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"Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Lower Elkhorn Natural Resources District, *Revision 1*

Prepared for the:

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Summary of Updates in *Revision 1, dated January 18, 2019,* to the *"Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Lower Elkhorn Natural Resources District*

1) LENRD 2018 and Pierce County Block KMZ's in Appendix 3 have been updated to include, if present, three (3) layers of aquifer materials and two (2) layers of coarse aquifer materials as well as including the elevations of the water table (circa 1995) and the ***To***, Bedrock, ***Kp***, ***Kn***, ***Kc***, ***Kgg***, ***Kd***, and ***IP***.

2) The LENRD 2018 AEM Interpretative KMZs in Appendix 3 have been subdivided into eight (8) smaller KMZ's covering different sub-areas within the LENRD 2018 acquisition area not including the Pierce County combined data block area. This is due to issues with Google Earth that have been noted when attempting to load a single KMZ for the entire LENRD 2018 AEM survey area. These issues are due to the amount of data locations within the LENRD 2018 AEM survey and the number of interpretative details included at each AEM sounding location. A new image (Figure 4-1) has been added to the Google Earth Readme presenting the regions covered by the KMZ sub-areas.

3) New xyz interpretative data files have been created for both the LENRD 2018 survey area and the combined Pierce County Block that contain the same details as in the LENRD 2018 and Pierce County Block KMZ's. These files are in Appendix 3/ProcessedData/Interpretation.

4) A new xyz SCI inversion result data file has been created listing the line number, the easting, northing, elevation, and depths and elevations of the top, middle, and bottom of each SCI inversion model cell. Also included is the individual SCI-inverted AEM resistivity value for each cell. This file is also in Appendix 3/ProcessedData/Interpretation.

Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled *"Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Lower Elkhorn Natural Resources District*.

An understanding of the hydrogeological framework in the survey area is desired to assist in resource management. AGF entered into an agreement with the Lower Elkhorn Natural Resources District (LENRD) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the LENRD 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 An AEM survey utilizing the SkyTEM304M system was flown over the LENRD project area. These flights have been provided as preliminary AEM inversions and the final AEM data and inversions are included as a product attached to this data report.

1.2 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 LENRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies.

Upon conclusion of the design process the LENRD reconnaissance flight lines were approximately 77 miles in length at their longest in the east-west direction and about 43 miles at their longest in the north-south direction and were separated by approximately 2.5 - 3 miles in both east-west and north-south directions. The Pierce County Block were about 20 miles long west to east with a separation of about .4 miles (625 m).

1.4 AGF acquired AEM data over the LENRD, commencing 6 July 2018 and finishing on 20 July 2018, to support development of the hydrogeological framework. Approximately 1,694.9 line-miles (2,745.7 line-kilometers) were acquired over the LENRD AEM survey area. Status reports of the flying were provided to the Contract Representative of LENRD daily, including the areas flown, production rates, and flight plan for the following day.

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 July 7-21, 2018. Approximately 1,323-line-miles (2,143.3-line kilometers) were retained for inversion amounting to a retention rate of 78.1%. This high rate is the result of careful flight line planning and design.

1.6 AGF inverted the AEM data. These final inverted georeferenced data are delivered to the LENRD 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, and

maps of estimated potential recharge 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 and was important for several areas in the LENRD that had limited or no contrast in the electrical resistivity between the different geologic formations. The dependence on just boreholes for geologic interpretation also has its limitations because sometimes the boreholes are wrong, improperly located, have improper stratigraphic/lithology picks, and/or other errors. These errors in the boreholes are usually encountered in the NE-DNR registered wells. Very rarely inconsistencies are encountered in the oldest of the CSD wells. The limited errors in the CSD wells may very well be due to poor positioning from a time before GPS and modern survey methods. The use of boreholes with AEM needs to be approached in a thoughtful professional manner. In areas of obvious electrical resistivity units (i.e. ***Kp*** and ***Kc***) the AEM can easily flag errors.

2.2 **Digitizing Interpreted Geological Contacts** - Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Cretaceous Pierre Shale (***Kp***), Niobrara Formation (***Kn***), Carlile Shale (***Kc***), Greenhorn Limestone and Graneros Shale (***Kgg***), Dakota Group (***Kd***) undifferentiated Pennsylvanian (***IP***). 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. Because this is the last part of the 5-year regional AEM survey acquisition, it has become apparent that there needs to be integration work done to bring all the years together in one package using the same parameters such as projection, nomenclature, and stratigraphic divisions.

2.3 **Resistivity/Lithology Relationship** - Assessment of the sediment character in both the Quaternary/Tertiary Ogallala aquifer system and the bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A numerically robust assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-20 ohm-m), and aquifer (20-50 ohm-m), including coarse sand-rich intervals (>50 ohm-m) was determined. This allowed for the characterization of the ranges of resistivities present in the major geologic units described in this report. The ***Kd*** was also subdivided into a sand/sandstone and a clay/shale-dominant zones.

2.4 **Hydrogeological Framework of the LENRD** - The 2018 LENRD AEM survey reveals variability in the Quaternary (***Q***) deposits across the LENRD AEM survey area. When combined with the ***To***, they represent the aquifer materials in the AEM survey area, where saturated. The ***To*** is generally thick in the west and is thin to absent in the eastern regions of the AEM survey area. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units. In the eastern and southern parts of the AEM survey area, the aquifer materials are predominantly marginal to non-aquifer materials which are glacial till and loess and which can be more than 200 feet thick. ***Q*** sediments found predominately on the west side are often associated with

prevalent alluvial and coarse aquifer material deposits. The ***Q*** and ***To*** materials (where present) are sitting on the ***Kp***, ***Kn***, ***Kc***, ***Kgg,*** and ***Kd*** which may or may not be the bedrock aquicludes for the area as there are some areas of the ***Kn*** and ***Kd*** that provide local aquifers. The regional framework is complete with the 2018 survey and can be used to identify geographic area within the LENRD for different types of groundwater management. Additional block flights may be useful to better characterize certain areas for which estimates of aquifer storage and extractable yield may later be deemed to be required, as discussed next.

2.5 Potential Recharge Zones within the LENRD AEM Survey Area - The use of block flights in Pierce County illustrates the preferred method to use AEM to identify areas where the potential for recharge to the aquifer can be high and low. Locations where the flight lines are closely spaced show either aquifer or coarse aquifer material at the land surface should be considered as locations for higher likelihood for recharge because of the 2D and 3D spatial nature of the aquifer material distribution. The opposite is also true where AEM data analysis shows non-aquifer or marginal aquifer material; Those areas will likely not be optimal recharge locations Figure xx. The area throughout Pierce Block has potential recharge that is widespread and is a likely location for MAR and ASR activity. The groundwater in storage and potential yield from the aquifer has been calculated for the Pierce Block area. It supports the determination that high rates of recharge are available. It also shows the importance of this area to irrigation and water supply within the LENRD. Areas with aquifer and coarse aquifer materials at the surface can also become conduits for infiltration of nitrates into the groundwater system. A potential solution to this problem is adding additional fresh surface water as recharge to select areas of rangeland that can dilute any potential nitrate contaminant problem. Additional work can be done to identify where the best locations are for these type of management efforts.

3. RECOMMENDATIONS

Recommendations provided to the LENRD 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 LENRD about their management challenges.

3.1 **Integration of 2007-2018 AEM Hydrogeological Investigations** - The LENRD has acquired AEM data from 2007 to 2018 with three different AEM systems and contractors performing the work including the USGS, XRI Geophysics, and AGF with oversight from the LENRD and the ENWRA. Priorities have evolved from finite projects like Oakland, City of Madison, Clarkson, and the Pierce Block to the large-scale reconnaissance investigations of the LENRD and ENWRA. With the completion of this current study, being the last part of a 5-year regional AEM survey acquisition program, it has become apparent that there needs to be additional work done to bring all the work from all the years together in one package using the same parameters such as geographic projection (NAD83 UTM Zone 14N (meters), NAD83 Zone 14N (feet), and NAD83 Sate Plane Nebraska (feet) have been used over the past 10-years), hydrologic nomenclature, and stratigraphic divisions. Recent communication with LENRD and their consultants has also brought to light that additional effort is needed to quantify the NE-DNR boreholes relationship to the aquifer materials that the AEM has mapped. Specifically, it was found that the 2015 interpretations of the ***Kn*** need to be modified with additional input from the NE-DNR wells to increase the overall elevation of the ***Kn*** under the ***To*** and ***Q*** deposits due to the lack of resistivity contrast. In addition, there apparently exists confusion on the use of “principal aquifer material” versus “aquifer material “ versus “Principal Aquifer” as determined by NE-DNR. While these are

apparently minor additions and changes, they can add to the overall usability and portability of the AEM analysis results within the LENRD.

3.2 **Additional AEM Mapping** - The hydrogeologic maps provided in this report represent the completed the hydrogeologic framework developed for the LENRD at an approximate 3-mile spacing of flight line reconnaissance level. Beginning in 2014, the District has been collecting AEM data at approximately 3-mile grid spacing, as financial resources have allowed per their yearly plan. The interpretations match well with the CSD and NE-DNR test holes. At this point the LENRD need only select local block flights for detailed information when required using this framework map to support groundwater models, rural water supply well locations, water quality monitoring wells, areas for further irrigation development or selecting MAR or ASR locations.

3.3 **Update the Water Table map** - The groundwater data used in the analyses presented in this report utilized the 1995 CSD water table map which is now 24 years old (Nebraska CSD, 1995). Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. This is especially true on the west side of LENRD in Pierce and Madison counties. The areas of glacial till and loess covering the eastern side of the district will need great care in developing a water level map of potentiometric heads due to the confined to semiconfined nature of the area.

3.4 **Siting new test holes and production wells** – The AEM hydrogeological framework profiles, maps, and surfaces provided in this report provide great insight in 3D on the relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the LENRD 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 more 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. A good example of this would be confined aquifers with large volumes of coarse aquifer and aquifer material. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the LENRD.

3.5 **Aquifer testing and borehole logging** - Aquifer tests are recommended to improve estimates of aquifer characteristics. Limited aquifer properties from previous reports were available outside the larger cities in the survey area. 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 could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailing aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR) at a reduced cost when compared to traditional aquifer tests. 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.

3.6 **Recharge Zones** - The LENRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer in Pierce Block. Reconnaissance level AEM investigations provide limited detailed information between the lines for understanding recharge throughout the survey area. It is recommended that additional AEM data be collected and interpreted similar to the Pierce Block which utilized closely-spaced flight lines using an AEM system that has good near-surface resolution in areas identified by the LENRD that are of priority importance for management purposes. It is further recommended that future work integrate new soils and land use 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. A potential solution to water quality, quantity, and stream depletions is adding additional fresh surface water as recharge to select areas of rangeland or other areas. Additional work can be done to identify where the best locations are for these type of management efforts.

3.7 Managed Aquifer Recharge – The areas which may have potential for managed aquifer recharge (MAR) can be approximately located by the interpreted results from AEM reconnaissance line interpretations. Detailed analysis for this purpose would need to be done to determine where viable opportunities for the LENRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping in new block flight locations and along the streams in the LENRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the LENRD for storage and release of water for stream flow and other uses.

4. DELIVERABLES

In summary, the following are included as deliverables:

- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz
- Interpretations as ASCII *.xyz
- Raw Data Files - SkyTEM files *.gex, *skb, *.lin
- ESRI ArcView grid files – surface, topo, *.flt, *.grd, etc
- Voxel Grid of the Pierce Block ***Q*** and ***To*** *.csv
- 2D Profiles and 3D fence diagrams of the AEM survey lines

Google Earth KMZs for LENRD AEM 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
ASR	Aquifer Storage and Recovery
dB/dt	Change in amplitude of magnetic field with time
BMP	Best management plan
CSD	Conservation and Survey Division
DEM	Digital Elevation Model
DOI	Depth of Investigation
DGPS	Differential global positioning system
em, EM	Electromagnetic
ENWRA	Eastern Nebraska Water Resources Assessment
FT	Fourier Transform
ft	Feet
ft^3	cubic feet
Fm	Formation
GIS	Geographic Information System
HEM	Helicopter Electromagnetic
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
IP	Undifferentiated Pennsylvanian units
Km/km	Kilometers
KMZ/kmz	Keyhole Markup language Zipped file
Kc	Cretaceous Carlile Shale
Kd	Cretaceous Dakota Group
Kgg	Cretaceous Greenhorn Limestone and Graneros Shale
Kn	Cretaceous Niobrara Formation
Kp	Cretaceous Pierre Shale
LENRD	Lower Elkhorn Natural Resources District
LCI	Laterally-constrained Inversions
MAG	Magnetic (data); Magnetometer (instrument)
MCG	Minimum curvature gridding
m	Meters
mi^2	Miles squared
NAD83	North American Datum of 1983
MAR	Managed Aquifer Recharge
NAVD88	North American Vertical Datum of 1988
NE	Nebraska
NED	National Elevation Dataset
NE-DNR	Nebraska Department of Natural Resources
NMR	Nuclear Magnetic Resonance
NOGCC	Nebraska Oil and Gas Conservation Commission
NRD	Natural Resources Districts
NWIS	National Water Information System

OM	Geosoft Oasis montaj
PFC	Primary Field Compensation
PLNI	Power Line Noise Intensity
Q	Quaternary
Rx	Receiver
recon	Reconnaissance
SCI	Spatially-Constrained Inversion
STD	Standard Deviation
To	Tertiary Ogallala Group
TEM	Transient Electromagnetic
TDEM	Time-Domain Electromagnetic
Tx	Transmitter
UNL	University of Nebraska Lincoln
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
V/m^2	Volts per meter squared
XRI	Exploration Resources International

1 Introduction

1.1 Purpose of Current Project

Sound management of groundwater and surface water in eastern 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 the persistent threat of drought.

The combination of these stresses on water resources has increased the need for detailed hydrogeologic frameworks of the subsurface. Groundwater management strategies and policies implemented to address water quality concerns is another effort that can be improved with 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. 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. This is best accomplished by block flights similar to Pierce County. Additional uses of this survey will be to determine potential areas of Managed Aquifer Recharge (MAR) for addition to current supplies of groundwater in areas if need to replace depletions from development or supply future development. This data can be used to enhance the hydrogeologic framework for groundwater modeling for testing management scenarios at a regional level where boreholes are not sufficient or are of limited use. Where AEM block flights exist, this dense flight line data would be excellent for local groundwater models by having high resolution framework to build the model.

To ensure that demands for both new and existing uses of water are met, additional subsurface information that is directly measured in high definition mapping the aquifer systems of the groundwater resource is necessary for refining management plans. LENRD is mostly covered by glacial deposits that are the most complicated hydrogeologic environment to understand without detailed data. Therefore, beginning in 2014, the District has been collecting AEM data at approximately 3-mile grid spacing (Carney et al., 2015a), as financial resources have allowed. In 2018 the Lower Elkhorn Natural Resources District's (LENRD) commitment to completing the regional framework as part of a 5-year plan across the entire District has completed that task. The LENRD has pursued this mapping effort since the original pilot project at Oakland in 2007. By completing this effort, the LENRD has direct measurements mapping the significant geologic variability which will complements the existing hydrogeologic data set. This report is for the portion of this regional scale framework that was collected in 2018.

This report describes the general hydrogeologic conditions, assessed using data collected from this AEM survey. In addition to the AEM data, reports from previous studies, analysis of historic groundwater levels, and geologic descriptions from University of Nebraska-Lincoln Conservation and Survey Division (CSD) test holes, Nebraska Oil and Gas Conservation Commission (NEOGCC), and drillers logs obtained from registered wells at the Nebraska Department of Natural Resources (NE-DNR) were used. The AEM

survey data were collected along reconnaissance (recon) lines spaced approximately 3 miles (Figure 1-1). This AEM survey was planned and selected by LENRD and AGF with assistance from scientists from CSD to assist in the development of a 3D hydrogeologic framework of these project areas and recommend future work to enhance groundwater management activities. This work was supported by the Natural Resources Commission Water Sustainability Fund, LENRD and in-kind service from CSD.

A location map showing the LENRD survey flight areas and flight lines is presented in Figure 1-1. .A Google Earth KMZ (kmz) of the "As-Flown" flight lines are included in Figure 1-2 and in Appendix 3_Deliverables\KMZ\FlightLines.

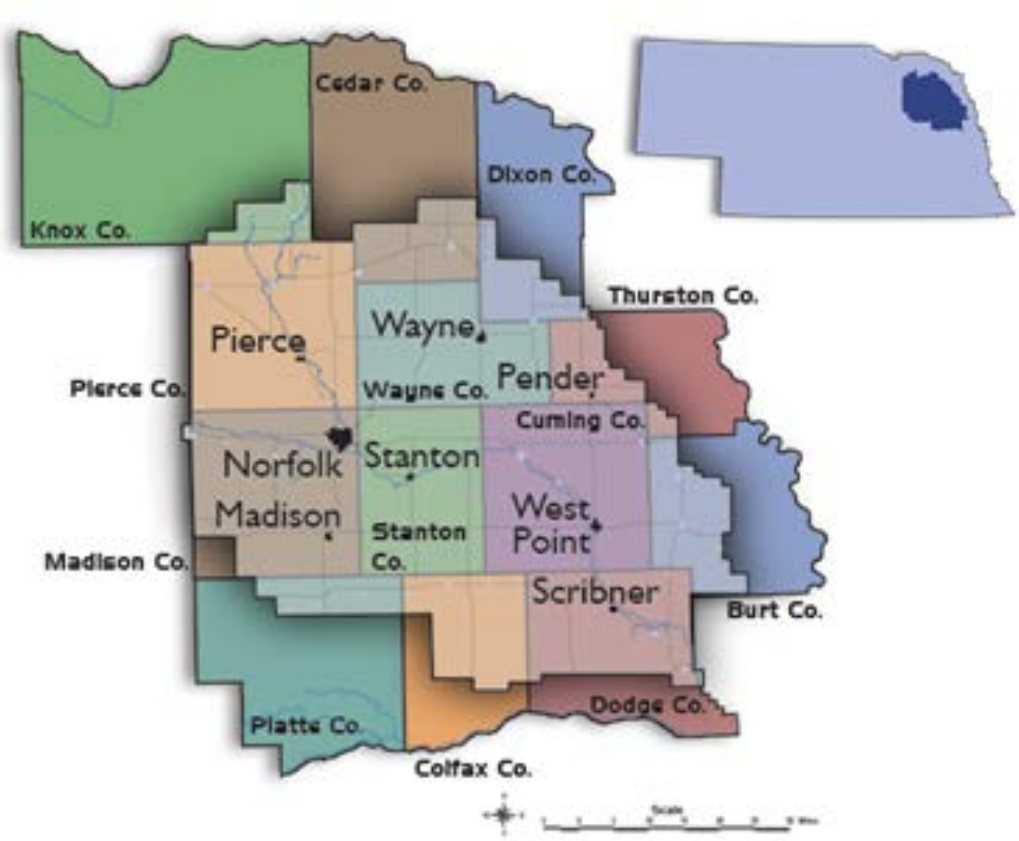


Figure 1-1. Map of Nebraska counties, indicating the location of the Lower Elkhorn Natural Resources District (LENRD) airborne electromagnetic (AEM) survey with an inset of the project area (modified from LENRD website).

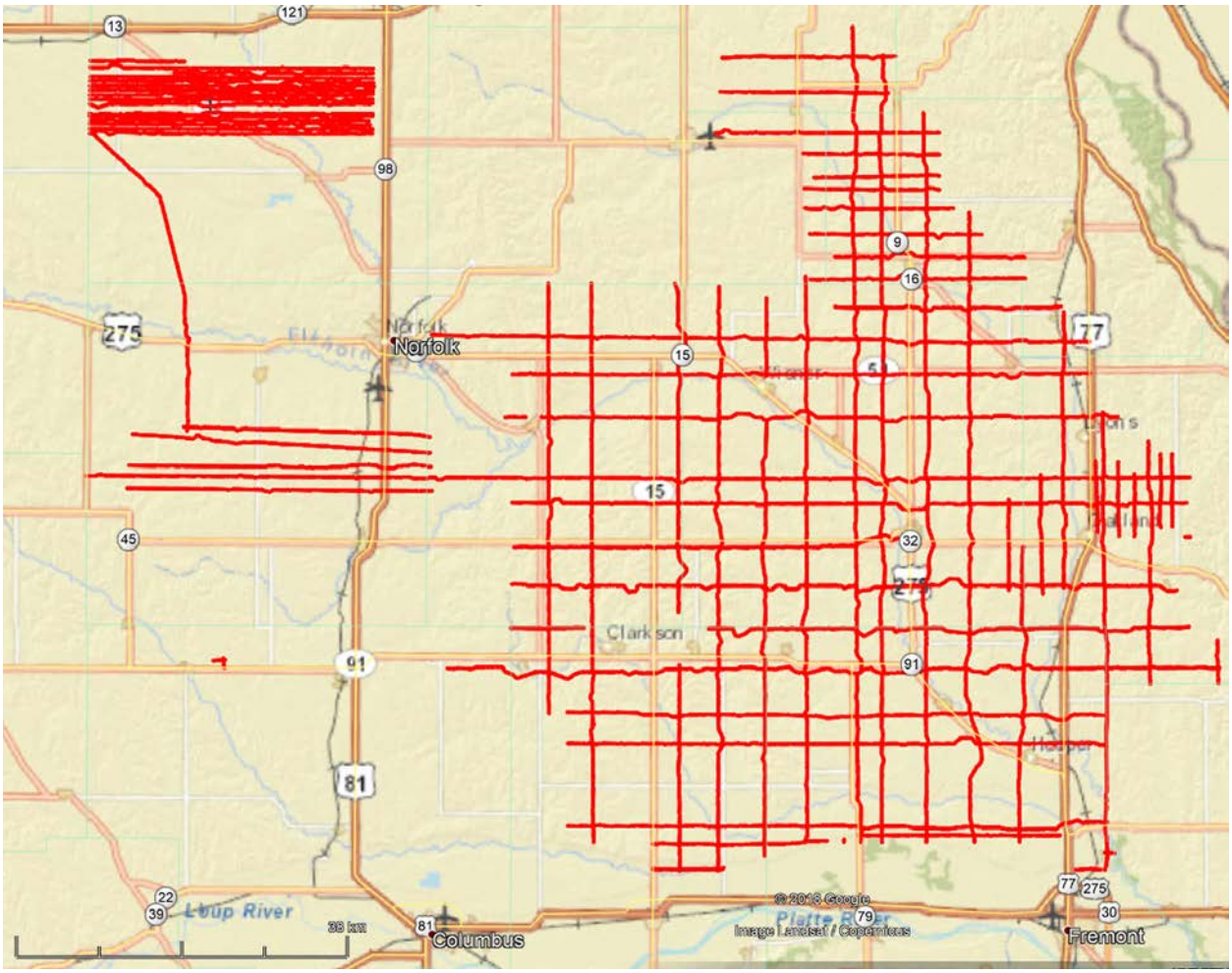


Figure 1-2. The LENRD 2018 AEM survey area including county lines and major roads.

1.2 Background

In January of 1997, with the approval of the LENRD Groundwater Management Plan, the LENRD established a districtwide Groundwater Management Area, which contained information and trigger levels for purposes of managing groundwater quality and quantity. The initial Groundwater Management Plan established different Phases (or Action) Levels: Phase 1, Phase 2 and Phase 3, each containing elevated levels of requirements to address a specific level of groundwater condition. The Groundwater Management Plan has subsequently undergone some additions or revisions, most recently to require the installation of flow meters on all high capacity wells (regardless of use) in the District, and to modify and include a set of controls for a Phase 4 Area, which (if implemented) contains an ambitious set of action items meant to remediate acute groundwater contamination issues

The District continues to monitor groundwater quality and quantity by collecting groundwater data each year at new and repeat locations. The conclusions from these studies indicated that groundwater aquifers continue to be contaminated to varying degrees with nitrate/nitrogen and that the causes were

likely related to nonpoint source contamination due to leaching of nutrient applications, both from organic and inorganic sources, and irrigation practices.

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 Eastern Nebraska Water Resources Assessment (ENWRA) has coordinated efforts between 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, LENRD, ENWRA, and CSD are cooperating with AGF because of the shared aquifer boundaries and similar groundwater management efforts between these NRDs.

1.3 Description of the LENRD 2018 AEM Project Area

The LENRD spans approximately 4,050 square miles (mi^2) in northeast Nebraska. The elevation of the area ranges from 835 ft to 2235 ft above sea level**.** It is underlain by parts of six of Nebraska's eight topographic regions— Bluffs and Escarpments, Dissected Plains, Plains, Rolling Hills, Sand Hills and Valleys (Elder et al., 1951). This area stretches from the rolling, loess-mantled, glacially-derived landscape (Gosselin et al., 1996) on the east to the Holocene, sand-covered, non-glaciated areas on the west.

Principal cities within the project area, based on 2010 population estimates, include (largest to smallest) Norfolk (24,210), Wayne (5,660), Madison (2,438), Oakland (1,183), Pierce (1,767), Stanton (1,577), West Point (3,340) and Wisner (1,170) (U.S. Census Bureau, 2013).

2 Geophysical Methodology, Acquisition and Processing

2.1 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 2-1 gives a conceptual illustration of the airborne TEM method.

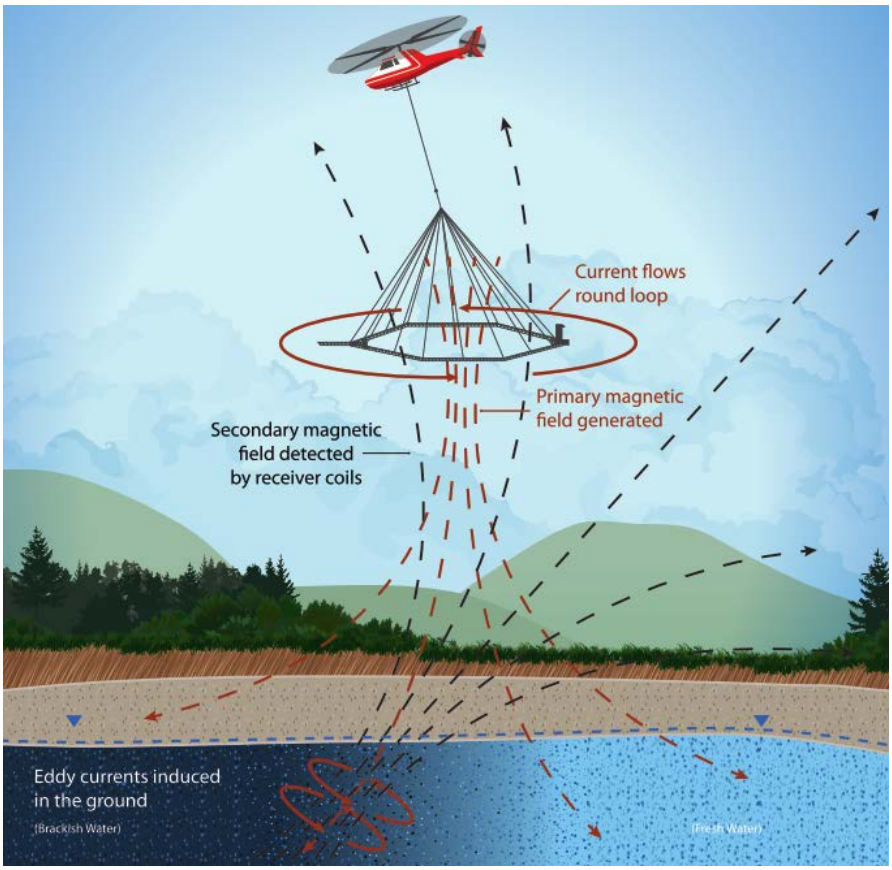
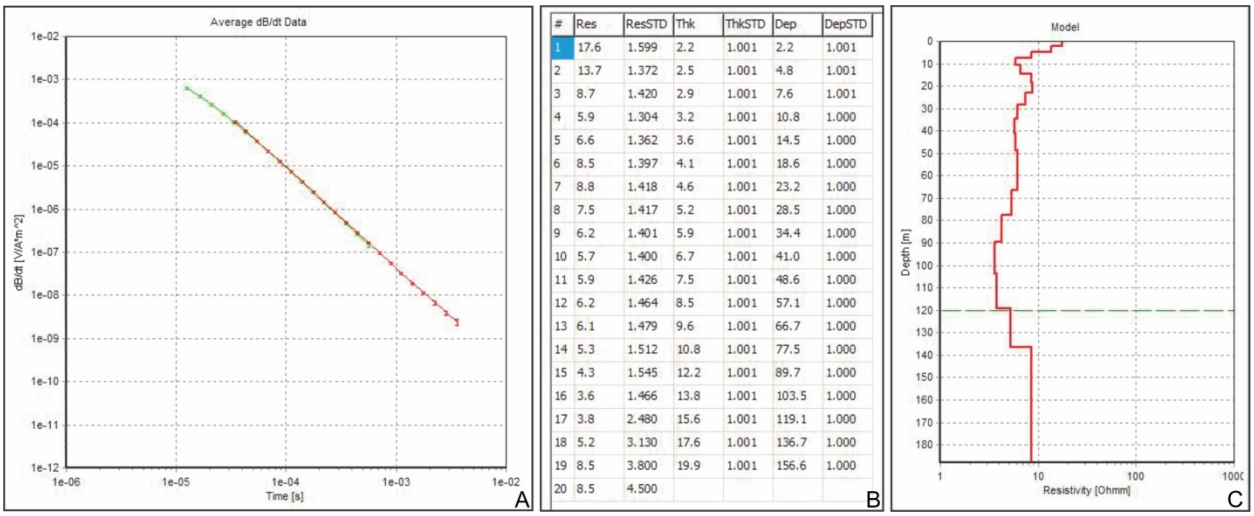


Figure 2-1: Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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

2.2 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 LENRD, three types of utilities (pipelines, railroads, and power lines) were located. Various public power districts in Eastern Nebraska provided 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.

Public power entities that provided power line location data to ENWRA included: Auburn Board of Public Works, Burt County Power District, Butler County Power District, Cedar-Knox Power District, City of Freemont, Cornhusker Public Power District, Cuming County Power District, Elkhorn Rural Public Power District, Lincoln Electric Systems, Loup Power District, Nebraska Public Power District, Nemaha-Marshall Electric Cooperative, Norris Public Power District, North Central Public Power District, Northeast Nebraska Public Power District, Omaha Public Power District, Polk County Rural Public Power District, Seward County Public Power District, and the Stanton County Public Power District.

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, 2014) and a shapefile of the

pipelines in Nebraska was provided by the ENWRA group. Maps of the three 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 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 the LENRD reconnaissance flight lines were approximately 77 miles in length at their longest in the east-west direction and about 43 miles at their longest in the north-south direction and were separated by approximately 2.5 - 3 miles in both east-west and north-south directions (Figure 1-2 and Figure 2-5). The Pierce County Block were about 20 miles long west to east with a separation of about .4 miles (625 m).

2.3 AEM Survey Instrumentation

AEM data were acquired using the SkyTEM304M (304M) airborne electromagnetic system (SkyTem Airborne Surveys Worldwide, 2018). 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 about 110 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 2-3 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 2-1 lists the positions of the instruments (in feet) and Table 2-2 lists the corners of the transmitter loop in feet (whereas units of meters are presented in Figure 2-3).

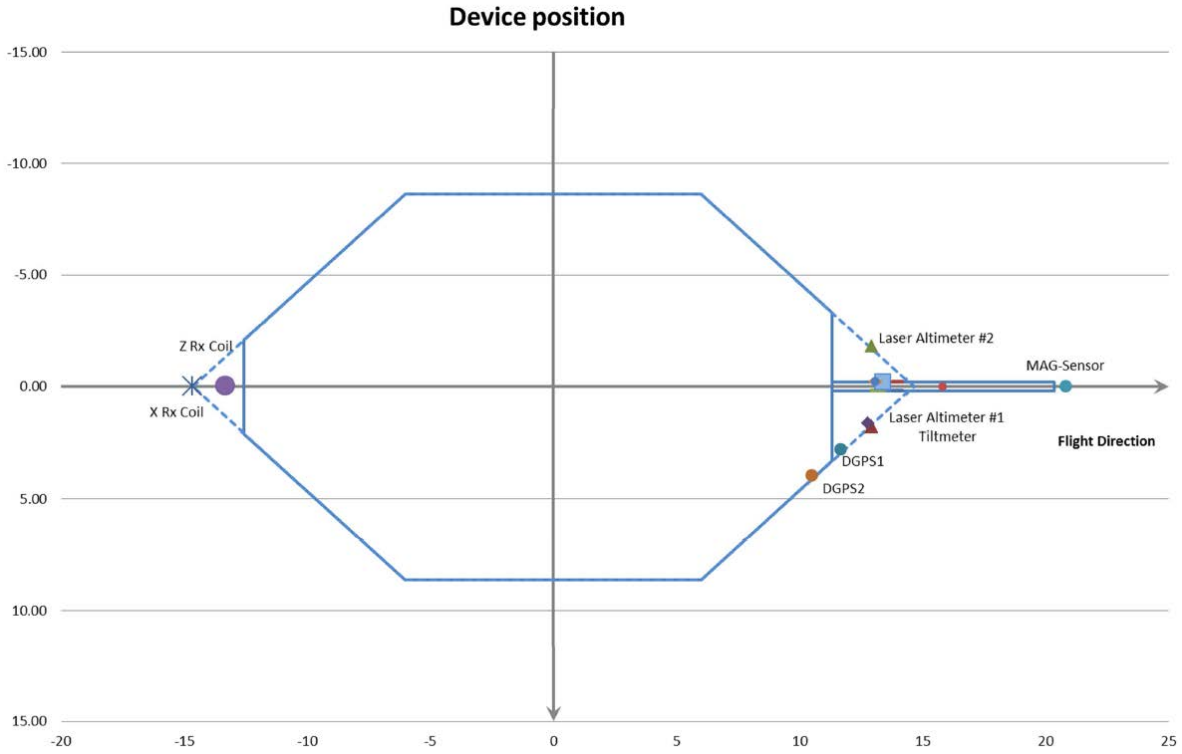


Figure 2-3: SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 2-1.



Figure 2-4: Photos of the SkyTEM304M system in suspension beneath the helicopter.

For this project, the 304M was flown at an average speed of 62 mi/hr (100.5 kilometers/hr) at an average flight height of 36.4 m above land surface, using the sling-load cargo system of a Eurocopter AS350 helicopter. Figure 2-4 displays a couple of images of the 304M in operation.

Table 2-1: 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	38.31	34.47	41.95	41.95	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 2-2: 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	-41.16	-19.78	18.83	37.19	39.19	18.83	-19.78	-41.16
Y	-6.89	-27.98	-28.18	-10.85	10.85	28.18	27.98	6.89

2.4 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 these surveys, installation of the navigational instruments in the helicopter and assembly of the SkyTEM304M system commenced at the beginning of the ENWRA project. The helicopter and the SkyTEM304M system were initially located at the Nebraska City, Nebraska 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 1,695 line-miles (2,745.7 line-kilometers) were acquired over the LENRD AEM survey area between July 6 and July 20, 2018. The Columbus, Norfolk, David City, Creighton, Hartington, and Wayne airports were used for landing and refueling between production flights. A data acquisition map is presented in Figure 2-5 with the flight lines grouped by acquisition date.

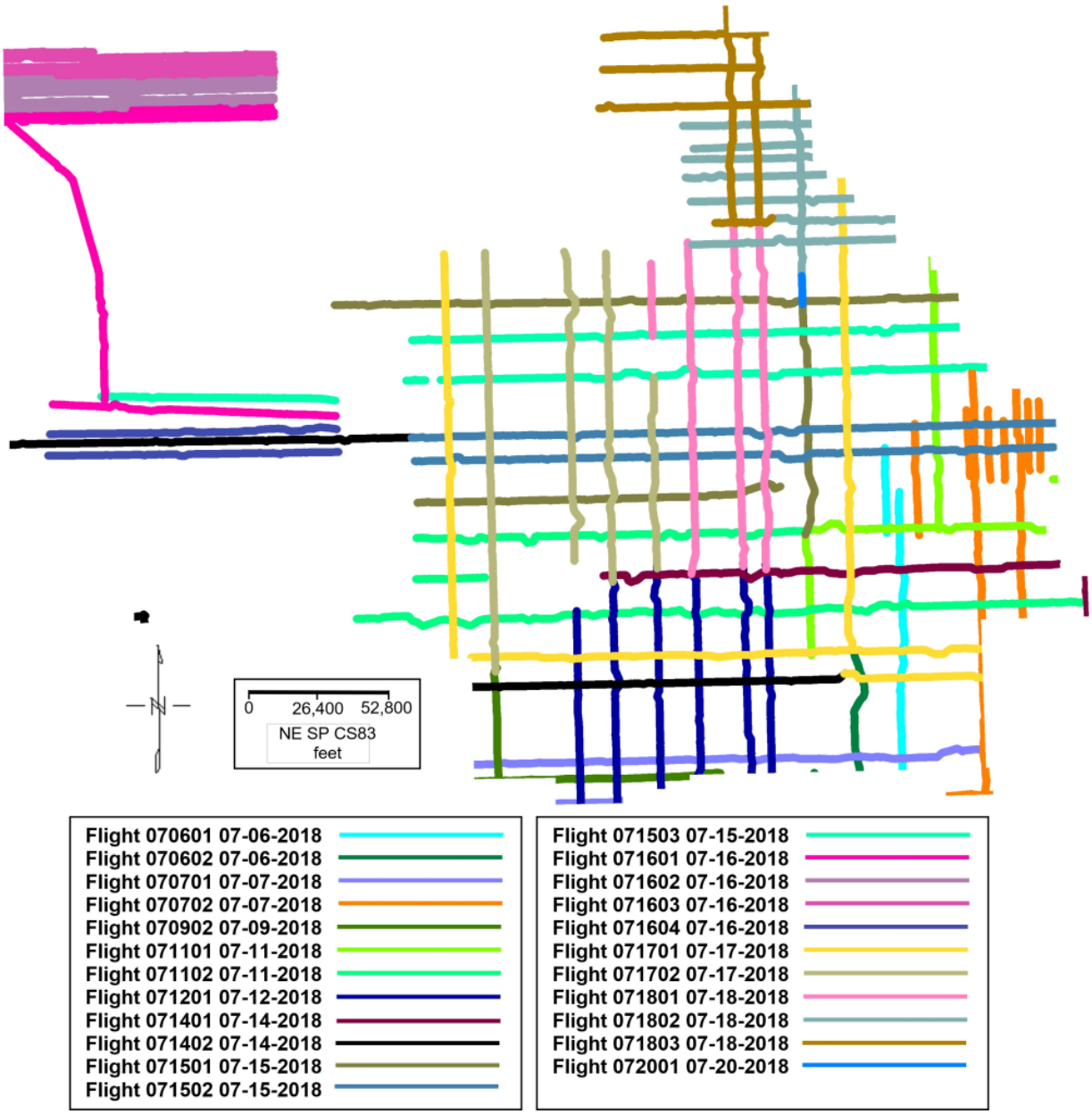


Figure 2-5: LENRD 2018 AEM flight lines grouped by acquisition date.

2.4.1 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.

2.4.2 Automatic Processing

The AEM data collected by the 304M were processed using Aarhus Workbench version 5.8.3.0 (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 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 twelve (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 20 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

2.4.3 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 2-6 and Figure 2-7, respectively. Examples of two inversions, one without EM coupling and the other with EM coupling, are shown in Figure 2-8. 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 major rivers and streams due to the tall cottonwood trees.

The AEM data were then inverted using a Laterally-Constrained Inversion (LCI) algorithm (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, 1,323 line-miles (2,143.3 line-km) of data were retained for the final inversions for the LENRD 2018 AEM reconnaissance survey. This amounts to a data retention of 78%. This high rate is the result of careful flight line planning and design.

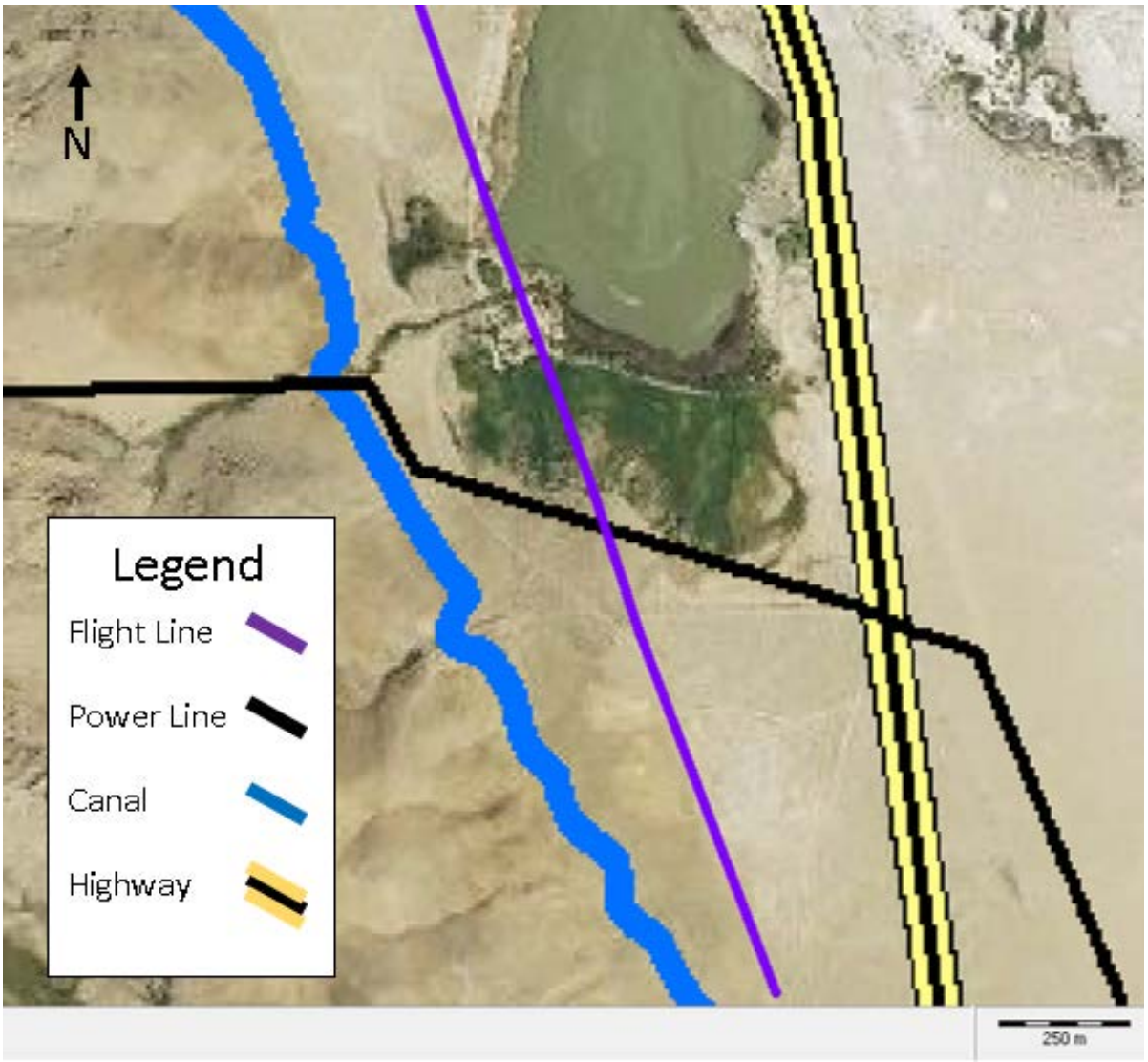


Figure 2-6: Example locations of electromagnetic coupling with pipelines or power lines.

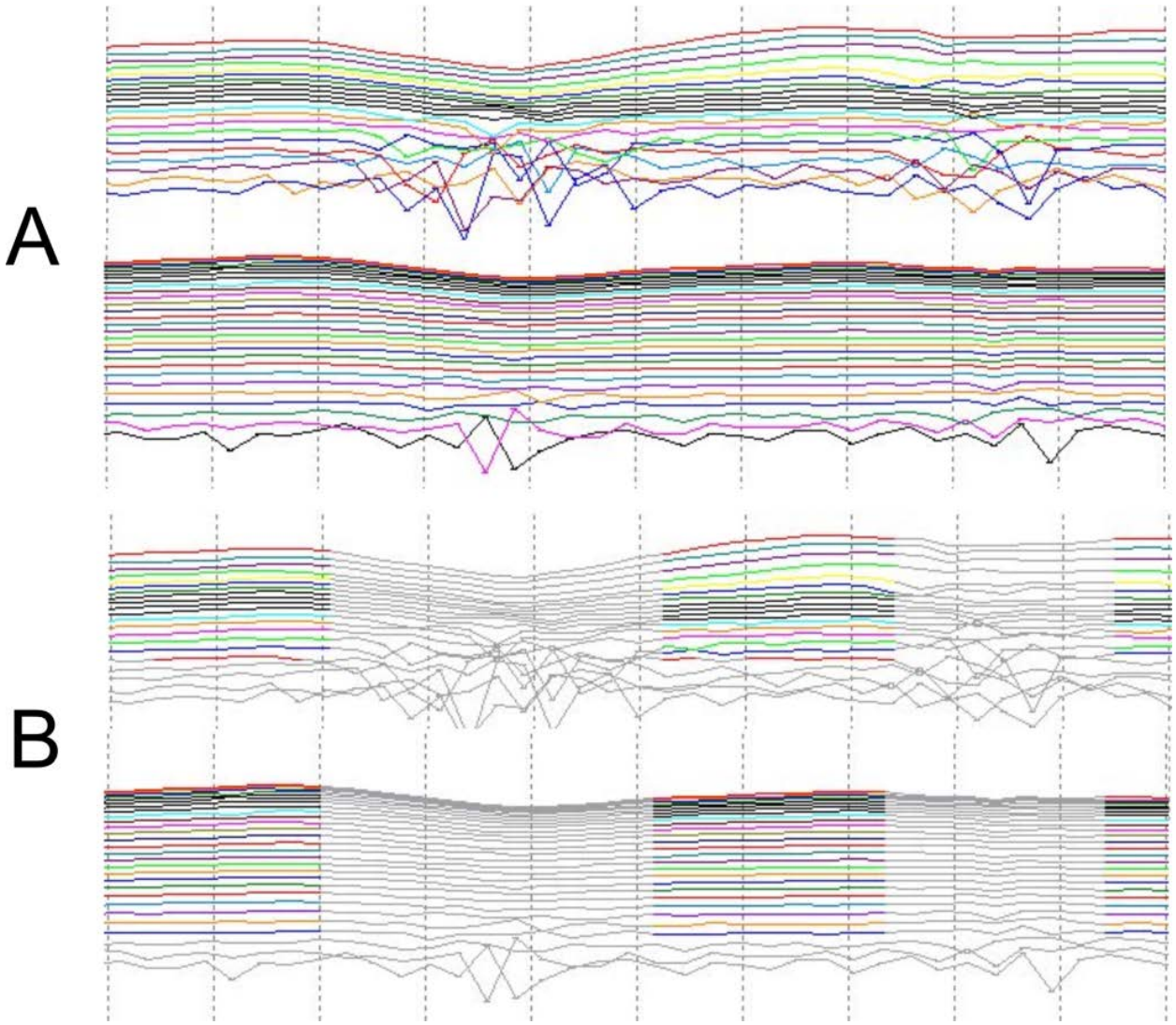


Figure 2-7: A) Example of AEM data from the LENRD AEM survey affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

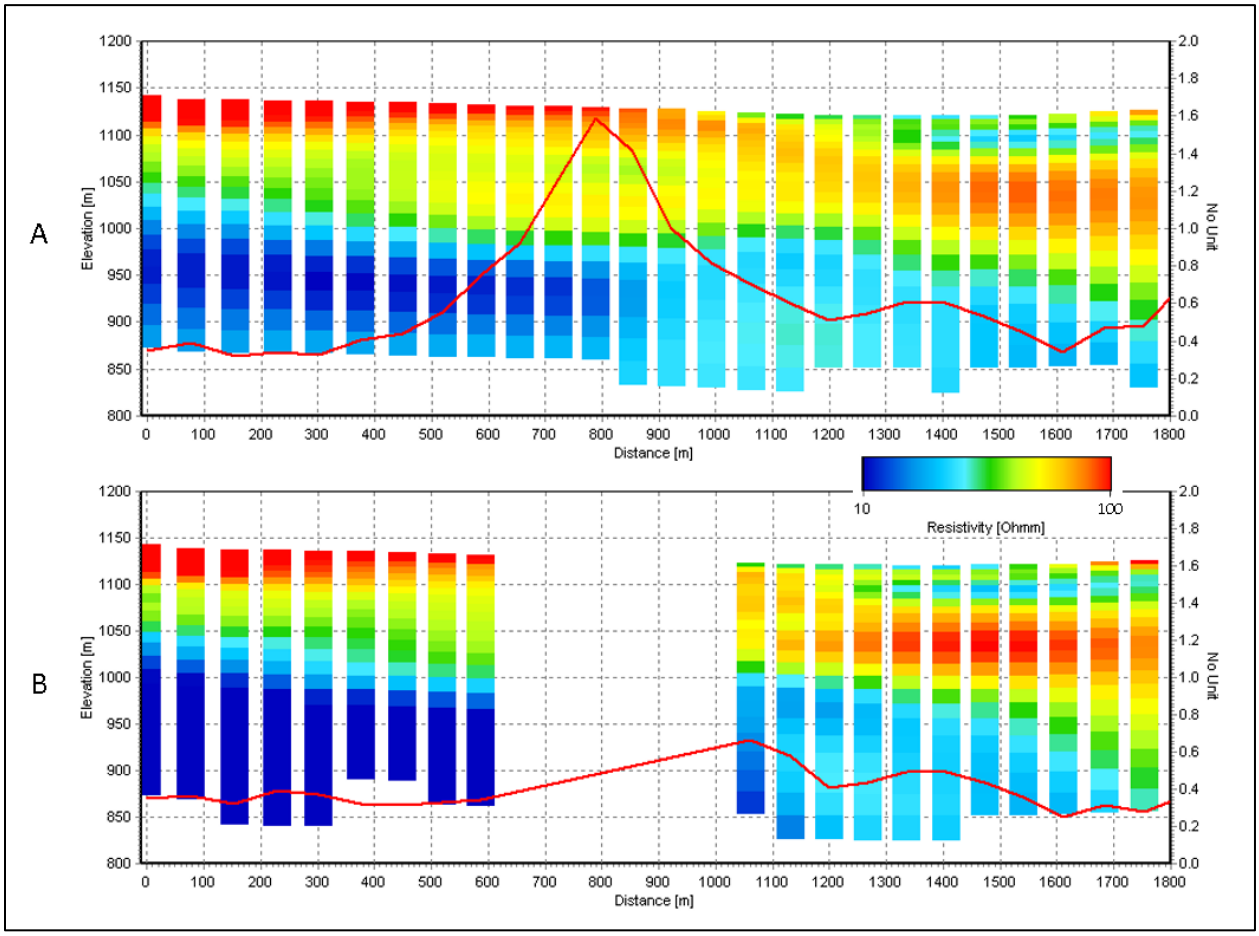


Figure 2-8: A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

2.4.4 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 LENRD 2018 AEM survey are presented in Figure 2-9. The LENRD-flight lines with blue colors representing data retained for inversion and red lines representing data removed due to infrastructure and late time noise are presented in Figure 2-10.

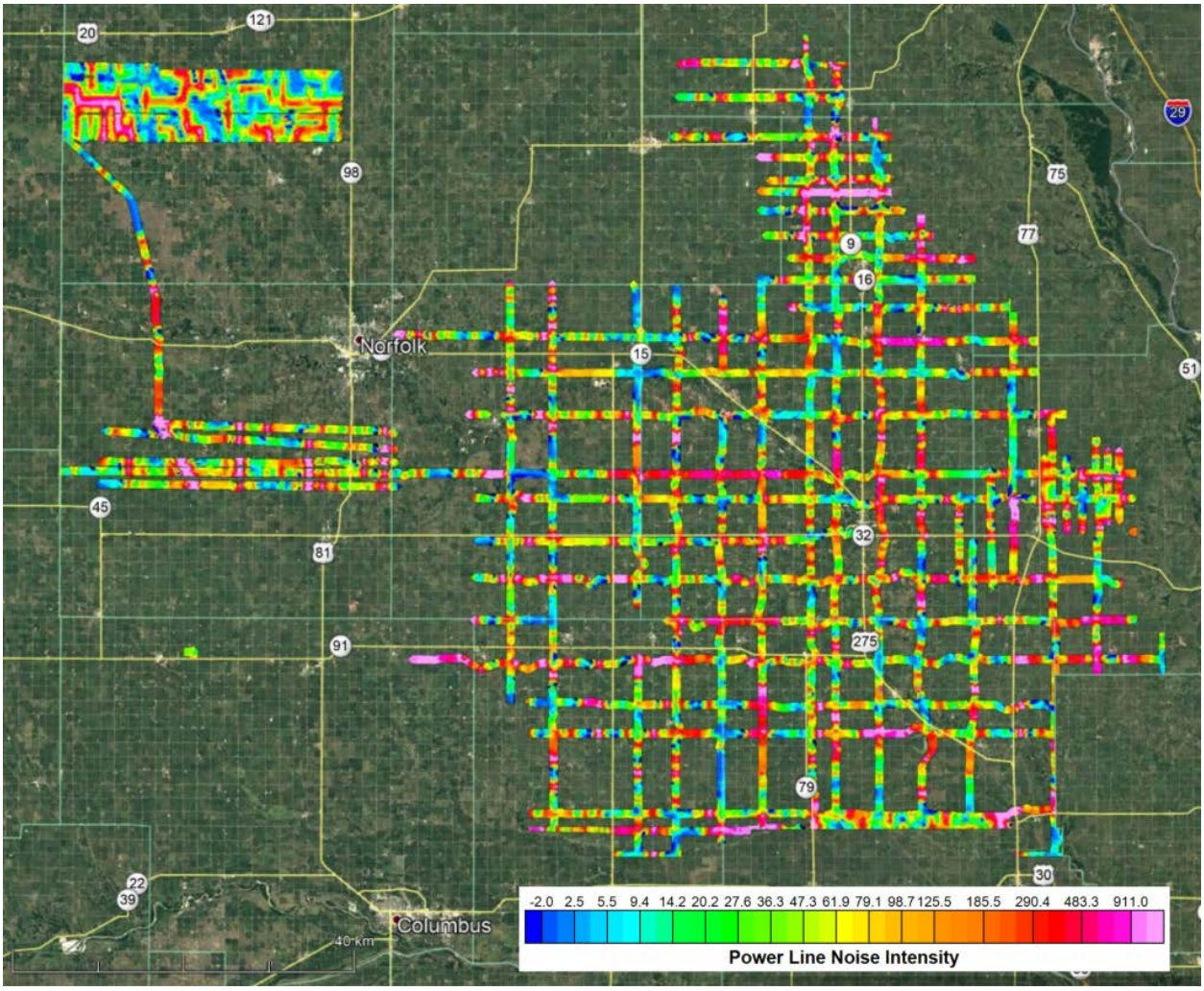


Figure 2-9: Power Line Noise Intensity (PLNI) map of the LENRD 2018 project area.

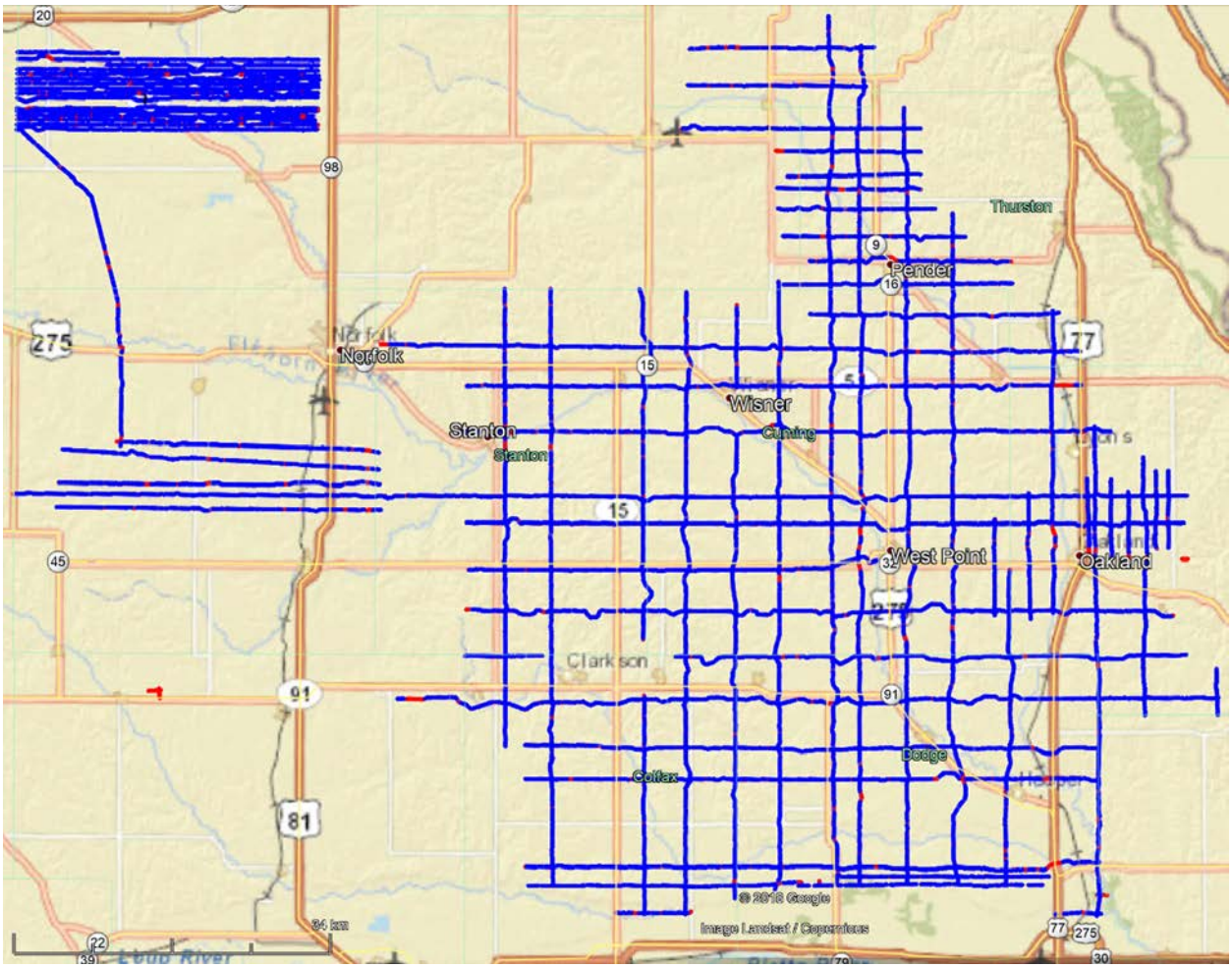


Figure 2-10: Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LENRD 2018 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. 78% of the acquired data was retained for inversion and interpretation. Google Earth kmz's of the inverted data locations as well as the "as-flown" flight lines are included in Appendix 3\KMZ.

2.4.5 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 2-11 shows the magnetic Total Field intensity data for the LENRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). This data is used in decoupling efforts.

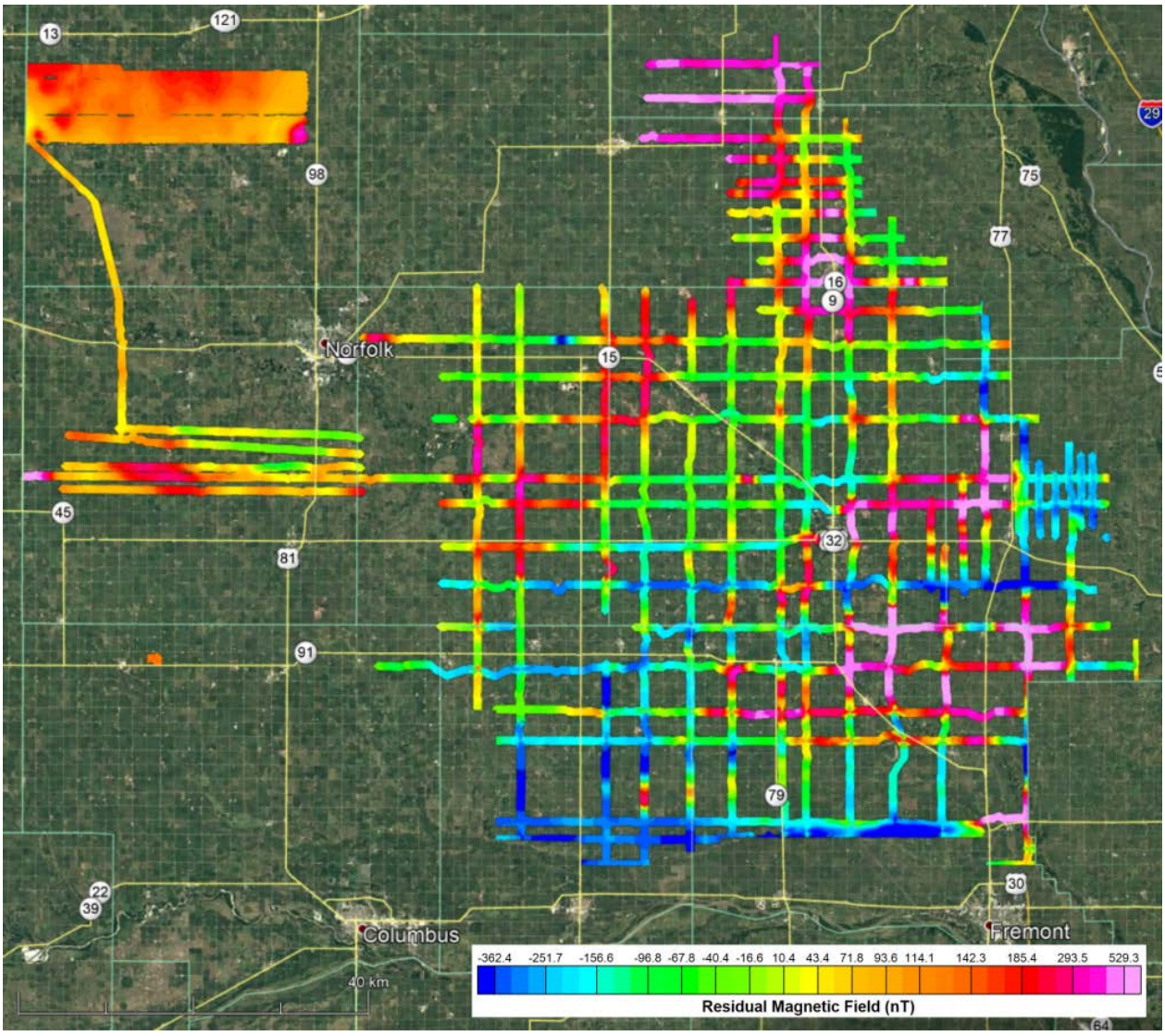


Figure 2-11: Magnetic Total Field intensity data for the LENRD 2018 survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

2.5 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 LENRD 2018 AEM data were inverted using the same 30-layer model structure as was used for the 2016 LENRD AEM investigation in order to facilitate merging of the 2018 inversion results with the 2016 inversion results. The SCI inversions used smooth models, 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 1.08. The depths to the bottoms of the 29th layers were set to 1,023 ft, with thicknesses up to about 85 ft. The thicknesses of the layers increase with depth (Table 2-3 and Figure 2-12) as the resolution of the technique decreases. The spatial reference distance, ***s***, for the constraints were set to 308 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; SkyTEM Airborne Surveys Worldwide, 2012). 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 2-3: 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)	Layer	Depth to Bottom (ft)	Thickness (ft)
1	9.8	9.8	16	298.4	31.2
2	20.5	10.6	17	332.1	33.7
3	31.9	11.5	18	368.5	36.4
4	44.3	12.4	19	407.8	39.3
5	57.7	13.4	20	450.3	42.5
6	72.2	14.5	21	496.2	45.9
7	87.8	15.6	22	545.7	49.5
8	104.7	16.9	23	599.2	53.5
9	122.9	18.2	24	657.0	57.8
10	142.5	19.7	25	719.4	62.4
11	163.8	21.2	26	786.8	67.4
12	186.7	22.9	27	859.5	72.8
13	211.5	24.8	28	938.1	78.6
14	238.3	26.8	29	1023.0	84.9
15	267.2	28.9			

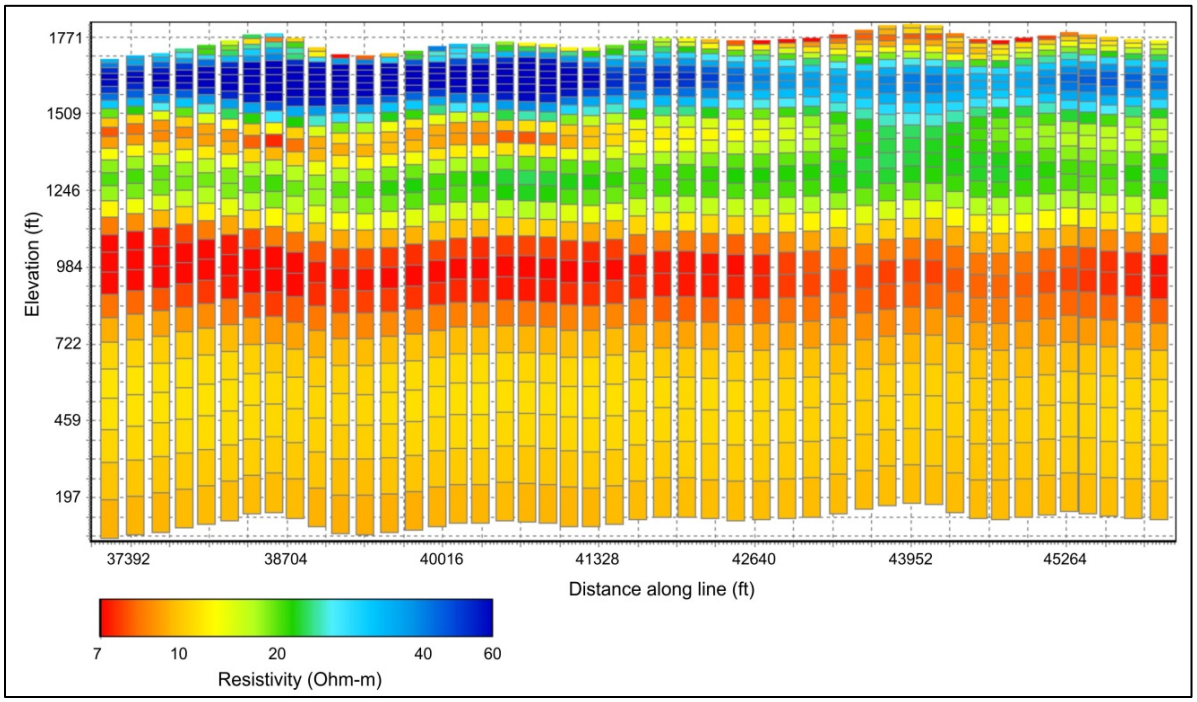


Figure 2-12: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

Figure 2-13 presents a histogram of the LENRD SCI inversion data/model residuals and a map of data residuals is presented in Figure 2-14.

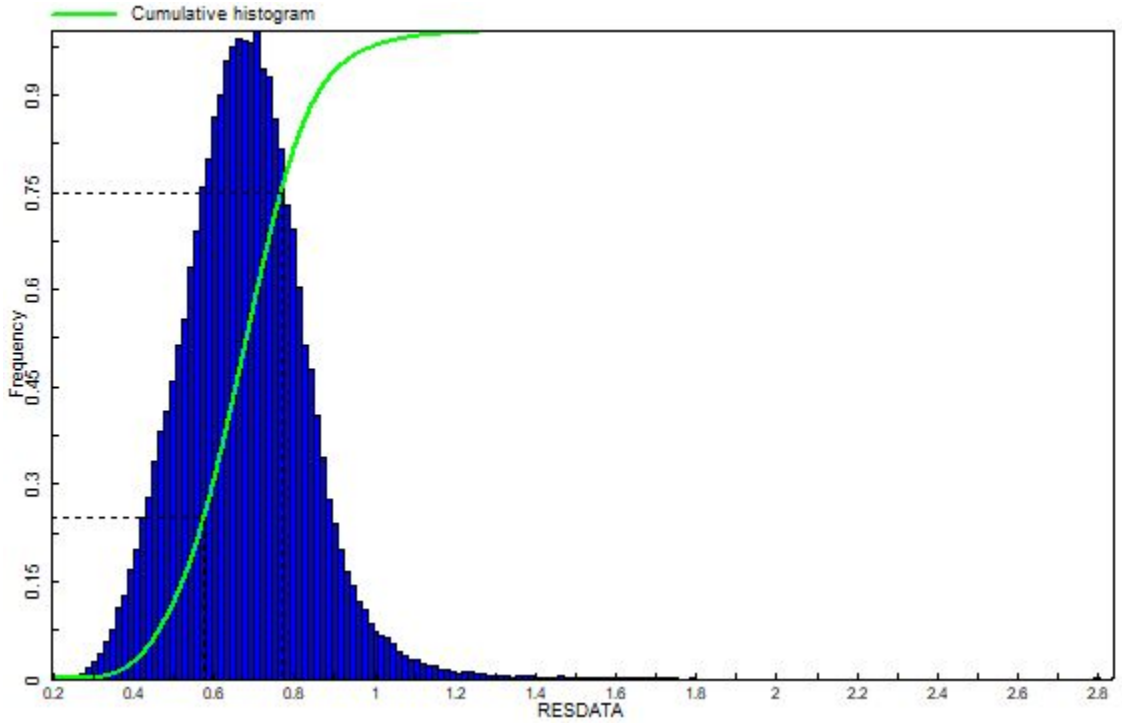


Figure 2-13: Data/model residual histogram for the LENRD 2018 SCI inversion results.

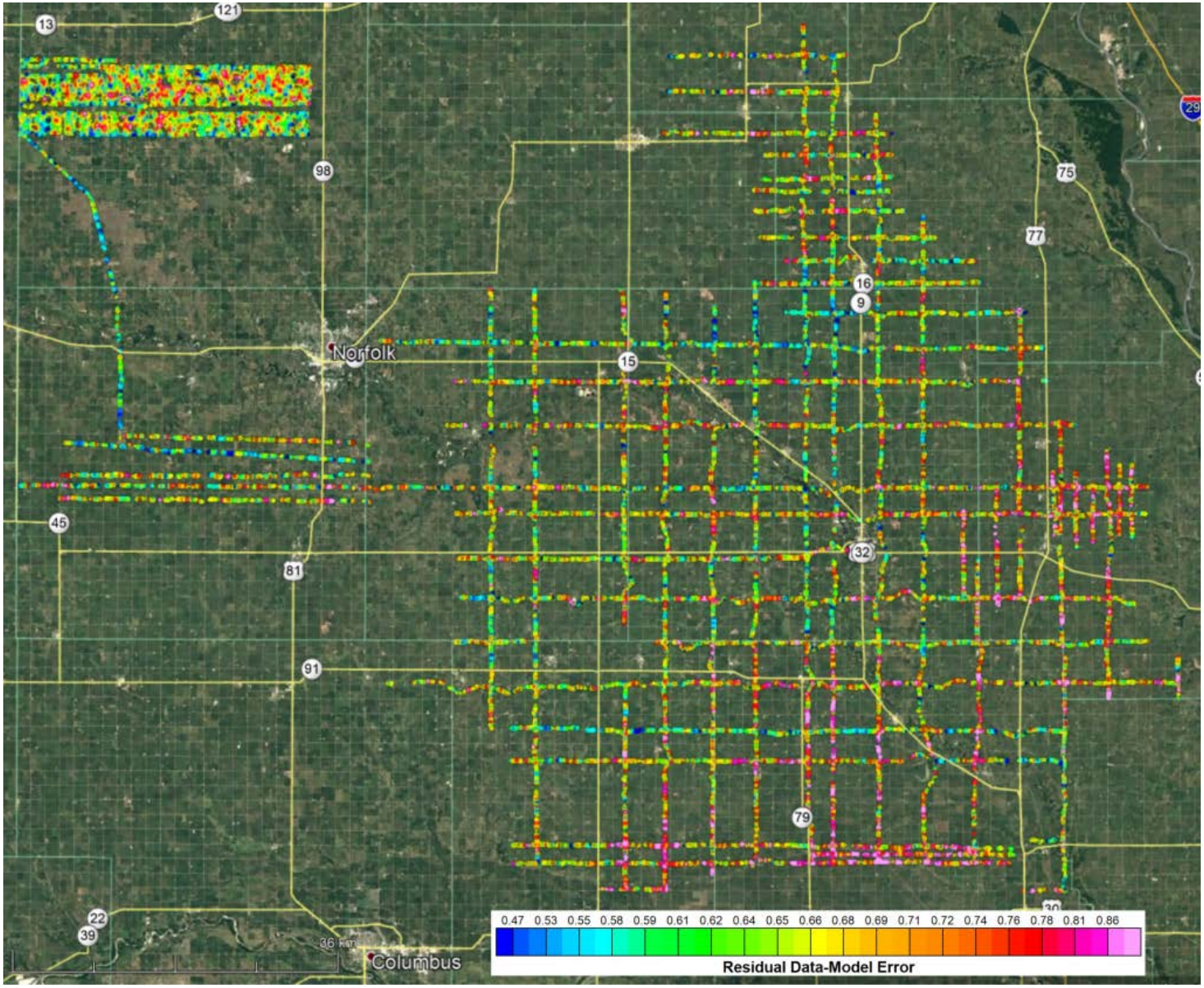


Figure 2-14. Map of data residuals for the LENRD 2018 SCI inversion results.

3 AEM Results and Interpretation

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

3.1 Interpretive Process

3.1.1 Merge AEM Databases from Different Flights

After the inversion process several short lines were combined to form continuous lines within the survey area including the lines that composed the 3-mile reconnaissance AEM grid. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. Table 3-1 lists the original named lines and the new combined lines.

Table 3-1. Combination of flight lines within the LENRD 2018 AEM survey.

Original Source Lines	Direction	New Line
L500501, and L500502	East-West	L500500
L904501, and L904502	East-West	L904500
L905201, and L905202	East-West	L905200
L906901, and L907001	East-West	L906900
L500101, L907401, and L907601	East-West	L907400
L908001, and L908002	East-West	L908000
L908101, and L908201	East-West	L908100
L908301, L908401, and L908501	East-West	L908300
L908701, and L908702	East-West	L908700
L1003901, and L1004001	North-South	L1003900
L1004101, and L1004201	North-South	L1004100
L1004301 and L1004302	North-South	L1004300
L1004401, L1004501 and L1004502	North-South	L1004400
L1004601, and L1004602	North-South	L1004600
L1004701, L1004702, and L1004703	North-South	L1004700
L1004801, L1004802, and L1004803	North-South	L1004800
L1004901, L1004902, L1004903, L1004904, and L1004905	North-South	L1004900
L1005001 and L1005002	North-South	L1005000

A substantial portion of the LENRD has had AEM data collection before that is summarized in Carney et al. (2015a) and AGF (2017). For the Pierce Block data acquired in 2014 and 2016 existed within the boundaries of the 2018 block. The 2014 and 2016 lines were added to the 2018 AEM data set to provide the best possible data coverage for interpretation. Table 3-2 is a summary of the additional lines added to the Pierce Block for interpretation and Figure 3-1 plots the lines that were used.

In addition to the Pierce Block, the area around Oakland, Nebraska has received a large amount of attention over the years and has been the subject of several studies including Smith et al.(2008), Abraham et al. (2011), and Carney et al. (2015a). To this end, the 2014 AEM data were combined with the 2018 data to provide an enhanced interpretation of the area and to allow for the construction of fence diagrams. The nominal line spacing in the Oakland area is still on the order of 1-mile and 3D voxels are not recommended with this line spacing. Table 3-3 is a summary of the 2014 AEM lines that were combined with the 2018 data to improve the interpretation. Figure 3-2 is a plot of the lines that were used in the interpretation of the Oakland area and the construction of the Oakland Fence diagrams.

Table 3-2. Additional lines added to the Pierce Block.

Line Number	Direction	Year Acquired	System
L100501	East-West	2014	SkyTEM 508
L200101	North-South	2014	SkyTEM 508
L200201	North-South	2014	SkyTEM 508
L200301	North-South	2014	SkyTEM 508
L200401	North-South	2014	SkyTEM 508
L200501	North-South	2014	SkyTEM 508
L200601	North-South	2014	SkyTEM 508
L200701	North-South	2014	SkyTEM 508
L125701	East-West	2016	SkyTEM 304M
L683206	North-South	2016	SkyTEM 304M

Table 3-3. Additional lines added to the Oakland area Interpretation

Line Number	Direction	Year Acquired	System
L101301	East-West	2014	SkyTEM 508
L101601	East-West	2014	SkyTEM 508
L201901.1	East-West	2014	SkyTEM 508
L201901	North-South	2014	SkyTEM 508
L201901.2	North-South	2014	SkyTEM 508
L202001	North-South	2014	SkyTEM 508

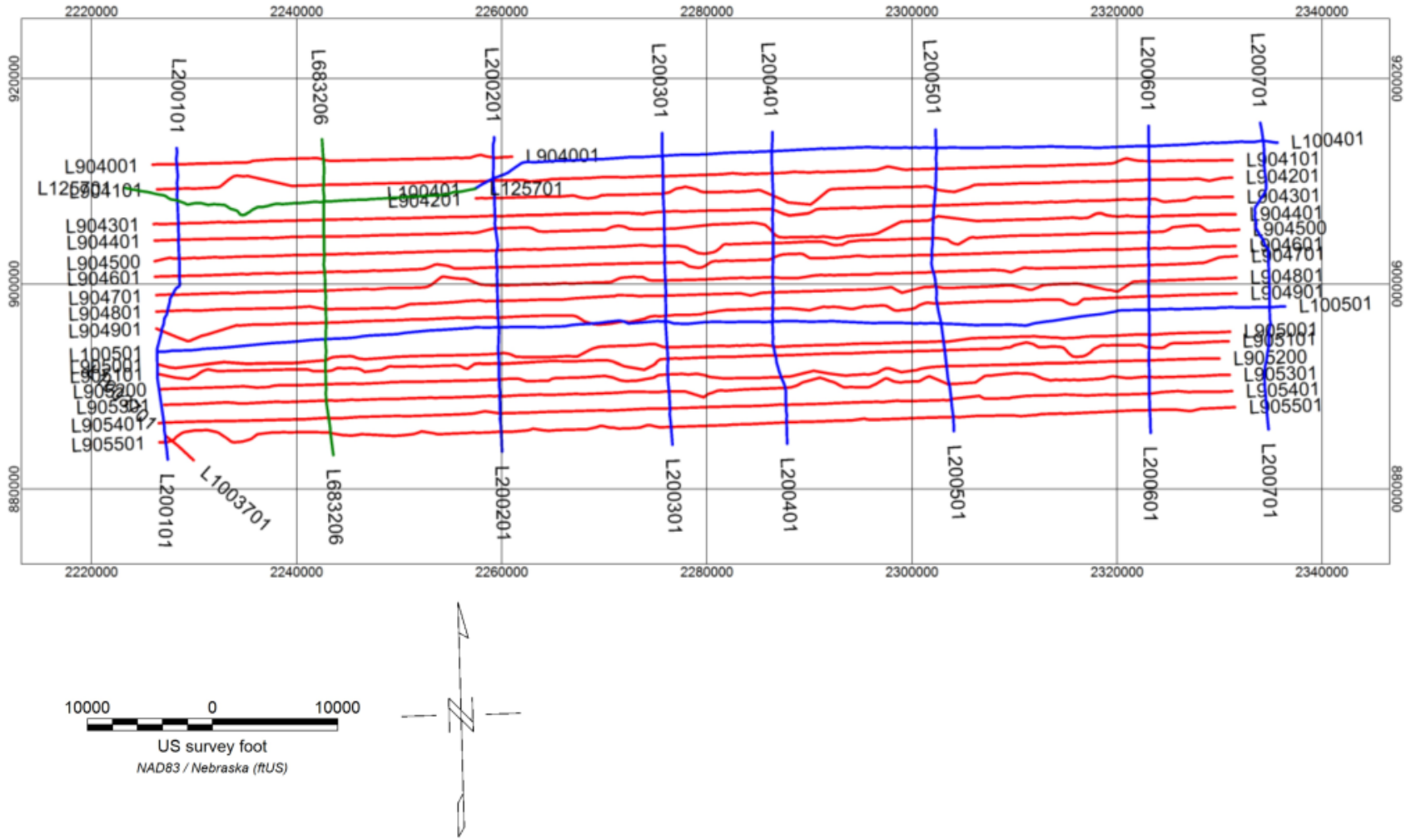


Figure 3-1. Map of the AEM flight lines that were used for the Pierce Block interpretation. Blue lines are from 2014, green lines are from 2016, and red lines are from 2018.

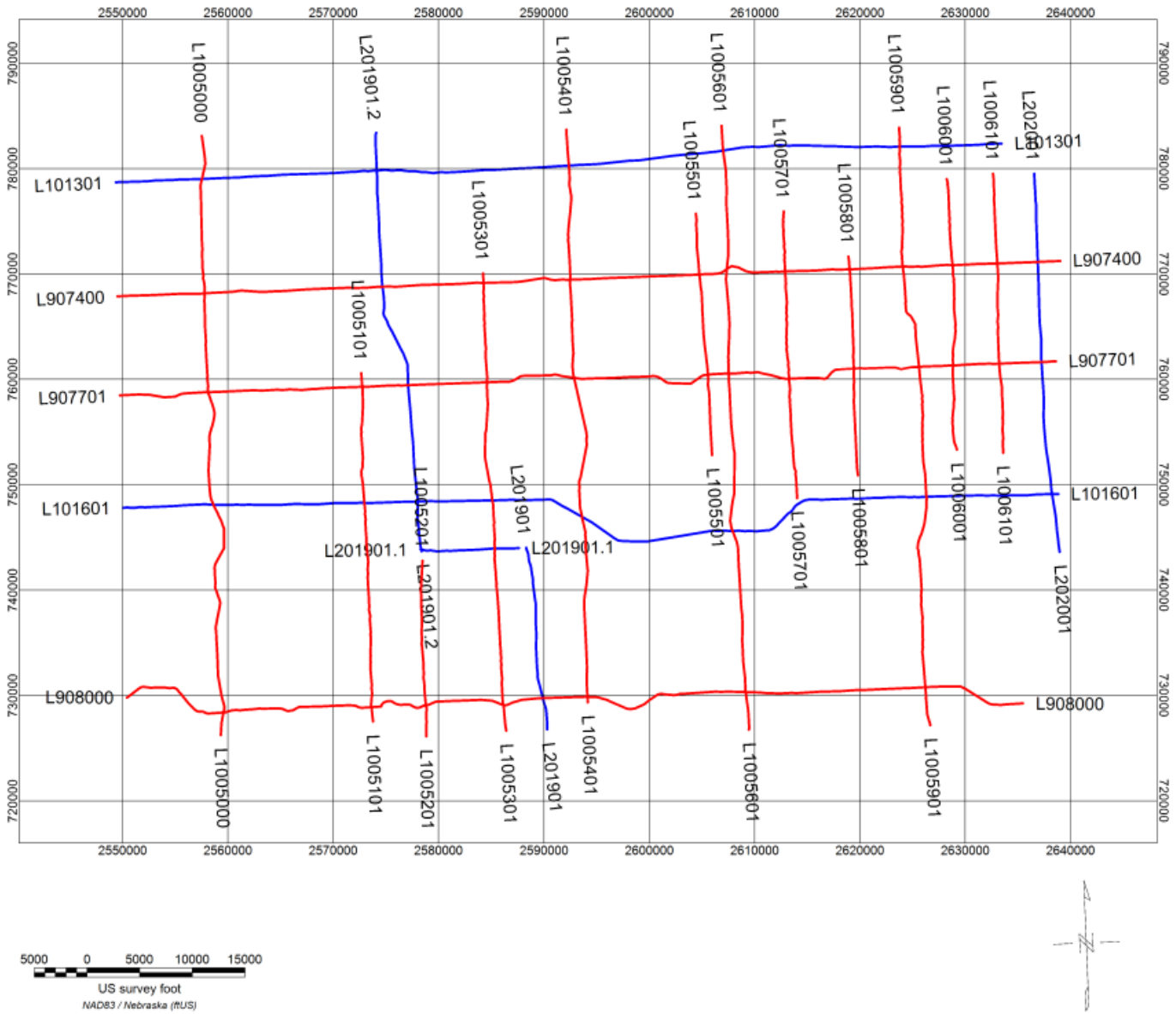


Figure 3-2. Map of the AEM flight lines that were used for the Oakland Interpretation. Blue lines are from 2014 and red lines are from 2018.

3.1.2 Construct 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 LENRD survey. The data was downloaded from the National Elevation dataset (NED) located at the National Map Website (U.S. Geological Survey, 2018) 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 3-3 is a map of the DEM showing a vertical relief of 1,024 ft with a maximum elevation of 2,041 ft and a maximum elevation of 1,984 ft. This DEM was used to reference all elevations within the AEM and borehole datasets. The major streams displayed on the maps for LENRD area utilized GIS files from NE-DNR (NE-DNR, 2018a).

3.1.3 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, 2018). 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 process is digitizing the contacts between the geologic units including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Cretaceous Pierre Shale (***Kp***), Cretaceous Niobrara (***Kn***), Cretaceous Carlile Shale (***Kc***), Cretaceous Greenhorn Limestone and Cretaceous Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***) units. The interpreted geological units included the ***Q***, ***To***, ***Kp***, ***Kn***, ***Kc***, ***Kgg***, ***Kd,*** and ***IP*** from the upper surface to the DOI. The interpretive process benefited from the use of CSD (UNL, 2018), NE-DNR (NE-DNR, 2018b), and NEOGCC (NOGCC, 2018) 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 in the final interpretation.

The interpretation began with picking the ***Kp***, ***Kc, Kn***, ***Kgg, Kd,*** and ***IP*** contacts and then, finally, the ***To*** interface. The process was iterative around the eroded units due to their irregular boundary.

The interpretation of the ***To*** included examination of the CSD and NE-DNR boreholes and comparison with the AEM resistivities. Unlike the ***Kp/To*** and ***Kp/Q*** surfaces, there is not a strong resistivity contrast between the ***Q*** and the ***To***. For this reason, the borehole information is critical in the determination of an estimated top of the ***To***. The following characteristics were used to locate the ***To*** top: 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 a generally lower electrical resistivity than the overlying ***Q*** alluvial deposits. Patterns in the inverted resistivity results were also used to match the differences between the ***Q*** and the ***To***.

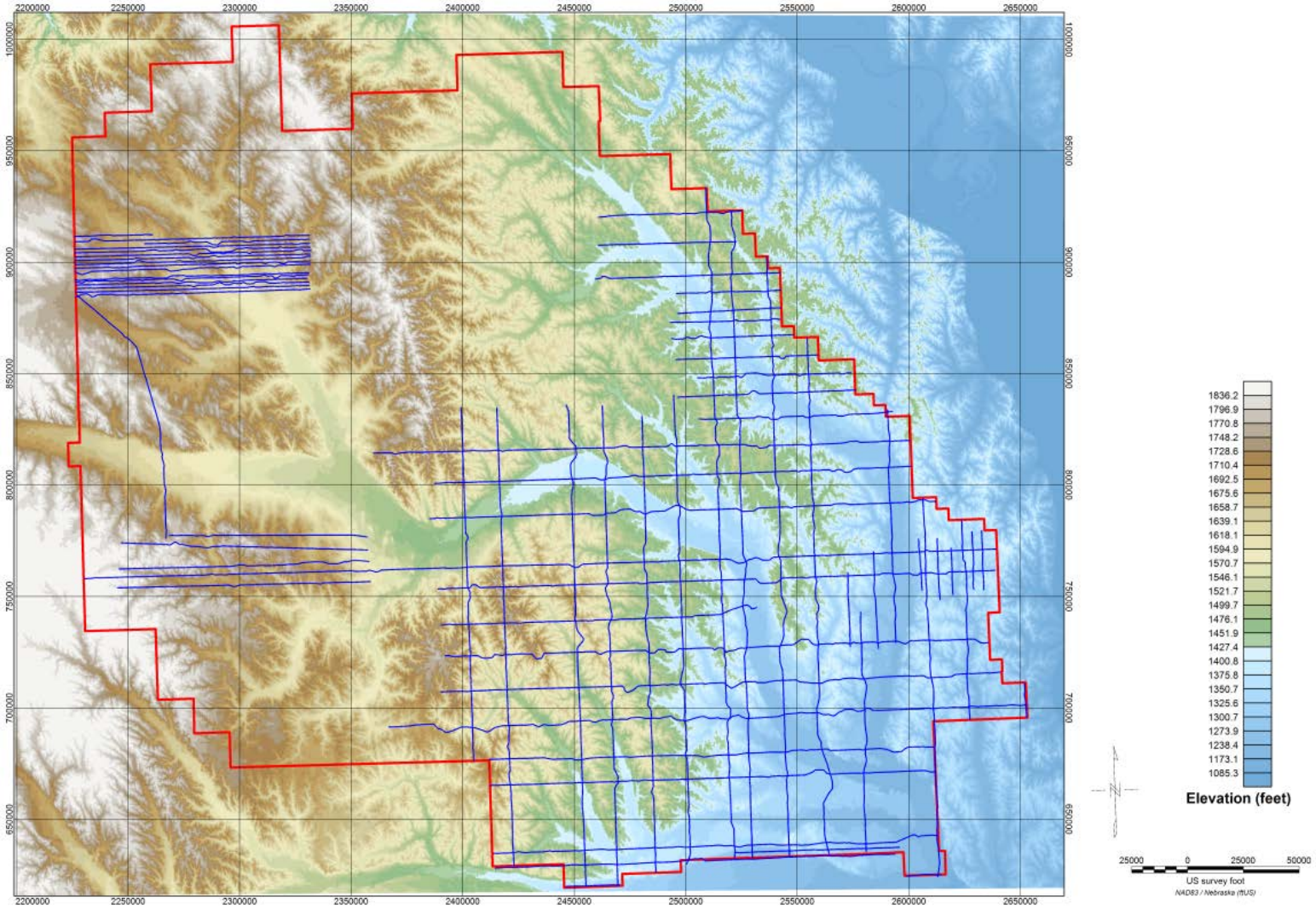


Figure 3-3. Map of the Digital Elevation Model (DEM) for the LENRD Study area. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). The red line is the boundary for the Lower Elkhorn Natural Resources District. The blue lines are the 2018 flight lines. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

The interpretation of the ***Kp*** included examining the AEM profile sections for a low electrical resistivity layer. Many of the CSD, as well as the NE-DNR borehole logs, stop at the ***Kp*** due to the ***Kp*** not being considered an aquifer because it is composed predominantly of shale containing clay minerals. Some 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 one half mile or 2,640 ft, the NEOGCC wells were clipped at 2.84 miles or 15,000 ft, and the NE-DNR boreholes were clipped to a distance of a quarter mile or 1,320 ft. The inversion DOI was also inspected when interpreting the profiles but was observed to be almost always below the top of the ***Kp*** in the LENRD 2018 AEM flight area.

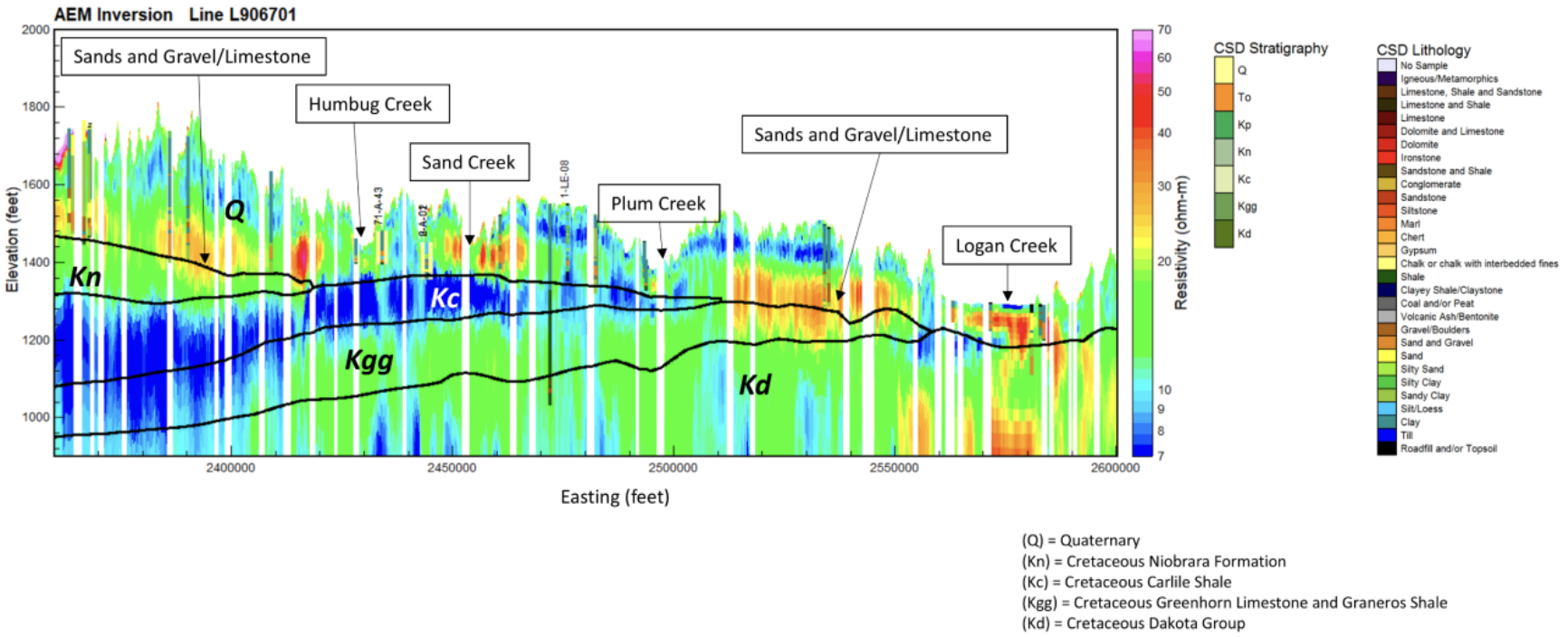
The top of the ***Kn*** was a much more challenging unit to interpret when the ***Kp*** is eroded off the ***Kn***. This is due to the highly variable nature, in terms of electricity resistivity, of the ***Kn.*** The unit goes from a resistive unit to a conductive unit based on the presence of clay minerals within the shale, chalk, and limestone beds. The best way to interpret the unit is to use the boreholes in the area and then use the underlying ***Kc*** as a guide to the dip of the ***Kn***. Several of the CSD and the NE-DNR holes have shale, chalk, or limestone indicated at the bottom. This provides a clear indication of the ***Kn***. When the CSD holes contain stratigraphic information that boundary can be confidently interpreted. However, in some instances there are no indications of the ***Kn*** at the bottom of the holes. Inspecting the area for the average depths of the NE-DNR holes provides another clue to the position of the ***Kn*** as many wells stop on top of the ***Kn***.

The ***Kc*** unit is identified as a low resistivity unit in the LENRD. As the ***Kc*** is composed of shale containing clay minerals the conductive nature of this unit is easily identified and interpreted. Additional, CSD and NE-DNR wells can provide further verification of the lithology and the stratigraphic contacts.

The ***Kgg*** can be difficult to detect depending on the depth at which it is encountered. The ***Kgg*** is generally a thin unit, less than 100 feet, composed of resistive limestone and conductive shale. When detectable, the resistive limestone of the Greenhorn Limestone is interrupted beneath the ***Kc***. The interpretation of the bottom of the ***Kgg*** is more challenging due to the variable resistivity of the ***Kd*** immediately below the conductive Graneros Shale. When the ***Kd*** contains resistive sands/sandstone, the lower contact of the ***Kgg*** and the top of the ***Kd*** is identifiable. Deep CSD test holes and rare, but deep, NE-DNR wells can assist in the verification of the position of the ***Kgg*** and ***Kd*** contact. On the eastern edge of the LENRD 2018 AEM survey area the ***Kgg*** is more commonly identified in the CSD wells.

The general location of the ***Kd*** is detectable when there are resistive sands/sandstones at depth. Use of general thickness constraints can also assist in interpreting the location of the ***Kd***. The NEOGCC wells in the area also provide general stratigraphic control assisting in the location of the geologic units. When the ***Kd*** is the only Cretaceous bedrock unit, much greater care should be taken due to the low resistivity contrast between the ***Q*** and the ***Kd***. Many of the holes in the area indicate sand and or sand and gravel at the bottom of the ***Q*** while the ***Kd*** is also sand and or sandstone. The resistivity contrast between the ***Q*** sand and the ***Kd*** sand is almost nonexistent. Thus, use of CSD stratigraphy calls and the presence of sandstone and shale in the NE- DNR registered wells were used to pick the ***Q/Kd*** contact when no resistivity contrast was present.

Figure 3-4 is an approximately 46-mile-long east-west flight line, designated L906701, that is north of the towns of Stanton, Pilger, Wisner, and Bancroft. The line crosses Humbug, Sand, Plum, and Logan Creeks. This line encompasses many of the Cretaceous units present in eastern Nebraska including the ***Kn***, ***Kc***, ***Kgg*** and ***Kd***. This line illustrates the regional dip of the Cretaceous units toward the west and how those units are eroded off toward the east. Several CSD test holes and many NE-DNR wells penetrate or stop at the top of the Cretaceous units. As indicated above, the top of the ***Kn*** is difficult to differentiate from the ***Q*** and boreholes are required to determine the top. The extent of the electrically conductive ***Kc*** is easily detected (the continuous, thick blue zone in Figure 3-4). As such, when the ***Kc*** is the bedrock in the area, it is detectable as compared with the resistive ***Q*** materials (the upper red zones in Figure 3-4) with the exception of when the ***Q*** material contains large areas of conductive clays. On the eastern end of this line the presence of the electrically resistive ***Kgg*** is detectable under the ***Kc***. The ***Q-Kgg*** contact in the region of the resistive sands and gravels of the ***Q*** overlying the ***Kgg*** is not detectable and boreholes are required for that region. At the far western end of the profile in Figure 3-4, the ***Kgg*** is not easily separated from the ***Kc*** due to similar resistivities and is only estimated from the regional thickness of the ***Kgg***. The location of the top of the ***Kd*** is estimated from the thickness of the ***Kgg*** and the geological map. Figure 3-4 illustrates the regional nature of a long reconnaissance lines within the LENRD and illuminates the Cretaceous units and their structural attitude. After the completion of the interpretation of the Cretaceous bedrock units, the ***Q*** materials can be inspected. Along Line L906701 in Figure 3-4, many positive correlations of the AEM resistivity and the lithology can be observed in the CSD and the NE-DNR wells.



(Q) = Quaternary
(Kn) = Cretaceous Niobrara Formation
(Kc) = Cretaceous Carlile Shale
(Kgg) = Cretaceous Greenhorn Limestone and Graneros Shale
(Kd) = Cretaceous Dakota Group

Figure 3-4. 46-miles long east-west line L906701. CSD (labeled) and Nebraska DNR (unlabeled) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names. The profile projection is NE State Plane, NAD83, US survey feet.

Figure 3-5, Line L906801, is an approximately 41-mile-long east-west line north of the town of Wisner and south of Pilger. The line crosses the Elkhorn River and Sand Plume and Logan creeks. Similarly, as seen in Figure 3-4, the ***Kn***, ***Kc***, ***Kgg*** and ***Kd*** are present, and this line illustrates the regional dip of the Cretaceous units towards the west and how those units are eroded off toward the east. Below the ***Kn***, the ***Kc*** is detectable as a conductor (blue zone on left in Figure 3-5). On the left side of the profile and on top of the ***Kc***, there is a detectable paleochannel that is incised into the ***Kc***. The ND-DNR wells in the area confirm the presence of materials within the paleochannel below the regional surface level of the ***Kc***. The Elkhorn River channel and associated alluvium are easily detectable as more resistive materials. Note that the flight line is parallel to the channel in this area. The region of the ***Kgg*** in contact with the ***Q*** is hard to detect and the addition of the NE-DNR registered wells assist in placing the contact. Within the ***Q*** deposits many positive correlations with the test holes and wells can be observed. Changes in the lithology within the ***Q*** is drastic in some areas and is reflected by the high contrast in inverted resistivity values.

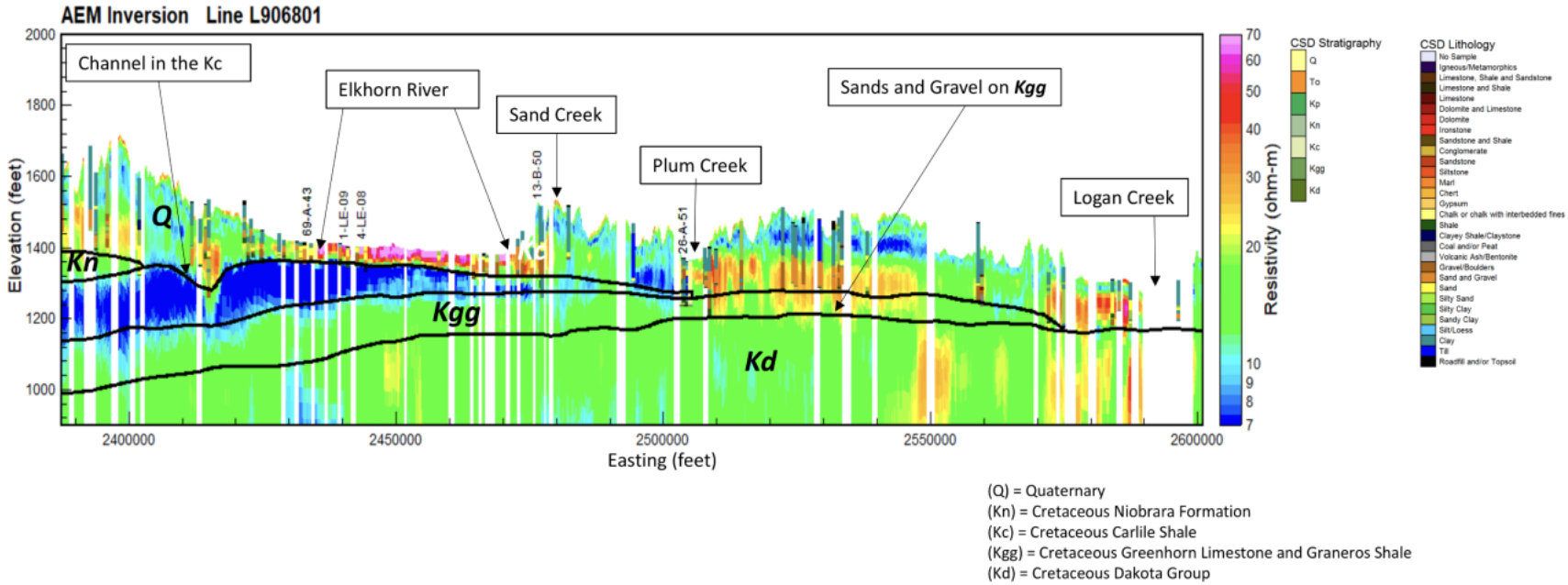
Figure 3-6 is Line L906900, a 44-mile-long east-west line located north of the towns of Stanton and Beemer and south of the towns of Pilger and Wisner. The flight line crosses the Elkhorn River in two places as well as Plum Creek. In this location, the ***Kn*** is not present and the ***Kc*** and ***Kgg*** are the bedrock units. As noted above, the Cretaceous units dip toward the west in this area and are eroded off the eastern end of the flight lines. The top of the ***Kc*** is easily interpreted along this line. The interpretation of the top of the ***Kgg*** is also confidently interpreted in Figure 3-6 due to the conductive nature of the ***Kc***. However, the top of the ***Kgg*** is not easily detected in the region where the ***Kc*** is eroded off and the NE-DNR registered wells are used to estimate the ***Kgg*** due to the low resistivity contrast with the ***Q***. Within this section there is an erroneous NE-DNR well (indicated by the red oval in Figure 3-6) that indicates penetration into the ***Kc*** and ***Kgg*** and the lithology is indicated as siltstone and sand. This well may be incorrectly located or just be in error within the DNR database. Using the AEM, it is easily to detect that the lithology from this well needs to be ignored. Within the ***Q*** section (above the upper thick black line in Figure 3-6) many of the wells indicate good agreement with the AEM resistivities.

Figure 3-7 is Line L908300, a 56 mile east-west line south of the towns of Clarkson, Howells, Dodge, and Snyder and north of the town of Scribner. The ***Kc, Kgg,*** and the ***Kd*** are the Cretaceous bedrock units in this area. As noted above, the ***Kc*** is easily detectable and interpreted on the western end of the flight line but is harder to interpret toward the east. The ***Kgg*** can also be interpreted in this area and is confidently placed due to CSD well *01-LE-18*. The ***Kd*** is interpreted using the regional thickness, geological map, and the presence of sandstone in the NE-DNR registered wells. On the eastern end of flight line L908300, the CSD test hole *7-B-63* indicates a deep channel in the ***Kd.*** The NE-DNR registered wells on either side of the CSD test hole do not indicate the deep channel but do indicate sandstone and shale at depth. This may be a channel or an error in the stratigraphy of *7-B-63*.

Figure 3-8 is a 20-mile-long east-west line, L904500, located within the Pierce Block north of the town of Foster. The flight line crosses the North Fork of the Elkhorn River as well as Dry Creek and Yankton Slough. Within the Pierce Block, the ***Kp*** and ***Kn*** are the Cretaceous bedrock units. The ***Kc*** is also detected below the ***Kn,*** but has low resolution in areas of thick ***Kp.***

The ***To*** is also present in the area. As indicated above the estimated interpretation of the ***To*** is done with the use of the lithology from the NE-DNR registered wells indicating sandstone, siltstone, or shale as well as CSD stratigraphic calls. There is good agreement between the AEM resistivity and the borehole lithologies. Areas of clay rich sediments are clearly imaged by the AEM versus the more sand and gravel rich areas.

The above examples illustrate the interpretive process that was used on the profiles provided within this report. Each flight line with an interpretation including the Quaternary/Tertiary Aquifer material mapping (Section 3.2.1) are included as 2D profiles and 3D images in Appendices 1 and 2.



(Q) = Quaternary
(Kn) = Cretaceous Niobrara Formation
(Kc) = Cretaceous Carlile Shale
(Kgg) = Cretaceous Greenhorn Limestone and Graneros Shale
(Kd) = Cretaceous Dakota Group

Figure 3-5. 41-mile east-west line L906801. CSD (labeled) and Nebraska DNR (unlabeled) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names. Intersection with the different creeks and rivers in the area are indicated. The projection is Nebraska State Plane, NAD83, US survey feet.

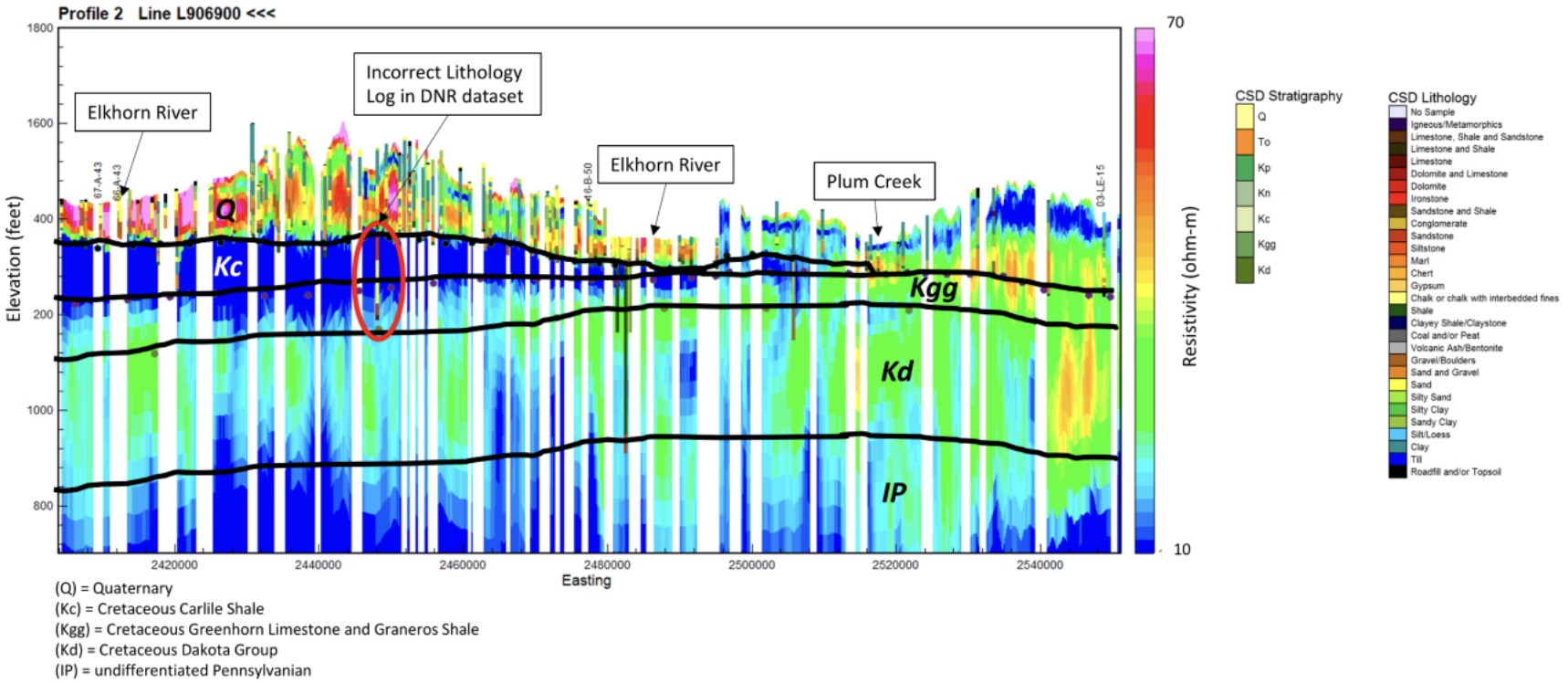


Figure 3-6. 44-mile east-west line L906900. CSD (labeled) and Nebraska DNR (unlabeled) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names. The red oval on the left indicates a NE-DNR borehole with incorrect lithologies noted. Intersection with the different creeks and rivers in the area are indicated. The projection is Nebraska State Plane, NAD83, US survey feet.

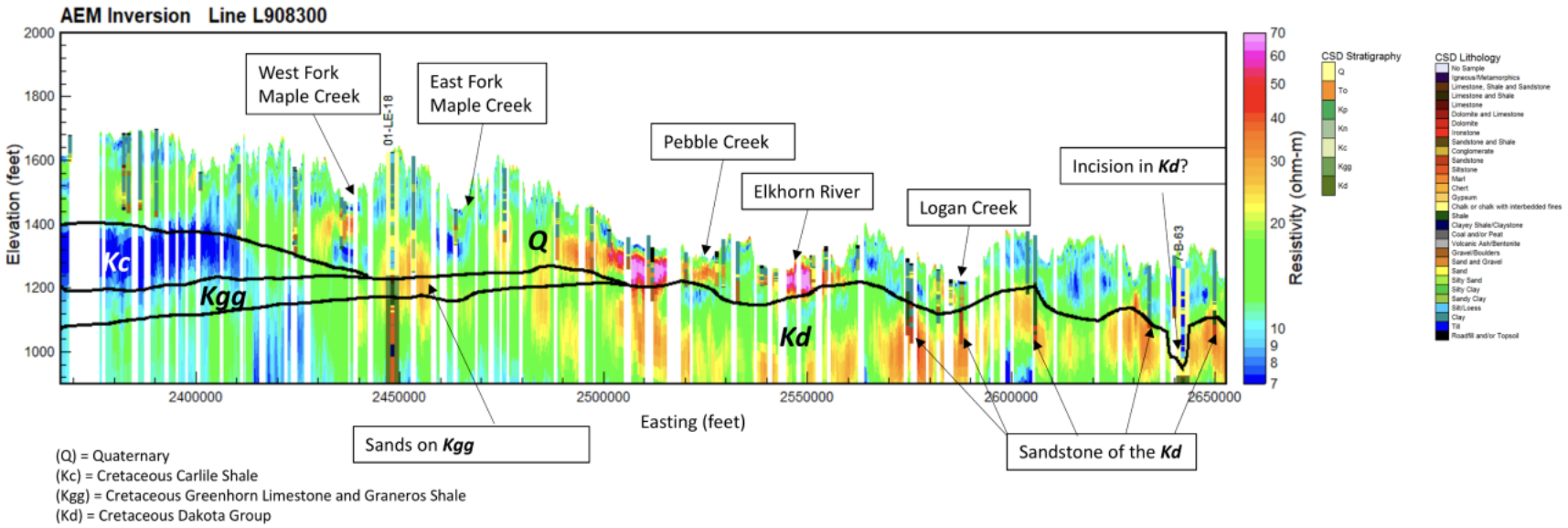


Figure 3-7. 23-milelong east-west line L121501 north of Pilger, Nebraska. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names. Intersection with the different creeks and rivers in the area are indicated. The projection is Nebraska State Plane, NAD83, US survey feet.

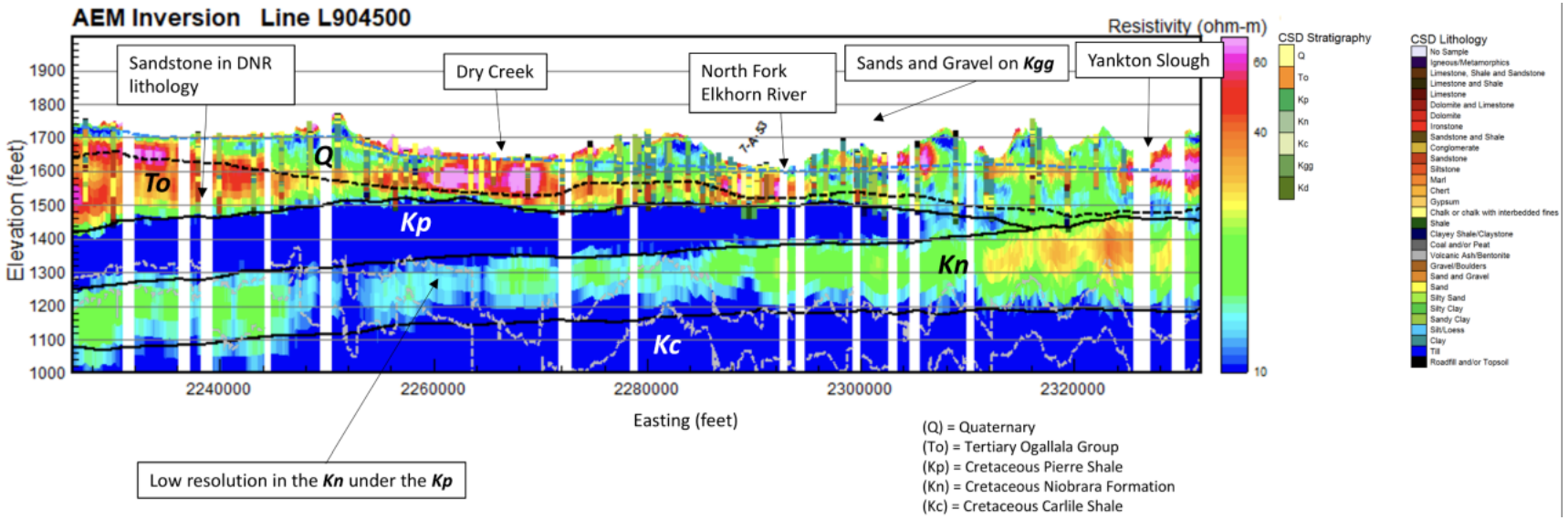


Figure 3-8. 20-mile east-west line L904500 within the Pierce Block. CSD (labeled) and Nebraska DNR (unlabeled) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names. Intersection with the different creeks and rivers in the area are indicated. The projection is Nebraska State Plane, NAD83, US survey feet.

3.1.4 Create Interpretative Surface Grids

LENRD survey area surface grids of geologic formations have been created. To produce these grids, the elevations of the AEM-interpreted tops of the formations were imported to a Geosoft Oasis montaj (OM) database (Geosoft, 2018). The interpreted elevation data were then gridded for each formation independently using the OM minimum curvature gridding (MCG) algorithm.

For the top surface of the ***To*** 1,245 AEM picks were used in the grid including the adjacent picks from the 2016 AEM data (AGF, 2017). The cell size was set to one-half mile or 2,640 feet and the "cells to extend beyond" was set to 5. All other parameters were either left as the default or blank. The grid was then clipped to the interpreted erosional contact and then clipped again to the LENRD survey area. Figure 3-9 is a map of the elevation of the estimated top of the ***To*** within the LENRD survey area. For the Pierce Block an enhanced ***To*** surface was created due to the dense flight block using a cell size of 500 feet that was clipped to the area of the Pierce Block. As indicated above in Section 3.1.1 additional lines were added from the 2014 AEM survey (Carney et al., 2015a) and the 2016 AEM survey (AGF, 2017) for the Pierce Block. Figure 3-10 is a map of the top of the ***To*** within the Pierce Block.

For the ***Kp*** top surface 4,019 AEM picks were used in the grid including the adjacent picks from the 2016 AEM data (AGF, 2017). The cell size was set to one-half mile or 2,640 feet and the cells to extend beyond was set to 5. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the interpreted erosional contact and then clipped again to the LENRD survey area. On the margins of the survey area some areas are blank due to a lack of data. Figure 3-11 is a map of the elevation of the top of the ***Kp*** within the LENRD survey area. For the Pierce Block an enhanced ***Kp*** surface was created due to the dense flight block using a cell size of 500 feet that was clipped to the area of the Pierce block. As indicated above in Section 3.1.1 additional lines were added from the 2014 AEM survey (Carney et al., 2015a) and the 2016 AEM survey (AGF, 2017) for the Pierce Block. Figure 3-12 is a map of the top of the ***Kp*** within the Pierce Block.

For the ***Kn*** top surface 2,232 AEM picks were used in the grid including adjacent picks from the 2016 AEM data (AGF, 2017). The cell size was set to one-half mile or 2,640 feet and the cells to extend beyond was set to 5. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the interpreted erosional contact and then clipped again to the LENRD survey area. On the margins of the survey area some areas are blank due to a lack of data. Figure 3-11 is a map of the elevation of the top of the ***Kn*** within the LENRD survey area.

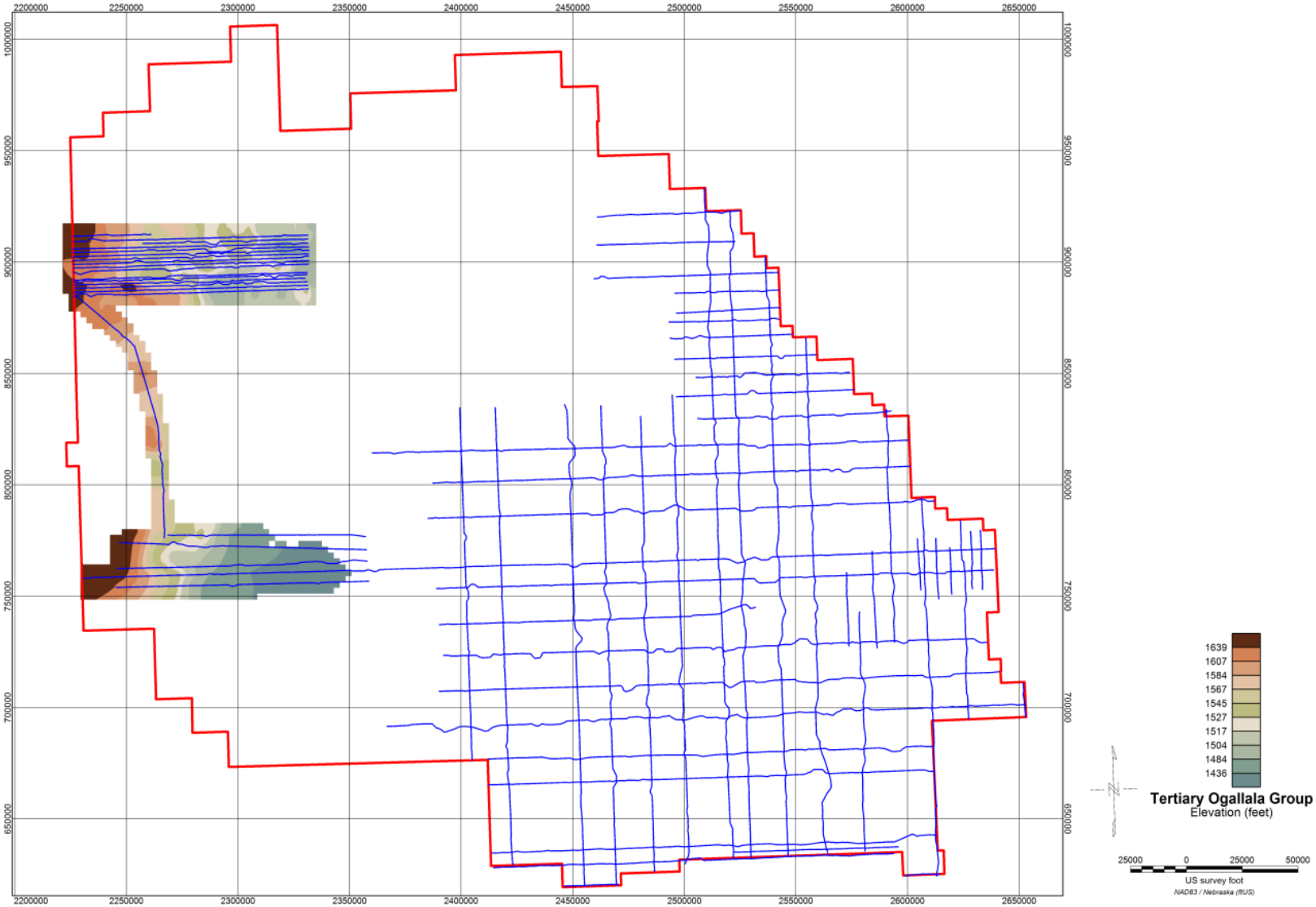


Figure 3-9. Map of the elevation of the top of the Tertiary Ogallala Group (*To*) within the LENRD (redline) from the 2018 survey. 2018 flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

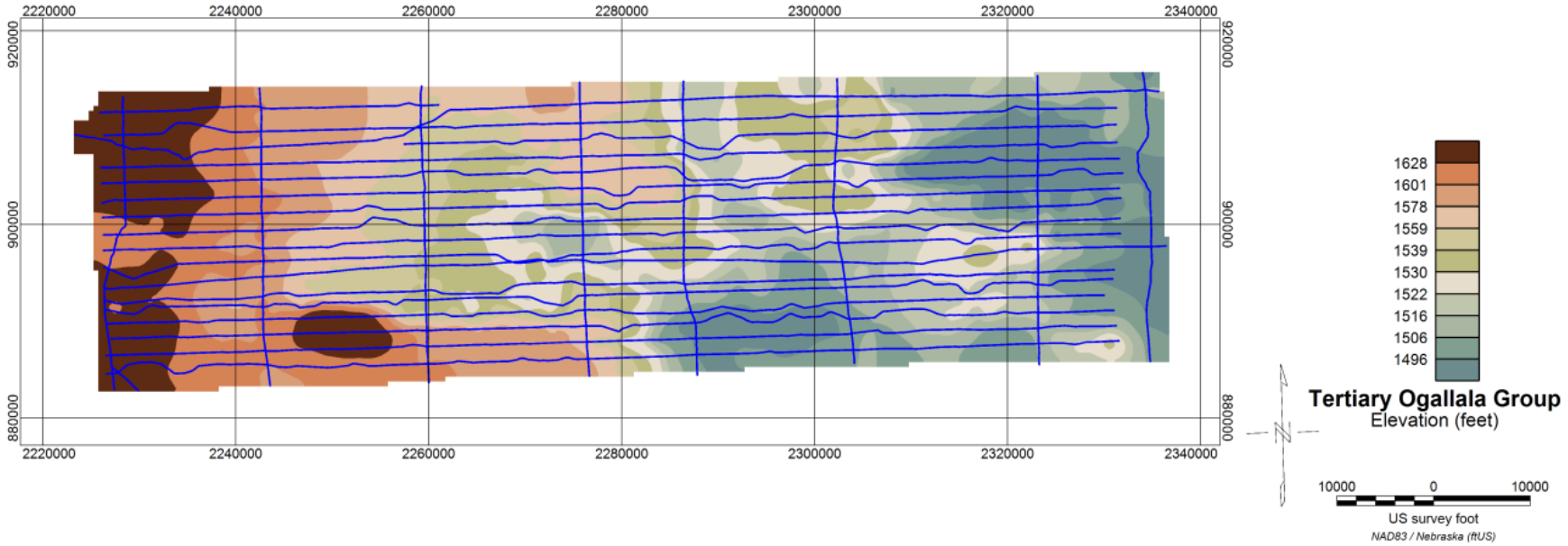


Figure 3-10. Map of the elevation of the top of the Tertiary Ogallala Group (*To*) within the Pierce Block from the 2014, 2016, and 2018 survey. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

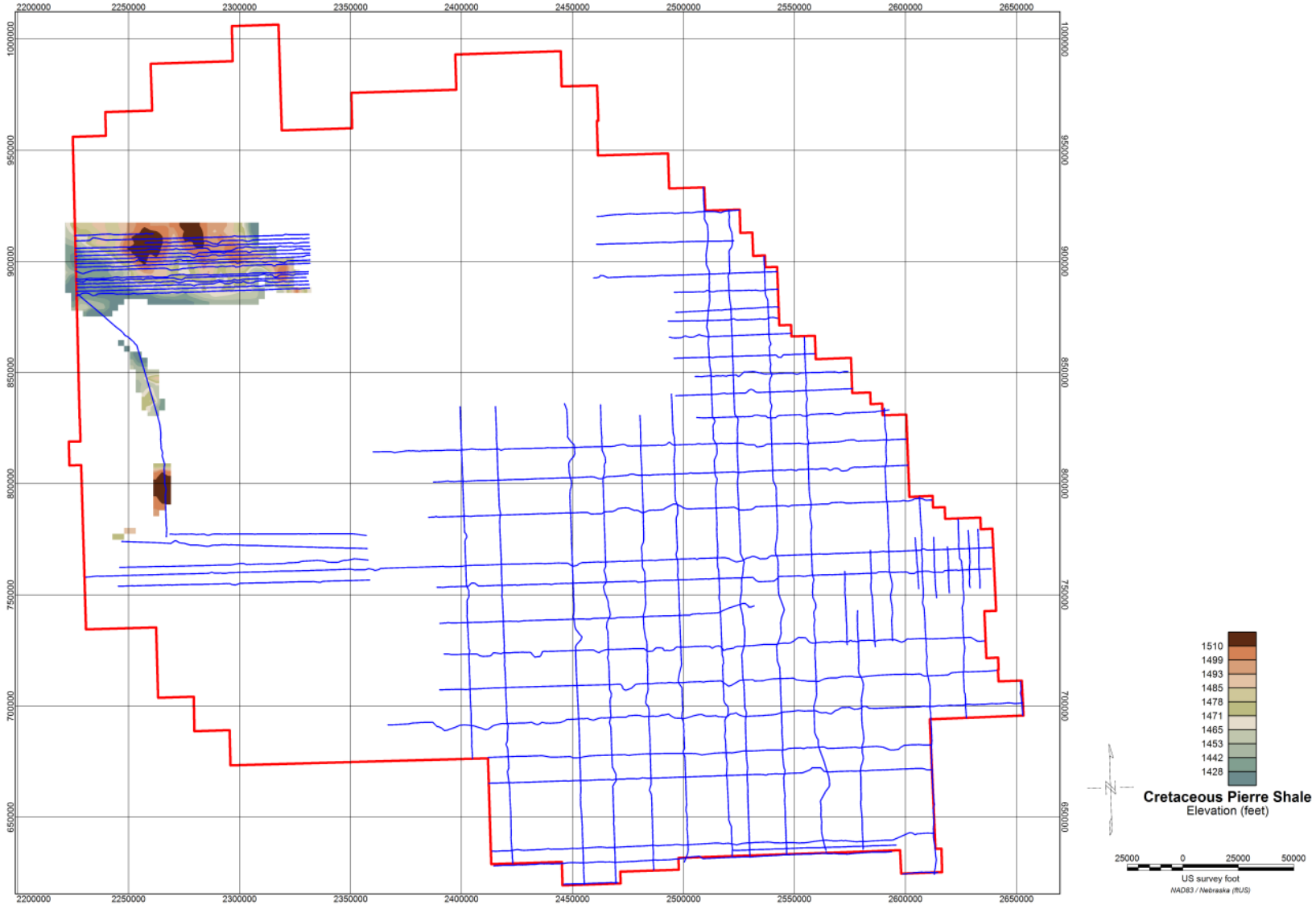


Figure 3-11. Map of the elevation of the top of the Cretaceous Pierre Shale (*Kp*) within the LENRD (redline) from the 2018 survey. 2018 flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

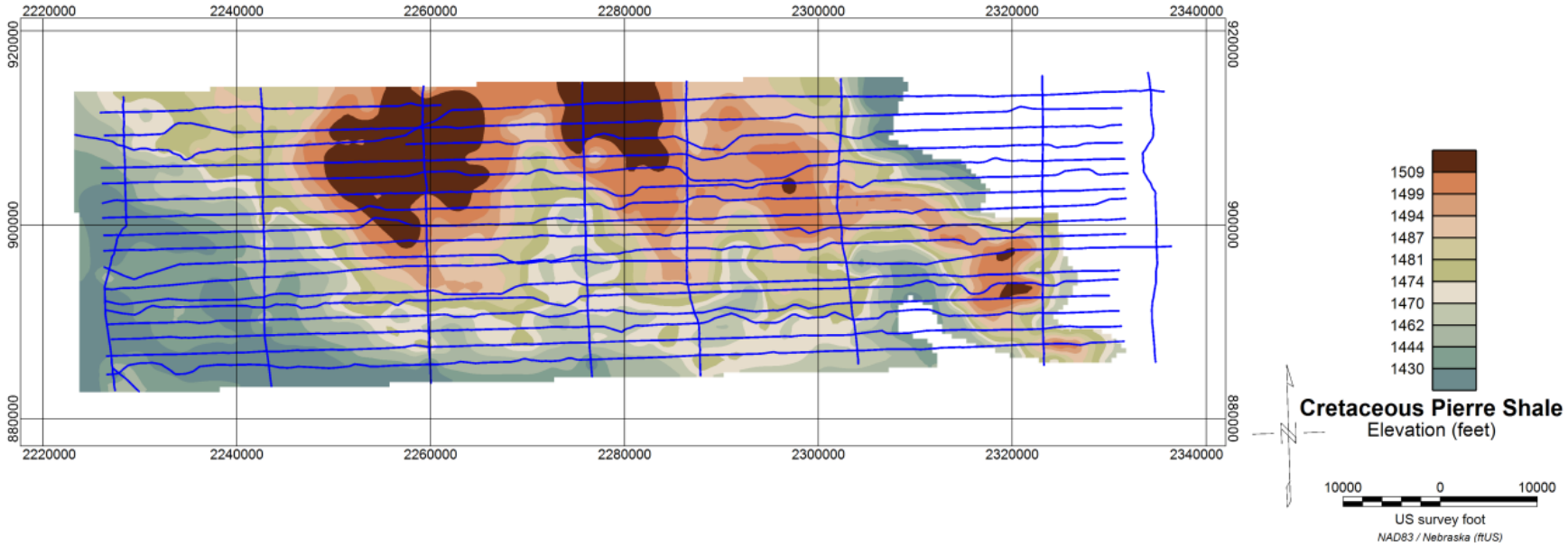


Figure 3-12. Map of the elevation of the top of the Cretaceous Pierre Shale (*Kp*) within the Pierce Block from the 2014, 2016, and 2018 survey. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

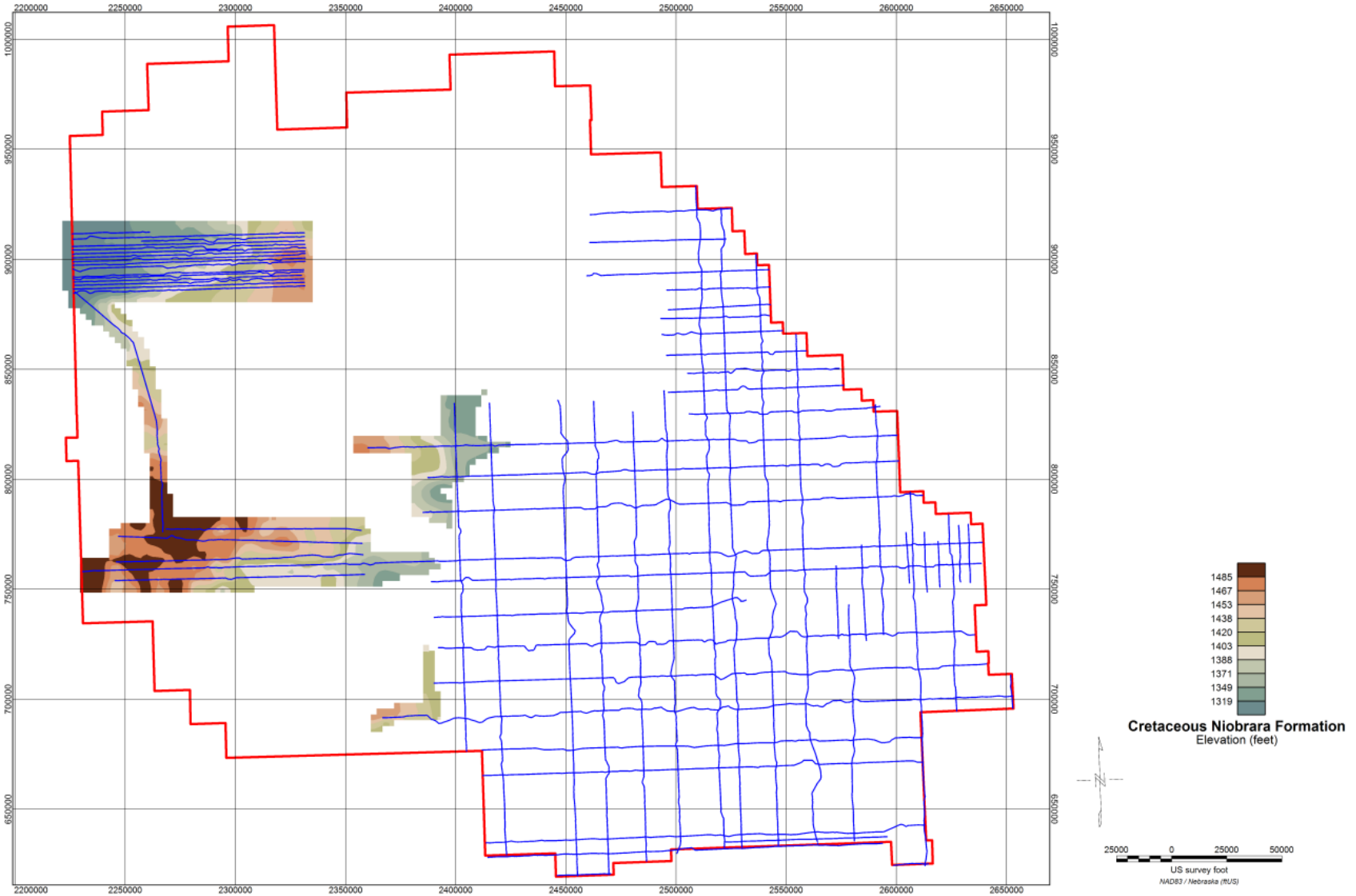


Figure 3-13. Map of the elevation of the top of the Cretaceous Niobrara Formation (*Kn*) within the LENRD (redline) from the 2018 survey. 2018 flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

For the Pierce Block an enhanced ***Kn*** surface was created due to the dense flight block using a cell size of 500 feet that was clipped to the area of the Pierce block. As indicated above in Section 3.1.1, additional lines were added from the 2014 AEM survey (Carney et al. 2015a) and the 2016 AEM survey (AGF, 2017) for the Pierce Block. Figure 3-14 is a map of the top of the ***Kn*** within the Pierce Block.

For the ***Kc*** top surface, 2,611 AEM picks were used in the grid including the adjacent picks from the 2016 AEM data (AGF, 2017). The cell size was set to one-half mile or 2,640 feet and the cells to extend beyond was set to 5. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the interpreted erosional contact and then clipped again to the LENRD survey area. On the margins of the survey area some areas are blank due to lack of data. Figure 3-15 is a map of the elevation of the top of the ***Kc*** within the LENRD survey area. For the Pierce block an enhanced ***Kc*** surface was created due to the dense flight block using a cell size of 500 feet that was clipped to the area of the Pierce block. As indicated above in Section 3.1.1, additional lines were added from the 2014 AEM survey (Carney et al., 2015a). and the 2016 AEM survey (AGF, 2017) for the Pierce Block. Figure 3-16 is a map of the top of the ***Kc*** within the Pierce Block.

For the ***Kgg*** top surface 1,624 AEM picks were used in the grid including the adjacent picks from the 2016 AEM data (AGF, 2017). The cell size was set to one-half mile or 2,640 feet and the cells to extend beyond was set to 5. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the interpreted erosional contact and then clipped again to the LENRD survey area. On the margins of the survey area some areas are blank due to lack of data. Figure 3-17 is a map of the elevation of the top of the ***Kgg*** within the LENRD survey area.

For the ***Kd*** top surface 1,924 AEM picks were used in the grid including the adjacent picks from the 2016 AEM data (AGF, 2017). Additional, picks were added from the 2014 AEM flights (Carney et al. 2015a) in and around Oakland, Nebraska as indicated in Section 3.1.1. The cell size was set to one-half mile or 2,640 feet and the cells to extend beyond was set to 5. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the LENRD survey area. On the margins of the survey area some areas are blank due to lack of data. Figure 3-18 is a map of the elevation of the top of the ***Kd*** within the LENRD AEM survey area.

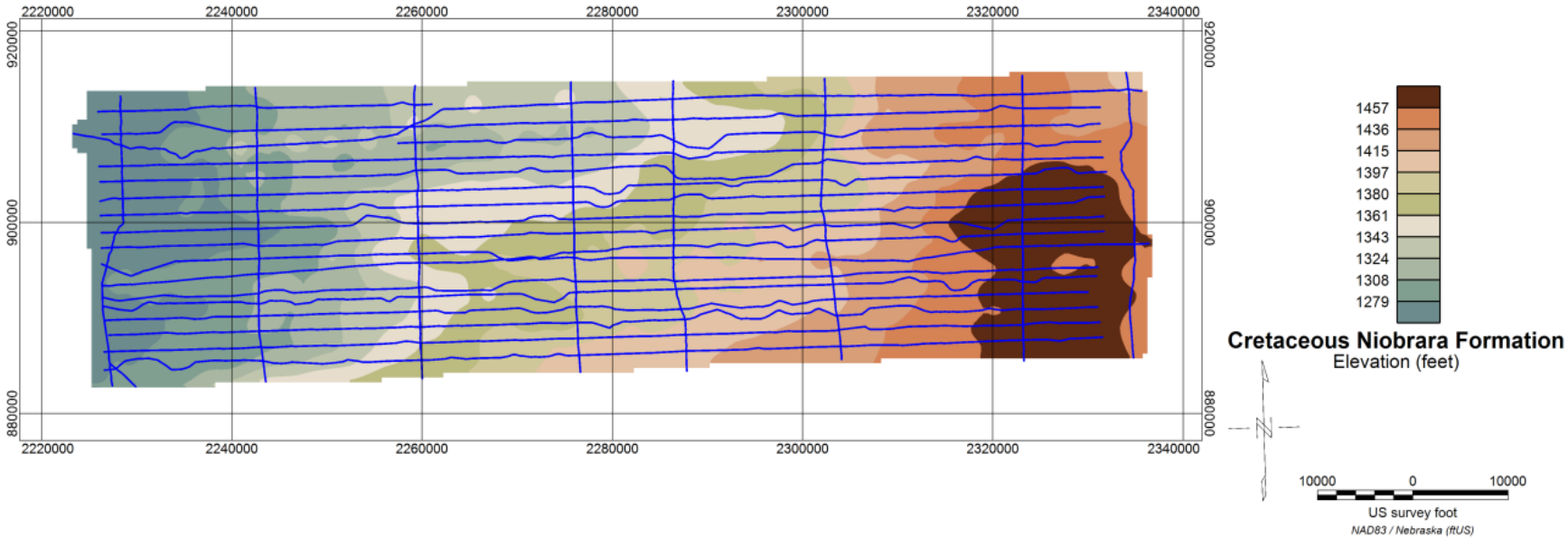


Figure 3-14. Map of the elevation of the top of the Cretaceous Niobrara Formation (*Kn*) within the Pierce Block from the 2014, 2016, and 2018 survey. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

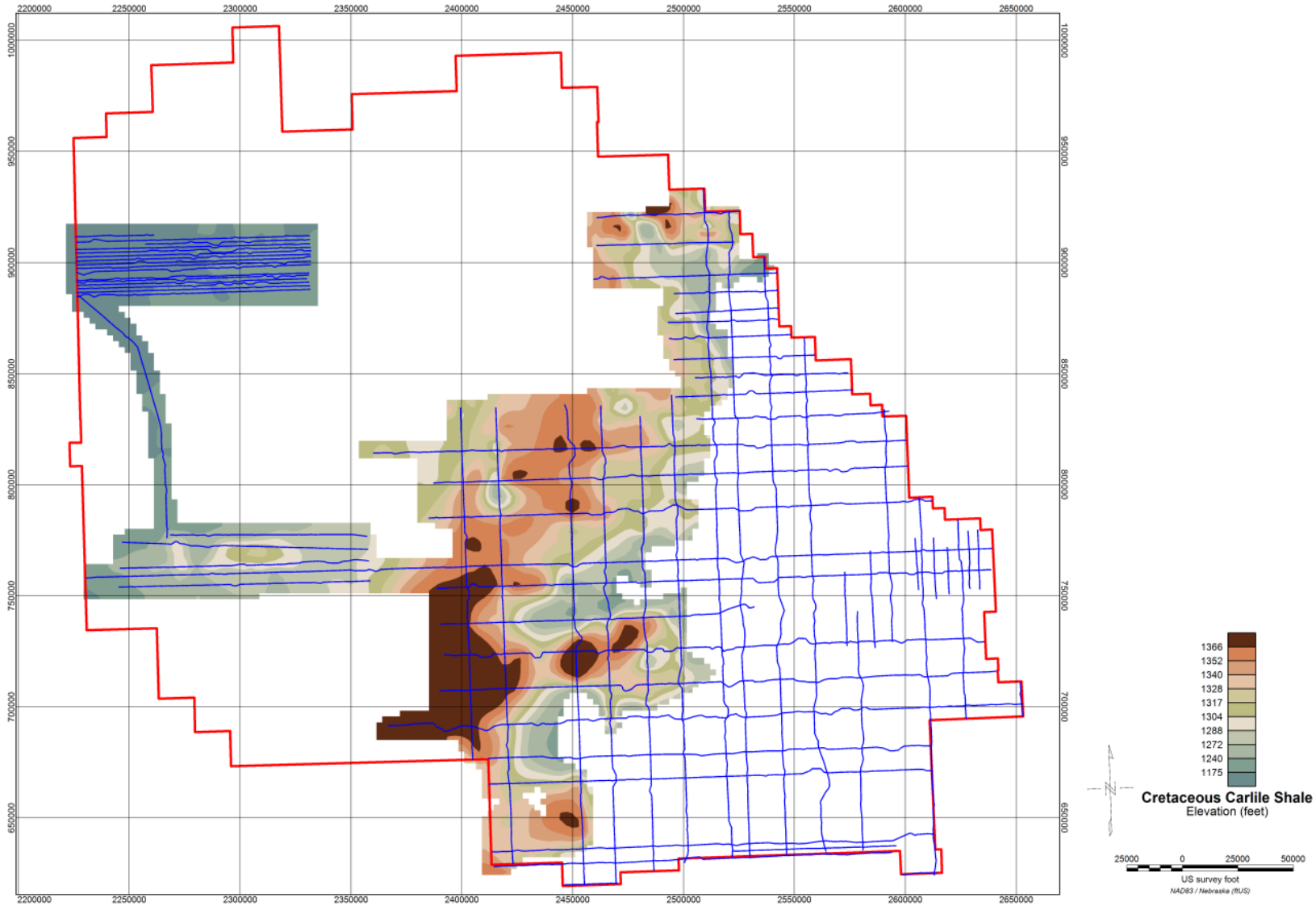


Figure 3-15. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the LENRD (redline) from the 2018 survey. 2018 flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

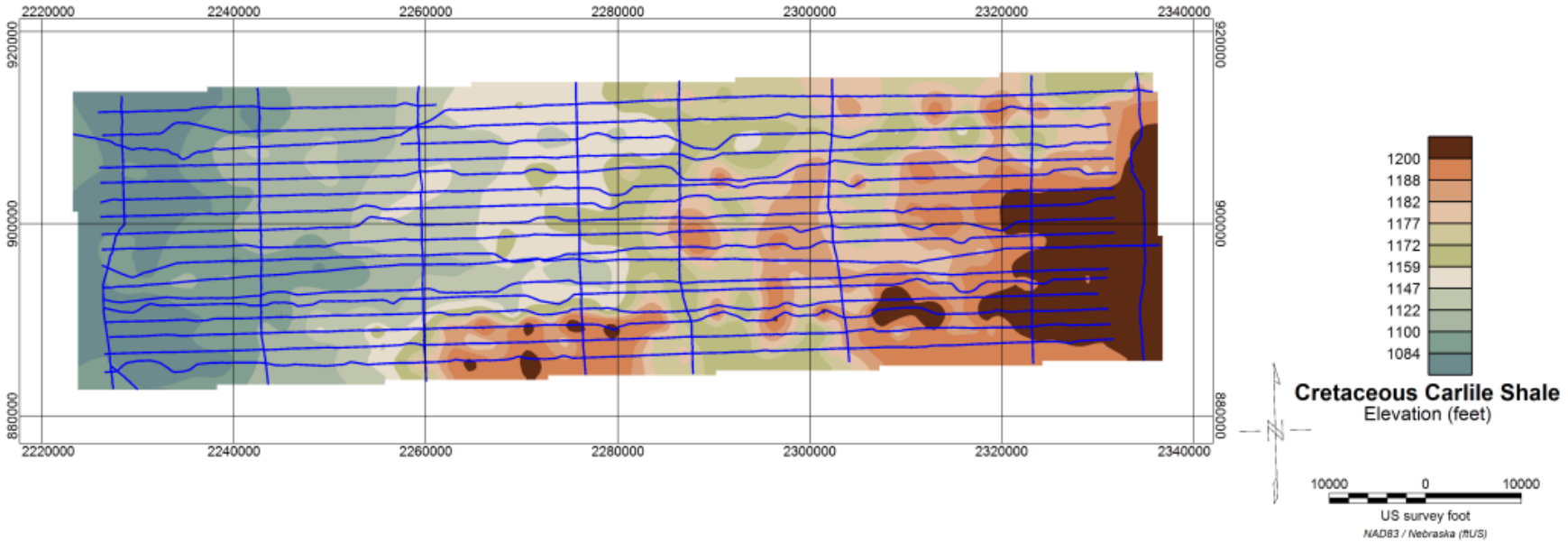


Figure 3-16. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the Pierce Block from the 2014, 2016, and 2018 survey. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

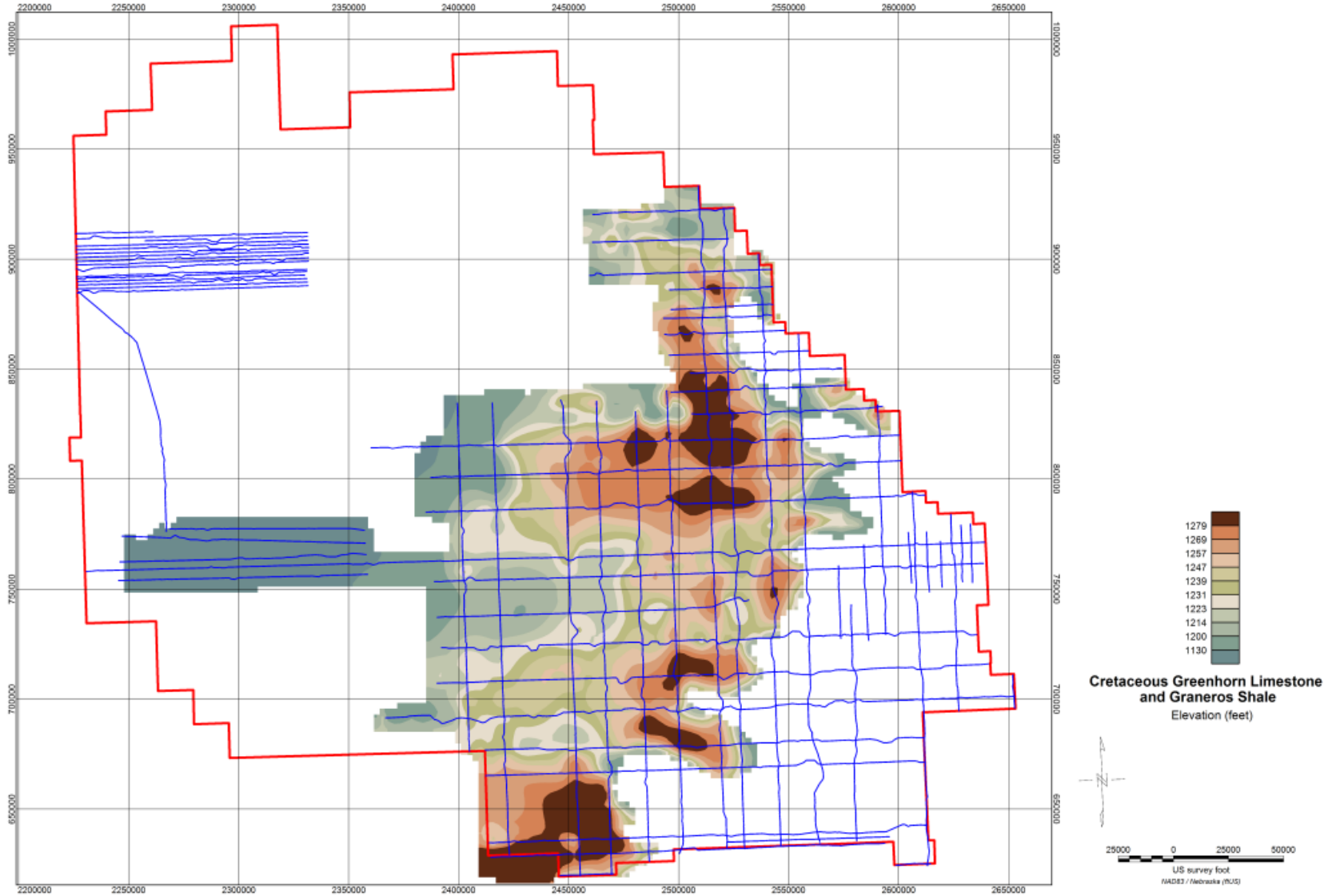


Figure 3-17. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the LENRD (redline) from the 2018 survey. 2018 flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

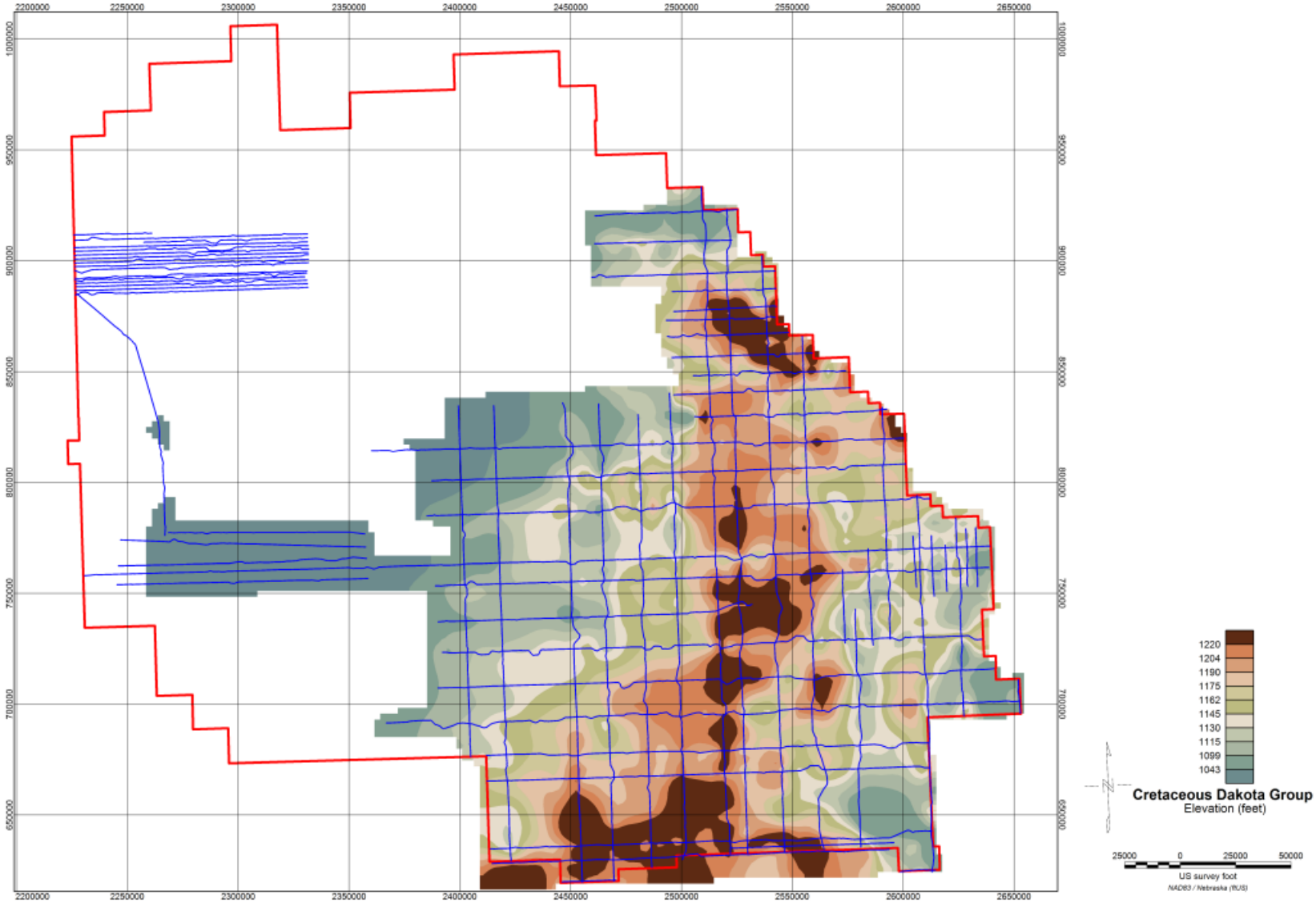


Figure 3-18. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the LENRD (redline) from the 2018 survey. 2018 AEM flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

For the undifferentiated Pennsylvanian (***IP***) top surface 534 AEM picks were used in the grid. The cell size was set to one-half mile or 2,640 feet and the cells to extend beyond was set to 5. All other parameters were either left as the default or blank. The large extended area was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. The grid was then clipped to the LENRD survey area. On the margins of the survey area some areas are blank due to a lack of data. Figure 3-19 is a map of the elevation of the top of the ***IP*** within the LENRD survey area.

The Cretaceous bedrock or the base of the Quaternary (***Q***) and Tertiary Ogallala (***To***) aquifer throughout the LENRD is a combination of the ***Kp, Kn, Kc***, ***Kgg,*** and ***Kd*** surfaces. The ***Kp, Kn, Kc*** and ***Kgg*** are successively eroded off toward the east with the ***Kd*** the last Cretaceous unit on the eastern side of the LENRD. To construct the top of bedrock or the base of the aquifer system the four surfaces were combined into one surface at 2,640 ft cell size. The Cretaceous bedrock grid was then clipped to the LENRD survey area (Figure 3-20). A Cretaceous bedrock grid was also created for the Pierce Block that is composed of the ***Kp*** and the ***Kn***. The cell size of the grid was set to 500 feet and the area was clipped to the boundary of the Pierce Block (Figure 3-21).

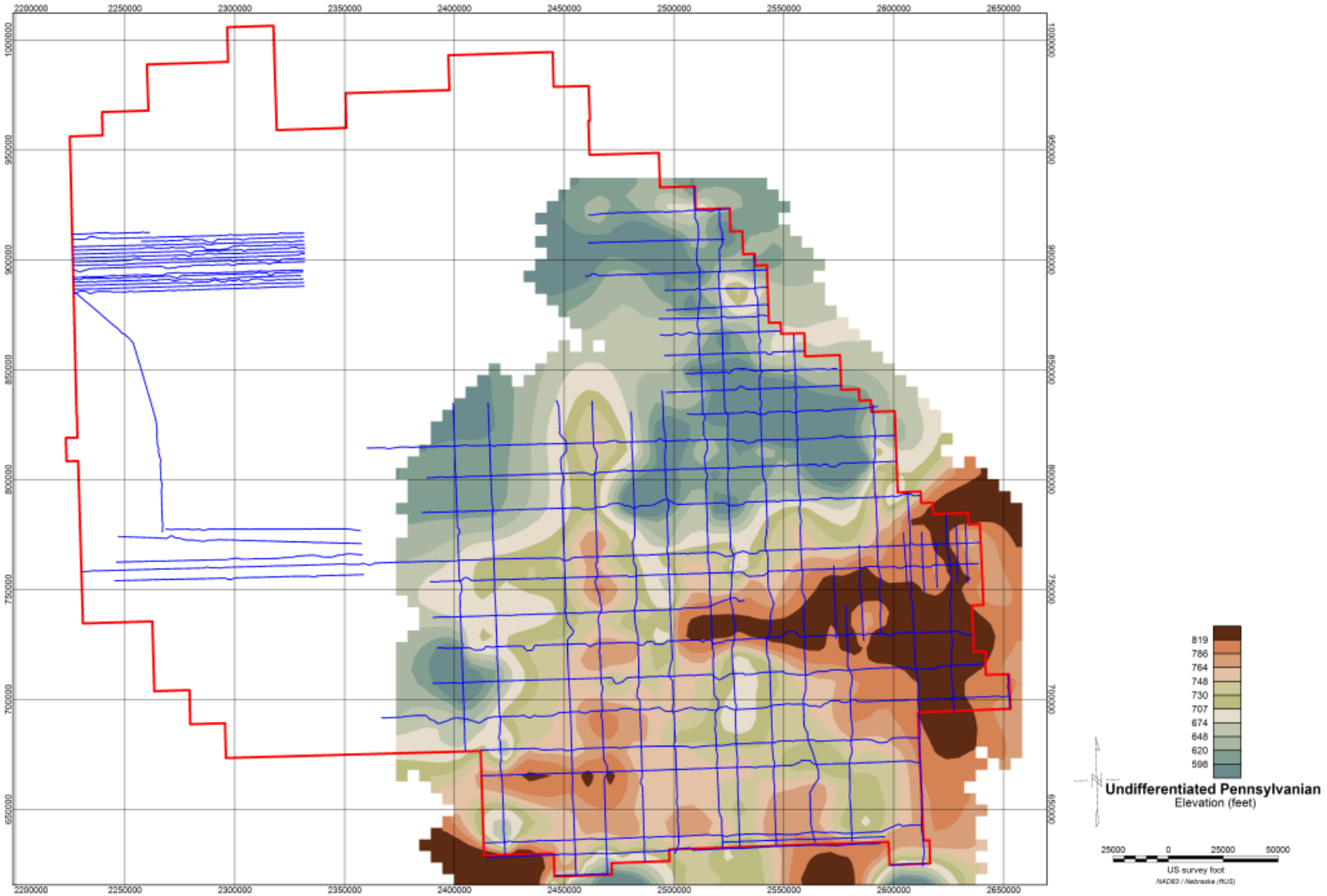


Figure 3-19. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the LENRD (redline) from the 2018 survey. 2018 flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

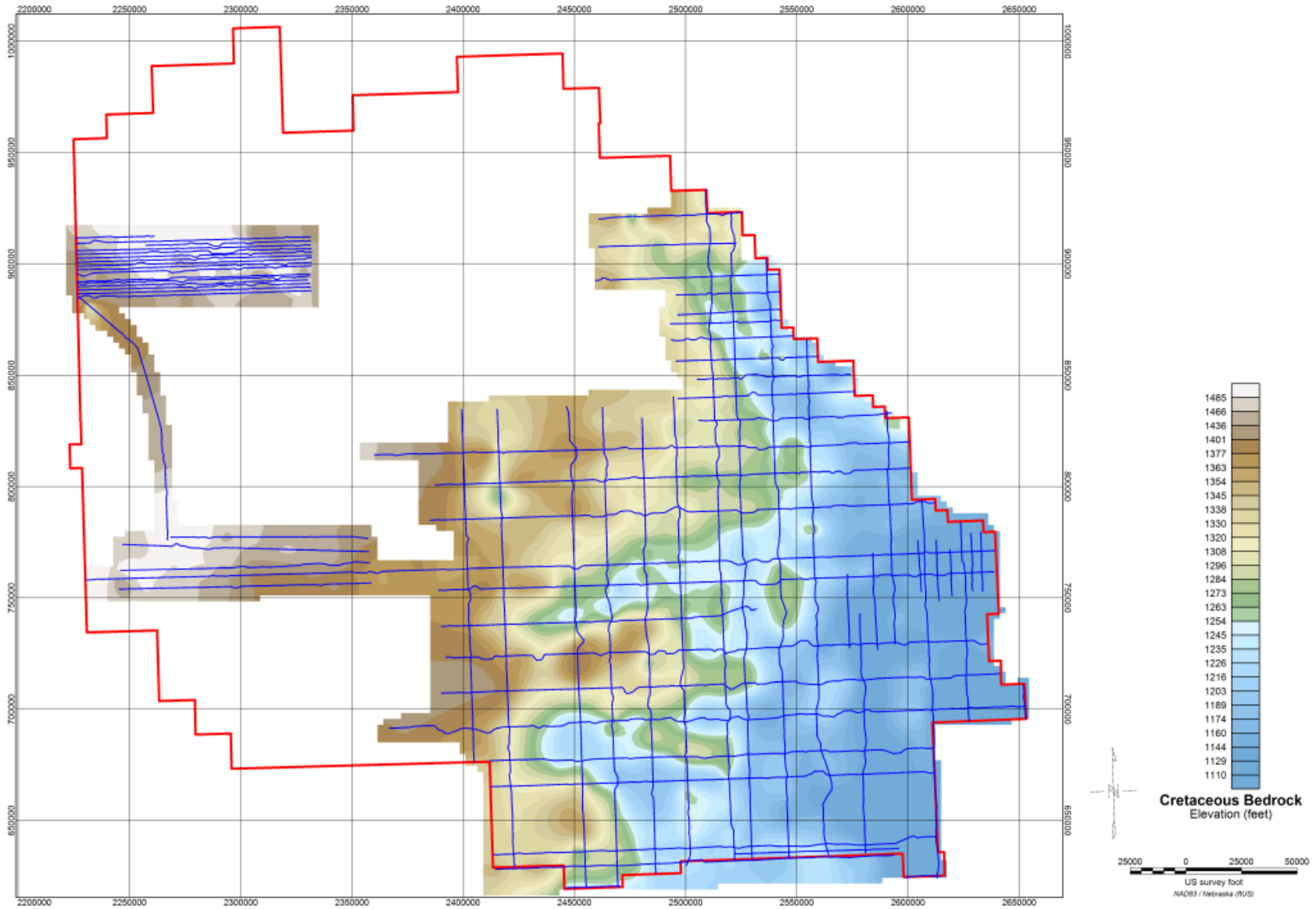


Figure 3-20. Map of the elevation of the top of the Cretaceous bedrock within the LENRD (redline) from the 2018 survey. 2018 flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

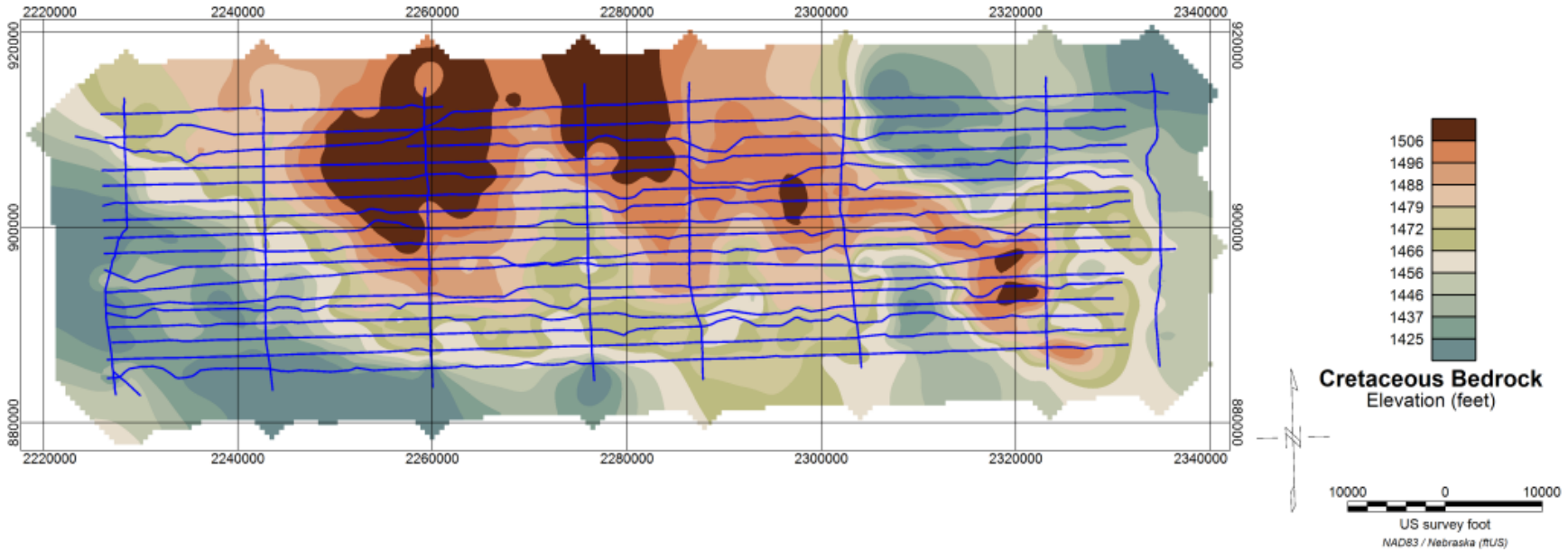


Figure 3-21. Map of the elevation of the top of the Cretaceous bedrock within the Pierce Block from the 2014, 2016, and 2018 survey. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

Following construction of the Cretaceous bedrock surface, the consolidated and unconsolidated ***Q***/***To*** deposits were isolated within the AEM data. The aquifer and non-aquifer materials in the Quaternary and Tertiary system were separated by four major resistivity thresholds selected in Datamine Discover Profile Analyst (Datamine Discover, 2018). These ranges include less than 12 ohm-m, representing non-aquifer materials ("aquitard"- primarily glacial till, loess), 12-20 ohm-m, representing marginal aquifer deposits with potential for interlayered silt and clay, 20-50 ohm-m, indicating the Quaternary/Tertiary system's aquifer materials composed predominantly of sands and gravels, and an interval of 50 ohm-m or greater, indicating the coarsest, sand-rich intervals within the aquifer (further discussion regarding the selection of these threshold ranges is provided in Carney et al. (2015a). Results of these interpretations can be found in Appendix 1 – 2D Profiles and Surfaces.

Pierce Block grids were prepared of the thicknesses of the Quaternary (***Q***) (Figure 3-22) and the Tertiary Ogallala Group (***To***) (Figure 3-23) by subtracting the top of the ***To*** (Figure 3-5) from the DEM (Figure 3-3) and, subsequently, the top of the Cretaceous bedrock (Figure 3-21) from the top of the ***To*** Figure 3-5).

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 mapped into the cross-sections. 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 2018 LENRD AEM survey and local conditions have likely deviated in areas with variable topography. The water table in the LENRD area is close to the surface in some of the areas. Thus, a topographic correction was required to adjust the water table height to be below the surface topography. The original water table contour lines were gridded at a 1,000 ft cell size using the OM MCG 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 3-3) of the LENRD survey area. In areas where the water table was greater than the topography the water table was set to an elevation of the topography minus three feet. The grid was then clipped to the LENRD survey area. The result is presented in Figure 3-24. Using the derived water table, the thickness of the saturated thickness of the Pierce Block (Figure 3-25) could be calculated by subtracting the water table (Figure 3-24) from the Cretaceous bedrock (Figure 3-21).

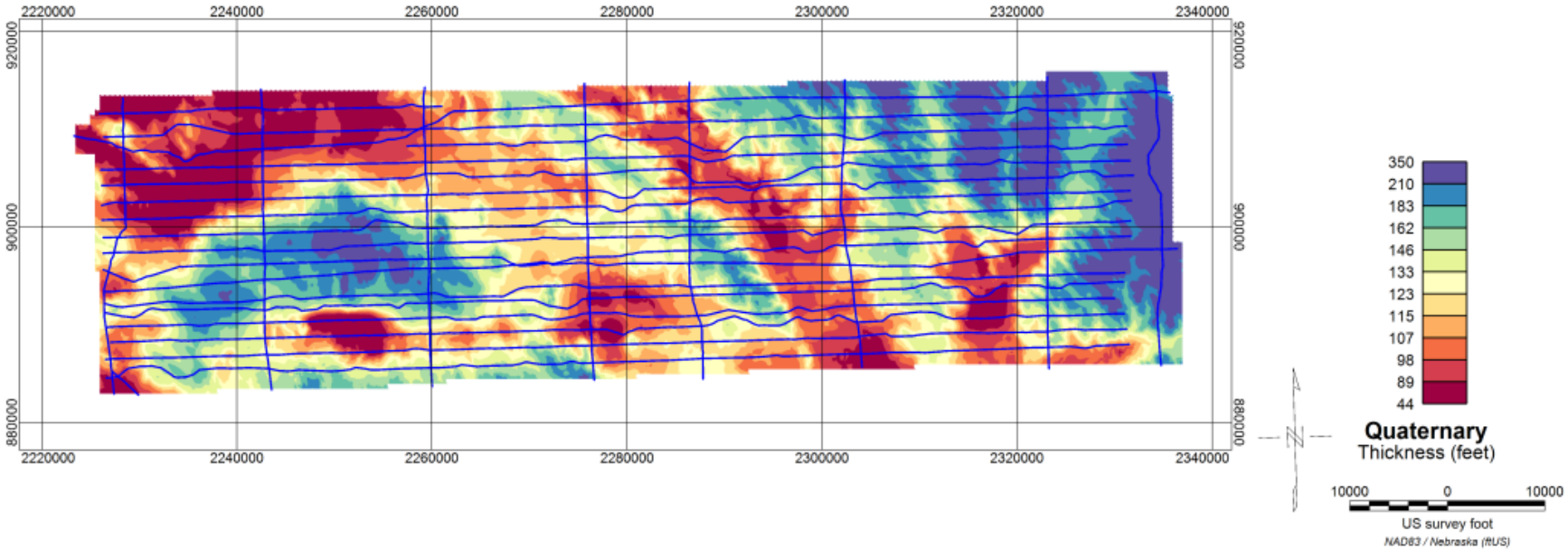


Figure 3-22. Map of the thickness of the Quaternary (*Q*) within the Pierce Block from the 2014, 2016, and 2018 survey. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

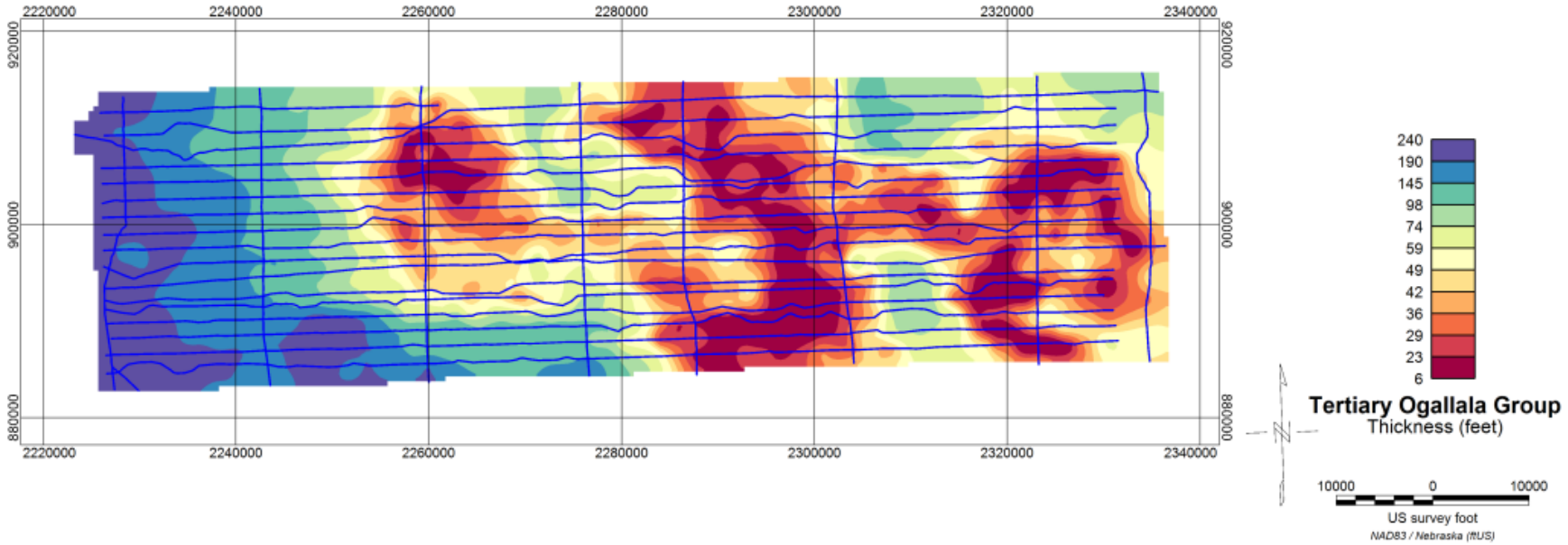


Figure 3-23. Map of the thickness of the Tertiary Ogallala Group (*To*) within the Pierce Block from the 2014, 2016, and 2018 survey. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

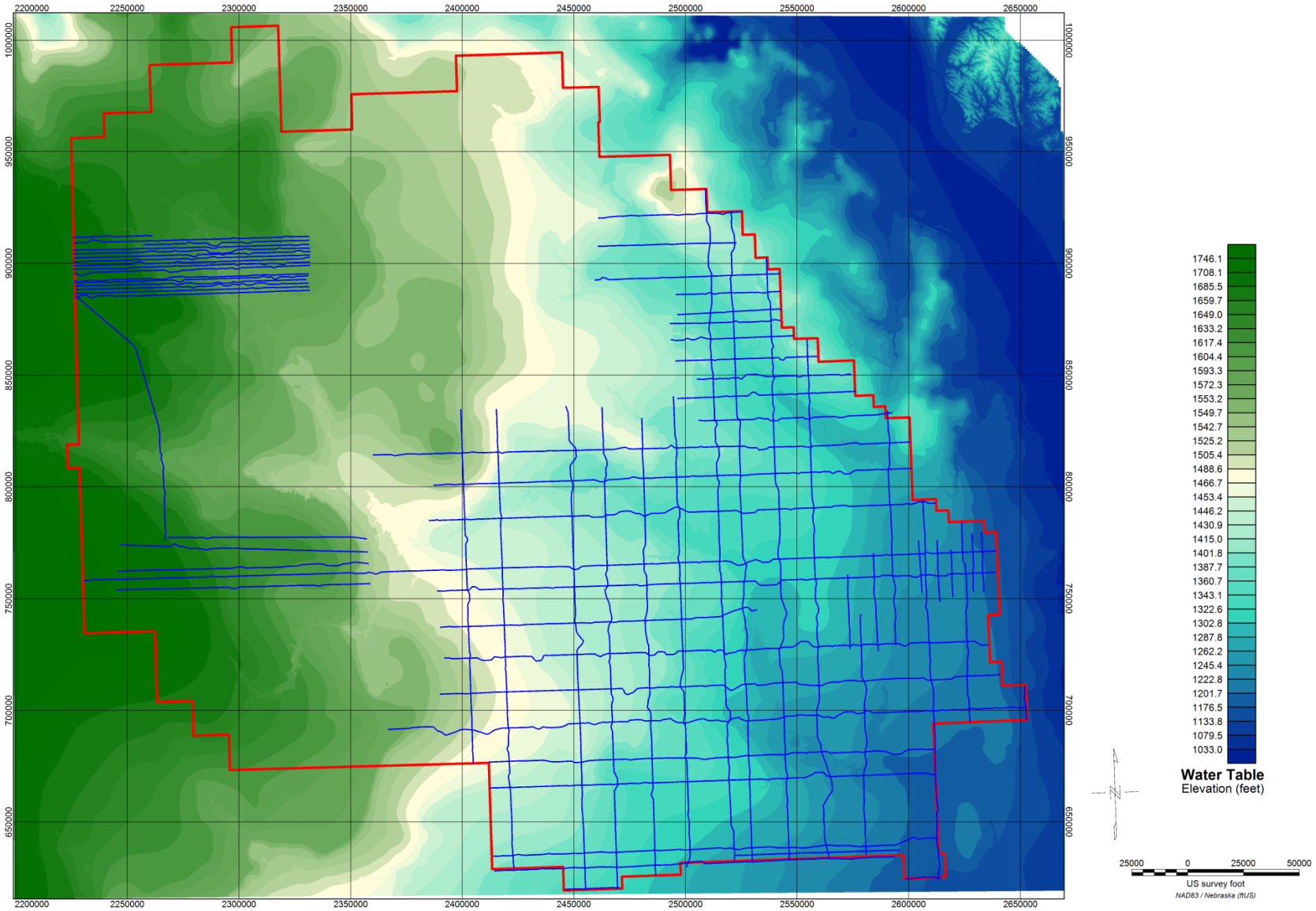


Figure 3-24. Map of the elevation of the 1995 CSD water table within the LENRD survey area (redline). Major streams are indicated for reference. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

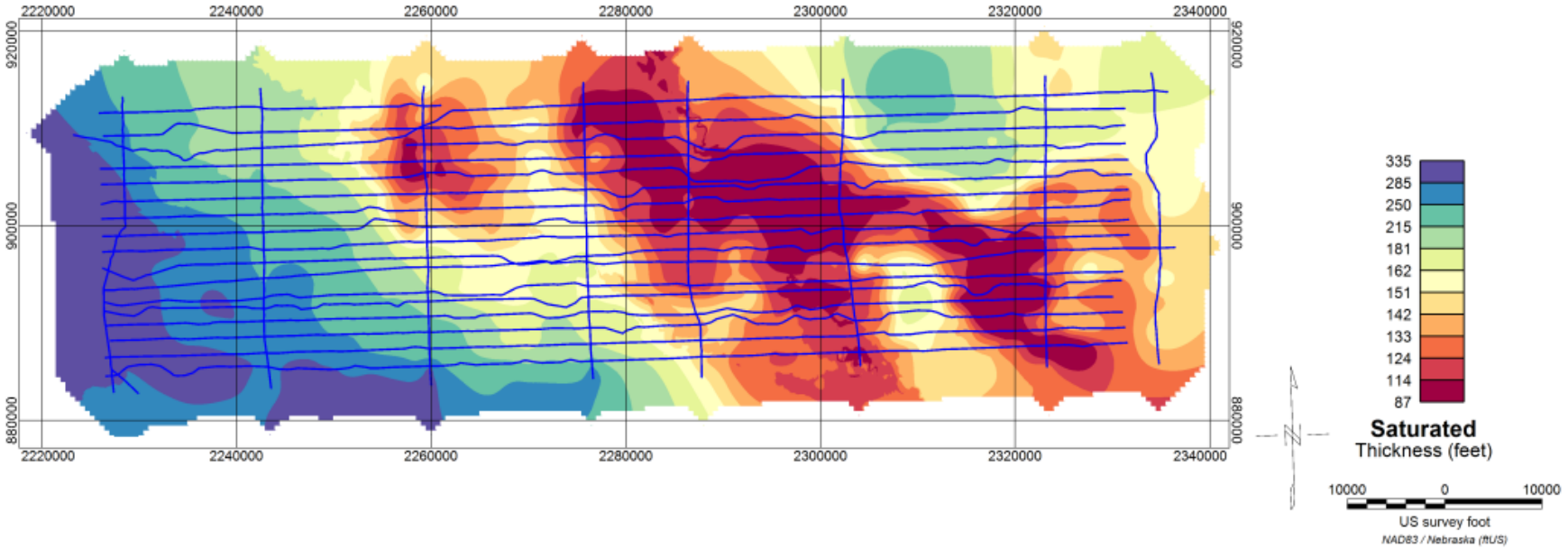


Figure 3-25. Map of the thickness of the Saturated Quaternary (*Q*) and the Tertiary Ogallala Group (*To*) within the Pierce Block from the 2014, 2016, and 2018 survey. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

3.1.5 Create 3D Interpretative Voxel Grids

A voxel grid was completed for the Pierce Block. The voxel grids were made using a 500 feet grid cell size and the model layer thickness provided in Table 2-3 in Section 2.5. A minimum curvature method was used within Datamine Discover PA (Datamine Discover, 2018). All layers were referenced to their depth from the surface and then projected onto the area DEM. After the grid was calculated, the grid was split at the top of the Tertiary Ogallala Group (***To***) and at the top of the Cretaceous bedrock, composed of ***Kp*** and ***Kn***, using the surface elevation grids discussed above in Section 3.1.4. These resulting voxel grids can be used to explore the distribution of the aquifer materials within the area in 3D. Specifically, these grids allow for visual inspection of the volume of materials above the bedrock as well as surface materials. The grid was also split at the water table providing a voxel of the volume of material above and below the water table.

The ***Q*** and ***To*** materials can also be separated by the thresholds developed above for the four lithology classes. Utilizing the voxel grids of the ***Q*** analysis, thicknesses of the different materials within the section can be determined. Figure 3-26 is a plot of the ***Q*** and ***To*** material above the Cretaceous bedrock looking to the north. Figure 3-27 is a plot of ***To*** material only, looking to the northeast. The voxel grids can be found in *Appendix 3-Deliverables**Voxel*.

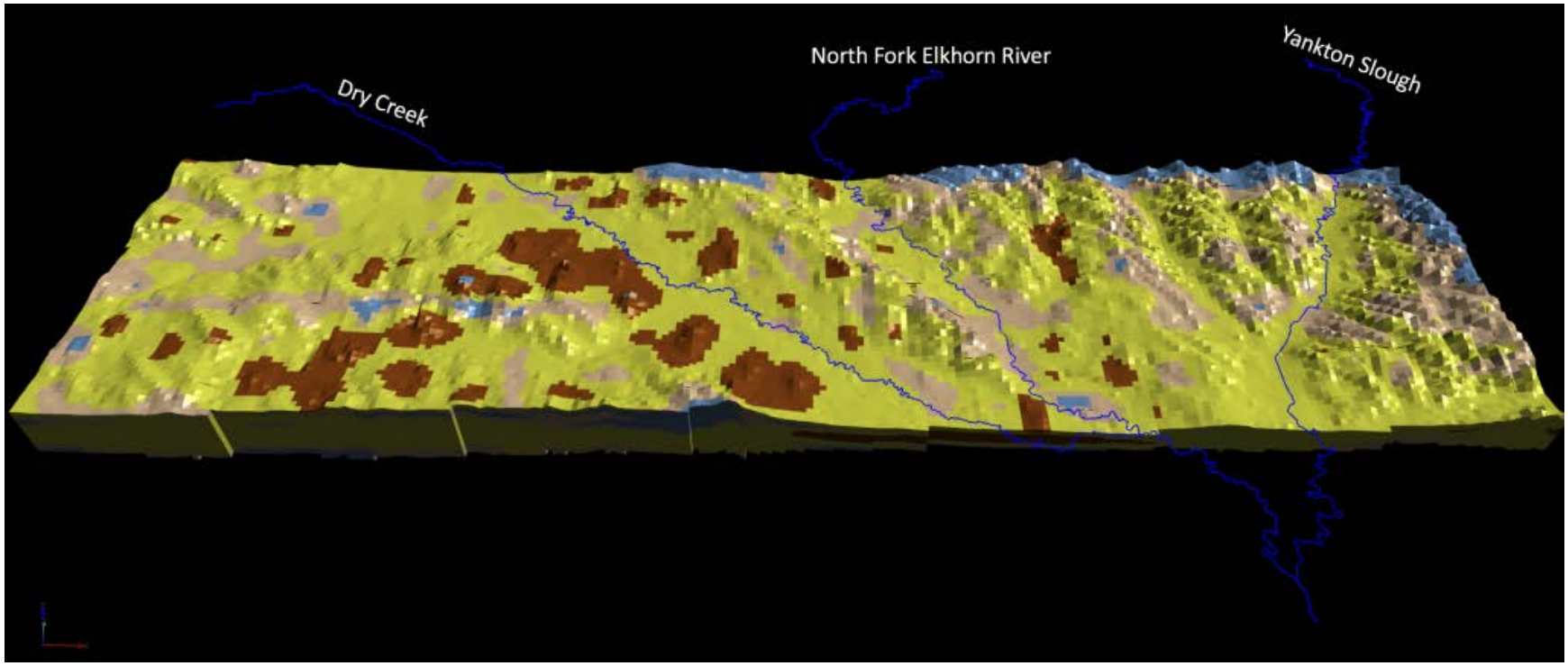


Figure 3-26. Voxel model of the aquifer material types for the Pierce Block of the Quaternary (*Q*) and the Tertiary Ogallala Group (*To*). Vertical scale is 15 x. Major streams are indicated by blue lines.

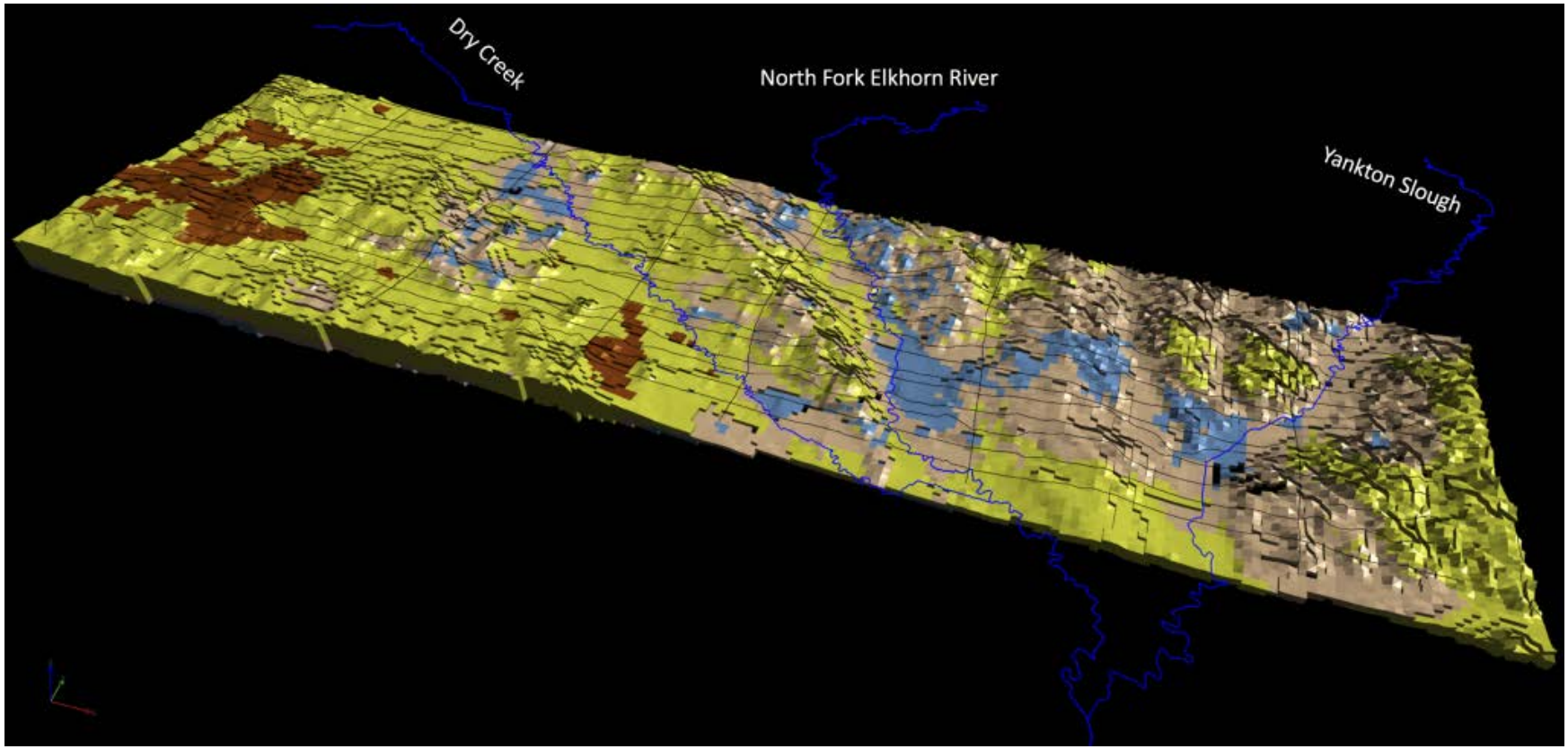


Figure 3-27. Voxel model of the aquifer material types for the Pierce Block of the Tertiary Ogallala Group (*To*). Vertical scale is 15 x. Major streams are indicated by blue lines. Black thin lines indicate flight lines.

3.2 Resistivity-Lithology Relationship

3.2.1 Quaternary/Tertiary Ogallala Aquifer System

A critical aspect of a geophysical survey, for whatever purpose, is assessing the nature of the material detected by the geophysical method applied in the investigation. In regard to the LENRD 2018 survey, assessment of the sediment character in both the Quaternary/Tertiary Ogallala aquifer system and the consolidated bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A numerically robust assessment of the resistivity thresholds used to characterize non-aquifer, marginal, and aquifer, including sand-rich intervals was calculated. This allows for the characterization of the ranges of resistivities present in the major geologic units described in this report. It should be noted that this analysis encompasses all Quaternary/Tertiary Ogallala (***Q/To***) aquifer system and bedrock data from the ENWRA project area (Carney et al., 2015a). The original analysis that was completed as part of Carney et al. (2015a) included the overall area of the LENRD. This analysis has been used in the current report for the categorization of the Quaternary/Tertiary Ogallala aquifer system.

Data for this analysis was utilized from locations across the ENWRA reconnaissance line area (Carney et al., 2015a). The relationship between resistivity and lithology type was assessed by performing an association function that linked nine lithologic descriptor codes for ***Q/To*** sediments used in the CSD test hole lithologic characterization with the resistivity values across that depth interval as indicated in 58 high-graded resistivity logs applied in the AEM data inversion (25 from the southern area, 33 from the northern area). With this approach, several thousand points became available for each lithologic description in the test holes used in this analysis. From this list of associated resistivity levels and pre-categorized lithologies, statistical analyses were performed to aide in defining the various thresholds used to determine the aquifer material type in the project area subsurface. Details of the analysis can be found in Carney et al. (2015a). A summary of the resistivities and the color scale used in the remainder of this report is shown in Figure 3-28.

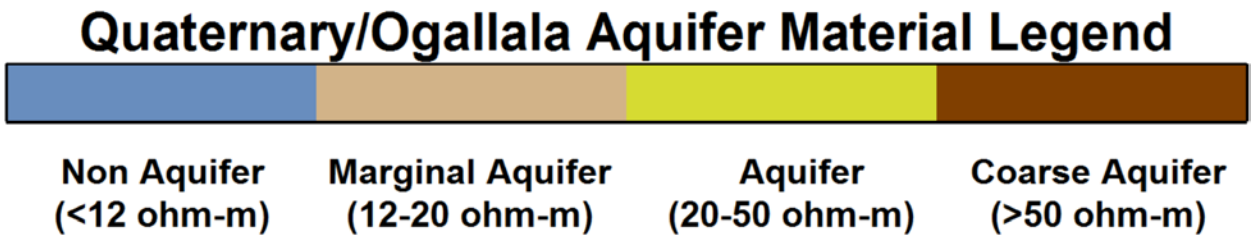


Figure 3-28. Plot displaying the resistivities by major aquifer material color categories (blue- non-aquifer material, tan- marginal aquifer, yellow- aquifer, brown- coarse intervals of the aquifer material).

3.2.2 Bedrock Resistivity Thresholds

The bedrock in the LENRD analyzed in this study includes the ***Kp, Kn, Kc, Kgg, and Kd.*** These were included to demonstrate the overall distribution in resistivity of bedrock materials across the entire LENRD. The median resistivity values for each unit are 9 ohm-m for the ***Kp***, 38 ohm-m for the ***Kn,*** 16 ohm-m for the ***Kc*** and the ***Kgg*** lumped together, and 35 ohm-m for the ***Kd*** (Carney et al., 2015a). For the ENWRA study, the ***Kc*** and the ***Kgg*** were interpreted together. For this study, the proximity of the ***Kgg*** to the surface allows for a more accurate interpretation. The low resistivity character of 3 to 9 ohm-m for the ***Kc*** made the interpretation of the ***Kc*** relatively straight forward. The ***Kgg*** showed a more resistive character on the order of 15 ohm-m. The ***Kd*** within the LENRD displayed some low resistivities on the order of 9 to 20 ohm-m indicating either clay/shale dominant lithology or the presence of saline waters mostly in the western portions of the LENRD. Above 20 ohm-m the ***Kd*** displays characteristics of sand and sandstone dominant materials. (Carney et al., 2015b).

3.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs

Two recent CSD borehole geophysical resistivity logs were selected from the LENRD survey area for comparison with the AEM inversions. These are CSD test holes *01-LE-18* and *02-LE-18*. These logs were acquired with modern equipment after the CSD logging tool was recently repaired and calibrated at the manufacture (personal communication K. Cameron, ENWRA Coordinator, August 2018).

Figure 3-29 is a plot of *01-LE-18* 16-inch and 64-inch normal resistivity log plotted with the inverted AEM resistivity for line L908300. *01-LE-18* is located 607 feet from line L908300 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the resistivity is generally good. The high resistivity peaks in the 16-inch and 64-inch logs at ~300 ft and ~400 feet are not imaged by the AEM, but rather a board increase in the resistivity is indicated from ~250 to ~625 feet. This encompasses the zones of the sand in the ***Q*** sections as well as the ***Kgg*** and portions of the ***Kd***. The DOI is indicated as a shaded box derived from Christiansen and Auken (2012). However, the point that the AEM diverts from the resistivity logs is ~640 feet lower than the numerically calculated DOI. As a comparison, the 2014 AEM regional interpretation (Carney et al., 2015b) predicted that the ***Kgg*** was at a depth of 381 feet, ***Kd*** was at 450 feet, and the ***IP*** was 927 feet.

The results of the drilling of *01-LE-18* before the 2018 AEM flights were completed resulted in the ***Kgg*** at 412 feet, the ***Kd*** at 462 feet, and the ***IP*** at 867 feet. This results in differences between the borehole logging of *01-LE-18* and the AEM interpretation of 31 feet in the ***Kgg***, 12 feet in the ***Kd***, and ***60*** feet in the ***IP***. This translates to errors of 2.9 % in the ***Kgg***, 2.6% in the ***Kd***, and 6.9% in the ***IP***. Note that was no line over the area of the borehole at the time of the 2014 regional interpretations.

Figure 3-30 is a plot of *02-LE-18* 16-inch and 64-inch normal resistivity log plotted with the inverted AEM resistivity for lines L908700, L1004600, and L1004700. *02-LE-18* is located several miles from the closest 2018 AEM flight lines: 8,714 feet from line L908700, 10,987 feet from L1004600, and 7,389 feet from L1004700. The AEM soundings are selected as being the closest points to the borehole geophysical log. The agreement in the resistivity is generally fair. While the high resistivity zones in the 16-inch and 64-inch logs at ~125 feet and ~210 feet are not imaged by the AEM on lines L908700 nor L1004600, line

L1004700 does indicate a slight increase in the resistivity over that range. This encompasses the zones of the ***Kgg*** and portions of the ***Kd***. A larger resistive zone is indicated in L1004600 and L1004700 within the ***Kd*** from ~225 feet to ~610 feet. This is also indicated in the electrical logs with a high resistivity zone from ~380 to ~410 feet that is not detected in the AEM. The Upper and Lower DOI's are indicated as the top and bottom of the shaded box in the Figure 3-30 and are derived from Christiansen and Auken (2012). However, the point that the AEM diverts from the resistivity logs is ~680 feet lower than the numerically calculated Upper DOI. As a comparison, the 2014 AEM (Carney et al., 2015a) regional interpretation predicted that the ***Kgg*** was not present, ***Kd*** was at 218 feet, and the ***IP*** was 591 feet.

The results of the drilling of *02-LE-18* before the 2018 AEM flights were completed resulted in the ***Kgg*** at 99 feet, the ***Kd*** at 115 feet, and the ***IP*** at 678 feet. This results in differences between the borehole logging of *02-LE-18* and the AEM interpretation of 99 feet in the ***Kgg***, 103 feet in the ***Kd***, and 87 feet in the ***IP***. This translates to errors of 100 % in the ***Kgg***, 89% in the ***Kd***, and 13% in the ***IP***. The reader is reminded that borehole *02-LE-18* is many thousands of feet from the closest AEM sounding locations and it is reasonable that the local geology would vary over several thousand feet. Also note that there was no line over the area of the borehole at the time of the 2014 regional interpretations.

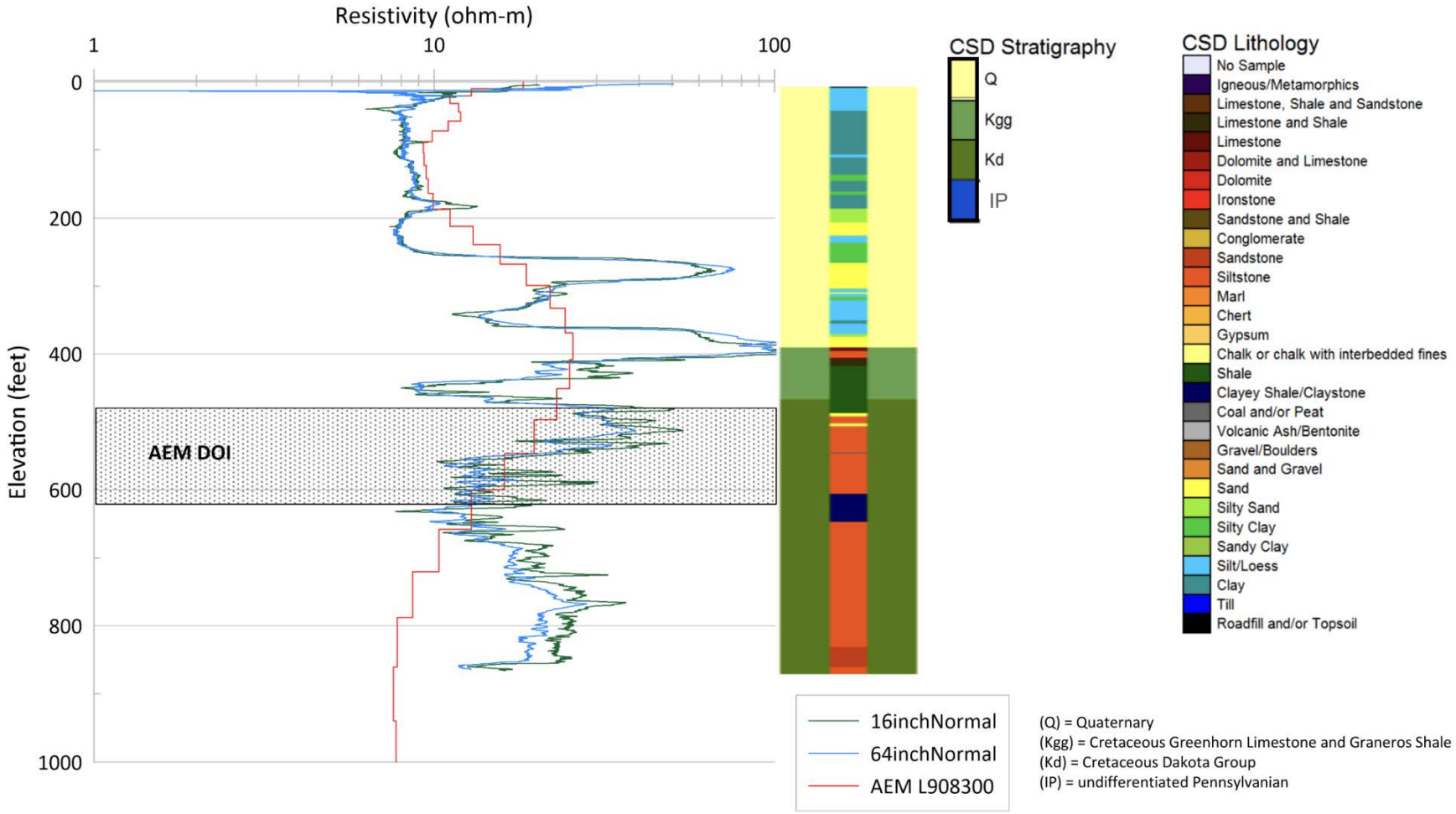


Figure 3-29. Graph of the *01-LE-18* 16-inch normal (green line) and 64-inch normal (blue line) resistivity log values and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *01-LE-18*. The shaded box indicates the Upper (top of box) and Lower (bottom of box) Depths of Investigation (DOI) as defined by Christiansen and Auken (2012).

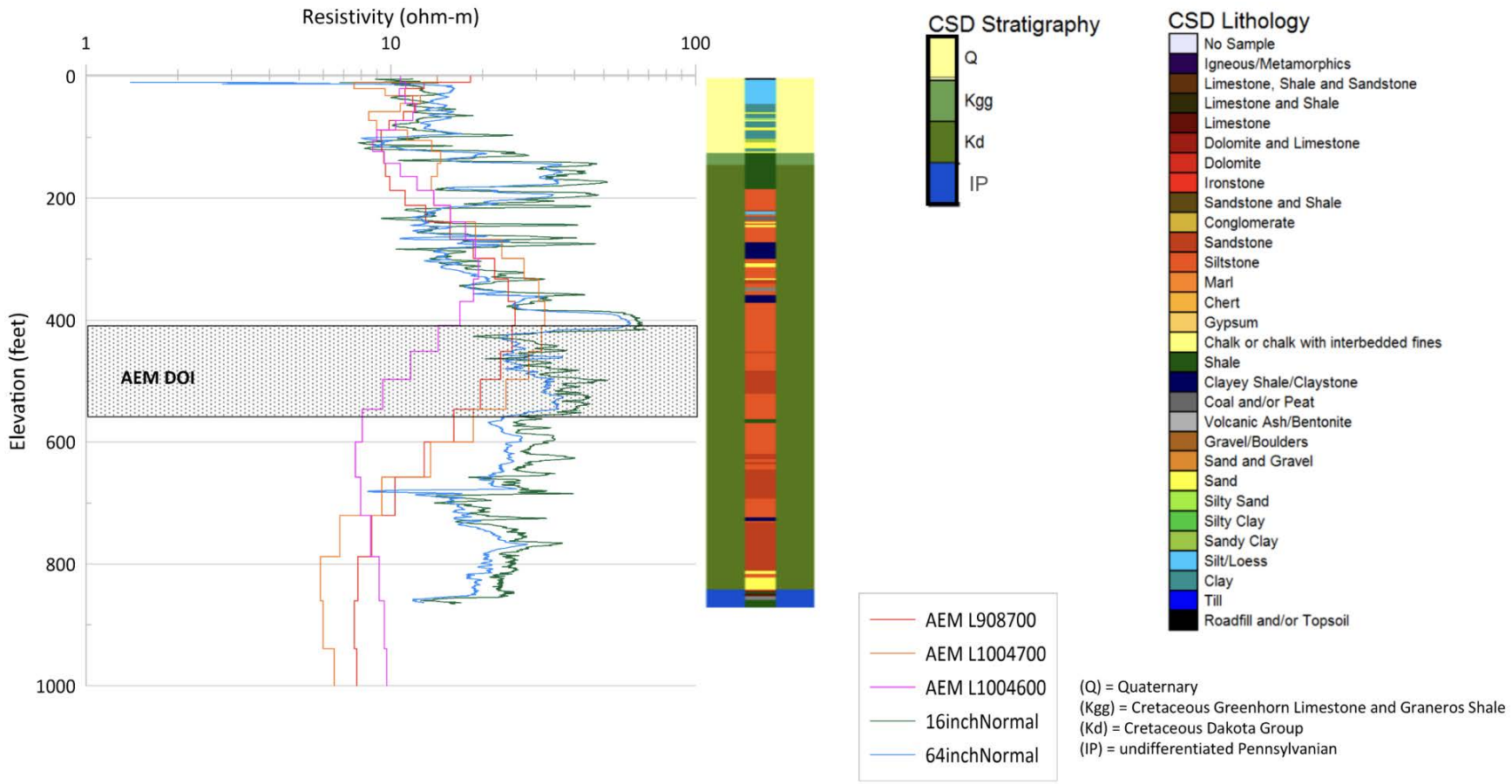


Figure 3-30. Graph of the *02-LE-18* 16-inch normal (green line) and 64-inch normal (blue line) resistivity log values and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *02-LE-18*. The shaded box indicates the Upper (top of box) and Lower (bottom of box) Depths of Investigation (DOI) as defined by Christiansen and Auken (2012).

3.3 Hydrogeological Framework of the LENRD 2018 AEM Survey Area

The 2018 survey continues to build upon the previous AEM survey efforts within LENRD since the Oakland 2007 survey (Smith et al., 2008) and continuing with the 2013 study of Clarkson and Howells (Abraham et al., 2013), the 2014 reconnaissance lines (Carney et al., 2015a), and the 2016 reconnaissance lines (AGF, 2017). These AEM-derived results provide new information on the hydrogeology in areas that was previously unknown to the LENRD or were only known to a limited extent from just the borehole information. The survey completed in 2018 by AGF provides the basis for this section of the report. The following highlights the additions to the current multi-year project being conducted by the LENRD and ENWRA.

The 2018 AEM survey reveals variability in the Quaternary (***Q***) deposits across the LENRD AEM survey area. When combined with the ***To***, they represent the aquifer materials in the AEM survey area, where saturated. The Pierce County Block, a dense flight block, is presented later in this report. In the region of the reconnaissance lines, ***To*** is generally thickest in the west in and near Madison and Pierce counties and is thin to absent in the eastern regions of the 2018 AEM survey area. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units in the west and the ***Q*** makes up the aquifer materials in the east. Figure 3-31, looking north, and Figure 3-32, looking south, display in 3D the overall distribution of aquifer materials across the LENRD AEM survey area reconnaissance lines.

The subsurface distribution of ***Q*** materials can generally be characterized into two somewhat overlapping, but distinct, areas distributed over various locations within the AEM survey area. These areas are glacial till material that is dominated by marginal aquifer and non-aquifer deposits mostly in the middle to east side of the survey area and aquifer and coarse aquifer materials found predominately on the west side and along the stream valleys, often associated with prevalent alluvial deposits. Profile L907400 (Figure 3-33) shows an example of the different geologic units in the survey area: ***Q***, ***To***, ***Kn***, ***Kc***, ***Kgg***, ***Kd*** and ***IP***. The ***Kp*** is missing in this profile due to erosion. The youngest Cretaceous units shown are in the west and the oldest are in the east dipping from east to west. ***To*** is present in the west and the pinches out to the east with ***Q*** sediments covering all units.

3.3.1 The Quaternary and Tertiary Aquifer

The ***Q*** and ***To*** aquifer materials of the survey area are composed of unconsolidated non-aquifer (blue color in figures), marginal aquifer (tan color in figures), aquifer (yellow color in figures), and coarse aquifer (brown color in figures) materials. These materials are composed predominantly of alluvial sediments in the Pierce and Madison County portions of the survey area and are mostly glacial, periglacial alluvial, and minor Quaternary alluvial deposits related to the current drainages in the eastern parts of the AEM survey area. In the eastern and southern parts of the AEM survey area, the ***Q*** aquifer materials are predominantly marginal to non-aquifer materials which are glacial till and loess interbedded with minor glacial outwash that can be more than 200 feet thick. The ***Q,*** and where ***To*** is present, aquifer materials are sitting on the ***Kp***, ***Kn***, ***Kc***, ***Kgg*** and ***Kd*** which are the Cretaceous bedrock aquicludes for the area. The thickness of the ***Q*** and ***To*** materials within the LENRD 2018 AEM survey area range from 25 to greater than 500 feet thick. The thickness of the ***Q*** *and* ***To*** materials increase

toward the west near a bedrock channel along the western border. The ***Q*** and ***To*** alluvial system can be very heterogeneous in places with a mix of all aquifer materials. When moving from west to east across the survey area, the ***To*** thins and is eroded off of the AEM survey area to the east. Near the western survey boundary to approximately 10-20 miles east of the boundary, the mix of ***Q*** and ***To*** aquifer and coarse aquifer materials act as the groundwater supply which is hydrologically connected to the surface water system in many areas.

Where the ***To*** is eroded off, the ***Q*** is a primary source of groundwater. On the far eastern edge of the survey area the ***Kd*** also serves as a primary source of groundwater discussed more later. The ***Q*** sediments can be hydrologically connected to the streams. Beginning east of the transition line in Figure 3-34, a change in the make up of the aquifer materials occurs from mostly aquifer and coarse aquifer material to marginal and non-aquifer materials. The marginal and non-aquifer materials are typically glacial tills and loess proximally located to near-surface loess deposits, basal silts and clays, and continuous layers of fine-grained material. These layers can locally act as aquicludes and prevent or inhibit hydrologic connection to streams, recharge areas, or serve as locally confining units.

Figure 3-35 presents an example of the confining units displayed as a 3D image. Several of these layers of marginal (tan color) and non-aquifer (blue color) materials are found in the central-west part of the survey area. This is a boundary condition within the groundwater flow system between the streams and the aquifer and coarse aquifer material on the eastern side of the survey area (the shaded area of the map). This occurs as a quick change in aquifer material types from west to east.

Figure 3-36 presents a profile view of line L1005601, a south to north flight line that illustrates hydrologic connection to the Elkhorn River of the ***Q*** and the ***Kd***. All ***Q*** aquifer type materials are present along this profile with a majority of the profile indicating the presence of marginal and non-aquifer materials which impact the area hydrologically by impeding groundwater movement to and from the surface water features in the south. The alluvium is the main groundwater supply with a hydrologic connection to the stream. This profile also indicates the limited potential for water movement from the land surface to the aquifer as recharge. Note the contact highlighted in blue of the Elkhorn River alluvium on the south end directly above the ***Kd*** sand/sandstone which is a potential hydrologic connection between these units.

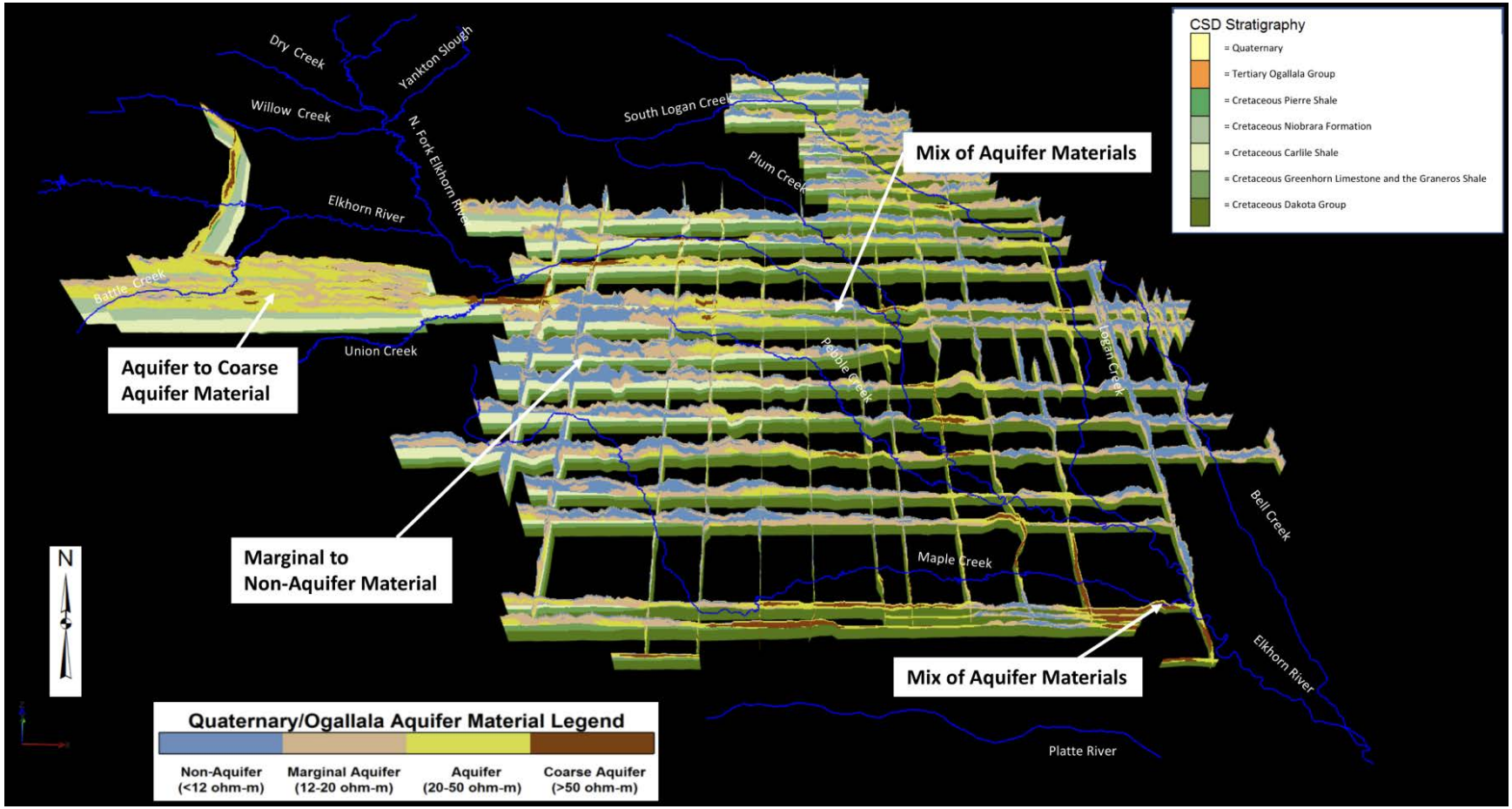


Figure 3-31. 3D map looking to the north of the interpreted distributions of aquifer materials within the survey area. Vertical exaggeration is 25x. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet).

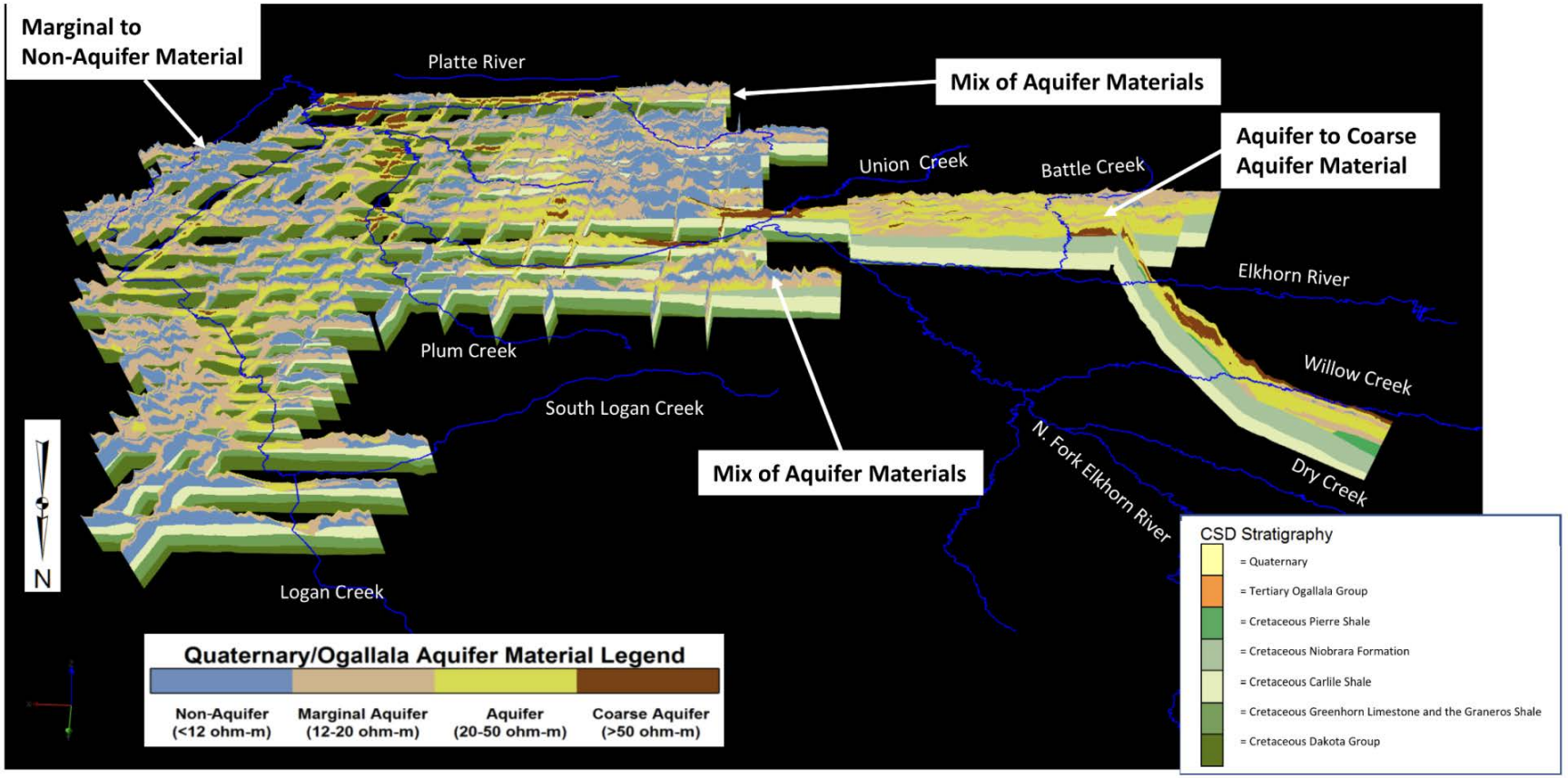


Figure 3-32. 3D map looking to the south of the interpreted distributions of aquifer materials within the survey area. Vertical exaggeration is 25x. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet).

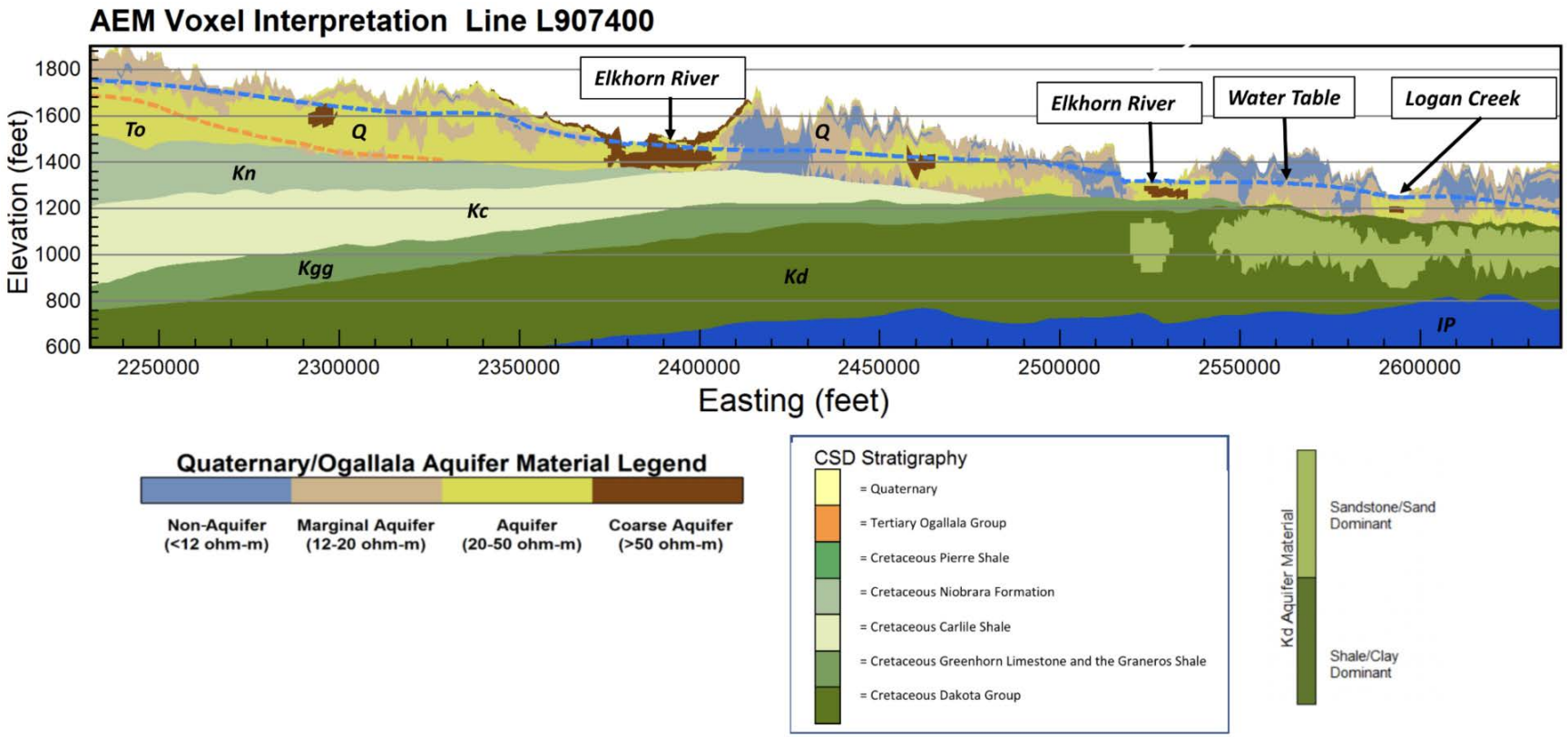


Figure 3-33. Profile view of line L907400 from west-east. The *Q* and *To* aquifer materials are deposited on the Cretaceous bedrock which from west to east are Cretaceous Niobrara (*Kn*), Cretaceous Carlile (*Kc*), Cretaceous Greenhorn-Graneros (*Kgg*) and Cretaceous Dakota (*Kd*) which overlies the undifferentiated Pennsylvanian (*IP*). Note the discontinuous thin nature of the Tertiary Ogallala group (*To*) on the west side of profile. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

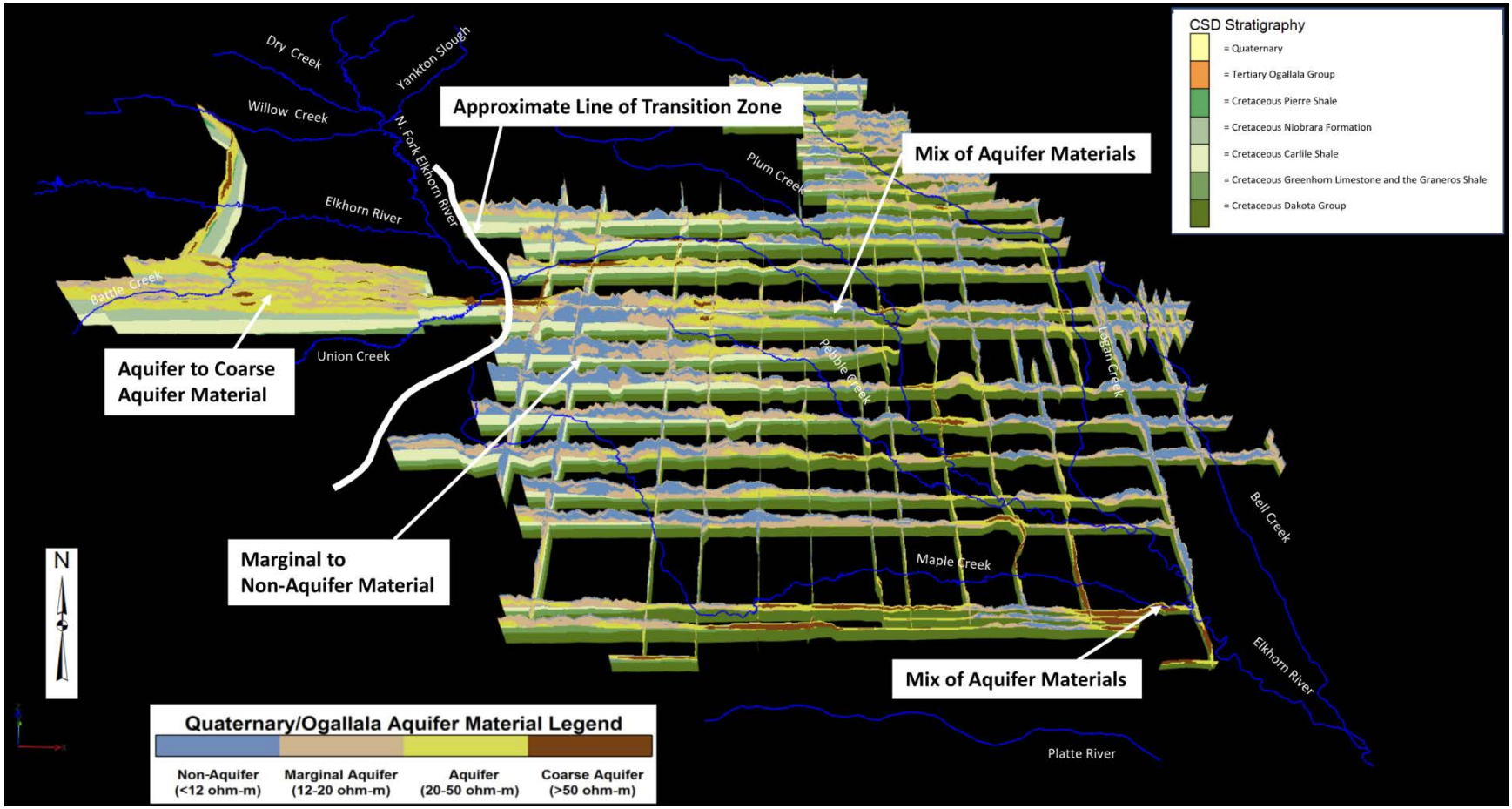


Figure 3-34. 3D map looking to the north of the interpreted distributions of aquifer materials within the 2018 survey area. Note the change in aquifer materials at the transition line as a change to finer grained materials towards the east. Vertical exaggeration is 25x. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet).

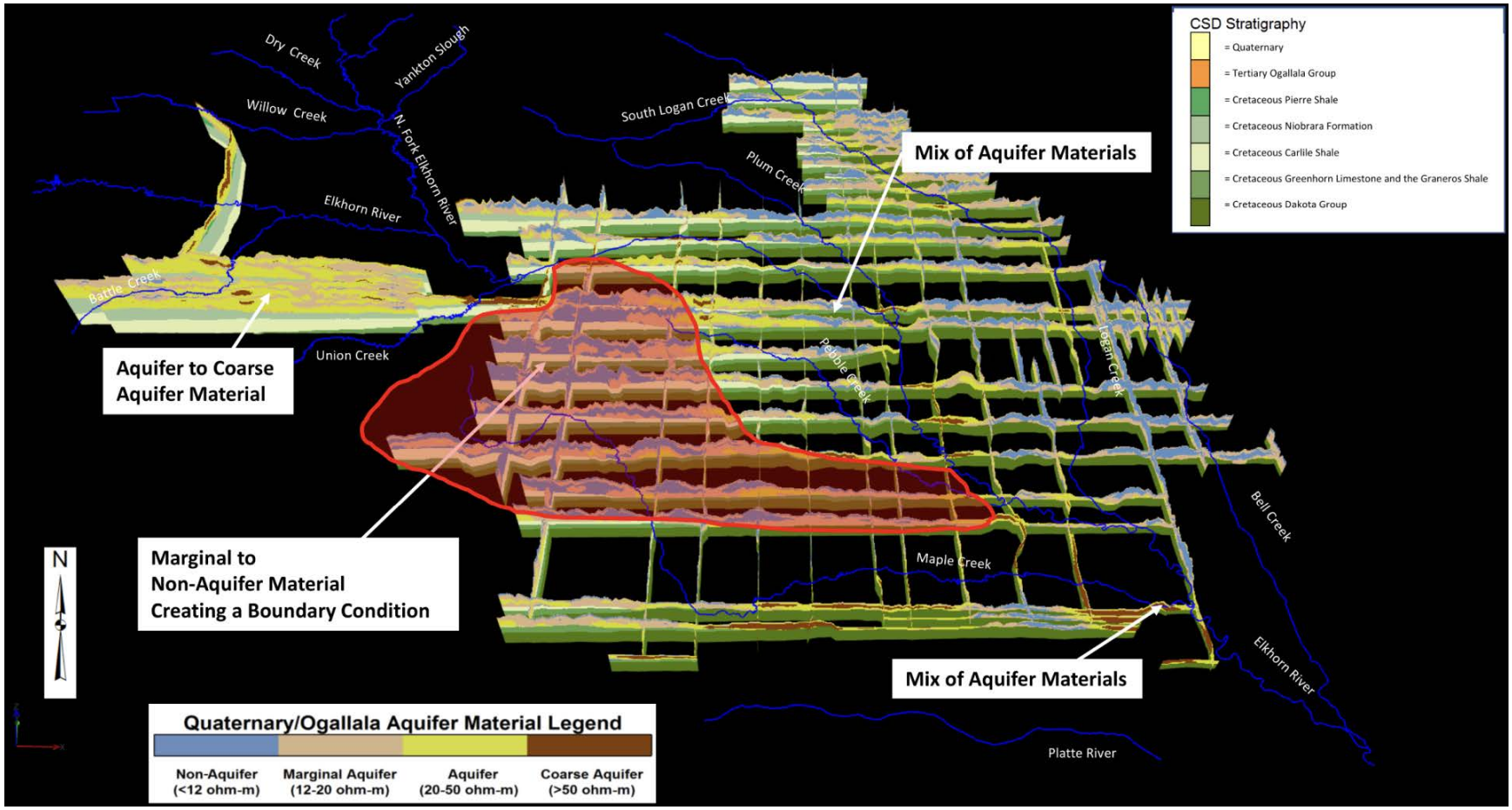


Figure 3-35. 3D map looking to the north of the interpreted distributions of aquifer materials within the 2018 survey area. The shaded area is a zone where local non-aquifer and marginal aquifer materials act as boundaries to groundwater flow. Vertical exaggeration is 25x. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet).

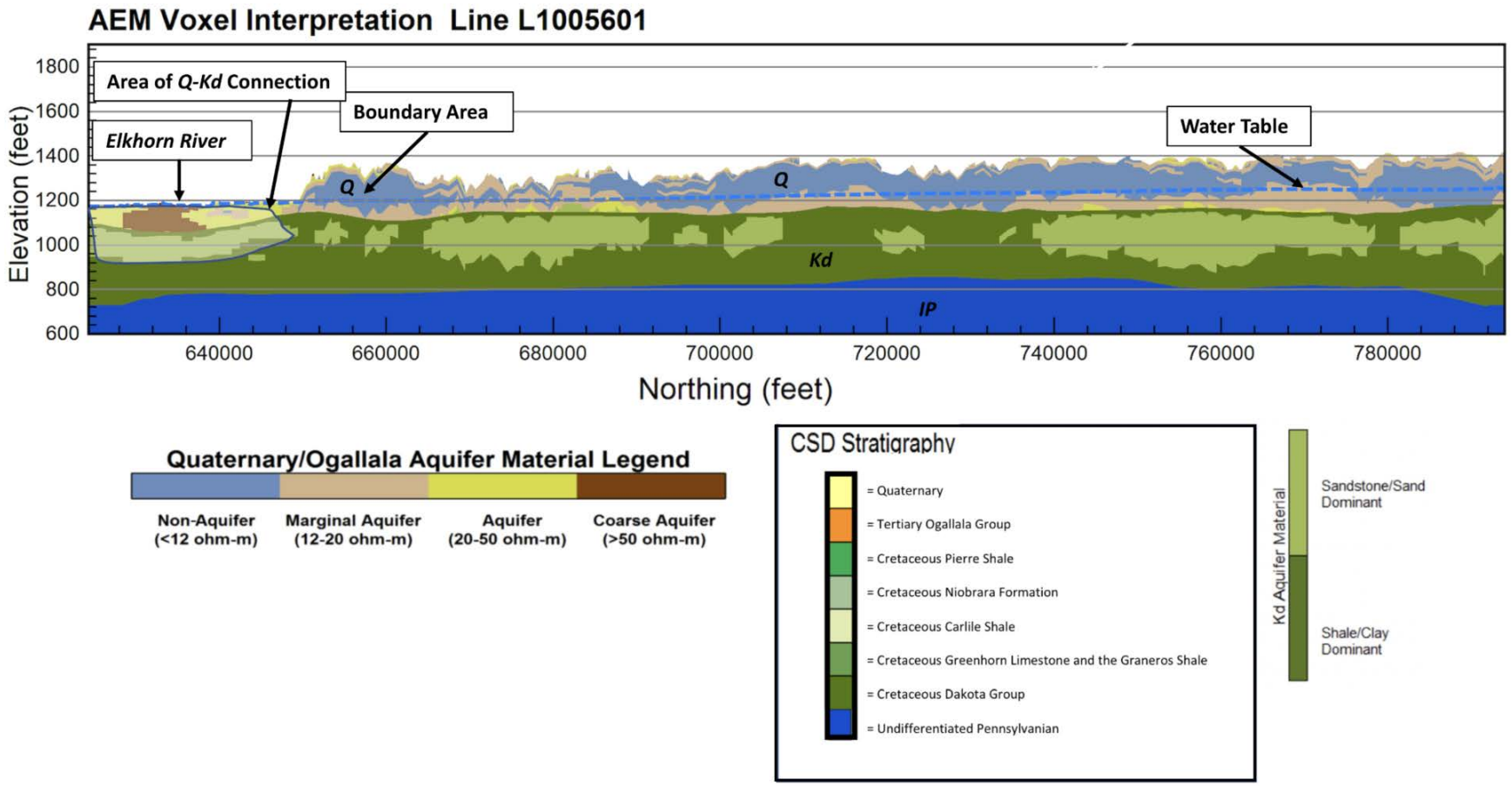


Figure 3-36. Profile view of line L1005601 from south-north. All the *Q* aquifer materials are resting on the Cretaceous bedrock which, from north to south, is Cretaceous Dakota (*Kd*). Note the boundary area and areas of Elkhorn River alluvium in direct connection with *Kd* sand and sandstone. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

The Oakland area is a difficult area for interpretation and hydrological framework development. This stems from the widely spaced flight lines in the area, the low electrical resistivity contrast, and the complicated geology. Figure 3-37 is the 3D fence diagram of the area showing the ***Q*** materials on the ***Kgg*** and ***Kd*** bedrock. In many locations along the profiles ***Q*** aquifer material and coarse aquifer material are in direct contact with the ***Kd*** sand/sandstone which is most likely a weathered surface. Profiles L101601(Figure 3-38), which is oriented east-west, and L201901.2 (Figure 3-39), which is oriented south-north, show these areas. The geological configuration in the Oakland area limits the resistivity contrasts between the units, and thus the aquifer materials that can be delineated by geophysics. Hence, the boreholes of the area are required to facilitate the interpretation of this contact which provides a hydrologic connection between the ***Q*** and ***Kd***.

In the Pierce Block a detailed framework could be constructed because the dense flight lines provide adequate resolution which allow a 3D voxel to be produced. An estimate of groundwater in storage and recharge areas can also be made because of this density of data. Figure 3-40 shows a 3D fence diagram of the Pierce County Block looking to the north. The ***Q*** and ***To*** are present throughout this block and are predominantly coarse aquifer and aquifer material above the Cretaceous bedrock with zones of minor non-aquifer and marginal aquifer materials related to loess deposits within the ***Q*** and fine grained deposits related to slack water and or lacustrine deposits within the ***Q*** and ***To***. This is a significant aquifer system for the LENRD which is currently being used for groundwater irrigation and is hydrologically connected to the surface water system of the North Fork of the Elkhorn River. Profile L100401 shows the continuous nature of the ***Q*** and ***To*** from west to east across the area (Figure 3-41). Figure 3-42 is a 3D map showing the volume of the ***Q*** aquifer and coarse aquifer materials only, which are extensive and shows the direct hydrologic connection to the streams. The saturated thickness in the pierce block ranges from less than 90 feet to greater than 335 feet in thickness (Figure 3-43). The saturated thickness is greater in the west and thins to the east but is thinnest in the area of the streams.

Recharge areas can be estimated within the Pierce Block flight area based on aquifer material type at the land surface and immediately below. Figure 3-44 shows the unsaturated ***Q*** coarse aquifer (brown) and aquifer materials (yellow) at the land surface as a voxel volume. The marginal and non-aquifer materials are not shown. Beneath the unsaturated ***Q*** aquifer and coarse aquifer materials is the estimated ***To*** top surface displayed as a visualization aid. Note the large extent of ***Q*** coarse aquifer and aquifer materials across the area and their connection to the streams. Any precipitation that falls in this area is likely to recharge the groundwater system. Any irrigation water applied will have the same effect. This a good area for Managed Aquifer Recharge (MAR) or Aquifer Storage and Recovery (ASR) activities. It is also an area with a high probability of leaching nitrates to the aquifer system. This map along with other information in the Pierce Block lock can guide management activities for water quality and quantity. This should also be inspected with regard to the distribution of minor amounts of marginal and non-aquifer materials as these units will have a tendency not to allow infiltration and impact runoff (Figure 3-26).

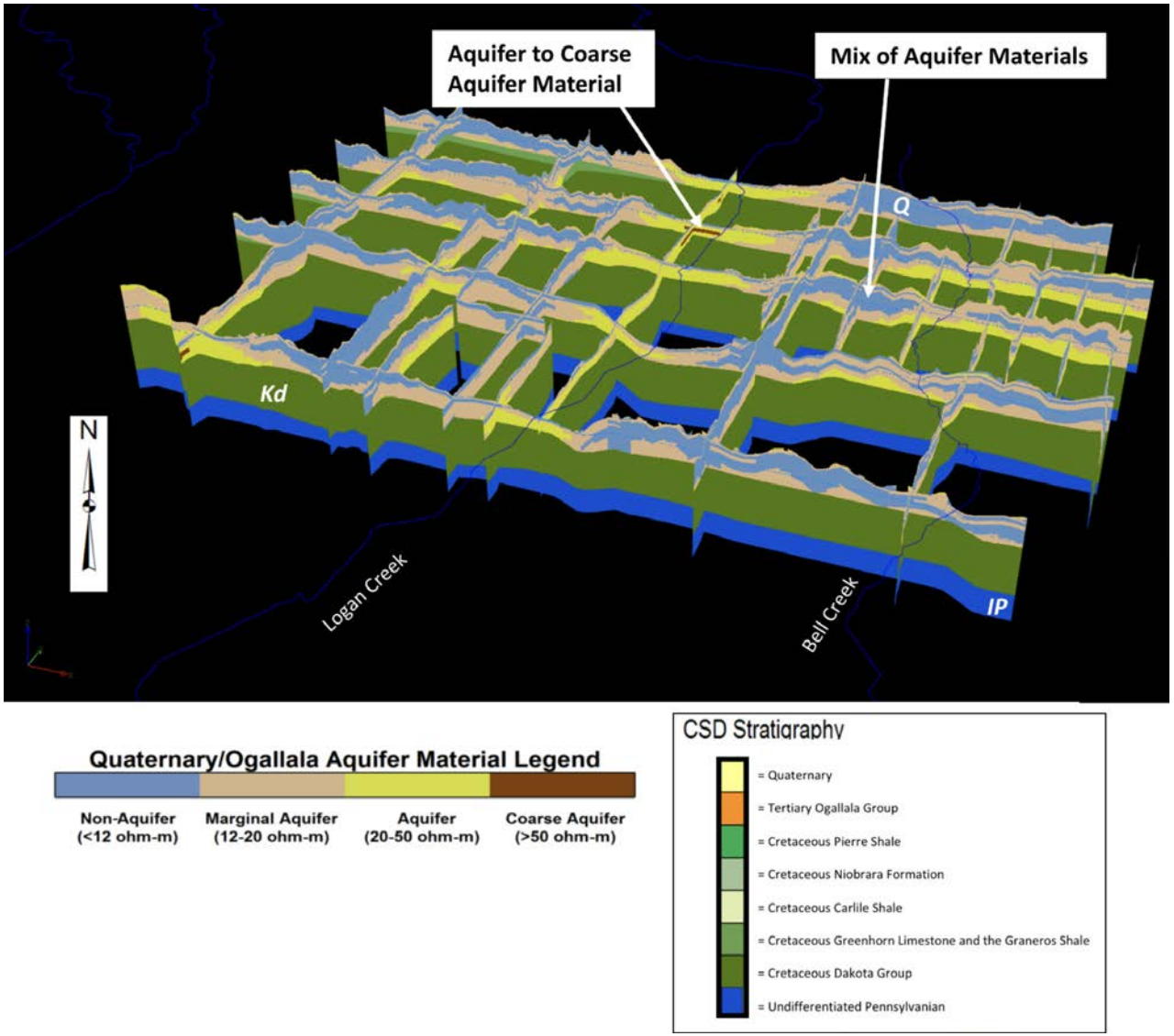


Figure 3-37. 3D map looking to the north of the interpreted distributions of Quaternary (*Q*) aquifer materials within the Oakland area. These materials are deposited on the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) and Cretaceous Dakota (*Kd).* Note the *Kgg* bedrock area to the northwest and west. Vertical exaggeration is 15x. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet).

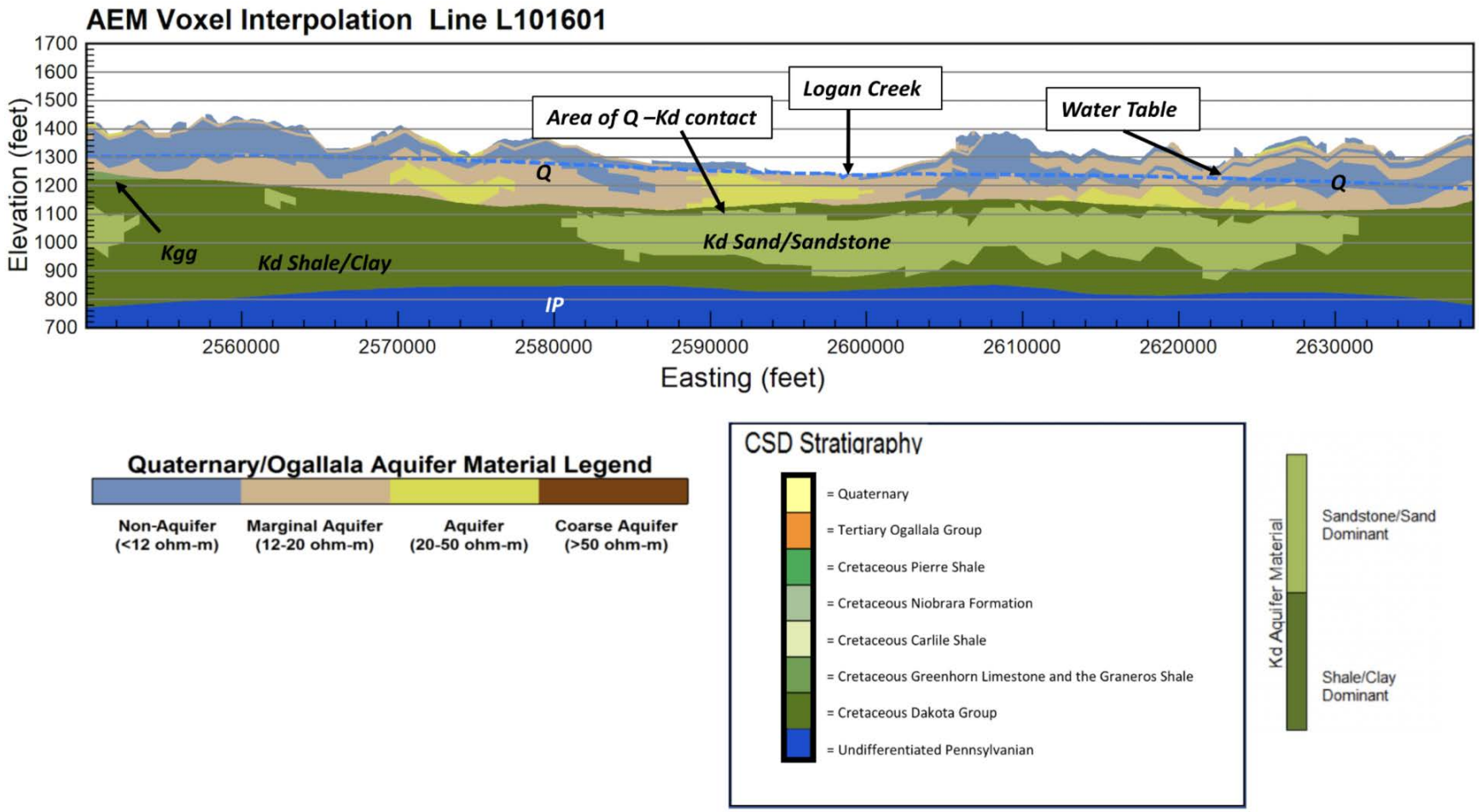


Figure 3-38. Profile view of line L101601 from west-east. All the Q aquifer materials are resting on the Cretaceous bedrock which from west to east is Cretaceous Dakota (Kd). Note areas of Quaternary (Q) in direct connection with Kd sand/sandstone. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

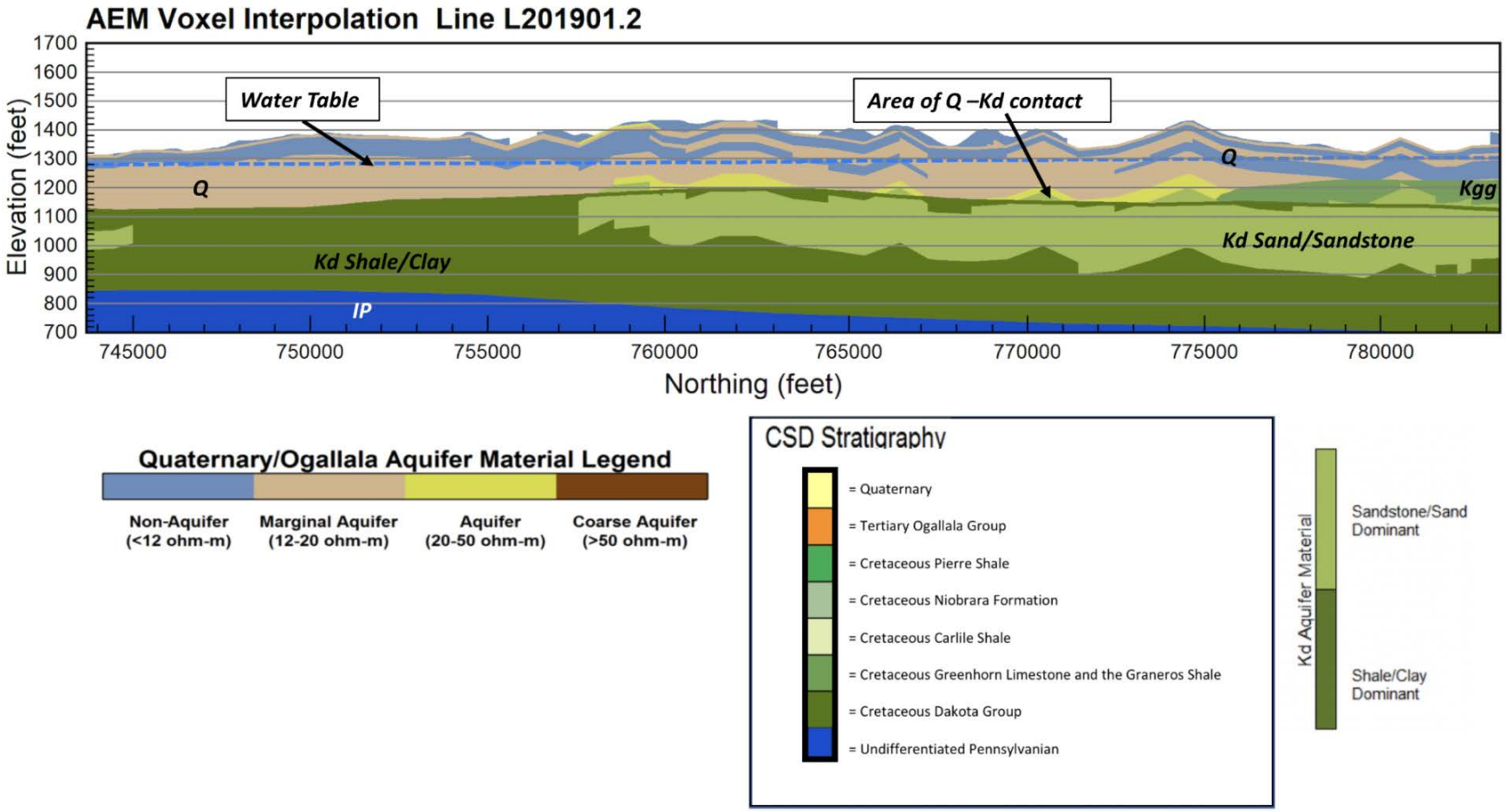
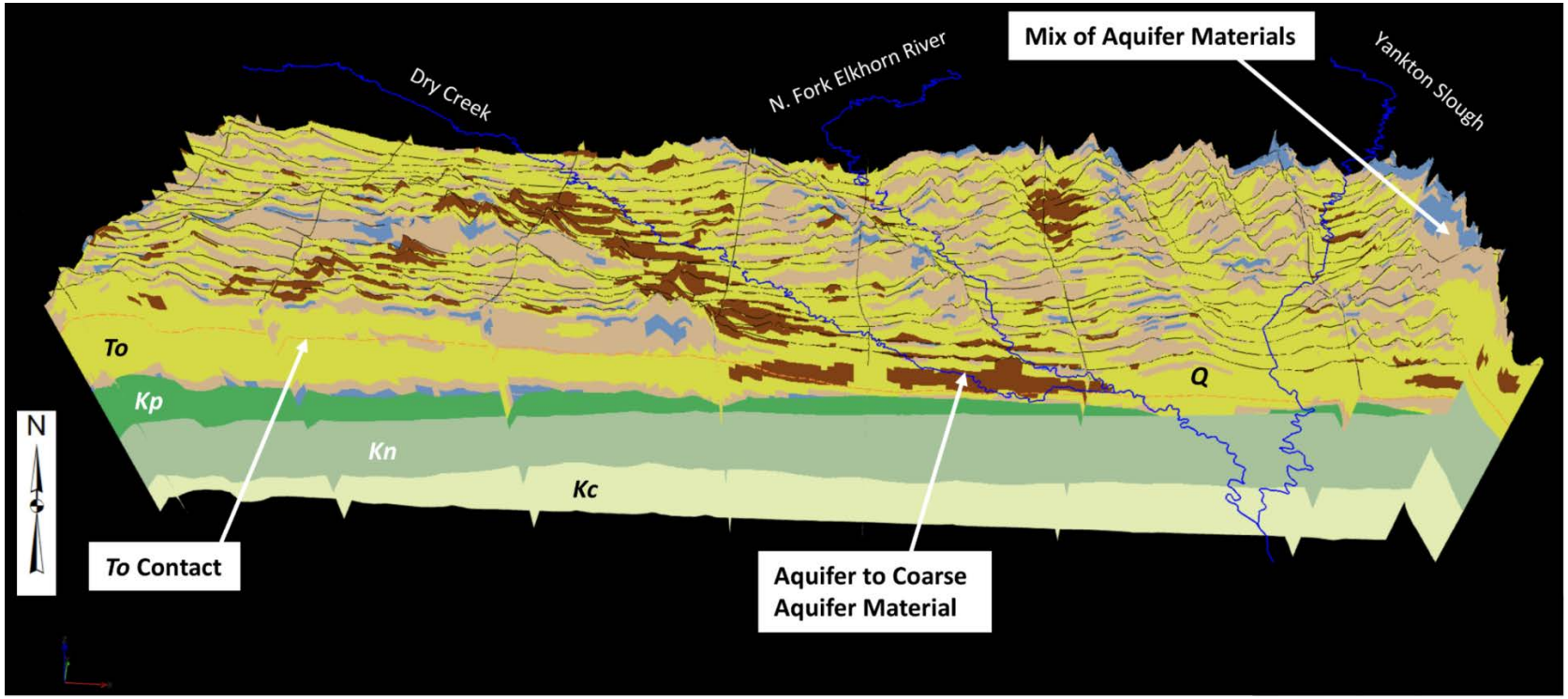
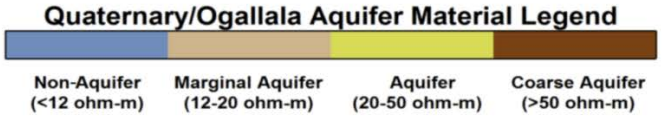


Figure 3-39. Profile view of line L201901.2 from south-north. The *Q* aquifer materials are resting on the Cretaceous bedrock which from south to north is Cretaceous Dakota (*Kd*) and then Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) to the north. Note areas of Quaternary (Q) in direct connection with *Kd* sand/sandstone. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).





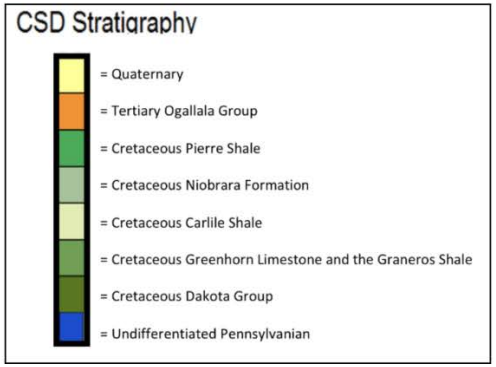


Figure 3-40. 3D fence diagram looking to the north of the interpreted distributions of Quaternary (*Q*) and Tertiary Ogallala Group (*To*) aquifer materials within the Pierce Block. These materials lie upon Cretaceous Pierre Shale (*Kp*), Cretaceous Niobrara Formation (*Kn*). Vertical exaggeration is 20x. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet).

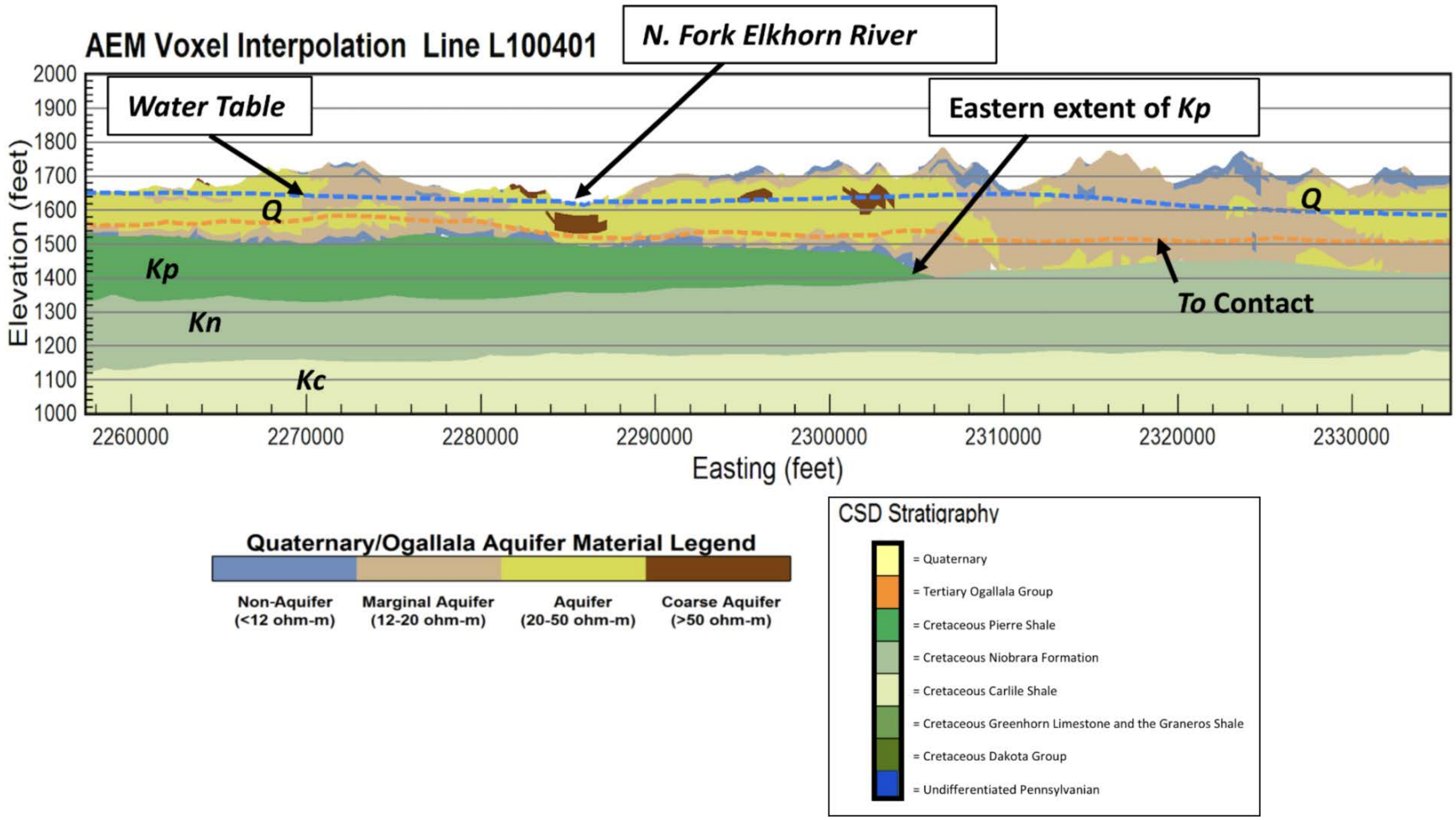


Figure 3-41. Profile view of profile L100401 from east to west. The *Q* and *To* aquifer materials are resting on the bedrock, which, from west to east, is the Cretaceous Pierre Shale (*Kp)* and Cretaceous Niobrara Formation (*Kn*). Note the continuous nature of the *Q* and *To*. This profile shows the dominance of aquifer and coarse aquifer materials which make this area an important groundwater resource for the Lower Elkhorn Natural Resources District (LENRD). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

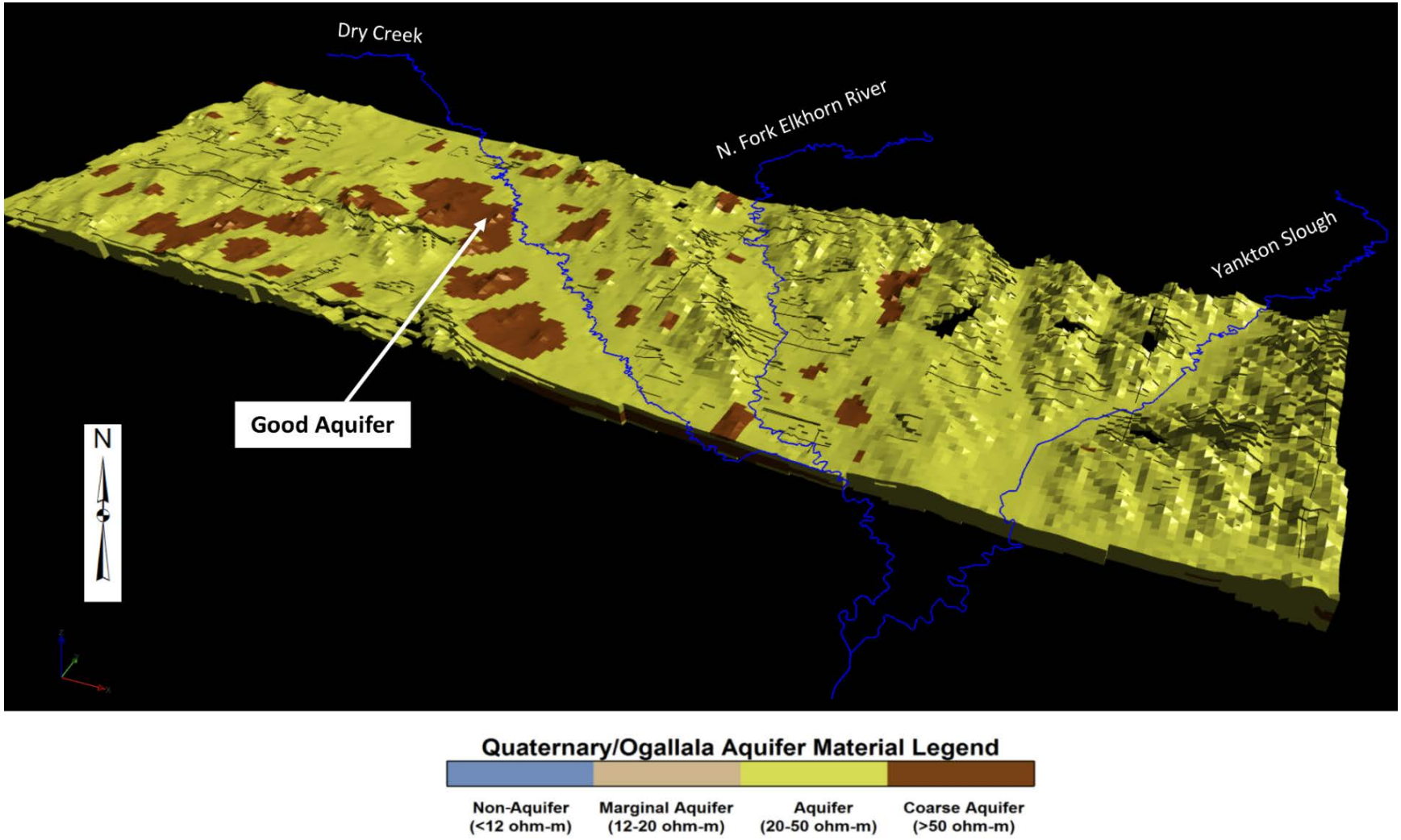


Figure 3-42. 3D voxel map looking to the northeast of the interpreted volume distributions of Quaternary (*Q*) aquifer and coarse materials within the Pierce Block area. Note the streams superimposed on the aquifer materials indicating a strong hydrologic connection. Vertical exaggeration is 15x. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet).

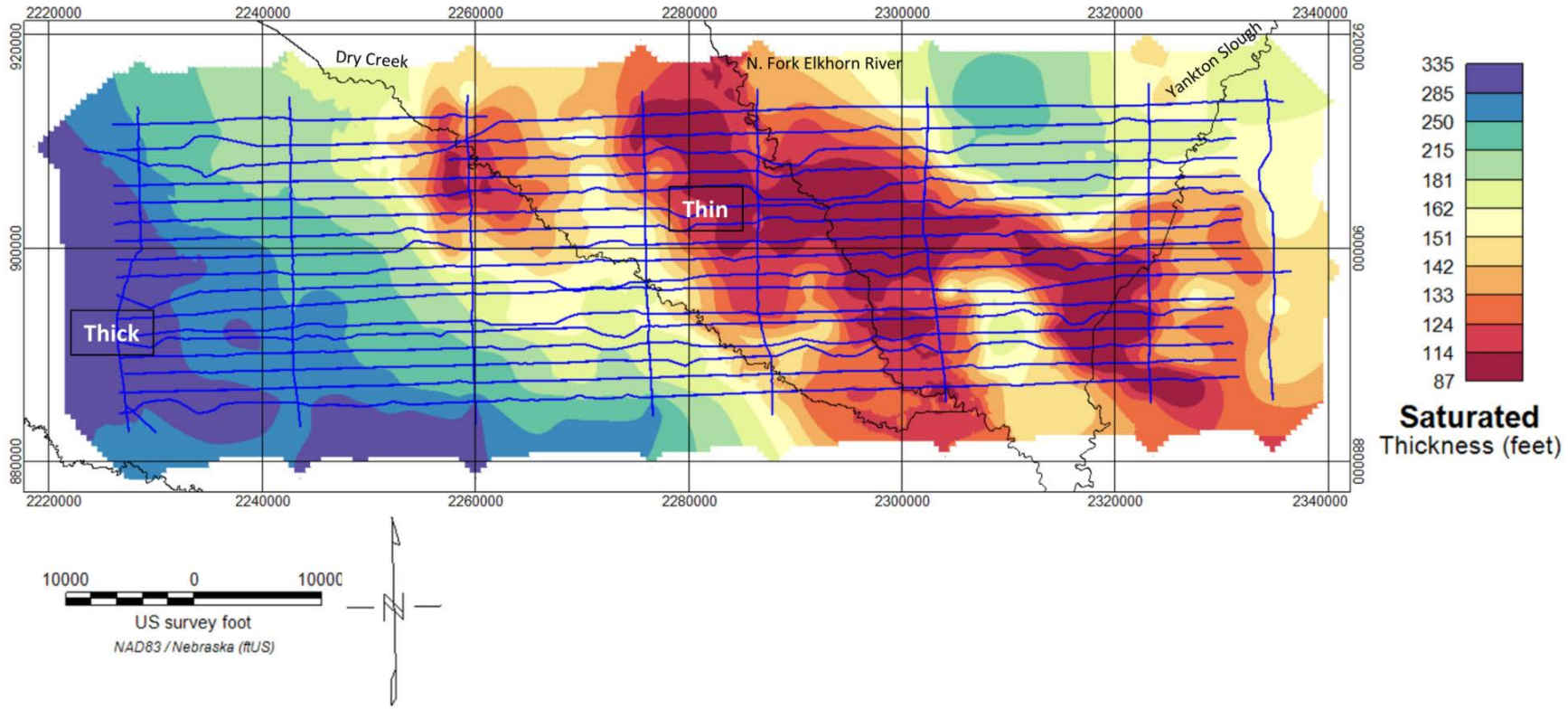


Figure 3-43. 2D map looking to the north of the saturated thickness of the Quaternary (*Q*) aquifer and the Tertiary Ogallala Group (*To*) materials within the Pierce Block area. The thickest saturation is to the west and thinnest is to the east. It varies in thickness from approximately 87 to 335 feet. Blue lines indicated flight lines. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

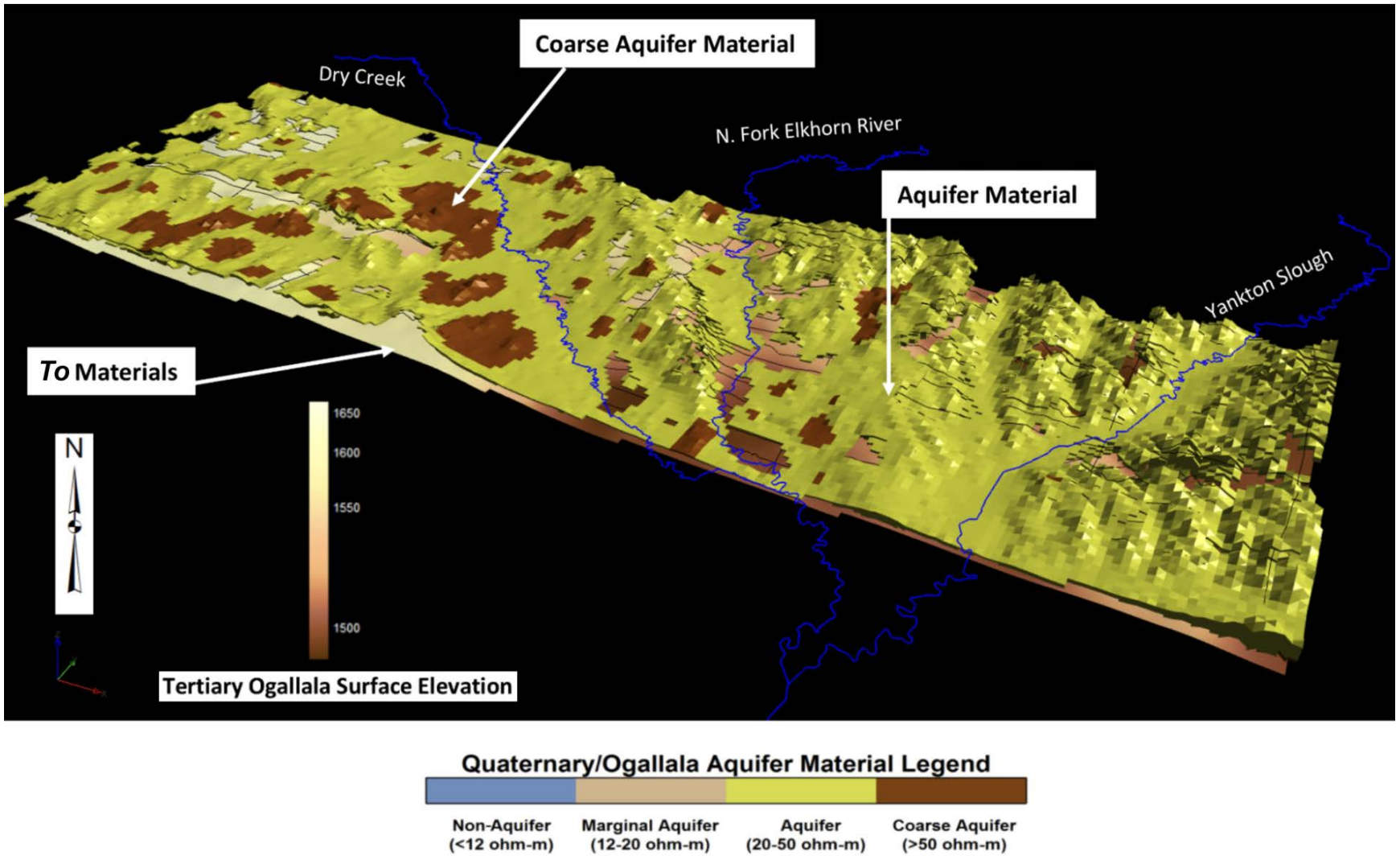


Figure 3-44. Pierce Block unsaturated Quaternary (*Q)* coarse aquifer (brown) and aquifer materials (yellow) at the land surface underlain by the top surface of the Tertiary Ogallala Formation (*To*). Note the large extent of *Q* coarse aquifer and aquifer materials across the area and their connection to the streams. Marginal and non-aquifer materials are not shown.

Using the Pierce Block as a comparison to the Oakland area and the LENRD Reconnaissance lines acquired over that area, a disadvantage of the reconnaissance lines is that they have only identified these aquifer and coarse aquifer material deposits along AEM acquisition flight lines. With the 1-3 mile distance of the reconnaissance lines in the Oakland area a detailed image as provided by the Pierce Block (approximately 1,300 feet line spacing) cannot be achieved.

Thus, the complete extent of these deposits within the reconnaissance area cannot be determined expediently without further AEM acquisition or exhaustive, and expensive, interpretation from added boreholes. Appendix 1-2D Profiles and Surfaces contains interpreted profiles and surfaces that illustrate the details of the Quaternary/Tertiary Ogallala Group and the Cretaceous Dakota in the LENRD 2018 AEM survey area. Appendix 2- 3D Images contains 3D Fence diagrams and voxel images of the LENRD 2018 AEM survey area that have been rotated around to allow viewing of the overall distribution of materials at various angles.

3.3.2 The Cretaceous Bedrock

The Cretaceous bedrock is made up of the ***Kp, Kn, Kc, Kgg*** and ***Kd*** from west to east (Figure 3-45). These units make up a continuous surface beneath the ***Q*** and ***To*** sediments that combine to act as an aquiclude restricting groundwater flow across the boundaries and over limited areas aquifers. As indicated in Carney et al. (2015a), the ***Kn*** can be a local aquifer when fractured and the fractures have connection to surface water sources. The ***Kd*** on the eastern side of the LENRD also provides substantial groundwater sources especially when it is in hydrogeologic connection to surface water. The Cretaceous bedrock units vary in elevation from approximately 1,500 in the west to less than 1,000 feet in the east. The Cretaceous bedrock has been eroded post-uplift by processes in the Tertiary and Quaternary. Profile line L1004100 displays the effects of erosion where the ***Kc*** has been removed or thinned considerably (Figure 3-46) to the north and south with a channel in between. These erosional features have been filled by ***Q*** materials. Overall, the elevation decreases from north to south. Profile L906801 is a west to east flight line and shows a Quaternary-age narrow erosional channel into the ***Kc*** which is filled by ***Q*** materials. Figure 3-47 shows this as a depression which is also shown in Figure 3-5 of Section 3.1.3. The

The ***Kd*** is a bedrock unit located in the eastern part LENRD AEM survey area and is characterized by a combination of sandstone/sand dominant and shale/clay dominant units. The ***Kd*** is covered by ***Q*** alluvium and glacial deposits. The patterns that define the surface of present day ***Kd*** are related to erosion over many episodes of glaciation and fluvial processes. Many areas of ***Kd*** have sufficient saturated thickness of sandstone/sand dominant materials to be an effective water supply to wells. This is most likely where the sandstone/sand dominant materials are in direct contact with the ***Q*** aquifer and coarse aquifer materials. Selection of drilling sites based on the greatest ***Kd*** sand/sandstone dominant thickness improves the chances of a successful water supply. This AEM characterization does not take into account the effect of cementation of the pore space of the sandstone/sand unit, which would lead to lower yield and transmissivity. Many of the NE-DNR registered wells in the eastern part of the LENRD show completion within the Kd. As explained above in Sections 3.1.3 and 3.2 the *Kd* was interpreted to highlight these areas of sandstone/sand. Interpretative profiles within *Appendix 1 - 2D profiles and Surfaces* contain the areas highlighted as being sand/sandstone dominant. Figure 3-48 is a 3D fence

diagram of the ***Kd*** with the sand/sandstone dominant areas highlighted overlaying the interpreted undifferentiated Pennsylvanian (***IP***). Note the light green areas to the east that the reconnaissance lines highlight. Some of these zones can be tracked from line to line. It is important to note that the areas of the ***Kd*** to the west may contain higher TDS water than the areas to the east that have been eroded and exposed to the Quaternary system. The high TDS waters can mask the electrical signature from the sand/sandstone, possibly lowering the bulk resistivity to the same range as the clay/shale zones.

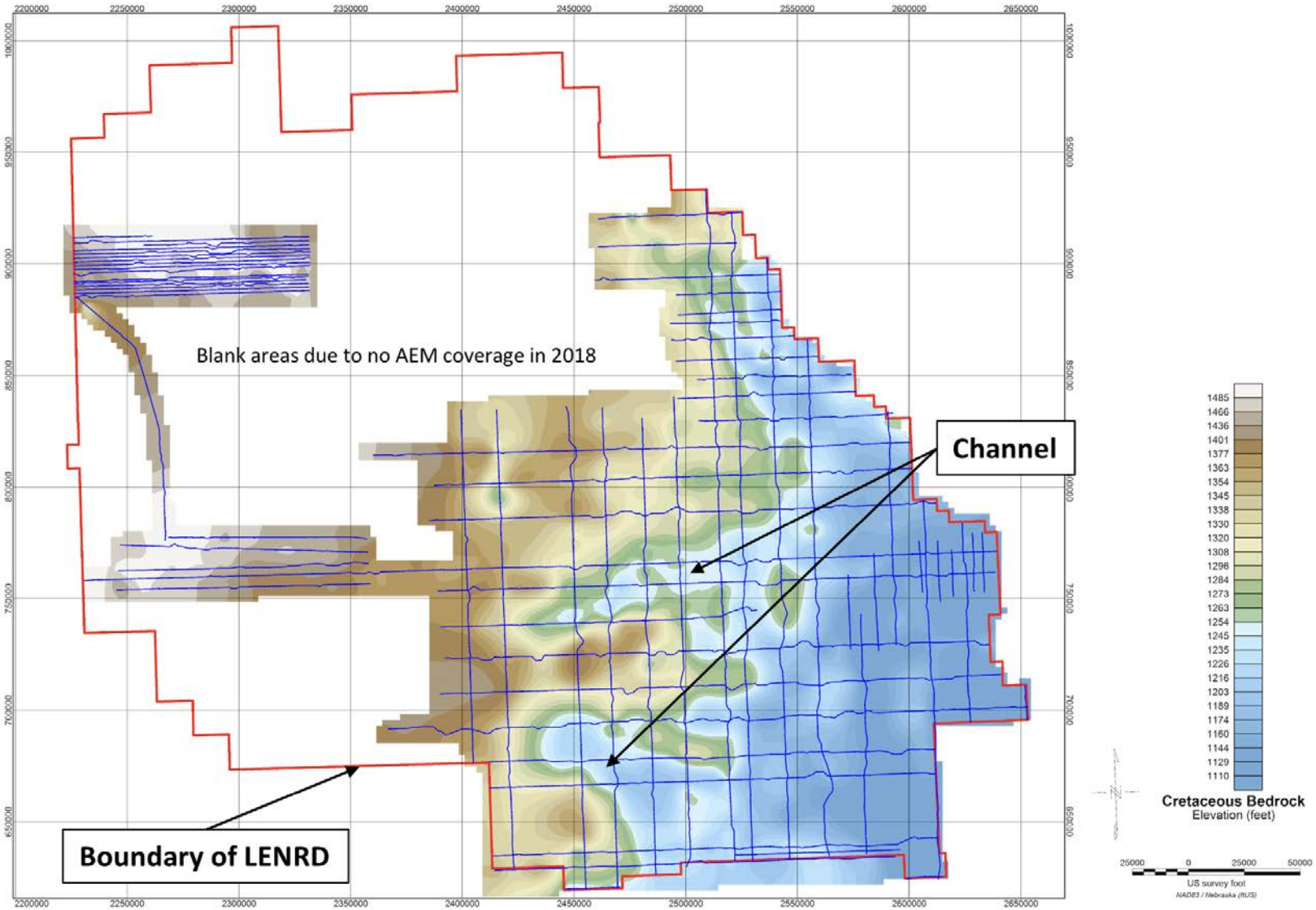


Figure 3-45. 2D map looking to the north of the bedrock elevation within the LENRD survey area (red line). Note the bedrock high to the north and south separated by a channel between them. The image projection is NAD 83, UTM Zone 14 North and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

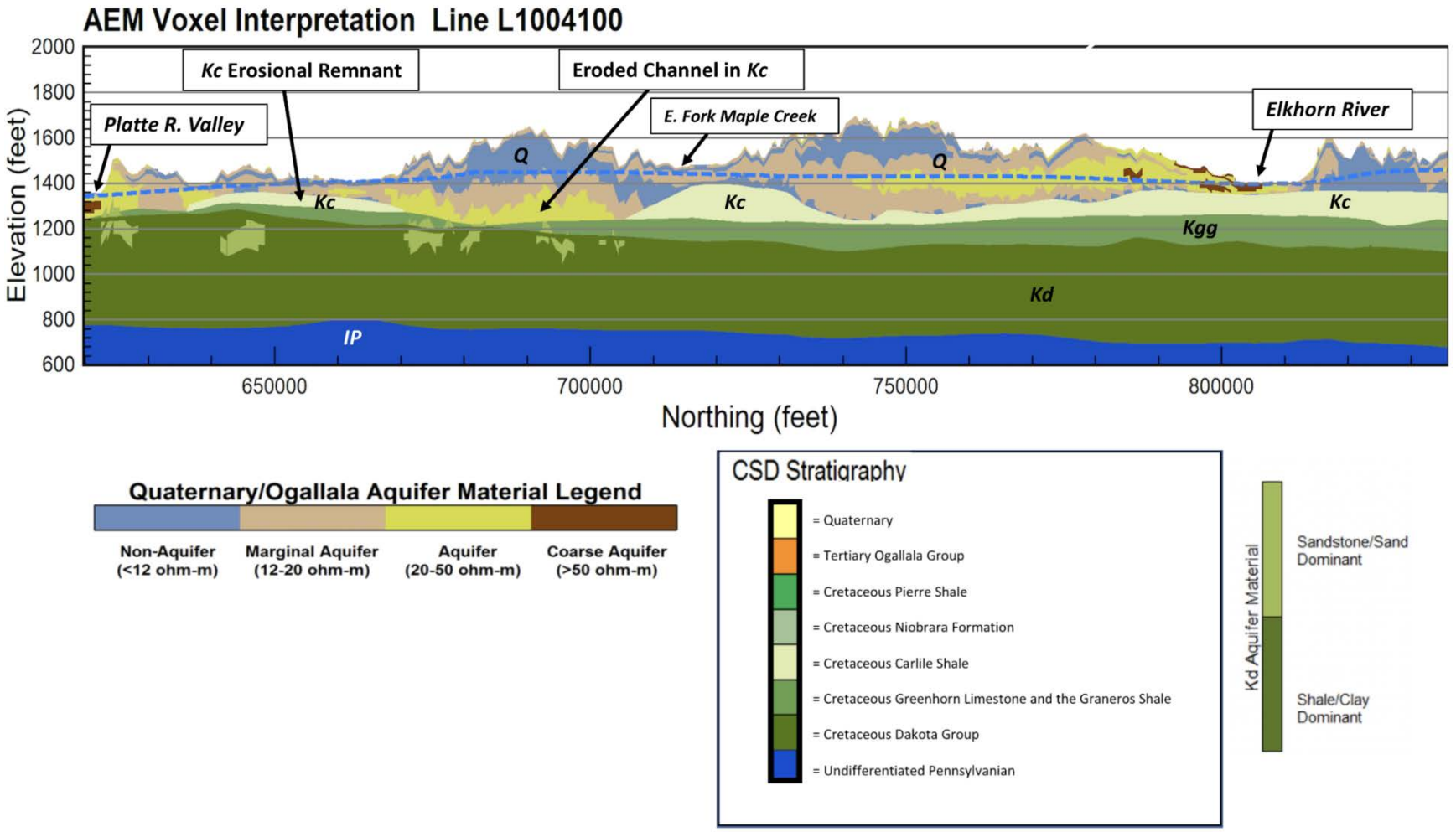


Figure 3-46. Profile view of flight line L1004101 from south to north. All the Quaternary (*Q*) aquifer materials are resting on the bedrock, which, from south to north, are the Cretaceous Carlile Shale (*Kc)* and Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*). Note the *Q* has eroded into and filled the erosional surface of *Kc* and *Kgg*. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

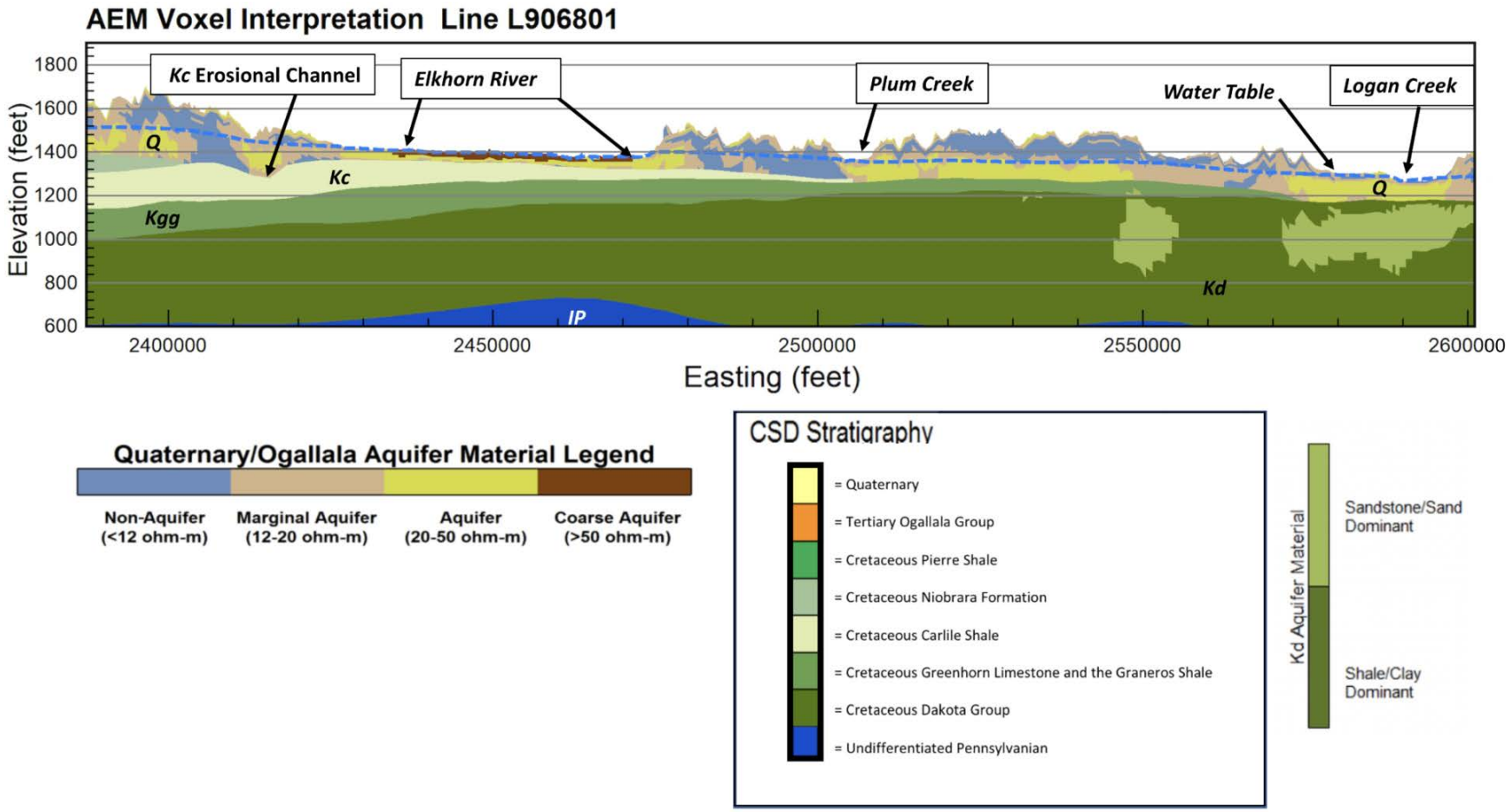


Figure 3-47. Profile view of flight line L906801 from east to west. All the Quaternary (*Q*) aquifer materials are resting on the Cretaceous Carlile (*Kc)* bedrock. Note *Q* has eroded into and filled the erosional surface of *Kc*. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

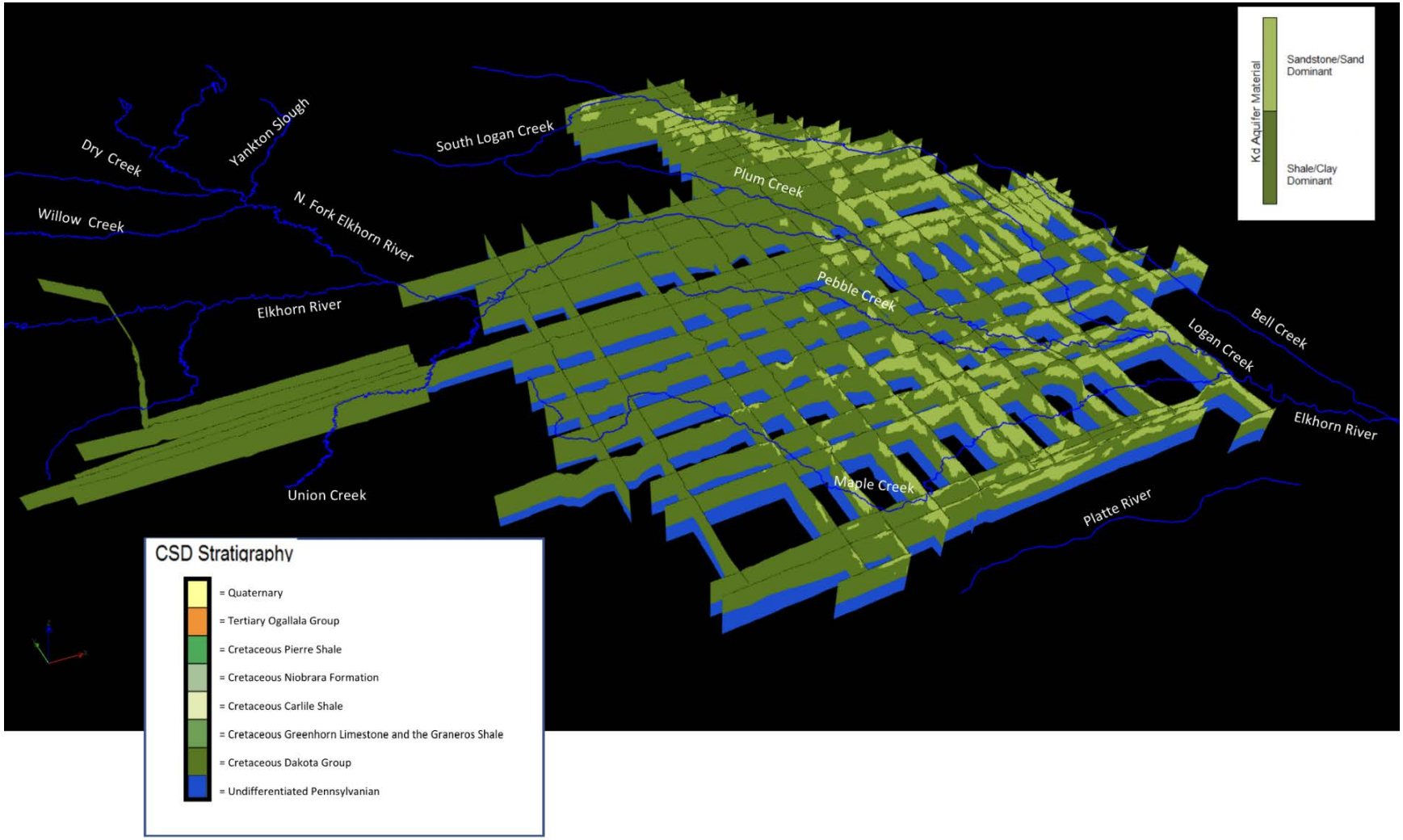


Figure 3-48. 3D fence diagram of only the Cretaceous Dakota Group (*Kd*) overlaying the undifferentiated Pennsylvanian (*IP*). Note the many zones of *Kd* sandstone/sand dominated in the eastern area of the reconnaissance lines. Vertical exaggeration is 15x. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet).

3.4 Pierce County Block Estimates of Aquifer Volumes and Yield

Within the Pierce County block a detailed surface (500 feet grid cell size) of the Cretaceous bedrock is presented in Figure 3-49. The high resolution provided by dense flight line coverage shows the erosional nature of the bedrock in the area. To the west is a paleochannel oriented from northwest to southeast. In the middle of the block is a bedrock high which in turn is flanked by a channel to the east. Elevations of the bedrock vary from approximately 1420 to 1515 feet in altitude.

The 1995 CSD water table (Nebraska CSD, 1995) map (Figure 3-50) has been used in every AEM survey project for the LENRD since 2007 (Smith et al., 2008; Abraham et al., 2013; Carney et al., 2015a; and AGF, 2017). It is a regional map that is now 24 years old but is still relevant as there is no other continuous water table map that covers all of the ENWRA area. This map has been used in this report to identify regional groundwater flow direction and saturated and unsaturated sediments which in turn can be used to determine groundwater in storage volumes.

In the Pierce Block which has densely spaced flight lines estimates of groundwater in storage and approximate yield can be made. A 3D representation of the subsurface derived from the AEM imaging provides users the ability to more accurately identify the total saturated aquifer volumes for the ***Q*** and the ***To***. The saturated zones of the ***Q*** and ***To*** materials can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present.

All aquifer materials within the ***Q*** and ***To*** sediments, 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 sand making up the aquifer material and sand and gravel making up coarse aquifer material 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*** aquifer materials were selected from Heath (1983). For non-aquifer materials it is 0.02 and for marginal aquifer materials a value of 0.05 was selected. For the aquifer material the estimated specific yield is 0.22 and for coarse aquifer material it is 0.19.

The ***To*** calculations used similar numbers but were reduced by 25 percent arbitrarily in recognition of the consolidated nature of the sediments. For non-aquifer materials the specific yield is 0.015, for marginal aquifer materials a value of 0.038 was selected, for the aquifer material a specific yield of 0.17, and for coarse aquifer materials a value of 0.14.

Cretaceous formations dip to the west and are heavily eroded as they thin to the east.

Table 3-4 and Table 3-5 have the calculations for groundwater in storage for the saturated and unsaturated ***Q*** materials for the Pierce County Block and Table 3-6 has the calculations for groundwater in storage for the ***To*** materials which is fully saturated because the top of the ***To*** is below the 1995 water table (NE-CSD, 1995). These calculations and the maps herein can be used to select sites for managed

aquifer recharge to address both water quantity, stream depletions, and water quality management efforts. Future work on detailed analysis of potential MAR sites for the best locations within the Pierce County block would provide the best possible locations, (this is not part of the scope of the 2018 study). An example of this would be to select a site that has thick unsaturated ***Q*** materials that are mostly coarse and aquifer materials from the surface downward in rangeland that can allow surface water to recharge the system with fresh water from a surface water source.

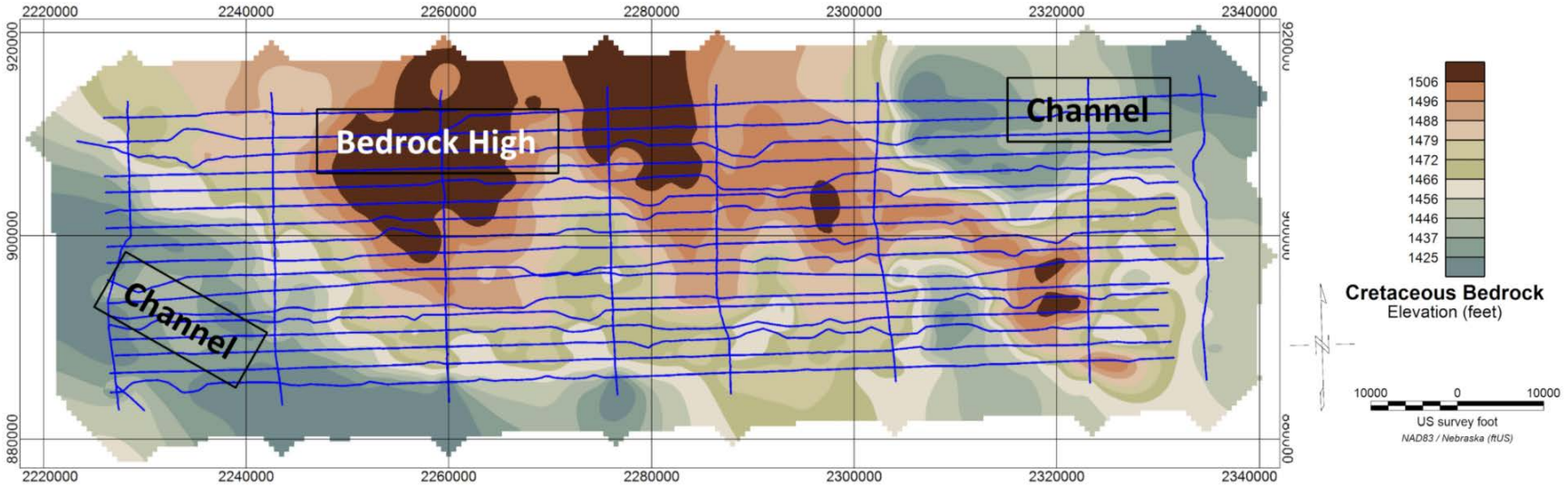


Figure 3-49. 2D map looking to the north of the Pierce County Block bedrock map. Note the areas that were eroded out form channels. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

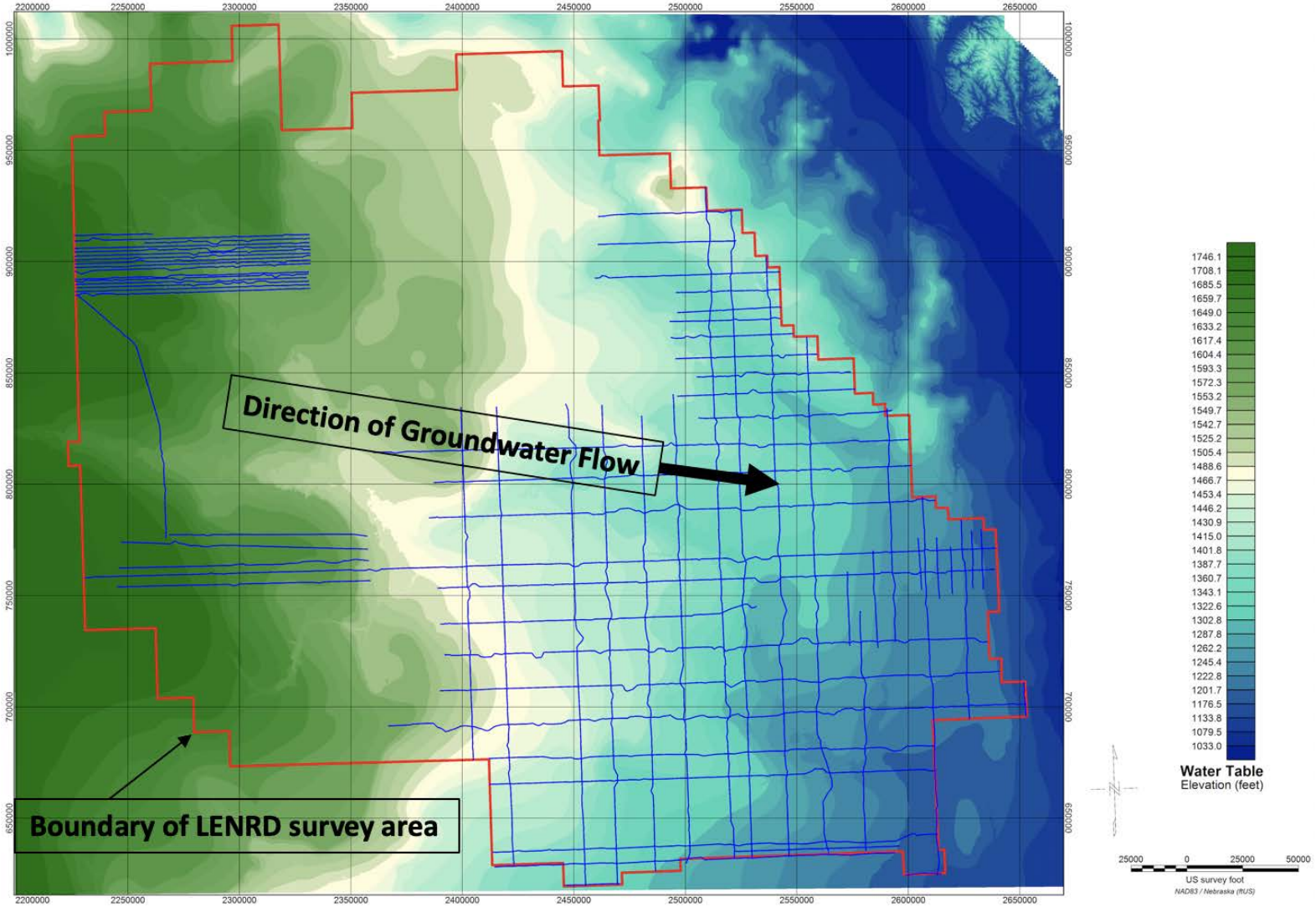


Figure 3-50. The groundwater elevation map modified for the project DEM for the area (Section 3.1.2). The arrow is pointing in the general direction of groundwater flow. The highest elevation is in the west at approximately 1,760 feet and the lowest is in the east at approximately 1,030 feet. These estimated groundwater elevations are used to calculate groundwater in storage for the Pierce Block area. Projection is Nebraska State Plane, NAD83, US survey feet.

Table 3-4. Saturated *Q* aquifer materials underlying the Pierce County Block 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	3,686,553,750	84,632	0.40	33,853	0.02	677
Marginal	81,385,098,750	1,868,348	0.35	653,922	0.05	32,696
Aquifer	190,819,082,500	4,380,610	0.20	876,122	0.22	192,747
Coarse Aquifer	45,465,576,250	1,043,748	0.25	260,937	0.19	49,578
TOTAL	321,356,311,250	7,377,337		1,824,834		275,698

Table 3-5. Unsaturated *Q* aquifer materials underlying the Pierce County Block 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	11,901,002,500	273,210	0.40	109,284	0.02	2,186
Marginal	71,154,426,250	1,633,483	0.35	571,719	0.05	28,586
Aquifer	77,192,245,000	1,772,093	0.20	354,419	0.22	77,972
Coarse Aquifer	10,855,091,250	249,199	0.25	62,300	0.19	11,837
TOTAL	171,102,765,000	3,927,985		1,097,722		120,581

Table 3-6. Fully saturated *To* aquifer materials underlying the Pierce County block 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	37,357,511,250	857,610	0.40	343,044	0.015	5,146
Marginal	76,179,342,500	1,748,837	0.35	612,093	0.038	23,259
Aquifer	135,557,392,500	3,111,969	0.20	622,394	0.17	105,807
Coarse Aquifer	11,725,067,500	269,170	0.25	67,292	0.14	9,421
TOTAL	260,819,313,750	5,987,586		1,644,823		143,633

3.5 Key AEM Findings

3.5.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results and was important for several areas in the LENRD that had limited or no contrast in the electrical resistivity between the different geologic formations. The dependence on just boreholes for geologic interpretation also has its limitations because sometimes the boreholes are wrong, improperly located, have improper stratigraphic/lithology picks, and/or other errors. These errors in the boreholes are usually encountered in the NE-DNR registered wells. Very rarely inconsistencies are encountered in the oldest of the CSD wells. The limited errors in the CSD wells may very well be due to poor positioning from a time before GPS and modern survey methods. The use of boreholes with AEM needs to be approached in a thoughtful professional manner. In areas of obvious electrical resistivity units (i.e. ***Kp*** and ***Kc***) the AEM can easily flag errors.

3.5.2 Digitizing Interpreted Geological Contacts

Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***), Tertiary Ogallala Group (***To***), Cretaceous Pierre Shale (***Kp***), Niobrara Formation (***Kn***), Carlile Shale (***Kc***), Greenhorn Limestone and Graneros Shale (***Kgg***), Dakota Group (***Kd***) undifferentiated Pennsylvanian (***IP***). 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. Because this is the last part of the 5-year regional AEM survey acquisition, it has become apparent that there needs to be integration work done to bring all the years together in one package using the same parameters such as projection, nomenclature, and stratigraphic divisions.

3.5.3 Resistivity/Lithology Relationship

Assessment of the sediment character in both the Quaternary/Tertiary Ogallala aquifer system and the bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska (Carney et al., 2015a, b). A numerically robust assessment of the resistivity thresholds was used to characterize non-aquifer (<12 ohm-m), marginal (12-20 ohm-m), and aquifer (20-50 ohm-m), including coarse sand-rich intervals (>50 ohm-m) was determined. This allowed for the characterization of the ranges of resistivities present in the major geologic units described in this report. The ***Kd*** was also subdivided into a sand/sandstone and a clay/shale-dominant zones.

3.5.4 Hydrogeological Framework of the LENRD

The 2018 LENRD AEM survey reveals variability in the ***Q*** deposits across the LENRD AEM survey area. When combined with the ***To***, they represent the aquifer materials in the AEM survey area, where saturated. The ***To*** is generally thick in the west and is thin to absent in the eastern regions of the AEM survey area. The ***Q*** and ***To*** make up the aquifer materials overlying the Cretaceous bedrock units. In the eastern and southern parts of the AEM survey area, the aquifer materials are predominantly marginal to non-aquifer materials which are glacial till and loess

and which can be more than 200 feet thick. ***Q*** sediments found predominately on the west side are often associated with prevalent alluvial and coarse aquifer material deposits. The ***Q*** and ***To*** materials (where present) are sitting on the ***Kp***, ***Kn***, ***Kc***, ***Kgg,*** and ***Kd*** which may or may not be the bedrock aquicludes for the area as there are some areas of the ***Kn*** and ***Kd*** that provide local aquifers. The regional framework is complete with the 2018 survey and can be used to identify geographic area within the LENRD for different types of groundwater management. Additional block flights may be useful to better characterize certain areas for which estimates of aquifer storage and extractable yield may later be deemed to be required, as discussed next.

3.5.5 Potential Recharge Zones within the LENRD AEM Survey Area

The use of block flights in Pierce County illustrates the preferred method to use AEM to identify areas where the potential for recharge to the aquifer can be high and low. Locations where the flight lines are closely spaced show either aquifer or coarse aquifer material at the land surface should be considered as locations for higher likelihood for recharge because of the 2D and 3D spatial nature of the aquifer material distribution. The opposite is also true where AEM data analysis shows non-aquifer or marginal aquifer material; Those areas will likely not be optimal recharge locations (Figure 3-51). The area throughout Pierce Block has potential recharge that is widespread and is a likely location for MAR and ASR activity. The groundwater in storage and potential yield from the aquifer has been calculated for the Pierce Block area. It supports the determination that high rates of recharge are available. It also shows the importance of this area to irrigation and water supply within the LENRD. Note that areas with aquifer and coarse aquifer materials at the surface can also become conduits for infiltration of nitrates into the groundwater system. A potential solution to this problem is adding additional fresh surface water as recharge to select areas of rangeland that can dilute any potential nitrate contaminant problem. Additional work can be done to identify where the best locations are for these type of management efforts.

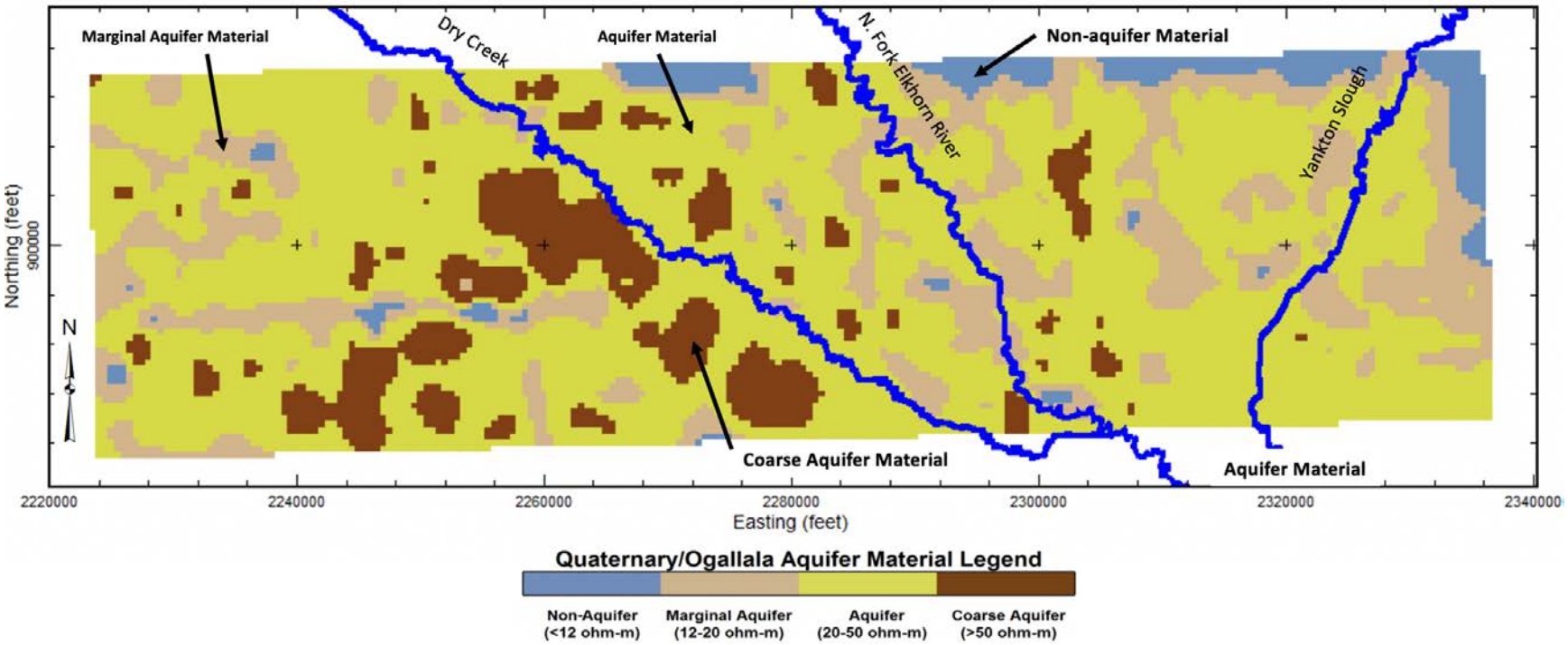


Figure 3-51. 2D map looking to the north towards the Pierce Block showing all aquifer materials at the land surface. Quaternary (*Q*) aquifer and coarse materials within the Pierce Block area are the most likely to allow recharge to groundwater. Note the streams superimposed on the aquifer materials indicating a strong hydrologic connection.

3.6 Recommendations

Recommendations provided to the LENRD 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 LENRD about their management challenges.

3.6.1 Integration of 2007-2018 AEM Hydrogeological Investigations

The LENRD has acquired AEM data from 2007 to 2018 with three different AEM systems and contractors performing the work including the USGS, XRI Geophysics, and AGF with oversight from the LENRD and the ENWRA. Priorities have evolved from finite projects like Oakland, City of Madison, Clarkson, and the Pierce Block to the large-scale reconnaissance investigations of the LENRD and ENWRA. With the completion of this current study, being the last part of a 5-year regional AEM survey acquisition program, it has become apparent that there needs to be additional work done to bring all the work from all the years together in one package using the same parameters such as geographic projection(NAD83 UTM Zone 14N (meters), NAD83 Zone 14N (feet), and NAD83 Sate Plane Nebraska (feet) have been used over the past 10-years), hydrologic nomenclature, and stratigraphic divisions. Recent communication with LENRD and their consultants has also brought to light that additional effort is needed to quantify the NE-DNR boreholes relationship to the aquifer materials that the AEM has mapped. Specifically, it was found that the 2015 interpretations of the ***Kn*** (Carney et al., 2015a) need to be modified with additional input from the NE-DNR wells to increase the overall elevation of the ***Kn*** under the ***To*** and ***Q*** deposits due to the lack of resistivity contrast. In addition, there apparently exists confusion on the use of “principal aquifer material” versus “aquifer material “versus “Principal Aquifer” as determined by NE-DNR. While these are apparently minor additions and changes, they can add to the overall usability and portability of the AEM analysis results within the LENRD.

3.6.2 Additional AEM Mapping

The hydrogeologic maps provided in this report represent the completed the hydrogeologic framework developed for the LENRD at an approximate 3-mile spacing of flight line reconnaissance level. Beginning in 2014, the District has been collecting AEM data at approximately 3-mile grid spacing, as financial resources have allowed per their yearly plan. The interpretations match well with the CSD and NE-DNR test holes. The 3D fence diagram in Figure 3-52 shows the reconnaissance lines collected from 2014 through 2018 in the entire district with the exception of the 2007 Oakland (Smith et al., 2008), the 2013 City of Madison investigation (Carney et al., 2014), and the 2013 Clarkson-Howells AEM investigations (Abraham et al., 2013). At this point the LENRD need only select local block flights for detailed information when required using this framework map to support groundwater models, rural water supply well locations, water quality monitoring wells, areas for further irrigation development or selecting MAR or ASR locations.

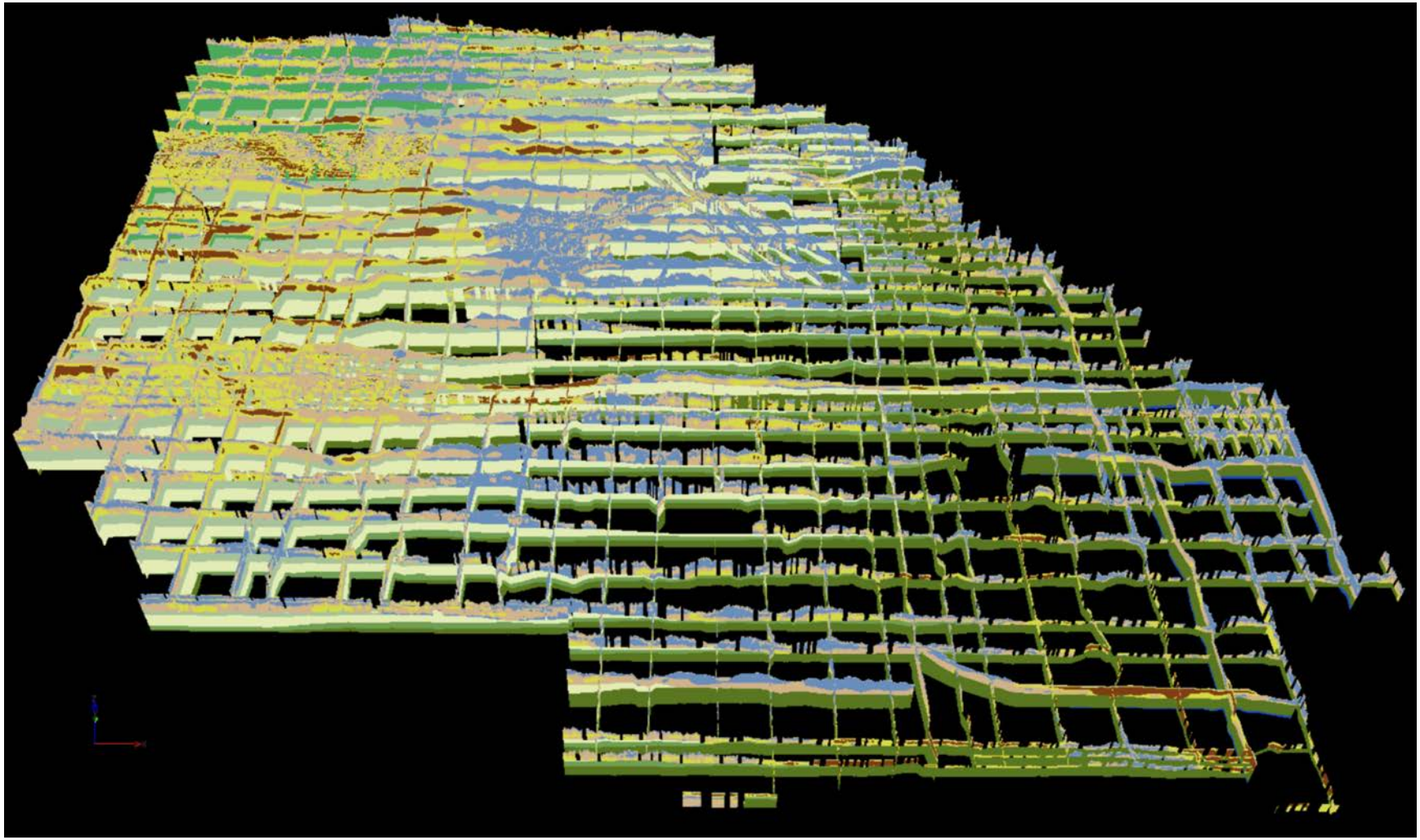


Figure 3-52. 3D fence diagram of the LENRD block flights in the west and 3-mile center reconnaissance lines in the south and east. Vertical exaggeration is 25x

3.6.3 *Update the Water Table map*

The groundwater data used in the analyses presented in this report utilized the 1995 CSD water table map which is now 24 years old (Nebraska CSD, 1995). Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. This is especially true on the west side of LENRD in Pierce and Madison counties. The areas of glacial till and loess covering the eastern side of the district will need great care in developing a water level map of potentiometric heads due to the confined to semiconfined nature of the area.

3.6.4 *Siting new test holes and production wells*

The AEM hydrogeological framework profiles, maps, and surfaces provided in this report provide great insight in 3D on the relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the LENRD 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 more 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. A good example of this would be confined aquifers with large volumes of coarse aquifer and aquifer material. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the LENRD (personal communication K. Cameron, ENWRA Coordinator and S. Olafsen-Lackey CSD Hydrologist).

3.6.5 *Aquifer testing and borehole logging*

Aquifer tests are recommended to improve estimates of aquifer characteristics. Limited aquifer properties from previous reports were available outside the larger cities in the survey area. 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 could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailing aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR) at a reduced cost when compared to traditional aquifer tests. 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.

3.6.6 Recharge Zones

The LENRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer in Pierce Block. Reconnaissance level AEM investigations provide limited detailed information between the lines for understanding recharge throughout the survey area. It is recommended that additional AEM data be collected and interpreted similar to the Pierce Block which utilized closely-spaced flight lines using an AEM system that has good near-surface resolution in areas identified by the LENRD that are of priority importance for management purposes. It is further recommended that future work integrate new soils and land use 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. A potential solution to water quality, quantity, and stream depletions is adding additional fresh surface water as recharge to select areas of rangeland or other areas. Additional work can be done to identify where the best locations are for these type of management efforts.

3.6.7 Managed Aquifer Recharge

The areas which may have potential for managed aquifer recharge (MAR) can be approximately located by the interpreted results from AEM reconnaissance line interpretations. Detailed analysis for this purpose would need to be done to determine where viable opportunities for the LENRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping in new block flight locations and along the streams in the LENRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the LENRD for storage and release of water for stream flow and other uses.

4 Description of Data Delivered

4.1 Tables Describing Included Data Files

Table 4-1 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, twenty-three (15) flights were required to acquire the LENRD AEM data (Figure 2-5). Grouped by flight date, there are four (4) data flies included in Appendix 3\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 2.4.1). 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 4-2 describes the data columns in the ASCII *.xyz file LENRD_EM_MAG_UTM14n_feet.xyz. This file contains the electromagnetic data, plus the magnetic and navigational data, as supplied directly from SkyTEM.

The result of the SCI is included in LENRD_AEM_SCI_INV_v1.xyz and the data columns of these databases are described in Table 4-3.

The interpretation results are included in data files LENRD_InterpSurfaces_v2.xyz and PierceCoBlk_InterpSurfaces_v2.xyz in ASCII formats. Table 4-4 describes the data columns of those files. Note that these data have been segmented into approximately 10-mile segments, similar to the KMZ's.

A new table of data has been compiled (Table 4-5) that lists, model layer by model layer, the top, middle, and bottom depths and elevations of each model cell layer along with the inverted model resistivity for that cell.

ESRI Arc View Binary 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 4-6. And stored in Appendix 3_Deliverables\Grids.

The format of the voxel grids that have been created from the AEM data in the Pierce Block is described in Table 4-7. The voxel grid is presented as an xyz file, *Pierce_Block_Q_To_Voxel.xyz*.

In summary, the following are included as deliverables:

- Raw Data Files - SkyTEM files *.gex, *skb, *.lin
- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz in array and an individual column format by model layer.
- Interpretations as ASCII *.xyz
- ESRI ArcView files – surface, topo, etc
- Voxel Grid of the Pierce Block ***Q*** and ***To*** *.csv
- 2D profiles and 3D fence diagrams of the AEM survey inversion results

KMZs for LENRD AEM flight lines (Discussed in Section 4.2).

Table 4-1. 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	20180823_304_DualWaveform_60Hz_skb.gex	304M System Description
Mask	LENRD_Linefile.lin	Production file listing dates, flights, and assigned line numbers

Table 4-2: Channel name, description, and units for LENRD_EM_MAG_NESP83_Feet.xyz with DEM, 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]
E_NESP83_ft	Easting, NAD83 Nebraska State Plane	Feet [ft]
N_NESP83N_ft	Northing, NAD83 Nebraska State Plane	Feet [ft]
DEM	Digital Elevation	Meters [m]
Alt	DGPS Altitude above sea level	Meters [m]
GDSpeedL	Ground Speed	Kilometers/hour [km/h]
Curr_LM	Current, Low Moment	Amps [A]
Curr_HM	Current, High Moment	Amps [A]
LMZ_G01	Normalized (PFC-Corrected) Low Moment Z-RxCoil values array	$pV/(m^4*A)$
HMZ_G01	Normalized (PFC-Corrected) High Moment Z-RxCoil values array	$pV/(m^4*A)$
LMX_G01	Normalized (PFC-Corrected) Low Moment X-RxCoil values array	$pV/(m^4*A)$
HMX_G01	Normalized (PFC-Corrected) High Moment X-RxCoil values array	$pV/(m^4*A)$
PLNI	Power Line Noise Intensity monitor	V/m^2
Bmag_f	Raw Base Station Mag Data filtered	nanoTesla [nT]
MAG_Raw	Raw Mag Data	nanoTesla [nT]
Mag_Ed	Mag filtered	nanoTesla [nT]
Diurnal	Diurnal Mag Data	nanoTesla [nT]
Mag_CD	Mag Data Corrected for Diurnal Drift	nanoTesla [nT]
RMF	Residual Magnetic Field	nanoTesla [nT]
TMI	Total Magnetic Intensity	nanoTesla [nT]

Table 4-3. Channel name, description, and units for LENRD_AEM_SCI_Inv_v1.xyz with EM inversion results.

/Parameter	Description	Unit
LINE	Line Number	
Easting_FT	Easting NAD83, Nebraska State Plane	Feet (ft)
Northing_FT	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
Easting_M	Easting NAD83, UTM Zone 14	Meters [m]
Northing_M	Northing NAD83, UTM Zone 14	Meters [m]
DEM_M	DEM from survey	Meters [m]
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_28	Inverted resistivity of each layer	Ohm-m
RHO_STD	Inverted resistivity error per layer	
SIGMA_I_0 THROUGH SIGMA_I_28	Conductivity	S/m
DEP_TOP_0_FT THROUGH DEP_TOP_28_FT	Depth to the top of individual layers	Feet [ft]
DEP_BOT_0_FT THROUGH DEP_BOT_28_FT	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT THROUGH THK_28_FT	Thickness of individual layers	Feet [ft]
DEP_TOP_0_M THROUGH DEP_TOP_28_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_M THROUGH DEP_BOT_28_M	Depth to the bottom of individual layers	Meters [m]
THK_0_M THROUGH THK_28_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 4-4. Channel name description and units for the interpretation results files LENRD_InterpSurfaces_v2.xyz and PierceCoBlk_InterpSurfaces_v2.xyz. Note that there are no occurrences of *Kgg*, *Kd*, and *IP* in the Pierce County Block AEM data.

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[28]	Array of Inverted model resistivities of each layer	Ohm-m
RHO_STD[0] through RHO_STD[28]	Array of inverted resistivity errors per layer	
RESDATA	Inversion model residuals of each individual sounding	
RESTOTAL	Inversion model average of all residuals	
DEP_TOP_FT[0] through DEP_TOP_FT [28]	Depth to the top of individual layers	Feet [ft]
DEP_BOT_FT [0] through DEP_BOT_FT [28]	Depth to the bottom of 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]
WaterTable_1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
AquiferTyp[0] through AquiferTyp[28]	Array of Aquifer Material types: 0 - Bedrock; 1 - Non-Aquifer Material; 2 - Marginal Aquifer Material; 3 - Aquifer Material; 4 - Coarse Aquifer Material	Integer Array
Top_AqMat1	Elevation of top of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Bot_AqMat1	Elevation of bottom of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Top_AqMat2	Elevation of top of middle Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Bot_AqMat2	Elevation of bottom of middle Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Top_AqMat3	Elevation of top of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Bot_AqMat3	Elevation of bottom of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Top_Coarse_AqMat1	Elevation of top of Upper Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bot_Coarse_AqMat1	Elevation of bottom of Upper Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Top_Coarse_AqMat2	Elevation of top of Lower Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bot_Coarse_AqMat2	Elevation of bottom of Lower Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
To	Elevation of the top of the Tertiary Ogallala Group.	Feet [ft]
Bedrock	Elevation of interpreted bedrock surface	Feet [ft]
Kp	Elevation of the top of the Cretaceous Pierre Formation	Feet (ft)
Kn	Elevation of the top of the Cretaceous Niobrara Formation.	Feet [ft]
Kc	Elevation of the top of the Cretaceous Carlile Shale.	Feet [ft]
Kgg	Elevation of the top of the Cretaceous Greenhorn-Graneros Shale	Feet [ft]
Kd	Elevation of the top of the Cretaceous Dakota Formation.	Feet [ft]
IP	Elevation of the top of the Undifferentiated Pennsylvanian.	Feet [ft]

Table 4-5. LENRD Inversion Model Structure with DEM and Layer Top-, Bottom-, and Mid-points in Depth and Elevation plus Inverted Cell Resistivities (*LENRD_XYDEM_Dep_Elev_Rho.xyz*).

Parameter	Description	Unit
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]
Dep_Top_ft		Feet [ft]
Dep_Mid_ft		Feet [ft]
Dep_Bot_ft		Feet [ft]
Elev_Top_ft		Feet [ft]
Elev_Mid_ft		Feet [ft]
Elev_Bot_ft		Feet [ft]
RHO	Cell Resistivity	Ohm-m

Table 4-6. Files containing ESRI ArcView Binary Grids *.flt (Nebraska State Plane, NAD83, feet)

Grid File Name	Description	Grid Cell Size (feet)
LENRD_2018_DEM_Elev	Elevation (NAVD88 feet) of the Digital Elevation Model of the 2018 LENRD survey area, NAD 83State Plane Nebraska, feet	100
LENRD_2018_DEM_Pierce_Elev	Elevation (NAVD88 feet) of the Digital Elevation Model of the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	100
LENRD_2018_IP_Elev	Elevation (NAVD88 feet) of the top of the undifferentiated Pennsylvanian (***IP***) for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	2,640
LENRD_2018_K_Bedrock_Elev	Elevation (NAVD88 feet) of the top of the Cretaceous (***K***) bedrock for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	2,640
LENRD_2018_K_Bedrock_Pierce_Elev	Elevation (NAVD88 feet) of the top of the Cretaceous (***K***) bedrock for the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	500
LENRD_2018_Kc _Elev	Elevation (NAVD88 feet) of the top of the Cretaceous Carlile Shale (***Kc***) for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	2,640
LENRD_2018_Kc _Pierce_Elev	Elevation (NAVD88 feet) of the top of the Cretaceous Carlile Shale (***Kc***) for the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	500
LENRD_2018_Kd _Elev	Elevation (NAVD88 feet) of the top of the Cretaceous Dakota Group (***Kd***) for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	2,640
LENRD_2018_Kgg _Elev	Elevation (NAVD88 feet) of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***) for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	2,640
LENRD_2018_Kn _Elev	Elevation (NAVD88 feet) of the top of the Cretaceous Niobrara Formation (***Kn***) for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	2,640

LENRD_2018_Kn _Pierce_Elev	Elevation (NAVD88 feet) of the top of the Cretaceous Niobrara Formation (***Kn***) for the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	500
LENRD_2018_Kp _Elev	Elevation (NAVD88 feet) of the top of the Cretaceous Pierre Shale (***Kp***) for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	2,640
LENRD_2018_Kp _Pierce_Elev	Elevation (NAVD88 feet) of the top of the Cretaceous Pierre Shale (***Kp***) for the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	500
LENRD_2018_Q_Pierce_Thickness	Thickness (feet) of the Quaternary (***Q***) sections within the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	500
LENRD_2018_Sat_QandTo_Pierce_Thickness	Thickness (feet) of the Saturated Quaternary (**Q**) and Tertiary Ogallala Group (***To***) sections within the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	500
LENRD_2018_To _Elev	Elevation (NAVD88 feet) of the top of the Tertiary Ogallala Group (***To***) for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	2,640
LENRD_2018_To _Pierce_Elev	Elevation (NAVD88 feet) of the top of the Tertiary Ogallala Group (***To***) for the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	500
LENRD_2018_To _Pierce_Thickness	Thickness (feet) of the Tertiary Ogallala Group (***To***) sections within the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	500
LENRD_2018_WT_Elev	Elevation (NAVD88 feet) of the top of the water table from the 1995 Conservation and Survey Division (CSD), for the 2018 LENRD survey area, NAD83 State Plane Nebraska, feet	100
LENRD_2018_WT_Pierce_Elev	Elevation (NAVD88 feet) of the top of the water table from the 1995 Conservation and Survey Division (CSD), for the 2018 LENRD Pierce Block survey area, NAD83 State Plane Nebraska, feet	100

Table 4-7. Channel name, description, and units for Pierce_Block_*Q*_*To*_Voxel.xyz.

Parameter	Description	Unit
X	Easting NAD83, State Plane Nebraska	feet [ft]
Y	Northing NAD83, State Plane Nebraska	feet [ft]
Z	Elevation of Voxel Node	NAVD88 [ft]
Resistivity	Voxel cell resistivity value of the Quaternary (***Q***) and the Tertiary Ogallala Group (***To***)	Ohm-m

4.2 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\KMZ\FlightLines*".

Unique KMZ files were created for each individual flight line in 10-mile segments or shorter. 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 plus the elevations of tops and bottoms of aquifer material and coarse aquifer material as well as bedrock, the 1995 water table, and the elevations of the tops of the Cretaceous Pierre, Niobrara, Carlile, Greenhorn and Graneros, Dakota and Undifferentiated Pennsylvanian formations. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\LENRD18_Profiles*" folder. A similar folder is included for the Pierce County Block (*Pierce_Profiles*). In these folders are "*GoogleE_Readme.pdf*" files that provide instructions regarding 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. This LENRD GoogleE_Readme.pdf file is repeated below as a convenience. A map of the sub-areas of the LENRD 2018 AEM data collection is presented in Figure 4-1 and an example of the LENRD interpretation KMZ is presented in Figure 4-2 and one for the Pierce County Block is in Figure 4-3.

4.2.1 Included README for the LENRD Interpretation KMZ's

README for:

LENRD18_Interp_Area-1, …,-_Area-8.kmz's

Data Files - Please copy the folder *LENRD18_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: There are eight (8) kmz files covering the LENRD 2018 survey area because of the size of the area investigated and the amount of data acquired. The KMZ's are divided by overlapping areas. Files *LENRD18_Interp_Area-1, ….Area-2, …..Area-3, …..Area-4, …..Area-5, ……Area-6, …..Area-7, and …Area-8.kmz* within the folder named *LENRD18_Profiles* can now be opened and viewed in Google Earth. Note that the files contain a lot of data and may

take some time to load and that the loading of too many of these files at one time may interfere with the display and that not all the files may display even though they are loaded.

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) – DEM elevation in feet

WaterTable1995 Elev (ft) – 1995 Water Table elevation, in feet

Top Quaternary Upper AqMat (ft) – Elevation of Top of Quaternary Aquifer Materials zone, in feet

Bottom Quaternary Upper AqMat (ft) – Elevation of Bottom of Quaternary Aquifer Materials zone, in feet

Top Quaternary Middle AqMat (ft) – Elevation of Top of Quaternary Aquifer Material zone, in feet

Bottom Quaternary Middle AqMat (ft) – Elevation of Bottom of Quaternary Aquifer Materials zone, in feet

Top Quaternary Lower AqMat (ft) – Elevation of Top of Quaternary Aquifer Material zone, in feet

Bottom Quaternary Lower AqMat (ft) – Elevation of Bottom of Quaternary Aquifer Materials zone, in feet

Top Quaternary Upper Coarse AqMat (ft) – Elevation of Top of Coarse Aquifer Materials zone, in feet

Bottom Quaternary Upper Coarse AqMat (ft) – Elevation of Bottom of Coarse Aquifer Materials zone, in feet

Top Quaternary Lower Coarse AqMat (ft) – Elevation of Top of Coarse Aquifer Materials zone, in feet

Bottom Quaternary Lower Coarse AqMat (ft) – Elevation of Bottom of Coarse Aquifer Materials zone, in feet

Elev To (ft) – Elevation of Tertiary Ogallala Group formation, in feet.

Elev Bedrock (ft) – Elevation of Bedrock surface, in feet

Elev Kp (ft) – Elevation of Cretaceous Pierre Fm, in feet.

Elev Kn (ft) – Elevation of Cretaceous Niobrara Fm, in feet

Elev Kc (ft) – Elevation of Cretaceous Carlile Fm, in feet

Elev Kgg (ft) – Elevation of Greenhorn and Graneros formations, in feet

Elev Kd (ft) – Elevation of Top of Cretaceous Dakota Group, in feet

Elev IP (ft) – Elevation of Top of Undifferentiated Pennsylvanian units

Profile – Link to Interpreted AEM profile images

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

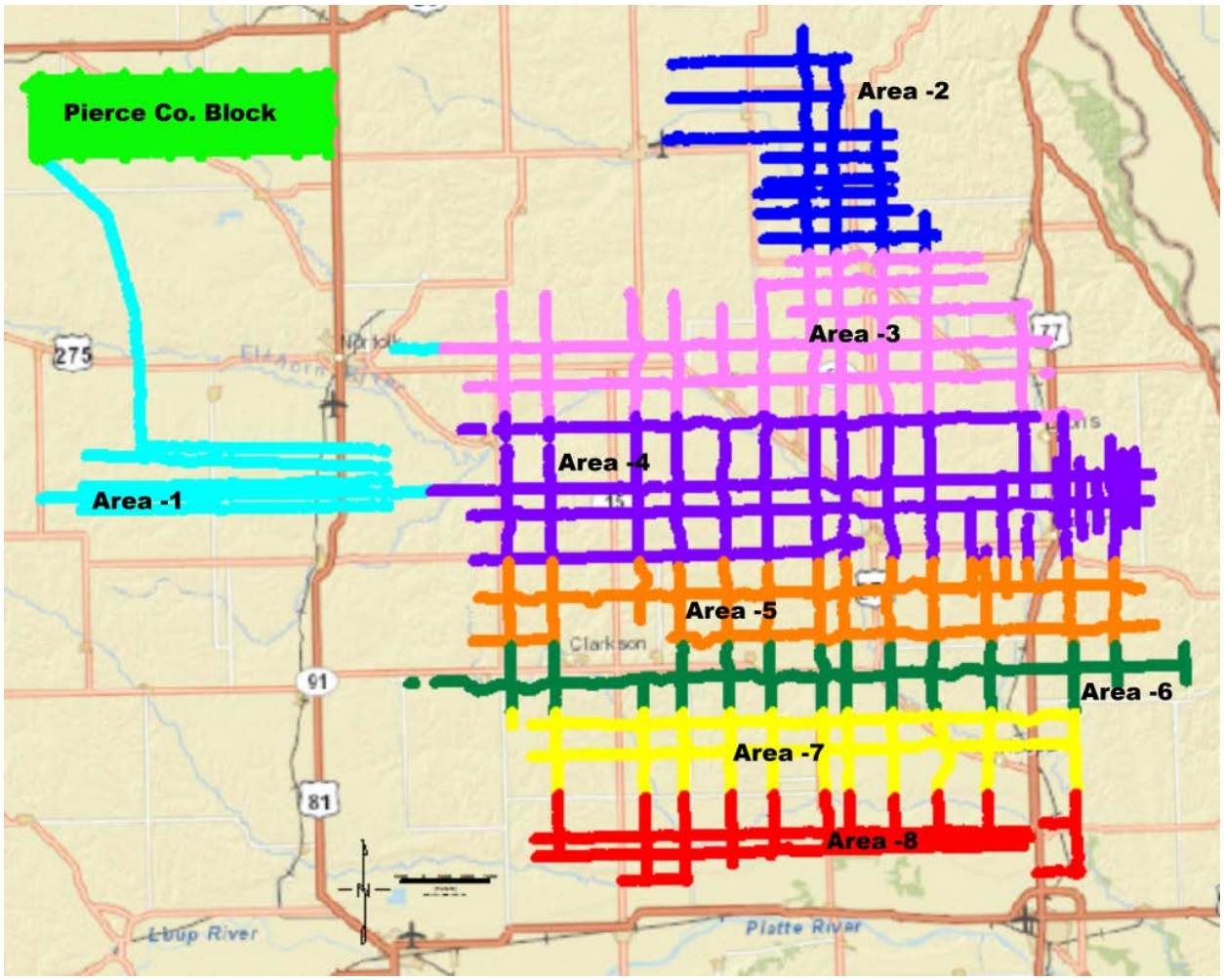


Figure 4-1. LENRD 2018 KMZ sub-areas. If the user were interested in the interpretation results in one of these areas, they would just have to select the KMZ covering that sub-area.

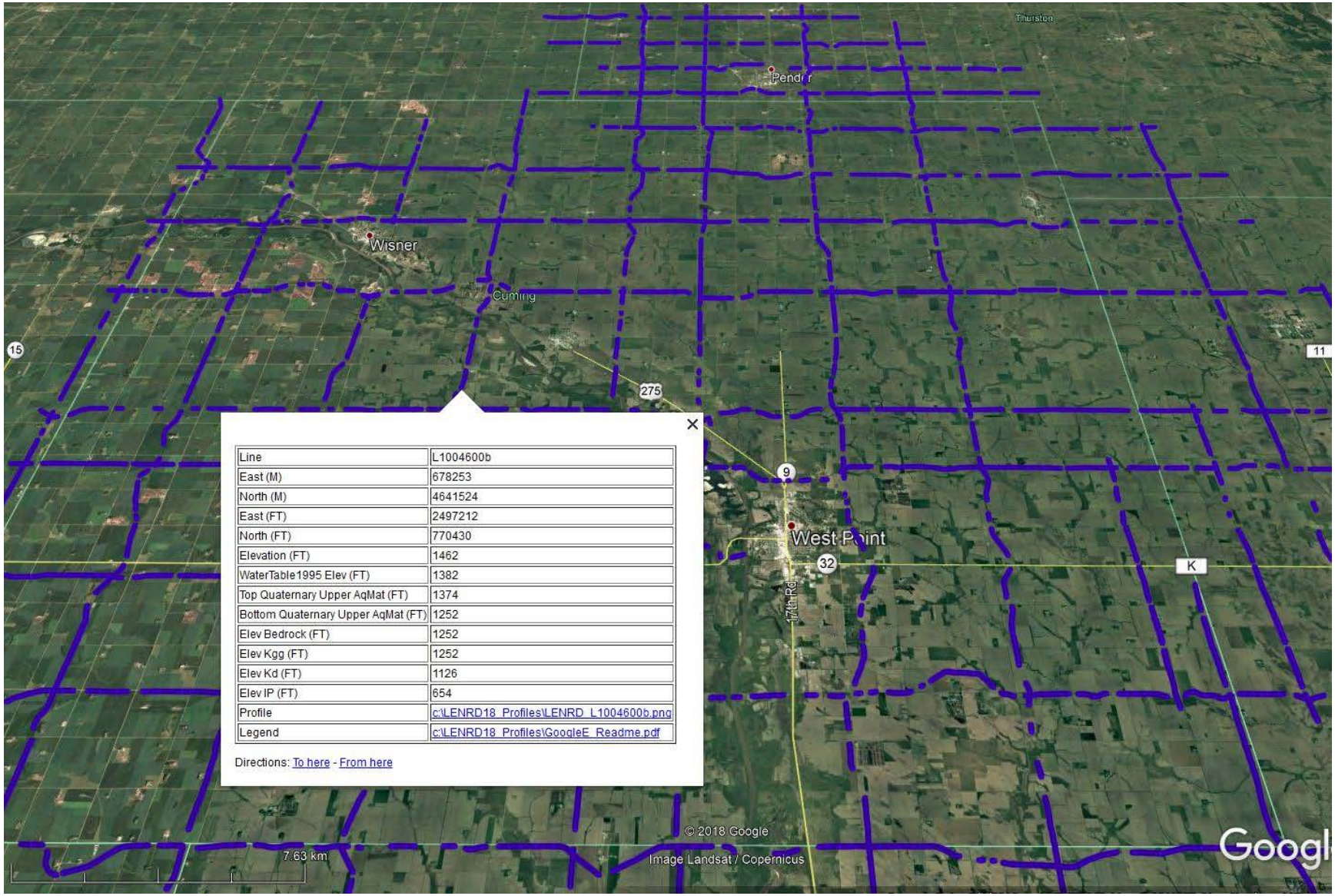


Figure 4-2. Example Google Earth image for the LENRD Interpretation kmz.

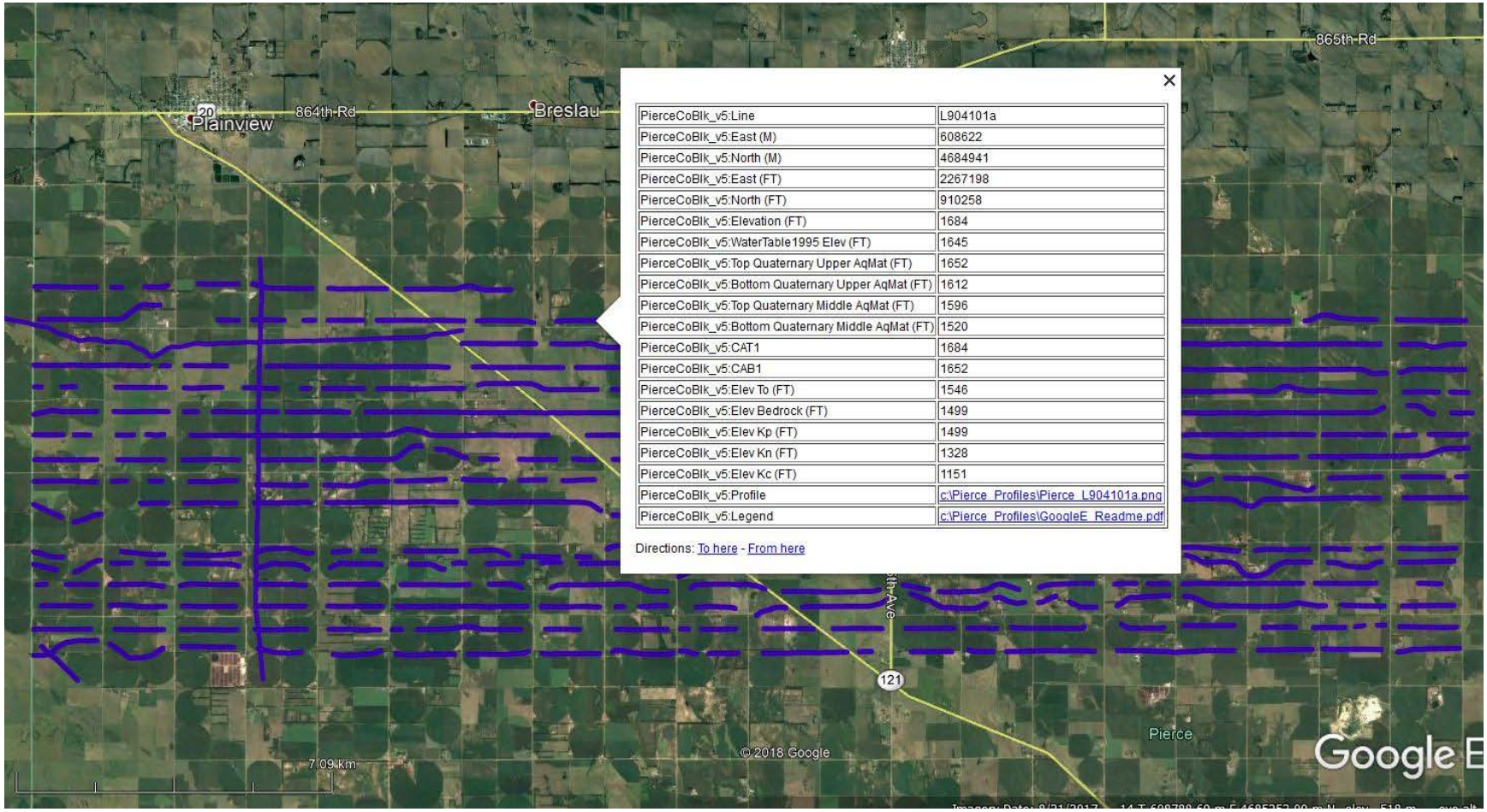


Figure 4-3. Example Google Earth image for the Pierce County Block Interpretation kmz.

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