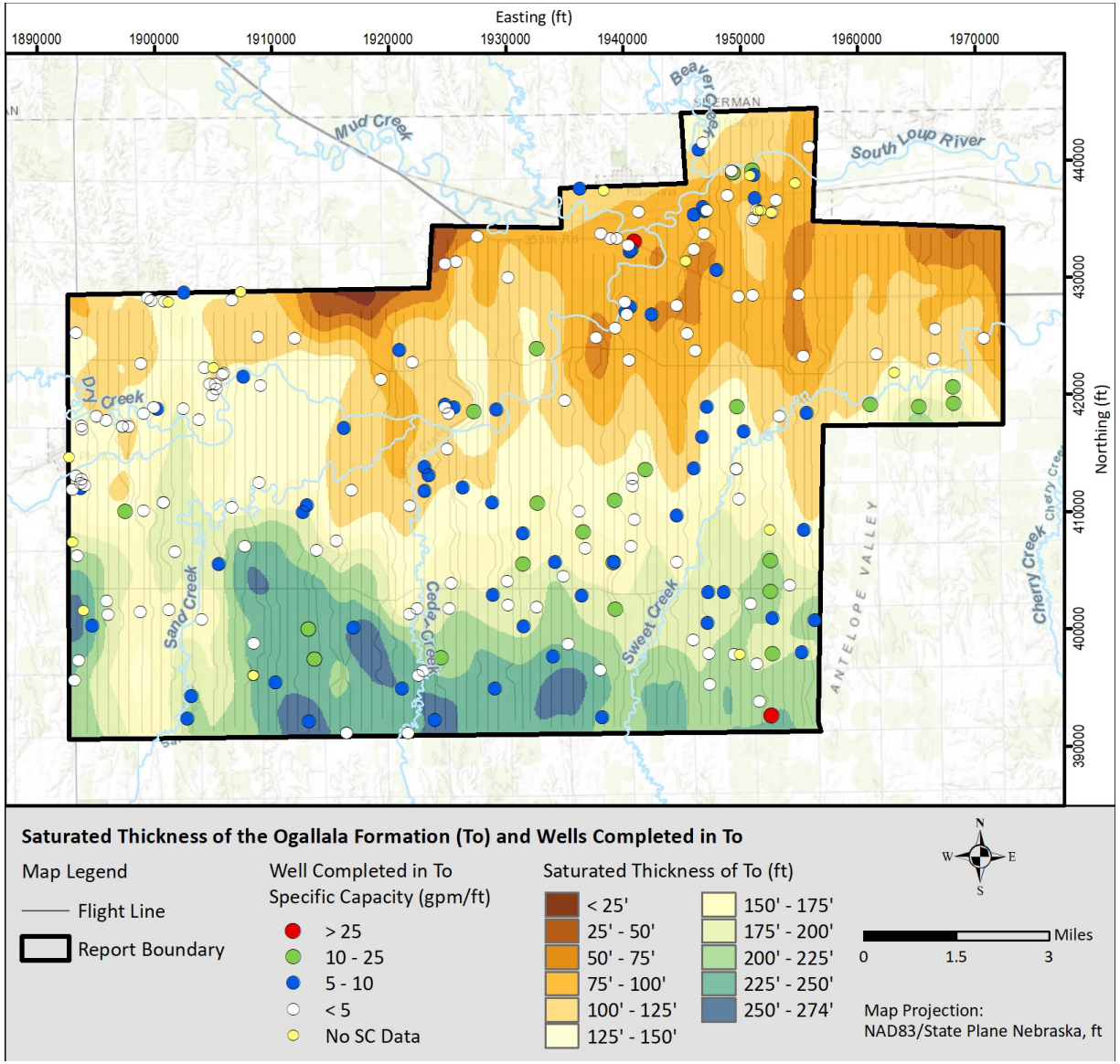


Figure 5-13. Map of the thickness of the Ogallala Formation (*To*) with well points displaying estimated specific capacity within the LLNRD AEM survey area. Flight lines are indicated by the gray lines.

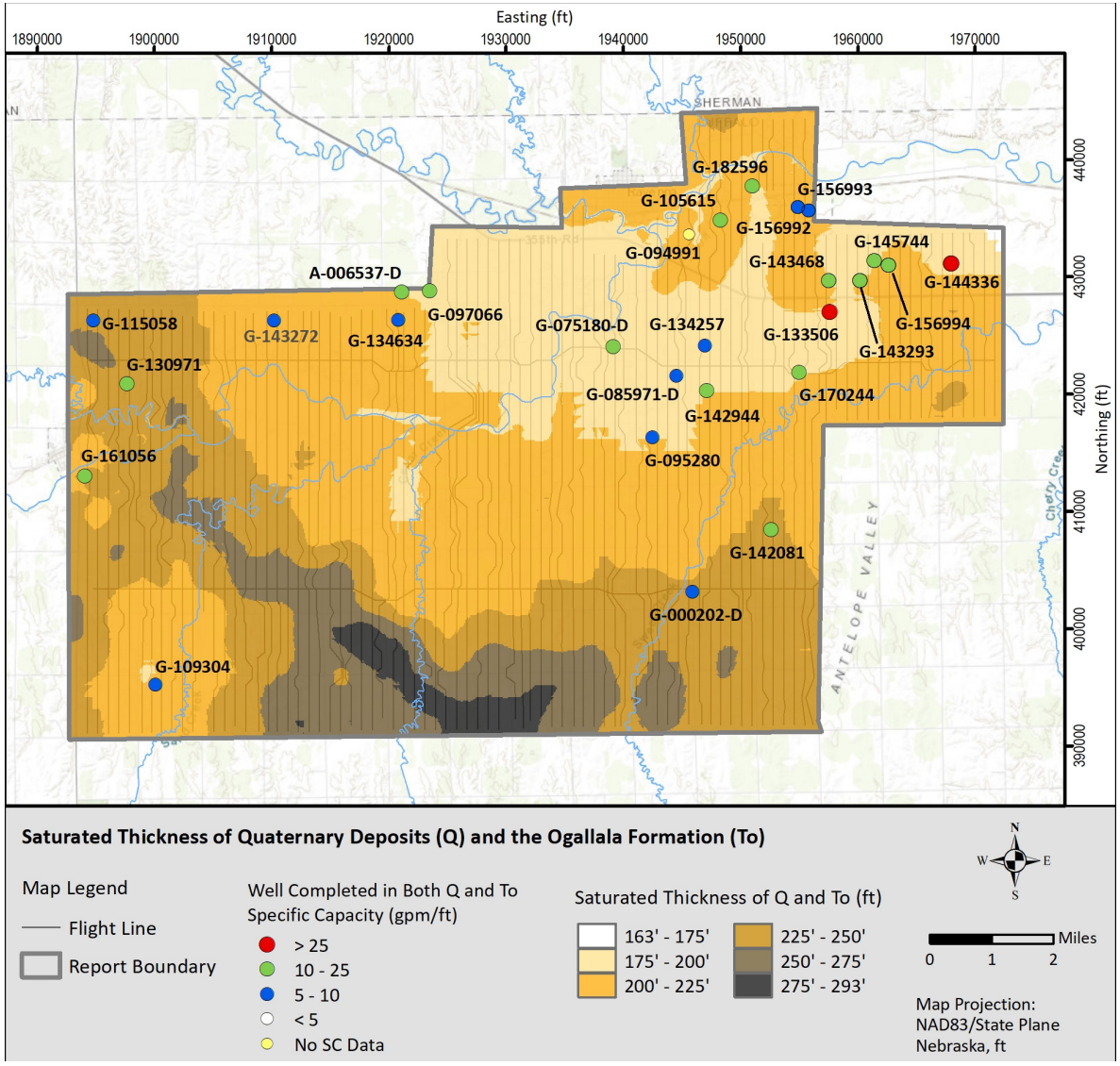


Figure 5-14. Map of the saturated thickness of Quaternary (*Q*) material plus the thickness of the Ogallala Formation (*To*) with well points displaying estimated specific capacity within the LLNRD AEM survey area. Flight lines are indicated by the gray lines.

5.1.5 Resistivity Relationship in the Quaternary and Ogallala Aquifer System

A critical aspect of a geophysical survey is assessing the nature of the material detected by the geophysical method applied in the investigation. Regarding the LLNRD AEM survey area, assessment of the sediment character in the Quaternary (***Q***) and Tertiary Ogallala (***To***) aquifer system is required to determine the overall composition of the major categories used to define the aquifer and aquitards. This is typically done by unitizing the borehole geophysical logs associated with lithology. In the LLNRD 2019 AEM survey area there are only three geophysical logs to complete this analysis. Unlike the work that was presented in Carney et al. (2015) three logs are grossly inadequate. However, in 2017 a detailed examination was completed in the areas of the Central Platte and Twin Platte Natural Resources Districts (AGF, 2017b). An assessment of the resistivity thresholds used to characterize non-aquifer, marginal, aquifer, and coarse aquifer materials was conducted. This allowed for the characterization of the ranges of resistivities present in the ***Q*** and ***To*** units described in this report. This analysis has been used in the current report for the categorization of the Quaternary and Ogallala aquifer system over the LLNRD survey area. The ***Q*** and ***To*** aquifers were broken down by resistivity for aquifer materials (less than 12 ohm-m – non-aquifer material, 12-25 ohm-m – marginal aquifer material, 25-40 ohm-m for aquifer material, and greater than 40 ohm-m for coarse aquifer material). These values are slightly different then the assessment in the Eastern Nebraska Water Resources Assessment (ENWRA) presented in Carney et al. (2015). This difference is related to the glacial versus non glacial sediments encountered in the two areas. Figure 5-15 is a plot of the color bar used and the resistivity ranges for the four aquifer material types.

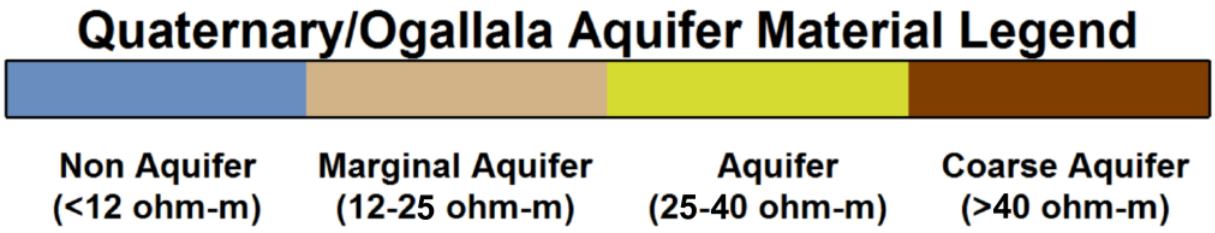


Figure 5-15. Color bar for aquifer types and resistivity range thresholds used in the LLNRD 2019 AEM survey.

5.1.6 Create 3D Interpretative Voxel Grids

A voxel grid was completed for the LLNRD 2019 AEM survey area. The voxel grids were made using a 100 feet grid cell size and the model layer thickness (from Table 4-4). A minimum curvature method was used within Datamine Discover PA (Datamine Discover, 2020). All layers were referenced to their depth from the surface and then projected on the area DEM. After the grid was calculated, the grid was split at the estimated top of the Tertiary Ogallala Group (***To***) and the top of the Cretaceous Pierre Shale (***Kp***) using the surface elevation grids discussed above in Section 5.1.4. These resulting voxel grids can be used to explore the distribution of the aquifer materials within the area in 3D. Specifically, these grids can allow for visual inspection of the volume of materials above the bedrock as well as surface materials. The Quaternary (***Q***) and ***To*** materials can also be separated by thresholds developed above for the four lithology classes. Utilizing the voxel grids of the ***Q***, analysis can be made of the thickness of the different materials within the section. Additionally, the ***Q*** voxel can be split into unsaturated and saturated portions utilizing the CSD 1995 water table (NE-CSD, 1995). Figure 5-16 is an exploded diagram of the plot of the ***Q*** and ***To*** material above the ***Kp*** looking to the north. The voxel grids can be found in *Appendix 3-Deliverables\Voxel*.

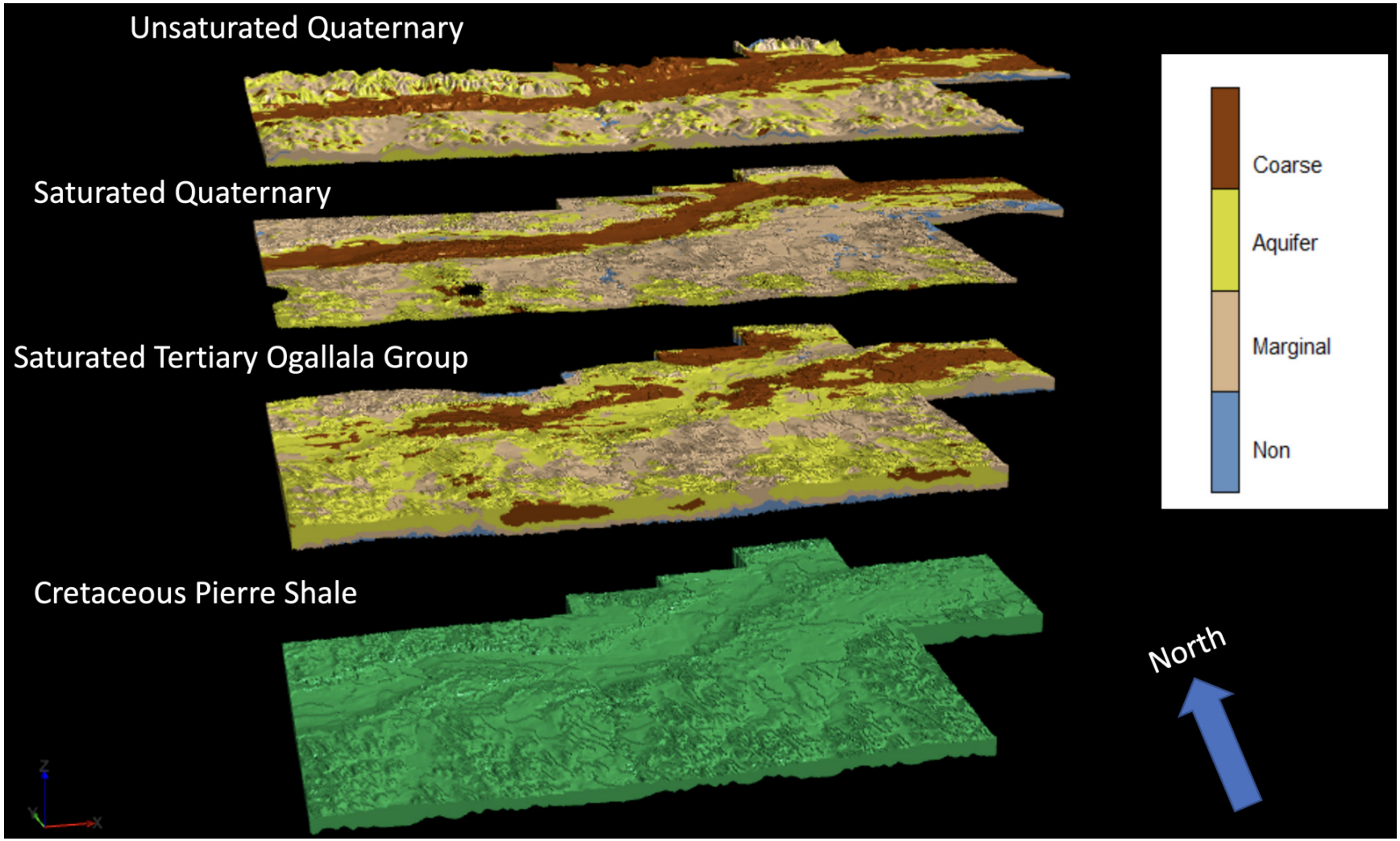


Figure 5-16. Exploded 3D Voxel model of the aquifer material types of the Quaternary (*Q*) unsaturated and saturated, saturated Tertiary Ogallala Group (*To*), and the Cretaceous Pierre Shale (*Kp*). Not to scale.

5.2 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs

Three geophysical logs existed in the NE-CSD database. These included *36-A-54*, *37-A-54*, and *38-A-54*. These logs included a Short Normal 16-inch geophysical resistivity log or electric log (E-log) as well as detailed lithology and stratigraphic characterization. All three logs were in close proximity to an AEM flight line. The resistivity logs within the CSD database are of various vintages and conducted by various staff with differing equipment. A critical examination of the absolute values of the resistivity needs to include an awareness of errors in calibration and in the proper operation of the equipment. Many of the early 1940-1980's electric logs were paper logs that were scanned and digitized and then included in the database. There is a long-standing issue with using geophysical logs as ground truth when comparing to AEM acquisition systems and inversions that are well calibrated using modern techniques. Throughout much of the geophysical logging at the time it was acquired, the relative deflections of the resistivity measurements were all that was required or expected from a geophysical log. Operators were seldom trained in the proper operation of a calibrated sonde or in the ability to recognize high contact resistance of a cable head. This has led to many geophysical logs that are uncalibrated within the CSD database. Note that these logs still have scientific merit in their ability to relatively indicate an increase or a decrease in the formation resistivity. The logs used herein are for qualitative comparison to the AEM because detailed calibration and corrections would need to be carried out for the resistivity values in the logs to be directly used as numerical constraints in the inversion of the AEM data (Ley-Cooper and Davis, 2010).

Figure 5-17 is a plot of *36-A-54* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L104101. Borehole *36-A-54* is located within 380 feet from line L104101 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is reasonable with the AEM indicating a lower overall resistivity compared to the geophysical log. The shape of the curves shows a good agreement but again show a difference in the overall resistivity. The key is that the AEM clearly indicates the ***To*** and ***Kp*** contact. The E-log however has the resistivity of the ***Kp*** at almost 30 ohm-m. This is substantially higher than the ***Kp*** in many other studies in Nebraska including Carney et al. (2015) and AGF (2017a) which showed that ***Kp*** is typically on the order of 3-8 ohm-m. Figure 5-18 is a plot of the *36-A-54* E-log and the AEM inversions at the same color scale for a portion of line L104101. The increase in the resistivity of the E-log can be seen as compared with the AEM inversions.

Figure 5-19 is a plot of *37-A-54* 16-inch Short Normal resistivity log plotted with the inverted AEM resistivity for line L104101. Borehole *37-A-54* is located within 400 feet from line L104101 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is good with the AEM indicating a lower overall resistivity compared to the geophysical log. The E-log shows a lower resistivity zone at around 140 feet at the ***Q***/***To*** contact which the AEM doesn't fully capture. This is most likely related to the resolution of the AEM and the averaging effect that occurs with depth. The key is that the AEM clearly indicates the ***To*** and ***Kp*** contact as well as the low resistivity silt in the ***Q***. Figure 5-20 is a plot of the *37-A-54* E-log and the AEM inversion at the same

color scale for a portion of line L104101. The good comparison in the resistivity of the E-log can be observed as compared with the AEM inversions.

Figure 5-21 is a plot of borehole *38-A-54* 16-inch Short Normal resistivity log plotted with the inverted AEM resistivity for line L103901. Borehole *38-A-54* is located within 400 feet from line L104101 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity curves is good with the AEM indicating a lower overall resistivity compared to the geophysical log. The key is that the AEM clearly indicates the ***To*** and ***Kp*** contact as well as the low resistivity silt in the ***Q***. Figure 5-22 is a plot of the *38-A-54* E-log and the AEM inversion at the same color scale for a portion of line L104101. The good comparison in the resistivity of the E-log can be observed as compared with the AEM inversions.

The three E-logs available show that two are well calibrated (*37-A-54* and *38-A-54*) and one is not (*36-A-54*). The big indicator that the E-log from *36-A-54* is not calibrated is the very high resistivity indicated for the ***Kp***. These comparisons do show however that the AEM is responding well to the resistivities of the materials within the survey area.

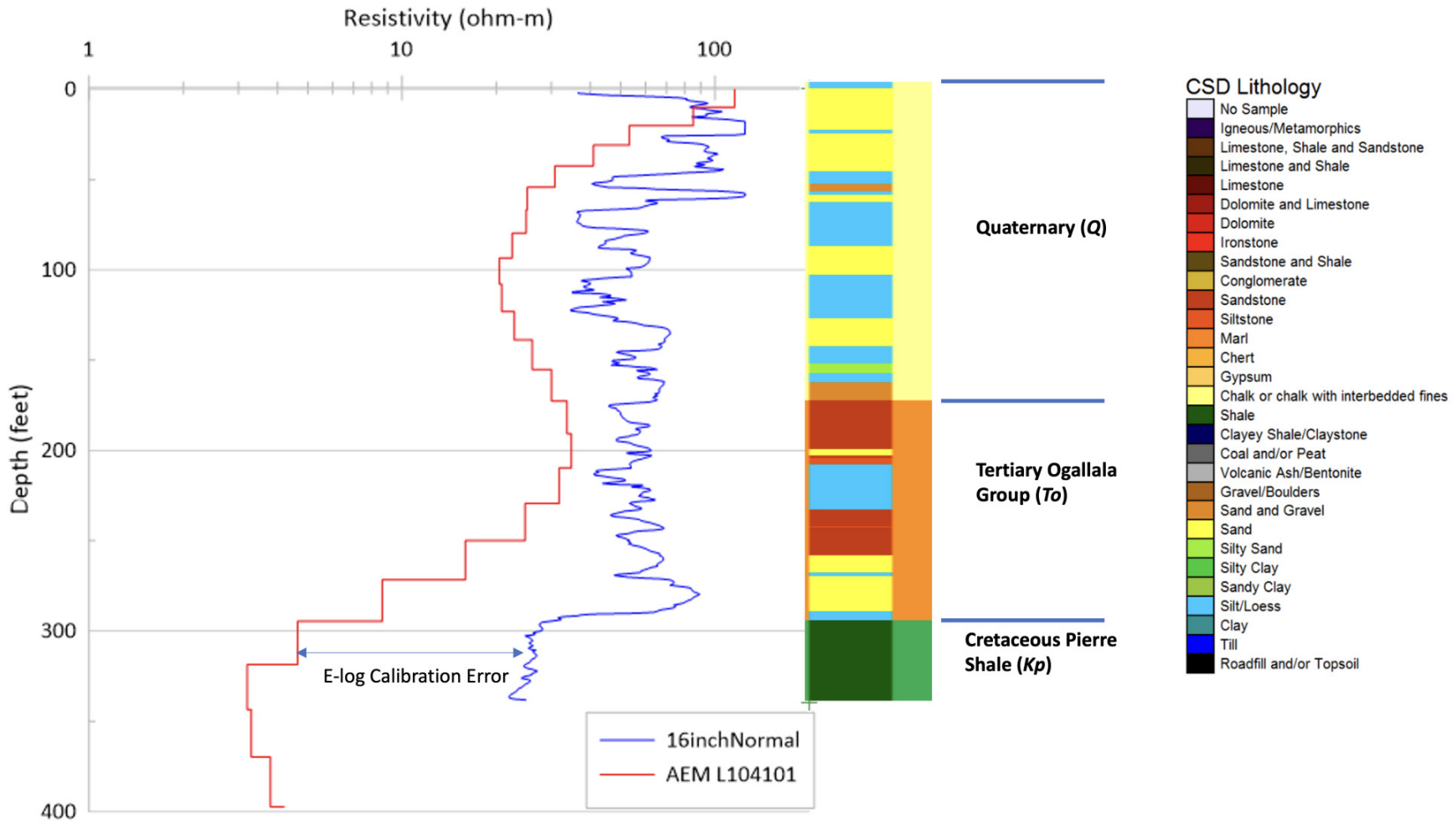


Figure 5-17. Graph of the *36-A-54* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *36-A-54*. Note the calibration error in the E-log.

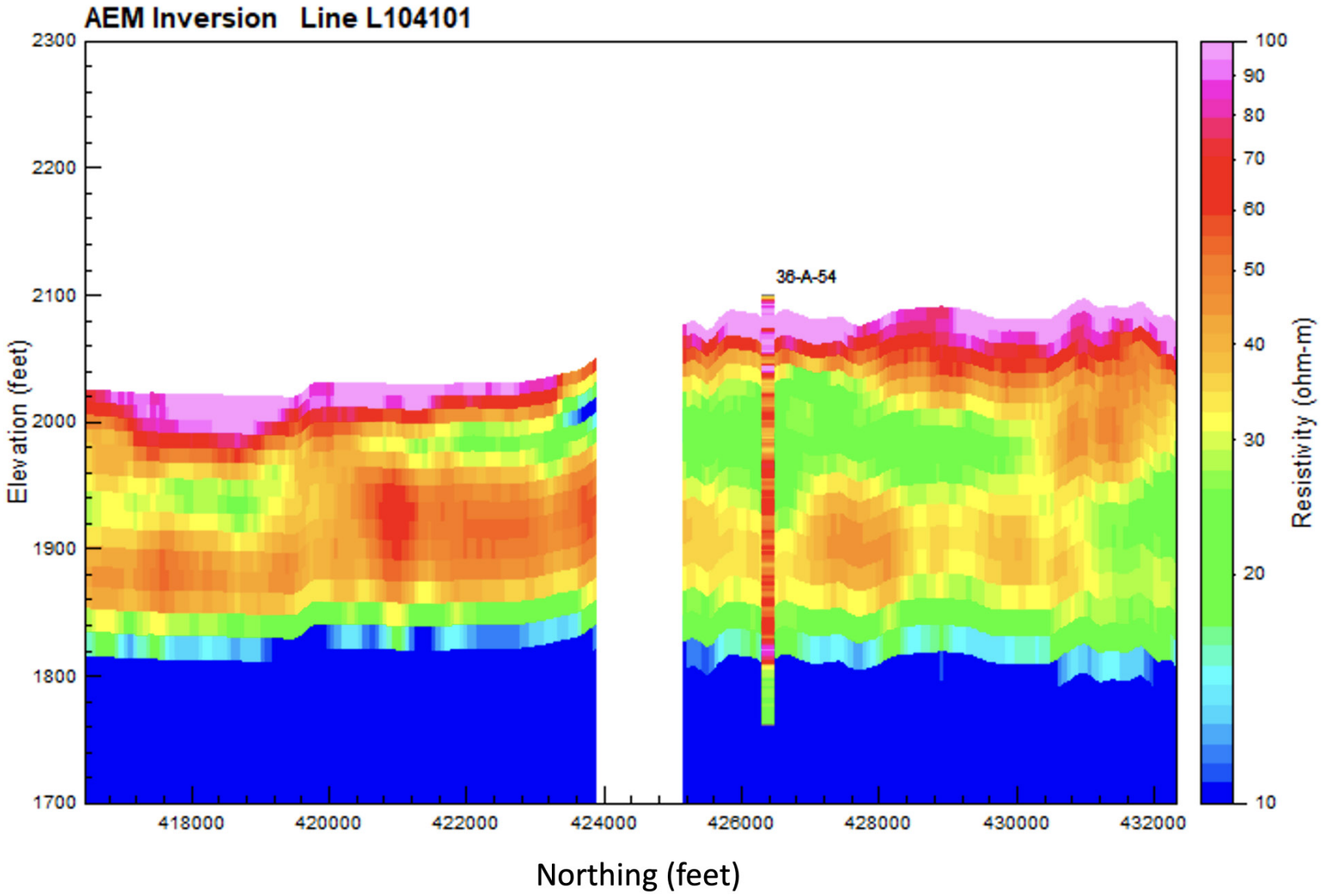


Figure 5-18. Profile of a portion of Line L104101 with the *36-A-54* 16-inch normal resistivity log resistivity values projected on the flight line at the same color scale.

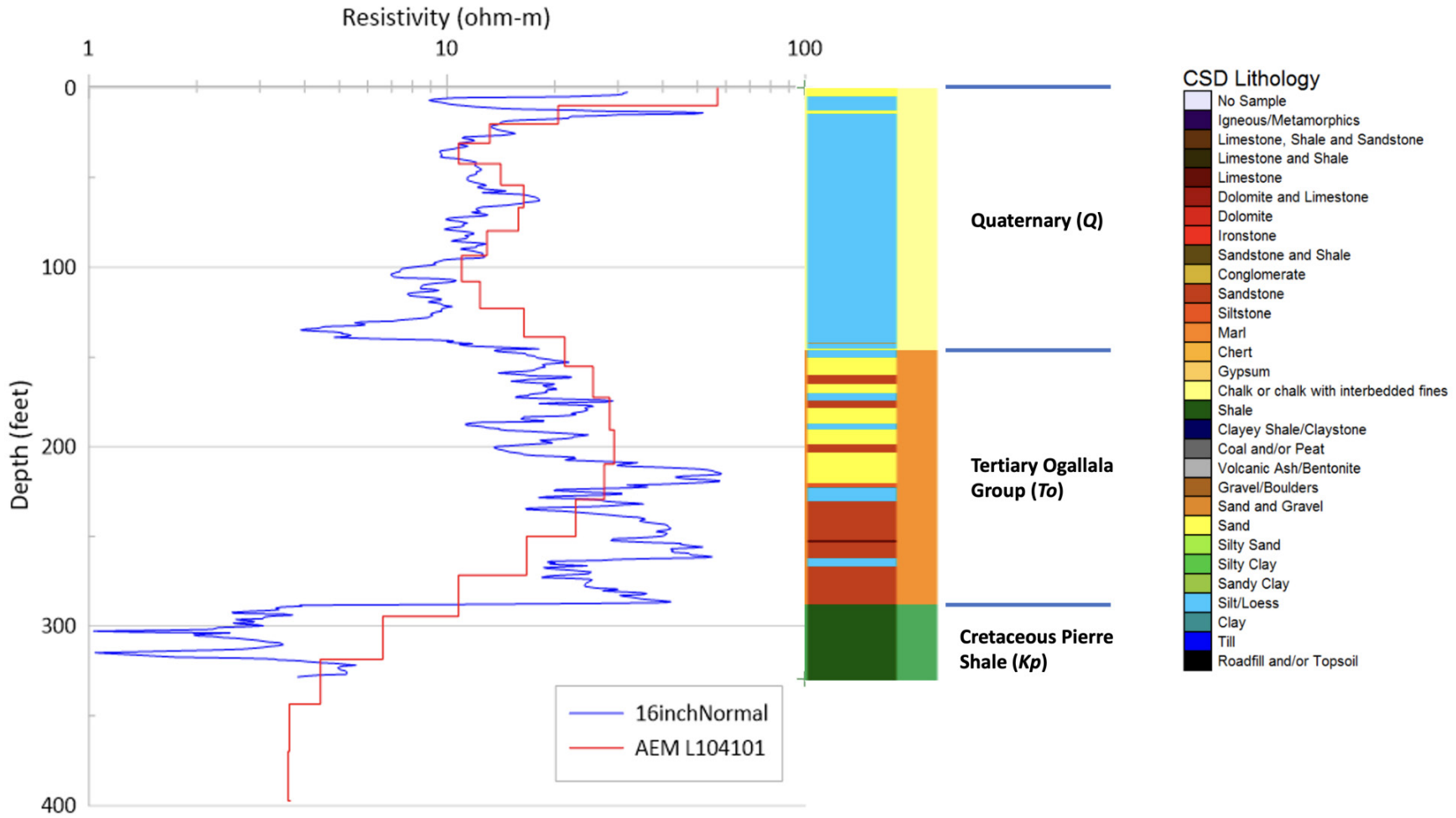


Figure 5-19. Graph of the *37-A-54* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *37-A-54*.

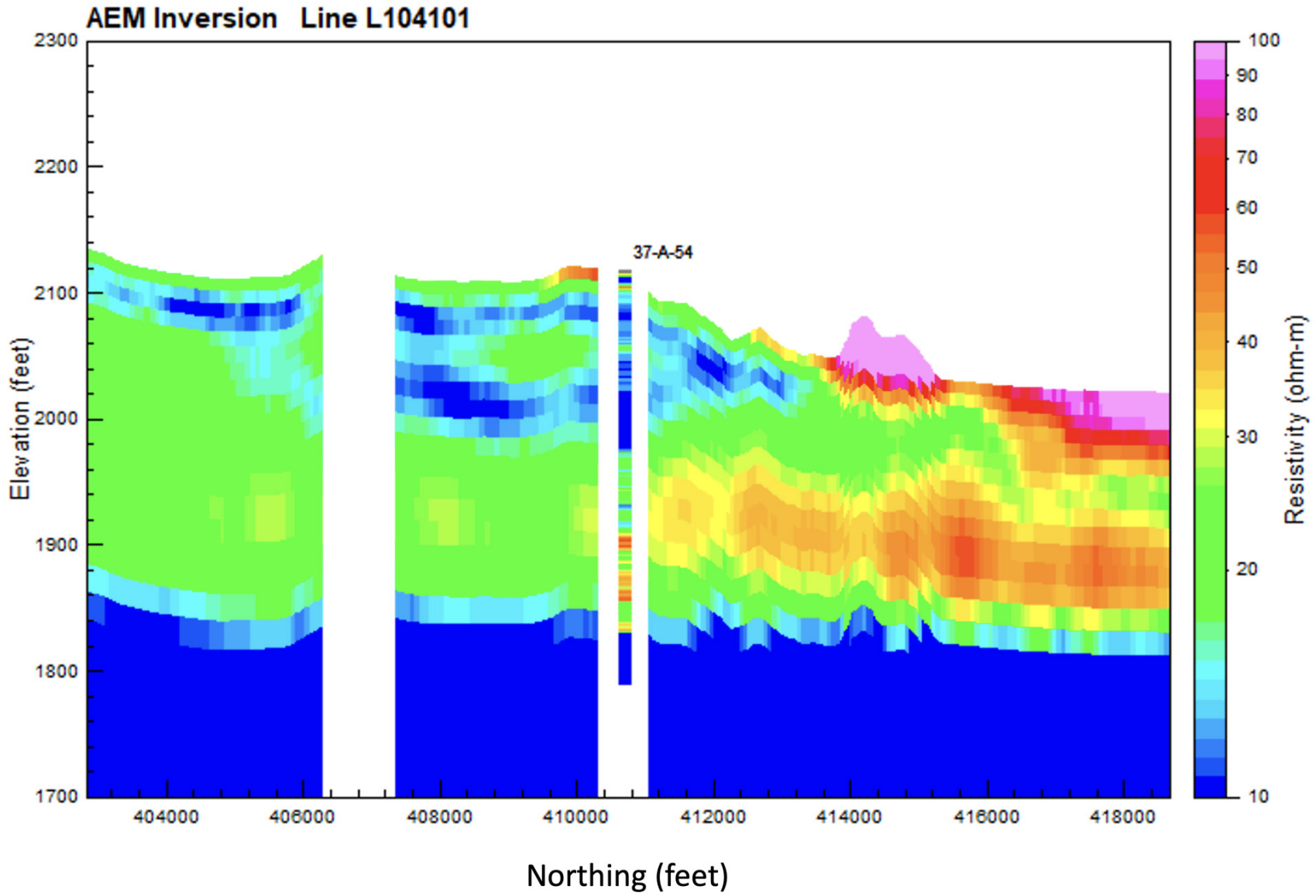


Figure 5-20. Profile of a portion of Line L104101 with the *37-A-54* 16-inch normal resistivity log resistivity values projected on the flight line at the same color scale.

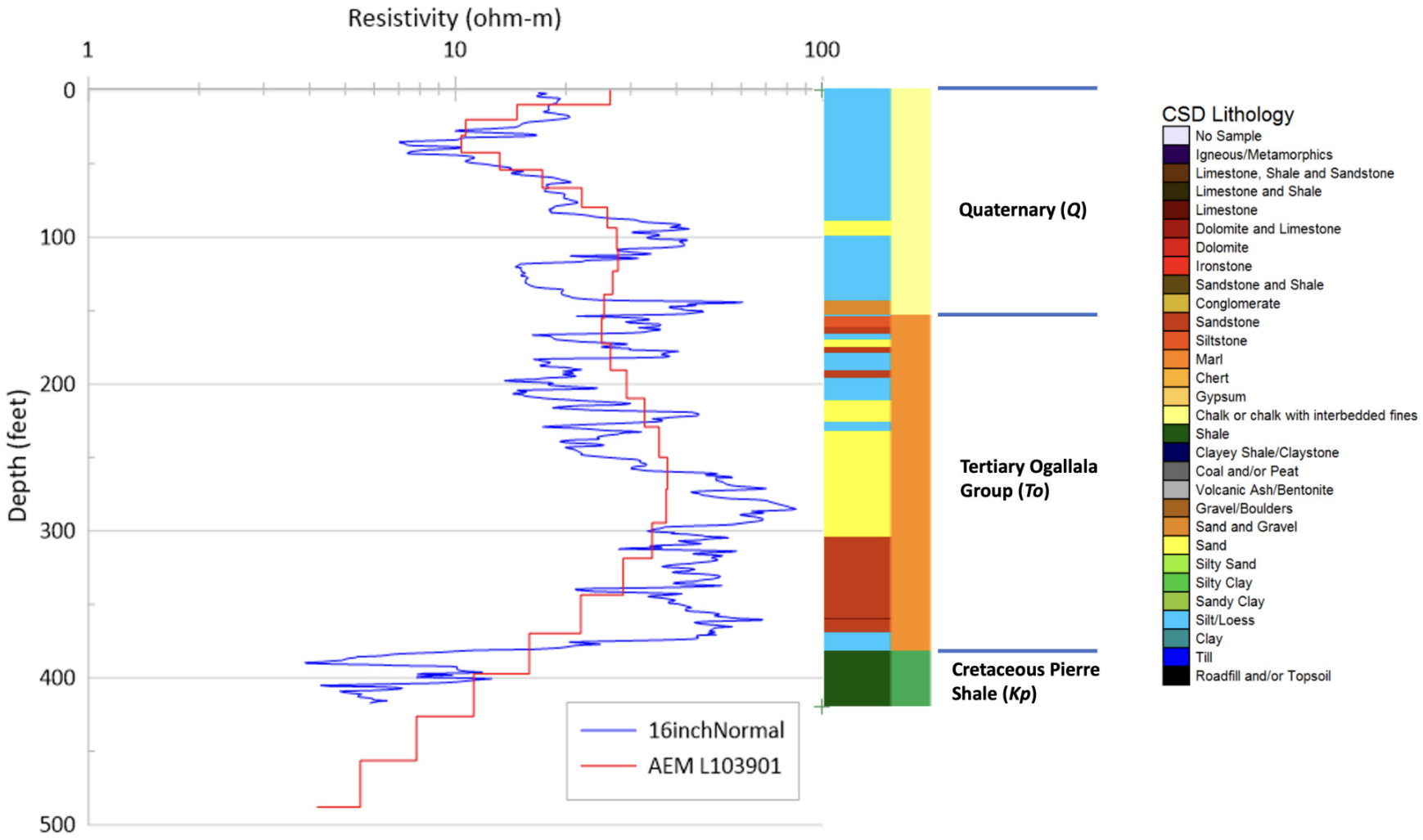


Figure 5-21. Graph of the *38-A-54* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *38-A-54*.

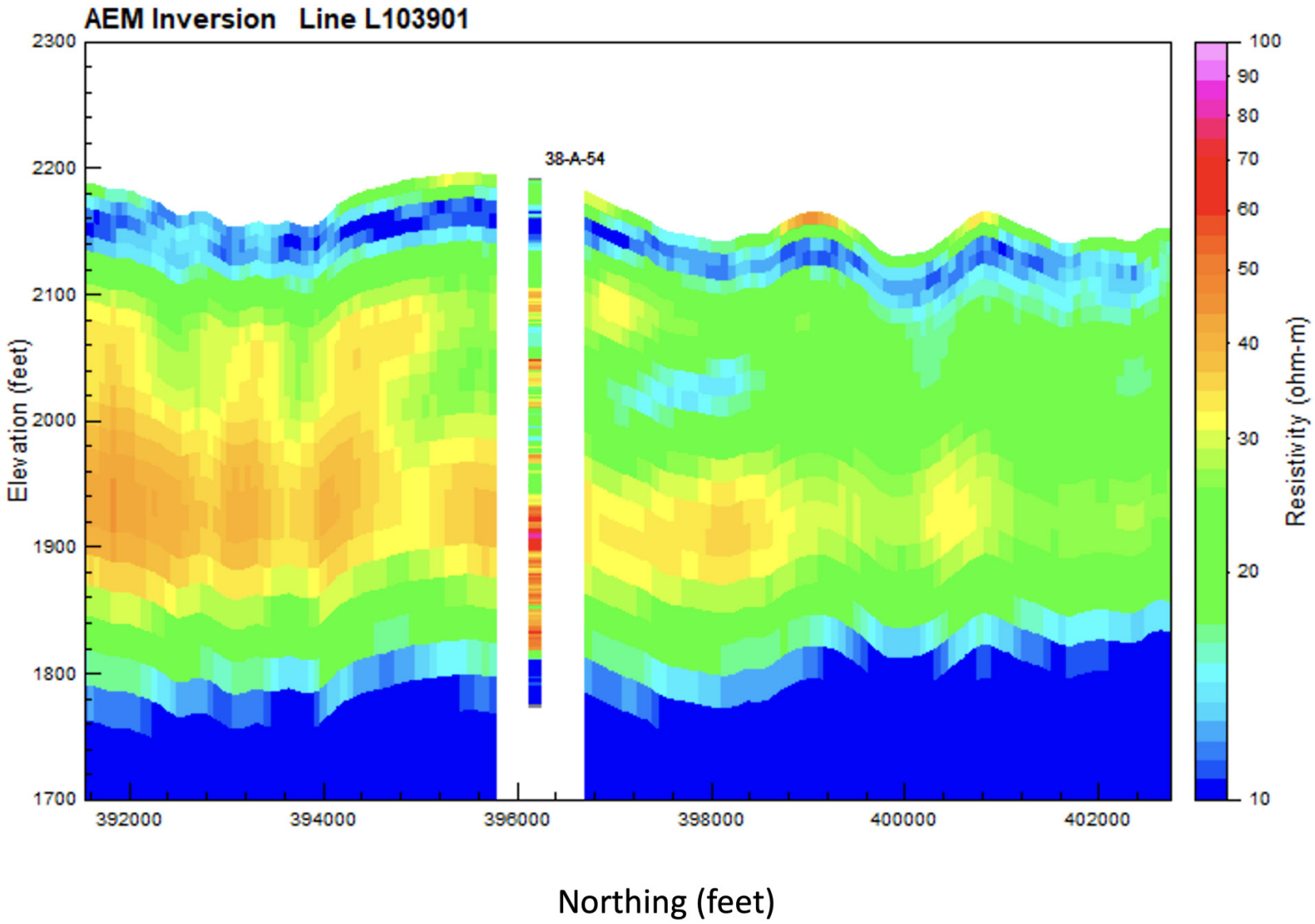


Figure 5-22. Profile of a portion of Line L103901 with the *38-A-54* 16-inch normal resistivity log resistivity values projected on the flight line at the same color scale.

5.3 Hydrogeological Framework of the LLNRD 2019 AEM Survey Areas

The priority for this survey was to build a detailed hydrogeologic framework to better understand the relationship between groundwater declines and the hydrogeologic framework, Managed Aquifer Recharge (MAR), water quality, and a new understanding of AEM framework to water quantity management efforts in Buffalo County.

The AEM reveals variability of the aquifer materials within the ***Q*** and ***To*** deposits, which make up the aquifers which provide the groundwater supply, and their spatial relationship to each other and the surface water. These spatial relationships can provide insight into groundwater recharge in the AEM survey area. Figure 5-23 presents the CSD bedrock geology map of the area (Burchett, 1986) and shows that the ***To*** is the bedrock for the survey area. The ***Kp*** is present beneath the ***To*** throughout the AEM survey area and is the lower bedrock unit that serves as the regional aquiclude. The term bedrock in this report represents the lower bedrock/Cretaceous bedrock unit of the ***Kp***.

For purposes of this report the ***Q*** and ***To*** contain the aquifers for the survey area and share the aquifer materials description. The ***Q*** and ***To*** use the same resistivity color scale to present locations of aquifer materials composed of non-aquifer (blue color in figures), marginal aquifer (tan color in figures), aquifer (yellow color in figures), and coarse aquifer materials (brown color in figures). The ***Q*** materials are composed predominantly of eolian and alluvial deposits related to the current drainages. The ***Q*** is a minor aquifer bearing unit except in the South Loup River valley and its tributaries overlying the ***To***. Figure 5-24 and Figure 5-25, displayed as 3D fence diagrams, present the overall distribution of ***Q***, ***To***, and ***Kp*** materials (as described in Section 2) across the LLNRD 2019 AEM survey area. The ***Q*** aquifer materials can generally be characterized as two somewhat overlapping, but distinct, areas distributed at various locations within the survey area. These areas are the northern and southern tablelands separated by the South Loup River Valley. The tablelands are covered mostly by eolian deposits made up of silt, clay, and fine sand that have limited permeability. There are localized hydrologic connections to the South Loup River and its tributaries to the ***Q*** aquifer and coarse aquifer units beneath the tablelands with the exception of isolated aquifers.

The ***To*** is continuous across the survey area and lies in direct contact below the ***Q***.. In much of the area ***Q*** and ***To*** deposits consisting of aquifer and coarse aquifer materials are in hydrologic connection with each other and the South Loup River and its tributaries. ***To*** deposits tend to have marginal and non-aquifer materials near its base at the contact with the ***Kp.*** There is no hydrologic connection between the ***To*** and the ***Kp***. The ***Kp*** is an impermeable shale that is considered an aquiclude or boundary to groundwater flow that is present throughout the survey area.

Figure 5-26 presents an exploded 3D Voxel model of the unsaturated ***Q***, saturated ***Q, To***, and ***Kp*** units. Note that the unsaturated ***Q*** is thickest in the upland areas and thinnest in the river valley. The saturated ***Q*** is the reverse with thickest saturated materials in the valley and thin to no saturation in the uplands. The ***To*** is thin in the northwest and thick in the southern tablelands. The ***Kp*** underlies the entire survey area.

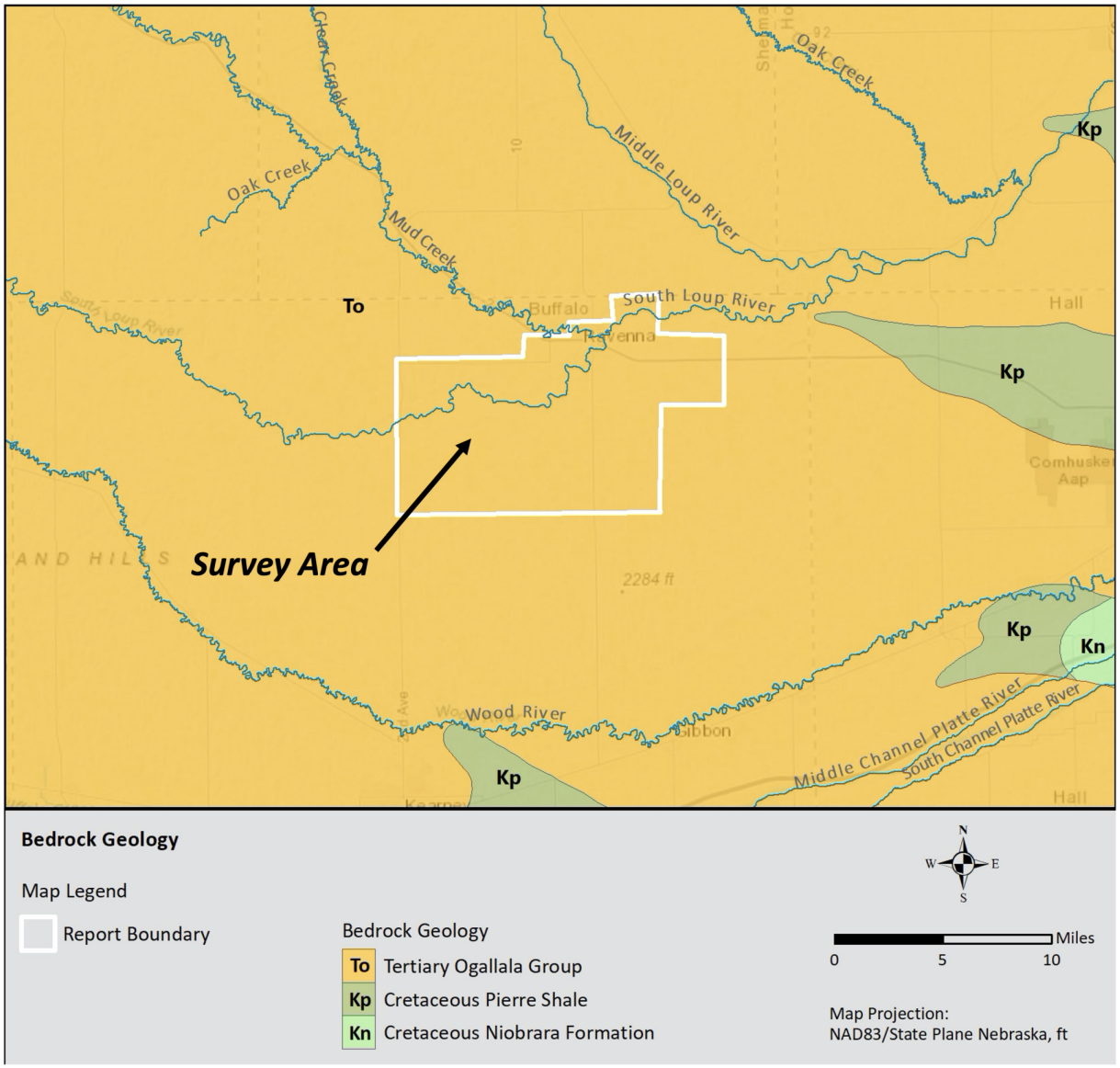


Figure 5-23. Bedrock map of the survey area modified from Burchett (1986). Note the entire area is composed of the Tertiary Ogallala Group (*To*) bedrock.

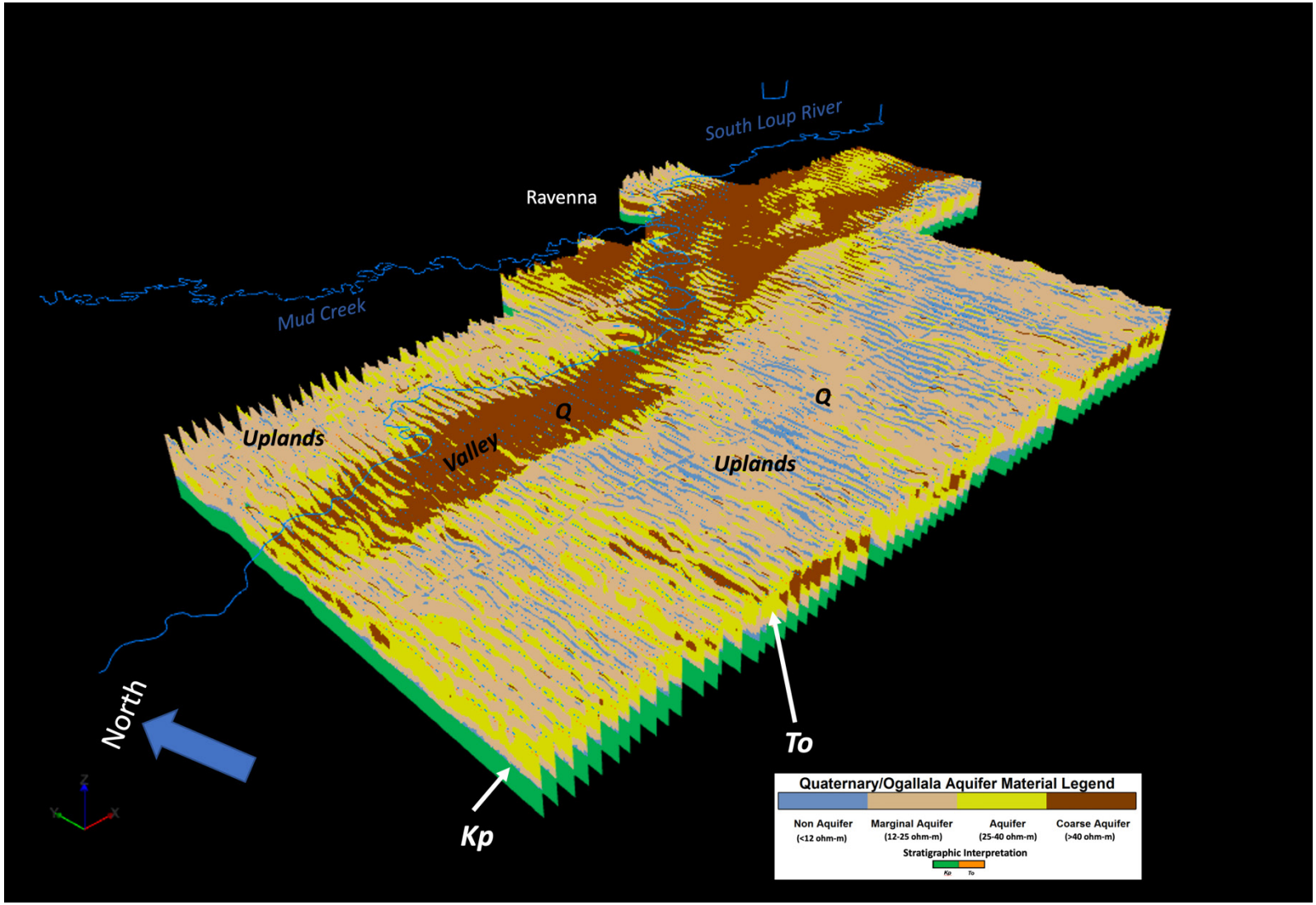


Figure 5-24. 3D Fence diagram looking to the northeast of the interpreted distributions of aquifer material within the LLNRD 2019 AEM survey area. Geological units include *Q* = Quaternary, *To* = Tertiary Ogallala Group (dashed orange line), and *Kp* = Cretaceous Pierre Shale. V.E.= 10x. Projection is NAD 83 Nebraska State Plane, feet.

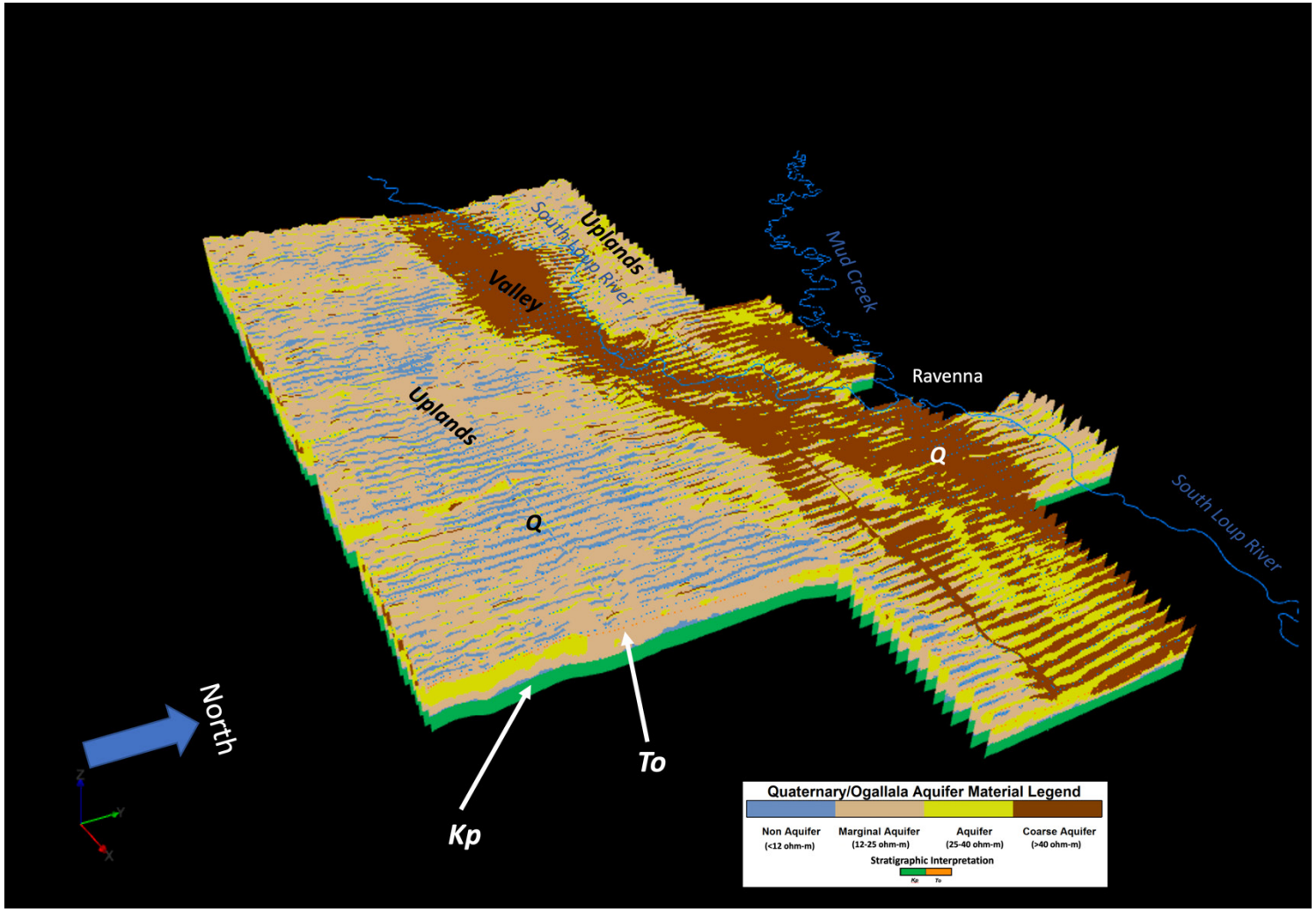


Figure 5-25. 3D Fence diagram looking to the west of the interpreted distributions of aquifer material within the LLNRD 2019 AEM survey area. Geological units include *Q* = Quaternary, *To* = Tertiary Ogallala Group (dashed orange line), and *Kp* = Cretaceous Pierre Shale. V.E.=10x. Projection NAD 83 Nebraska State Plane, feet.

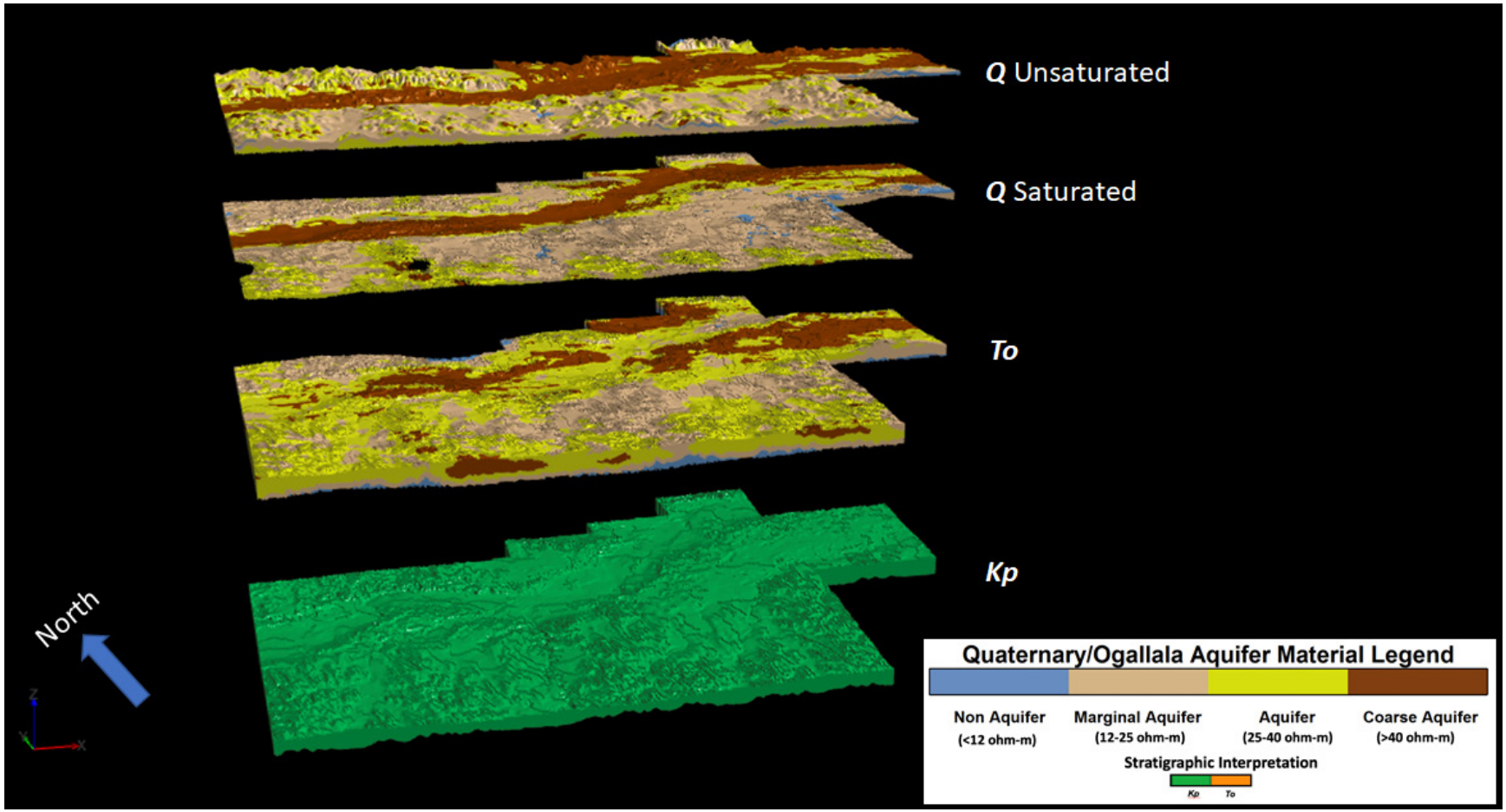


Figure 5-26. 3D exploded voxel model looking north of the LLNRD 2019 AEM survey area showing *Q* (Quaternary), *To* (Tertiary Ogallala Group), and *Kp* (Cretaceous Pierre Shale). The *Q* is separated into unsaturated and saturated. The figure is not to scale.

5.3.1 Hydrogeology of the Quaternary

The ***Q*** aquifer of the LLNRD 2019 AEM survey area is predominantly composed of unconsolidated aquifer material (yellow color in figures) and coarse aquifer materials (brown color in figures) composed of alluvial sediments of the South Loup River and its tributaries which are the dominant hydrogeologic features of the AEM survey area. The ***Q*** aquifer materials and coarse aquifer materials can act as the groundwater supply where it is saturated and/or that is hydrologically connected to the surface water system along the South Loup River. These materials lie on the ***To*** which is the bedrock for the LLNRD 2019 AEM survey area. The map of the elevation of the top of the ***To,*** which can be considered the base of ***Q,*** is presented in Figure 5-27. The ***To*** is lowest (1,841 ft) in the northeast and is highest (2,114 ft) in the south. The ***Q*** can be very heterogeneous in places with a changing mix of all aquifer materials found mostly on the tablelands. Figure 5-28 is a 3D voxel model looking west showing the distribution of all ***Q*** aquifer materials. Note the dominance of the coarse aquifer materials and aquifer materials along the South Loup River Valley versus the mix of aquifer materials found on the tablelands. Figure 5-29 is a 3D fence diagram looking east which presents the transition between the north tablelands and the south tableland into the South Loup River Valley. Note the abrupt change from marginal and non-aquifer materials in the upper portion of the ***Q*** in the uplands to the coarse aquifer and aquifer materials in the valley. This change is important because of the small amount of groundwater recharge in the tablelands versus the large amount of recharge in the valley. Figure 5-30 shows the total thickness of the ***Q*** deposits and reveal that the thickest ***Q*** deposits are on the tablelands in the northwest corner and just south of the confluence of Mud Creek and South Loup River. The ***Q*** varies in thickness from <75 ft along the South Loup River and its tributaries and the south tableland up to 308 ft thick on the tableland in the northwest corner of area. Figure 5-31 shows the saturated thickness of the ***Q*** deposits, present throughout the survey area, varying from 0 ft in the southern tablelands to 191 ft in the center north of the AEM study area between Mud Creek and the South Loup River. These saturated sediments can be hydrologically connected to the surface water where coarse aquifer materials and aquifer materials are in direct contact with the surface water.

Figure 5-32 is a profile view of north-south line L103401. The complex nature of the subsurface containing the ***Q*** and ***To*** aquifer materials can be seen along this profile. Aquifer materials and coarse aquifer materials beneath the South Loup River are hydrologically connected to the surface water. This includes the ***Q*** and ***To*** aquifer and coarse aquifer materials which extend south of the river a short distance and to the north to the end of the profile. The presence of marginal and non-aquifer materials near northing 405000 that is vertically continuous is a barrier to groundwater flow. Figure 5-33 shows the saturated thickness of ***Q*** coarse aquifer and aquifer materials across the area. The saturated thickness of the ***Q*** aquifer and coarse aquifer materials is thin below the south tableland, most of the northwest corner, and are thick along the South Loup River and its tributaries. Figure 5-34 provides insight into the relationship between ***Q*** saturated thickness and well specific capacity (SC). The thickest areas are along the South Loup River and its tributaries and show the limited number of ***Q*** wells completed in the area which is a result of limited saturated thickness of aquifer and coarse aquifer materials in the tablelands. There is a total of 6 registered wells completed in the ***Q*** sediments with three wells producing<5 gpm/ft, 2 producing 10 to 25 gpm/ft and one with no SC data.

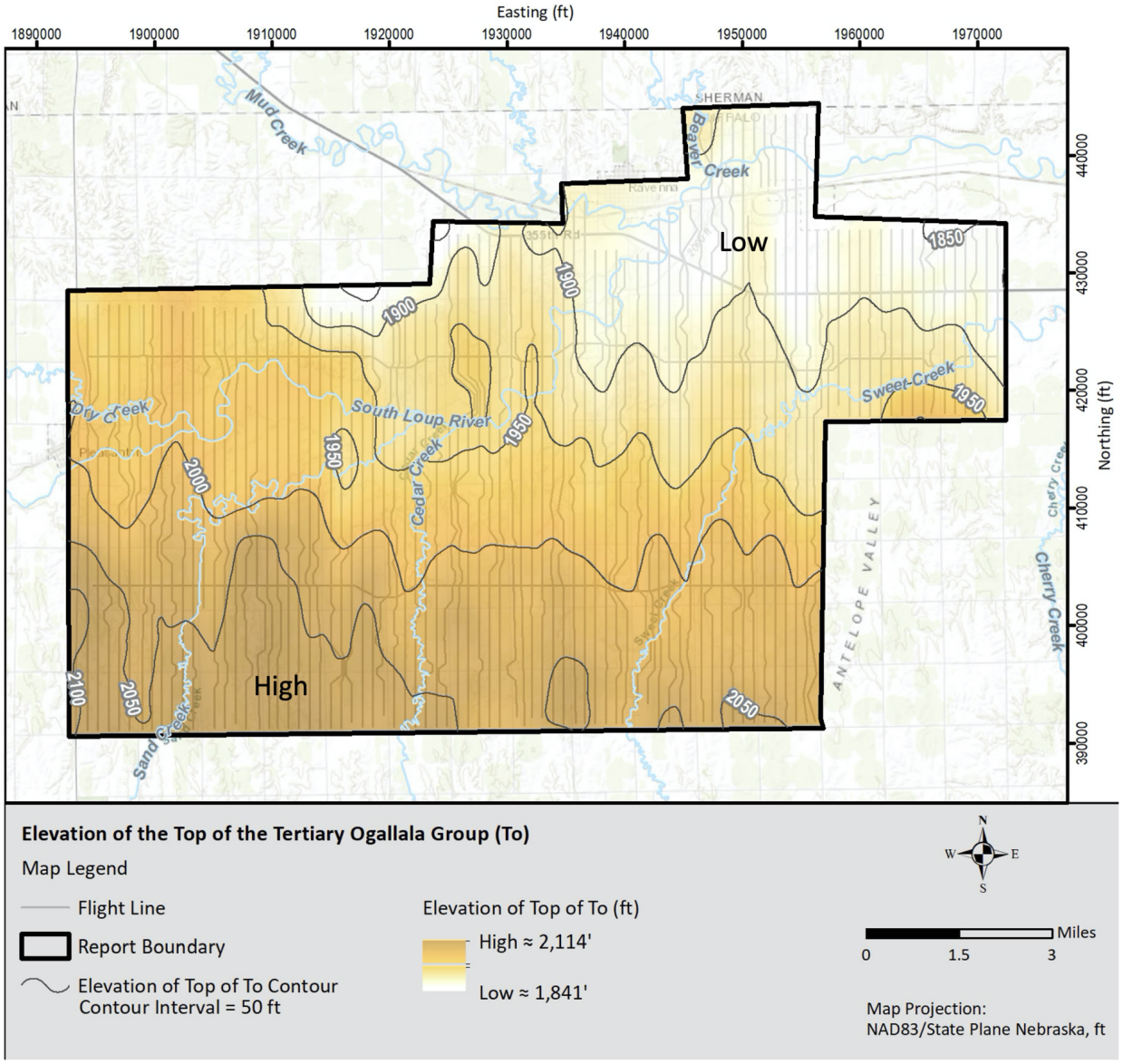


Figure 5-27. Map of the elevation of the top of the Tertiary Ogallala Group (*To*). Vertical elevations are referenced to NAVD88 (feet).

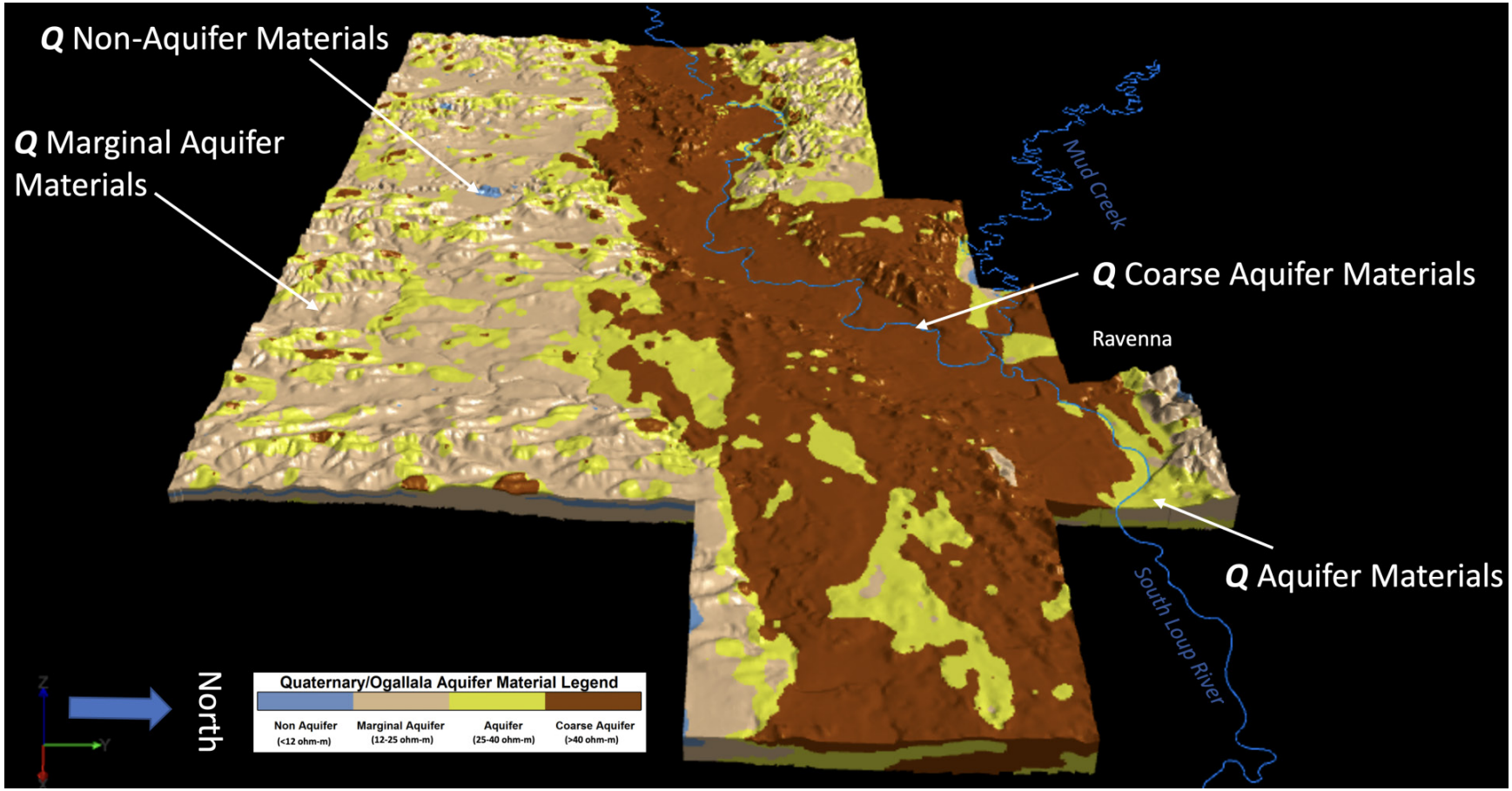


Figure 5-28. 3D voxel model of the LLNRD 2019 AEM survey area showing all aquifer materials in the Quaternary (*Q*). The *Q* is not separated into unsaturated and saturated. Only the Quaternary is present in this figure. V.E.= 10x.

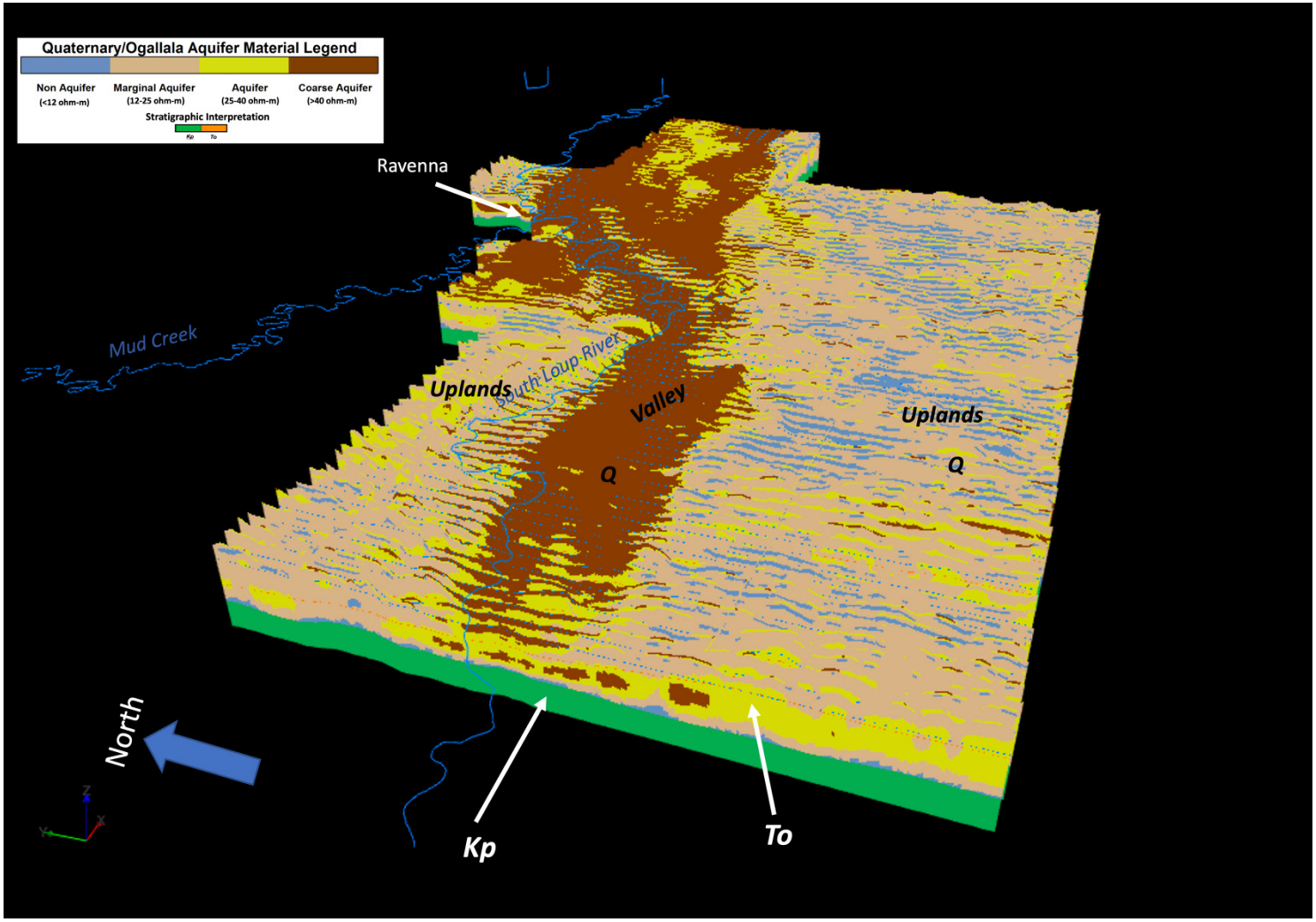


Figure 5-29. 3D Fence diagram looking to the east of the interpreted distributions of aquifer material within the LLNRD 2019 AEM survey area and the transition between the uplands to the South Loup Valley. The geologic units are *Q* = Quaternary, *To* = Tertiary Ogallala Group (dashed orange line), and *Kp* = Cretaceous Pierre Shale. V.E.= 10x. Projection NAD 83 Nebraska State Plane, feet.

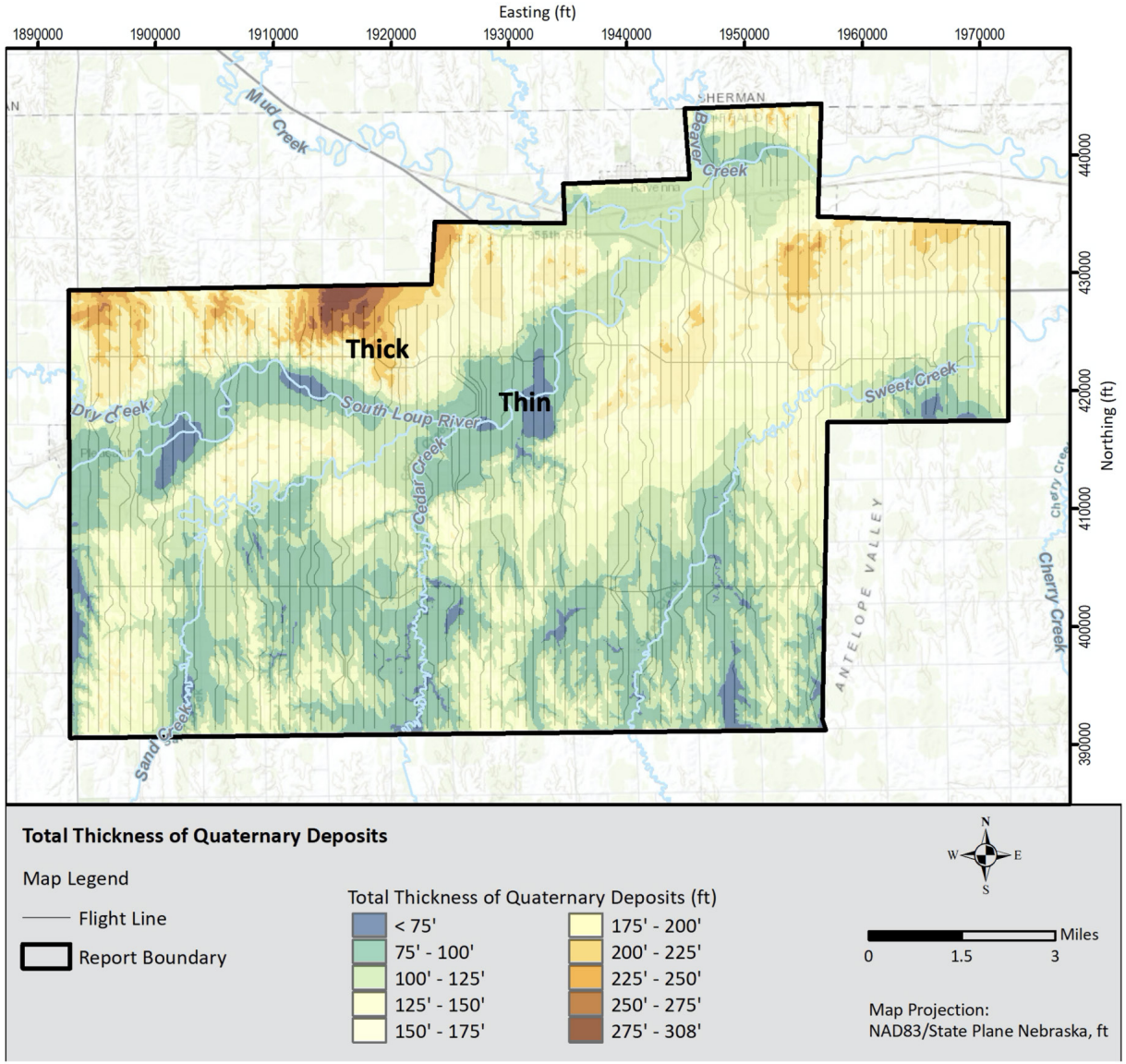


Figure 5-30. Map of the total thickness of the Quaternary (*Q*) deposits within the LLNRD 2019 AEM survey area. The deposits are thick in the northwest upland and thin to the south and along the South Loup River. Flight lines are indicated by the grey lines.

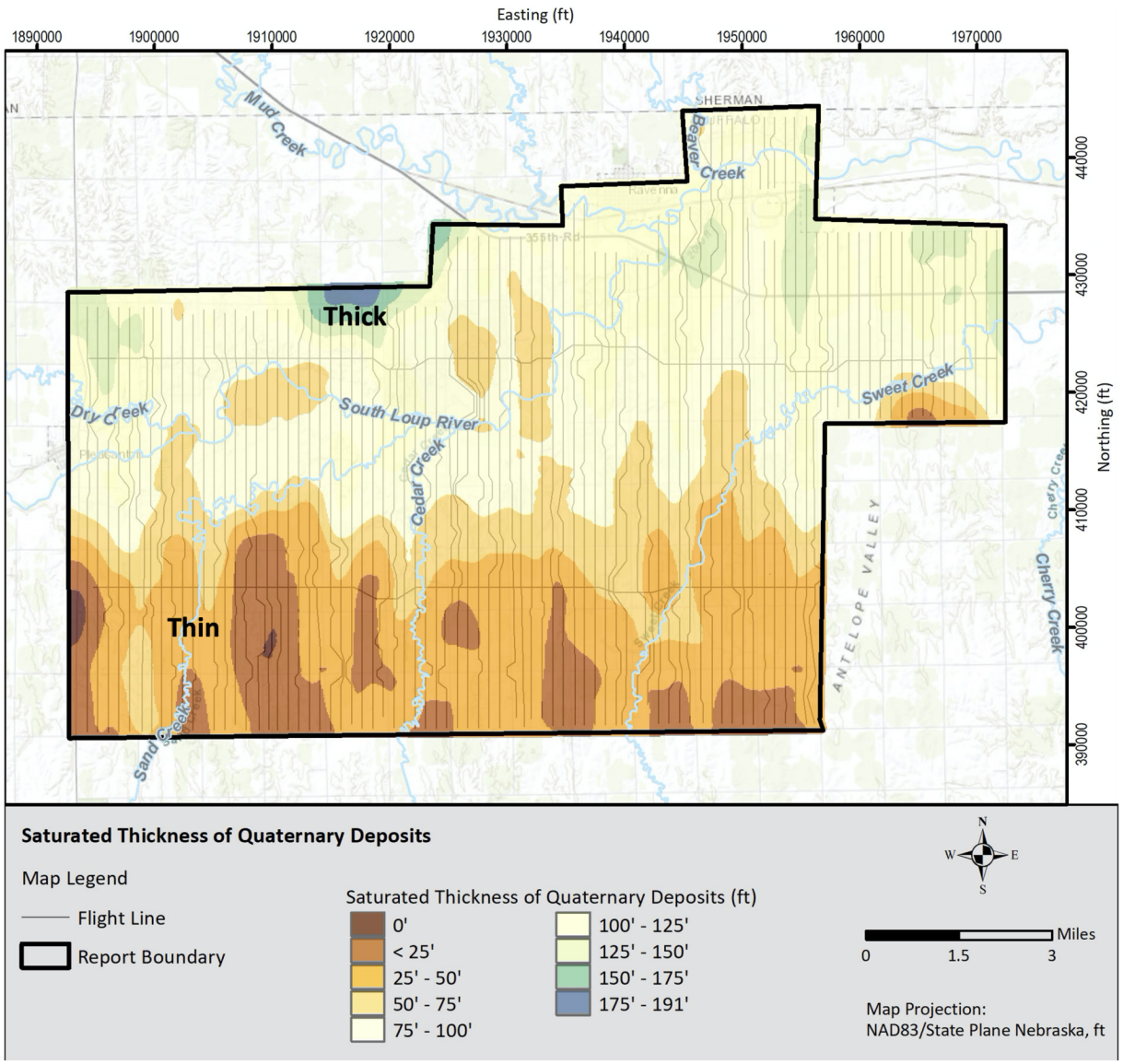


Figure 5-31. Map of the saturated thickness of the Quaternary (*Q*) deposits within the LLNRD 2019 AEM survey area. The deposits are thick in the northwest upland and thin to the south and along the South Loup River. Flight lines are indicated by the grey lines.

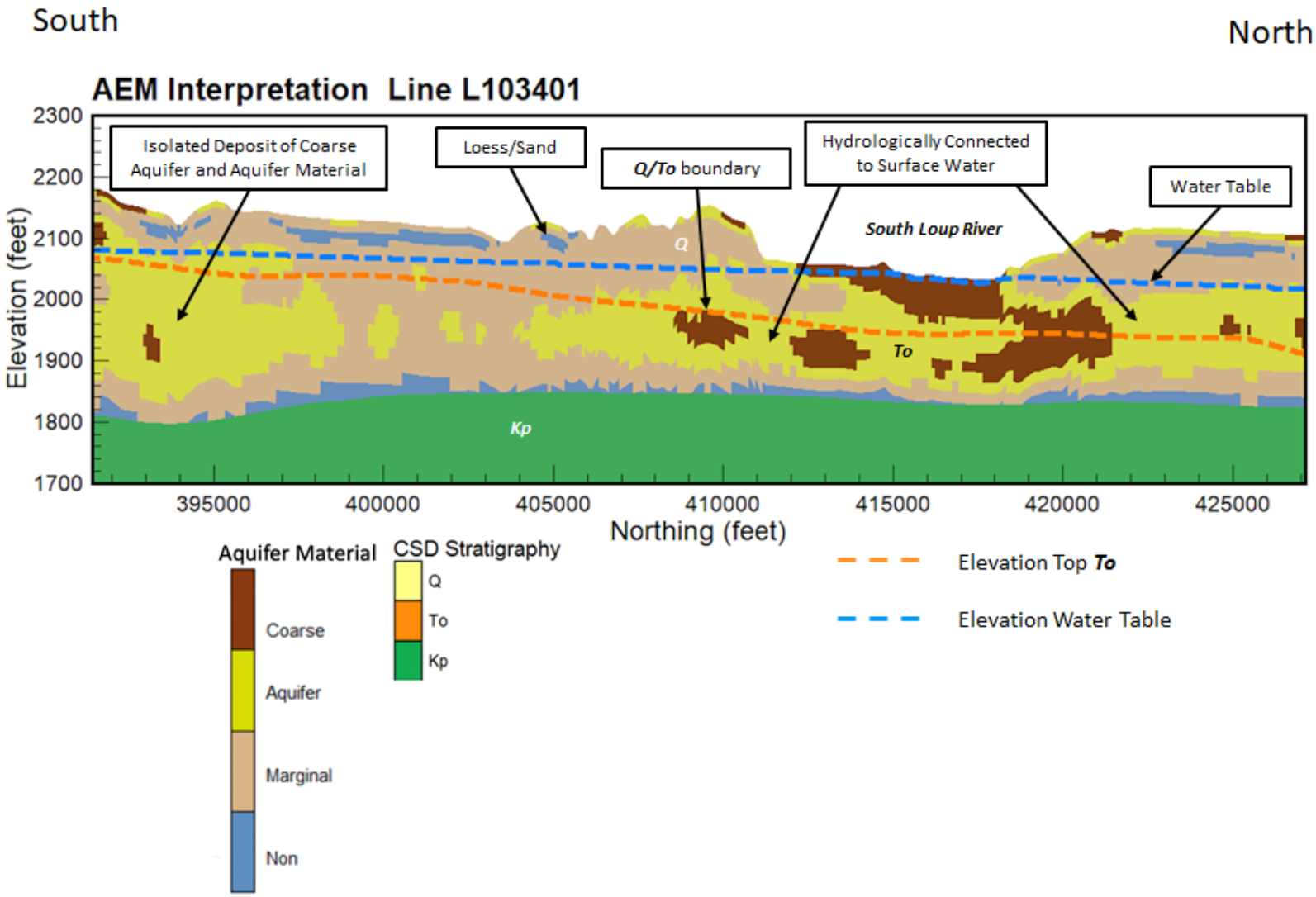


Figure 5-32. Profile view of north-south line L103401 showing *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials overlie the *Kp* (Cretaceous Pierre Shale). Groundwater from the *Q* and *To* is hydrologically connected to the South Loup River. The water table is the dashed blue line. The top of the *To* is the dashed orange line.

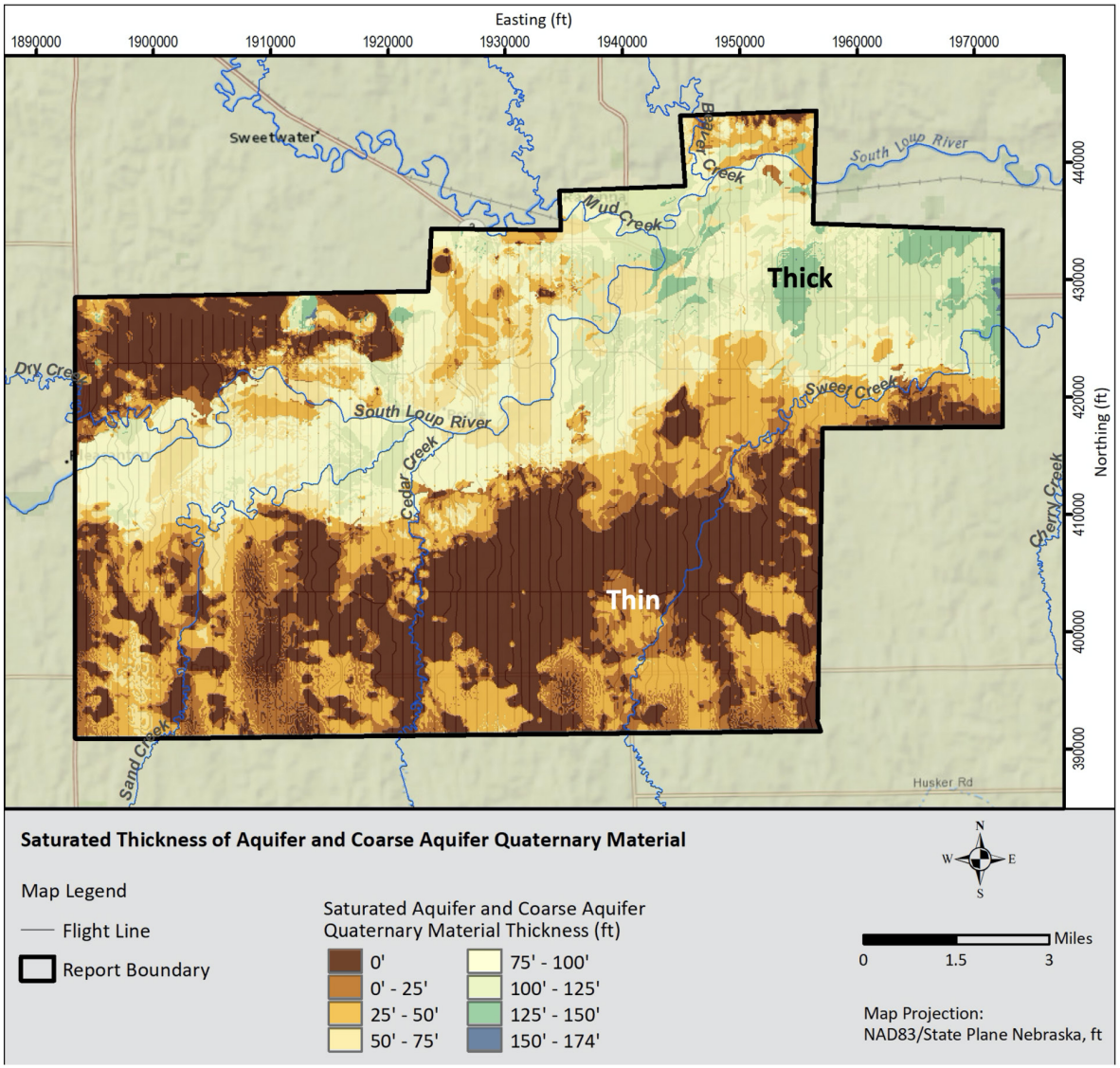


Figure 5-33. Map of the saturated thickness of the Quaternary (*Q*) aquifer and coarse aquifer material deposits within the LLNRD 2019 AEM survey area. The deposits are thick in the northeast and along the South Loup River; they thin below the south and northwest tablelands. Flight lines are indicated by the grey lines.

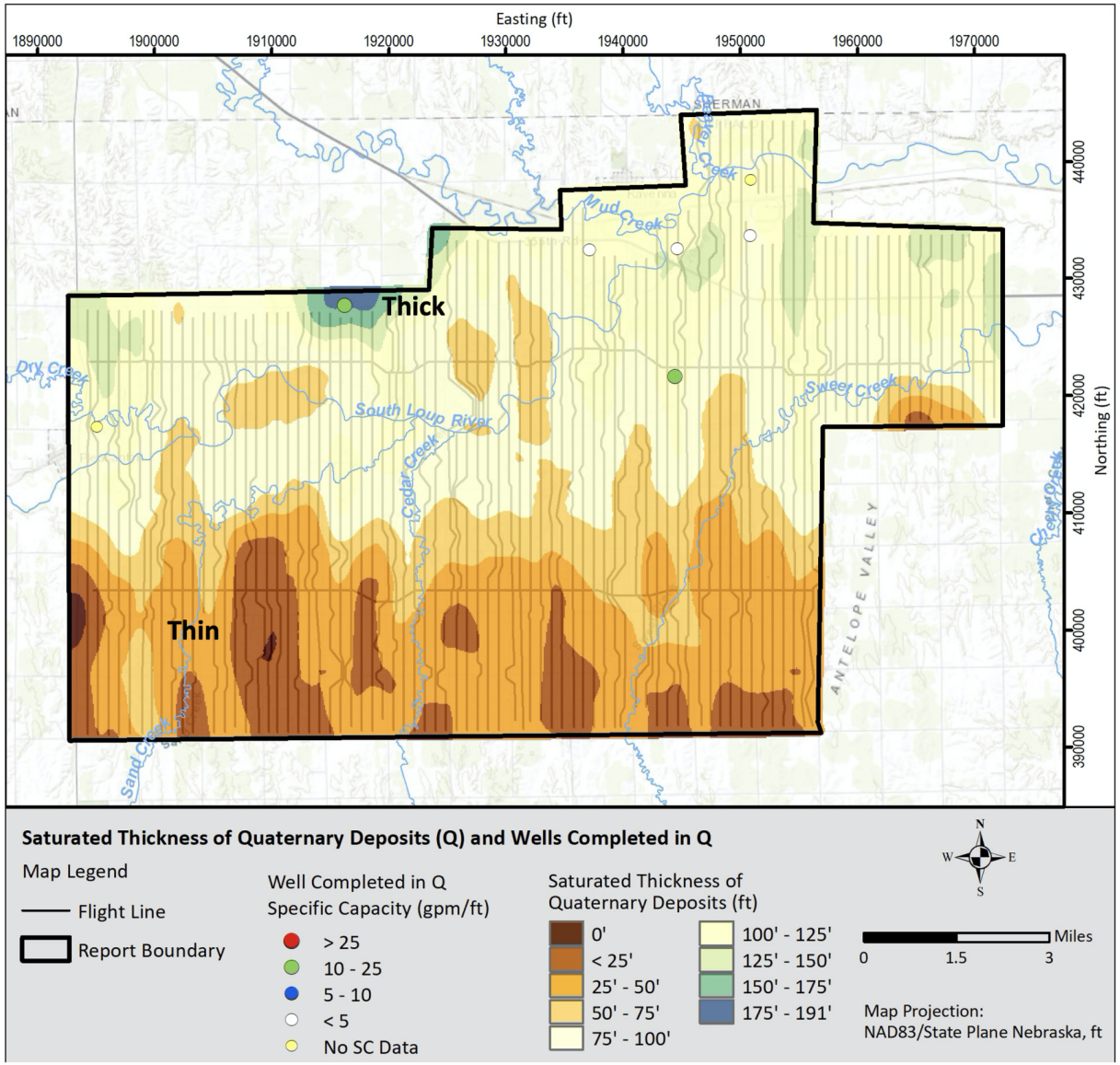


Figure 5-34. Map of the saturated thickness of all Quaternary (*Q*) aquifer material deposits within the LLNRD 2019 AEM survey area with the Specific Capacity (SC) of the wells in gpm/ft. Flight lines are indicated by the grey lines.

Viewing the 3D voxel Model of the ***Q*** saturated aquifer and coarse aquifer materials in Figure 5-35 shows where these materials are present which is mostly in the South Loup River Valley. Where the aquifer and coarse aquifer materials are absent, there is a barrier to flow from recharge or a reduction in any hydrologic connection between the deposits. This affects groundwater flow between deposits and movement towards the streams of the area. Figure 5-36 is a profile view of east-west line L200101 that generally parallels the South Loup Valley. It is an example of the complexity of the aquifer material deposits in the area. Starting on the west end (left side) and moving east along the profile layers of thick nearly continuous deposits of ***Q*** marginal and non-aquifer materials are present from northing ~1900000 to ~1910000. The geology then changes to a layer of aquifer material about ~100-150 feet thick lying on the ***To*** covered by ~100 feet of marginal aquifer material. As you approach the South Loup River Valley, the ***Q*** is mostly coarse aquifer materials and aquifer materials that are unconfined and hydrologically connected to the river. Between northing 1940000 and the east end of the profile there is a layer of marginal aquifer material that is between layers of aquifer and coarse aquifer materials. The coarse aquifer material and aquifer material deposits above the marginal aquifer material layer is mostly unsaturated while the coarse aquifer and aquifer deposit below the marginal aquifer layer is saturated and is still in hydrologic connection to the river. ***Q*** groundwater flow in this area is influenced by the depositional environment along the South Loup River.

In addition to the aquifer materials and coarse aquifer materials there are areas of non-aquifer and marginal aquifer materials that are mostly found on the tablelands near the ground surface as eolian loess deposits, silts and clays, and continuous layers of fine-grained material. These layers can locally act as aquicludes and prevent hydrologic connection to a stream or recharge. These layers can also serve as locally confining units. Figure 5-37 is a profile view of east-west line L200201 through the southern tablelands. It is an example of the complexity of the area showing several of layers of ***Q*** marginal (tan color) and ***Q*** non-aquifer (blue color) materials found in the area and the small amounts of ***Q*** aquifer materials and ***Q*** coarse aquifer materials, both saturated and unsaturated. The profile in the south tableland near easting 1930000 indicates a large amount of marginal and non-aquifer materials from the land surface to the ***To*** bedrock. As stated above, these fine-grained units restrict and limit recharge. Figure 5-38 shows the total saturated thickness of the ***Q*** non-aquifer and marginal aquifer materials. These materials are thickest to the northwest and south tablelands and are thin along the South Loup River. Figure 5-39 shows the unsaturated ***Q*** non-aquifer and ***Q*** marginal aquifer materials as a 3D voxel model looking north revealing the extensive coverage and thickness of these materials across the area. Note that the largest amounts of these materials are present on the south and the northwest tablelands. Also, note the breaks in caused by absence of these materials along the South Loup River and its tributaries. When compared with the 3D voxel model of the saturated ***Q*** marginal and non-aquifer materials (Figure 5-40), insight is provided as to why these materials limit the amount of recharge from the land surface to the groundwater system. The continuous nature of these materials both south and north of the South Loup River limit the flow of water from the land surface to the water table and below. This limitation to recharge is a leading cause of groundwater declines in the area because of the limited recharge moving downward.

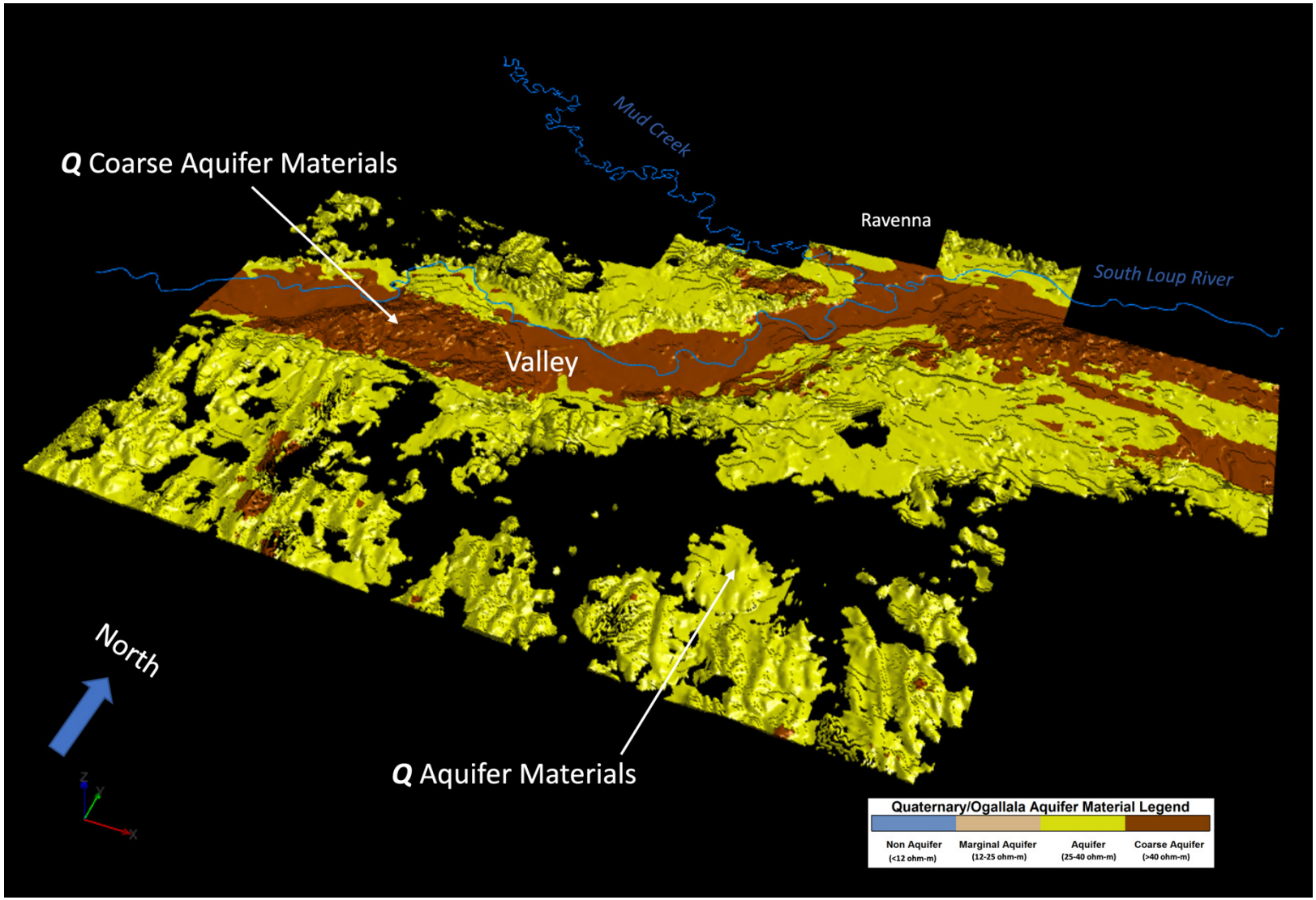


Figure 5-35. 3D voxel model of the survey area showing saturated coarse aquifer materials and aquifer materials in the *Q* (Quaternary). Note that the largest amounts of these materials are present along the South Loup River Valley. Note the breaks where there is no aquifer material and coarse aquifer material between the valley and the south tableland. V.E.= 10x.

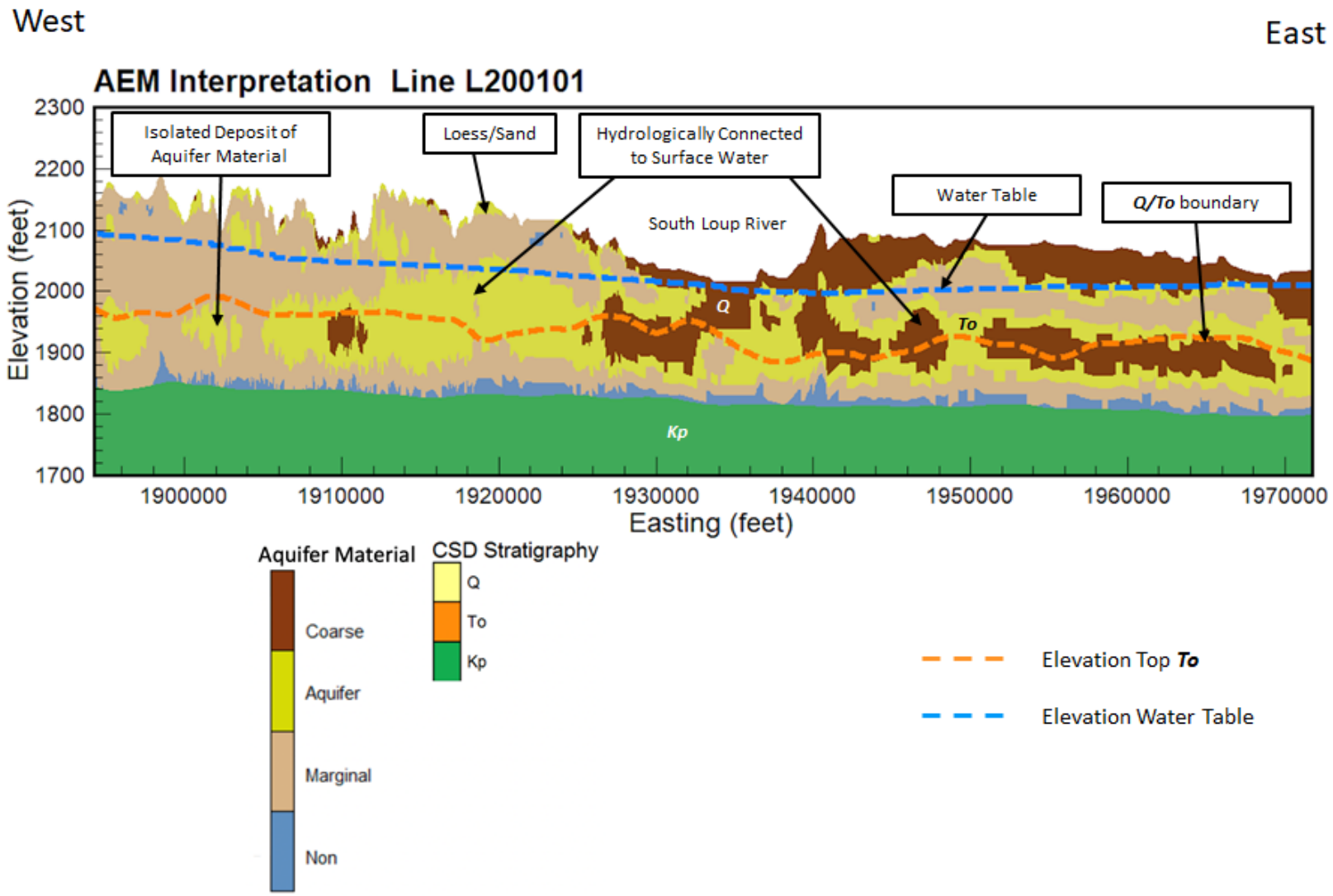


Figure 5-36. Profile view of east-west line L200101 with *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials above the *Kp* (Cretaceous Pierre Shale). Groundwater from the *Q* and *To* is hydrologically connected to the South Loup River. The CSD 1995 water table is the dashed blue line. The top of the *To* is the dashed orange line.

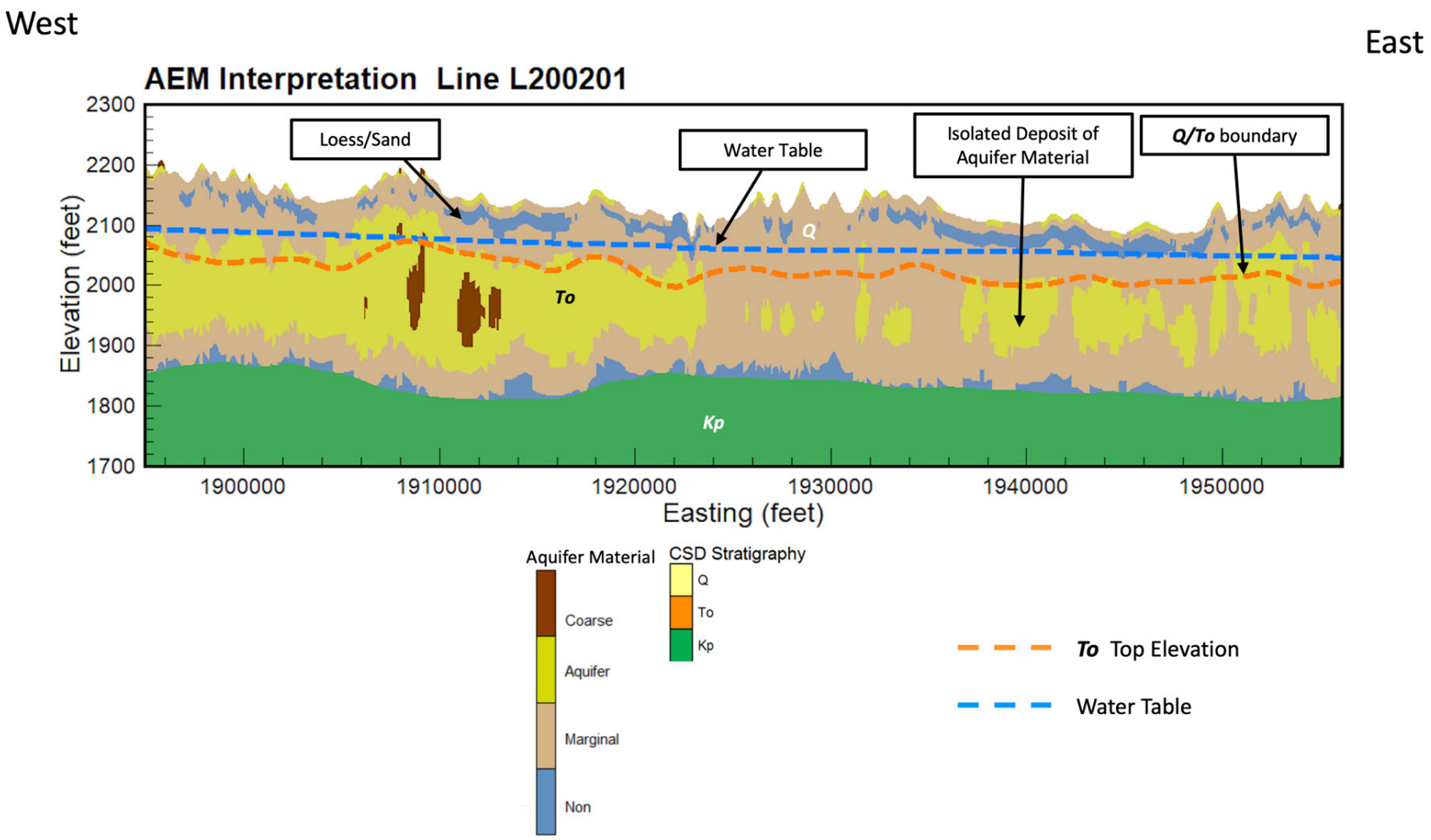


Figure 5-37. Profile view of east-west line L200201 in the tablelands showing *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials above the *Kp* (Cretaceous Pierre Shale). The CSD 1995 water table is the dashed blue line. The top of the *To* is the dashed orange line.

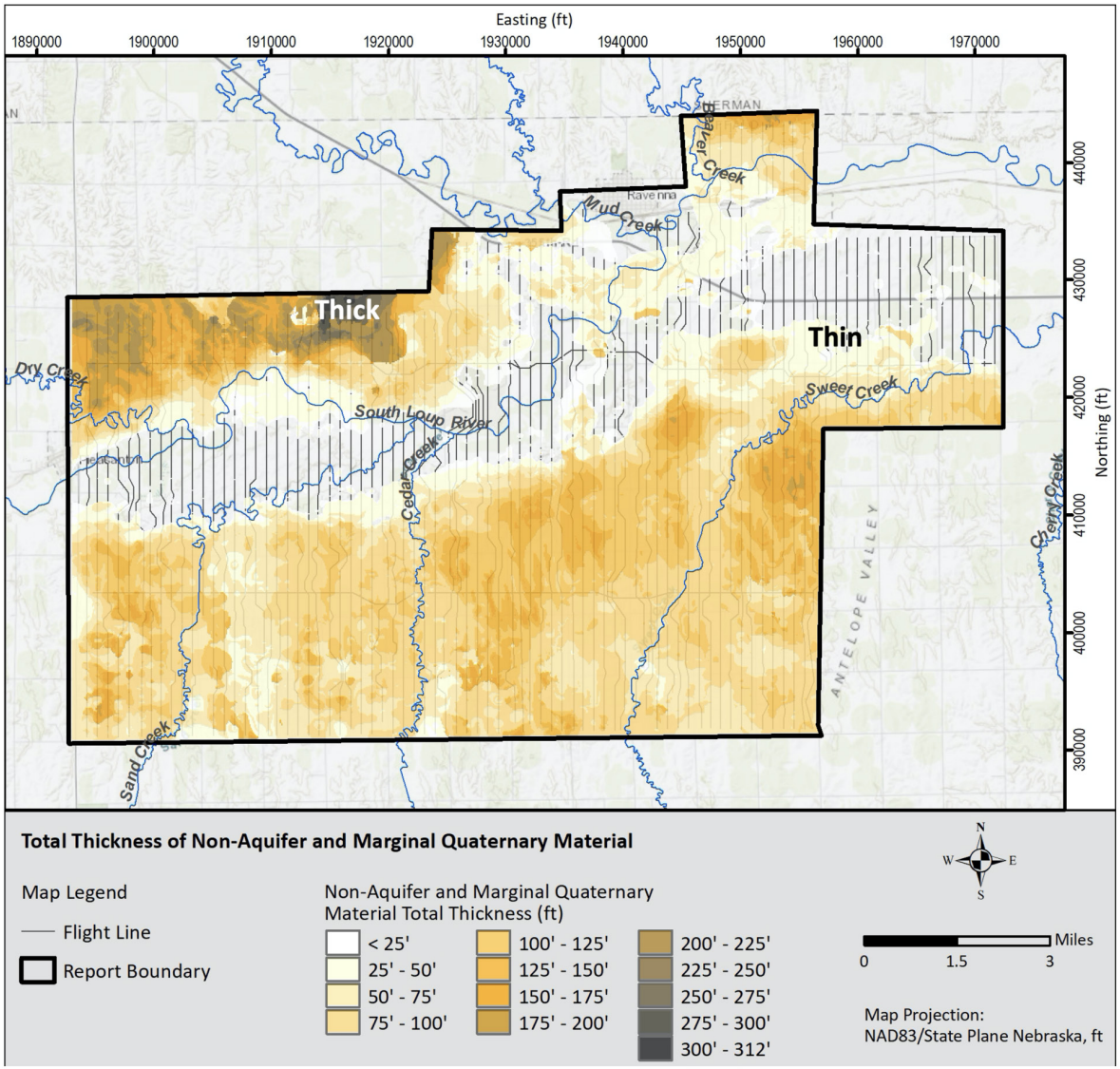


Figure 5-38. Map of the total thickness of the *Q* (Quaternary) non-aquifer and marginal aquifer material deposits within the survey area. These materials are thickest to the northwest and south tablelands. They are thin along the South Loup river. Flight lines are indicated by the grey lines.

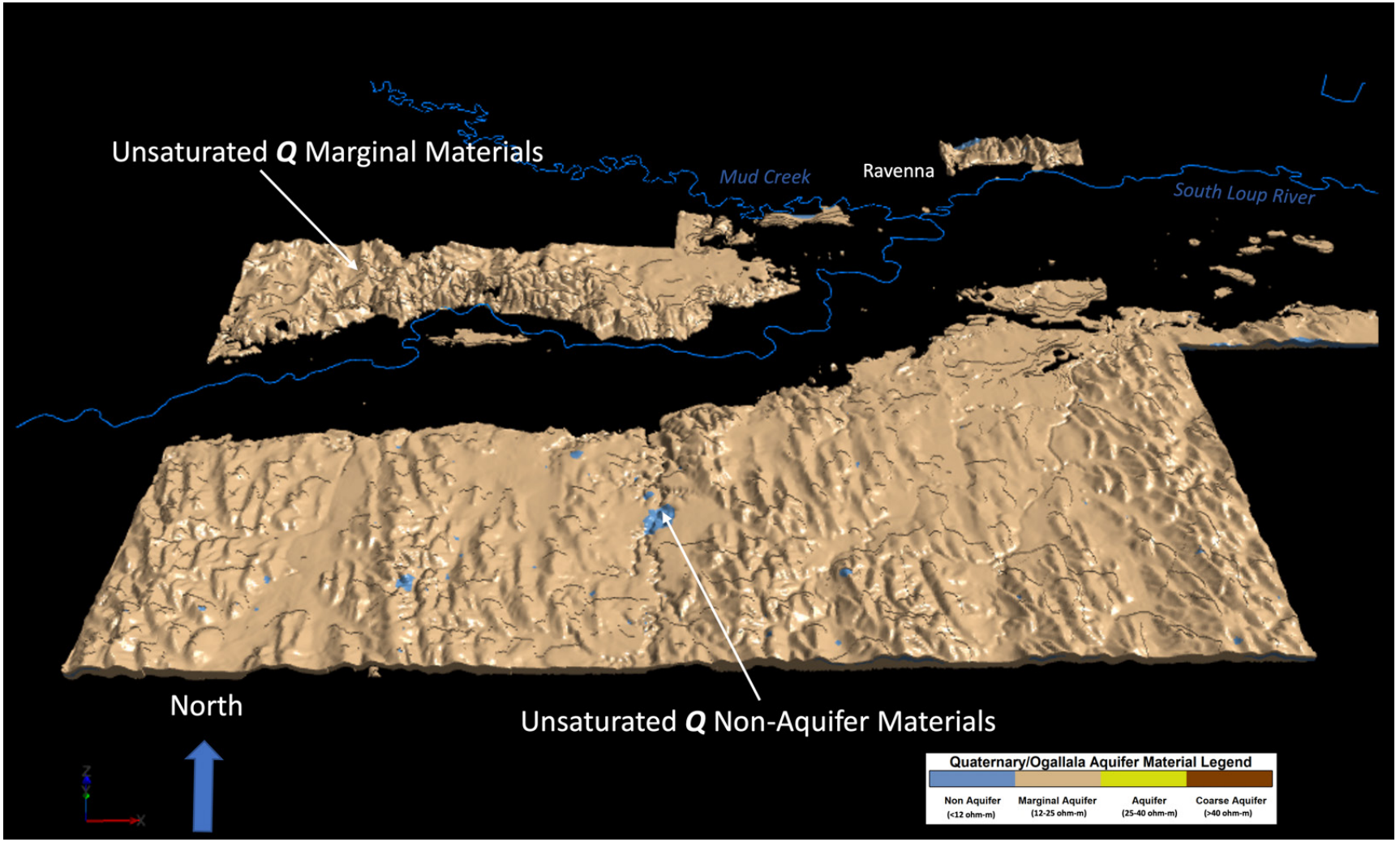


Figure 5-39. 3D voxel model of the LLNRD 2019 AEM survey area showing unsaturated marginal and non-aquifer materials in the *Q* (Quaternary). Note that the largest amount of these materials is present in the south and northwest tablelands. Also, note the breaks are caused by absence of these materials along the South Loup River and its tributaries. V.E.= 10x.

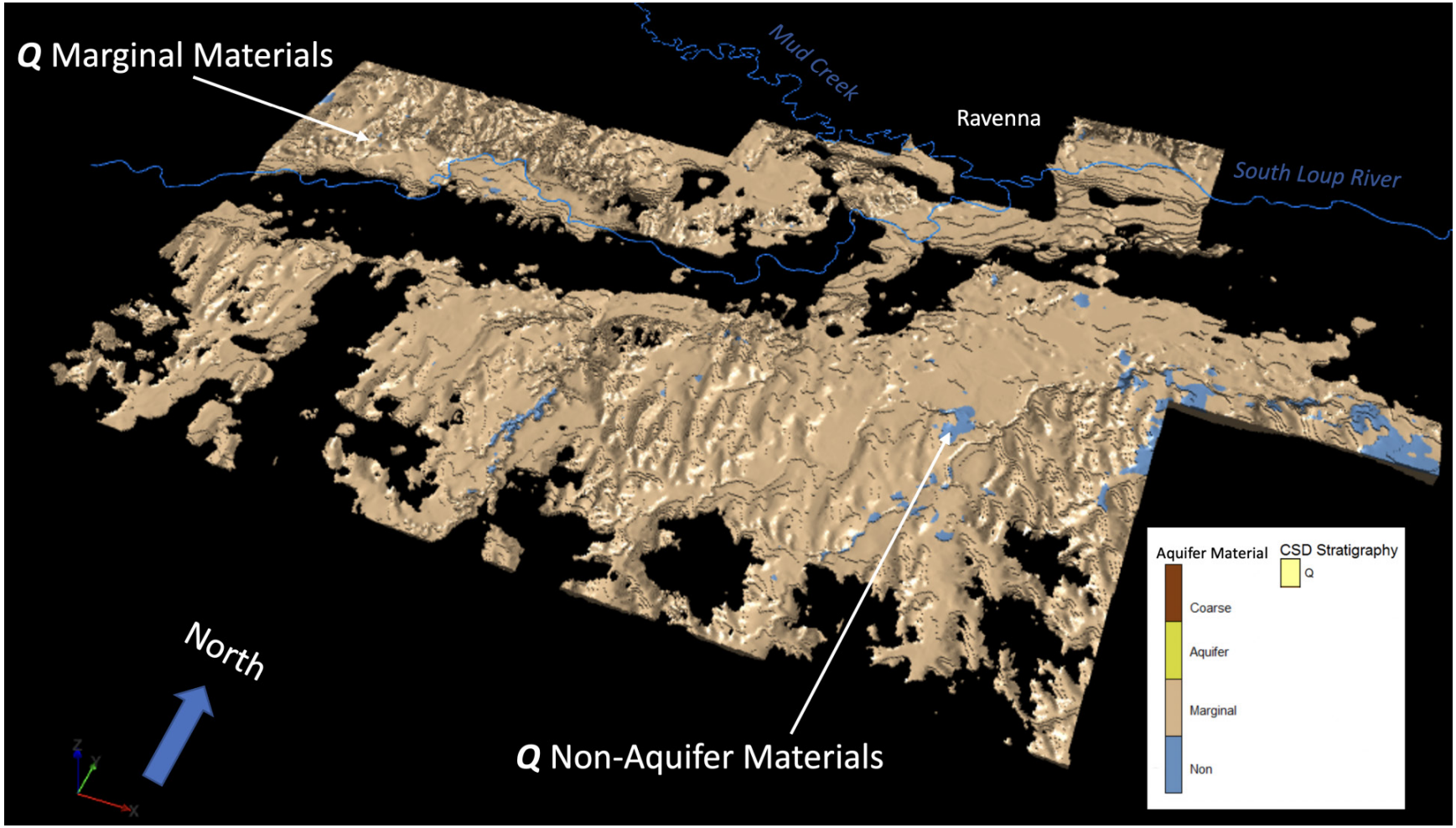


Figure 5-40. 3D voxel model of the survey area showing saturated marginal and non-aquifer materials in the *Q* (Quaternary). The largest amounts of these materials are present on the southern and northwest tablelands. There are gaps in these materials along the South Loup River and its tributaries with the exception of near Ravenna, Nebraska. V.E.= 10x.

5.3.2 Hydrogeology of the Tertiary Ogallala Group

The ***To*** bedrock of the LLNRD 2019 AEM survey area is predominantly composed of poorly sorted mixtures of clay, silt, sand, and gravel that is unconsolidated and semi consolidated aquifer materials (yellow color in figures) and coarse aquifer materials (brown color in figures) composed of alluvial sediments which are the dominant hydrogeologic feature of the survey area. These materials lie on the ***Kp*** which serves as the regional aquiclude. A map of the elevation of the top of the ***Kp*** which can be considered the base of ***To*** is presented in Figure 5-41. The top of the ***Kp*** had an impact on the depositional environment of the ***To*** due to the control the ***Kp*** surface had on the stream gradient at the time of deposition where aquifer materials were deposited; in particular in the paleochannel in the center of the study area and the related ***Kp*** lows. The ***To*** is heterogeneous in places with a changing mix of all aquifer materials found mostly in the tableland areas. The ***To*** is saturated throughout the survey area. Figure 5-42 is a 3D voxel model looking northwest showing the distribution of all ***To*** aquifer materials. Note the dominance of the coarse aquifer and aquifer materials along the axis of the South Loup River Valley. There is also coarse aquifer material deposited in the paleochannel areas of the ***Kp***. Figure 5-43 is a 3D voxel model looking west showing the distribution of ***To*** aquifer material and coarse aquifer material. Note the widespread distribution of the aquifer materials in the AEM survey area. Also note that there are gaps where there is no aquifer or coarse aquifer materials associated with the presence of non and marginal aquifer materials. Figure 5-44 is a fence diagram looking northeast of all ***Q*** and ***To*** aquifer materials sitting on the ***Kp***, with some of the ***To*** aquifer materials 3D voxel not displayed in order to highlight the ***To*** coarse aquifer material voxel showing its relationship to the rest of the area. The coarse aquifer material is the best material for water-containing aquifers in the study area. Figure 5-45 shows the total thickness of the ***To*** deposits and reveal that the thickest ***To*** deposits are in the southern end of the survey area. The ***To*** varies in thickness from <25 ft in the central north of the AEM survey area and is 274 ft in the south tableland. The LLNRD 2019 AEM survey area contains ***To*** aquifer materials and coarse aquifer materials that can act as the groundwater supply where it is saturated and/or that is hydrologically connected to the surface water system along the South Loup River.

Figure 5-46 is a view of north-south line L100101 on the western-most side of the AEM survey area. The complex nature of the subsurface deposits of all aquifer materials in the ***Q*** and ***To*** can be seen along this profile. Aquifer materials and coarse aquifer materials beneath the South Loup River are hydrologically connected to the surface water. This includes the saturated ***Q*** and ***To*** aquifer materials and coarse aquifer materials which extend south of the river past the end of the profile and also north a short distance. The presence of marginal and non-aquifer material near northing 419000 that is vertically continuous is a boundary to groundwater flow. Figure 5-47 shows the saturated thickness of the ***To*** deposits and the Specific Capacity (SC) of the wells which are completed in the ***To***. The saturated thickness varies from <25 ft in the South Loup river valley to 274 ft in southern tablelands. The SC varies from <5 gpm/ft to >25 gpm/ft. Wells are found in the ***To*** everywhere except in the northeast corner of the survey area. Figure 5-48 shows the saturated thickness of the ***Q*** combined with the ***To*** and the SC of the wells completed in both the ***Q*** and ***To***. The saturated thickness of the combined ***Q*** and ***To*** varies from 163 ft in the northeast and 293 ft in the south tablelands and contain wells with SC varying between 5-10 gpm/ft to >25 gpm/ft.

Figure 5-49 shows the thickness of the ***To*** aquifer materials and coarse aquifer materials. These materials vary from 245 ft thick in the south tableland to <25 ft thick in the northeast area of the South Loup River Valley. The thickness of the ***To*** coarse aquifer materials (Figure5-50) varies from 191 ft near the west end of the South Loup River Valley to <25 ft thick near the east end of the AEM survey area and near the confluence of Mud Creek and the South Loup River. The coarse aquifer materials in general follow the axis of the South Loup River, but do not precisely follow the river path suggesting a paleochannel system in the ***To*** that was collocated with the current South Loup River in this area.

Viewing the fence diagram of ***Q*** and ***To*** aquifer and coarse aquifer materials combined with the 3D voxel model of ***To*** saturated non-aquifer and marginal aquifer materials upon ***Kp*** in Figure 5-51 shows where there is a near continuous layer of ***To*** non-aquifer and marginal aquifer materials above the ***Kp***. This figure shows the isolation of much of the coarse aquifer material and aquifer materials caused by the presence of non-aquifer and marginal aquifer material layers above and below. The exception is the South Loup River valley where there is only a layer of non-aquifer material and marginal aquifer material above the ***Kp*** but below the coarse aquifer and aquifer materials that extend to the land surface.

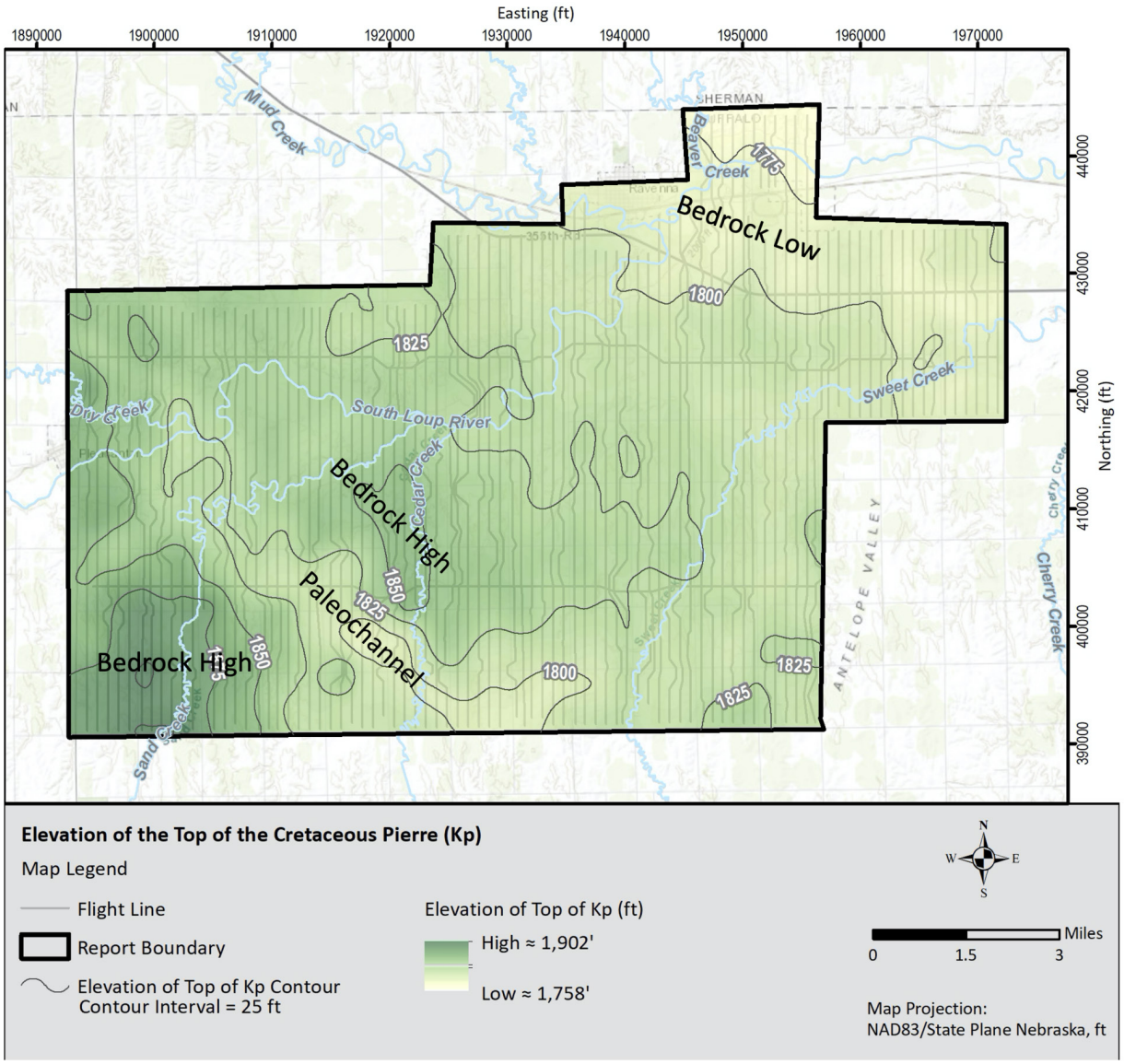


Figure 5-41. Map of the top of the *Kp* (Cretaceous Pierre Shale) within the LLNRD 2019 AEM survey area. The deposits are continuous across the area and there is a paleochannel in the center of the area. Flight lines are indicated by the grey lines.

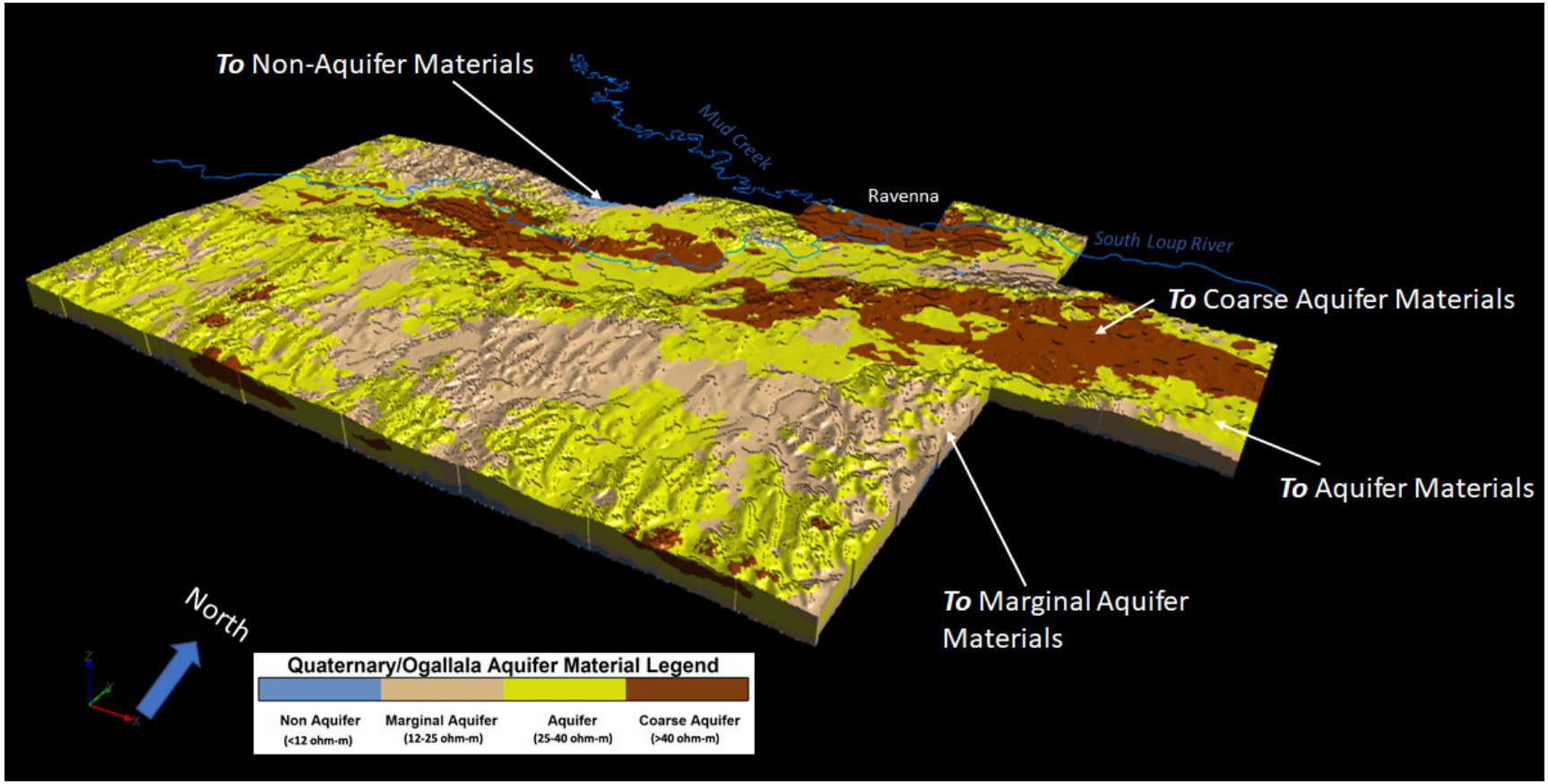


Figure 5-42. 3D voxel model looking northwest of the LLNRD 2019 AEM survey area showing all aquifer materials in the *To* (Tertiary Ogallala Group). Note the dominance of the coarse aquifer and aquifer materials along the axis of the South Loup River Valley. V.E.=10x.

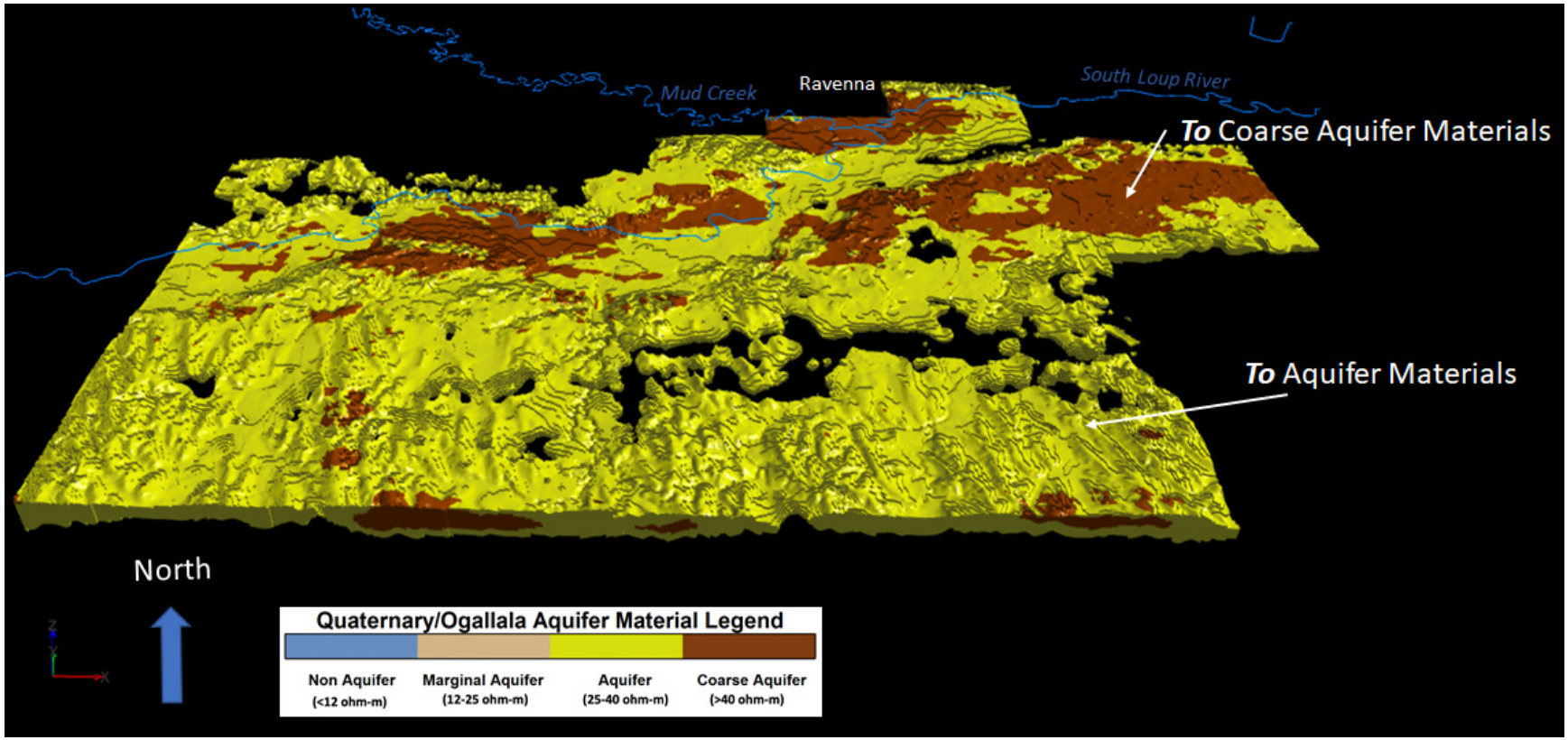


Figure 5-43. 3D voxel model looking north of the LLNRD 2019 AEM survey area showing *To* (Tertiary Ogallala Group) aquifer materials and coarse aquifer materials. Note the widespread distribution of the aquifer materials in the AEM survey area. V.E.=10x.

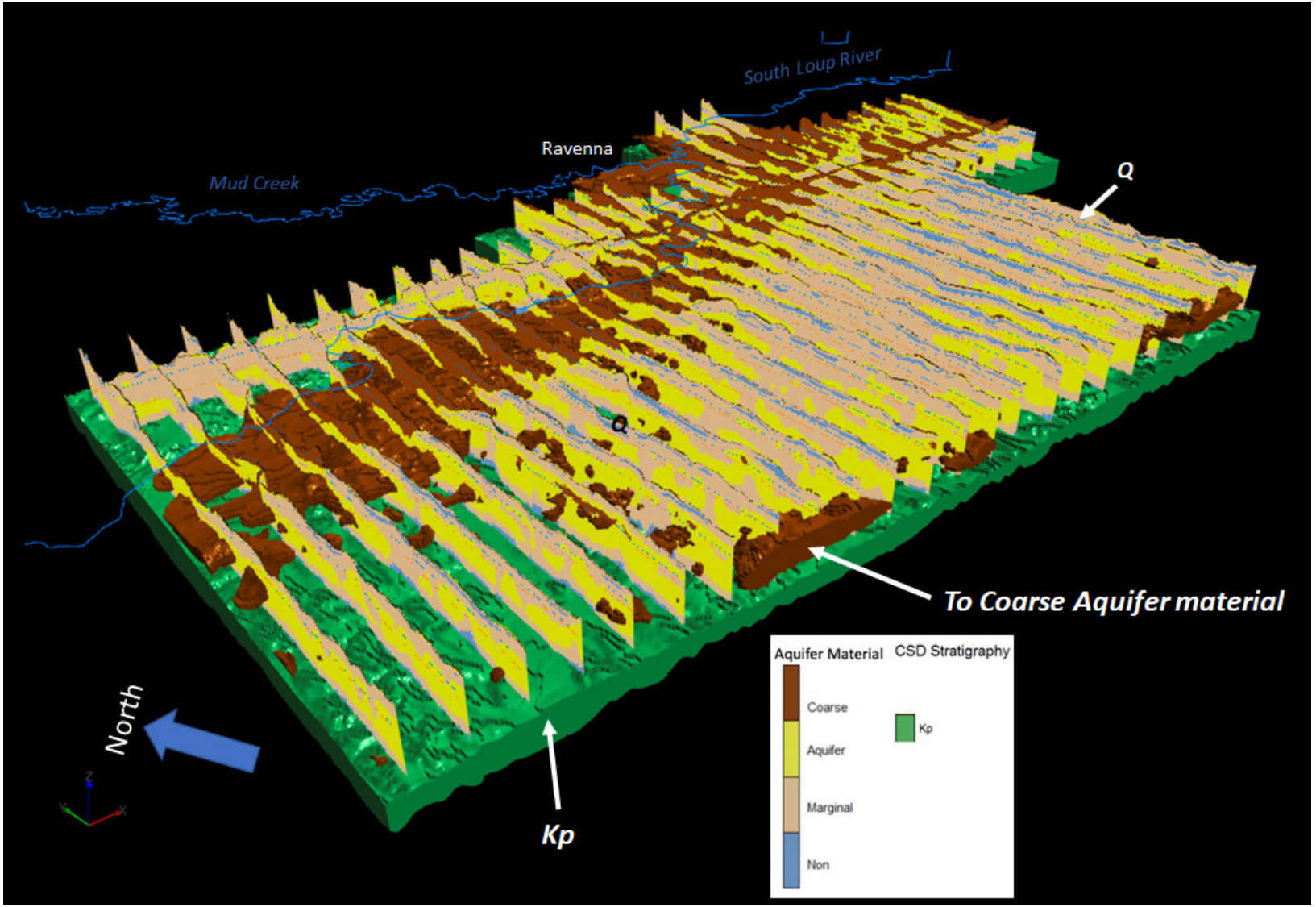


Figure 5-44. 3D Fence diagram looking to the northeast of all *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials sitting on the *Kp* (Cretaceous Pierre Shale) with the *To* coarse aquifer material 3D voxel showing its relationship to the rest of the LLNRD 2019 AEM survey area. V.E.=10x.

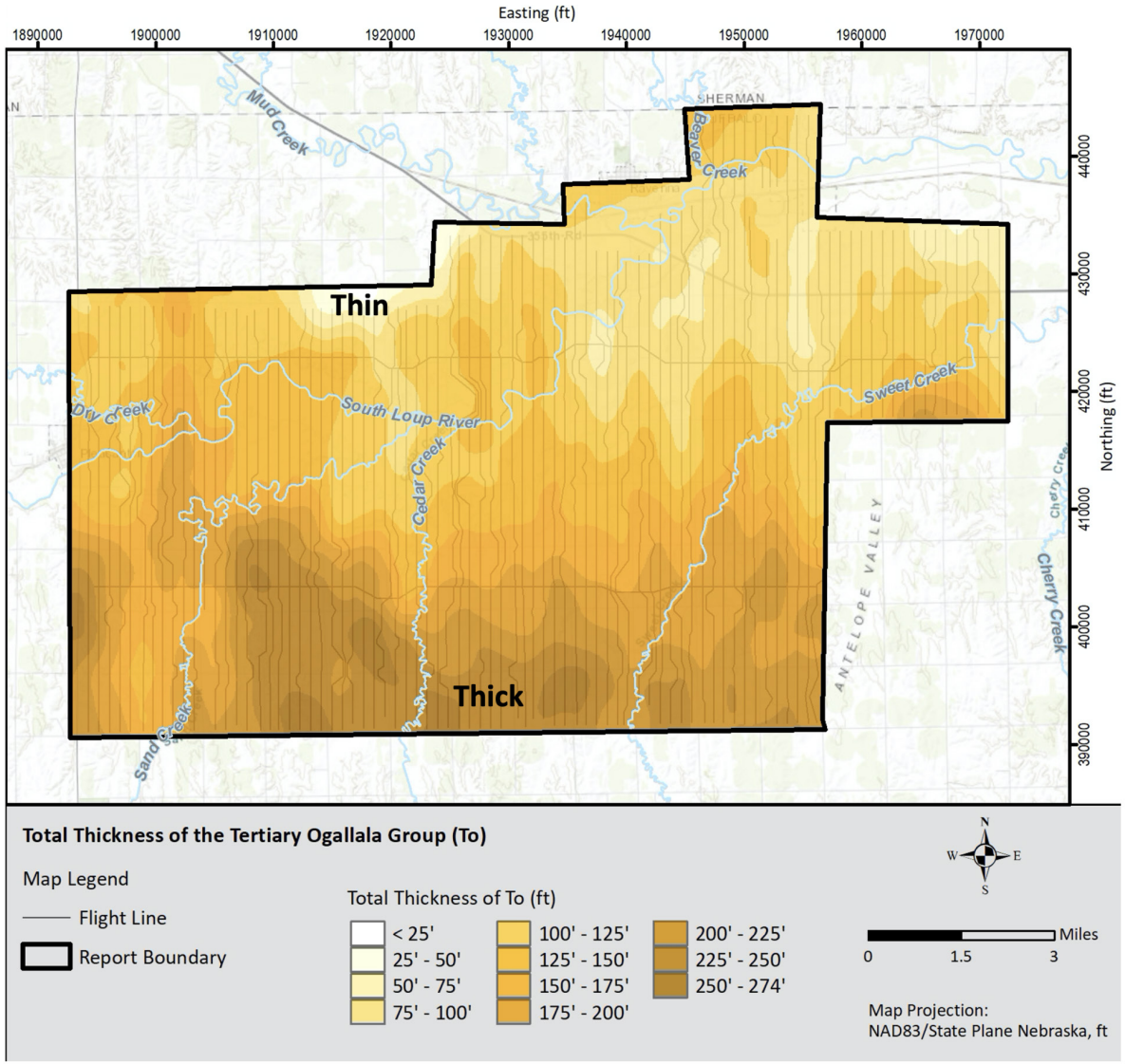


Figure 5-45. Map of the total thickness of the *To* (Tertiary Ogallala Group) deposits within the LLNRD 2019 AEM survey area. These materials are thick in the northwest and south tablelands. They are thin along the South Loup river. Flight lines are indicated by the grey lines.

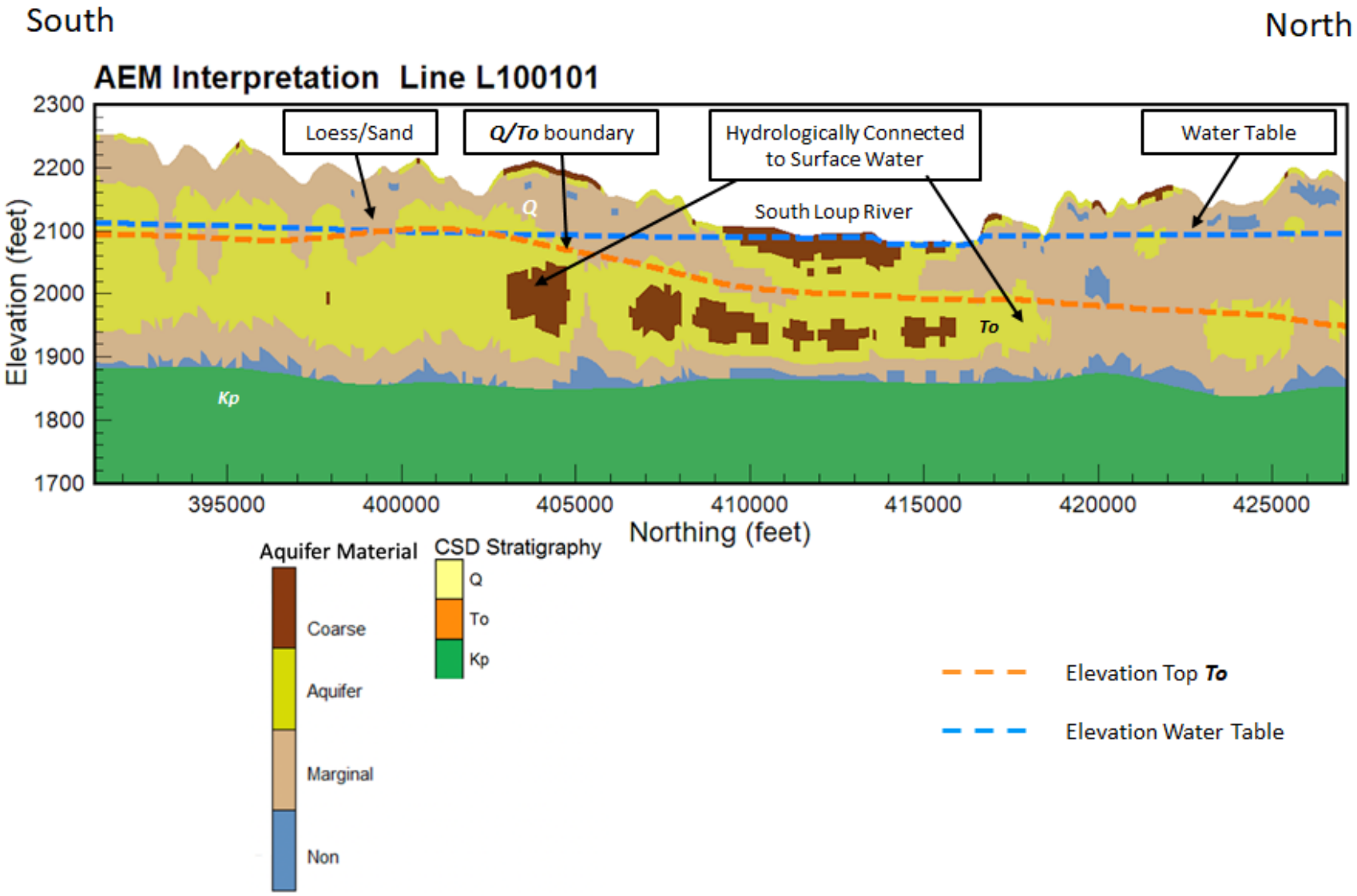


Figure 5-46. Profile view of north-south line L100101 with *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials above the *Kp* (Cretaceous Pierre Shale). Groundwater from the *Q* and *To* is hydrologically connected to the South Loup River. The CSD 1995 water table is the dashed blue line. The top of the *To* is the dashed orange line.

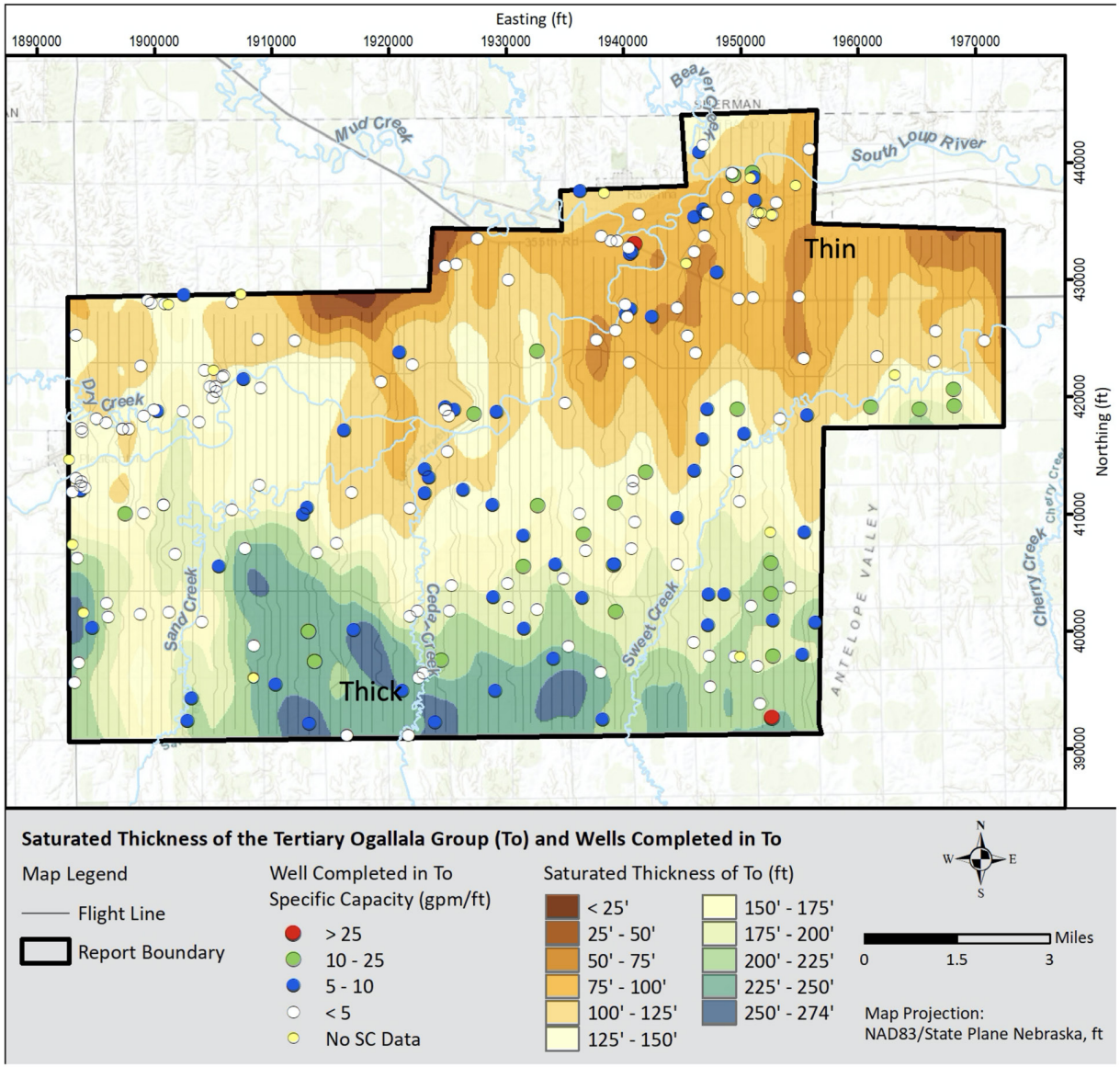


Figure 5-47. Map of the saturated thickness of the *To* (Tertiary Ogallala Group) within the LLNRD 2019 AEM survey area with the Specific Capacity (SC) of the wells in gpm/ft completed within the *To*. Flight lines are indicated by the grey lines.

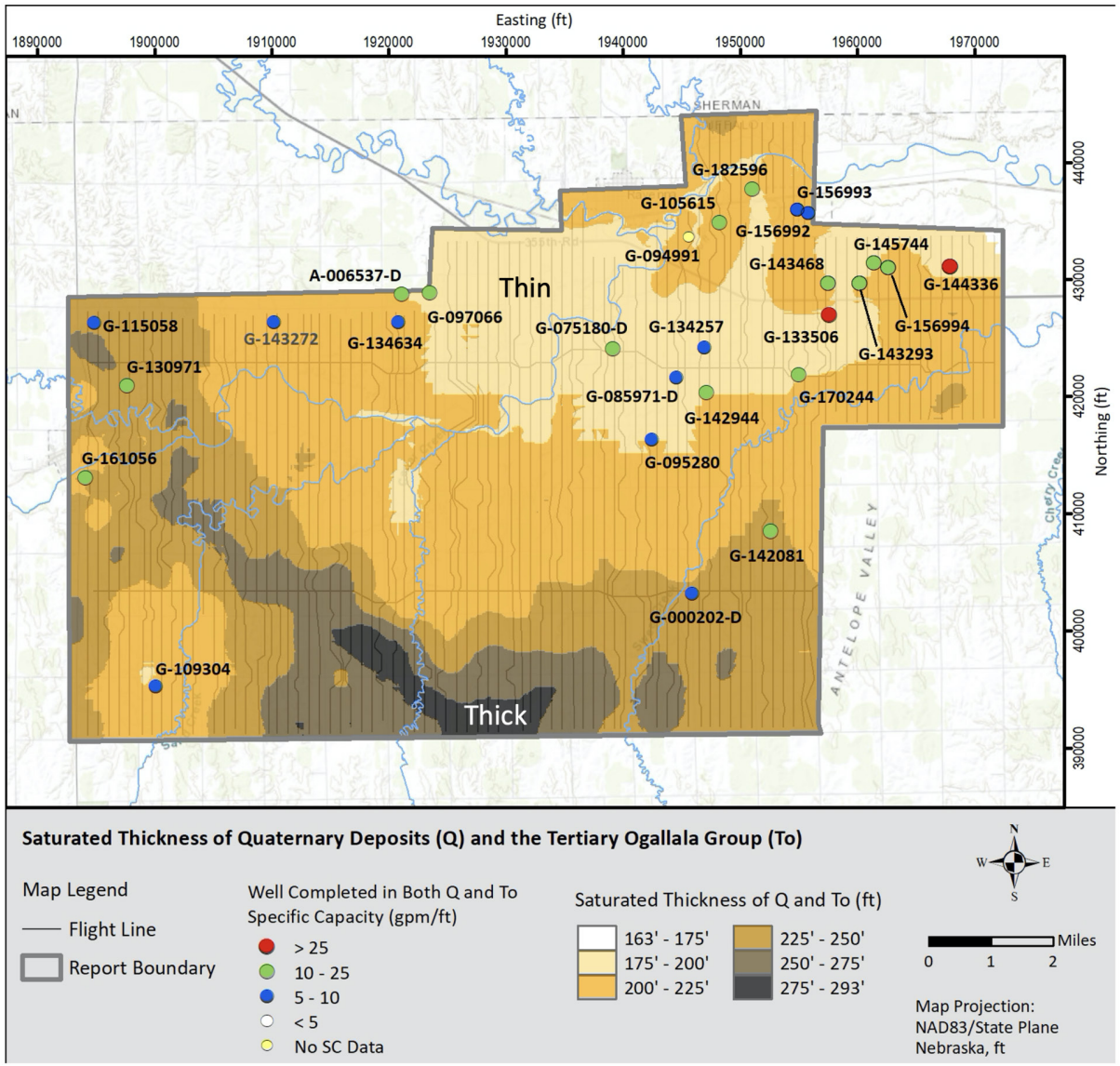


Figure 5-48. Map of the combined saturated thickness of the *Q* (Quaternary) and *To* (Tertiary Ogallala Group) within the LLNRD 2019 AEM survey area with the Specific Capacity (SC) of the wells in gpm/ft completed within the combined *Q* and *To*. Grey lines are flight lines.

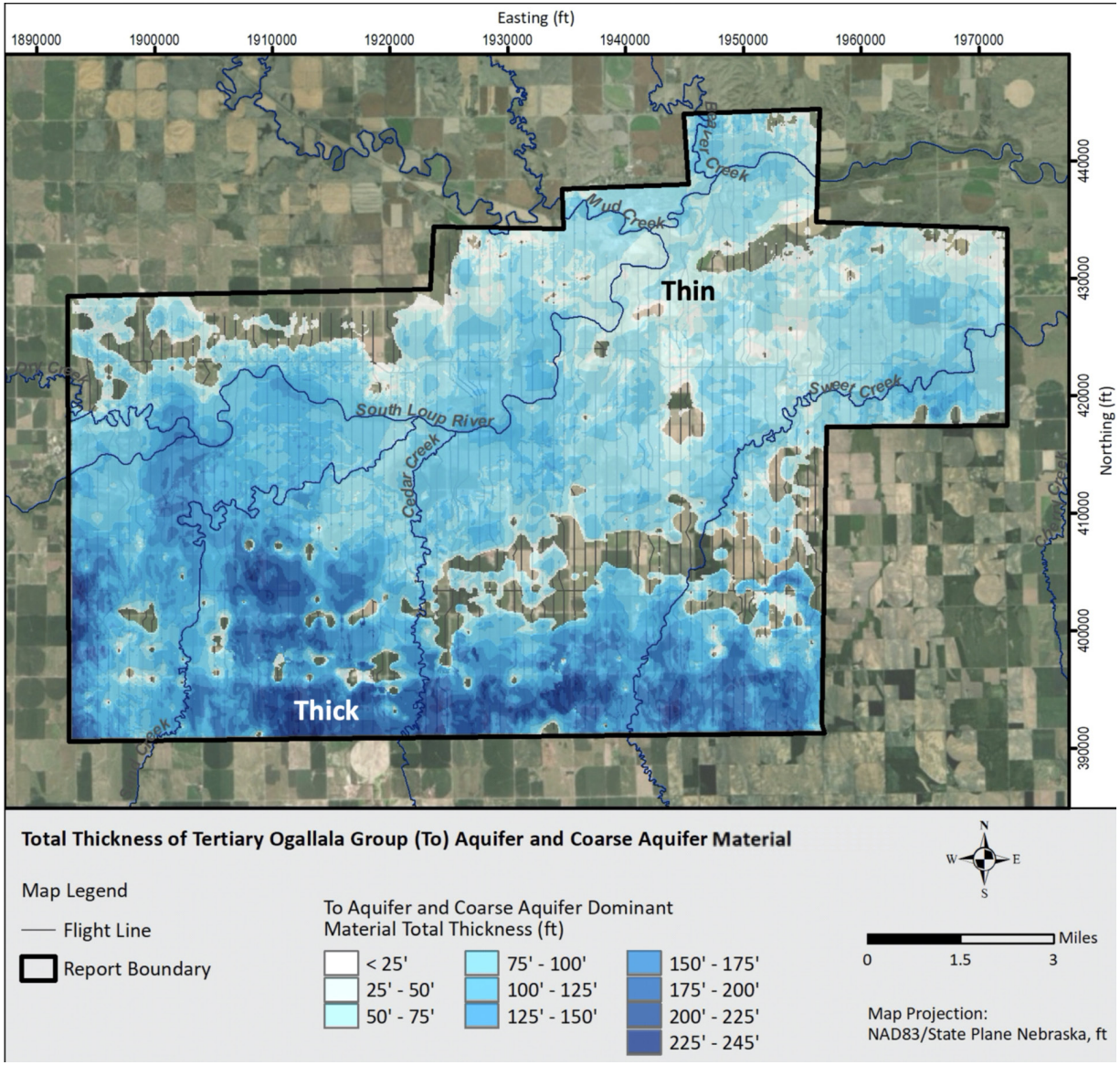


Figure 5-49. Map of the total thickness of the *To* (Tertiary Ogallala Group) aquifer material and coarse aquifer material deposits within the LLNRD 2019 AEM survey area. Grey lines are flight lines.

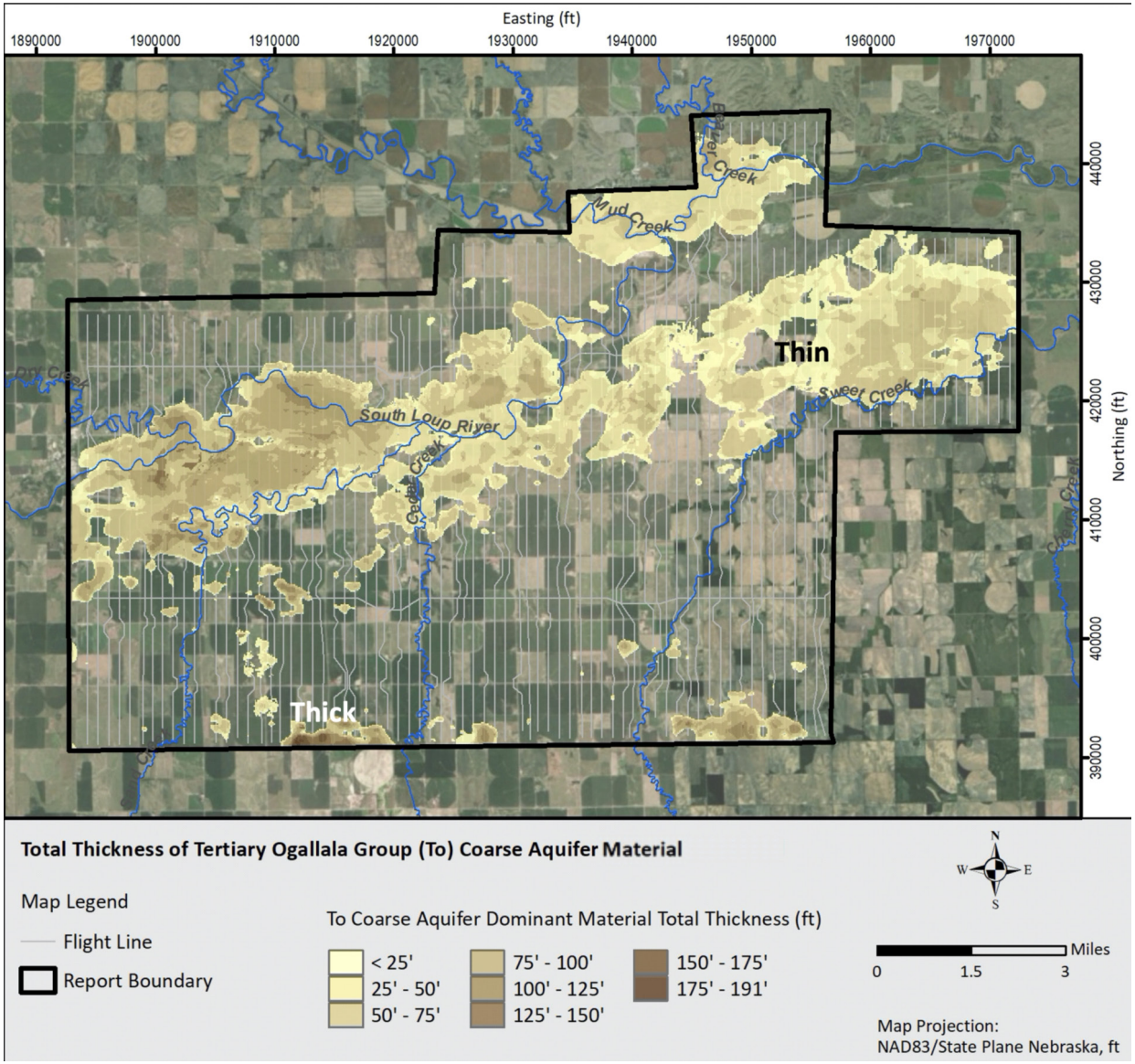


Figure 5-50. Map of the total thickness of the *To* (Tertiary Ogallala Group) coarse aquifer material deposits within the LLNRD 2019 AEM survey area. Flight lines are indicated by the grey lines.

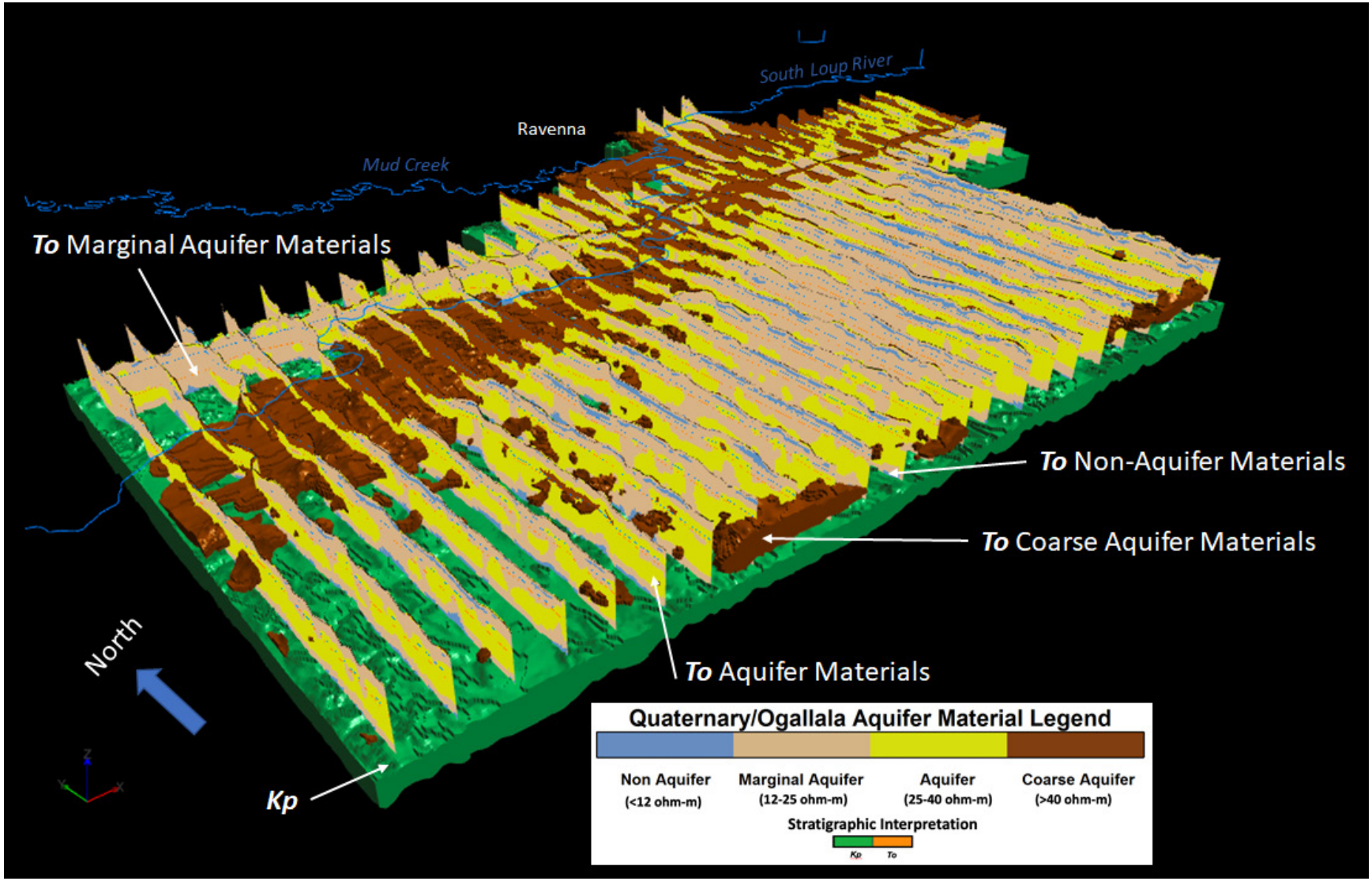


Figure 5-51. 3D Fence diagram of *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer and coarse aquifer materials combined with the 3D voxel model of *To* saturated non-aquifer and marginal aquifer materials upon *Kp* (Cretaceous Pierre Shale). V.E.=10x.

5.3.3 The Cretaceous Bedrock

The Cretaceous bedrock is made up of the ***Kp*** which lies below the ***To*** which is the upper bedrock of the LLNRD 2019 AEM survey area. Figure 5-41 from the previous section shows the ***Kp*** top surface which makes up a continuous surface beneath the ***To***. This surface has a gradient in elevation from 1,902 ft in the southwest to 1,758 ft in the northeast. The upper surface of the ***Kp*** is an erosional surface that was developed during the deposition of the ***To***. There is a paleovalley cut into the ***Kp*** in the south-southwest corner of the survey area that has bedrock highs to the west and east of the paleovalley. This paleovalley is filled with ***To*** aquifer materials and is coincident with, and contributes to, the overall thickness of the ***To*** in that area.

5.3.4 Comparison of Previous Hydrogeologic Framework with AEM-derived Hydrogeologic Framework

As part of the development of the AEM-based hydrogeologic framework, it is instructive to examine the differences between using just boreholes as was performed by JEO (2018) and using the boreholes integrated with the AEM-derived model. It is important to note that the borehole derived framework is not wrong; it is just limited in detail due to the lack of the thousands of additional data points provided by the AEM.

As just mentioned, the AEM-derived hydrogeological framework uses the same boreholes JEO (2018) used in addition to the interpreted data derived from the AEM survey. By using both sources of data, the AEM voxel interpretation profile includes more detail and is representative of the natural system. The AEM voxel interpretation profile also shows the detailed aquifer materials distribution of the ***To*** which the borehole derived profile is not able to do. The comparison analysis was conducted on three cross-sections near the town of Ravenna, Nebraska (JEO, 2018). Figure 5-52 is a comparison of profile A-A' between the two methods. It shows the location map in the first panel, the second panel shows the AEM resistivity profile, the third panel shows the AEM voxel interpretation profile, and the fourth panel shows WSP cross-section A-A'. By simple inspection, the differences between the two methods becomes apparent. The greater detail and fidelity to the natural system in the AEM analysis allows for detailed outlines of hydrologic boundary conditions, detailed mapping of the aquifer materials along the profile, and the ability to estimate the amount of groundwater in storage and its yield. Similar comparisons are shown for cross-sections B-B' (Figure 5-53) and C-C' (Figure 5-54). Cross-section B-B' (Figure 5-53) illustrates a common issue with lithology logs in large databases. For example, NE-DNR Well registration *G-148781* (Well ID *191643*) indicates clay in the first approximately 80 feet. The AEM-derived aquifer materials indicate coarse aquifer materials. Why the difference? This is a possible error in transcribing the data or logging the cuttings. The log indicates "Topsoil and clay". This was interpreted by WSP in cross section B-B' initially as clay in the borehole log. The AEM clearly show it is resistive and is not clay. Thus, a better more continuous section of aquifer materials is interpreted in the AEM enhanced profile.

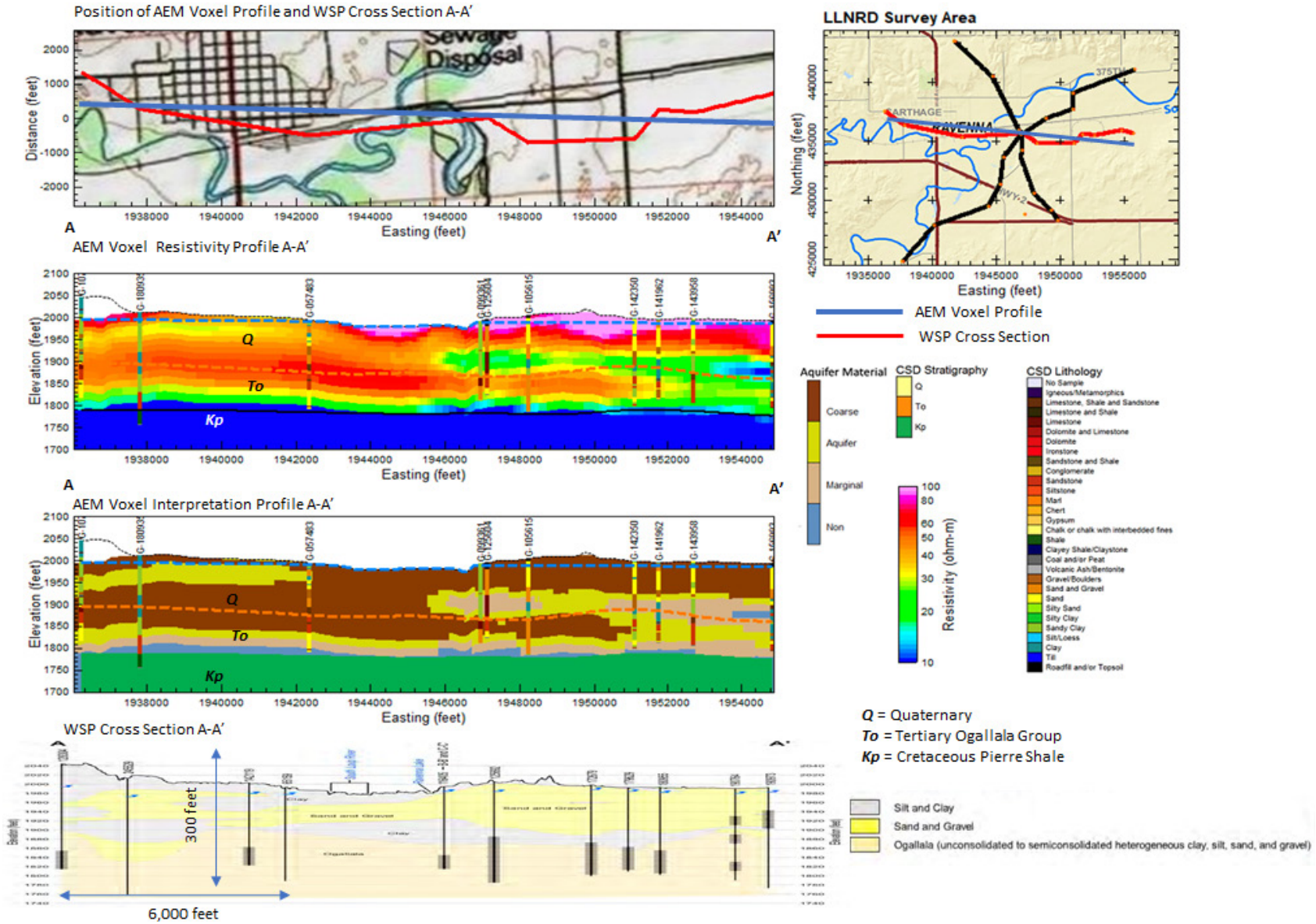


Figure 5-52. Profile views along cross-section line A-A' (modified from JEO, 2018) with a AEM flight path map (top), AEM Voxel Resistivity Profile (second), AEM Voxel Interpretation Profile (third) and WSP Cross Section A-A' (fourth). Projection NAD 83 Nebraska State Plane, feet.

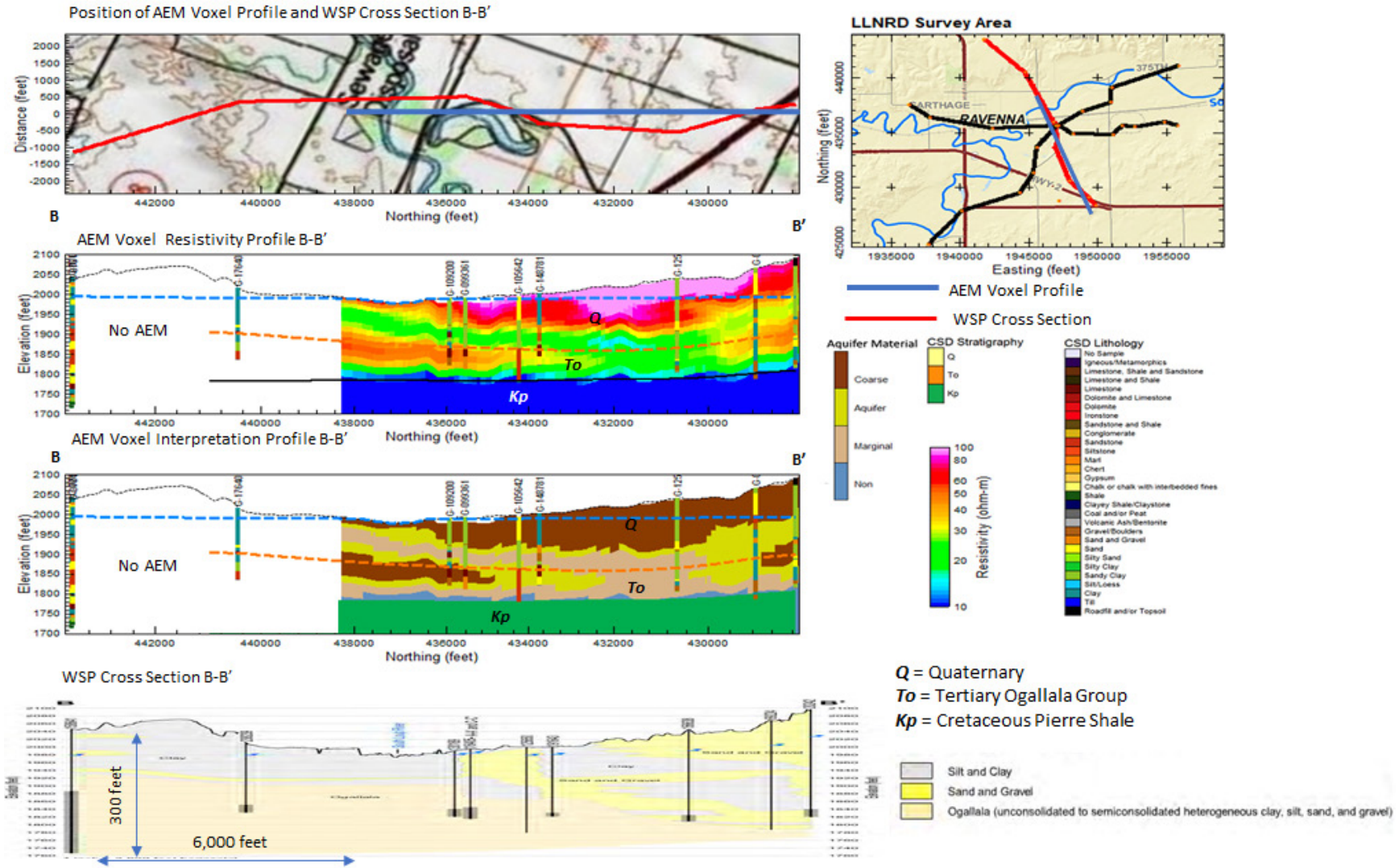


Figure 5-53. Profile views along cross-section line B-B' (modified from JEO, 2018) with a AEM flight path map (top), AEM Voxel Resistivity Profile (second), AEM Voxel Interpretation Profile (third) and WSP Cross Section A-A' (fourth). Projection NAD 83 Nebraska State Plane, feet.

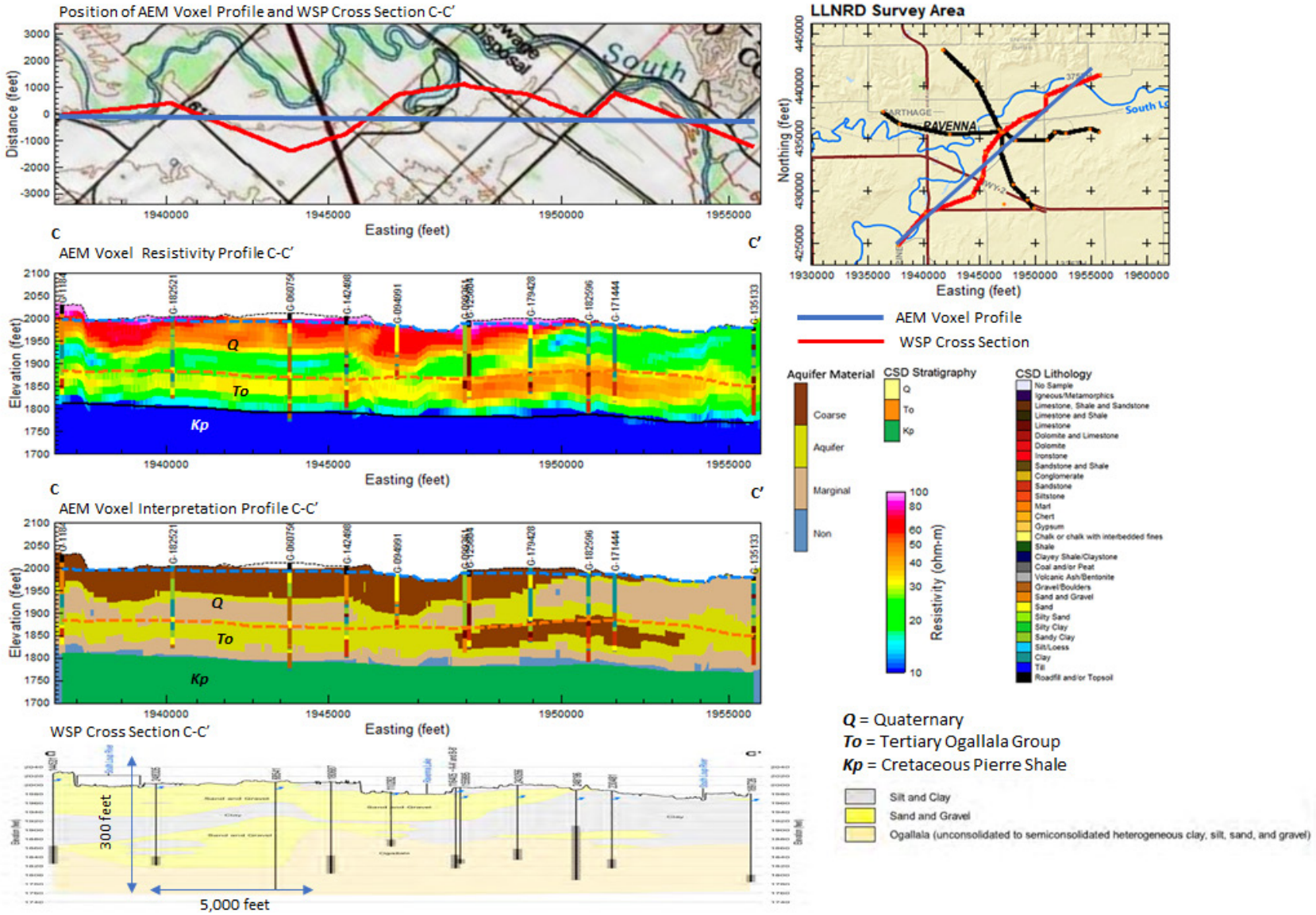


Figure 5-54. Profile views along cross-section line C-C' (modified from JEO, 2018) with a AEM flight path map (top), AEM Voxel Resistivity Profile (second), AEM Voxel Interpretation Profile (third) and WSP Cross Section A-A' (fourth). Projection NAD 83 Nebraska State Plane, feet.

5.3.5 Consideration of Managed Aquifer Recharge Site Locations

One of the products from the 2019 LLNRD AEM survey hydrogeologic framework is to provide the methodology of using the AEM information to locate potential locations and identify areas for Managed Aquifer Recharge (MAR) sites. Identifying all possible locations in the AEM study area is possible and this study identifies the best possible locations for future development efforts. Detailed hydrogeologic analysis and assessment for selected sites within the identified areas can be accomplished at a later time with additional information provided from new boreholes and aquifer tests under a new scope of work to be planned by the LLNRD and AGF. This future work would include groundwater storage estimates, specific yield, groundwater travel time, and groundwater model development assistance.

MAR is a management practice that uses surface water. In this case, water from the South Loup River and its tributaries, generally, during times of high flow or reduced demand can be applied to an off-stream area to store the water for future use. The stored water can also be allowed to return back to surface water system by baseflow. Another alternative is this water can be extracted by wells and delivered to the streams.

There are areas in AEM study area that can be used for MAR, but they have to meet criteria that can be analyzed to satisfy hydrogeologic, financial, property availability, water rights, and other criteria in order to identify a viable location. This section of the report deals with the hydrogeologic part of the selection process.

The criteria for selecting a site using the AEM hydrogeologic framework require the following information which is available in this report.

1. Appropriate aquifer materials in the subsurface which include the AEM-identified aquifer materials and coarse aquifer materials. These materials have the ability to readily allow groundwater movement. This would be the yellow and brown colored units on the aquifer material maps and profiles.
2. These materials need to be unsaturated and of sufficient volume so there is the ability to store water in the groundwater system to meet the MAR plan. This can be calculated by utilizing the voxel model of the area identified for the MAR and the aquifer material property volumes.
3. The site needs to be located in an area that water can either be allowed to move from the MAR site back to the surface water by groundwater flow or be located in an area that has geologic boundaries that inhibit such flow and the water is then extracted at a later time. This would include identifying areas of conduits to the surface water system, or basins with no connection to the surface water system
4. It needs to be sited where the groundwater table is at 50 feet or greater below land surface that water is not lost to evaporation, transpiration, does not cause local flooding, is easy to lift by pumping, is not impacted by negative water quality, and other criteria to be identified.
5. It should be in a highly permeable water recharge area that extends from the land surface down to the target aquifer material by natural infiltration.

An example location has been identified that meets the MAR criteria listed above for a site that is connected to the surface water on profile L200201 (Figure 5-55) which is located in the north central part of the LLNRD 2019 AEM survey area (Figure 5-56). This profile provides subsurface information along the flight line that can be used to determine the starting point for selecting the MAR site. The extent of the non-aquifer and marginal aquifer materials that exist near and below the land surface on the west end of the profile and extending to easting 1930000 does not lend itself to the high permeability needed to transmit water quickly downward to the aquifer material and coarse aquifer material of the ***Q*** and ***To***.

Along the same part of the profile there is ***Q*** and ***To*** aquifer material and coarse aquifer material that lie below the non-aquifer and marginal aquifer and are connected hydrologically to the South Loup River and have sufficient volume of saturated materials. Therefore, this area is not suitable to an MAR site.

From easting 1940000 to the east end of the profile is an example of a potential MAR site. There is aquifer and coarse aquifer material from the land surface to water table and there is sufficient unsaturated ~30 to 100 feet thick to fill with water. It is near the South Loup River limiting the costs of moving the water from the stream to the MAR site. Figure 5-57 shows a 3D fence diagram of the interpreted aquifer materials in the proposed site area. There is sufficient area of known hydrogeologic information to make this a worthy area for further research into MAR site or sites development.

Figure 5-58 shows the areas for potential MAR. The bright green areas contain all of the criteria listed above. These are areas best suited to find local sites for actual MAR development. To accomplish the actual development of an MAR site, much more work would need to be completed such as new boreholes with detailed geologic and geophysical logs, aquifer tests, analysis of groundwater travel times, and a determination of the suitability of MAR sites impact to meet the groundwater management plan goals.

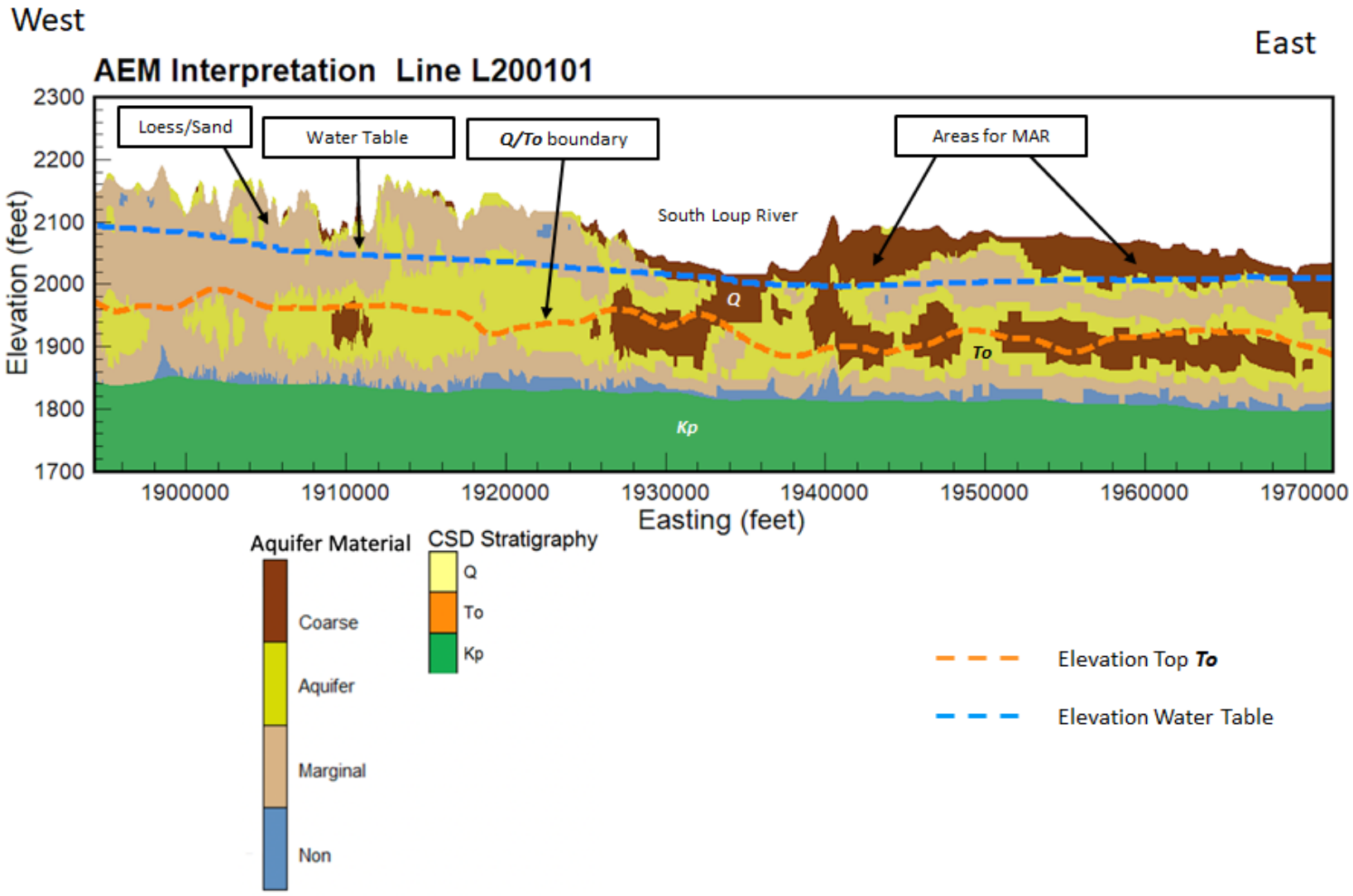


Figure 5-55. Profile view of east-west line L200201 showing *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials above the *Kp* (Cretaceous Pierre). Groundwater from the *Q* and *To* is hydrologically connected to the South Loup River. The water table is the dashed blue line. The top of the *To* is the dashed orange line.

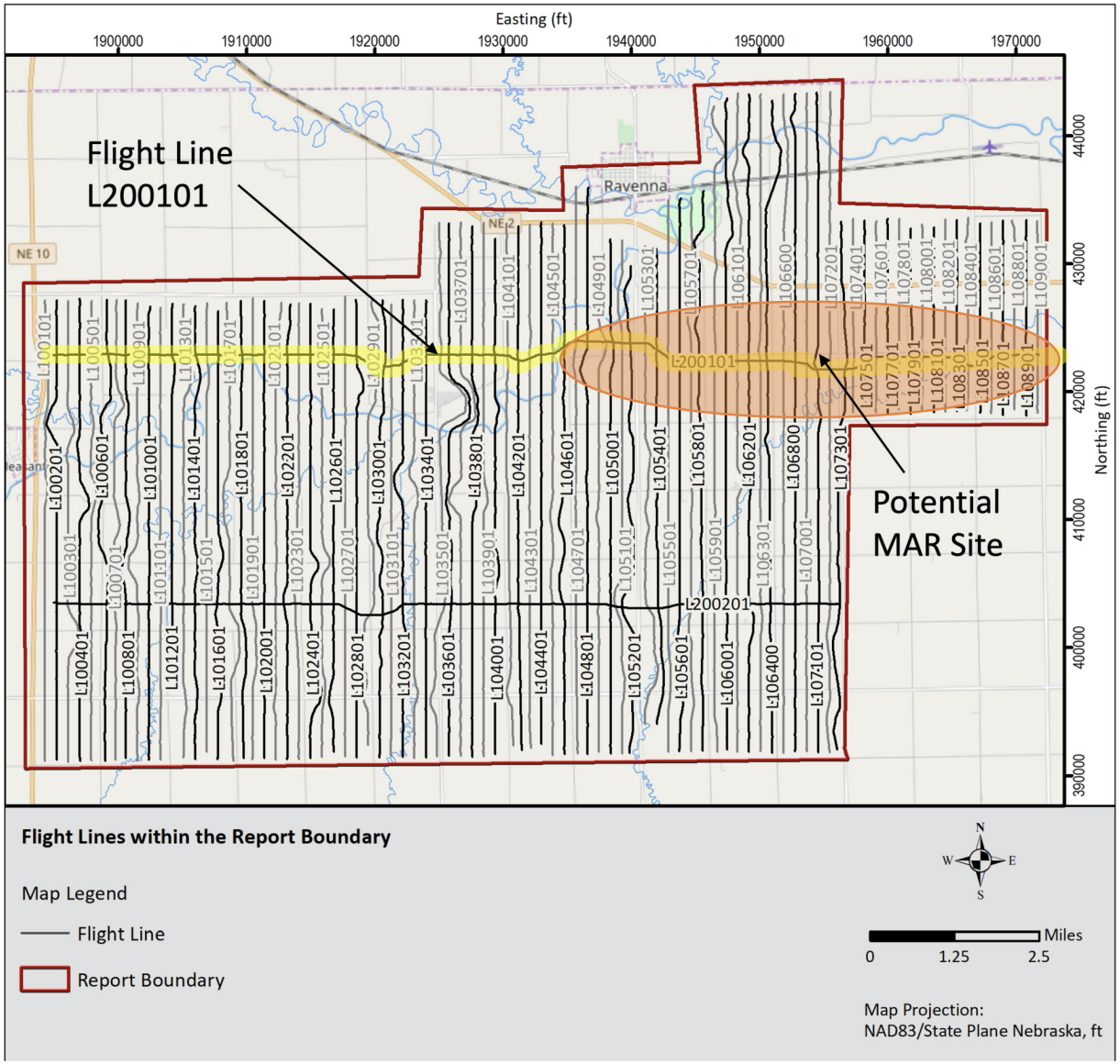


Figure 5-56. Flight line map for the LLNRD 2019 AEM survey area with east-west line L200201 highlighted in yellow. An area on the east end of the flight indicates an area of potential MAR sites.

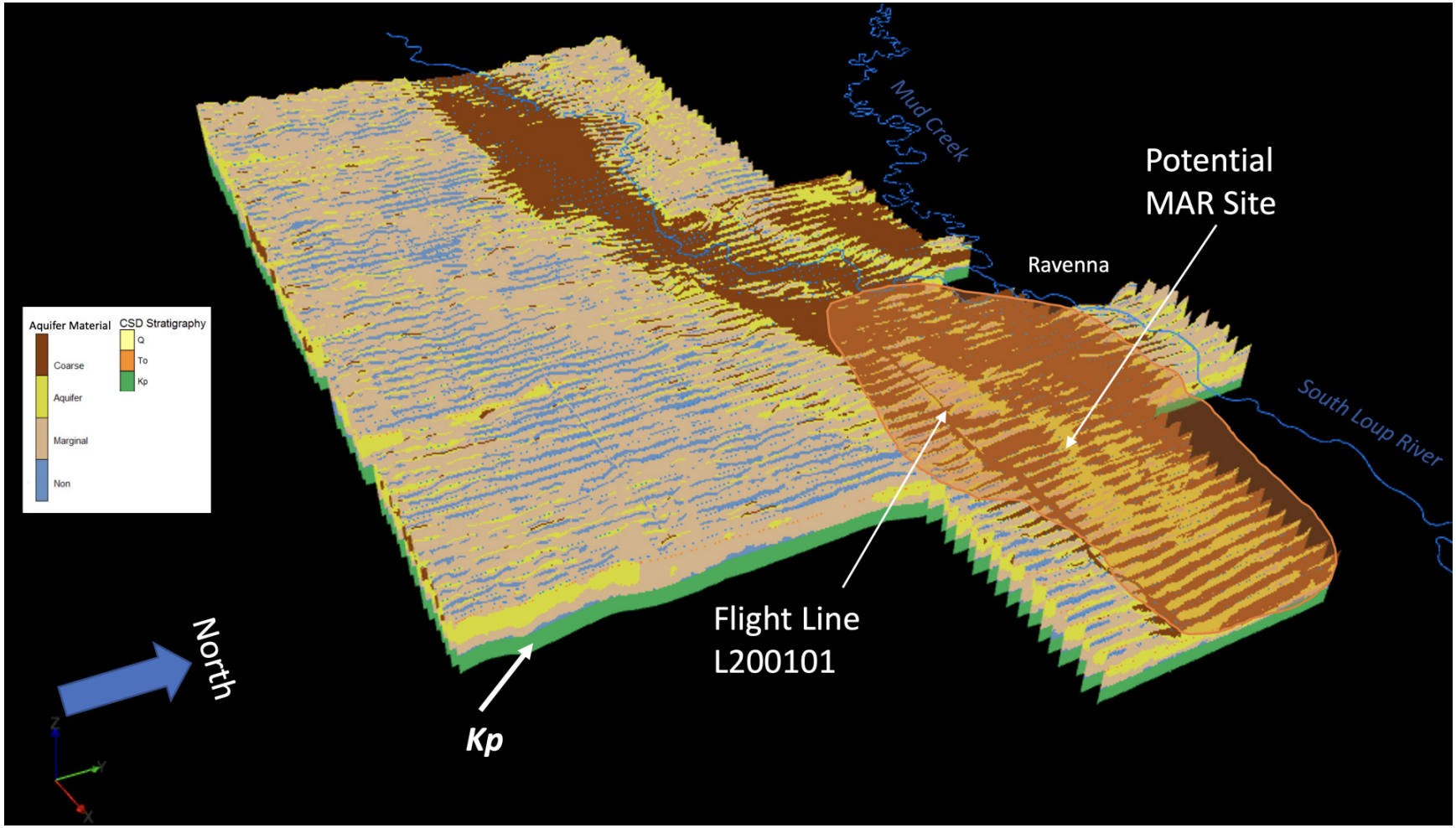


Figure 5-57. 3D fence diagram of *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials upon *Kp* (Cretaceous Pierre Shale). The highlighted area at the east end of the survey area shows the most likely area for development of MAR sites. V.E.=10x.

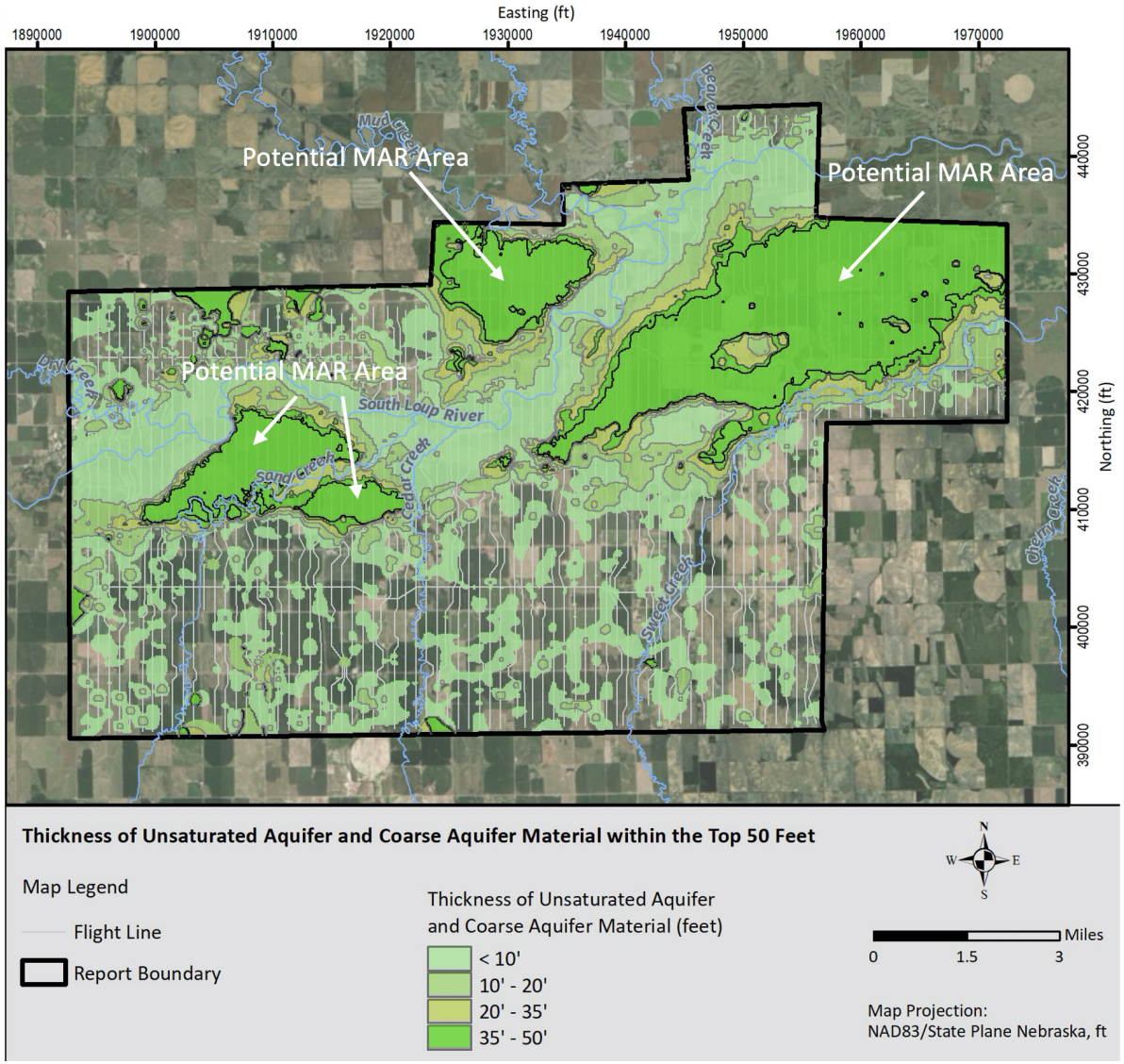


Figure 5-58. Map of thickness of unsaturated Quaternary (*Q*) Aquifer and Coarse Aquifer Material within the top 50 feet. This is a map of potential MAR sites within the survey area that meet all the criteria for selecting a MAR site .The bright green areas shown on the map have at least 50 feet of unsaturated thickness.

5.3.6 Groundwater in Buffalo County, Nebraska LLNRD

Groundwater declines are a chronic problem for the LLNRD in Buffalo County, Nebraska. Reviewing the LLNRD Spring Water Level Report shows hydrographs like the one presented in Figure 5-59, which indicates a declining long-term groundwater trend. The period of record for water levels on this graph is from 1982 to 2019and the water level trend over time from this well shows an approximately 7-foot average loss from predevelopment. Note that the period of record from 1994 to 1999 includes the most stable water table elevations on record. Figure 5-60 shows a map from the LLNRD report "Static Water level Change All Years Spring 1982 to Spring 2019" showing the area affected by long term declines in groundwater levels. Causes of these declines related to the hydrogeologic framework of the AEM survey area are mentioned throughout Sections 5.3.1 and 5.3.2. The main cause of these declines are the layers of unsaturated and saturated non-aquifer and marginal aquifer materials that are deposited as near continuous layers in the near surface of the ***Q*** (Figure 5-61). These layers limit the amount of recharge that can move from the land surface to the aquifer material and coarse aquifer material of the ***Q*** and ***To*** that make up the aquifers of the AEM survey area. The exception to this is the South Loup River Valley and its tributaries which contain aquifer materials and coarse aquifer materials from the land surface downward to the aquifers of the ***Q*** and ***To***.

The presence of isolated aquifers composed of aquifer materials and coarse aquifer materials is another potential reason for the declines seen in the wells of the area. Figure 5-62 shows Profile L107101 which is a north-south line and displays areas of the subsurface that have isolated aquifers. The definition of an isolated aquifer is a volume of aquifer material and coarse aquifer material that is saturated but not hydrologically connected to surface water or nearby volumes of similar materials. As can be seen there are numerous isolated aquifers along the profile. Wells completed in an isolated aquifer depend on the volume of groundwater available in that aquifer. The amount of water pumped from that aquifer can deplete the available water to the point that economic yield or the actual yield is exceeded and the well is no longer viable. The ability to recharge during and after irrigation season impacts the amount of decline seen in that well.

Additional water budget items that are needed to fully understand the declines beyond the hydrogeologic framework include precipitation, water use, crop type, recharge rate, and loss through base flow to streams to name a few. The complete analysis is beyond the scope for this project, but the information provided above is the basis for any water budget.

5.3.6.1 Groundwater Quality in Buffalo County, Nebraska LLNRD

The groundwater quality portion of this report is focused on non-point source nitrate contamination. This type of contamination is related to recharge of the groundwater system and the following discussion explains the results of hydrogeologic framework related to groundwater quality.

The LLNRD provided a data base of water quality sample well locations and 2019 sample results (LLNRD, 2019c). There were 12 wells samples in the AEM survey area in 2019 and are displayed on Figure 5-63 which is the saturated thickness of Quaternary (***Q***) and Tertiary Ogallala Group (***To***) deposits with well nitrate data. There are two wells with screened interval in the northeast corner of the AEM survey area

near Ravenna, Nebraska. These wells are low in nitrate which is most likely due to the deep depths of the screened interval. Nearly all of the wells presented are below 1.5 mg/l except for two wells in the west center area which is 8.2 mg/l and a well central area which is 10.2 mg/l. The last well which is 10.2 mg/l is screened from 192 to 265 feet. Due to the depths of the screen and the overlying layer containing non-aquifer and marginal aquifer materials and the fact that nitrate tends to stratify from the top of the water table downward, this sample is questionable as non-point source contamination. Figure 5-64, Figure 5-65, and Figure 5-66 show the recharge potential (described in Section 5.5) of the ***Q*** aquifer materials at 10, 20, and 50 feet respectively. Figure 5-64 shows that the 10 ft layer surrounding the well with the high reading is composed of aquifer and coarse aquifer material which has good recharge potential. Figure 5-65 shows the 20 ft layer and is made up of non-aquifer material which little recharge passing through it. Figure 5-66 is the 50 ft layer which is marginal aquifer material and limited ability to allow recharge water to pass. When inspecting the AEM interpretation for Profile 105301 (Figure 5-67) it can be seen there is a ~100 ft thick low permeability boundary in the near surface. The wells are completed below this zone. Therefore, nitrate originating as non-point source contamination from the land surface is very unlikely. There has to be another way for the nitrate to percolate downward. The same is true for the 8.2 mg/l near flight line L100801 (in the southwest corner of the AEM survey area, Figure 5-56). The water quality for nitrate non-point source pollution is very good for the entire area. The low permeability layer caused by the presence of non-aquifer and marginal aquifer materials reduces the risk for non-point source contamination.

Contamination of surface water by E. coli (a specific type of coliforms) is most likely caused by overland run off of precipitation or water releases. Groundwater can be contaminated by E. coli but it is most often a point source contaminate often caused by well construction, back flow into wells, septic tanks or flooding.

5.3.6.2 New Understanding of AEM Framework Applied To Water Quantity Management Efforts in Buffalo County, Nebraska LLNRD

The LLNRD asked for an analysis/discussion of their groundwater management in light of the AEM framework. This discussion only focuses on a limited review of known information for the survey area. A detailed analysis of groundwater management practices requires additional work to prepare the datasets for a water budget which is needed to accomplish this task. However, based on the information the District provided on groundwater use and the detailed information on the distribution of aquifer material types provided by the AEM survey, the current management practices are effective.

All management plans can be improved as new information is gathered and considered for modifying the management practices. In light of future needs of the LLNRD in local and state-wide groundwater management, it is recommended that a water budget and companion report be completed under separate contract in order to fully understand the effects of the current management plan and regulations. Water budget information and the AEM hydrogeologic framework should be the basis for developing a detailed groundwater model that best represents the natural system.

The LLNRD supplied the image in Figure 5-68 which is the 2020 LLNRD Land Use map for Buffalo County. The survey area is mostly cropland with a smaller percentage of rangeland (LLNRD, 2020a). Figure 5-69 is

a map of flow meter locations matched to the wells and irrigated land. There are 9 flowmeters in the AEM survey area (LLNRD, 2020b). During the 2017 irrigation year an average 8.37 inches of water was pumped across the survey area. This information is in the irrigation record for the survey area. Additional flow meter records would be helpful in future analysis of groundwater availability.

Section 5.4 contains the estimates for groundwater in storage. There is also an estimate for the amount of groundwater yield to wells. These estimates are the foundation for available water for irrigation use. When combined with the hydrogeologic framework there is a good basis for building a water budget for the area which can be used to evaluate groundwater management and its regulations.

A detailed process and data needs for building the water budget and identifying specific areas of the AEM survey area for special needs can be put into a proposal for the District. The report identifies the heterogeneity of the area and a useful water budget will need detailed information to be useful.

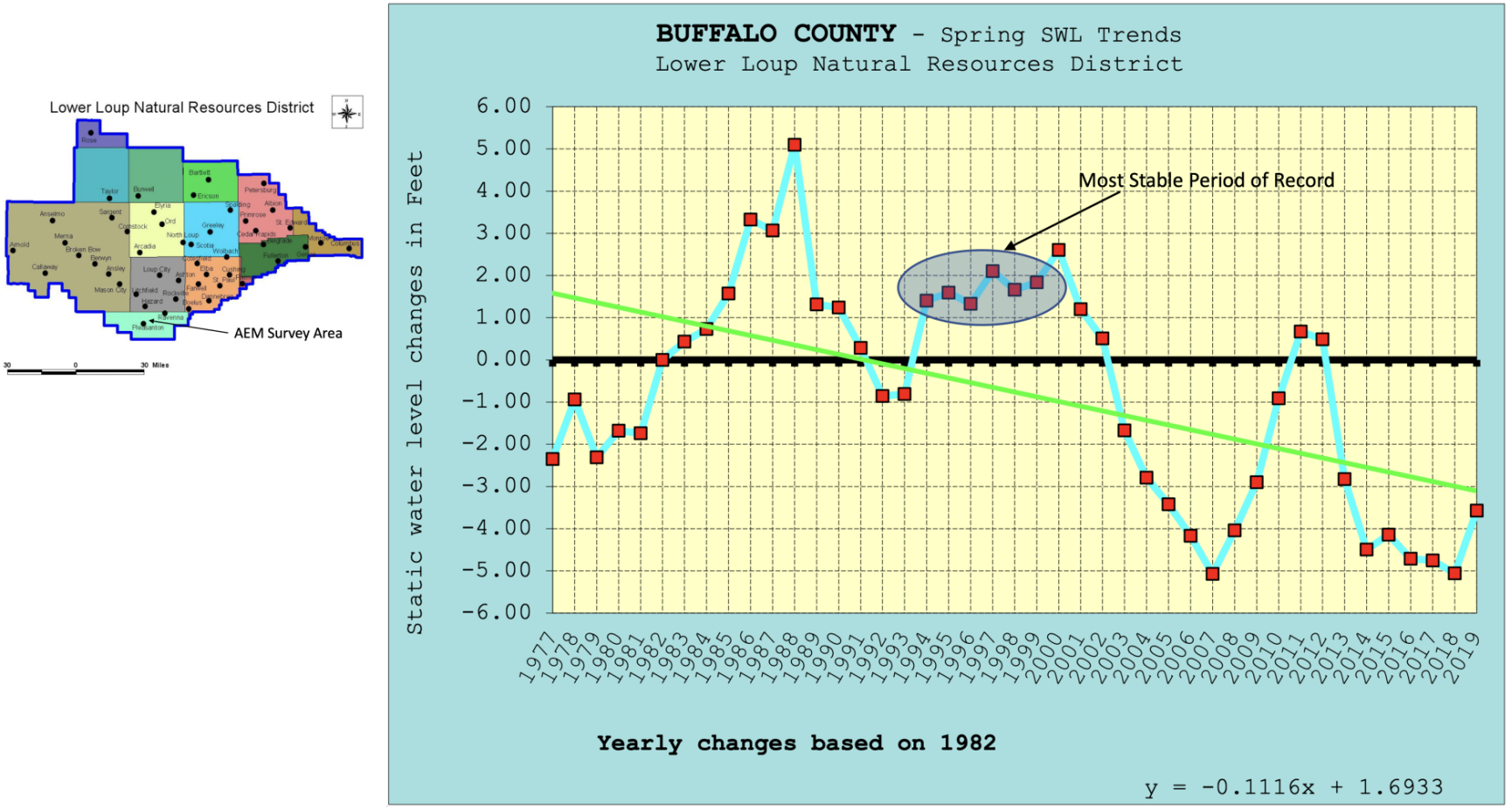


Figure 5-59. Hydrograph of spring groundwater levels from 1977 to 2019. Note the trend line on the graph showing a continuous decline over the period of record. (modified from personal communication from Cam Conrad, LLNRD, 2019b)

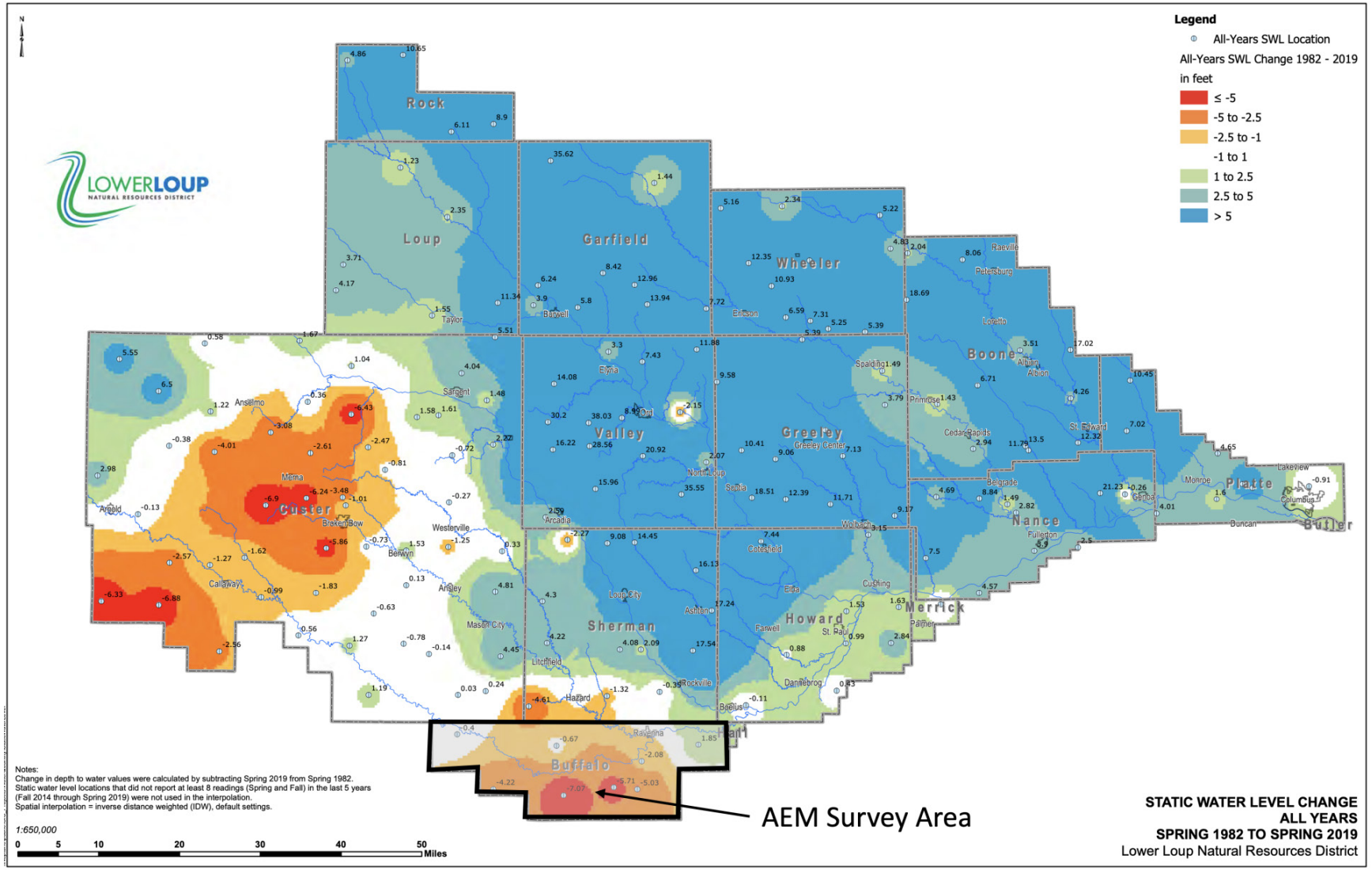


Figure 5-60. Map of "Static Water Level Change All Years Spring 1982 to Spring 2019" showing the affected area. Prepared by Lower Loup Natural Resources District, 2019, (modified from personal communication from Cam Conrad, LLNRD, 2019b)

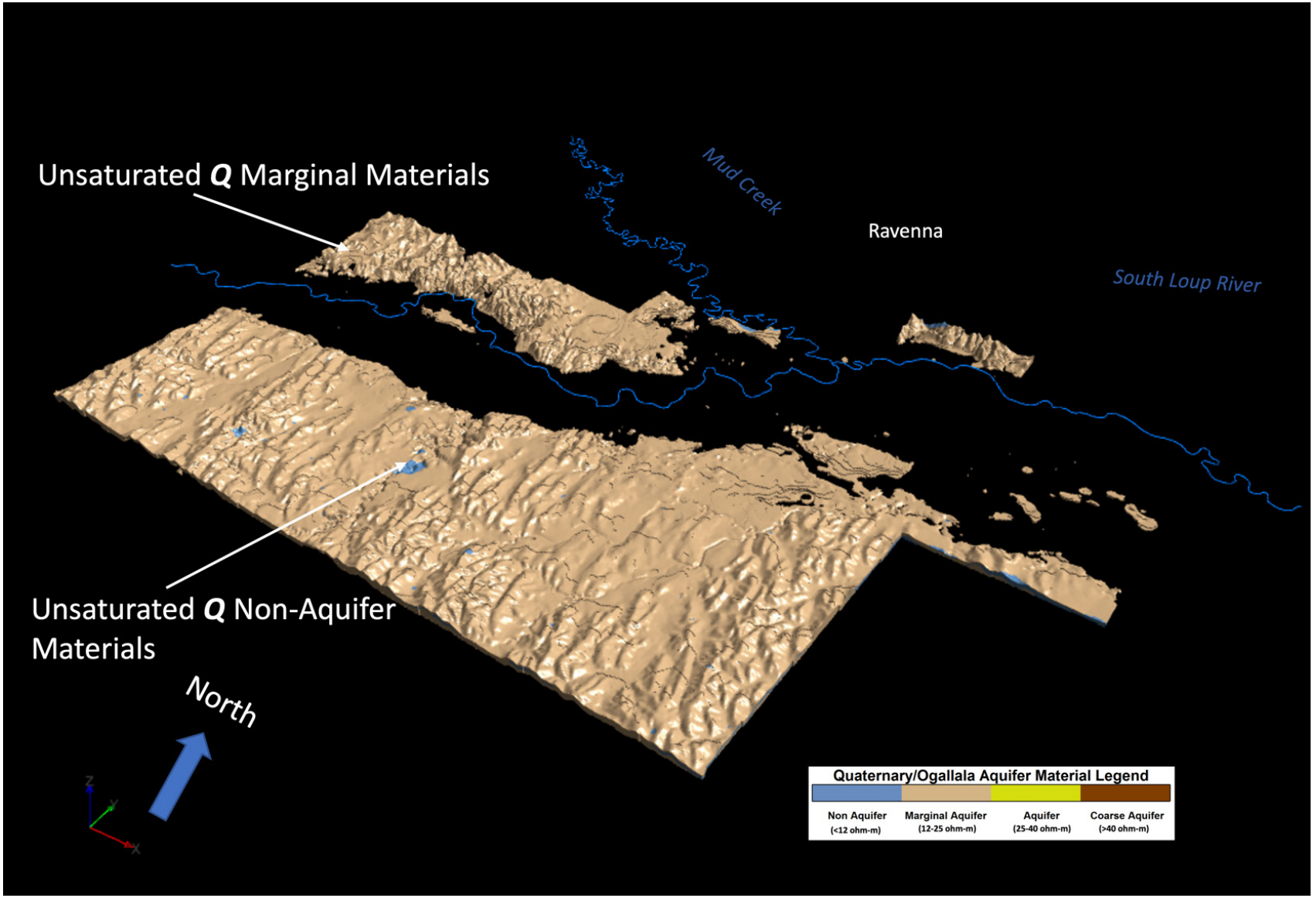


Figure 5-61. 3D voxel model of the survey area showing unsaturated *Q* (Quaternary) non-aquifer and marginal aquifer materials in the near surface. These materials reduce the amount of recharge that passes through them affecting the aquifer below. V.E.=10x.

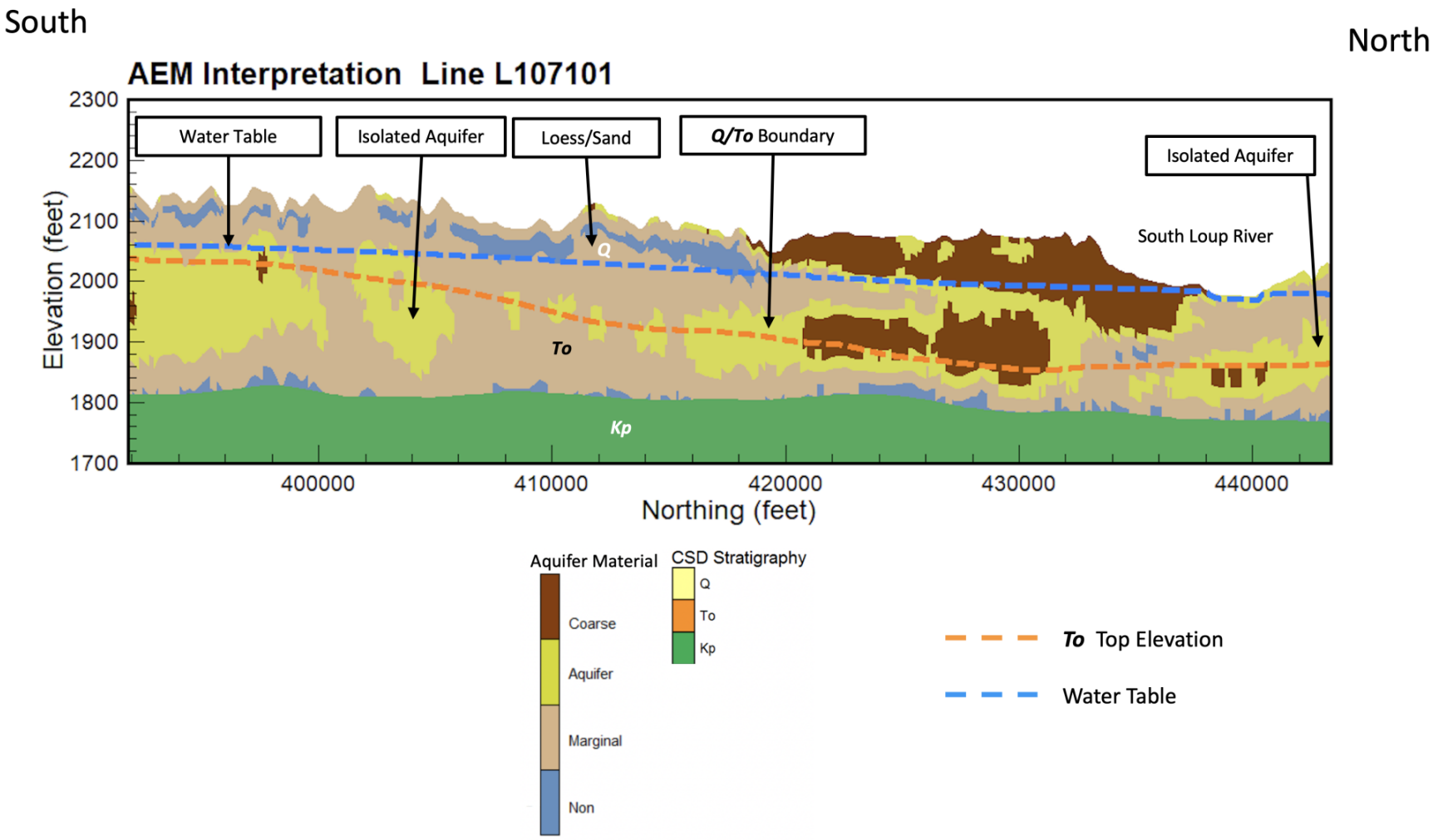


Figure 5-62. Profile view of north-south line L107101 showing *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials above the *Kp* (Cretaceous Pierre Shale). The CSD 1995 water table is the dashed blue line. Dashed orange line is *To* top.

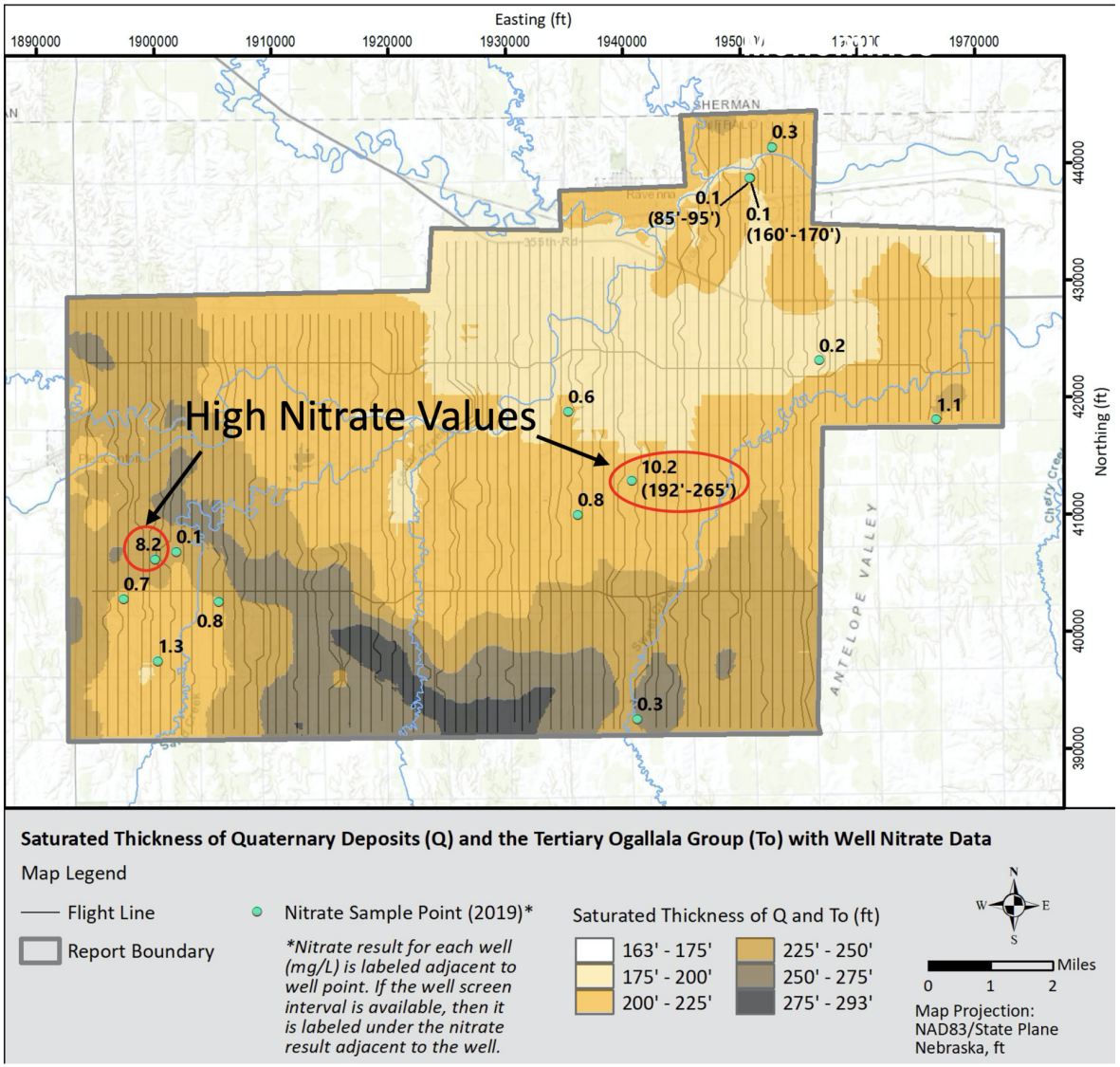


Figure 5-63. Map of Saturated Thickness of *Q* (Quaternary) and *To* (Tertiary Ogallala Group) with Well Nitrate Data. Note only 2 wells are above 1.5 mg/l. Prepared by Lower Loup Natural Resources District, 2019 (personal comm. from Cam Conrad, LLNRD, 2019c).

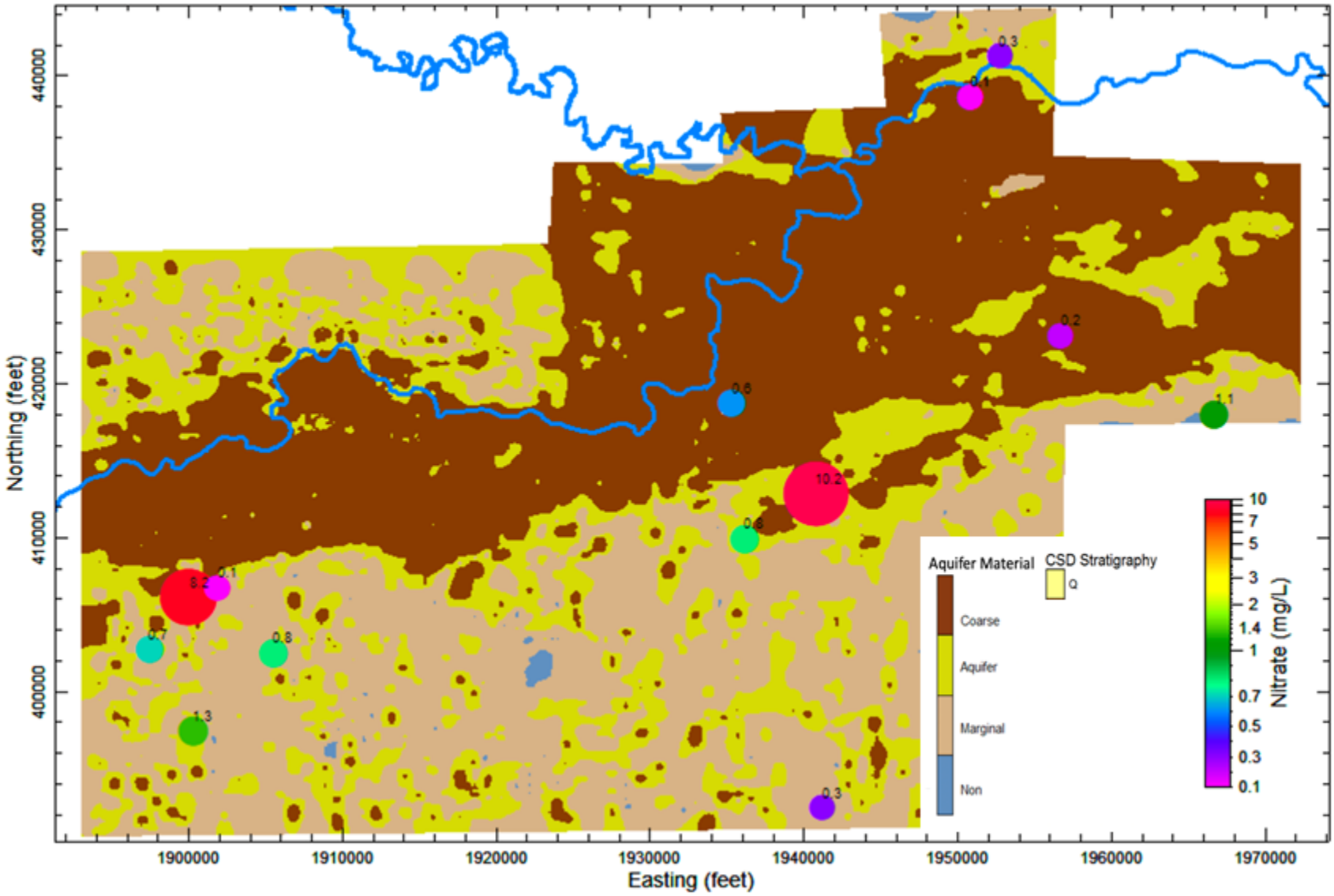


Figure 5-64. Map showing the aquifer materials present in 10-foot layer below land surface and the wells sampled for nitrate with the sample results in mg/l. Projection NAD 83 Nebraska State Plane, feet.

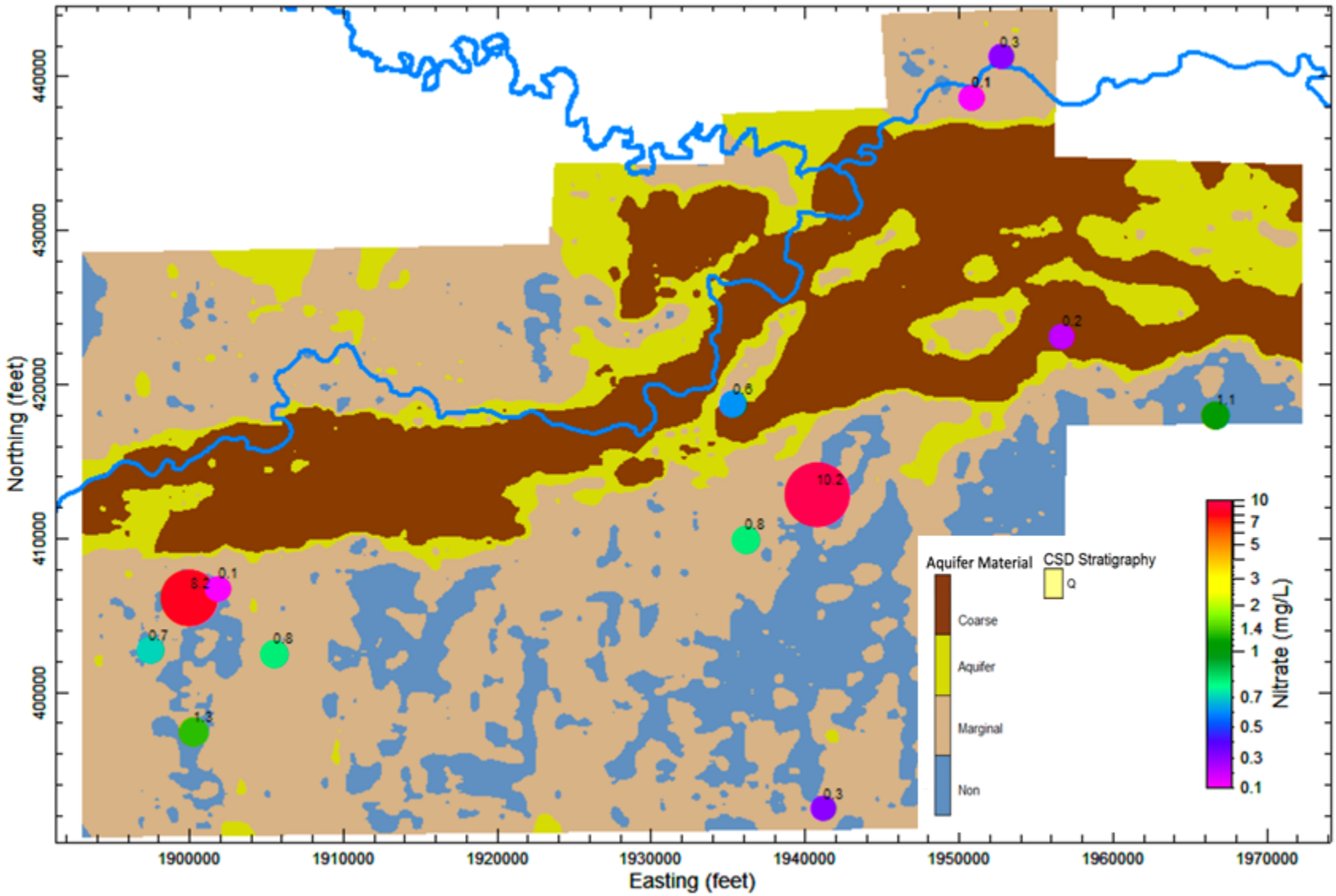


Figure 5-65. Map showing the aquifer materials present in 20-foot layer below land surface and the wells sampled for nitrate with the sample results in mg/l. Projection NAD 83 Nebraska State Plane, feet.

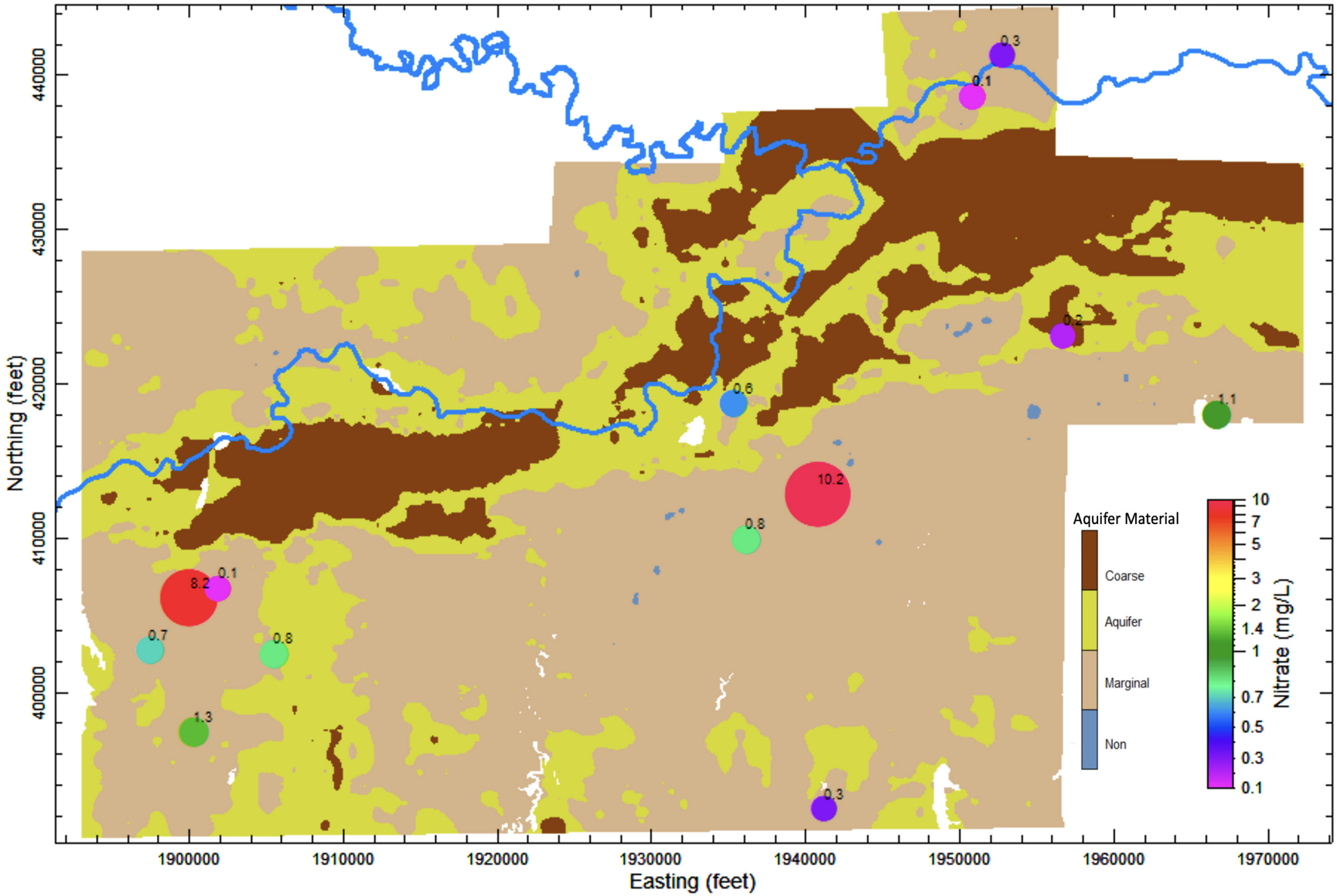


Figure 5-66. Map showing the aquifer materials present in 50-foot layer below land surface and the wells sampled for nitrate with the sample results in mg/l. Projection NAD 83 Nebraska State Plane, feet.

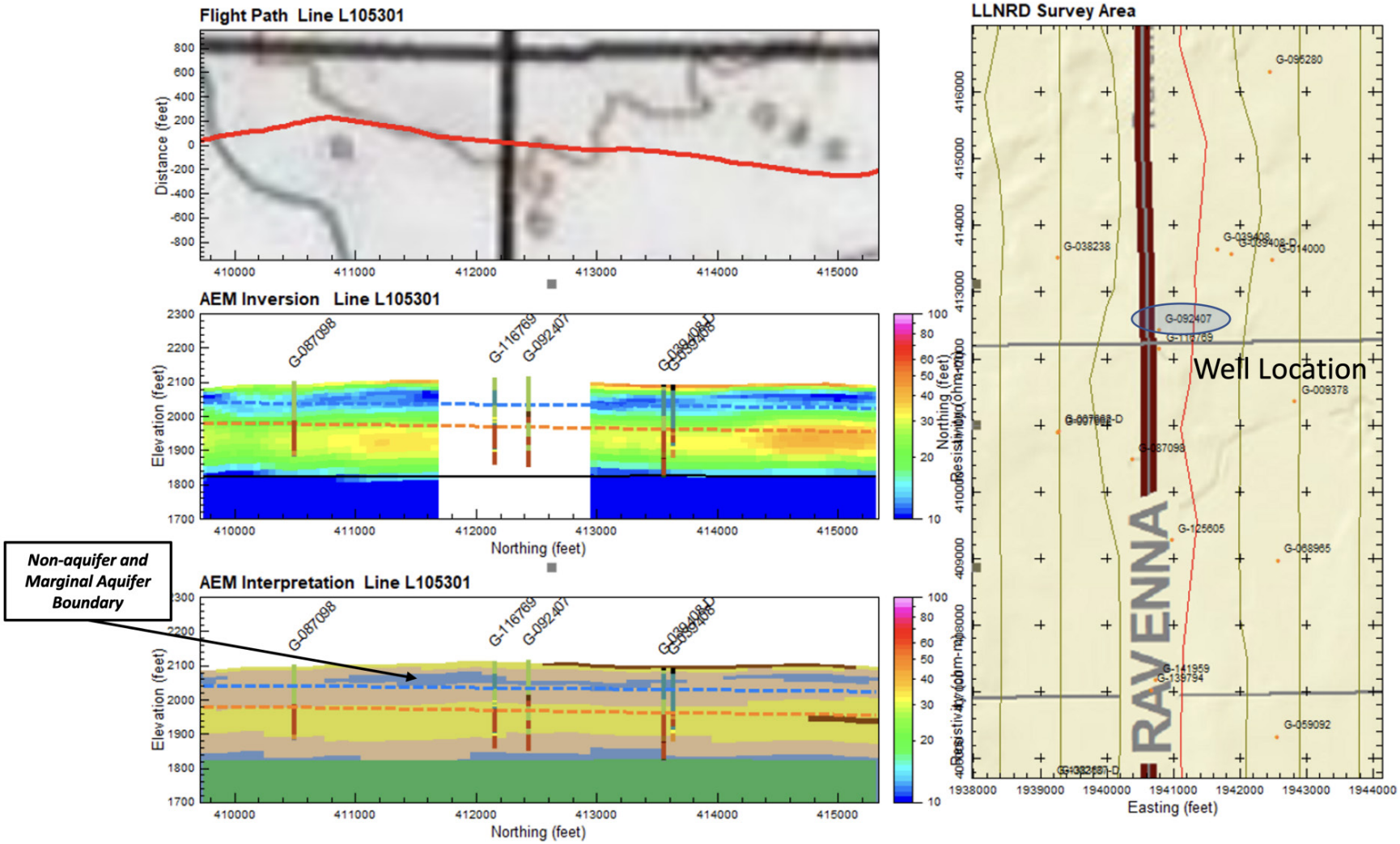
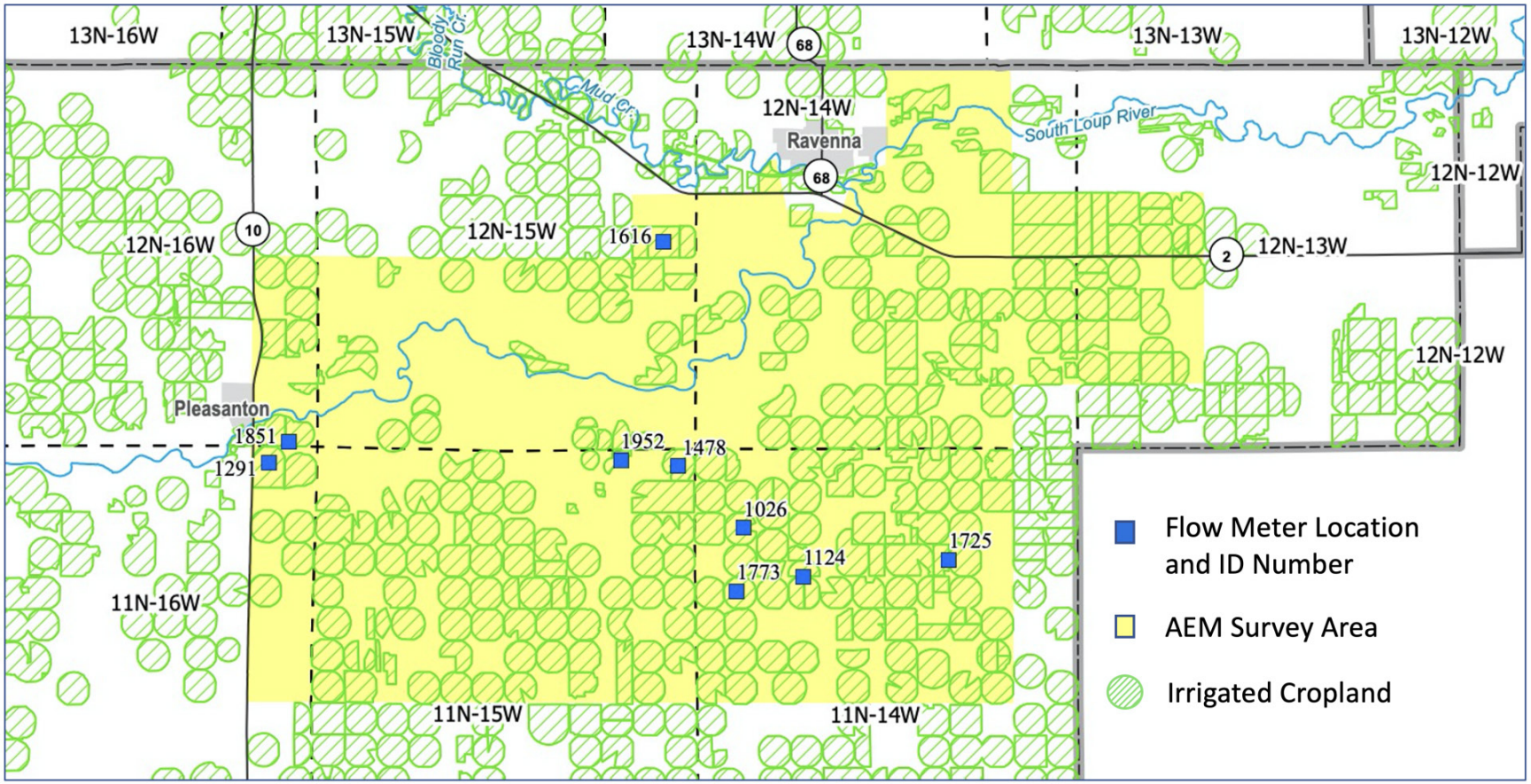


Figure 5-67. Profile 105301 showing the aquifer materials present in below land surface and the well *G-092407* which was sampled for nitrate with the sample result 10.2 mg/l. There is *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials above the *Kp* (Cretaceous Pierre Shale). The CSD 1995 water table is the dashed blue line. Dashed orange line is *To* top. Projection NAD 83 Nebraska State Plane, feet.



Land Use in Survey Area

Figure 5-68. Map showing the land use in the survey area (modified from personal communication from Cam Conrad, LLNRD, 2020a).

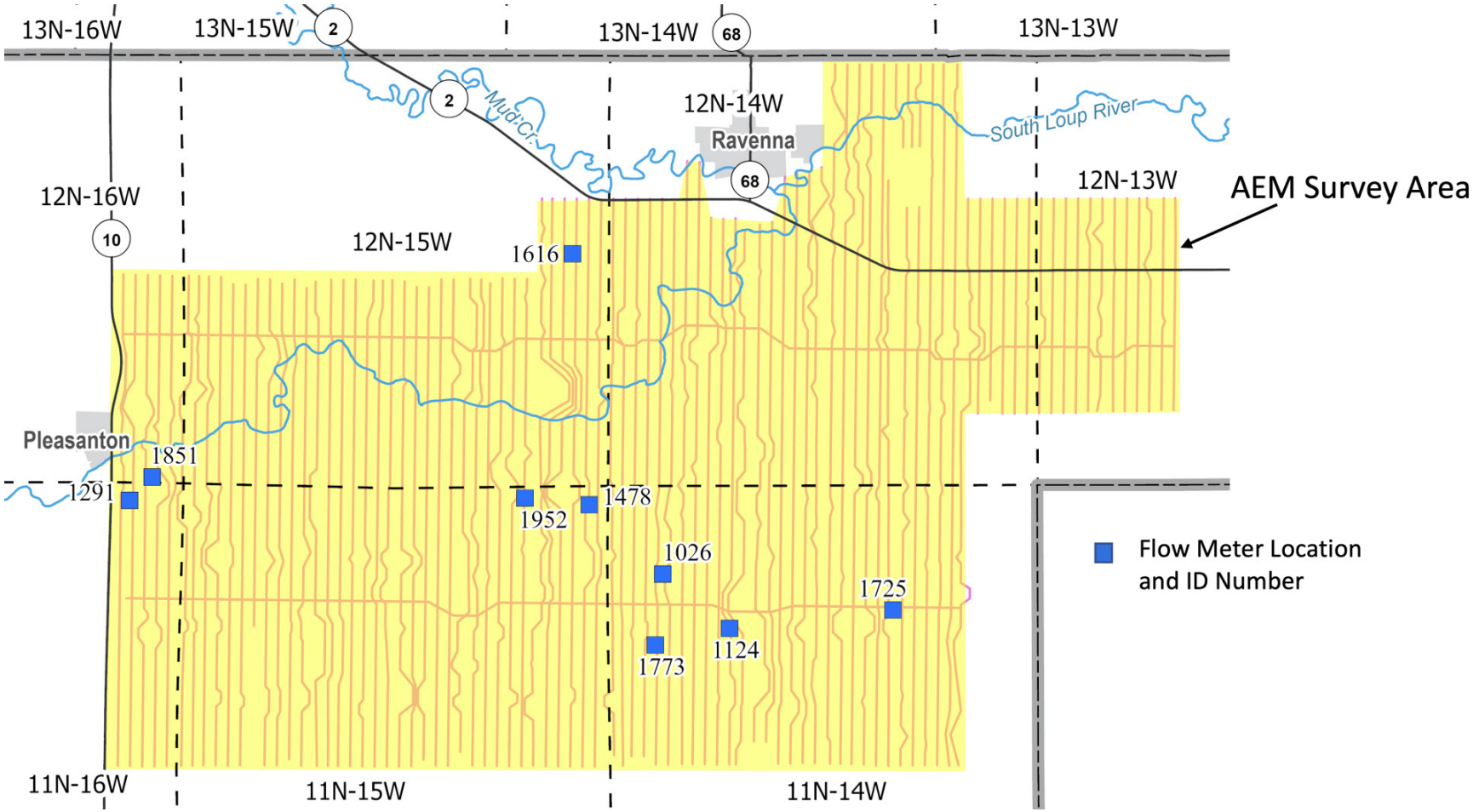


Figure 5-69. Map showing the flowmeter locations and identification number area (modified from personal communication from Cam Conrad, LLNRD, 2020b).

5.4 Estimation of Aquifer Volume and Water in Storage for the Lower Loup NRD 2019 AEM Survey Area

Three-dimensional digital representation of the subsurface resulting from the AEM method provides users the ability to more accurately estimate total unsaturated and saturated aquifer volume and the amount of extractable water present. The AEM survey area was mapped at high resolution for this purpose. An approximately 109 square mile (approximately 69,494 acres) area of AEM data were collected in the LLNRD 2019 AEM survey and interpreted as shown by the map of as flown flight lines in Figure 1-2.

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material for both ***Q*** and ***To*** are provided in Section 5.1.5. Figure 5-15 shows resistivity ranges for interpreted non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. This report provides information on unsaturated and saturated volumes of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials.

Figure 5-70 shows an exploded 3D voxel of the volumes of ***Q*** and ***To*** aquifer materials, including non-aquifer, marginal aquifer, aquifer, and coarse aquifer material from the land surface down to ***Kp*** bedrock illustrating the complex nature of the area. The AEM derived hydrogeologic framework provides a volume in picture form showing the complexity of the area. The mapped sedimentary deposits of the ***Q*** and ***To*** provides information from which the volumes of selected aquifer materials combined with estimated average values for porosity and specific yield are the best estimates for calculation of aquifer volume in acre/ft, groundwater in storage acre/ft and extractable water acre/ft. The area beneath the survey area is included in these calculations and are represented in Figure 5-70 was created in Datamine Discover PA, version 2015.1, Release Build 15.1.44 (Datamine Discover, 2020).

All aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material are used for calculating the groundwater in storage volume and the extractable water volumes for the survey area. Reported values of the average porosity for aquifer materials present are based on values from Freeze and Cherry (1979). Clay ranges from 40%-70%, silt ranges from 35%-50%, sand ranges from 25%-50% and gravel is from 25%-40%. Conservative estimates for the porosity values used in these calculations within the survey area are 40% for non-aquifer material, 35% for marginal aquifer material, 20% for the aquifer material, and 25% for the coarse aquifer material.

Specific yield values for all ***Q*** and ***To*** aquifer materials were selected by estimating values. Specific yield for non-aquifer materials was chosen at 0.02 (Heath, 1983) and for marginal aquifer materials a value of 0.05 was selected (Heath, 1983). The specific yield for the aquifer material is 0.22 (Heath, 1983). While coarse aquifer materials exist as localized deposits in the survey area, estimates of specific yield for the coarse aquifer material is 0.19 (Heath, 1983). The aquifer and marginal aquifer materials represent the dominant material types by total volume for groundwater storage in the survey area. For specific yield, maps of the area would be improved if new maps were produced using this new AEM survey information plus the addition of aquifer tests or other methods of gaining new data including NMR surveys to capture aquifer characteristics.

Table 5-2, Table 5-3, and Table 5-4 below show the results of calculations of the amount of groundwater in storage calculated by volume of all ***Q*** aquifer materials saturated and unsaturated then multiplied by the estimated porosity. The saturated ***To*** is reported in the same manner.

The values in the Table 5-2 for unsaturated ***Q*** aquifer materials shows the non-aquifer material has an estimated volume(If Saturated) of **322,539** acre-ft and contains **129,015** acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of **2,202,678** acre-ft and contains **770,937** acre-ft, aquifer material has an estimated volume of **764,293** acre-ft and contains an estimated volume of **152,858** acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of **959,632** acre-ft for a total of **239,908** acre-ft of groundwater in storage. The amount of groundwater in storage for all ***Q*** material groups is **1,292,718** acre-ft. The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. The results of these calculations as an example from values in the table for unsaturated ***Q*** aquifer materials shows non-aquifer material will yield approximately **2,580** acre-ft, marginal aquifer materials will yield approximately **38,546** acre-ft, aquifer materials will yield **33,628** acre-ft, and the coarse aquifer material will yield approximately **45,582** acre-ft. A total of **120,336** acre-ft is available from all materials. It should be noted that the water yield volume from the non-aquifer and marginal aquifer will drain at much reduced rate.

The values in the Table 5-3 for saturated ***Q*** aquifer materials shows the non-aquifer material has an estimated volume of **29,199** acre-ft and contains **11,679** acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of **2,131,881** acre-ft and contains **746,158** acre-ft, aquifer material has an estimated volume of **1,761,880** acre-ft and contains an estimated volume of **352,376** acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of **1,100,334** acre-ft for a total of **275,083** acre-ft of groundwater in storage. The amount of groundwater in storage for all ***Q*** material groups is **1,385,296** acre-ft. The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. The results of these calculations as an example from values in the table for saturated ***Q*** aquifer materials shows non-aquifer material will yield approximately **233** acre-ft, marginal aquifer materials will yield approximately **37,307** acre-ft, aquifer materials will yield **77,522** acre-ft, and the coarse aquifer material will yield approximately **52,265** acre-ft. A total of **167,327** acre-ft is available from all materials. It should be noted that the water yield volume from the non-aquifer and marginal aquifer will drain at much reduced rate.

The values in the Table 5-4 for saturated ***To*** aquifer materials shows the non-aquifer material has an estimated volume of **760,848** acre-ft and contains **304,339** acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of **3,958,652** acre-ft and contains **1,385,528** acre-ft, aquifer material has an estimated volume of **4,344,496** acre-ft and contains an estimated volume of **868,899** acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of **1,112,992** acre-ft for a total of **278,248** acre-ft of groundwater in storage. The amount of groundwater in storage for all ***To*** material groups is **2,837,014** acre-ft. The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. The results of these calculations as an example from values in the table for saturated ***To*** aquifer materials shows non-aquifer material will yield approximately **4,565** acre-ft, marginal aquifer materials will yield approximately

52,650 acre-ft, aquifer materials will yield **147,712** acre-ft, and the coarse aquifer material will yield approximately **38,954** acre-ft. A total of **243,881** acre-ft is available from all materials. It should be noted that the water yield volume from the non-aquifer and marginal aquifer will drain at much reduced rate.

These estimates are based on the CSD 1995 water table map. This map was produced during the most stable period of water table elevation change (Figure 5-59) and average precipitation Also, these volumetric estimates consider only the volume of water assumed in the pore spaces of the aquifer material defined by the resistivity threshold levels and do not account for the amount of the possible "confined or semi-confined" water under pressure (head above the aquifer). Note that additional analysis using future acquired data on what is confined, or semi-confined areas of the survey area would need to be completed before any designation of these areas can be made. This volume of water would add to the values reported in Table 5-2, Table 5-3, and Table 5-4. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-2, Table 5-3, and Table 5-4 are conservative estimates and the amount released from the decline in pressure are not considered.

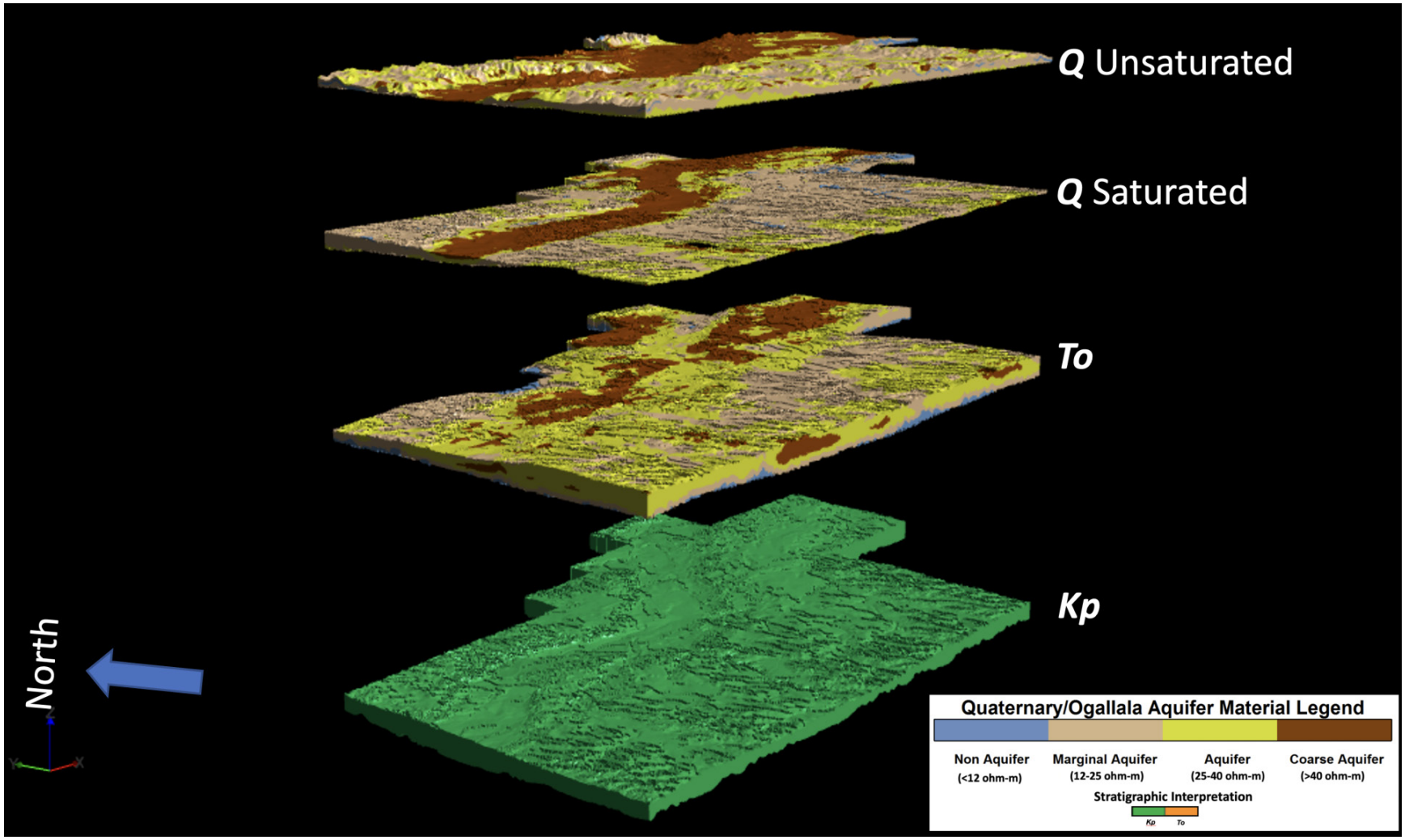


Figure 5-70. 3D voxel volumes of *Q* (Quaternary) and *To* (Tertiary Ogallala Group) aquifer materials, including non-aquifer, marginal aquifer, aquifer, and coarse aquifer material from the land surface down to *Kp* (Cretaceous Pierre Shale) bedrock.

Table 5-2. Unsaturated *Q* (Quaternary) aquifer materials underlying the Buffalo County area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Non-Aquifer	14,049,807,936	322,539	0.40	129,015	0.02	2,580
Marginal	95,948,550,143	2,202,678	0.35	770,937	0.05	38,546
Aquifer	33,292,593,678	764,293	0.20	152,858	0.22	33,628
Coarse Aquifer	41,801,521,317	959,632	0.25	239,908	0.19	45,582
TOTAL	185,092,473,074	4,249,144		1,292,718		120,336

Table 5-3. Saturated *Q* (Quaternary) aquifer materials underlying the Buffalo County area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Non-Aquifer	1,271,910,420	29,199	0.40	11,679	0.02	233
Marginal	92,864,640,903	2,131,881	0.35	746,158	0.05	37,307
Aquifer	76,747,387,105	1,761,880	0.20	352,376	0.22	77,522
Coarse Aquifer	47,930,508,507	1,100,334	0.25	275,083	0.19	52,265
TOTAL	218,814,446,935	5,023,295		1,385,296		167,327

Table 5-4. Saturated *To* (Tertiary Ogallala Group) aquifer materials underlying the Buffalo County area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Non-Aquifer	33,142,506,947	760,848	0.40	304,339	0.015	4,565
Marginal	172,438,631,050	3,958,652	0.35	1,385,528	0.038	52,650
Aquifer	189,245,964,490	4,344,496	0.20	868,899	0.17	147,712
Coarse Aquifer	48,481,901,290	1,112,992	0.25	278,248	0.14	38,954
TOTAL	443,309,003,777	10,176,989		2,837,014		243,881

5.5 Recharge Areas within the Lower Loup NRD 2019 AEM Survey Area

Three-dimensional representations of the subsurface resulting from the AEM method illustrate areas of aquifer materials from the ***Kp*** bedrock up to the land surface as shown by the exploded voxel model of the survey area in Figure 5-70 in Section 5.4 above. Within each layer of the voxel all aquifer materials are present, Coarse Aquifer, Aquifer, marginal Aquifer and Non-aquifer for the ***Q*** and ***To***. The ***Kp*** which is a marine shale is an aquiclude and has no aquifer materials identified in the 2019 AEM survey area. Close inspection of the voxels shows that the distribution of the aquifer materials with the marginal and non-aquifer materials in the quaternary being an important control for aquifer recharge from the land surface. These aquifer materials contain large percentages of silt and clay that restricts water movement downward to the saturated **Q** and ***To*** aquifer and coarse aquifer materials. The complex mix of aquifer materials and the relationship to each other is the main control for recharge. The materials beneath the South Loup River and Mud Creek shows more aquifer and coarse aquifer material at the land surface downward.

Figure 5-71 is a voxel model of unsaturated marginal and non-aquifer material shows the almost continuous extent of these materials in the near surface. This deposit is thick and can extend to the saturated zone as shown on Figure 5-72. The saturated marginal and non-aquifer materials are generally a continuation of the unsaturated non-aquifer and marginal aquifer materials seen in Figure 5-71. The presence of marginal and non-aquifer materials and their relationship to aquifer and coarse aquifer materials is the main control for recharge. The materials beneath the South Loup River and Mud Creek shows more aquifer and coarse aquifer material at the land surface downward. Note the South Loup River valley has little non-aquifer and marginal aquifer material present. This is a very good area for recharge.

A series of 2D maps were created to show the change in the interpreted aquifer materials layers for different depths below land surface. These maps are near-surface layer maps, which includes the 10-foot (Figure 5-73), 20-foot (Figure 5-74) and 50-foot (Figure 5-75) layers were constructed. Remember from the discussion around Table 4-4 that each model layer represents an average of the earth's resistivities within those depths, based on the physics of the electromagnetic exploration technique. These first layer maps show all aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material. The coarse aquifer material transmits the largest volume of water and the non-aquifer material being the least able to transmit water.

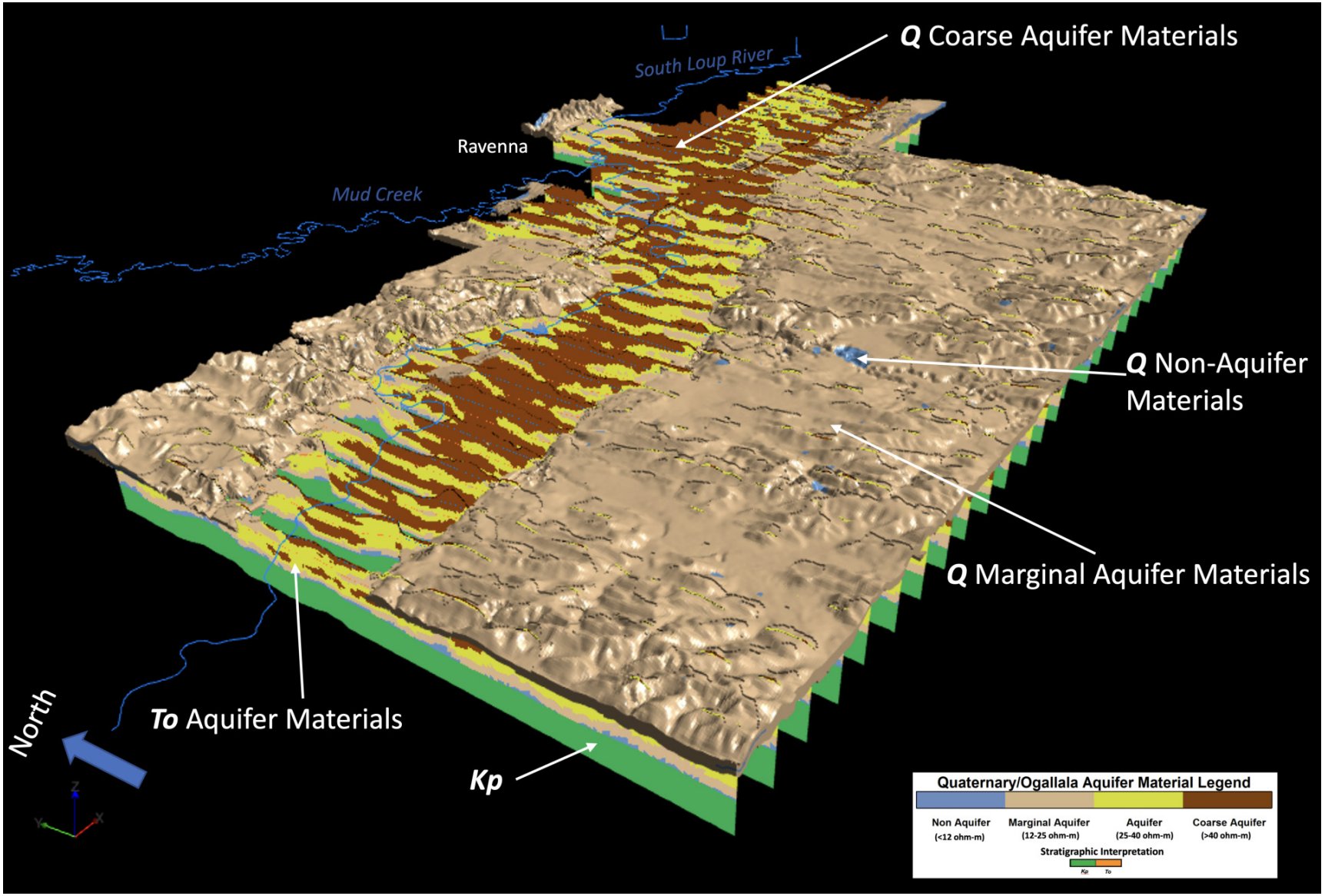


Figure 5-71. View of 3D voxel model looking northwest showing the unsaturated *Q* (Quaternary) non-aquifer material (blue) and marginal aquifer material (tan) on top of a 3D fence diagram of all other materials in AEM survey area. V.E.=10x.

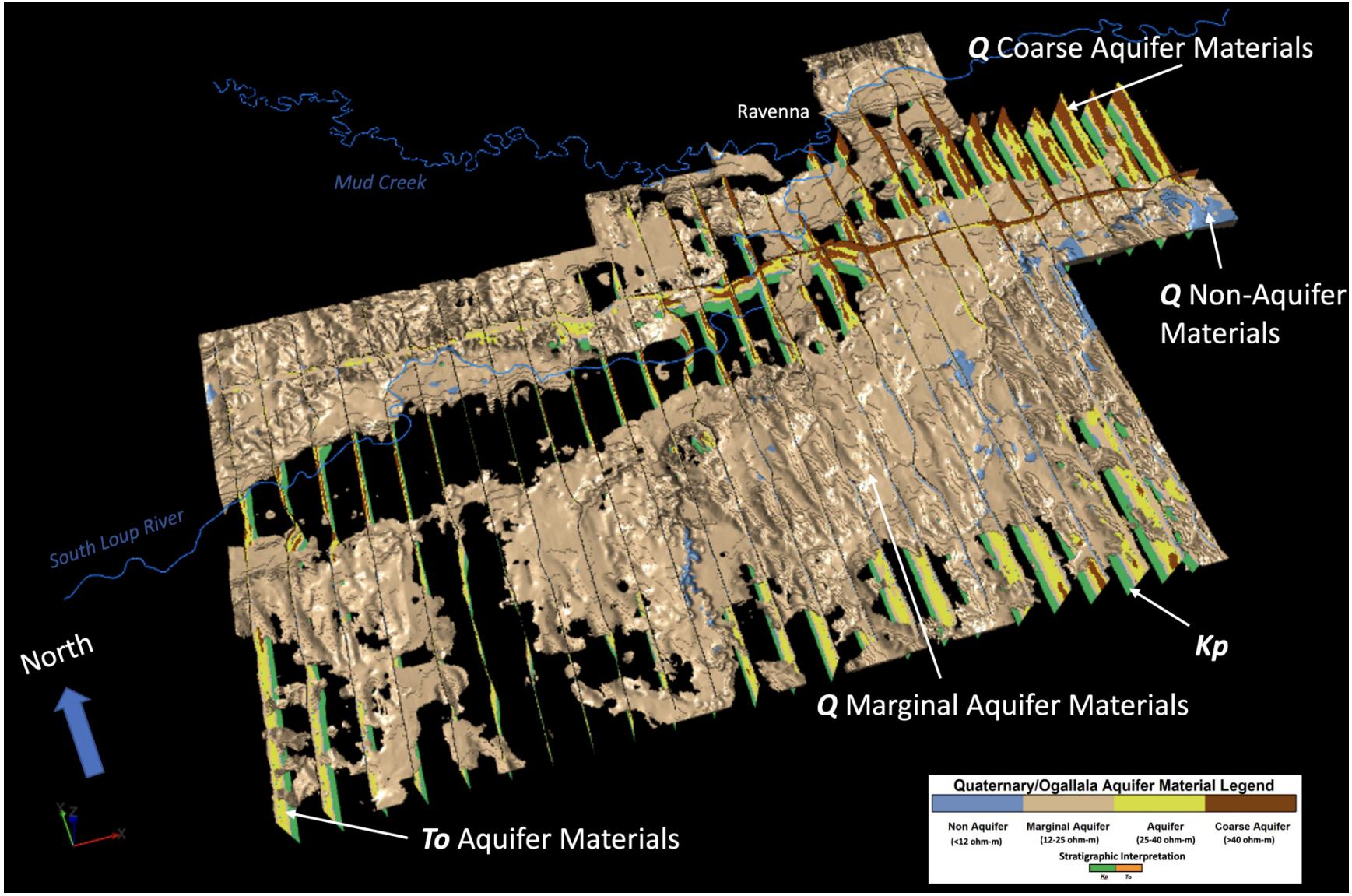


Figure 5-72. View of 3D voxel model looking northwest showing the saturated *Q* (Quaternary) non-aquifer material (blue) and marginal aquifer material (tan) on top of a 3D fence diagram of all other materials in AEM survey area. V.E.=10x.

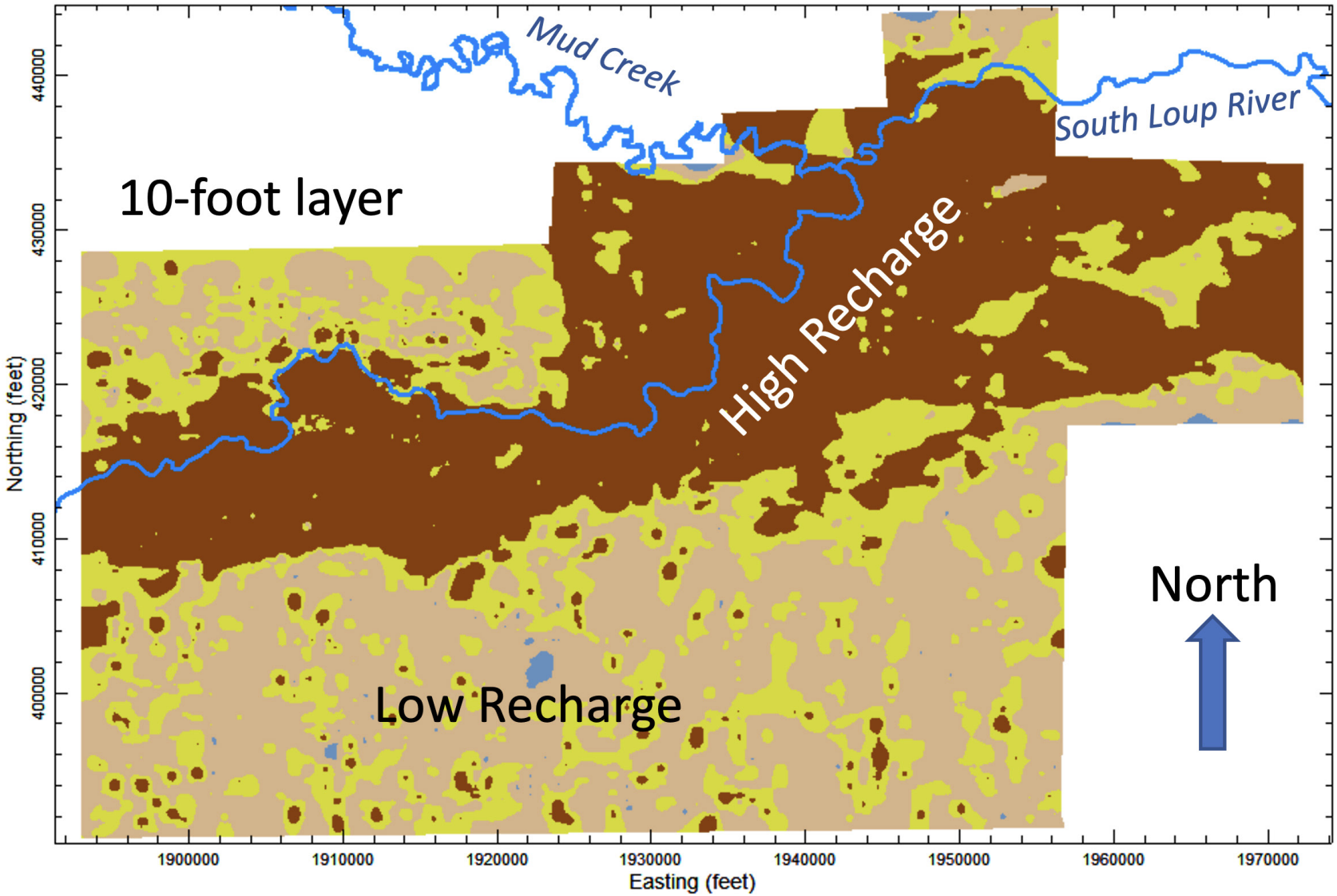


Figure 5-73. Map of aquifer materials for the 10-foot layer across AEM survey area. Area highlighted by blue and tan polygon shows area of least potential recharge. The brown and yellow areas have a moderate to high potential for recharge. Map projection is NAD 83, Nebraska State Plane, feet.

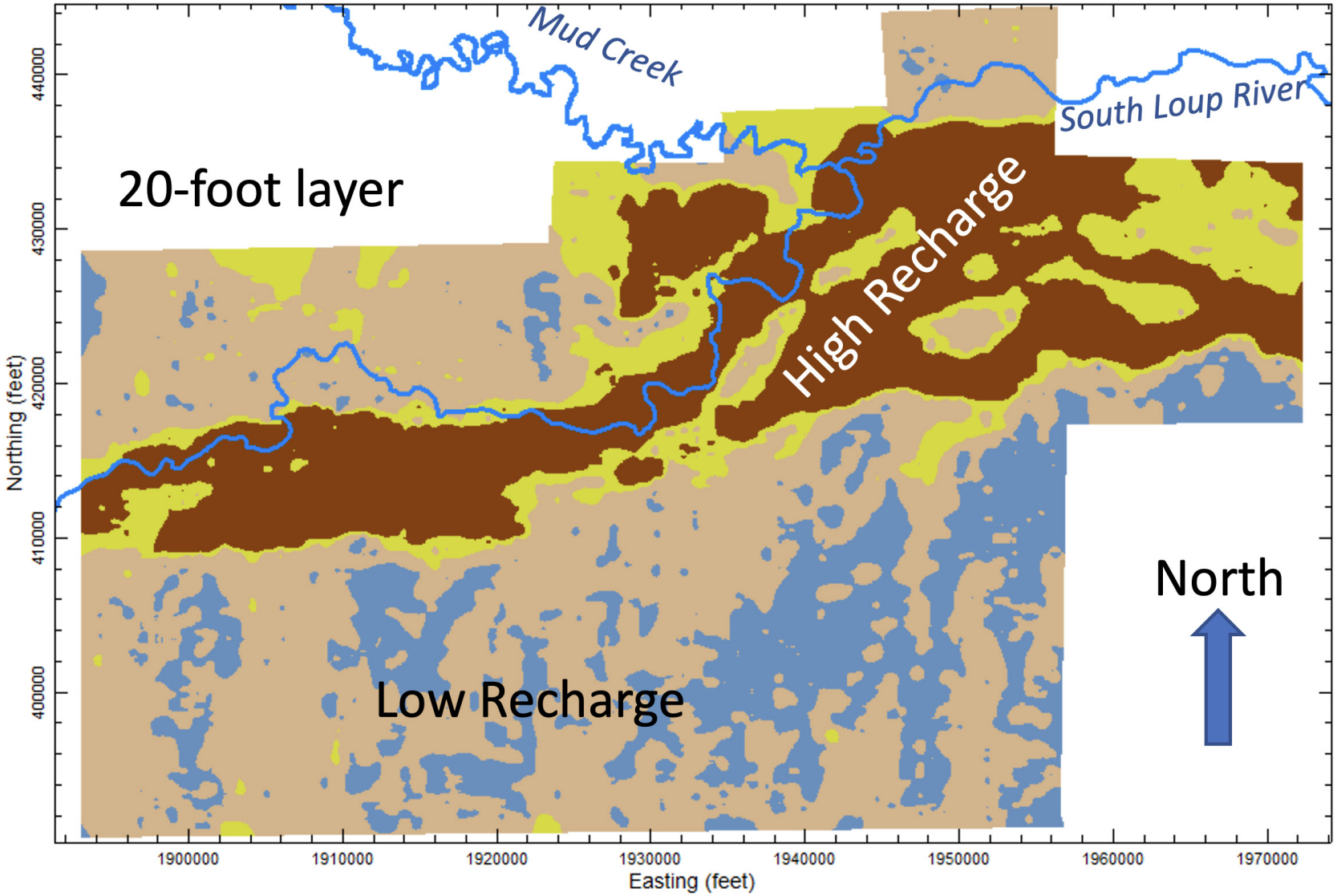


Figure 5-74. Map of aquifer materials for the 20-foot layer across AEM survey area. Area highlighted by blue and tan polygon shows area of least potential recharge. The brown and yellow areas have a moderate to high potential for recharge. Map projection is NAD 83, Nebraska State Plane, feet.

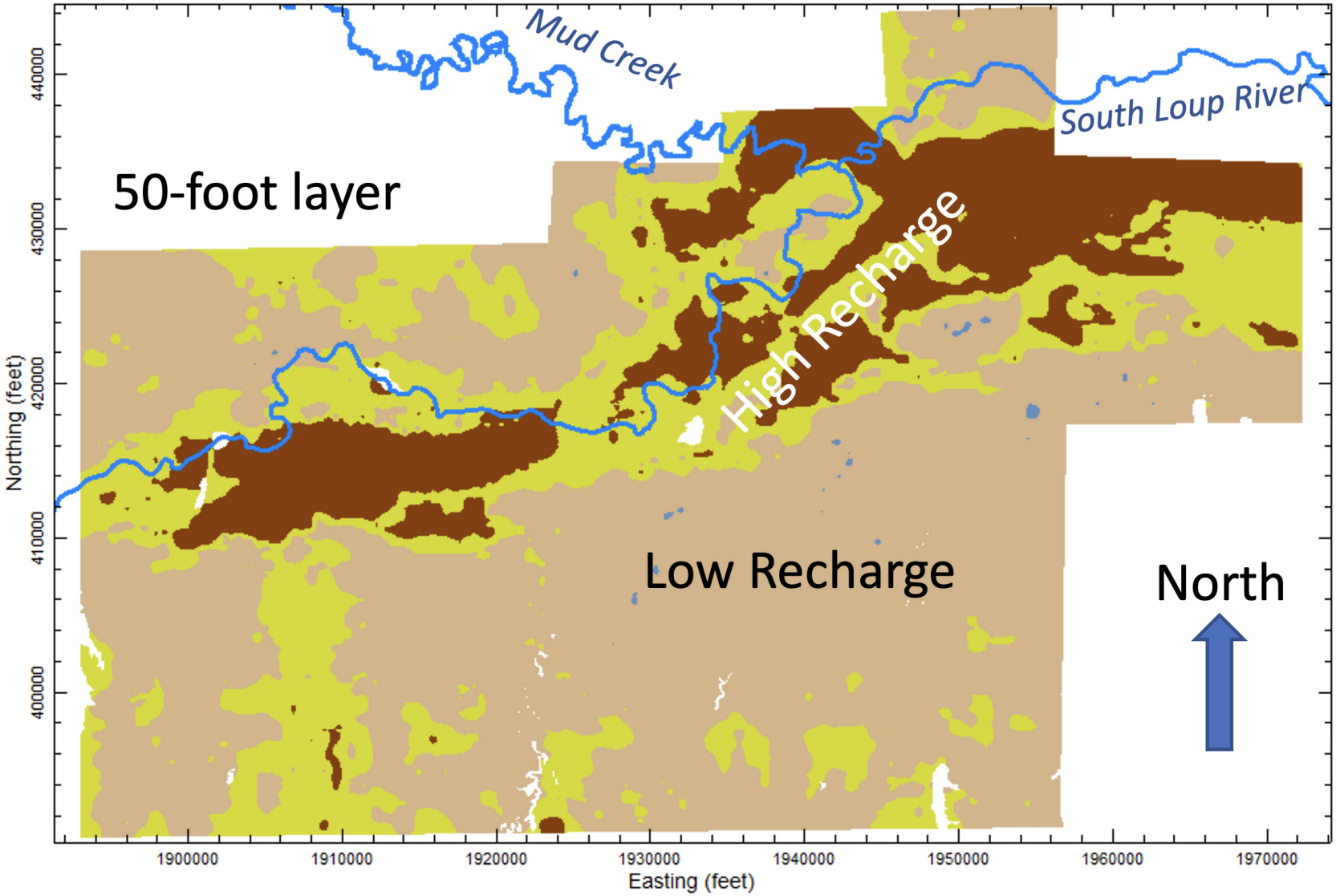


Figure 5-75. Map of aquifer materials for the 50-foot layer across AEM survey area. Area highlighted by blue and tan polygon shows area of least potential recharge. The brown and yellow areas have a moderate to high potential for recharge. Map projection is NAD 83, Nebraska State Plane, feet.

5.6 Key AEM Findings

5.6.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results. These included CSD information on seven (7) boreholes containing lithology and stratigraphic information, and three (3) holes contained geophysical information. NE-DNR wells totaled 509 registered well records containing usable lithology information.

5.6.2 Digitizing Interpreted Geological Contacts

Characterization and interpretation of the subsurface was performed in cross-section and in derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), and Cretaceous Pierre Shale (***Kp***). The interpretive process benefited from the use of CSD and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary/Tertiary aquifer material mapping are included in the appendices as well as interpretative surface grids.

5.6.3 Resistivity/Lithology Relationship

Assessment of the sediment character in both the Quaternary/Tertiary Ogallala aquifer system and the consolidated Cretaceous Pierre Shale bedrock was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in survey area. A numerically robust assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-25 ohm-m), and aquifer (25-40 ohm-m), including coarse sand-rich intervals (>40 ohm-m) was determined. This allowed for the characterization of the ranges of resistivities present in the major geologic units described in this report.

*5.6.4 Hydrogeological Framework of the **Buffalo County AEM Survey Area***

The AEM reveals considerable variability in the ***Q*** and ***To*** deposits across the AEM survey area. The subsurface distribution of materials can be generally characterized into two parts. The ***Q*** which covers the entire surface of the survey area including the South Loup River Valley and the upland areas north and south of the river. The ***Q*** aquifer within the AEM survey area is predominantly composed of unconsolidated aquifer and coarse aquifer materials composed of alluvial sediments. The ***Q*** also has nearly continuous areas of marginal and non-aquifer material layers in the near surface on the tablelands. ***Q*** materials lie upon ***To*** across the survey area. The ***To*** has a heterogeneous mix of aquifer materials which is the primary aquifer where there is aquifer and coarse aquifer materials. The ***To*** also has marginal and non-aquifer material deposits that can act as groundwater flow boundaries creating isolated aquifers and barriers to groundwater flow. The entire survey area has ***To*** non-aquifer and marginal aquifer layer lying on the ***Kp*** bedrock surface. The bedrock is eroded and has shallow paleochannels cut into it.

5.6.5 *Estimation of Aquifer Volume and Water in Storage in* ***the Buffalo County*** *AEM Survey Area*

The unsaturated Q aquifer materials shows the non-aquifer material has an estimated volume(If Saturated) of 322,539 acre-ft and contains 129,015 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 2,202,678 acre-ft and contains 770,937 acre-ft, aquifer material has an estimated volume of 764,293 acre-ft and contains an estimated volume of 152,858 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 959,632 acre-ft for a total of 239,908 acre-ft of groundwater in storage. The amount of groundwater in storage for all Q material groups is 1,292,718 acre-ft.

The saturated Quaternary (Q) non-aquifer material has an estimated volume of 29,199 acre-ft and contains 11,679 acre-ft of groundwater in storage. The saturated marginal aquifer material has an estimated volume of 2,131,881 acre-ft and contains 746,158 acre-ft. The saturated aquifer material has an estimated volume of 1,761,880 acre-ft and contains an estimated volume of 352,376 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 1,100,334 acre-ft for a total of 275,083 acre-ft of groundwater in storage. The amount of groundwater in storage for all aquifer material groups is 1,385,296 acre-ft. Non-aquifer materials in the Buffalo County AEM survey area will yield approximately 233 acre-ft, marginal aquifer materials will yield approximately 37,307 acre-ft, aquifer materials will yield 77,522 acre-ft, and the coarse aquifer material will yield approximately 52,265 acre-ft. A total of 129,787 acre-ft is available from the combined aquifer and coarse aquifer materials.

The saturated ***To*** aquifer materials shows the non-aquifer material has an estimated volume of 760,848 acre-ft and contains 304,339 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 3,958,652 acre-ft and contains 1,385,528 acre-ft, aquifer material has an estimated volume of 4,344,496 acre-ft and contains an estimated volume of 868,899 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 1,112,992 acre-ft for a total of 278,248 acre-ft of groundwater in storage. The amount of groundwater in storage for all ***To*** material groups is 2,837,014 acre-ft.

5.6.6 ***Groundwater Declines,*** *Water Quality, and the AEM Hydrogeologic Framework in the Buffalo County AEM Survey Area*

There is heterogeneity in the aquifer materials of the ***Q*** and ***To*** sediments**.** The AEM survey identified the areas of aquifer materials that will transmit the most, and the least, amounts of water within the subsurface. It showed pathways from the surface down to the groundwater system (recharge). The declines are directly related to the non-aquifer and marginal aquifer near surface layers on the tablelands. They limit the amount of recharge going to the aquifer system. There are also isolated aquifers in the subsurface. The LLNRD would benefit from building a water budget for the area based the hydrogeology, water use, land use, recharge, weather changes, and other factors.

Water quality samples for nitrate were compared to the AEM hydrogeologic framework. It was found that the water quality in the survey area was very good. The overlying ***Q*** near surface non-aquifer and

marginal aquifer material layers reduce recharge that carry nitrates down to the water table. Two wells had values of 8.2 and 10.2 mg/l that are anomalies when compared to the aquifer materials in which they are completed in and appear to not be non-point source pollution locations.

5.6.7 Potential Recharge Zones within the Lower Loup NRD 2019 AEM Survey Area

Each AEM flight line was interpreted for aquifer material for the first model layer (10 ft), the second model layer (20 ft) and the fifth model layer (50 ft). Areas of coarse aquifer and aquifer material will have the highest potential to transmit the largest amount of water to the groundwater system. The marginal aquifer material has the lowest potential to transmit some water downward and the non-aquifer material will transmit minimal to no water to the groundwater aquifer. Maps have been created that show broad areas along the South Loup River and some tributaries to be the best areas for recharge at all 3 model depths. The worst areas of recharge are the tablelands because of thick layers of non-aquifer and marginal aquifer materials present at those locations.

5.6.8 Evaluating Potential Locations for Managed Aquifer Recharge (MAR) areas in the Buffalo County AEM Survey Area

The northeast corner of the survey area is an example of using the AEM hydrogeologic framework to look for potential MAR sites. There appears to be enough unsaturated aquifer and coarse aquifer material to provide storage space. These materials are thick and have high rates of recharge. They are a reasonable distance from the river. The stored water can move naturally back to the river by base flow or can be pumped when there is a need. All areas with MAR potential have not been identified by this survey.

5.6.9 Using AEM Results to Understand the Effect of Groundwater Management and Regulations

The Groundwater Management Plan and regulations were briefly compared to the results of the AEM hydrogeologic framework. The hydrogeology has a role in understanding this plan. The information provided by LLNRD on flowmeter locations, 2019 average groundwater use, and land use provides insight to how effective groundwater management may be across the area which continues to show declines. This information has not been evaluated for the local impacts which can affect the annual average declines reported by the District. The data on groundwater level changes show that the geology is one of the controls. No definitive conclusion was reached on how to evaluate the management plan, but the hydrogeology was linked to the water use and crop use. A full water budget needs to be developed to fully understand the effects of groundwater management.

5.7 Recommendations

Recommendations provided to the LLNRD in this section are based on the interpretation and understanding gained from the addition of the AEM data to existing information and from discussions with the LLNRD about their management challenges.

5.7.1 Additional AEM Mapping

The aquifer maps provided in this report represent the detailed hydrogeologic framework developed for the Buffalo County AEM survey area. The interpretations match well with the CSD and NE-DNR boreholes. No additional high resolution AEM information is needed within Buffalo County Area to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or "block flights" be collected to develop detailed frameworks in other areas of the District.

Other management areas or potential management areas should be mapped in detail to provide information on the hydrogeologic framework which provides detail on recharge, groundwater movement, etc. This could potentially be done in cooperation with the neighboring NRDs to get details on the continuous aquifer system that is shared in the area. The line spacing for the block flights should be on the order of 0.25 mile (1,320 ft).

For example, the detailed hydrogeologic frameworks presented in this report have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield. It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of the LLNRD. This will supply the LLNRD with information on groundwater flow, aquifer sustainability, depletion to streams, well interference, groundwater withdrawal, and other management considerations. Locating MAR sites is an activity the LLNRD is pursuing and AEM data is a primary component. Evaluating a water budget is another component of understanding integrated management, water quality and quantity management efforts.

5.7.2 Update the Water Table map

Additional closely spaced water level measurement locations would improve the water table map. The transition from the flood plain to areas out of the flood plain into the tablelands would be a good addition to the network.

5.7.3 Siting new test holes and production wells

The AEM framework maps and profiles provided in this report provide insight on the 3D relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the LLNRD area was used in building the framework maps and profiles. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in optimal locations.

The location of any future new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution.

5.7.4 Aquifer testing and borehole logging

Aquifer tests are recommended to improve estimates of aquifer characteristics. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics is highly recommended. The few test holes with geophysical logs in the LLNRD survey area were inadequate. They were too few in number and none were calibrated. The borehole geophysical logs provided for this investigation demonstrate that additional calibrated and verified geophysical logs are required in the LLNRD.

Examples of additional logging would be borehole flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailed aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR). This is a quick and effective way to characterize porosity and water content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth. This is very cost effective when compared to traditional aquifer tests.

5.7.5 Recharge Zones

The LLNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. The block flights of AEM data acquisition provide the most detailed information for understanding recharge throughout the Buffalo County area. It is recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

It is recommended that additional focused high resolution AEM data be collected and interpreted along the streams utilizing closely spaced flight lines using an AEM system that has near-surface resolution. This will enhance the results of previous groundwater surface water interaction locations. By identifying these locations with precise placement of the sediment packages along the stream, rather than large stream reaches as seen in other studies, a more thorough understanding of gaining and losing reaches of the streams can be made.

5.7.6 Managed Aquifer Recharge

An area which lies out of the flood plain in the northeast corner of the survey area may have potential for managed aquifer recharge. There appears to be enough unsaturated aquifer material and coarse aquifer material to provide storage space. These materials are thick and have high rates of recharge. They are a reasonable distance from the river. The stored water can move naturally back to the river by

base flow or can be pumped when there is a need. A detailed analysis of the AEM data needs to be done to determine if there are other viable opportunities for the LLNRD.

5.7.7 Build a Water Budget to Understand the Effectiveness of Groundwater Quantity Management

Buffalo County has long term groundwater management declines. Future changes in management would benefit from a thorough understanding of the water budget. Significant data has already been collected such as the hydrogeologic framework, surface water measurements, groundwater level measurements, crop use, some flowmeter readings, etc. What needs to be completed is an evaluation and analysis of all of this information into a water budget. Doing a complete water budget is recommended for the survey area.

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6 Description of Data Delivered

6.1 Tables Describing Included Data Files

Table 6-1 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, six (6) flights were required to acquire the LLNRD 2019 AEM data (Figure 4-5). Grouped by flight date, there are four (4) data files included in Appendix_3_Deliverables\Raw_Data for each flight. These files have extensions of "*.sps" and "*.skb". The "*.sps" files include navigation and DGPS location data and the "*.skb" files include the raw AEM data that have been PFC-corrections (discussed in Section 4.4.1). Two additional files are used for all the flights. These are the system description and specifications file (with the extension "*.gex") in the GEO subdirectory and the 'mask' file (with the extension "*.lin"), in the MASK subdirectory, which correlates the flight dates, flight numbers, and assigned line numbers.

Table 6-2 describes the data columns in the ASCII EM_MAG *.xyz files for the LLNRD 2019 AEM survey area. This file, LLNRD2019_EM_MAG.xyz, contains the electromagnetic raw data plus the magnetic and navigational data as supplied directly from SkyTEM.

The results of the SCI are included in LLNRD2019_AEM_SCI_v1.xyz and the data columns of these files are described in Table 6-3.

Shapefiles with locations of the NE-CSD and NE-DNR borehole data used in the Quality Control and interpretation analysis are listed in Table 6-4.

The LLNRD 2019 interpretation results included in data file LLNRD2019_InterpSurfaces_v1.xyz are listed in Table 6-5. These include water table and bedrock elevations as well as Quaternary aquifer material types and their thicknesses. Some of these are included in the interpretation KMZ described in Section 6.2 below.

ESRI Arc View Binary FLT Grids of the surfaces that were used in the interpretation (DEM, water table) and derived from the interpretation (top of geological units) of the AEM and borehole are listed in Table 6-6 and are available for download in Appendix 3_Deliverables\Grids.

A 3D voxel model/grid of the 2019 LLNRD AEM resistivity inversion results was created. The voxel grid was made using a 500 ft grid cell size and the model layer thickness (Table 4-4). The voxel grid was clipped below the bedrock surf ace interpreted from the AEM and the boreholes. Table 6-7 presents a list of the channel names in the ASCII "*.xyz" file.

In summary, the following are included as deliverables:

- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz
- Borehole as ASCII *.xyz
- Interpretations as ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView FLT grid files – surface, topo, etc
- 3D fence diagrams of the LLNRD 2019 survey lines.
- 3D voxel models as ASCII *.xyz for the LLNRD AEM survey areas

KMZs for the LLRND AEM survey flight lines (Discussed in Section 6.2)

Table 6-1. Raw SkyTEM data files

Folder	File Name	Description
Data	..NavSys.sps, …PaPc.sps, ...RawData_PFC.skb, …DPGS.sps	Raw data files included for each flight used in importing to Aarhus Workbench
Geo	20008_SkyTEM_304_AGF_(DualWaveform)_60Hz_SKB.gex 20008_LLNRD_SkyTEM304.gex, 20008_LLNRD_SkyTEM304.sr2	304M System Description including System Response
Mask	20008_LLNRD_Production.lin	Production file listing dates, flights, and assigned line numbers

Table 6-2. Channel name, description, and units for LLNRD2019_EM_MAG.xyz with EM, magnetic, DGPS, Inclinometer, altitude, and associated data.

Parameter	Description	Unit
Fid	Unique Fiducial Number	
Line	Line Number	
Flight	Name of Flight	yyyymmdd.ff
DateTime	DateTime Format	Decimal days
Date	DateTime Format	yyyymmdd
Time	Time UTC	hhmmss.sss
AngleX	Angle (in flight direction)	Degrees
AngleY	Angle (perpendicular to flight direction)	Degrees
Height	Filtered Height Measurement	Meters [m]
Lon	Longitude, WGS84	Decimal Degrees
Lat	Latitude, WGS84	Decimal Degrees
E_UTM14N_M	Easting, NAD83 UTM Zone 14N	Meters [m]
N_UTM14N_M	Northing, NAD83 UTM Zone 14N	Meters [m]
DEM_M	Digital Elevation	Meters [m]
Alt	DGPS Altitude above sea level	Meters [m]
GDSpeed	Ground Speed	Kilometers/hour [km/h]
Curr_LM	Current, Low Moment	Amps [A]
Curr_HM	Current, High Moment	Amps [A]
LMZ_G01 [Gates 0-27]	Normalized (PFC-Corrected) Low Moment Z-RxCoil value	$pV/(m^4*A)$
HMZ_G01 [Gates 0-36]	Normalized (PFC-Corrected) High Moment Z-RxCoil value	$pV/(m^4*A)$
HMX_G01 [Gates 0-36]	Normalized (PFC-Corrected) High Moment X-RxCoil value	$pV/(m^4*A)$
_60Hz_Intensity	Power Line Noise Intensity monitor	
TMI	Total Field Magnetic field Intensity	nanoTesla [nT]
MAG_COR	Corrected Total Magnetic Field Intensity	nanoTesla [nT]
bmag_f	Raw Base Station Mag Data filtered	nanoTesla [nT]
Diurnal Drift	Diurnal Drift corrections	nanoTesla [nT]
MAG_ED	Total Magnetic Field Intensity corrected for Diurnal Drift	nanoTesla [nT]
RMF	Residual Magnetic Field	nanoTesla [nT]
IGRF	International Geomagnetic Reference Field	nanoTesla [nT]

INC	Magnetic field inclination	Degrees
DEC	Magnetic field declination	Degrees

Table 6-3: Channel name, description, and units for LLNRD2019_SCI_Inv_v1.xyz file with AEM inversion results.

Parameter	Description	Unit
LINE	Line Number	Feet [ft]
East_M	Easting NAD83, UTM Zone 14	Meters [m]
North_M	Northing NAD83, UTM Zone 14	Meters [m]
DEM_M	DEM from survey	Meters [m]
E_NESPFT	Easting NAD83, UTM Zone 14	Feet [ft]
N_NESPFT	Northing NAD83, UTM Zone 14	Feet [ft]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
FID	Unique Fiducial Number	
TIME	Date Time Format	Decimal days
ALT_M	Altitude of system above ground	Meters [m]
INVALT	Inverted Altitude of system above ground	Meters [m]
INVALTSTD	Inverted Altitude Standard Deviation of system above ground	Meters [m]
DELTAALT	Change in Altitude of system above ground	Meters [m]
RESDATA	Residual of individual sounding	
RESTOTAL	Total residual for inverted section	
RHO_I_0 THROUGH RHO_I_38	Inverted resistivity of each later	Ohm-m
RHO_STD_0 THROUGH RHO_STD_38	Inverted resistivity standard deviation	
SIGMA_I_0 THROUGH SIGMA_I_38	Conductivity	S/m
DEPTOP_0_FT THROUGH DEPTOP_38_FT	Depth to the top of individual layers	Feet [ft]
DEPBOT_0_FT THROUGH DEPBOT_38_FT	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT THROUGH THK_38_FT	Thickness of individual layers	Feet [ft]
DEPTOP_0_M THROUGH DEPTOP_38_M	Depth to the top of individual layers	Meters [m]
DEPBOT_0_M THROUGH DEPBOT_38_M	Depth to the bottom of individual layers	Meters [m]
THK_0_M THROUGH THK_38_M	Thickness of individual layers	Meters [m]
DOI_UPPER_FT	More conservative estimate of DOI	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI	Feet [ft]
DOI_UPPER_M	More conservative estimate of DOI	Meters [m]
DOI_LOWER_M	Less conservative estimate of DOI	Meters [m]

Table 6-4. Shapefiles containing borehole locations used in the LLNRD2019 AEM survey.

Database (*.xyz, *.gdb)	Description
LLNRD_CSD_boreholes.shp	ESRI Shapefiles containing borehole location information.
LLNRD_DNR_boreholes.shp	

Table 6-5. Channel name description and units for the interpretation results file LLNRD2019_InterpSurfaces_v1.xyz.

Parameter	Description	Unit
LINE	Line Number	
East_M	Easting NAD83, UTM Zone 14N	Meters (m)
North_M	Northing NAD83, UTM Zone 14N	Meters (m)
East_ft	Easting NAD83, Nebraska State Plane	Feet [ft]
North_ft	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
RHO [0] through RHO [38]	Array of Inverted model resistivities of each layer	Ohm-m
RESDATA	Inversion model residuals of each individual sounding	
RESTOTAL	Inversion model average of all residuals	
DEP_TOP_FT [0] through DEP_TOP_FT [38]	Depth to the top of 39 individual layers	Feet [ft]
DEP_BOT_FT [0] through DEP_BOT_FT [38]	Depth to the bottom of 39 individual layers	Feet [ft]
DOI_UPPER_FT	More conservative estimate of DOI from Workbench	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI from Workbench	Feet [ft]
SoilRecharge	1 = Surficial layer Non-Aquifer; 2 = Marginal; 3 = Aquifer; 4 = Coarse Aquifer Material	
WaterTable1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
NAT[0] through NAT[38]	Array of model cell top elevations of the Non-Aquifer Material (<12 ohm-m), if present	Feet [ft]
NAB[0] through NAB[38]	Array of model cell bottom elevations of the Non-Aquifer Material (<12 ohm-m), if present	Feet [ft]
ThkTot_NAq	Total Thickness of Non-Aquifer Material (<12 ohm-m) above bedrock	Feet [ft]
ThkWT_NAq	Total Thickness of Non-Aquifer Material (<12 ohm-m) below the water table and above bedrock	Feet [ft]

MAT[0] through MAT[38]	**Array of model cell top elevations of the Marginal-Aquifer Material (12 - 25 ohm-m), if present**	**Feet [ft]**
MAB[0] through MAB[38]	**Array of model cell bottom elevations of the Marginal-Aquifer Material (12 - 25 ohm-m), if present**	**Feet [ft]**
ThkTot_MAq	**Total Thickness of Marginal-Aquifer Material (12 - 25 ohm-m) above bedrock**	**Feet [ft]**
AMT[0] through AMT[38]	**Array of model cell top elevations of the Aquifer Material (25 - 40 ohm-m), if present**	**Feet [ft]**
AMB[0] through AMB[38]	**Array of model cell bottom elevations of the Aquifer Material (25 - 40 ohm-m), if present**	**Feet [ft]**
ThkTot_AqM	**Total Thickness of Aquifer Material (25 - 40 ohm-m) above bedrock**	**Feet [ft]**
CAT[0] through CAT[38]	**Array of model cell top elevations of the Coarse Aquifer Material (>40 ohm-m), if present**	**Feet [ft]**
CAB[0] through CAB[38]	**Array of model cell bottom elevations of the Coarse Aquifer Material (>40 ohm-m), if present**	**Feet [ft]**
ThkTot_CAq	**Total Thickness of Coarse Aquifer Material (>40 ohm-m) above bedrock**	**Feet [ft]**
ThkTot_Aq_CA	**Sum of Total Thicknesses of Aquifer Material (25 - 40 ohm-m) and Coarse Aquifer Material (>50 ohm-m) above bedrock**	**Feet [ft]**
ThkWT_Aq_CA	**Sum of Total Thicknesses of Aquifer Material (25 - 40 ohm-m) and Coarse Aquifer Material (>40 ohm-m) below the water table and above bedrock**	**Feet [ft]**
To	**Tertiary Ogallala Formation**	**Feet (ft)**
Cretaceous Bedrock	**Elevation of interpreted Cretaceous bedrock surface**	**Feet [ft]**
Kp	**Elevation of the top of the Cretaceous Dakota Group, if present**	**Feet [ft]**

Table 6-6. Files containing ESRI ArcView Binary Grids *.flt (NAD 83 Nebraska State Plane (US foot).

Grid File Name	Description	Grid Cell Size (feet)
LLNRD_DEM_ft	Digital Elevation Model (ground surface elevation) (NAVD88 feet) of the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_WT_1995	Elevation (NAVD88 feet) of the water table (1995) for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Kp_Top	Elevation (NAVD88 feet) of the top of Cretaceous Pierre (Kp) for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Saturated_Thickness	Saturated thickness (feet) of Quaternary deposits for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Total_Thickness	Total thickness (feet) of Quaternary deposits for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_To_Top	Elevation (NAVD88 feet) of the top of Ogallala Formation (To) for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_To_Total_Thickness	Total thickness (feet) of To for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Aquifer_and_Coarse_Saturated_Thickness	Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Aquifer_and_Coarse_Total_Thickness	Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Aquifer_and_Coarse_Unsaturated_Thickness	Unsaturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Aquifer_Total_Thickness	Total thickness (feet) of aquifer Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Coarse_Saturated_Thickness	Saturated thickness (feet) of coarse aquifer Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100

LLNRD_Q_Coarse_Total_Thickness	Total thickness (feet) of coarse aquifer Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Coarse_Unsaturated_Thickness	Unsaturated thickness (feet) of coarse aquifer Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Non_and_Marginal_Saturated_Thickness	Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Non_and_Marginal_Total_Thickness	Total thickness (feet) of non-aquifer and marginal Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_Q_Non_and_Marginal_Unsaturated_Thickness	Unsaturated thickness (feet) of non-aquifer and marginal Quaternary material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_To_Aquifer_and_Coarse_Total_Thickness	Total thickness (feet) of To aquifer and coarse aquifer dominant material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_To_Aquifer_Total_Thickness	Total thickness (feet) of To aquifer dominant material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_To_Coarse_Total_Thickness	Total thickness (feet) of To coarse aquifer dominant material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
LLNRD_To_Non_and_Marginal_Total_Thickness	Total thickness (feet) of To non-aquifer and marginal dominant material for the LLNRD survey area, NAD83/State Plane Nebraska, feet	100
Unsat_Aqua_Coarse_50ft_thickness	Total thickness of Unsaturated Quaternary Aquifer and Coarse Material within the first 50 feet of the ground surface	100

Table 6-7. Channel name, description, and units for LLNRD_Voxel.xyz.

Parameter	Description	Unit
X	Easting NAD83, State Plane Nebraska	US Foot [ft]
Y	Northing NAD83, State Plane Nebraska	US Foot [ft]
Z	Elevation of Voxel Node	NAVD88 [ft]
Resistivity	Voxel cell resistivity value	Ohm-m

6.2 Description of Included Google Earth KMZ Data and Profiles

In addition to the data delivered in ".xyz" format, Google Earth KMZ files were generated to view the geophysical AEM flight line locations and interpreted geologic data. KMZ files for all "*As-Flown*" flight lines and data "*Retained*" for inversion after editing are included in the folder "*Appendix_3_Deliverables\KMZs\FlightLines*".

Unique KMZ 2D profile files were created for each individual flight line in approximately 10-mile segments (some shorter, some longer). Within these specialized KMZ files, the AEM flight line is shown as well as place marks at each location where there are interpreted geologic results. The attribute data for each unique place mark contains location information, the water table elevation, soil recharge material information, thicknesses of the Quaternary Aquifer and Coarse Aquifer materials, and ***To*** and ***Kp*** bedrock elevations. These KMZ files are located within the "*Appendix_3_Deliverables\KMZs\Interpretation* folder. Also, in the profile folder is a "*GoogleE_Readme.pdf*" file that provides instructions in regards to the "*Settings*" changes that need to be made in Google Earth, and how to use the KMZ files in Google Earth including a legend of what attributes are displayed when an AEM sounding location is clicked. An example of the LLNRD 2019 KMZ is presented in Figure 6-1.

6.2.1 ncluded README for the LLNRD Interpretation KMZ's

README for:

LLNRD2019_Interpretation.kmz

Data Files - Please copy the folder *LLNRD19_Profiles* to your C:\ drive. Do not rename any of the images within the folder.

Google Earth Instructions:

STEP 1: In Google Earth, click "*Tools*", then "*Options*".

STEP 2: In the Google Earth Options box, click the "*General*" tab.

STEP 3: Under "*Placemark balloons*", make sure the box is checked to allow access to local files (the profiles).

STEP 4: Under "*Display*", make sure the box is checked to show web results in external browser.

STEP 5: The 2018 Interpretation kmz files within the folder named *LLNRD19_Profiles* can now be opened and viewed in Google Earth.

Data:

East (m) – Easting coordinate in NAD83, UTM 14N, in meters

North (m) – Northing coordinate in NAD83, UTM 14N, in meters

East (ft) – Easting coordinate in NAD83, Nebraska State Plane, in feet

North (ft) – Northing coordinate in NAD83, Nebraska State Plane, in feet

Elevation (ft) – Digital Elevation Model (DEM) elevation in feet

Soil Recharge Material – Aquifer material on the Surface: 1=Non-Aquifer Material; 2=Marginal Aquifer Material; 3=Aquifer Material; 4=Coarse Aquifer Material.

WaterTable1995 – 1995 Water Table elevation, in feet

Total Thickness Aq CAq Material (ft) – Sum of the thicknesses of Aquifer Material and Coarse Aquifer Material at the sounding location.

Total Thickness NonAq Material (ft) – Sum of thicknesses of Non-Aquifer Material at the sounding location.

Elevation To (ft) – Elevation of the Tertiary Ogallala Formation, in feet.

Elevation Cretaceous Bedrock (ft) – Elevation of the Cretaceous Bedrock surface, in feet

Elevation Kp (ft) – Elevation of Cretaceous Pierre Shale Formation, in feet.

Profile – Link to Interpreted AEM profile images.

Legend – Link to this write-up describing data channels listed here.

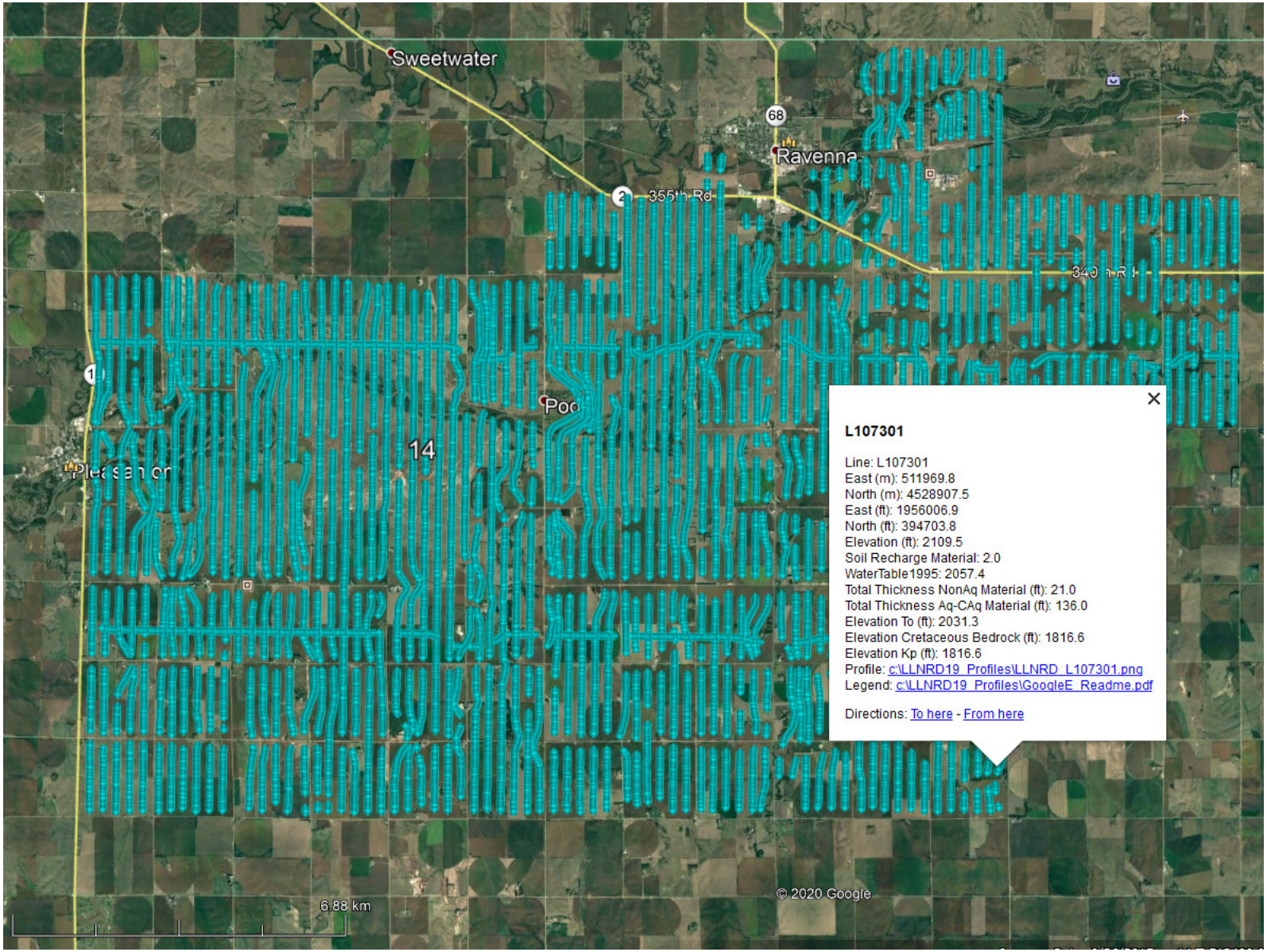


Figure 6-1. Example Google Earth image for the LLNRD Interpretation kmz.

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