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"Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Nemaha Natural Resources District

Prepared for the:

Nemaha Natural Resources District
62161 US-136
Tecumseh, Nebraska 68450

Submitted by:

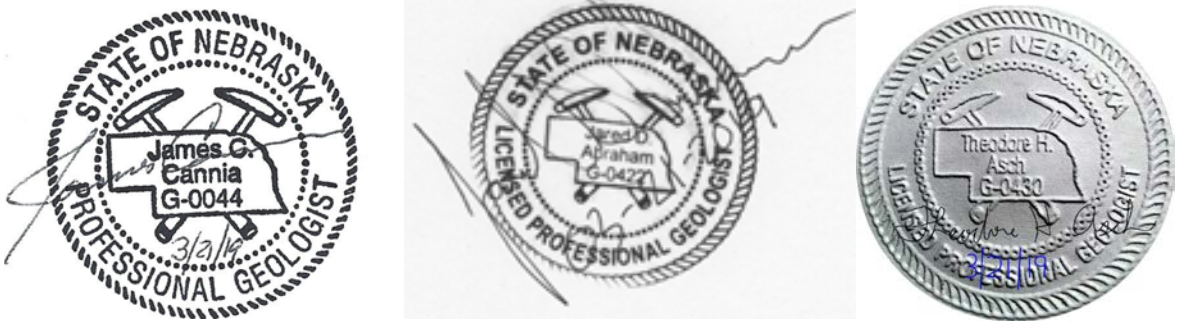
Aqua Geo Frameworks, LLC
130360 County Road D
Mitchell, NE 69357
Phone: (308) 641-2635

Jared D. Abraham, P.G.
jabraham@aquageoframeworks.com

Theodore H. Asch, P.G.
tasch@aquiageoframeworks.com

James C. Cannia, P.G.
jcannia@aquageoframeworks.com

Tammi L. Renninger
ElephantFish, LLC
tammi@elephantfishco.com



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 Nemaha 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 Eastern Nebraska Water Resources Assessment (ENWRA) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the Nemaha Natural Resources District (NNRD) 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 NNRD 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 NNRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies, if available.

Upon conclusion of the design process the NNRD reconnaissance flight lines were approximately 25 miles in length in the north-south direction and about 19 miles at their longest in the east-west direction and were separated by approximately 1 mile in both east-west and north-south directions. The Shubert Block, in the south east region of the investigation area, had east-west lines about 4.5 miles long separated by about 0.1 to 0.25 miles (200 m to over 300 m) and two north-south tie lines about 3 miles long.

1.4 AGF acquired AEM data over the NNRD, commencing 13 June 2018 and finishing on 17 June 2018, to support development of the hydrogeological framework. Approximately 579.8 line-miles (939.3 line-kilometers) were acquired over the NNRD AEM survey area. Status reports of the flying were provided to the Contract Representative of ENWRA and NNRD 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 June 15-19, 2018. Approximately 400.4-line-miles (648.7-line kilometers) were retained for inversion amounting to a retention rate of 69.1%. 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 NNRD 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 materials, 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 all areas in the NNRD. The top of the undifferentiated Pennsylvanian (***IP***) was a challenging unit to interpret due to the highly variable resistivity of the ***IP.*** This unit when compared to the Quaternary (***Q***) often 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 Nebraska Department of Natural Resources (NE-DNR) registered wells. Very rarely inconsistencies are encountered in the oldest of the Conservations and Survey Division (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 bedrock surface as developed by Leggette, Brashears, and Graham (LBG) (LBG, 2017) was used as a guide for the interpretation of the ***IP*** in areas of low electrical resistivity contrast and no boreholes. As in all surveys of this nature the use of boreholes with AEM needs to be approached in a thoughtful and considered manner as to the value of information from an individual borehole.

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)*** and undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, , Nebraska Oil and Gas Conservation Commission (NEOGCC), and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary aquifer material mapping are included in the appendices as well as interpretative surface grids. The known differences between the parameters of the 2015 AEM survey and 2018 AEM survey, 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, model layer parameters, and lithologic nomenclature.

2.3 **Resistivity/Lithology Relationship** - Assessment of the sediment character in the Quaternary 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.

2.4 **Hydrogeological Framework of the NNRD** - The 2018 NNRD AEM survey reveals variability in the Quaternary (***Q***) deposits across the NNRD AEM survey area. The ***Q*** make up the aquifer materials overlying the undifferentiated Pennsylvanian (***IP***) bedrock units. In the north and south parts of the AEM survey area, the aquifer material and coarse aquifer material exist in

paleochannels which are separated by ***Q*** deposits which consist of predominantly marginal to non-aquifer materials which are glacial till and loess and which can be more than 200 feet thick. ***Q*** aquifer and coarse aquifer materials are thick in the northwest part of the survey area. The Shubert Block flight area has very little aquifer and coarse aquifer material. Estimates of the groundwater in storage within the Shubert Block of aquifer material below the 1995 CSD water table elevation is 1,431 acre-ft and coarse aquifer material is 12 acre-ft. The amount of extractable groundwater from aquifer material is 315 acre-ft and coarse aquifer material is 2 acre-ft. The main aquifer material type in the Shubert Block is marginal aquifer materials. This material is composed of thin sand and gravel layers with silty sand, silty clay, and sandy clay. While these materials will produce water the yields and specific capacity will be reduced. The total estimate of the groundwater in storage below the 1995 water table is 275,619 acre-ft with 9,959 acre-ft extractable, demonstrating the impact of the fine-grained materials on the overall extractable groundwater.

2.5 Potential Recharge Zones within the NNRD AEM Survey Area - The use of block flights in Shubert area 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 showing 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. The area throughout the Shubert Block has potential recharge that is limited in extent. The groundwater in storage and potential yield from the aquifer has been calculated for the Shubert Block area. It supports the determination that low rates of recharge are available.

Within the Reconnaissance area the highest rate of recharge can be expected in the northwest area of the survey area due to the presence of aquifer and coarse aquifer materials from land surface down to the water table. Areas with aquifer and coarse aquifer materials at the surface can also become conduits for infiltration of nitrates into the groundwater system. These areas exist in the northwest section of the survey area where the reconnaissance lines are the basis for this determination. It should be noted that in these areas the results shown in the recharge maps are based on more interpolation between data points and less actual AEM data. A potential solution for any nonpoint source water quality contamination is adding additional fresh surface water as recharge to select areas of rangeland that can dilute any potential nitrate contaminant problem occurring from cropland. Additional work can be done to identify where the best locations are for these type of management efforts. A new feature for mapping recharge areas is the addition of the new 40-layer model for data analysis. This improves the recharge estimates by expanding the number of layers in the near surface providing a better estimate for the aquifer materials present. This allows for more accurate representation of the aquifer materials in the first 10 feet from the land surface downward.

3. RECOMMENDATIONS

Recommendations provided to the NNRD 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 NNRD about their management challenges.

3.1 **Integration of 2007-2018 AEM Hydrogeological Investigations** - The NNRD has acquired AEM data from 2007, 2015, and 2018 with three different AEM systems and contractors performing the work including USGS, XRI Geophysics and AGF with oversight from the ENWRA and the NNRD. With the completion of this current study there needs to be additional work done to bring all the work from previous years together in one seamless package using the same parameters such as the three different geographic projections NAD83 Zone 14N (meters), NAD83 Zone 14N (feet), and NAD83 Sate Plane Nebraska (feet), model layering structure, and hydrologic nomenclature. Recent communication with NNRD 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. 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 NNRD.

3.2 **Additional AEM Mapping** - The hydrogeologic maps provided in this report represent the completed hydrogeologic framework developed for the NNRD at reconnaissance level with approximately 1-mile spacing between flight lines. The Shubert Block flight area is the only exception to this flight line spacing which is about 0.1 to 0.25 miles (200 m to over 300 m). The first AEM project for the District was done in 2007 in the Firth Block that was collected with dense flight lines over a limited area. In 2015 AEM data was collected at an approximately 20-mile grid spacing. The interpretations match well with the CSD and NE-DNR test holes. The 2018 AEM project for NNRD selected areas for a hydrogeologic framework map to support groundwater models, selection of rural water supply well locations, locating water quality monitoring wells, determining the potential for areas make decisions about irrigation development and management policy, and selecting MAR or ASR locations. It is highly recommended that additional AEM data be collected and analyzed within the area of the Nemaha River basin northwest of the 2018 flights to complete the reconnaissance flights at 1-mile separation and addition of selected areas of block flights where detailed information is needed for decisions related to groundwater management. This information will strengthen the knowledge base of the important aquifer areas of the district. Most importantly it will provide information including the geographic distribution of amount of groundwater in storage, recharge areas, susceptibility to groundwater contamination and hydrologic connection to the streams in the block flight areas, within the NNRD that can be selected for current and future water development impacts.

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. Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. The areas of glacial till and loess covering the parts 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. Use of the data collected in this survey and future surveys will provide the best possible water table and conditions map for the district.

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 NNRD area was used in building the framework maps and profiles. Additional information from previous groundwater reports were helpful in this work. 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 with minimal sedimentary boundary conditions. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the NNRD.

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 NNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer in Shubert 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 Shubert Block which utilized closely-spaced flight lines using an AEM system that has good near-surface resolution in areas identified by the NNRD 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. This information can and has been used in Nebraska to improve Well Head Protection Areas by refining the estimated travel time estimates and the boundary areas.

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 NNRD 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 NNRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the NNRD for storage and release of water for stream flow and other uses.

3.8 **Updating previous groundwater reports and Groundwater Management Plans** - The groundwater report from LBG Hydrogeologic Assessment Report (LBG, 2017) should be updated with the AEM information which make it a more comprehensive publication. It should be noted that AGF conferred with LBG on some aspects of their report for this project. Future AEM work should be included in their report in order to achieve similar results. Should future AEM work be completed the results from that effort will help guide the future groundwater management plans for the district. The addition of estimates of groundwater in storage, recharge areas, hydrologic connection to streams and consideration of managed aquifer recharge sites will greatly improve and groundwater management plan.

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 Grids of the Shubert Block *.csv
- 2D Profiles and 3D fence diagrams of the AEM survey lines

Google Earth KMZs for NNRD 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
LBG	Leggette, Brashears and Graham
NNRD	Nemaha 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
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 Shubert in Richardson 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.

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 1 mile apart. This AEM survey was planned and selected by NNRD 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, NNRD and in-kind service from CSD.

A location map showing the NNRD 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. The flight area was north of Pawnee City and south of Nebraska City with reconnaissance flight lines west of Auburn and a block flight area, the Shubert Block, southeast of Auburn.

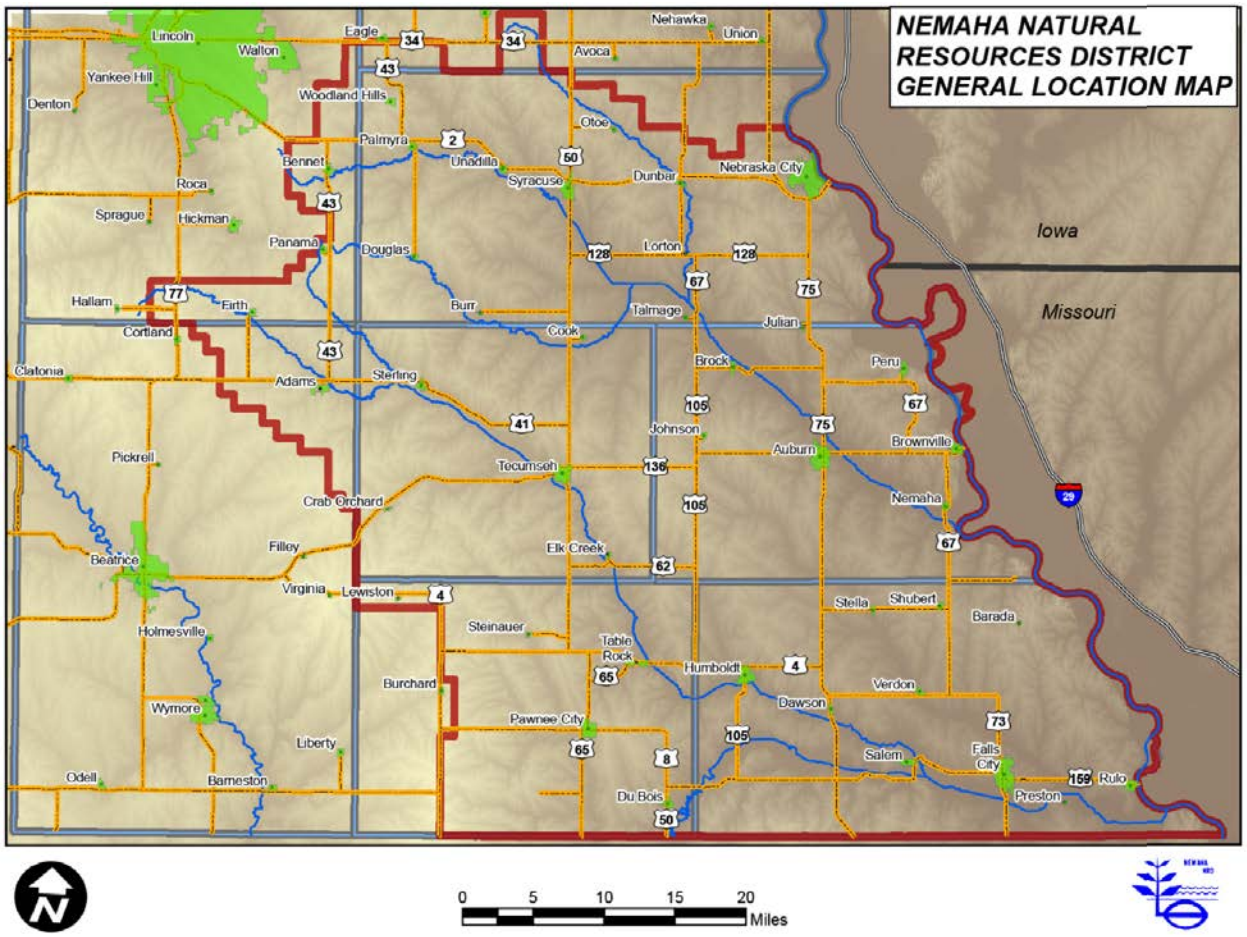


Figure 1-1. Map of the NNRD in southeastern Nebraska. The red line is the boundary of the NNRD (modified from www.NNRD.org).

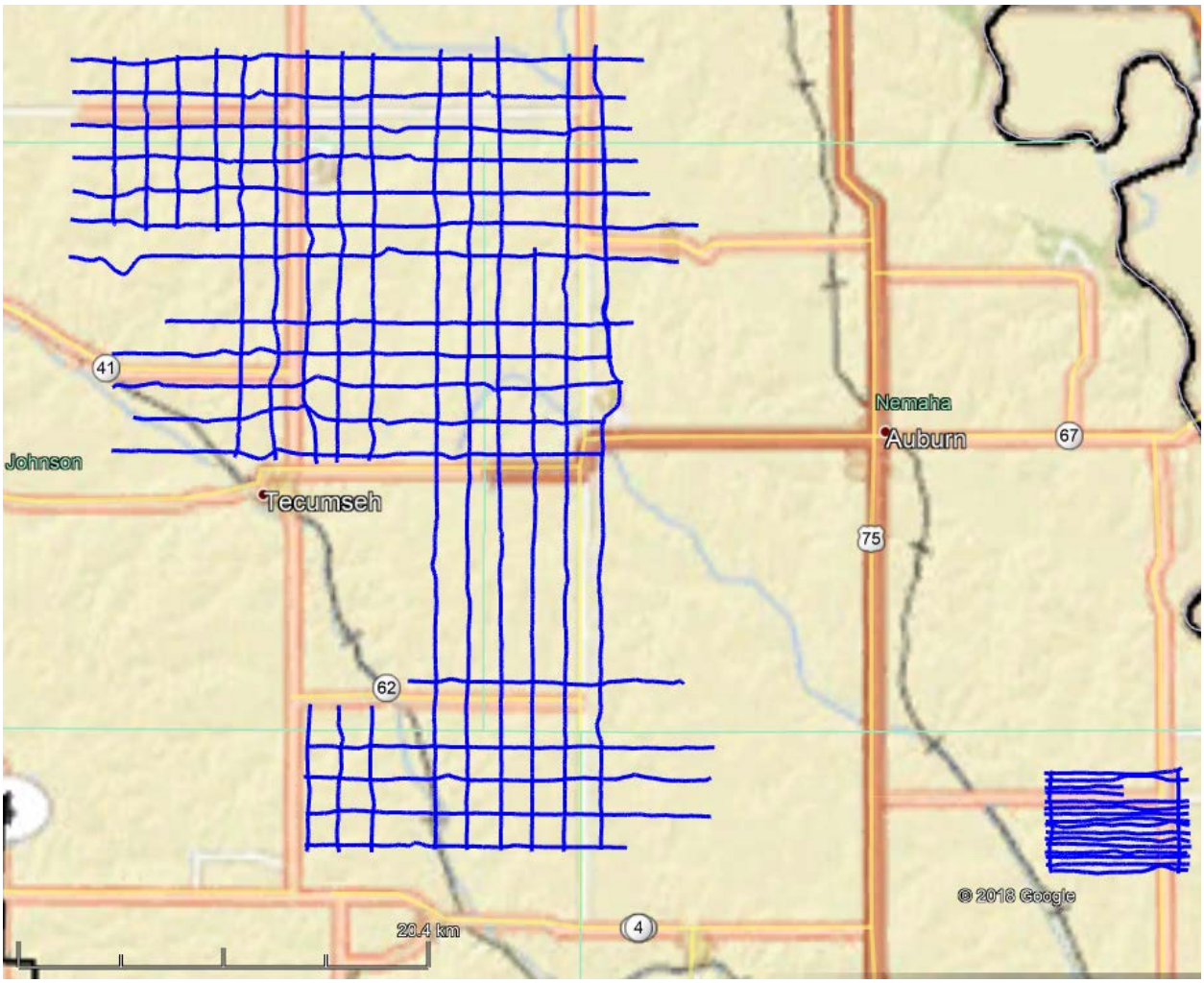


Figure 1-2. The NNRD 2018 AEM survey area including county lines and major roads.

1.2 Background

In January of 1986, with the approval of the NNRD Groundwater Management Plan, the NNRD established a districtwide Groundwater Management Area, for purposes of managing groundwater quality and quantity. The initial Groundwater Management Plan was updated in 1995 and 1999 for water quality and well permitting. It was updated again in 2003 designating selected areas in the survey area for phase II water quality management within parts of Johnson, Nemaha and Otoe counties. 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 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, NNRD, 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 NNRD 2018 AEM Project Area

The NNRD spans approximately 2,402 square miles (mi^2) in southeast Nebraska. The elevation of the area ranges from 881 ft to 1546 ft above sea level**.** It is underlain by parts of two of Nebraska's eight topographic regions—Rolling Hills and Valleys (Elder et al., 1951).

Principal cities within the project area, based on 2010 population estimates, include (alphabetically) Brock (112), Burr (5,660), Cook (321), Elk Creek (98), Johnson (328), Talmage (223), and Tecumseh (1,640) (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.

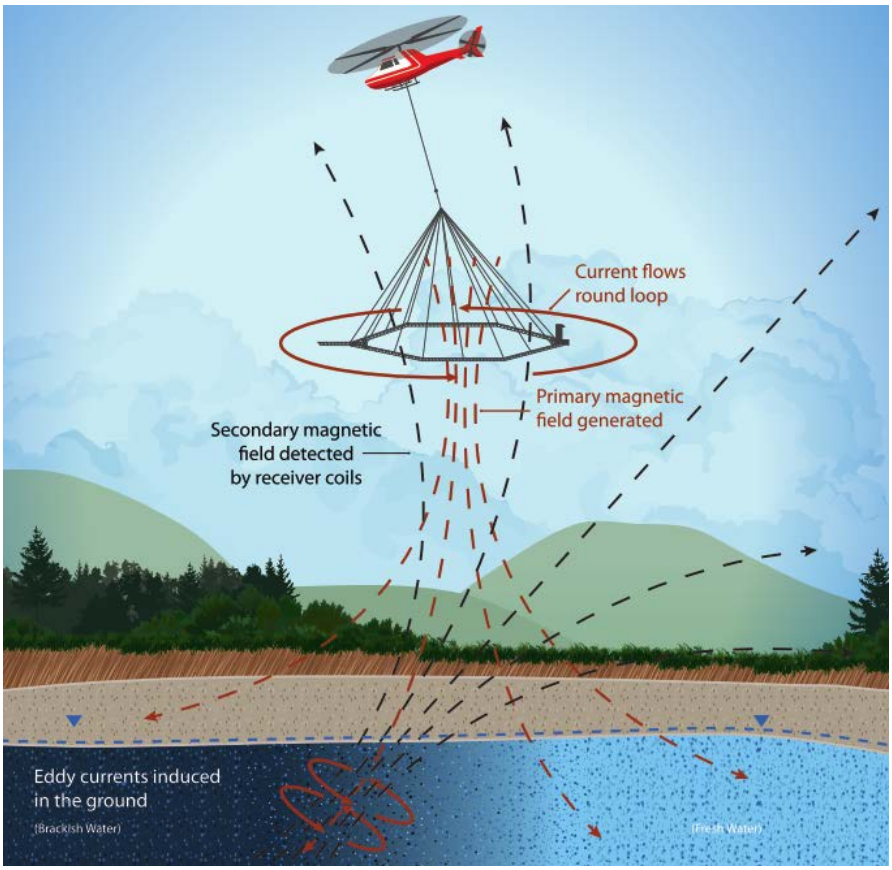


Figure 2-1: Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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.

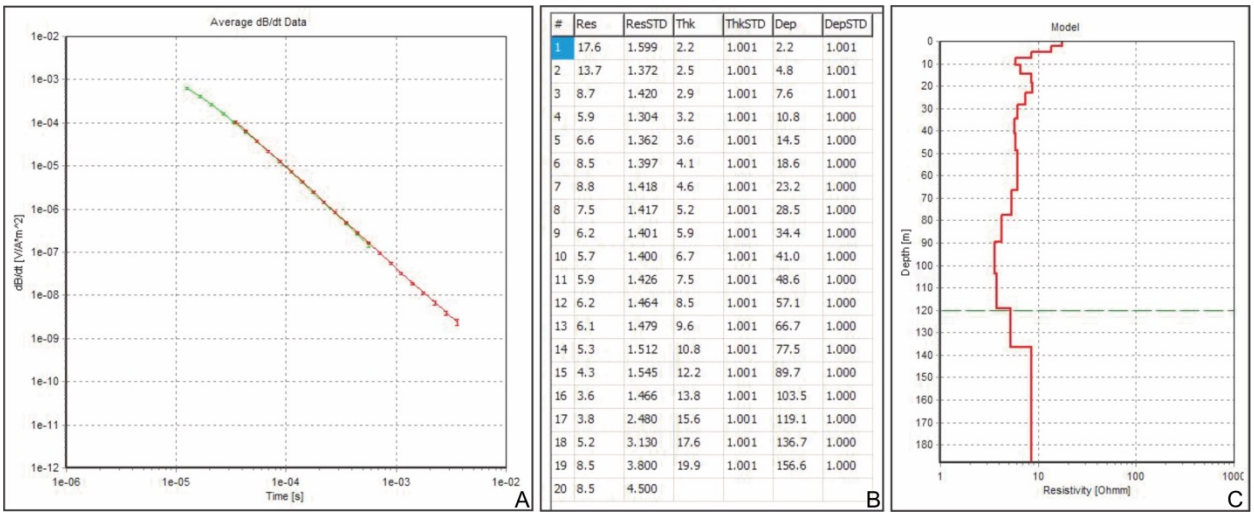


Figure 2-2: A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model.

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 NNRD, 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, Nebraska Public Power District, Nemaha-Marshall Electric Cooperative, and Omaha 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.

Upon conclusion of the design process the NNRD reconnaissance flight lines were approximately 25 miles in length in the north-south direction and about 19 miles at their longest in the east-west direction and were separated by approximately 1 mile in both east-west and north-south directions (Figure 1-2 and Figure 2-5). The Shubert Block in the southeast region of the investigation area, had east-west lines about 4.5 miles long separated by about 0.1 to 0.25 miles (200 m to over 300 m) and two north-south tie lines about 3 miles long.

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).

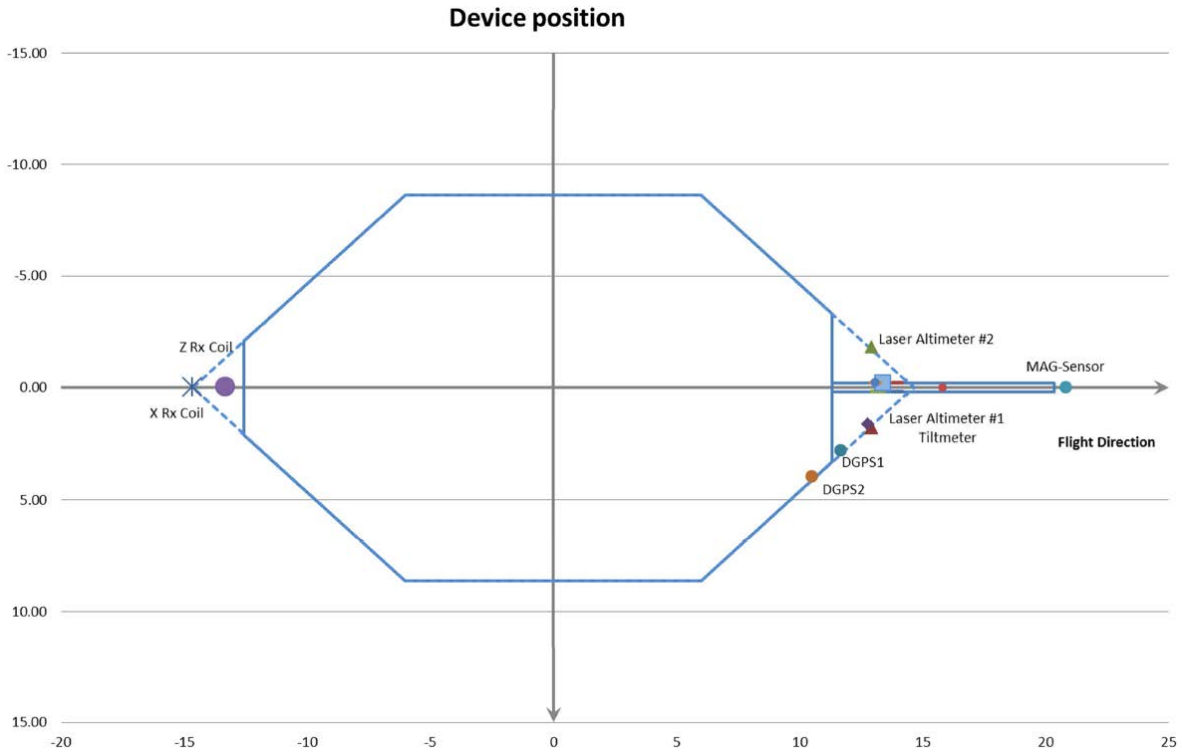


Figure 2-3: SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 2-1.



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 579.8 line-miles (939.3 line-kilometers) were acquired over the NNRD AEM survey area between June 13 and June 17, 2018. The Nebraska City airport, Pawnee City, and the Tecumseh 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.

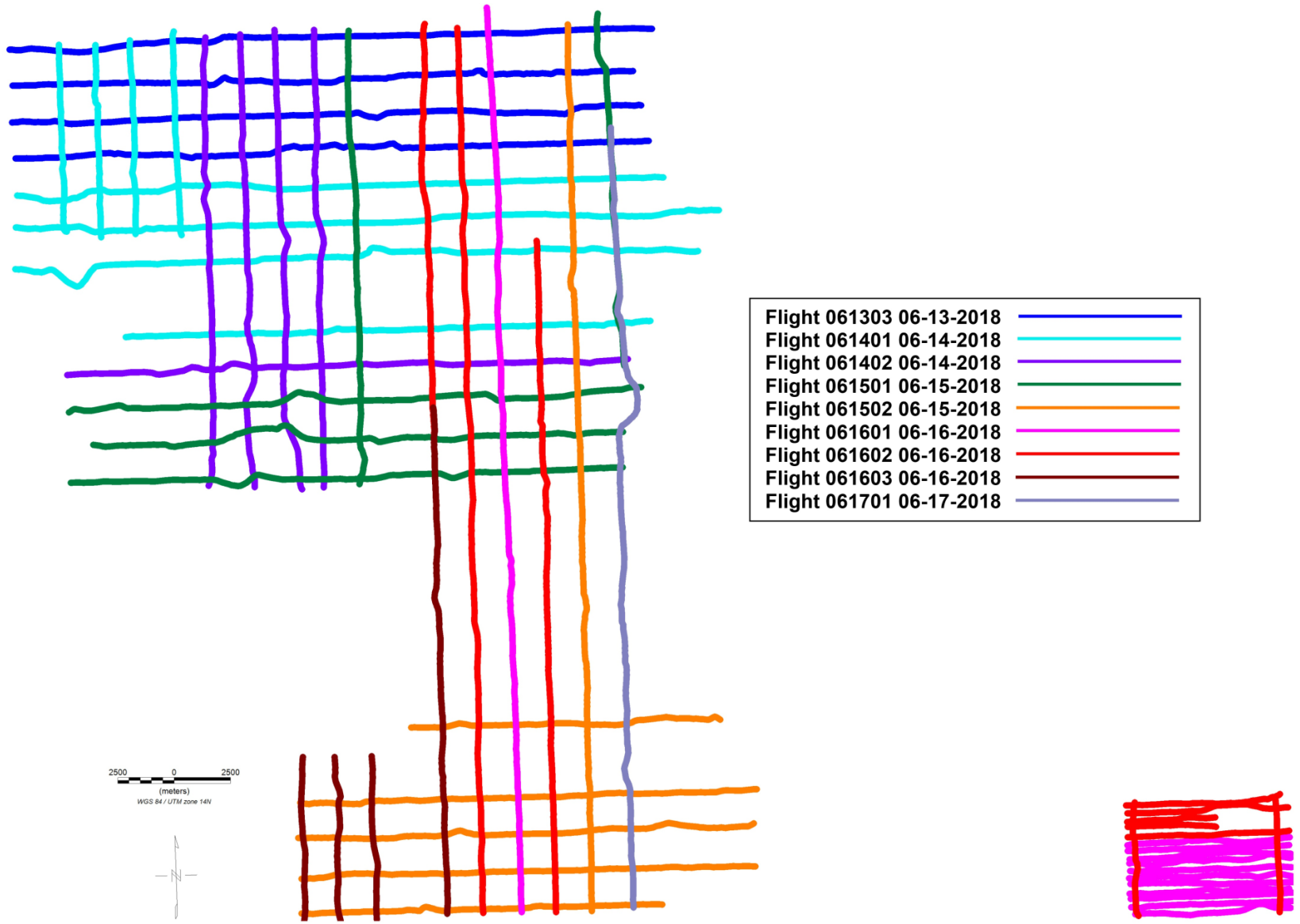


Figure 2-5: NNRD 2018 AEM flight lines grouped by acquisition date.

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, 400.4-line-miles (648.7-line kilometers) of data were retained for the final inversions for the NNRD 2018 AEM reconnaissance survey. This amounts to a data retention of 69.1%. This high rate is the result of careful flight line planning and design.

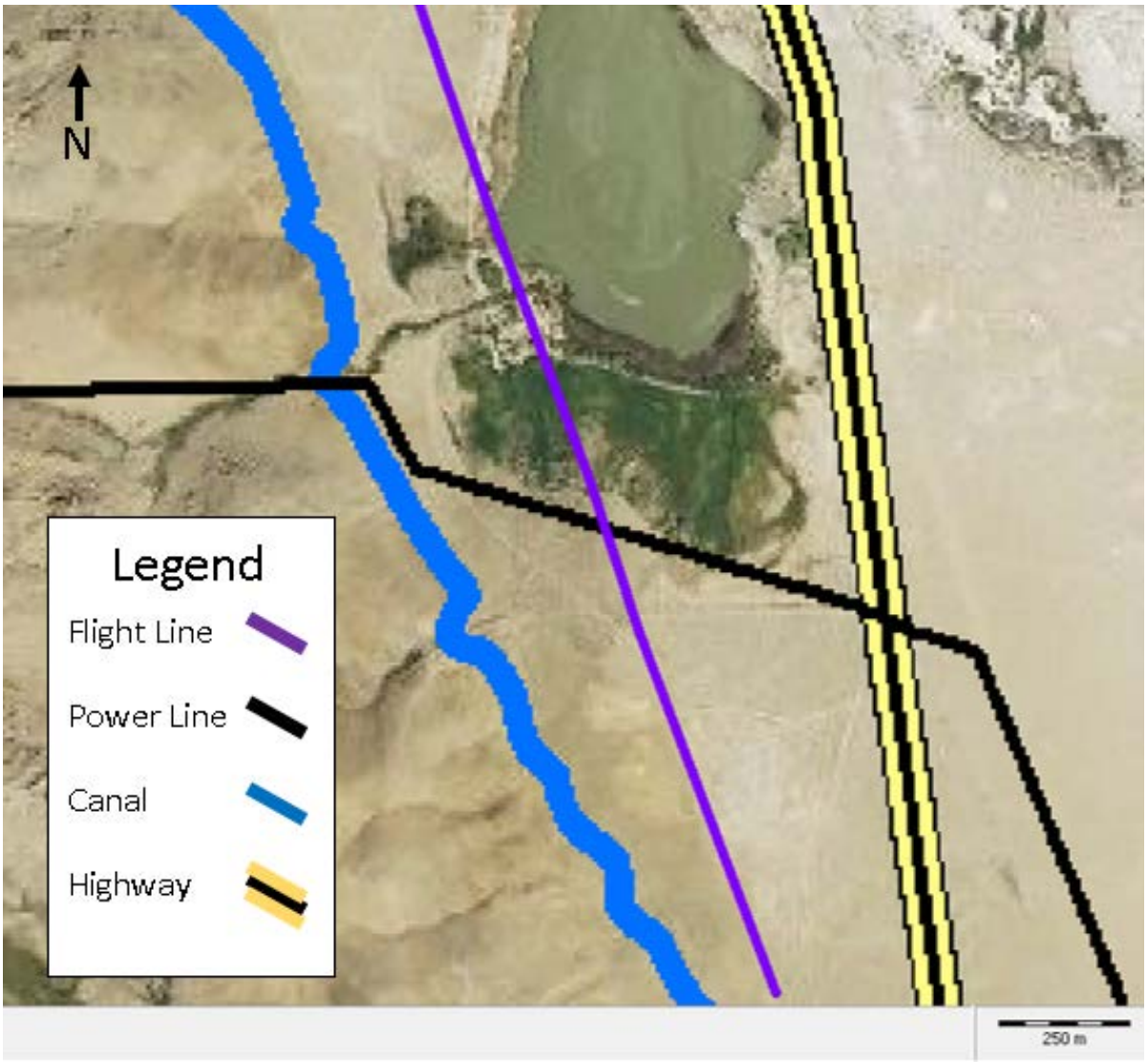


Figure 2-6: Example locations of electromagnetic coupling with pipelines or power lines.

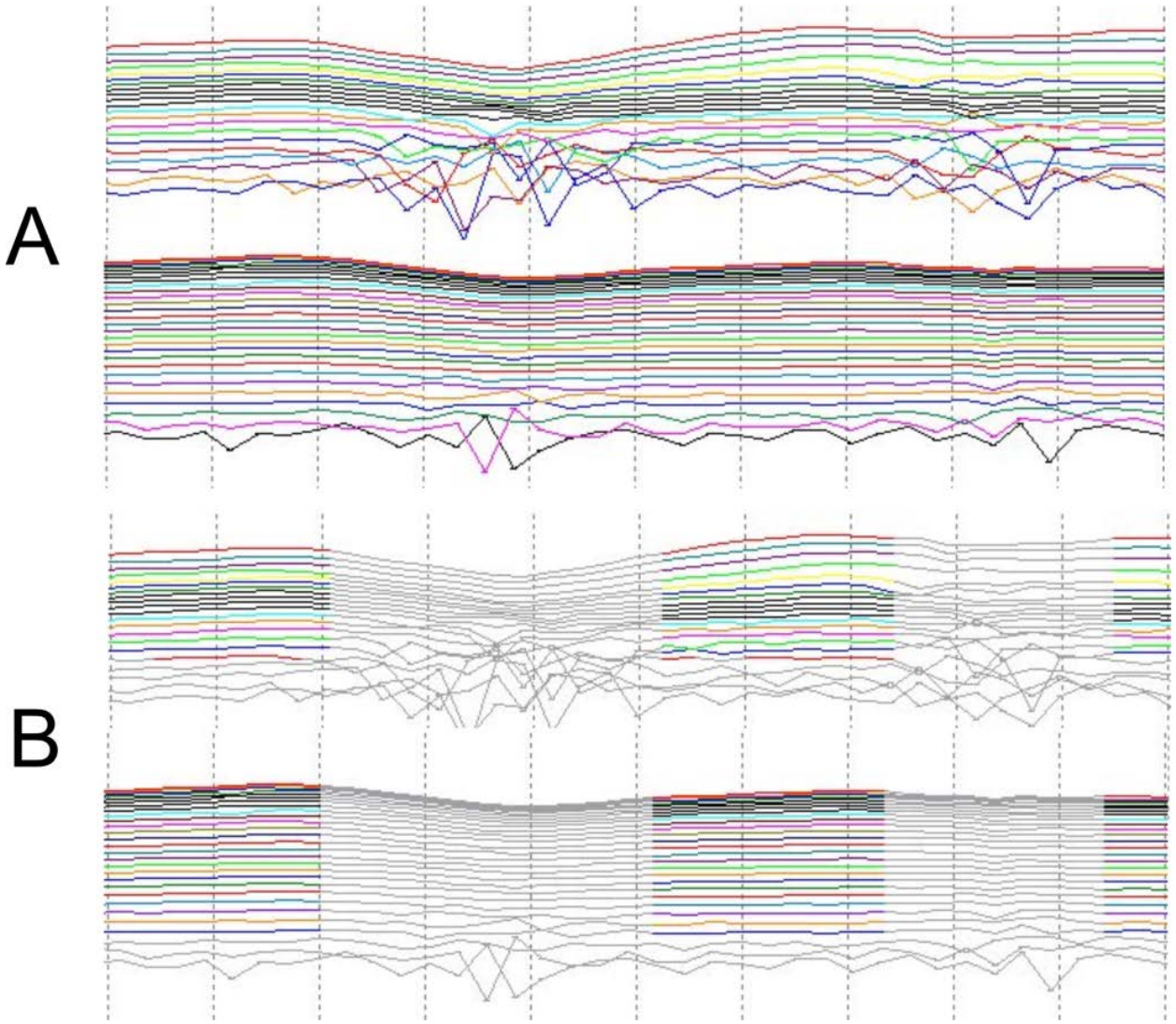


Figure 2-7: A) Example of AEM data affected by electromagnetic coupling as presented in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

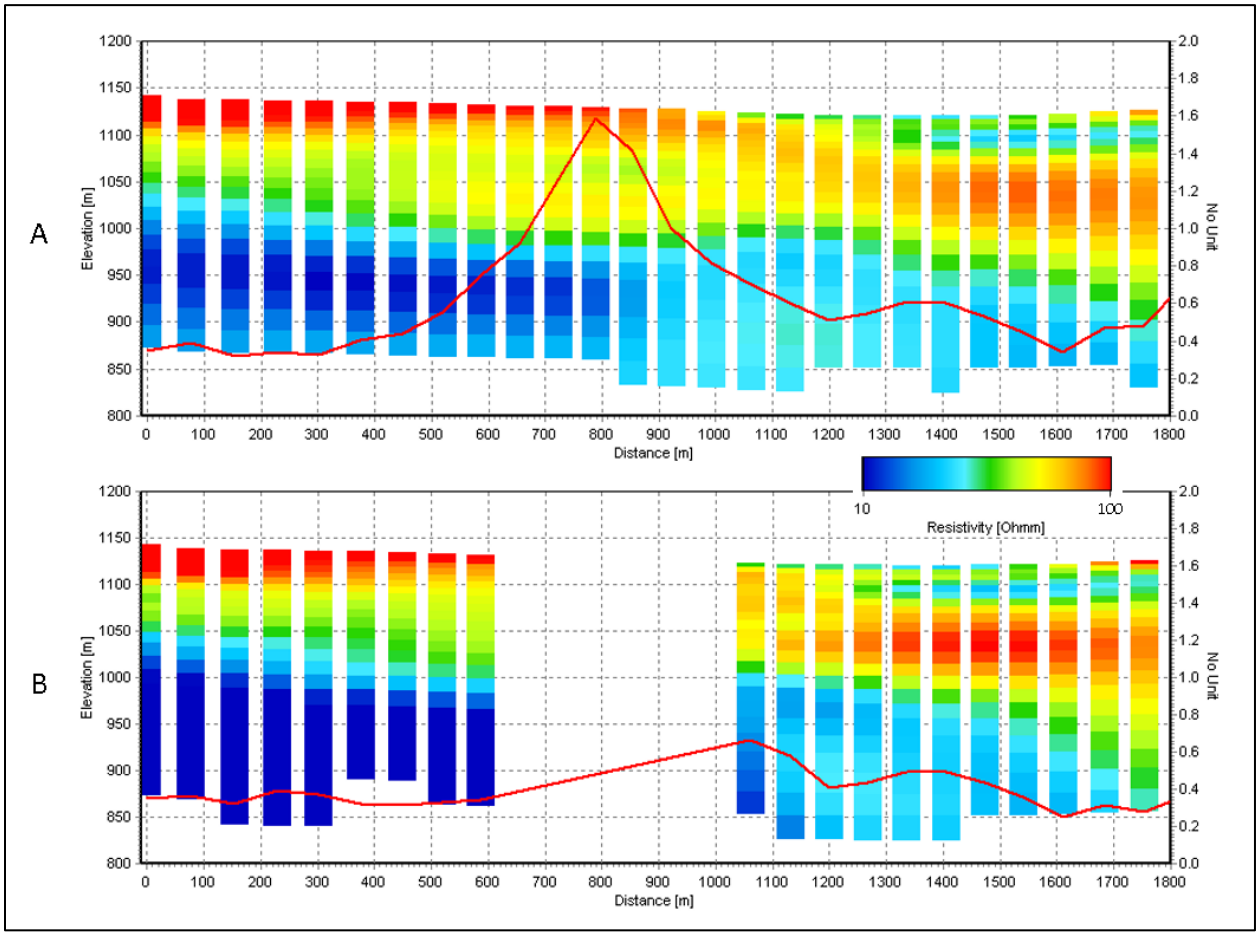


Figure 2-8: A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

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 NNRD 2018 AEM survey are presented in Figure 2-9. The NNRD-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.

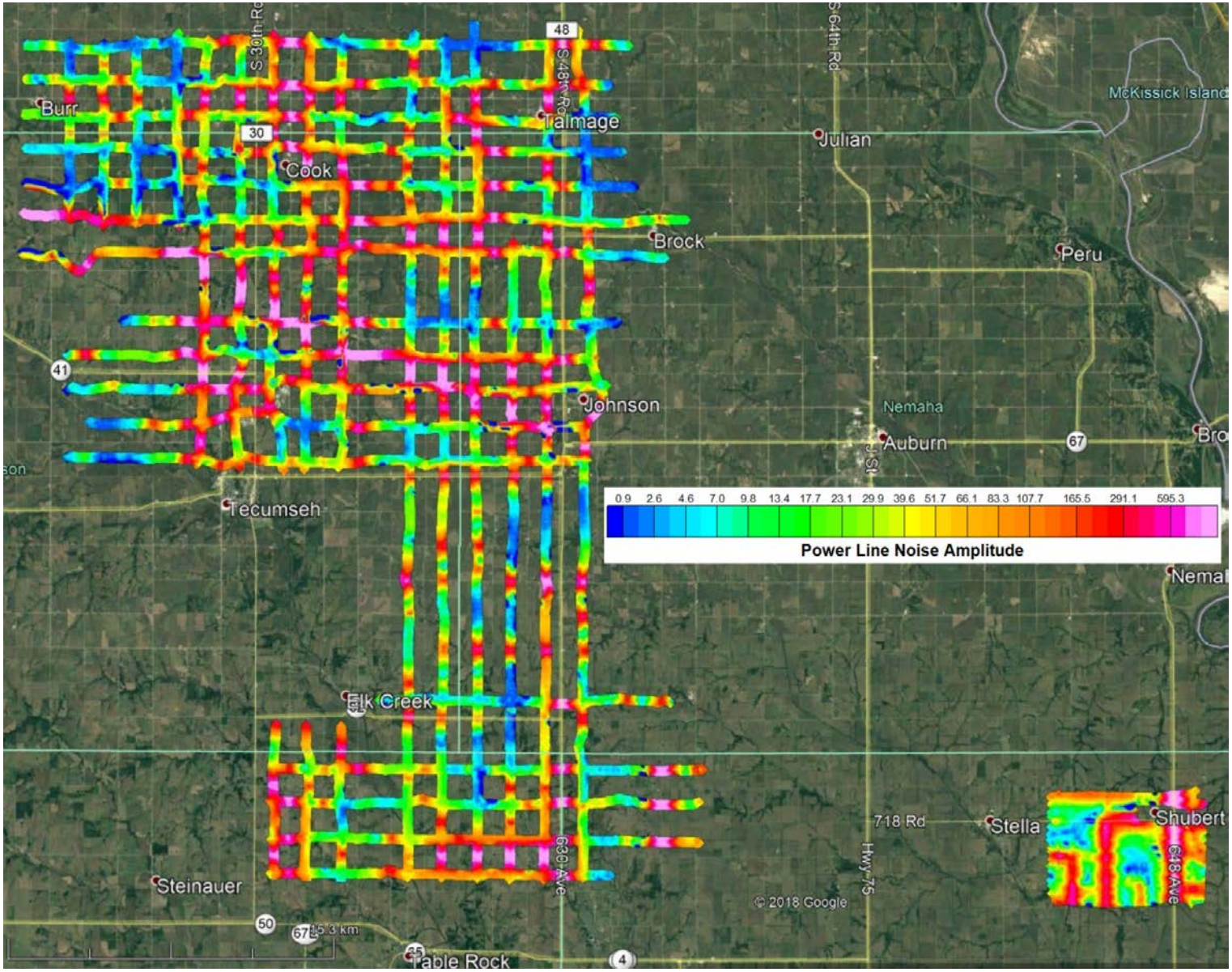


Figure 2-9: Power Line Noise Intensity (PLNI) map of the NNRD 2018 project area.

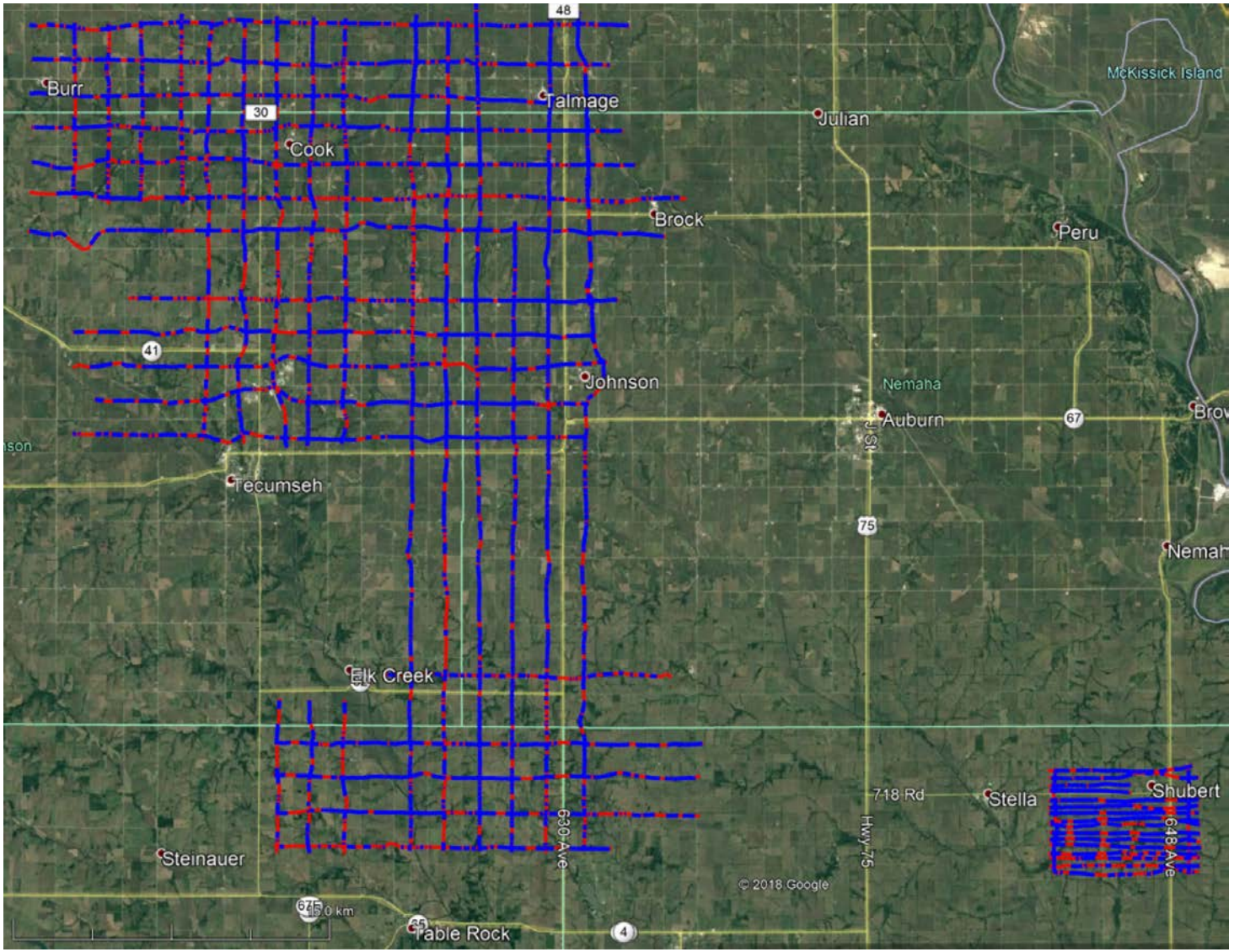


Figure 2-10: Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the NNRD 2018 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. 69.1% of the acquired data was retained for inversion and interpretation. Google Earth kmz's of the inverted 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 residual magnetic Total Field intensity data for the NNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). This data is used in decoupling efforts.

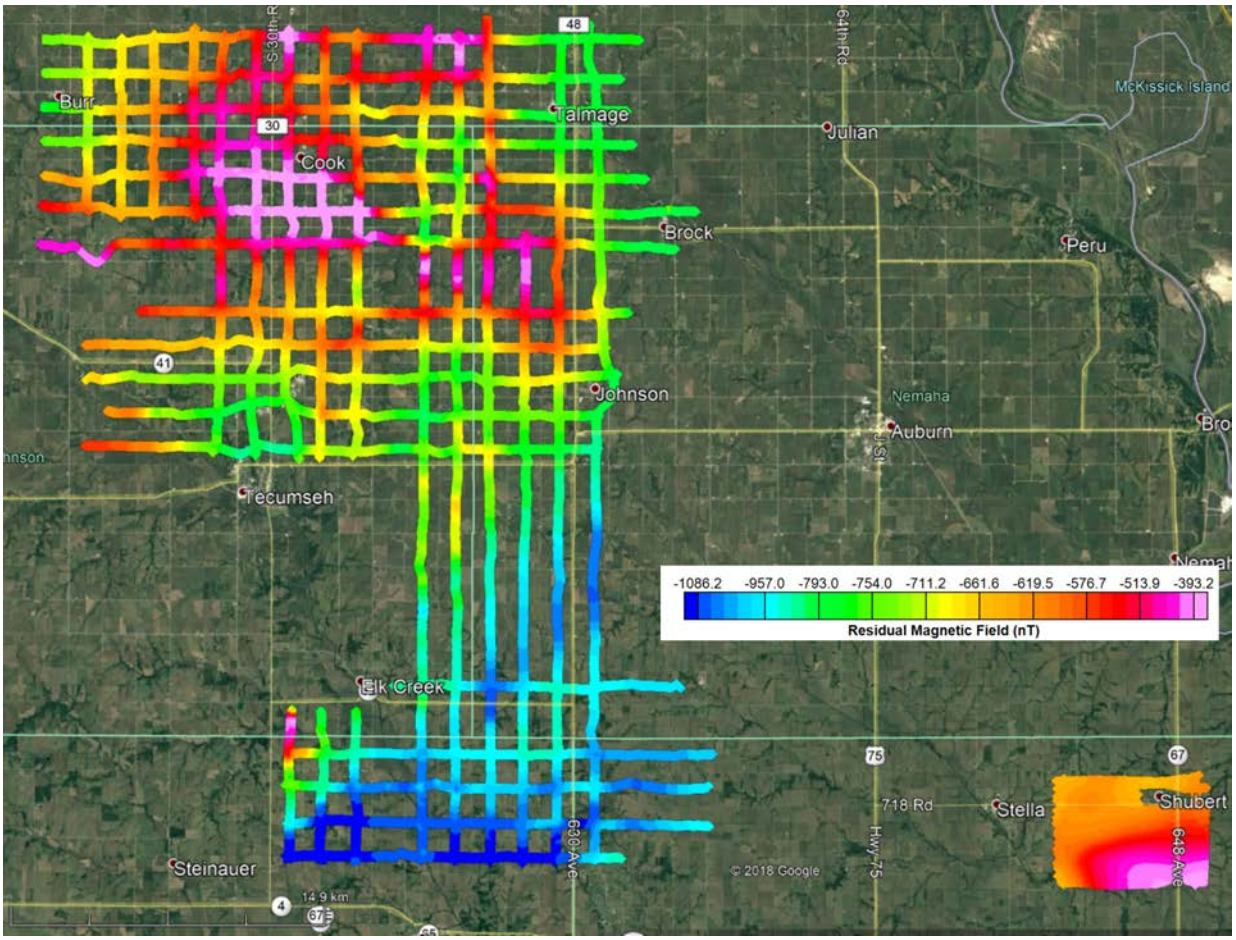


Figure 2-11: Residual magnetic Total Field intensity data for the NNRD 2018 survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

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 NNRD 2018 AEM data were inverted using a 40-layer model structure. 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 3 ft (1 m) 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).

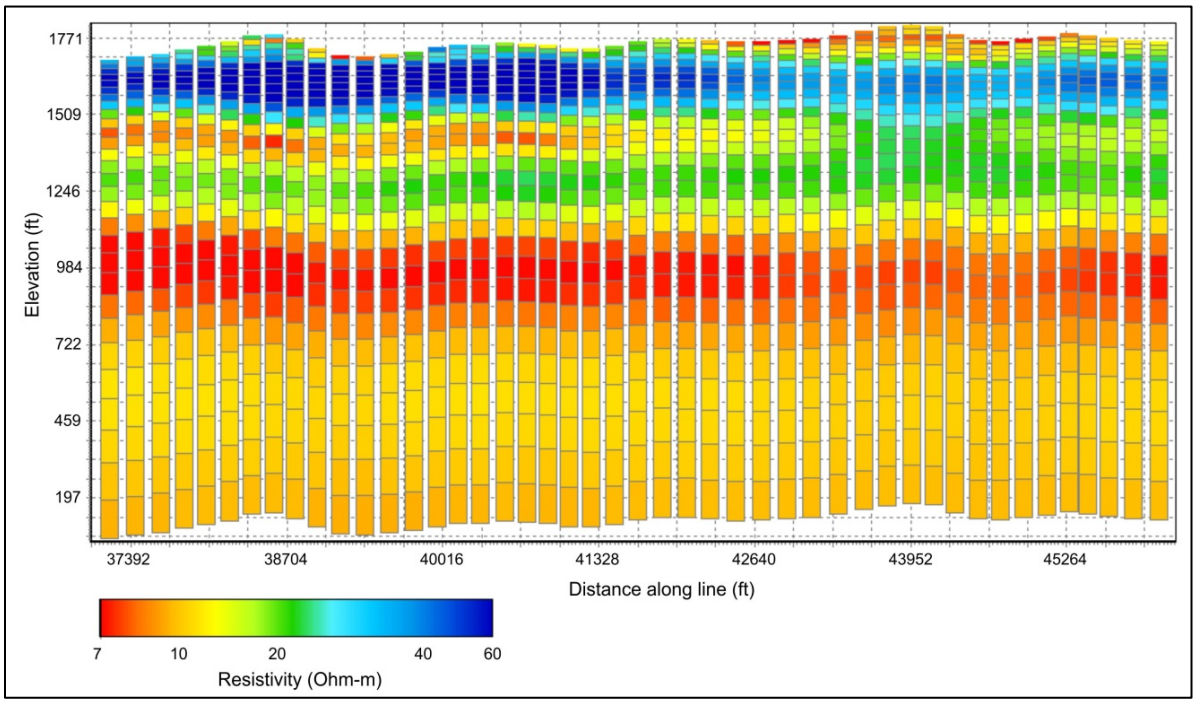


Figure 2-12: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

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	3.3	3.3	21	197.8	20.0
2	6.9	3.6	22	219.8	22.0
3	10.8	3.9	23	243.7	23.9
4	15.1	4.3	24	269.9	26.2
5	19.7	4.6	25	298.8	28.9
6	24.9	5.2	26	330.3	31.5
7	30.5	5.6	27	364.7	34.4
8	36.7	6.2	28	402.5	37.7
9	43.6	6.9	29	443.8	41.3
10	51.2	7.5	30	489.0	45.3
11	59.4	8.2	31	538.6	49.5
12	68.2	8.9	32	593.0	54.4
13	78.1	9.8	33	652.4	59.4
14	88.6	10.5	34	717.3	64.9
15	100.4	11.8	35	788.5	71.2
16	113.2	12.8	36	866.6	78.1
17	127.3	14.1	37	951.9	85.3
18	142.7	15.4	38	1045.3	93.5
19	159.4	16.7	39	1147.7	102.3
20	177.8	18.4			

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

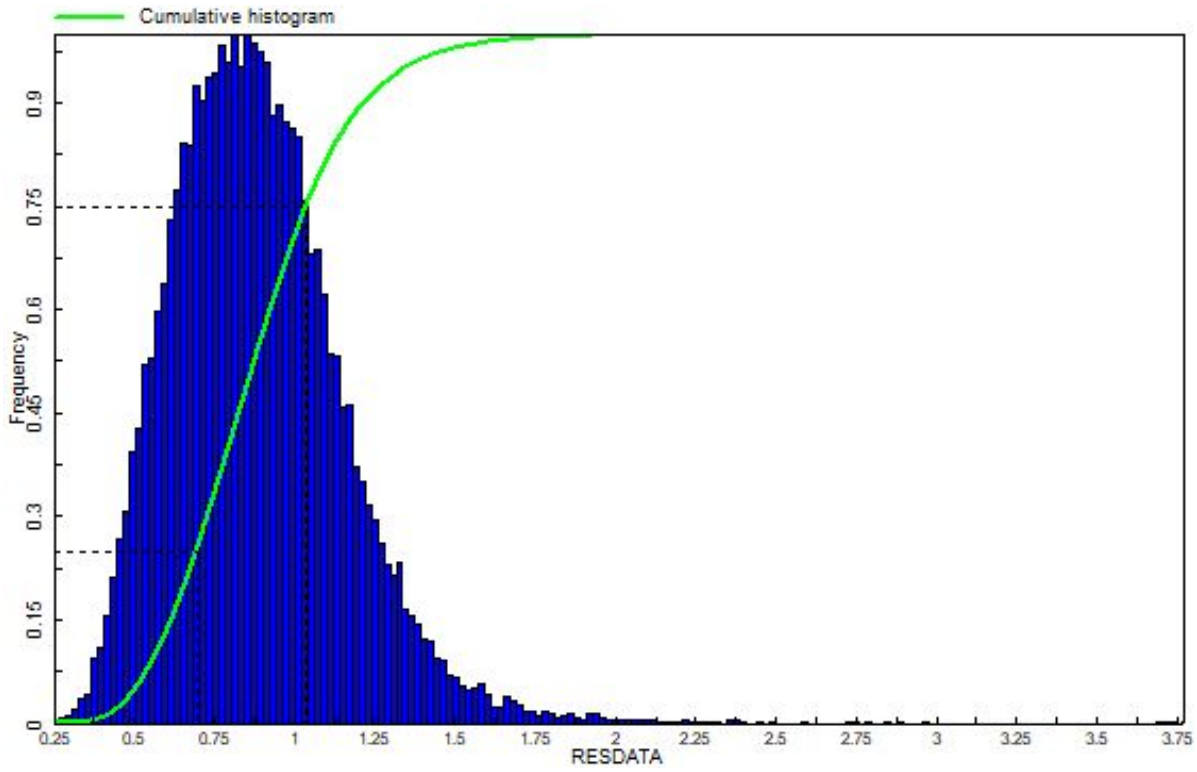


Figure 2-13: Data/model residual histogram for the NNRD 2018 SCI inversion results.

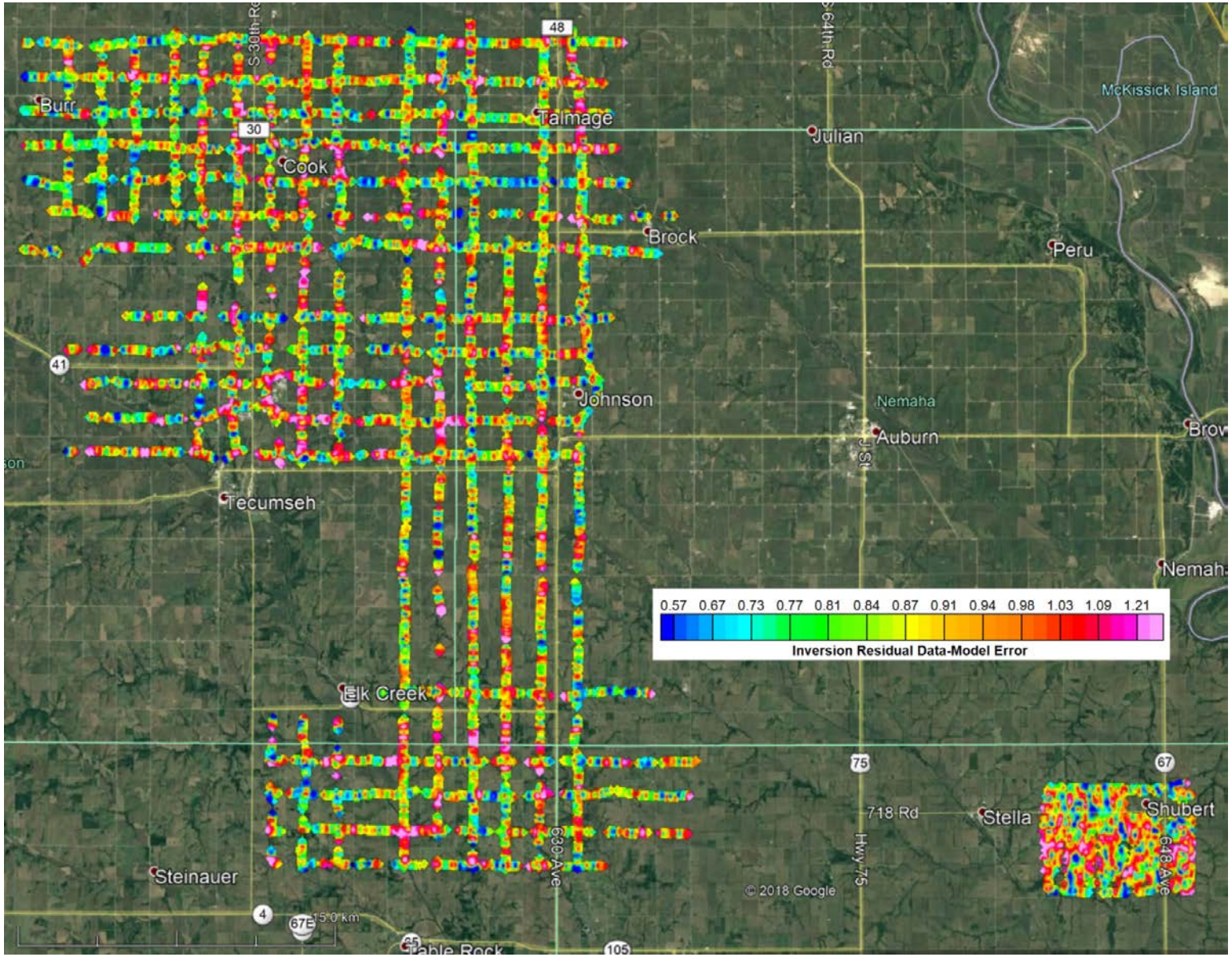


Figure 2-14. Map of data-inversion model residuals for the NNRD 2018 SCI inversion results.

3 AEM Results and Interpretation

This section provides the details on the process involved in the interpretation of the NNRD 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. This included lines that composed the 1-mile reconnaissance grid lines. 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 NNRD 2018 AEM survey.

Original Source Lines	Direction	New Line
L100501, and L100502	East-West	L100500
L102201, and L102202	East-West	L102200
L102401, and L102402	East-West	L102400
L102501, and L102502	East-West	L102500
L201301, and L201302	North-South	L201300

A portion of the NNRD has had AEM data collection before that is summarized in Carney et al. (2015b). Some of these lines are in the area of the 2018 NNRD data collection.

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 NNRD 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 3-1 is a map of the DEM for the reconnaissance line area having a vertical relief of 651 ft with a minimum elevation of 881 ft and a maximum elevation of 1,546 ft. This DEM was used to reference all elevations within the AEM and borehole datasets. Figure 3-2 is a DEM of The Shubert Block and has a vertical relief of 261 ft with a minimum elevation of 911 ft and a maximum elevation of 1,172 ft.

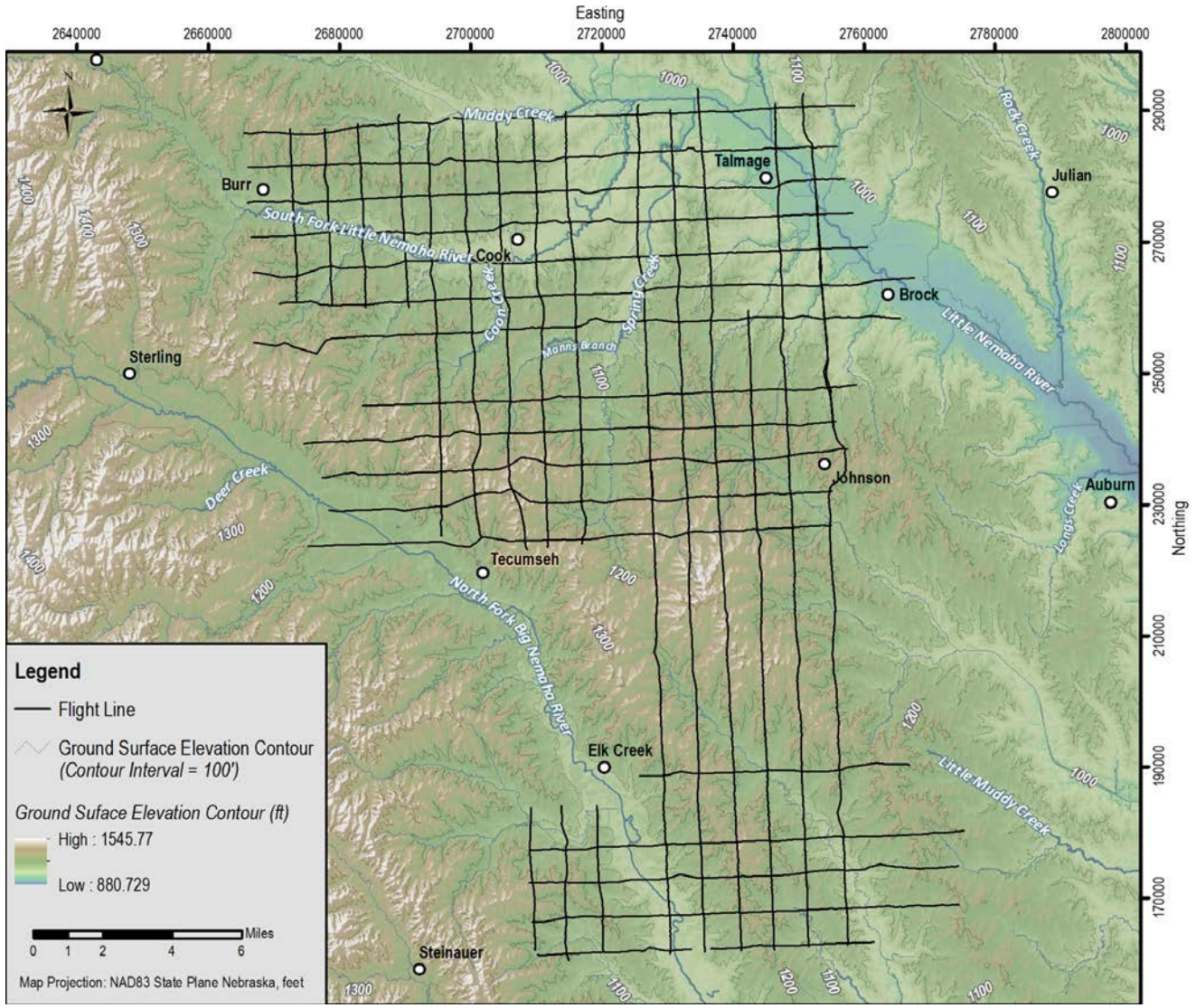


Figure 3-1. Map of the Digital Elevation Model for the NNRD Reconnaissance lines study area. Flight lines are indicated with black lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

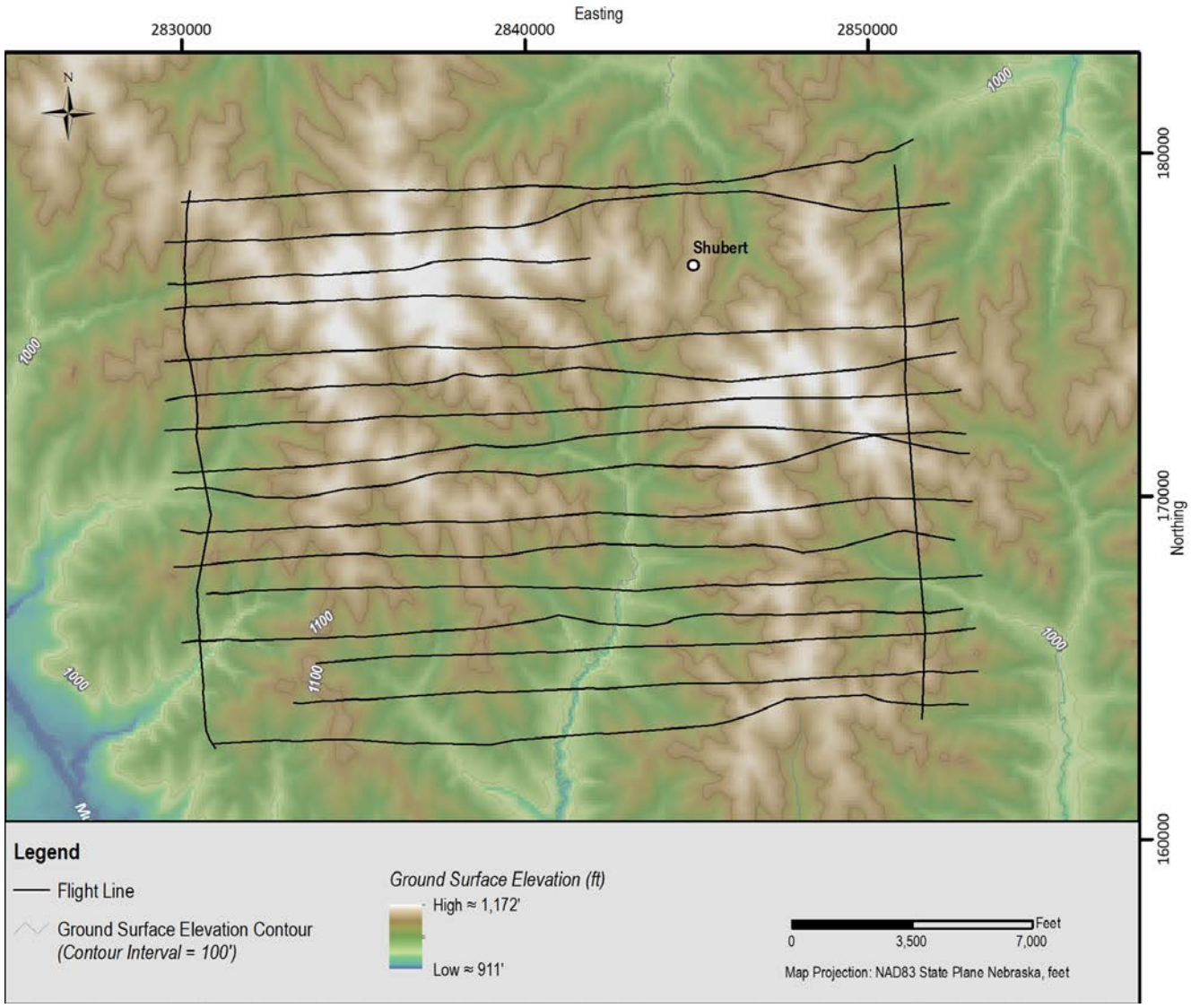


Figure 3-2. Map of the Digital Elevation Model for the Shubert Block AEM survey area. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2018). Flight lines are indicated by black lines. North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

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 PA (Datamine, 2019). During interpretation, the horizontal and vertical scale of the profiles were adjusted to facilitate viewing. The color scale of the resistivity data was also adjusted to illuminate subtle differences in the resistivity structure within the inverted AEM resistivity data related to the area being interpreted. The first step in the interpretation is digitizing the contacts between the geologic units including: Quaternary (***Q***) and the undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, NE-DNR, and NEOGCC borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (Burchett, 1986), but may differ due to the final interpretation. Additionally, the bedrock surface as developed by Leggette, Brashears and Graham (LBG) (2017) was used as a guide for the interpretation of the ***IP*** in areas of low electrical resistivity contrast and no boreholes.

The top of the ***IP*** was a challenging unit to interpret due to the highly variable resistivity of the ***IP.*** The unit goes from a resistivity unit to a conductive unit based on the presence of clay minerals within the shale and limestone units. The best way to interpret the unit is to use the boreholes in the area. Many of the CSD and the NE-DNR holes have shale, chalk, or limestone indicated at the bottom. This provides a clear indication of the ***IP***. When the CSD holes contain stratigraphic information that boundary can be confidently interpreted. In some instances, there are no indications of the ***IP*** at the bottom of the holes. Inspecting the area for the average depth of the NE-DNR holes provides another clue to the position of the ***IP*** as many wells stop on top of the ***IP***. The LBG bedrock provided a useful interpretive tool to supplement the boreholes.

Figure 3-3 is an approximately 25-mile-long north-south line L201501 that is west of the towns of Talmage and Johnson. The line crosses Long Branch, Muddy Creek, and the Little Nemaha river. Several CSD test holes and many NE-DNR wells penetrate or stop at the top of the ***IP***. As indicated above, the top of the ***IP*** is difficult to differentiate from the ***Q*** and boreholes are required to determine the top. This line displays several characteristics that are found throughout the survey area. On the southern end of the line a clear indication of a paleochannel system is observed in the resistivity and is confirmed with the CSD and DNR wells. The center section of the lines indicates a high bedrock covered with clay rich low resistivity quaternary aquifer material. Toward the north another high resistivity zone is indicated however this zone is above the CSD 1995 water table. The line terminates in the Little Nemaha river valley. The AEM indicates a low electrical resistivity layer overlying a high resistivity layer. This would indicate a clay rich layer overlying sands and gravels.

Figure 3-4 is an approximately 18-mile-long east-west line L102400 that is south of the towns of Burr and Talmage and north of Cook. The line crosses the South Fork of the Little Nemaha river twice and the Little Nemaha river. Several CSD test holes and many NE-DNR wells penetrate or stop at the top of the ***IP***. Line L102400 is dominated by a high resistivity zone along the western portion of the line. Several DNR registered wells confirm the presence of sands and sand and gravel. A majority of the deposit is unsaturated as indicated by the 1995 CSD water table.

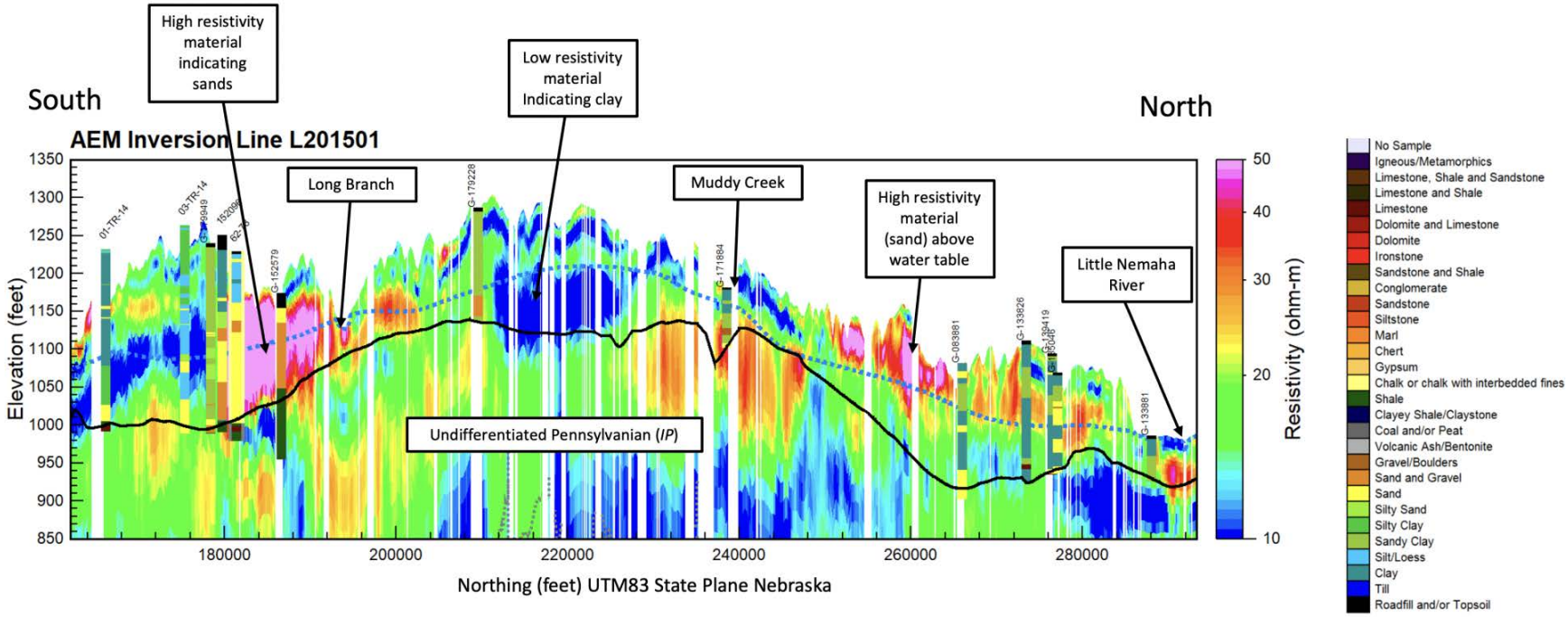


Figure 3-3. 25-mile-long north-south line L201501. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top undifferentiated Pennsylvanian (*IP*) is indicated by the black line. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line.

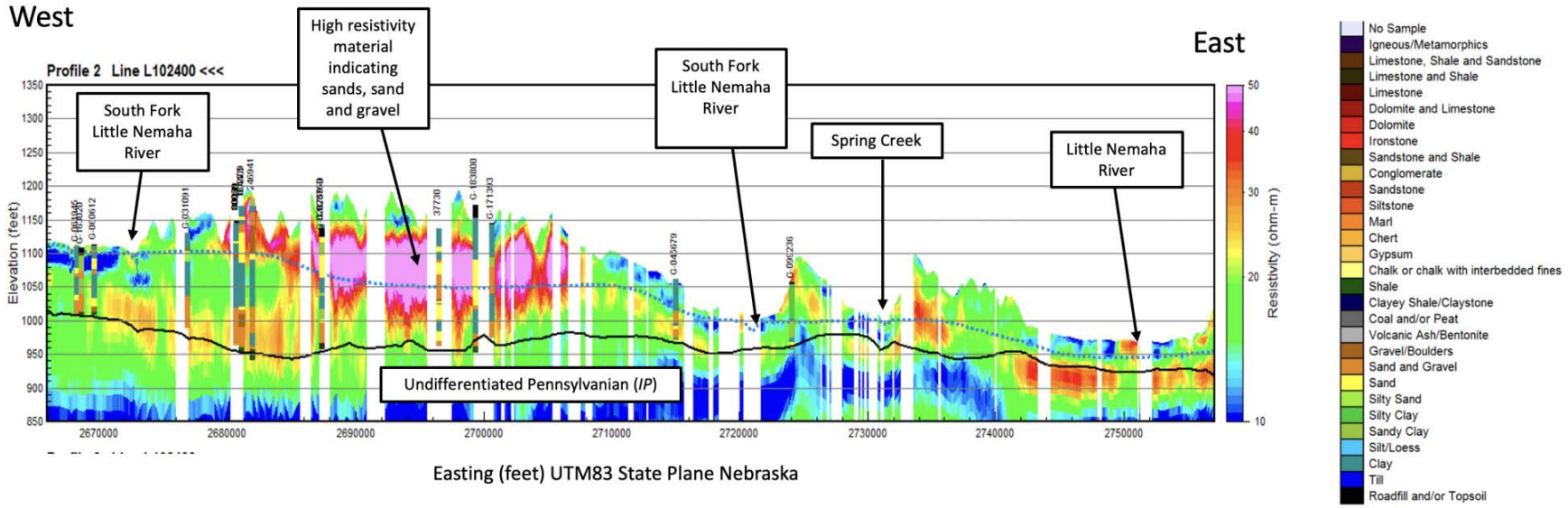


Figure 3-4. 18-mile-long east-west line L102400. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top undifferentiated Pennsylvanian (*IP*) is indicated by the black line. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line.

Figure 3-5 is an approximately 13-mile-long east-west line L100301 that is south of Elk Creek and north of Table Rock just south of the Richardson County Line. The line crosses the Big Nemaha River and Long Branch. Several CSD test holes and many NE-DNR wells penetrate or stop at the top of the ***IP***. This line is dominated by low resistivity materials in the western portion. On the eastern portion of the line two discrete zones of resistive materials occur. The zone around CSD test hole 56-78 indicates a sand zone that extends down to the bedrock that is partially saturated. The other high resistivity zone on the eastern end of the line is above the 1995 CSD water table.

Figure 3-6 is an approximately 4.5-mile-long east-west line L100701 that is north of the town of Shubert. The line crosses Whiskey Run. Several CSD test holes and many NE-DNR wells penetrate or stop at the top of the ***IP***. The Shubert area displays materials with a generally lower electrical resistivity as compared with the NNRD Reconnaissance Survey Area. The water table is generally indicating a thin area of saturation above the bedrock. There is a small zone of resistive materials around CSD test hole 18-U-40. Many of the boreholes indicate a sand and gravel at the base directly above the undifferentiated Pennsylvanian bedrock. The resistivity indicates a low to moderate resistivity of 20 ohm-m or under indicating thin sand and gravel layers and possible clay and silt interbedding.

Figure 3-7 is an approximately 4.5-mile-long east-west line L102101 that is on the south of the Shubert Block. The line crosses Sardine Creek. Several CSD test holes and many NE-DNR wells penetrate or stop at the top of the ***IP***. Line L102101 is dominated by moderate resistivity materials 20 ohm-m or under. There is an indication of resistive materials on the western end of the survey line by the 1995 CSD water table indicates that these materials maybe unsaturated. There is a low resistivity zone in the center section of the line. The DNR registered wells indicate a majority of the material is silty clay and sandy clay. There is a small indicated on resistive materials in Sardine Creek that are under the 1995 water table.

The above examples of the interpretation of the 2D profiles provide insight into the process of interpretation that was used in the project. *Appendix 1 – 2D Profiles* provides detailed profiles for each of the flight lines in the Reconnaissance Area and the Shubert Block.

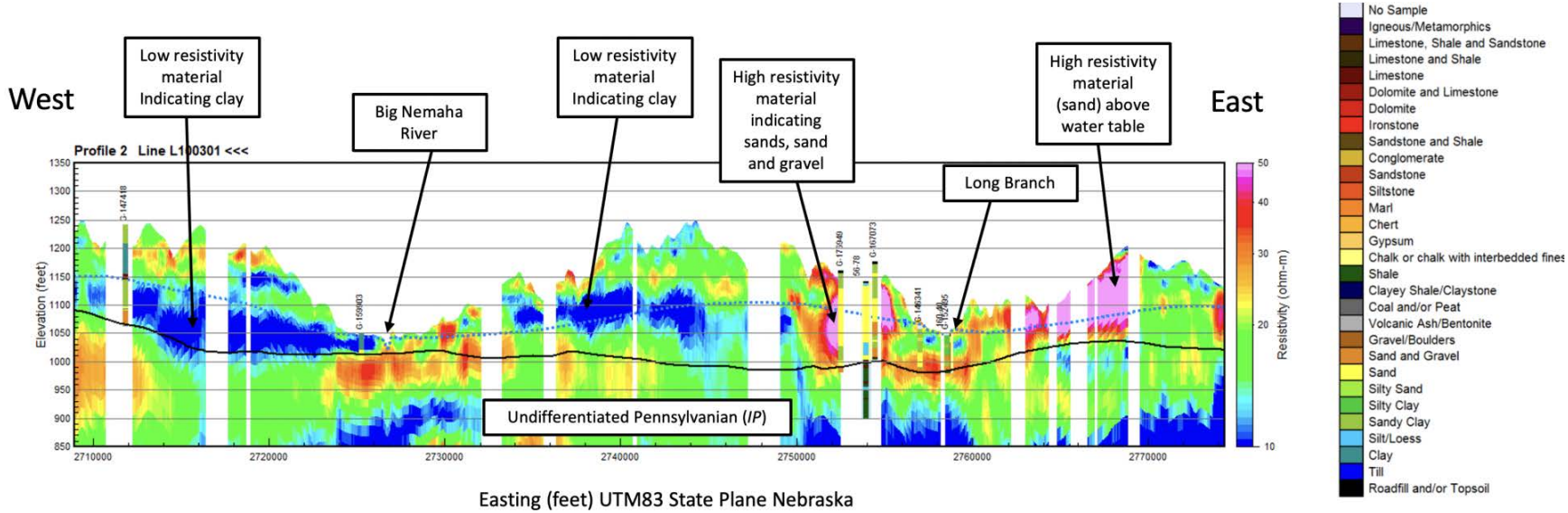


Figure 3-5. 13-mile-long east-west line L100301. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top undifferentiated Pennsylvanian (*IP*) is indicated by the black line. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line.

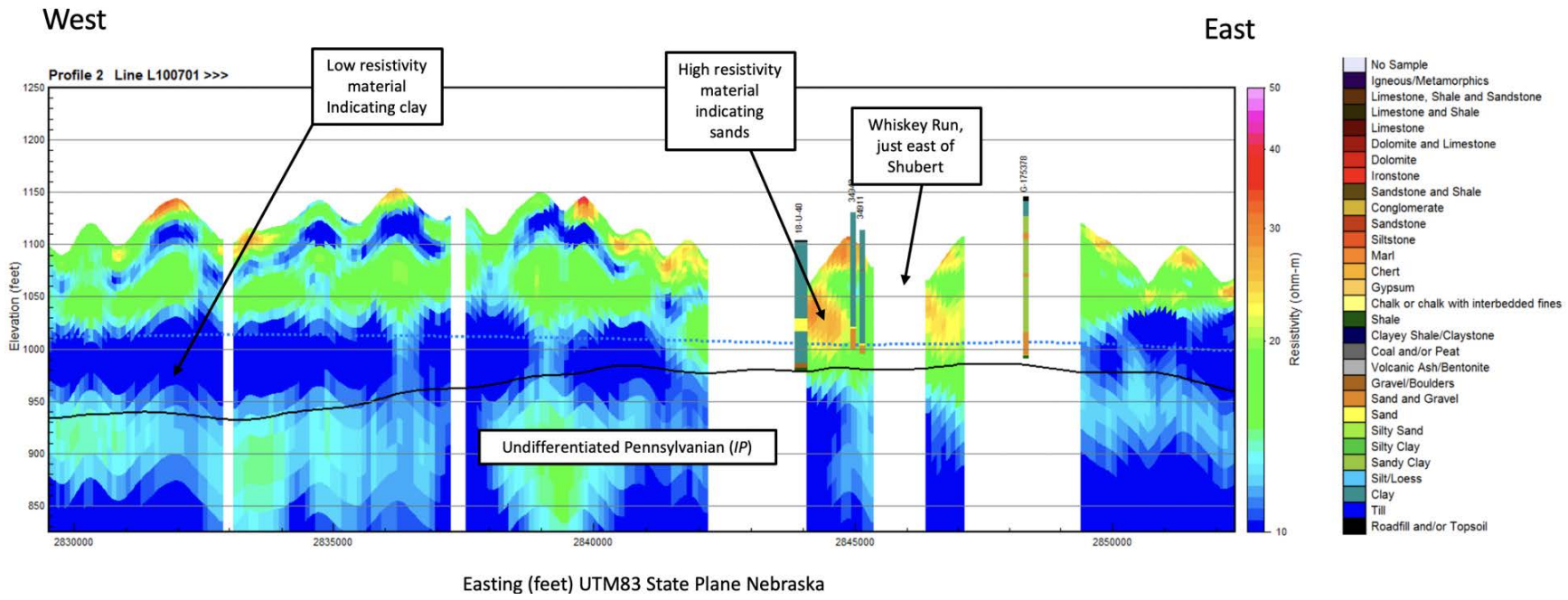


Figure 3-6. 4.5-mile-long east-west line L100701. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top undifferentiated Pennsylvanian (*IP*) is indicated by the black line. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line.

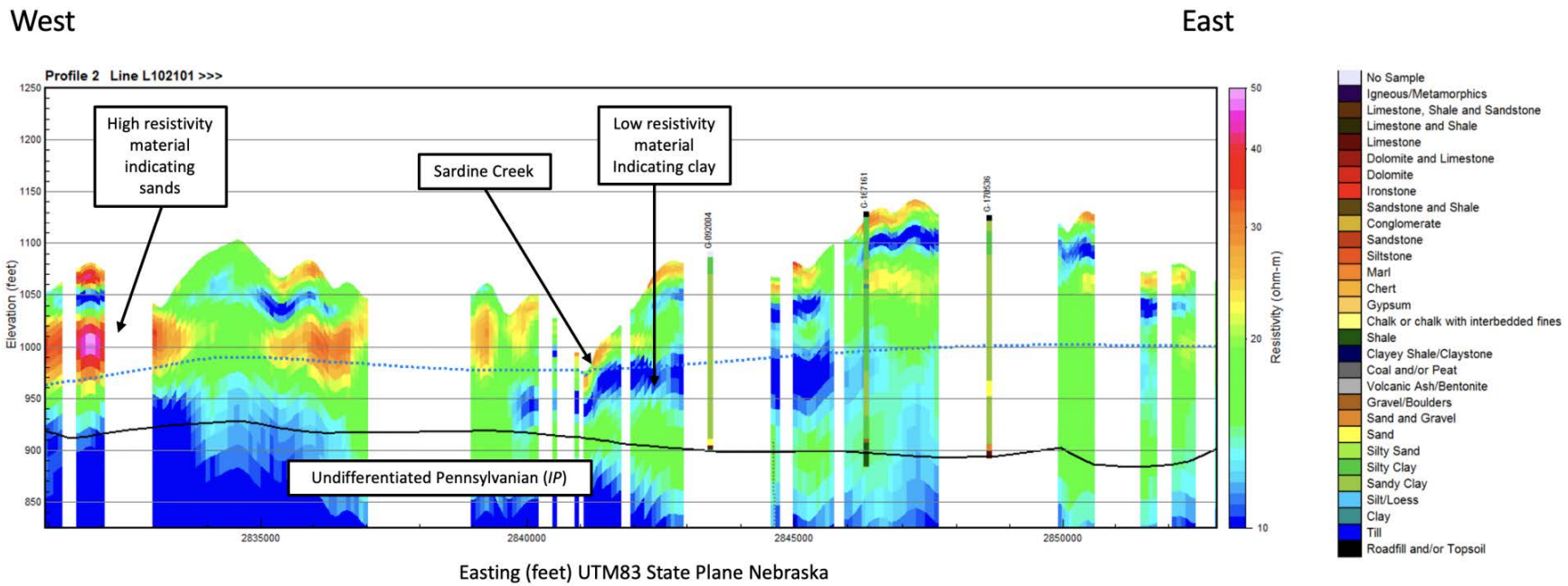


Figure 3-7. 4.5-mile-long east-west line L102101. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top undifferentiated Pennsylvanian (*IP*) is indicated by the black line. Gaps indicate areas removed due to coupling. The CSD 1995 water table is indicated with a dashed blue line.

3.1.4 Create Interpretative Surface Grids

NNRD survey area and Shubert block survey area surface and thickness grids were produced. To create these grids, data such as a ground surface digital elevation model (DEM), bedrock and water table (WT) elevations, and AEM interpreted point data of the survey area were imported into ArcGIS ArcMap. Point data were interpolated into a continuous surface using the kriging method and some of these surfaces were processed in ArcMap along with the Spatial and Geostatistical Analyst using tools such as raster calculator and the geostatistical model kriging.

For the top surface of the undifferentiated Pennsylvanian (***IP***), 2,437 AEM picks were used in the grid. This included the interpreted top of the ***IP*** from Carney et al. (2015b) for the lines that were collocated within the 2018 NNRD Reconnaissance survey area. The elevations of the AEM-interpreted top of the formation were imported to a Geosoft Oasis montaj (OM) database. The interpreted elevation data were then gridded for each formation independently using the OM minimum curvature gridding (MCG) algorithm. The cell size was set to 500 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. The grid was then clipped to the NNRD survey area. Figure 3-8 is a map of the elevation of the top of the ***IP*** within the NNRD Reconnaissance survey area. The Shubert Block was gridded using a 250 ft cell size and contained 436 AEM picks. Figure 3-9 is a map of the elevation of the top of the ***IP*** within the Shubert Block.

For the unconsolidated Quaternary (***Q***) total thickness grid for both the NNRD Reconnaissance survey and Shubert Block survey areas the top of the undifferentiated Pennsylvanian (***IP***) gridded surface was subtracted from the ground surface DEM (U.S. Geological Survey, 2018). Those cells where the thickness was less than zero (due to the variation in grid cell size between the undifferentiated ***IP*** top surface and the DEM grids) were set to zero. Cell size of the grids (500 feet) reflect the size of ***IP*** gridded surface. Figure 3-10 and Figure 3-11 are maps of the total thickness of the unconsolidated ***Q*** material in the NNRD reconnaissance survey and the Shubert block survey areas, respectively.

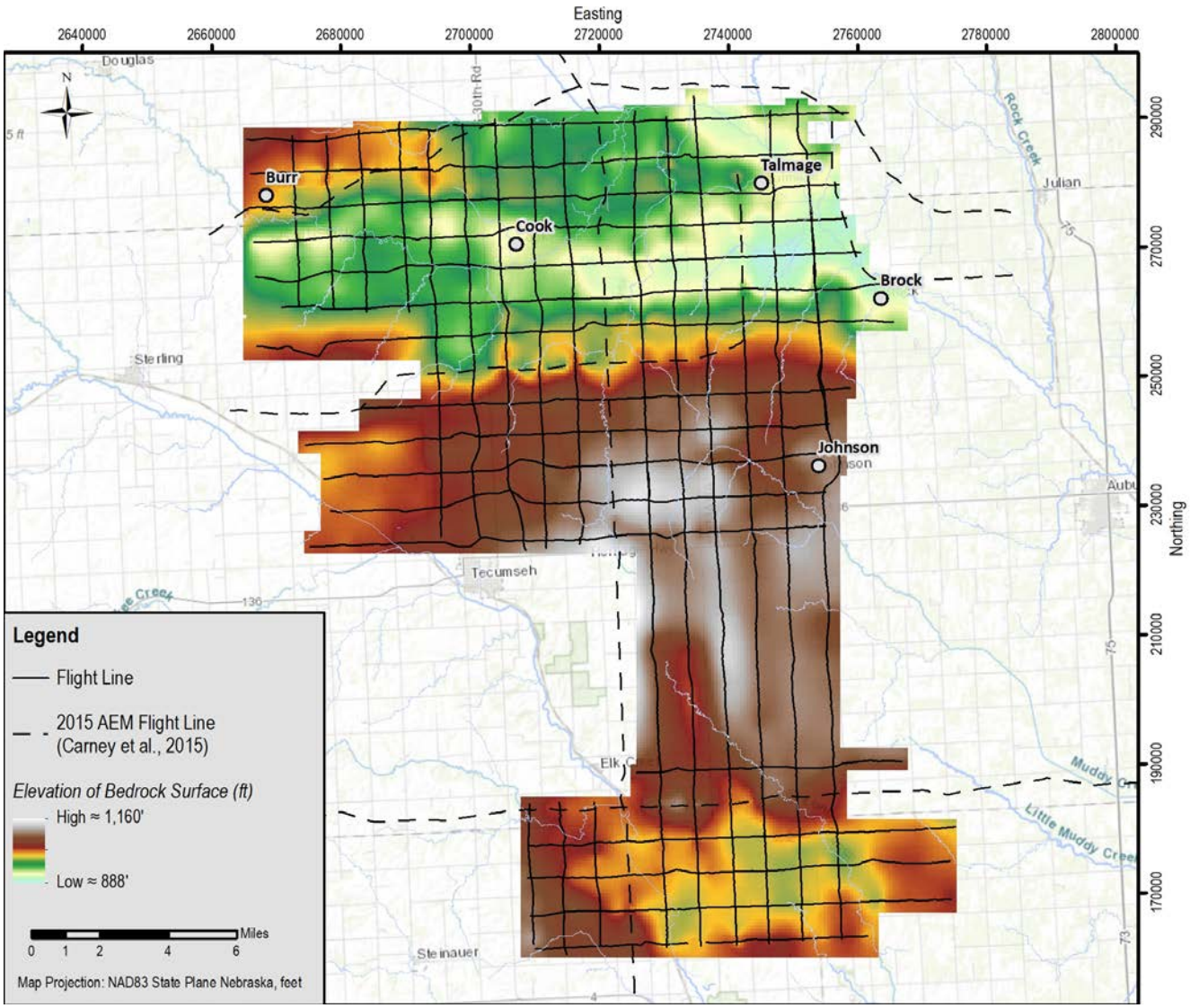


Figure 3-8. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the NNRD from the 2018 survey. 2018 flight lines are indicated by the black lines. 2015 lines are indicated by dashed black lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

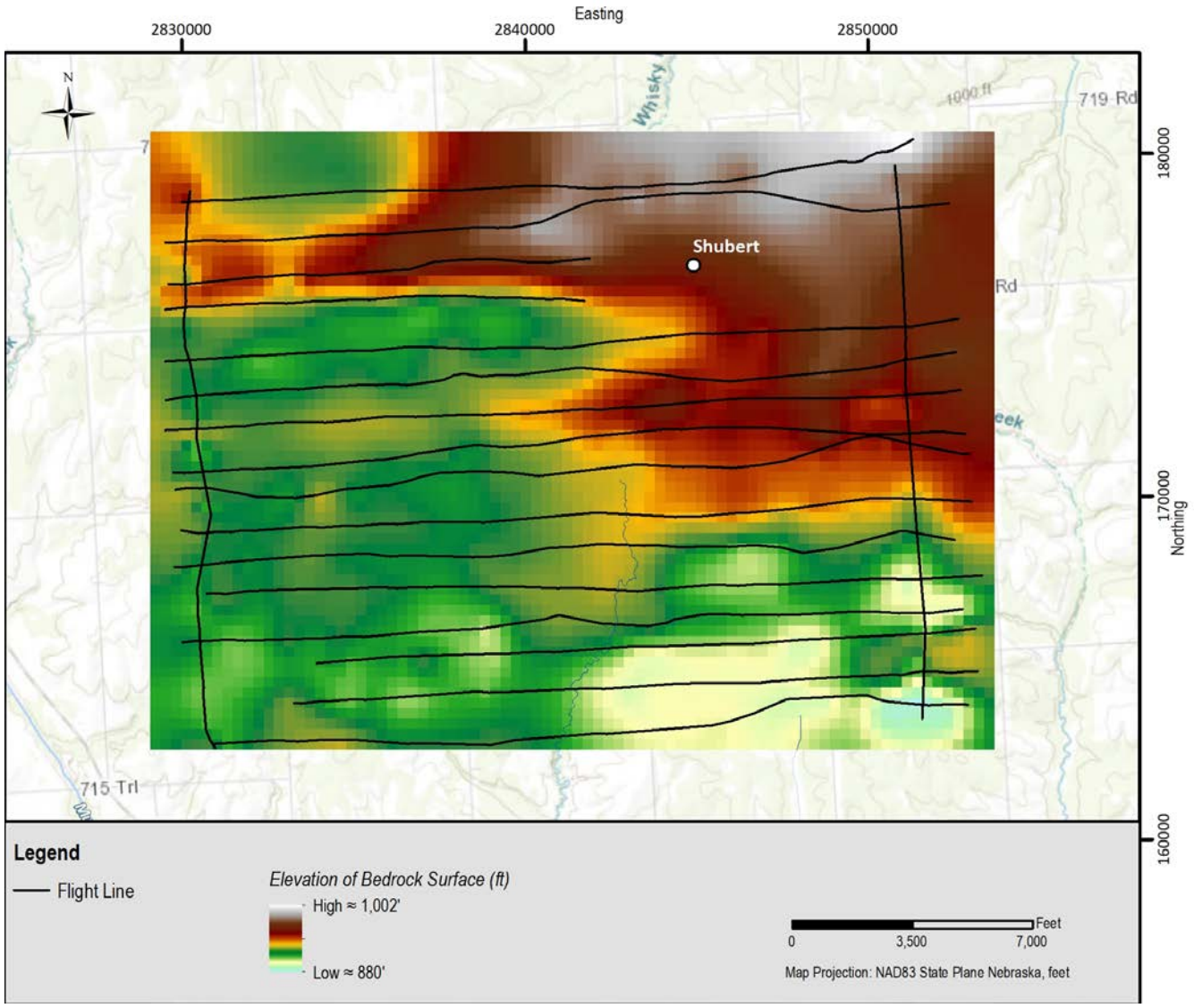


Figure 3-9. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the NNRD Shubert Block from the 2018 survey. 2018 flight lines are indicated by the black lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

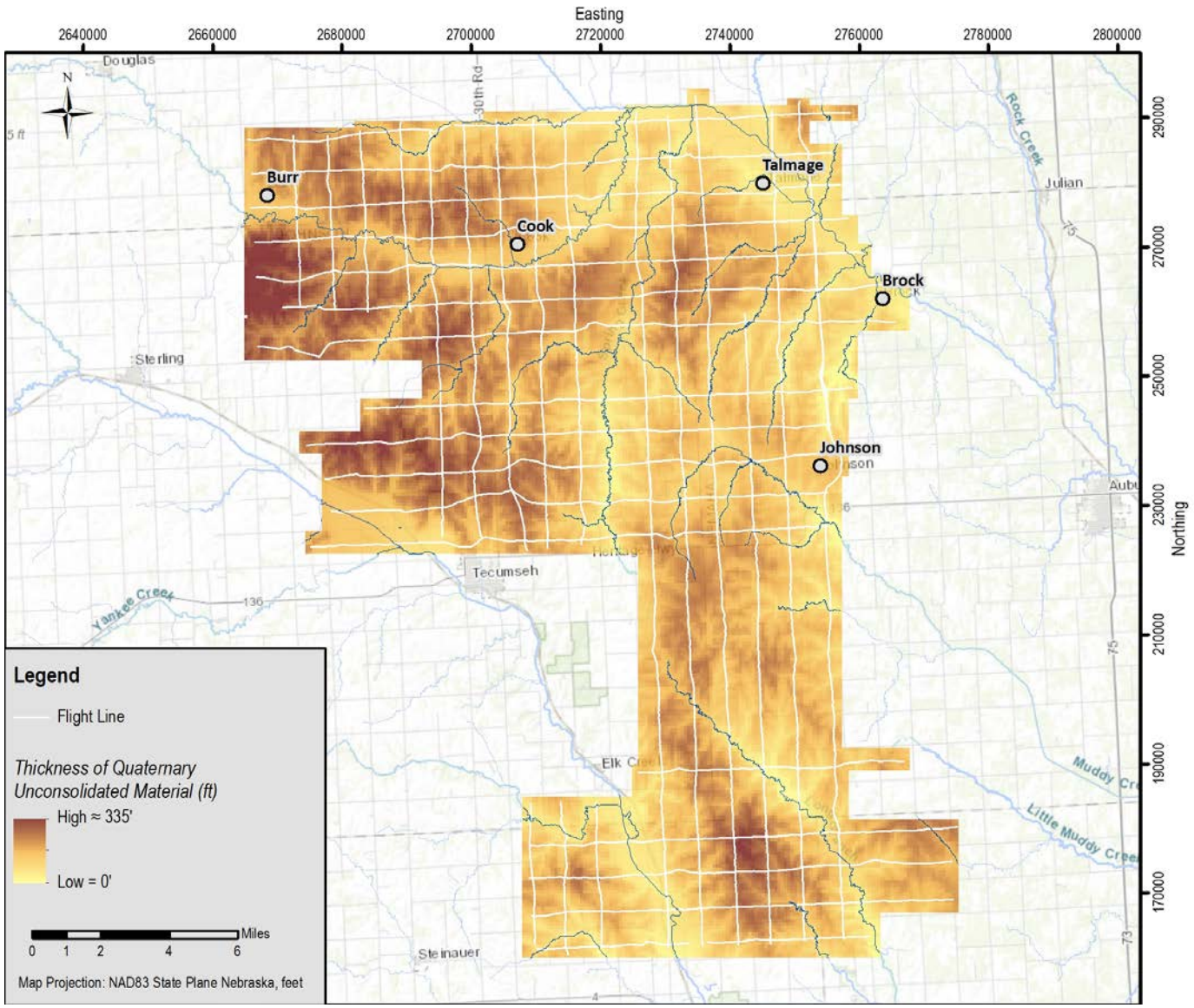


Figure 3-10. Map of the total thickness of Quaternary deposits within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by white lines. The projection is NAD83 State Plane Nebraska (feet).

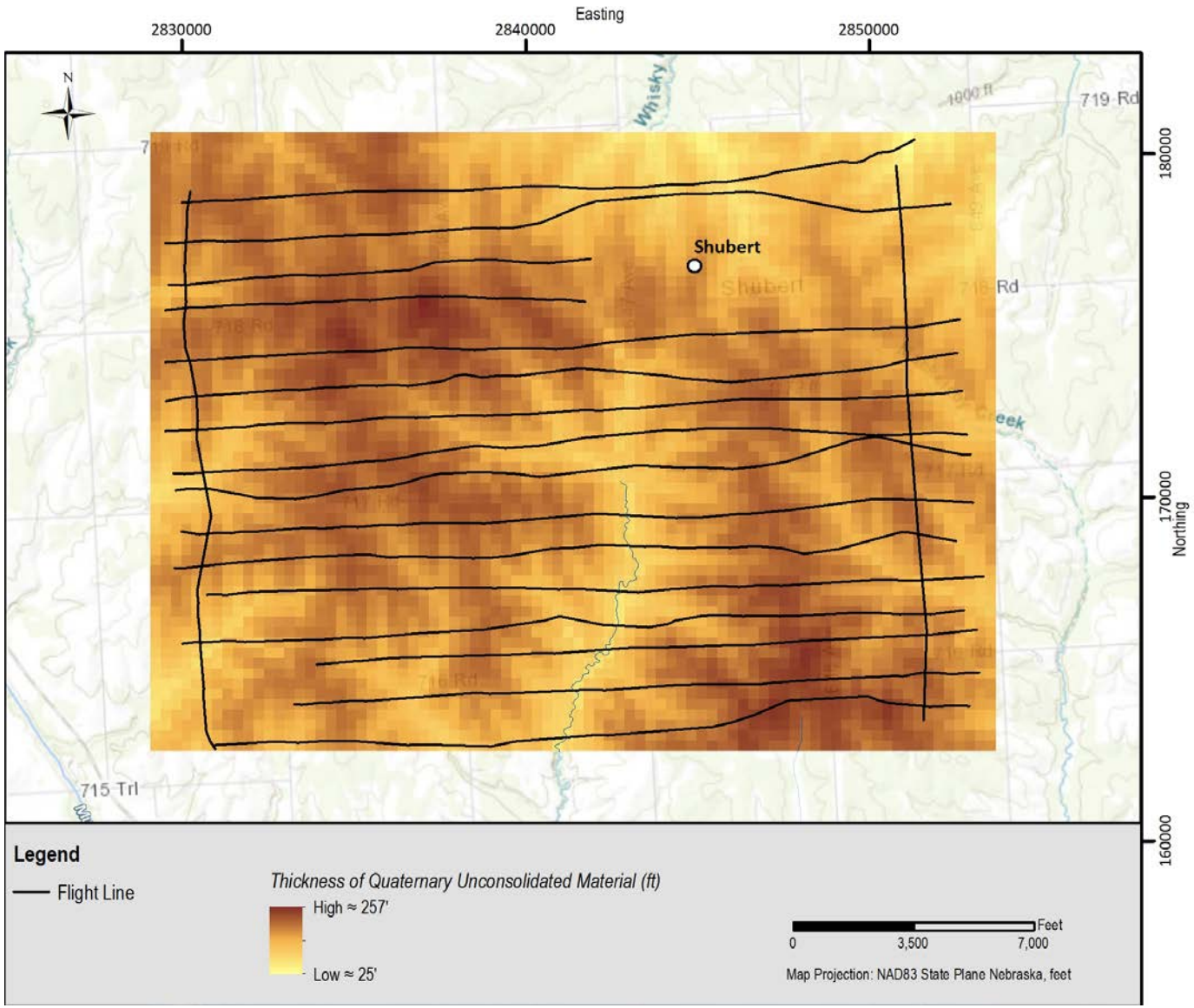


Figure 3-11. Map of the total thickness of Quaternary deposits within the 2018 Shubert Block. Flight lines are indicated by black lines. The projection is NAD83 State Plane Nebraska (feet).

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 NNRD AEM survey and local conditions have likely deviated in areas with variable topography. The water table in the NNRD 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 3-1) of the NNRD 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 NNRD Reconnaissance survey area (Figure 3-12) as well as the Shubert Block (Figure 3-13).

For the unconsolidated quaternary saturated thickness grid for both the NNRD Reconnaissance survey and Shubert Block survey areas, the bedrock surface elevation was subtracted from the 1995 CSD water table grid (Nebraska CSD, 1995). Figure 3-14 and Figure 3-15 are maps of the saturated thickness of the unconsolidated Quaternary material in the NNRD Reconnaissance survey and Shubert Block survey areas, respectively.

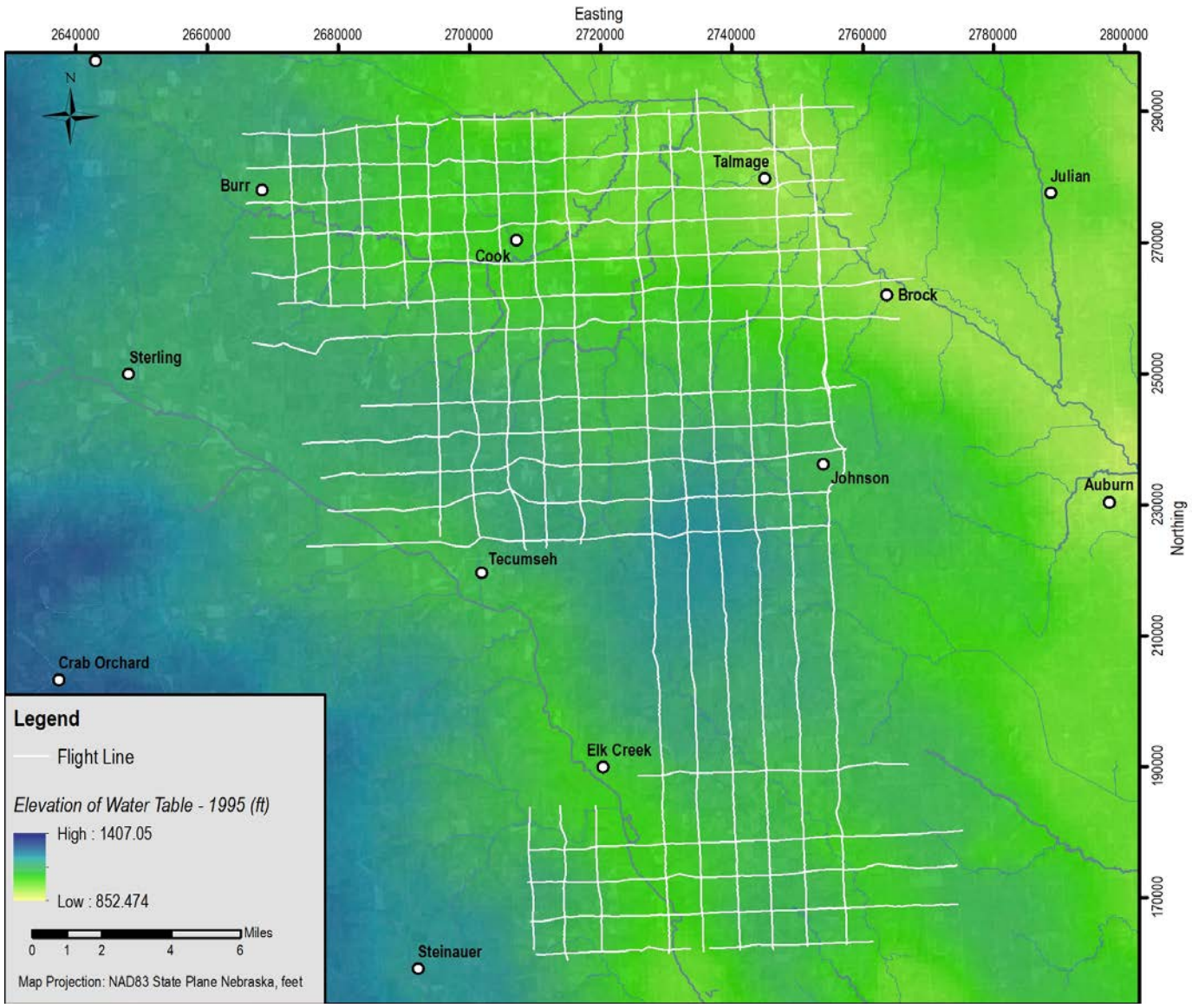


Figure 3-12. Map of the 1995 CSD water table elevation within the 2018 NNRD Reconnaissance survey area. White lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

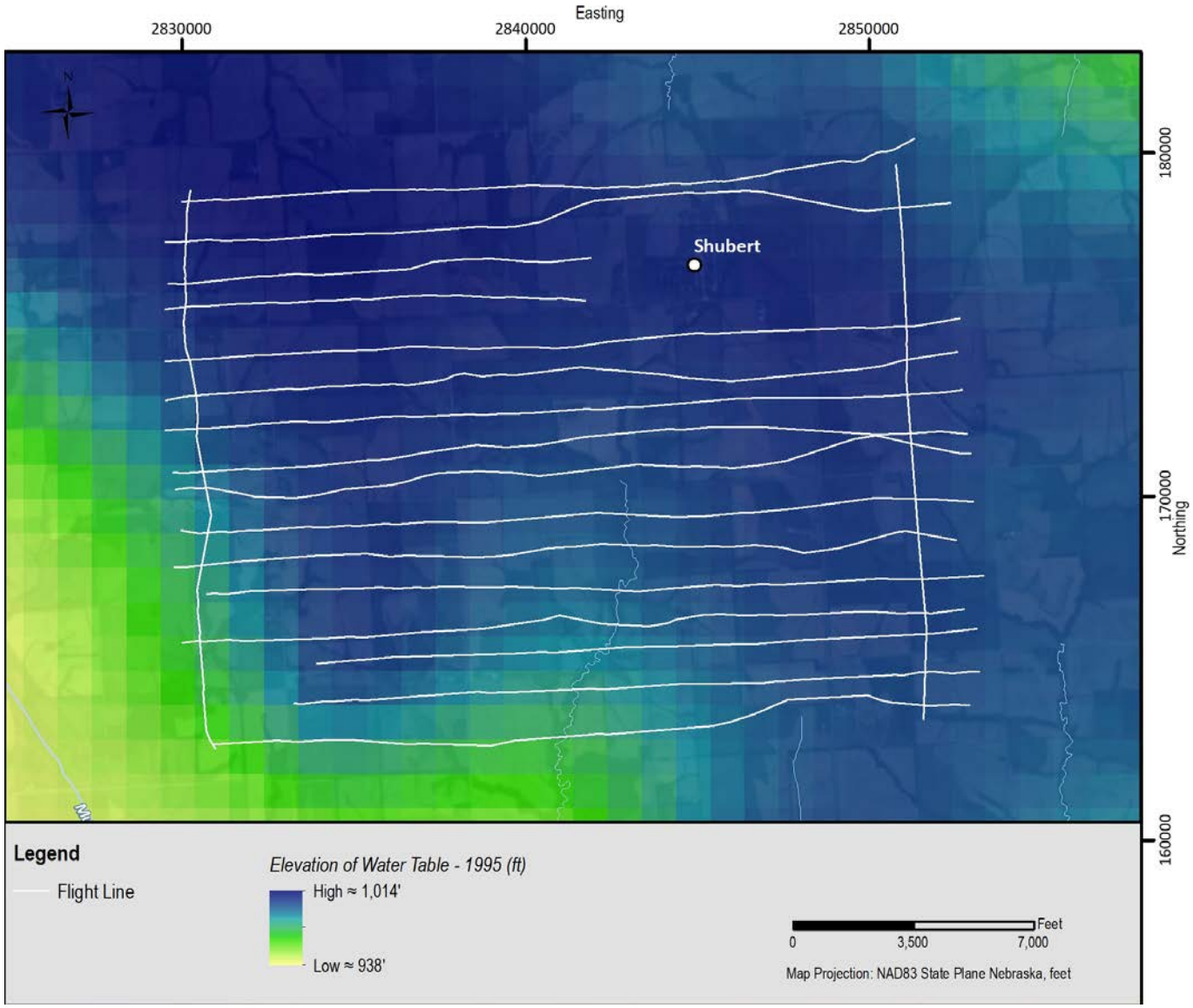


Figure 3-13. Map of the 1995 CSD water table elevation within the 2018 NNRD Shubert Block. White lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

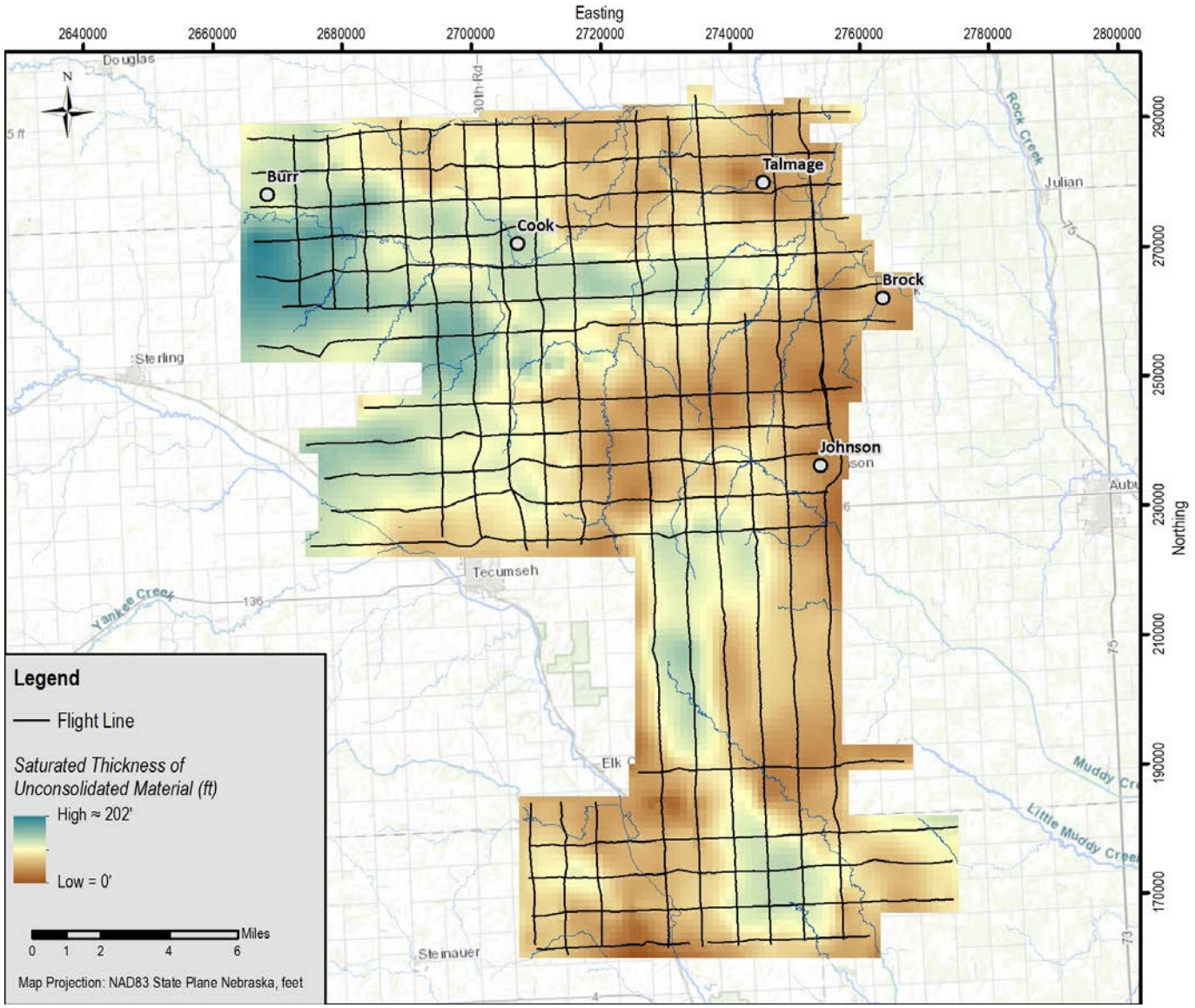


Figure 3-14. Map of the saturated thickness of Quaternary deposits within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by black lines. The projection is NAD83 State Plane Nebraska (feet).

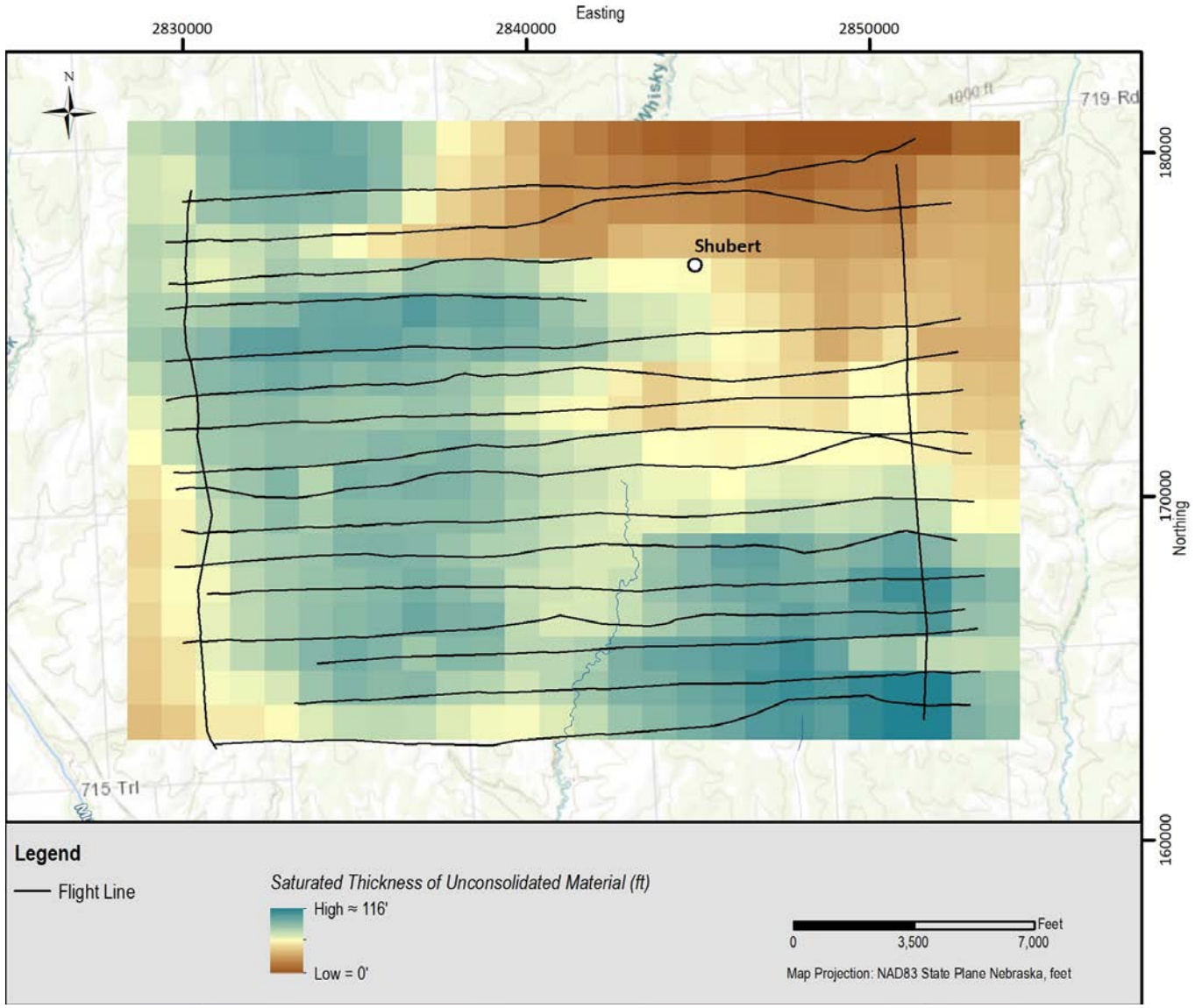


Figure 3-15. Map of the saturated thickness of Quaternary deposits within the 2018 Shubert Block survey area. Flight lines are indicated by black lines. The projection is NAD83 State Plane Nebraska (feet).

3.1.5 Resistivity-Lithology Relationship

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 NNRD 2018 survey, assessment of the sediment character in the Quaternary 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 aquifer system and bedrock data from the ENWRA project area (Carney et al., 2015b). The original analysis that was completed as part of Carney et al. (2015b) included the overall area of the NNRD. This analysis has been used in the current report for the categorization of the Quaternary aquifer system.

Data for this analysis was utilized from locations across the ENWRA reconnaissance line area (Carney et al., 2015b). 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. (2015b). A summary of the resistivities and the color scale used in the remainder of this report is shown in Figure 3-16.

The bedrock in the NNRD analyzed in this study includes the many units within the undifferentiated Pennsylvanian system. These were included to demonstrate the overall distribution in resistivity of bedrock materials across the study areas is approximately 16 ohm-m (the median resistivity) with a range from approximately 80 ohm-m to 1 ohm-m (Carney et al., 2015b). This wide range doesn't provide a clear indicator for the undifferentiated Pennsylvanian system. As indicated above use of boreholes was key to successful interpretation of the data.

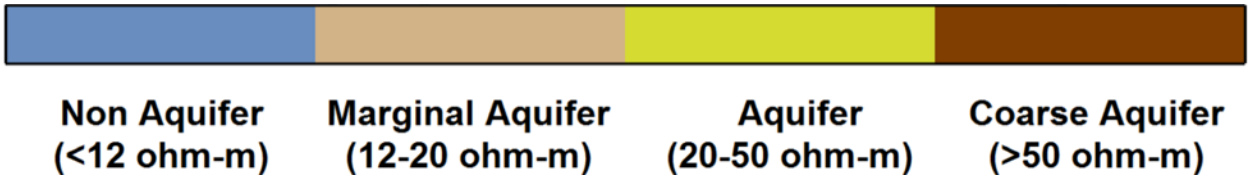


Figure 3-16. Plot displaying the resistivities by major aquifer material color categories: blue- non-aquifer materials, tan- marginal aquifer materials, yellow- aquifer materials, brown- coarse aquifer materials (Carney et al., 2015b).

3.1.6 Create aquifer material grids for the NNRD Reconnaissance area

For the total thickness of the aquifer material and coarse aquifer material within the NNRD Reconnaissance survey area, 27,232 AEM-interpreted aquifer material and coarse aquifer materials top(s) and bottom(s) elevation data points were input into ArcMap. The data points with NULL values, either indicating no presence of aquifer material and coarse aquifer material or 'no data' due to electromagnetic (em) obstructions such as power lines, were compared against the subsurface material profiles created in Datamine Discover PA. Those points where aquifer material and/or coarse aquifer material did not actually exist (indicating that the NULL value represents a zero thickness) were set to zero and retained and all other NULL values were removed from the point dataset. The remaining 25,223 points were interpolated into a continuous grid using ordinary kriging, circular model. The cell size was set to 1,200 feet due to the approximate 1 mile spacing across line and 100 feet down line spatial distribution of the point data. The resultant grid was clipped to the approximate extent of the flight lines and generally compared to the total unconsolidated Quaternary thickness (described above) for quality control. Figure 3-17 is a map of the total thickness of the aquifer material and coarse aquifer material within the NNRD Reconnaissance survey area.

For the saturated thickness of aquifer material and coarse aquifer material within the NNRD Reconnaissance survey area, the 25,223-point dataset (described above) was exported into Microsoft Excel where the top and bottom elevation data were subtracted from the water table elevation to differentiate between the thickness above the water table (unsaturated) from the thickness below the water table (saturated). The data were re-imported into ArcMap and the saturated-only thicknesses (as calculated in Excel) of each data point were interpolated using ordinary kriging, circular model to a continuous grid with a 1,200 feet cell size. The resultant grid was clipped to the approximate extent of the flight lines and compared to the total thickness of aquifer material and coarse aquifer material grid (described above) for quality control. Figure 3-18 is a map of the saturated thickness of the aquifer materials and coarse aquifer materials within the NNRD Reconnaissance survey area.

For the unsaturated thickness of aquifer materials and coarse aquifer materials within the NNRD Reconnaissance survey area, the saturated thickness of aquifer materials and coarse aquifer materials grid was subtracted from the total thickness of aquifer materials and coarse aquifer materials grid (both described above). The resultant grid retained the 1,200 ft cell size of the original grids as well as the clipped extent. Figure 3-19 is a map of the unsaturated thickness of the aquifer materials and coarse aquifer materials within the NNRD Reconnaissance survey area.

For the non-aquifer material total thickness within the NNRD Reconnaissance survey area, 27,592 AEM interpreted non-aquifer material thickness data points were input into ArcMap. The data points with NULL values, either indicating no presence or zero thickness of non-aquifer material or 'no data' due to em obstructions such as power lines, were compared against the subsurface material profiles created in Datamine Discover PA. Those points where non-aquifer material did not actually exist (indicating that the NULL value represents a zero thickness) were set to zero and retained and all other NULL values were removed from the point dataset. The remaining 26,664 points were interpolated into a continuous grid using ordinary kriging, spherical model. The cell size was set to 1,200 feet due to the approximate 1

mile spacing across line and 100 feet down line spatial distribution of the point data. The resultant grid was clipped to the approximate extent of the flight lines. Figure 3-20 is a map of the total thickness of the non-aquifer material within the NNRD Reconnaissance survey area.

The transmissivity of the NNRD Reconnaissance survey area was estimated using the equation:

$$T = K * b,$$

where *K* is the hydraulic conductivity (ft/sec) and *b* is the saturated aquifer thickness (ft).

The saturated thickness used in the estimation for the NNRD Reconnaissance survey area reflects the saturated thickness of the aquifer materials and coarse aquifer materials only; marginal aquifer material was not included in the calculation. The hydraulic conductivity value used in the equation is $3x10^{-3}$ feet/sec and is representative of clean sand/gravel (Freeze & Cherry, 1979). The resultant grid was converted to gpd/ft using a conversion factor with ArcMap's raster calculator. Figure 3-21 is a map of the estimated transmissivity of the saturated aquifer material and coarse aquifer material within the NNRD reconnaissance survey area.

Surface/near surface material types within NNRD Reconnaissance survey area, which could indicate potential areas for management of aquifer recharge and non-point source contamination, was gridded into four separate datasets including: 0' to 3.28' below ground surface (bgs), 3.28' to 6.89' bgs, 6.89' to 10.83' bgs, and an average from 0' to 10.83' bgs. The material types were separated by four major resistivity thresholds selected in Datamine Discover PA. These ranges include less than 12 ohm-m, representing non-aquifer materials ("aquitard"- primarily glacial till, clay, loess); 12-20 ohm-m, representing marginal aquifer deposits with potential for interlayered silt and clay; 20-50 ohm-m, indicating the Quaternary system's aquifer materials composed dominantly 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 the following section and in Carney et al. (2015b).

To create the grids, 27,592 AEM resistivity value data points for each interval were input into ArcMap. The data points with NULL values, indicating no data due to obstructions such as power lines, were removed and the remaining 26,400 data points were interpolated into a continuous grid using ordinary kriging, stable model. The three intervals (0' to 3.28' bgs, 3.28' to 6.89' bgs, 6.89' to 10.83' bgs) were then averaged together using the raster calculator in ArcMap to create the 0' to 10.83' bgs average dataset. The cell size was set to 1,200 feet due to the approximate 1 mile spacing across line and 100 feet down line spatial distribution of the point data. The resultant grid was clipped to the approximate extent of the flight lines. Figures 22, 23, 24, and 25 are maps of the surface/near surface material types for the three intervals described above and the average material type for the interval 0' to 10.83' bgs within the NNRD Reconnaissance survey area.

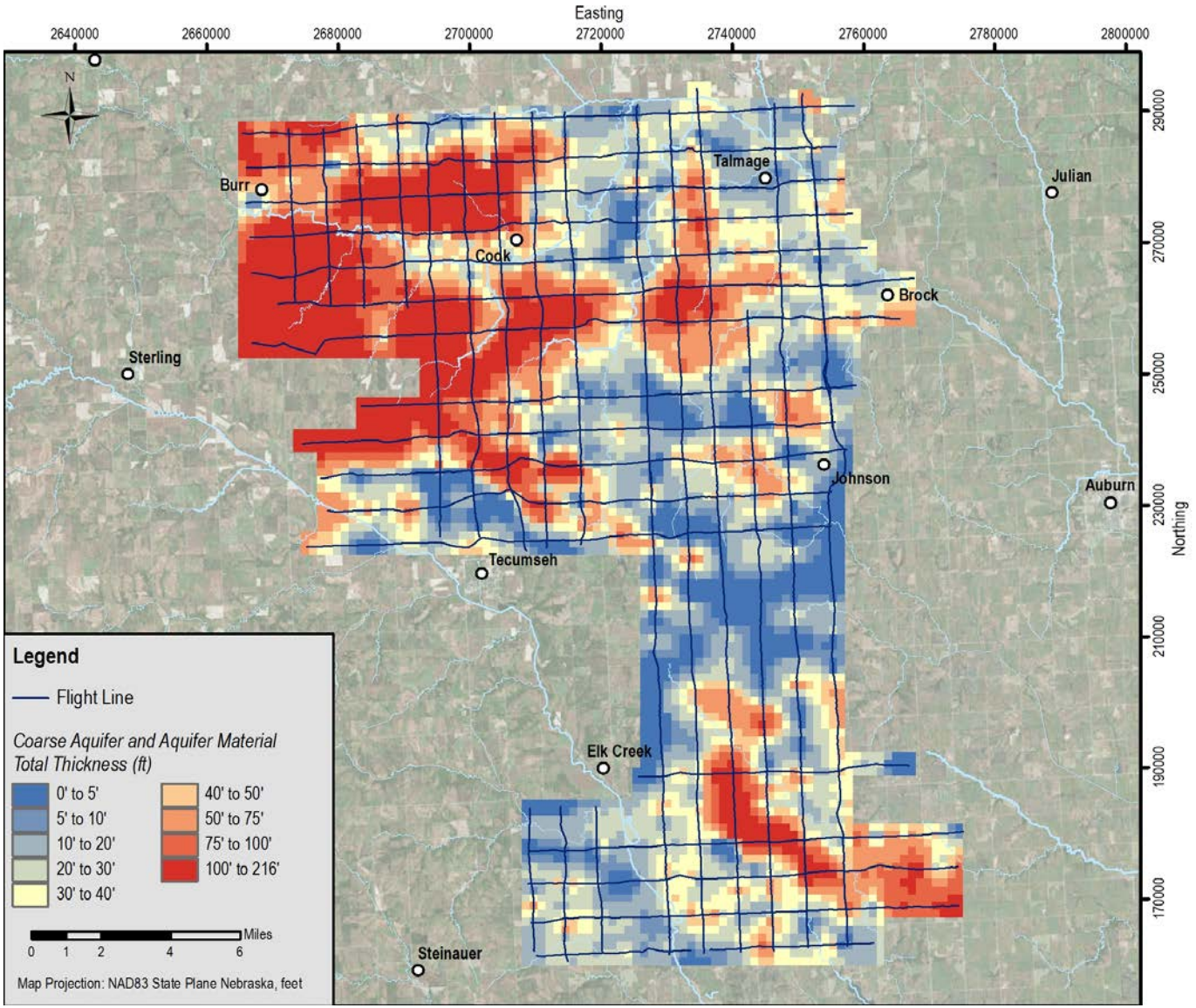


Figure 3-17. Map of the total thickness of Aquifer Material and Coarse Aquifer material within the 2018 NNRD reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

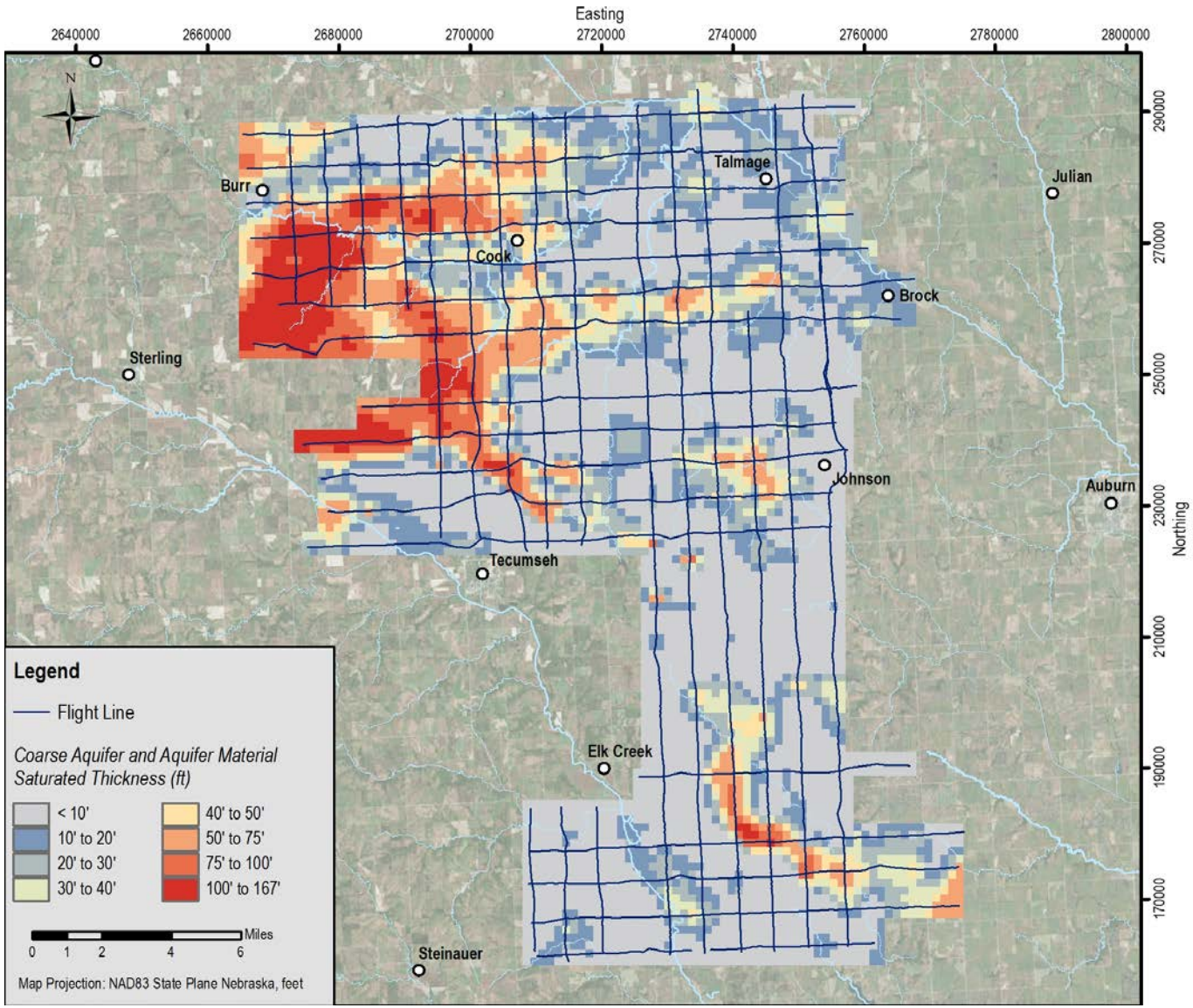


Figure 3-18. Map of the saturated thickness of Aquifer Material and Coarse Aquifer material within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

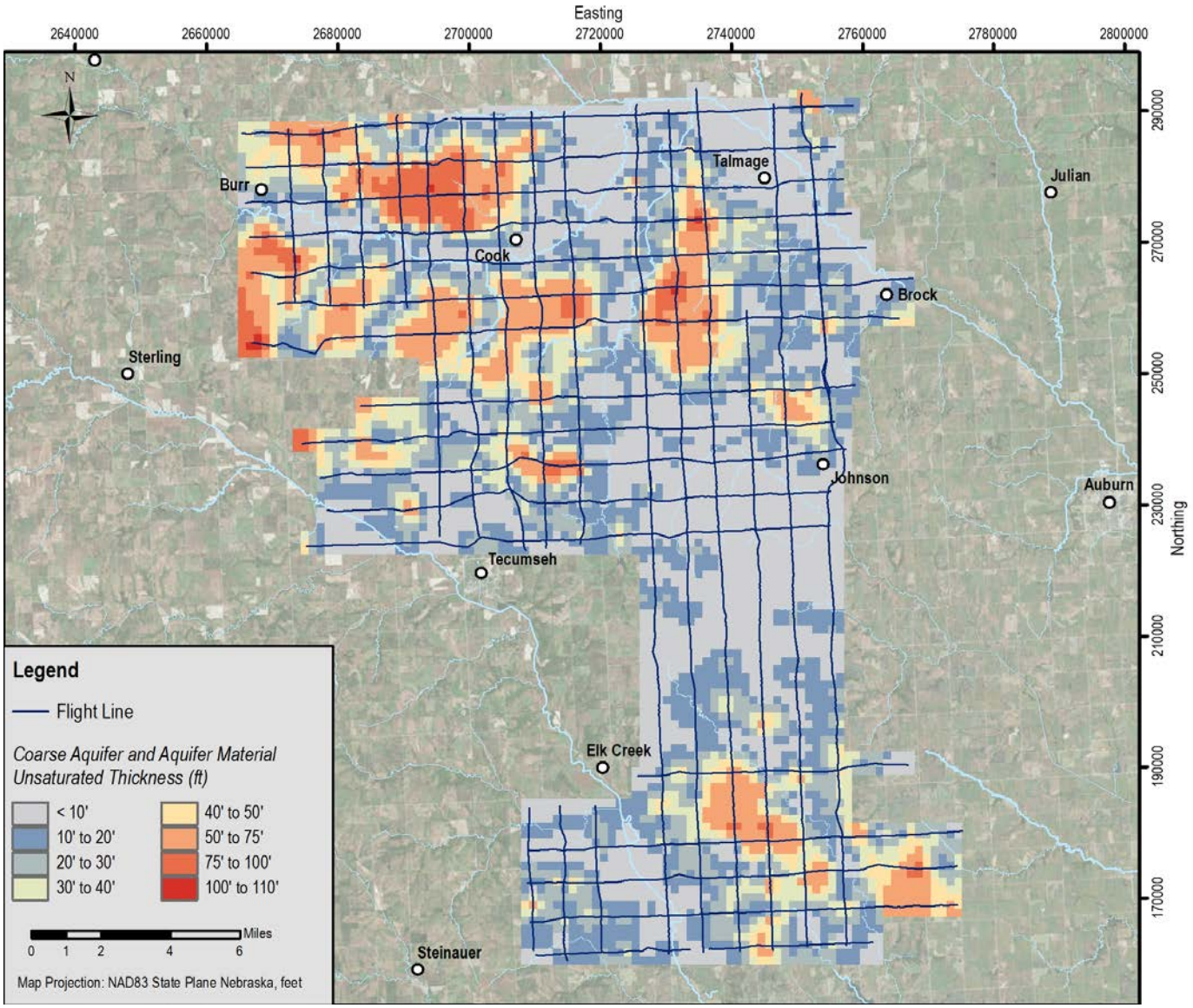


Figure 3-19. Map of the unsaturated thickness of Aquifer Material and Coarse Aquifer material within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

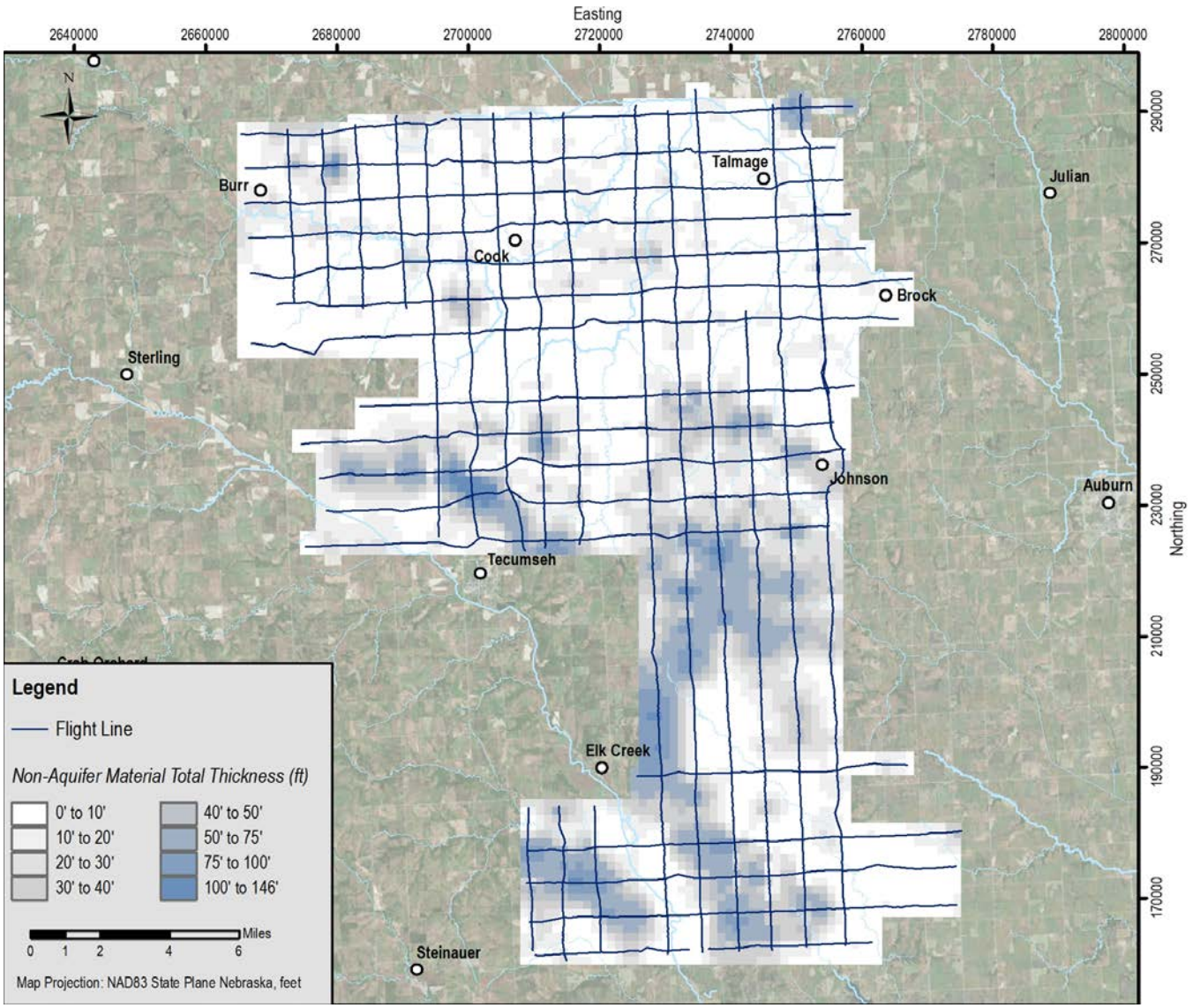


Figure 3-20. Map of the total thickness of Non-Aquifer material within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

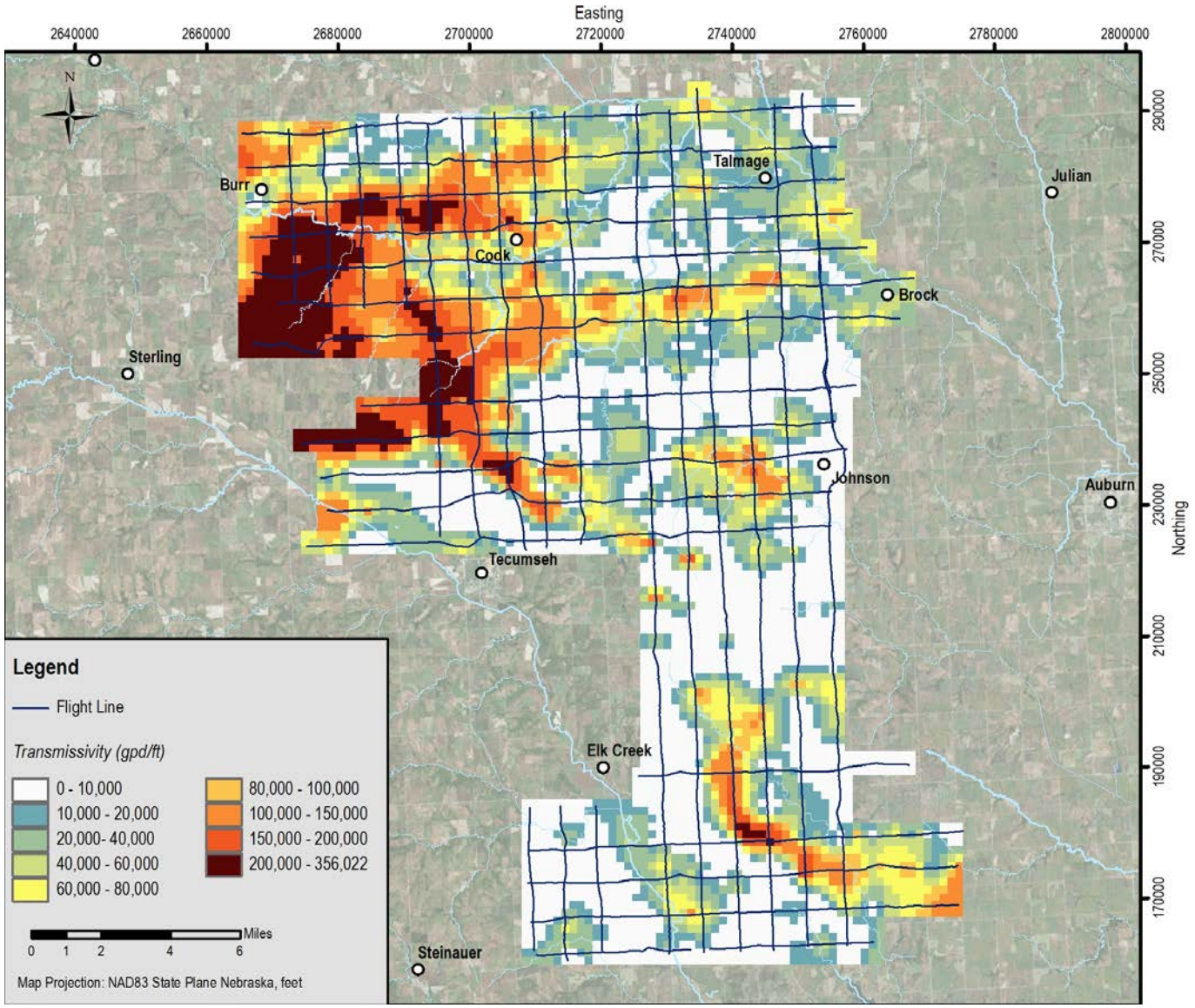


Figure 3-21. Map of the estimated transmissivity within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

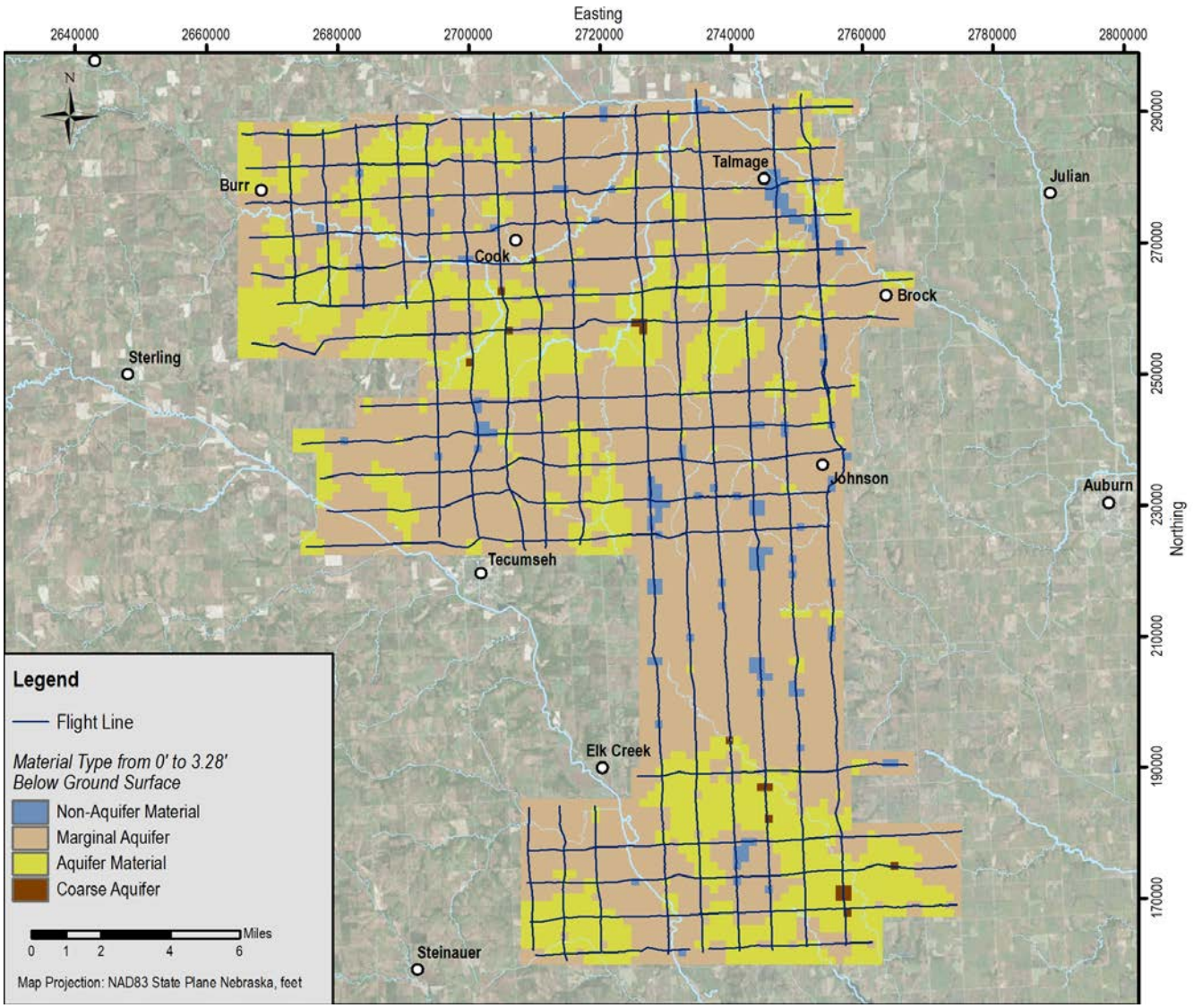


Figure 3-22. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 0' to 3.28' below ground surface within the 2018 NNRD Reconnaissance survey area. Blue lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet).

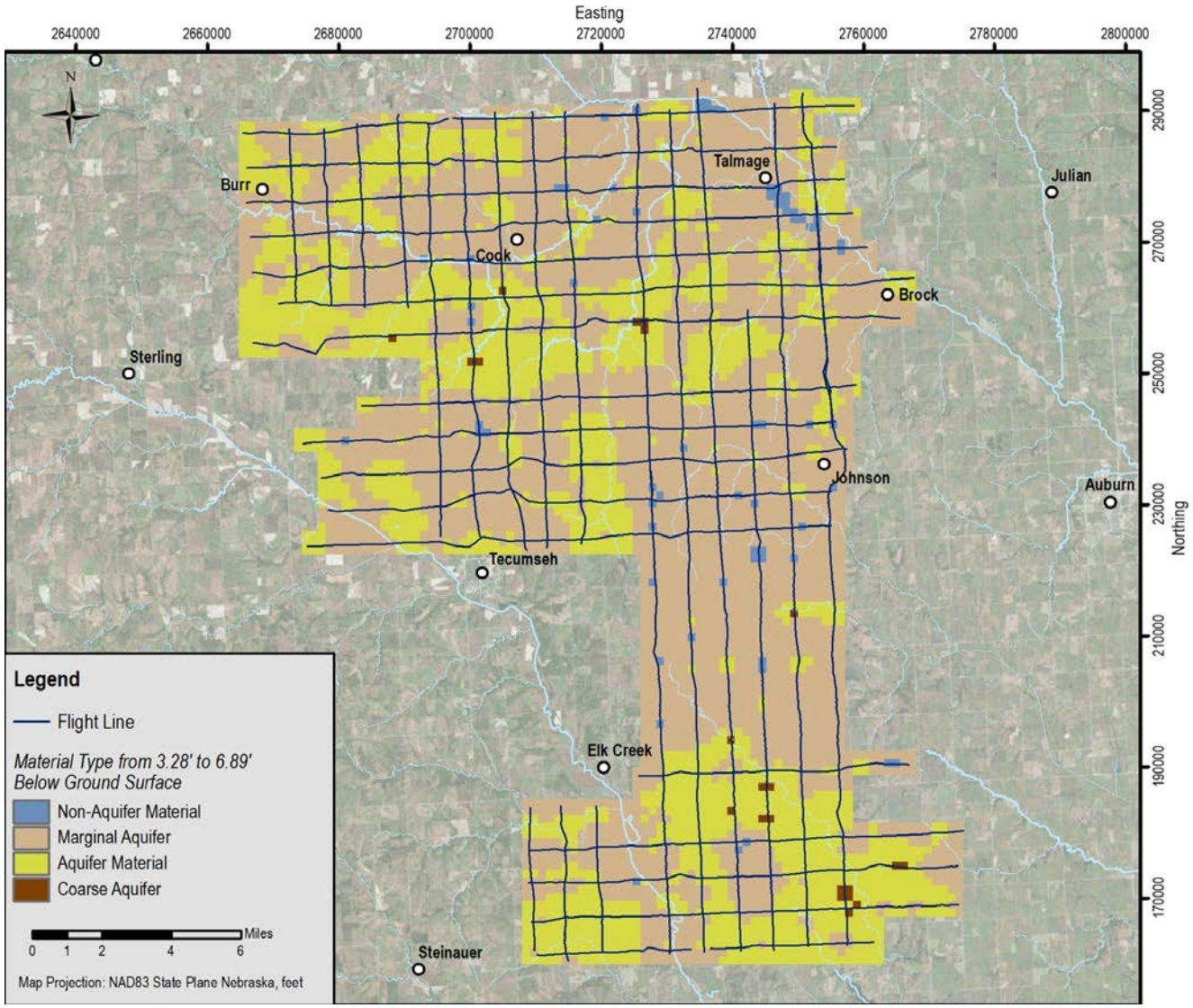


Figure 3-23. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 3.28' to 6.89' below ground surface within the 2018 NNRD Reconnaissance survey area. Blue lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet).

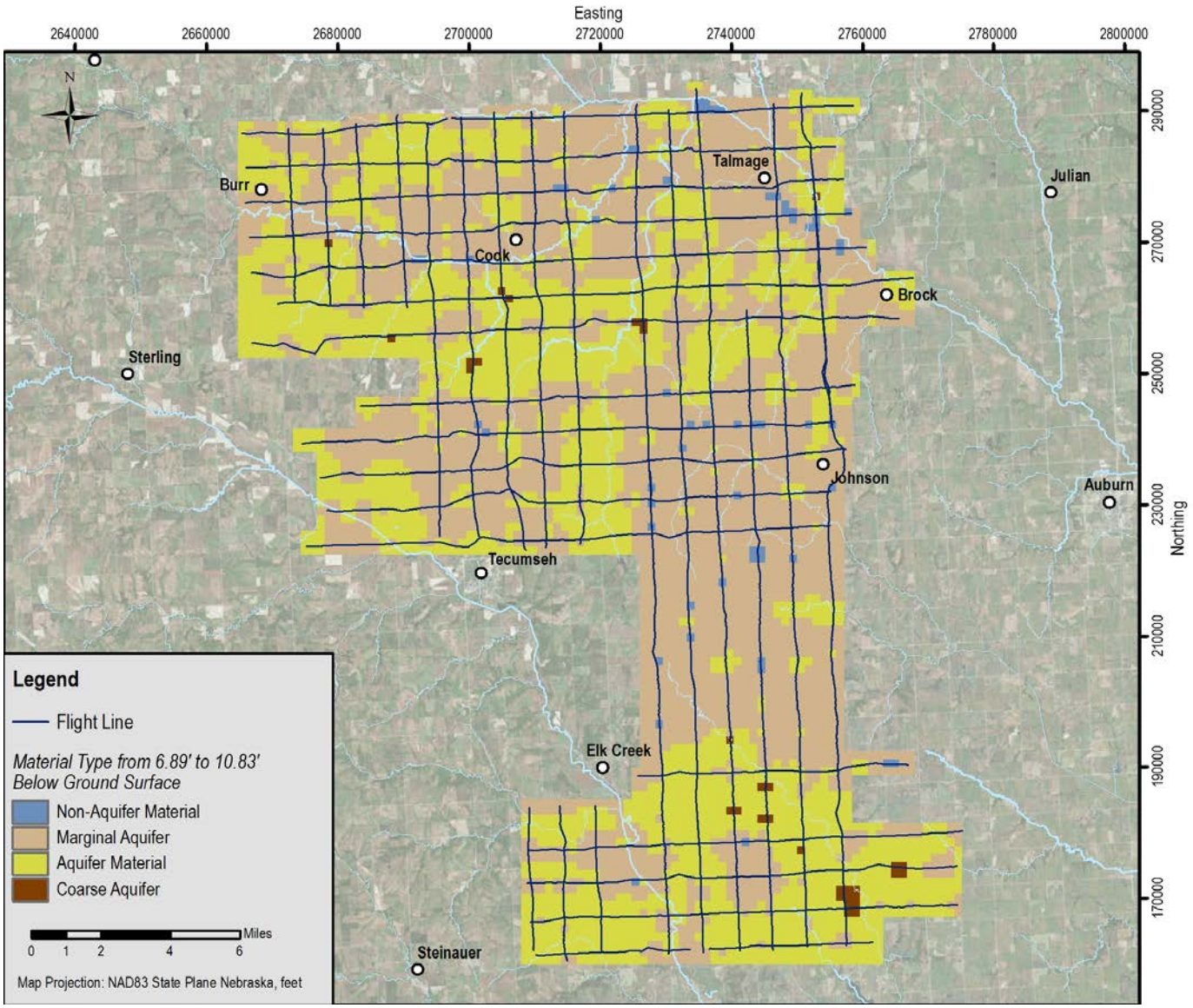


Figure 3-24. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 6.89' to 10.83' below ground surface within the 2018 NNRD Reconnaissance survey area. The projection is NAD83 State Plane Nebraska (feet).

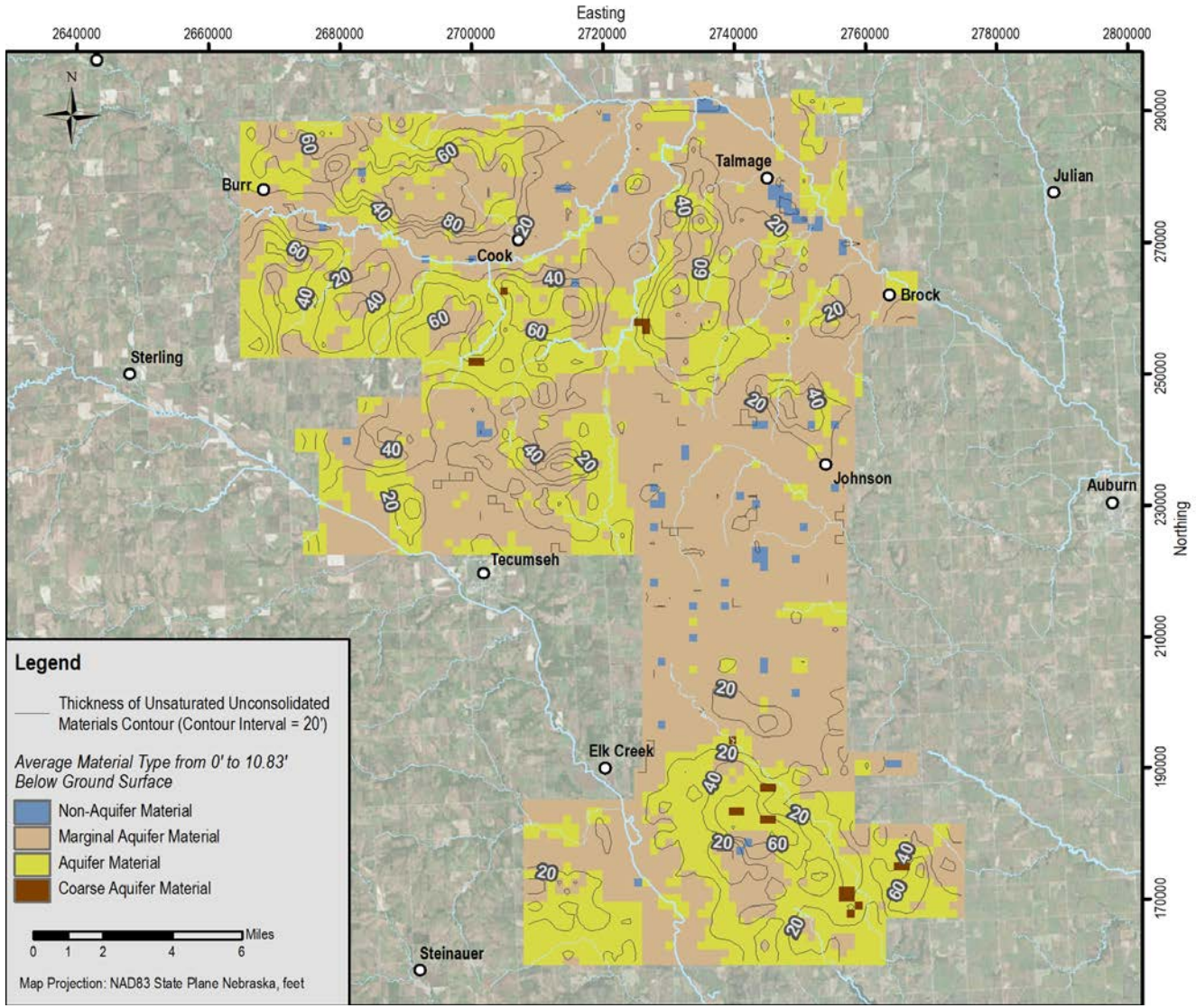


Figure 3-25. Map of the average material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 0' to 10.83' below ground surface with the thickness of unsaturated unconsolidated contours (black lines) of equal thickness within the 2018 NNRD Reconnaissance survey area. The projection is NAD83 State Plane Nebraska (feet).

3.1.7 Create 3D Interpretative Voxel Grids for Shubert Block

A voxel grid was completed for the Shubert Block. The voxel grids were made using a 250 feet grid cell size and the model layer thickness (Table 2-3 in the previous section). A minimum curvature method was used within Datamine Discover PA (Datamine Discover, 2019). All layers were referenced to their depth from the surface and then projected on the area DEM. After the grid was calculated, the grid was split at the top of the undifferentiated Pennsylvanian (***IP***) and the 1995 CSD water table. These resulting voxel grids can be used to explore the distribution of the aquifer materials within the area in 3D. Specifically, these grids can allow for visual inspection of the volume of materials above the bedrock as well as surface materials. The ***Q*** and materials can be separated by the thresholds developed above for the four lithology classes. Utilizing the voxel grids of the ***Q*** analysis can be made of the thickness of the different materials within the section. Figure 3-26 is a plot of the ***Q*** material above the ***IP*** bedrock looking to the north. Figure 3-27 is a map of the total marginal aquifer, aquifer, and coarse aquifer material thickness within the Shubert Block survey area. Figure 3-28 is a map of the *saturated* marginal aquifer, aquifer, and coarse aquifer material thickness within the Shubert Block survey area. Figure 3-29 is a map of the *unsaturated* marginal aquifer, aquifer, and coarse aquifer material thickness within the Shubert Block survey area. Figure 3-30 is a map of the non-aquifer material thickness within the Shubert Block survey area.

The voxel grids can be found in *Appendix 3-Deliverables\Voxel*.

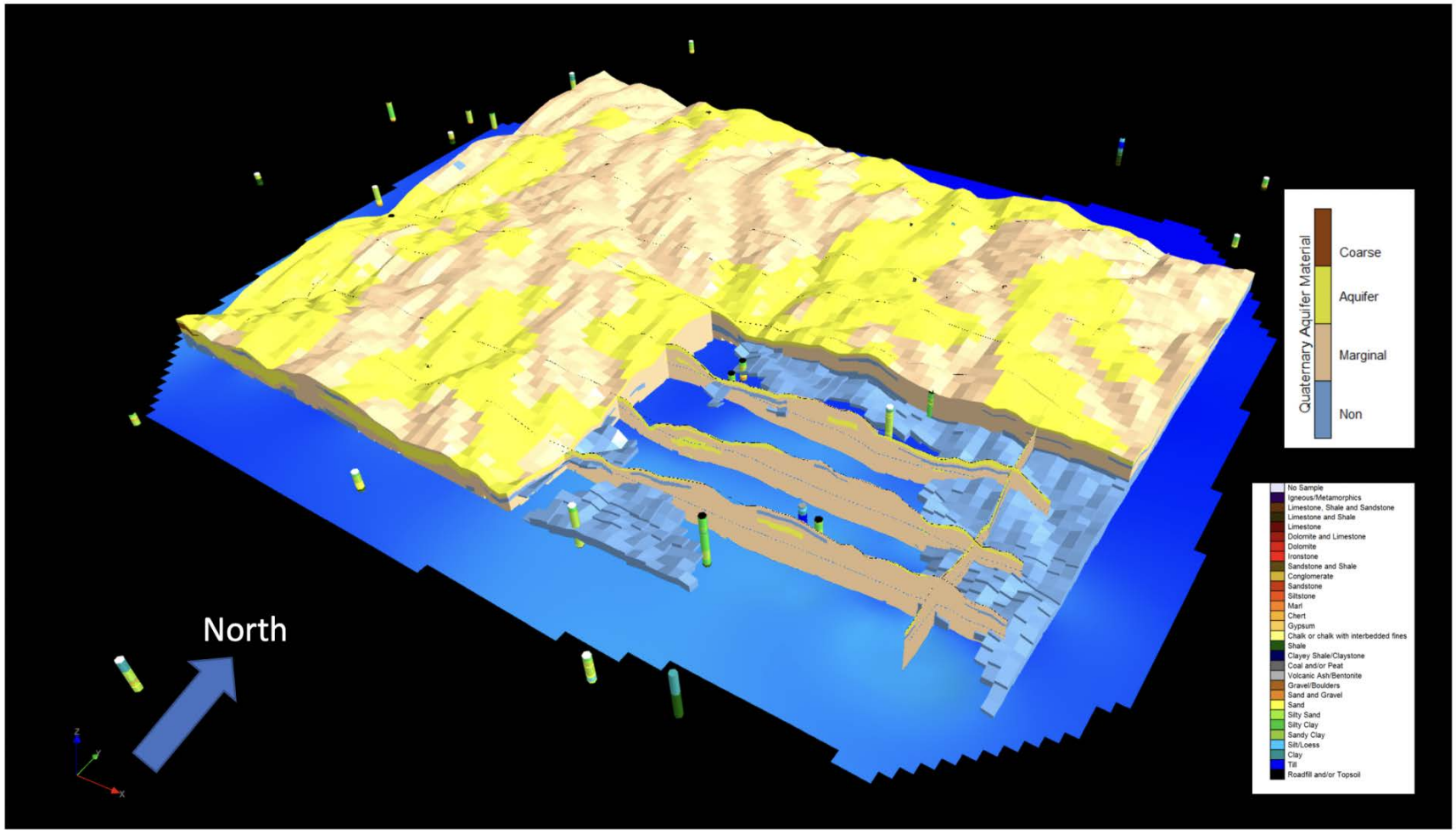


Figure 3-26. Voxel model of the aquifer material types for the Shubert Block of the Quaternary (*Q*). Vertical scale is 15x. The south-east corner of the block has all but the non-aquifer materials set to transparent. The Blue surface is the undifferentiated Pennsylvanian (*IP*). NE-DNR registered wells are colored by lithology as indicated by the legend. Selected flight lines are displayed as fence diagrams in the area of the transparency.

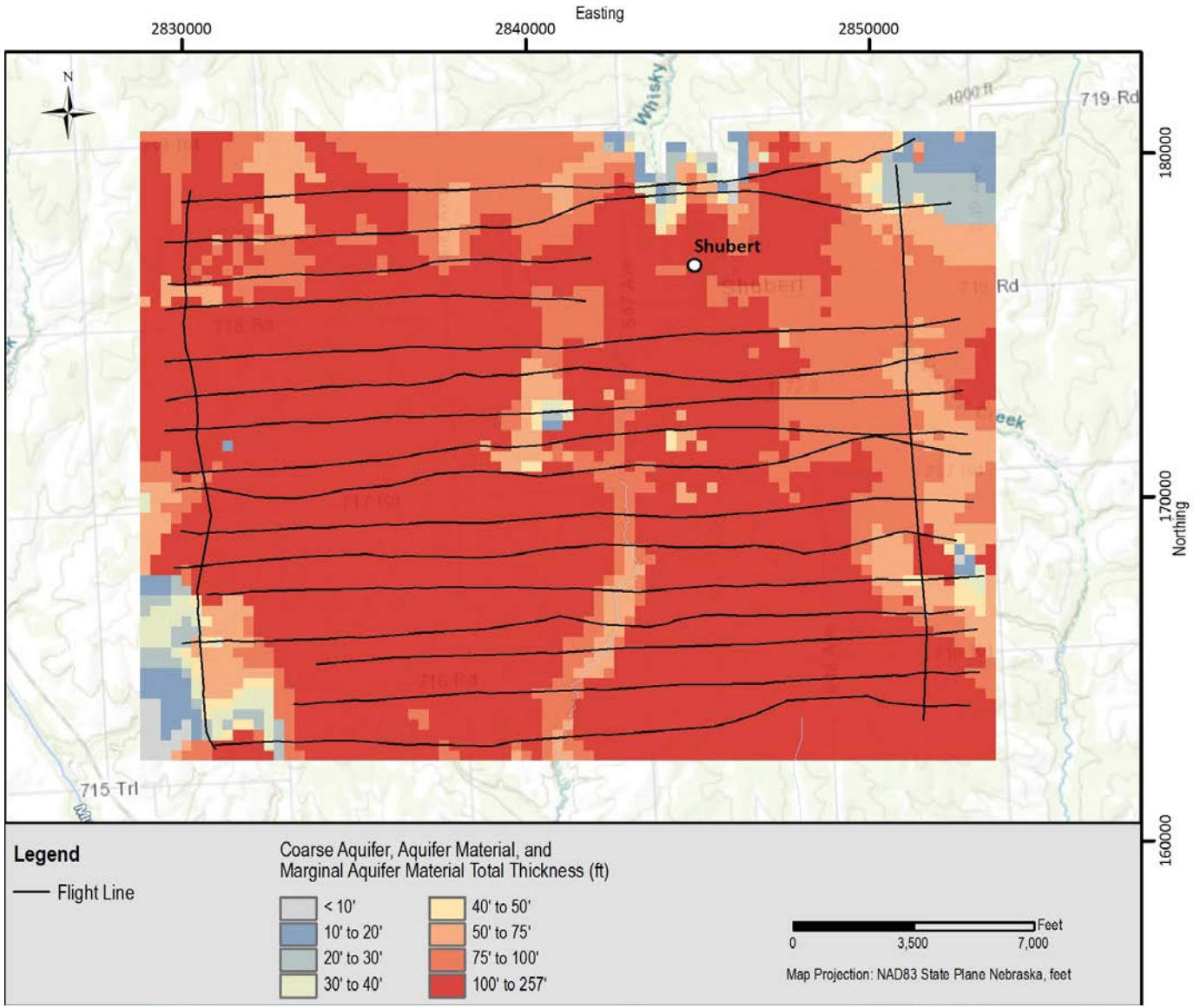


Figure 3-27. Map of the total thickness of Marginal Aquifer, Aquifer Material, and Coarse Aquifer materials within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

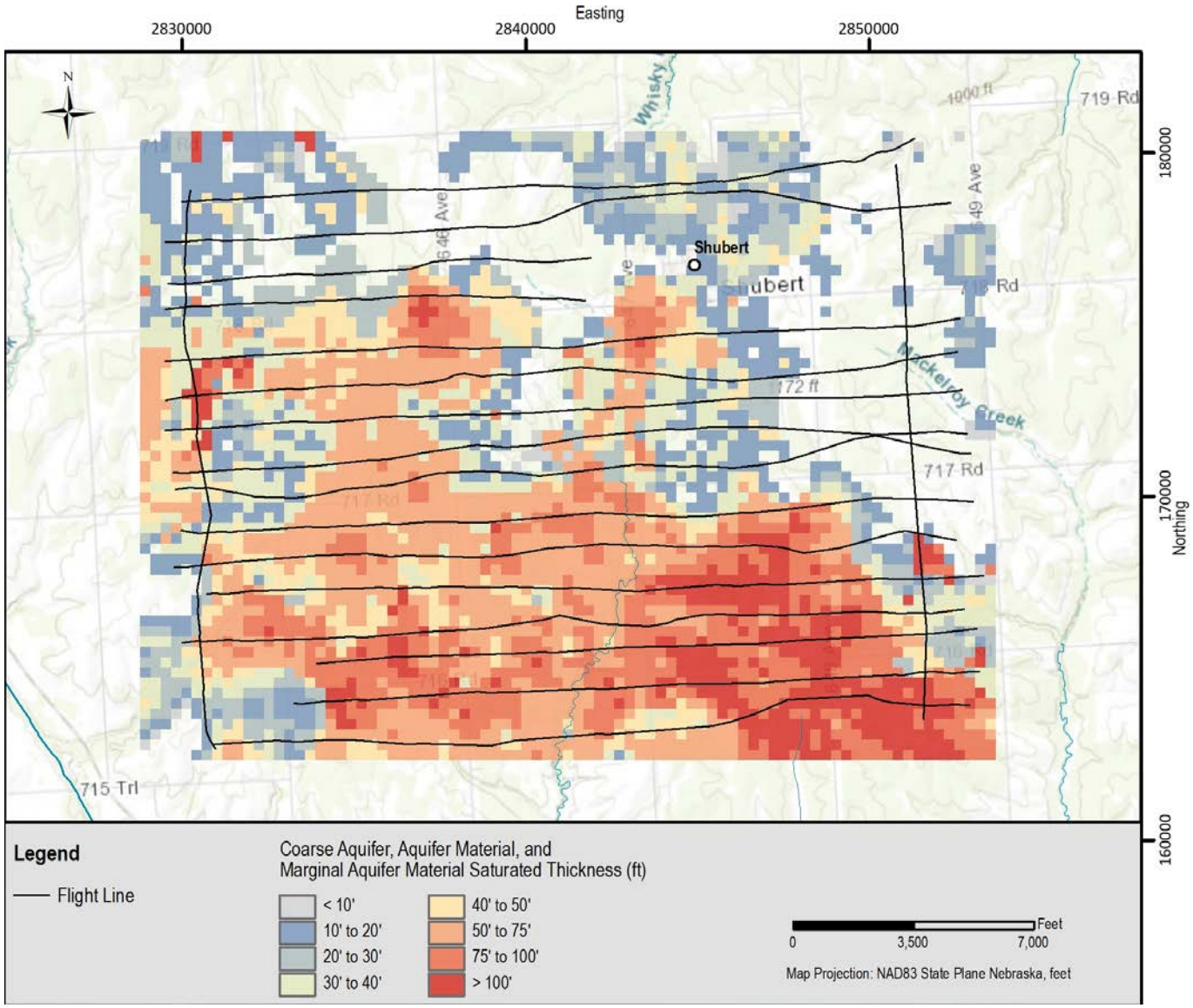


Figure 3-28. Map of the saturated thickness of Marginal Aquifer, Aquifer Material, and Coarse Aquifer materials within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

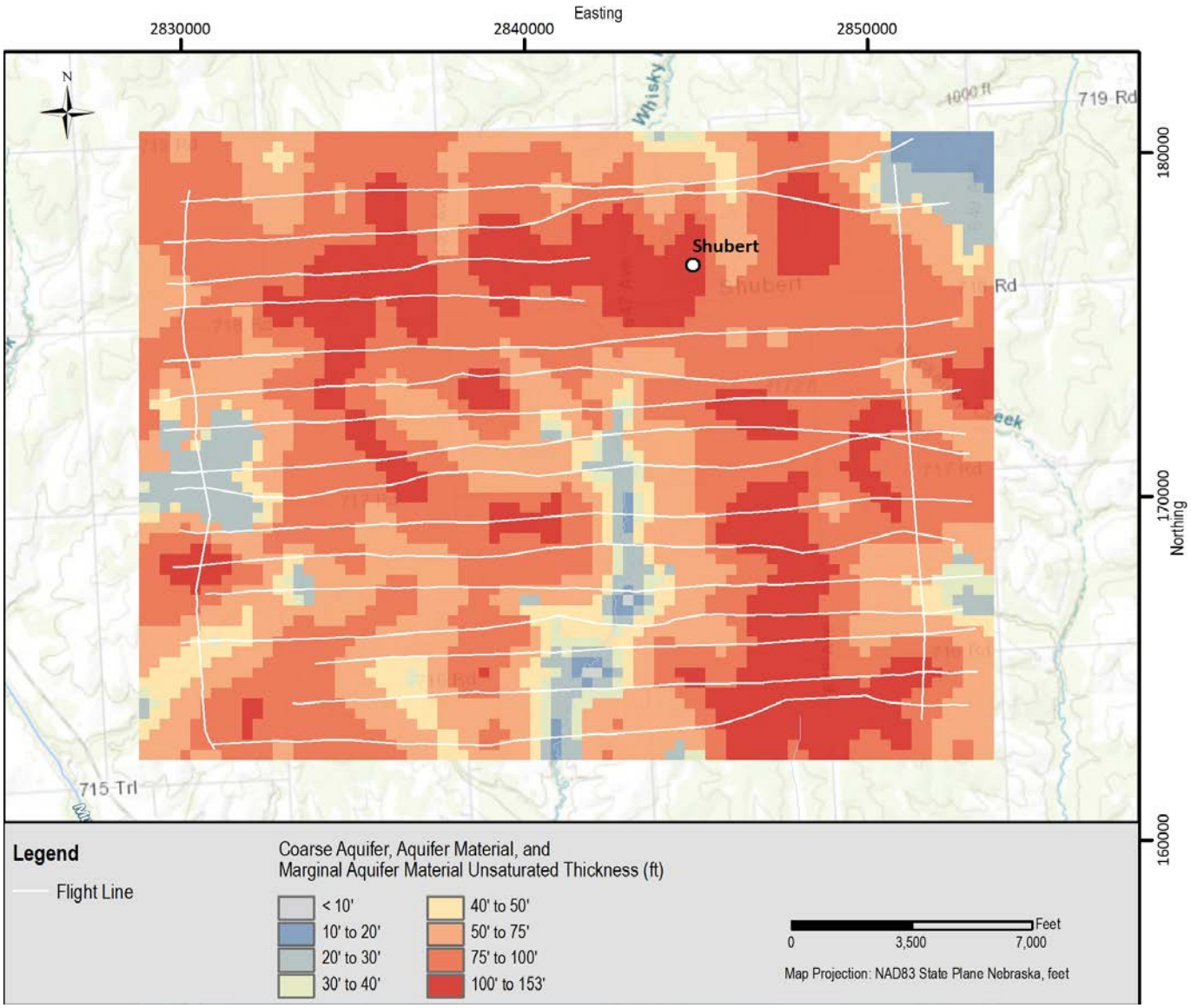


Figure 3-29. Map of the unsaturated thickness of Marginal Aquifer, Aquifer Material, and Coarse Aquifer materials within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

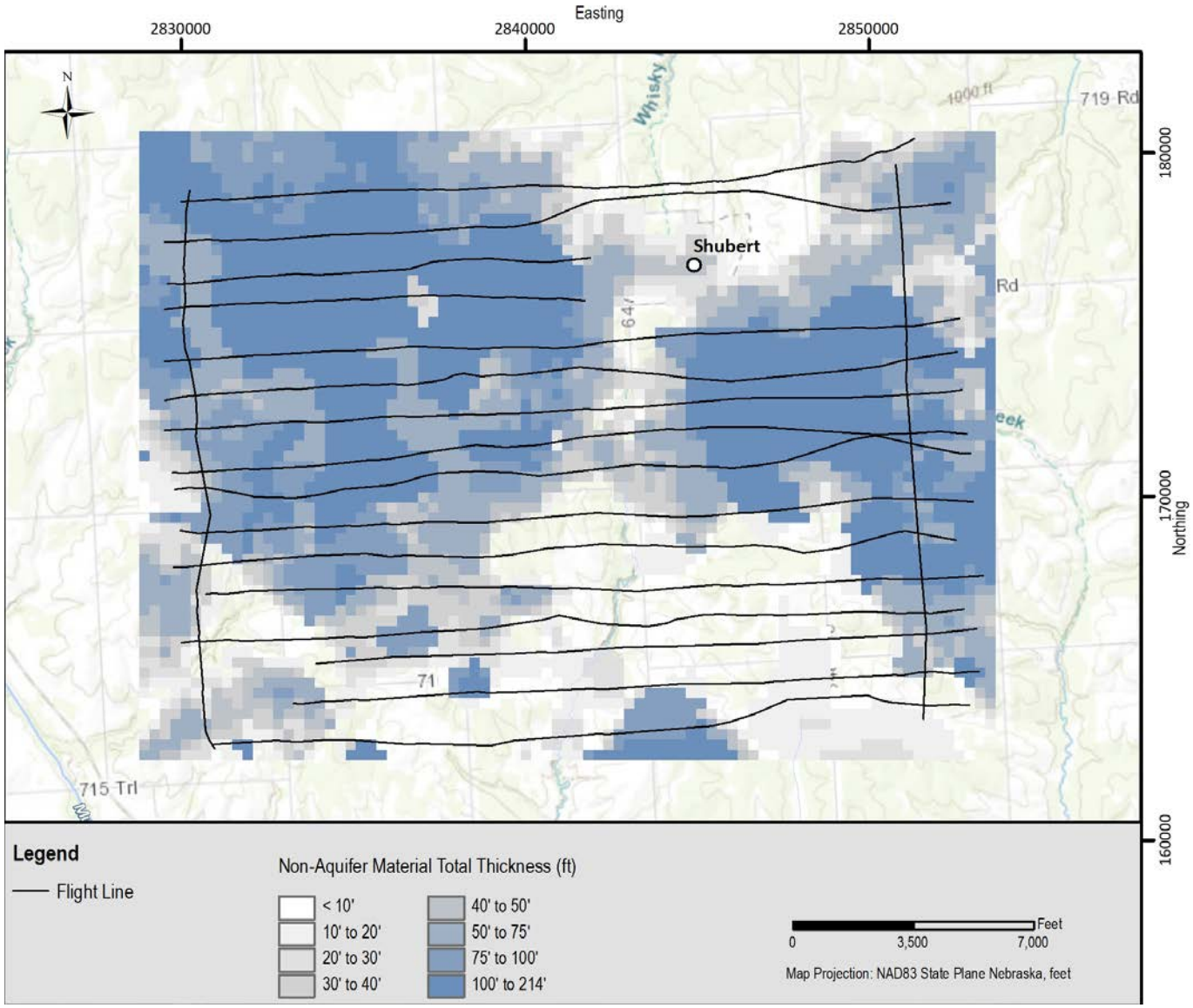


Figure 3-30. Map of the total thickness Non-Aquifer material within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

3.2 Borehole Resistivity and AEM Comparisons

CSD borehole geophysical resistivity logs are limited within the NNRD Reconnaissance survey area that are close to the flight lines; and many of those logs are historical, scanned E-logs. Since the resistivity logs within the CSD database are of various vintages and conducted by various staff with differing equipment, a critical examination of the absolute values of the resistivity needs to include an awareness of errors in calibration and in the proper operation of the equipment. There is a long-standing issue with using geophysical logs as ground truths when comparing to AEM inversions that are well calibrated using modern techniques. Throughout much of the geophysical logging world at the time it was acquired, the relative deflections of the resistivity measurements were all that was required or expected from a geophysical log. Operators were seldom trained in the proper operation of a calibrated sonde or in the ability to recognize high contact resistance of a cable head. This has led to many geophysical logs that are uncalibrated within the CSD database. Note that these logs still have scientific merit in their ability to relatively indicate an increase or a decrease in the formation resistivity. The logs used herein are for qualitative comparison to the AEM because detailed calibration and corrections would need to be carried out for the resistivity values in the logs to be directly used as numerical constraints in the inversion of the AEM data (Ley-Cooper and Davis, 2010). Line L100201 in the southern portion of the NNRD Reconnaissance survey area has two E-logs (*32-B-67* and *59-78*) that are within ¼ mile of the flight line but are also within areas that had EM-coupling removed. The E-logs, however, do show good correlation to the AEM on the edges of the coupling (Figure 3-31). The E-log from *32-B-67* shows an area of low electrical resistivity correlating to lithology of silt/loess, clay, and till with minor sand overlaying on Pennsylvania shale and limestone. The E-log from test-hole *59-78* indicates a high resistivity area below a thin low resistivity area overlying a variable low resistivity zone. This resistivity correlates well with the AEM and the lithology indicated a thin surface layer of silt/loess over sand overlaying shale and limestone.

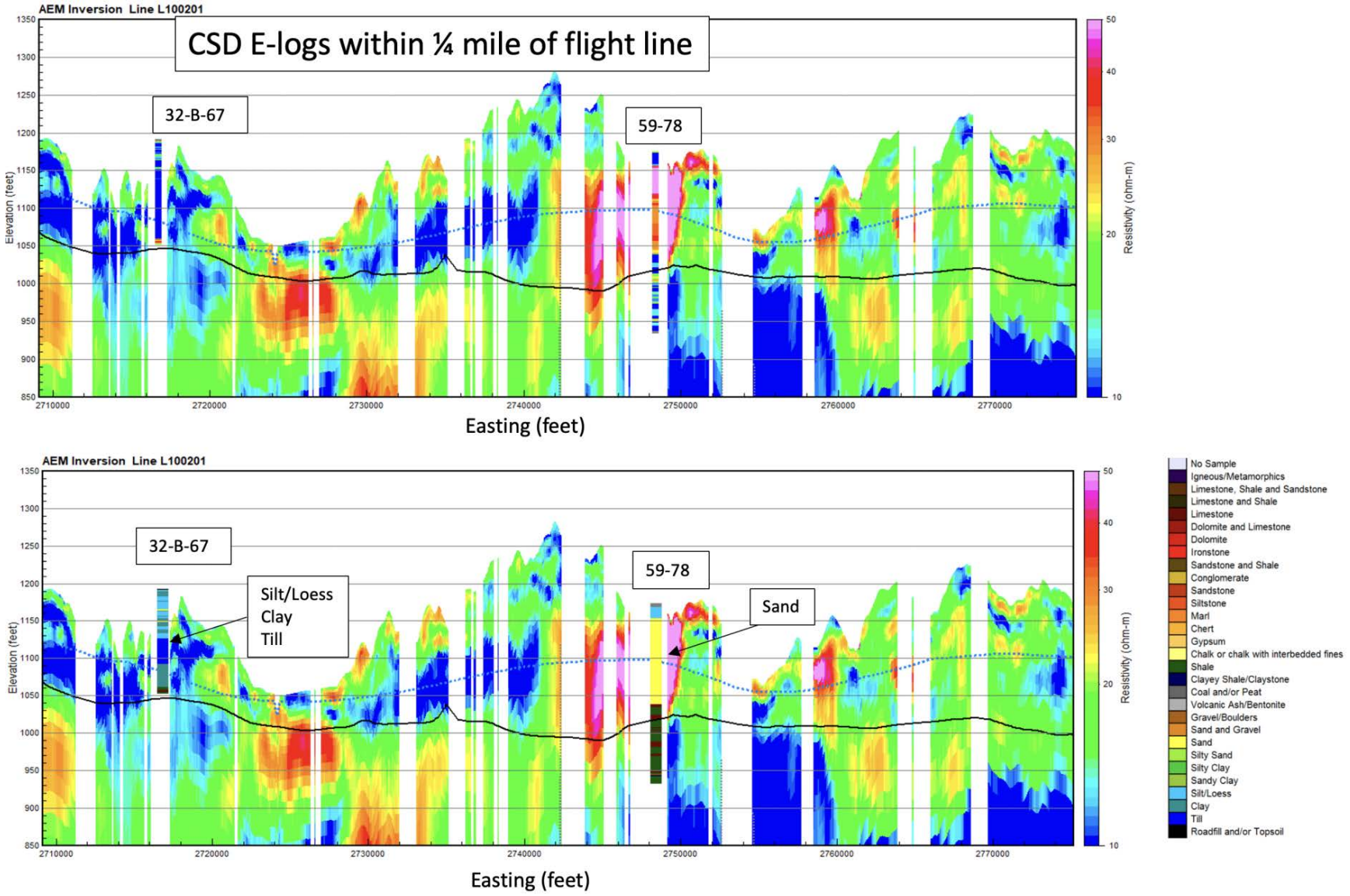


Figure 3-31. Comparison of Line L100201 AEM inversion results and the CSD E-logs for test-holes *32-B-67* and *59-78* that are within ¼ of a mile of the flight line. The projection is NAD83 State Plane Nebraska (feet).

3.3 Hydrogeological Framework of the NNRD 2018 AEM Survey Area

The 2018 survey continues to build upon the previous AEM survey efforts within NNRD since the Firth 2007 survey (Smith et al., 2008) and continuing with the 2015 reconnaissance lines (Carney et al., 2015b). These AEM-derived results provide new information on the hydrogeology in areas that was previously unknown to the NNRD 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 NNRD and ENWRA.

The 2018 AEM survey reveals variability in the Quaternary (***Q***) deposits across the NNRD AEM survey area. In the region of the reconnaissance lines, ***Q*** is generally thickest in the west associated with paleochannels. The ***Q*** materials make up the aquifer materials overlying the undifferentiated Pennsylvanian bedrock units. Figure 3-32, looking northeast, is a 3D Fence diagram of the NNRD reconnaissance lines with the ***IP*** bedrock surface. The ***Q*** aquifer materials are indicated by the legend. The paleochannels can be seen in the western portion of the survey area as well as the southern area of the Reconnaissance lines. Figure 3-33, looking north, is a 3D Fence diagram of the NNRD Shubert Block with the ***IP*** bedrock surface. The ***Q*** aquifer materials are indicated by the legend. The area of the Shubert is dominated by marginal aquifer materials (tan color). The undifferentiated Pennsylvanian units of the area are not considered aquifers and will not be discussed within this report.

3.3.1 The Hydrogeologic Framework of the NNRD Reconnaissance Survey Area

The ***Q*** 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 predominantly composed of glacial, pre-glacial alluvial, and minor alluvial deposits related to the current drainages. As noted above the dominant hydrogeologic feature in the NNRD Reconnaissance survey area are the paleochannels. These channels have been identified in previous studies by Korus et al. (2013) and LBG (2017). The CSD Nebraska Groundwater Atlas provides a general pattern to the paleochannels of the area and is in general agreement with the AEM results with the AEM results providing much more detail. Figure 3-34 is an overlay of the identified paleochannels form Korus et al. (2013) and the total thickness of aquifer and coarse aquifer material from the NNRD Reconnaissance survey area. Comparing the AEM to the LBG generated cross sections also shows a good agreement with the LBG results and have much more detail than the CSD Nebraska Groundwater Atlas. Figure 3-35 is a 3D image of the AEM interpretation as fence diagrams with the LBG cross sections looking to the southwest. Figure 3-36 is a comparison of the LBG total sand thickness and the AEM aquifer and coarse aquifer material. When comparing the LBG sand thickness to the AEM derived aquifer and coarse aquifer material total thickness, differences generally only occur in areas that did not contain test holes and registered wells. Plus, the AEM data display more consistency and less “bulls’ eyes” from the gridding artifacts of using boreholes only. The objective of this comparison is not to discount the product of LBG, but to show that with the addition of supplemental data between the boreholes, more fidelity is gained in the understanding of the distribution of aquifer materials.

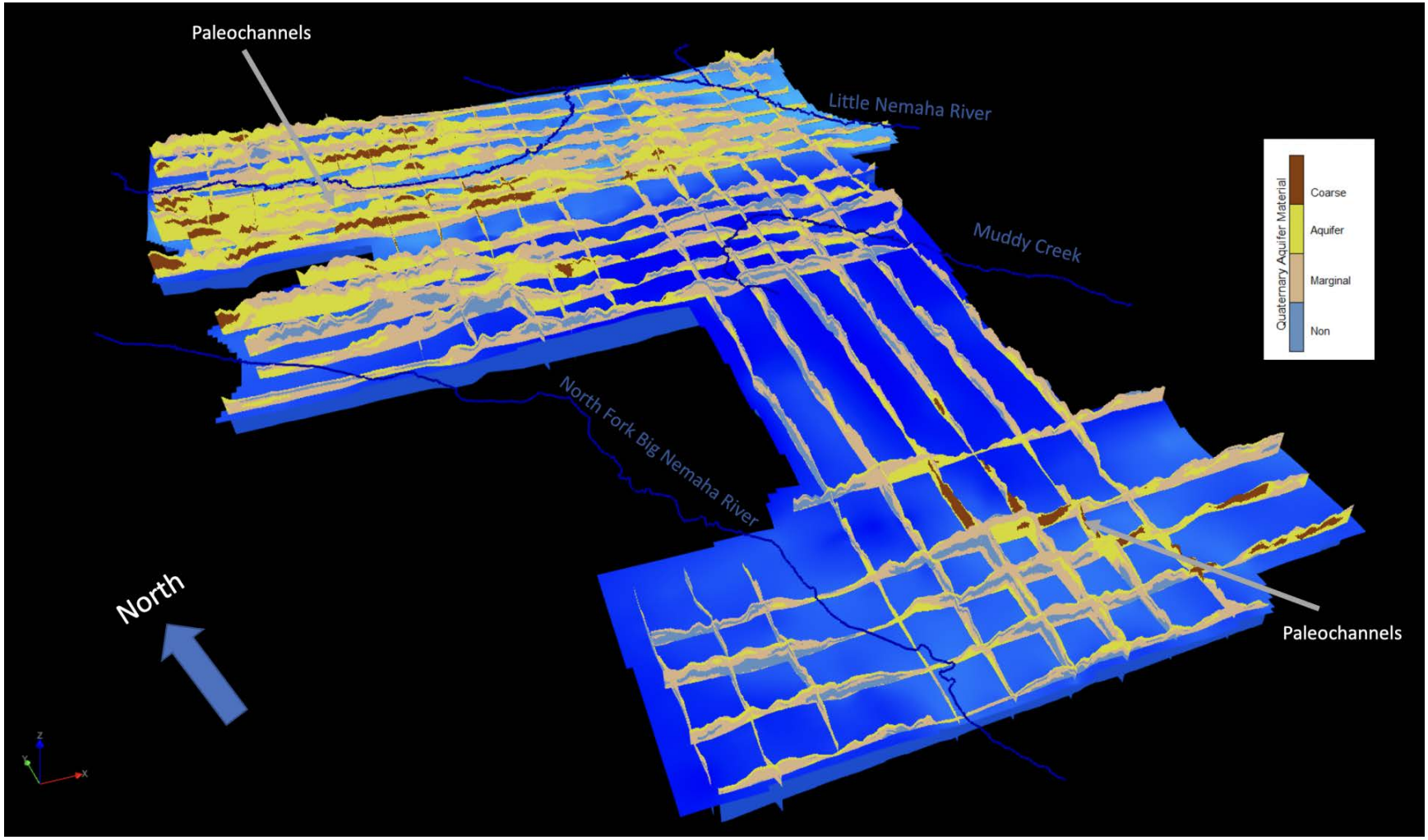


Figure 3-32. 3D fence diagram looking to the northeast of the NNRD Reconnaissance lines. The blue surface is the undifferentiated Pennsylvanian. Vertical exaggeration 15x.

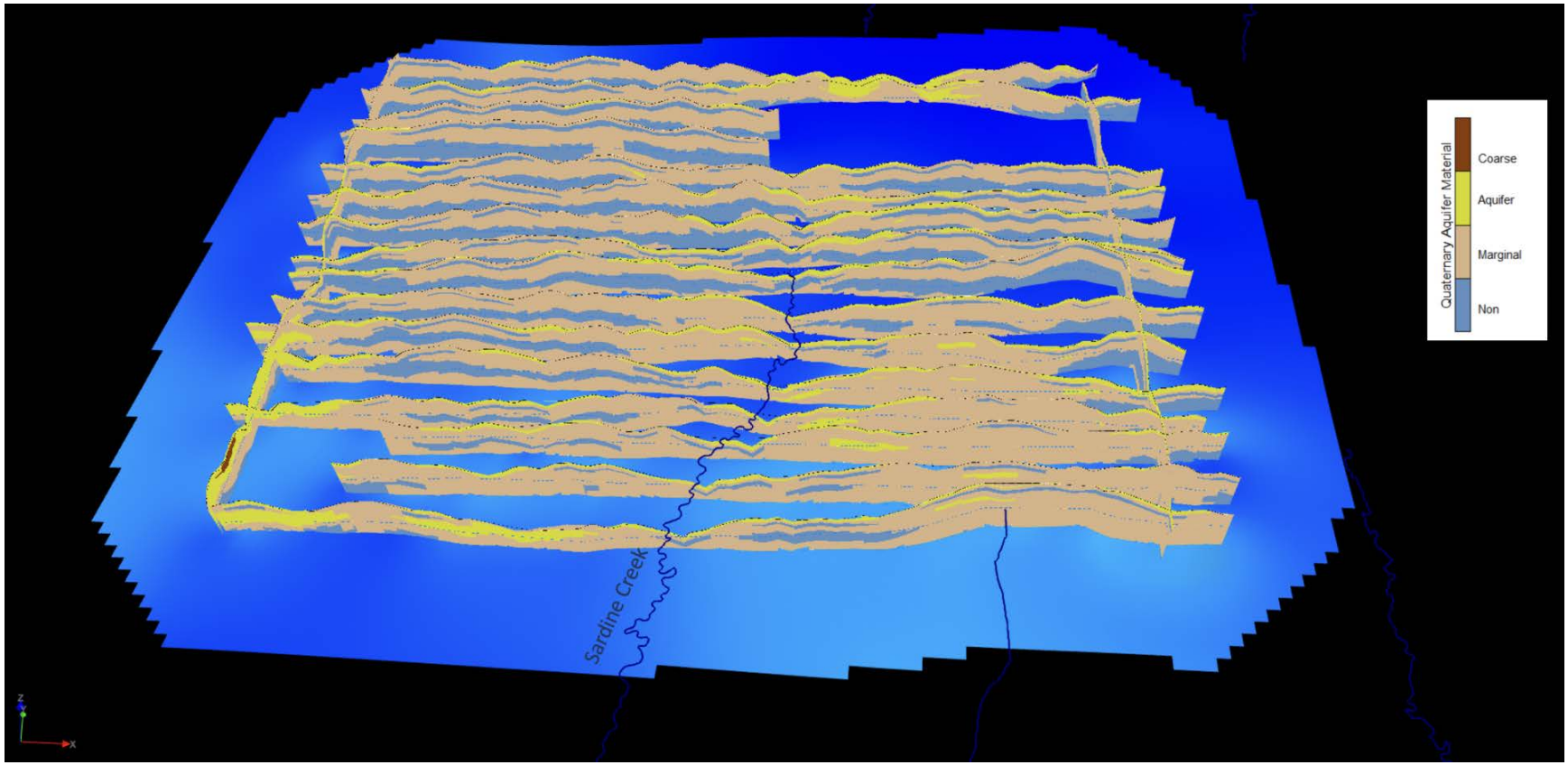


Figure 3-33. 3D fence diagram looking to the north of the Shubert Block lines. The blue surface is the undifferentiated Pennsylvanian (*IP*). Vertical exaggeration 7x.

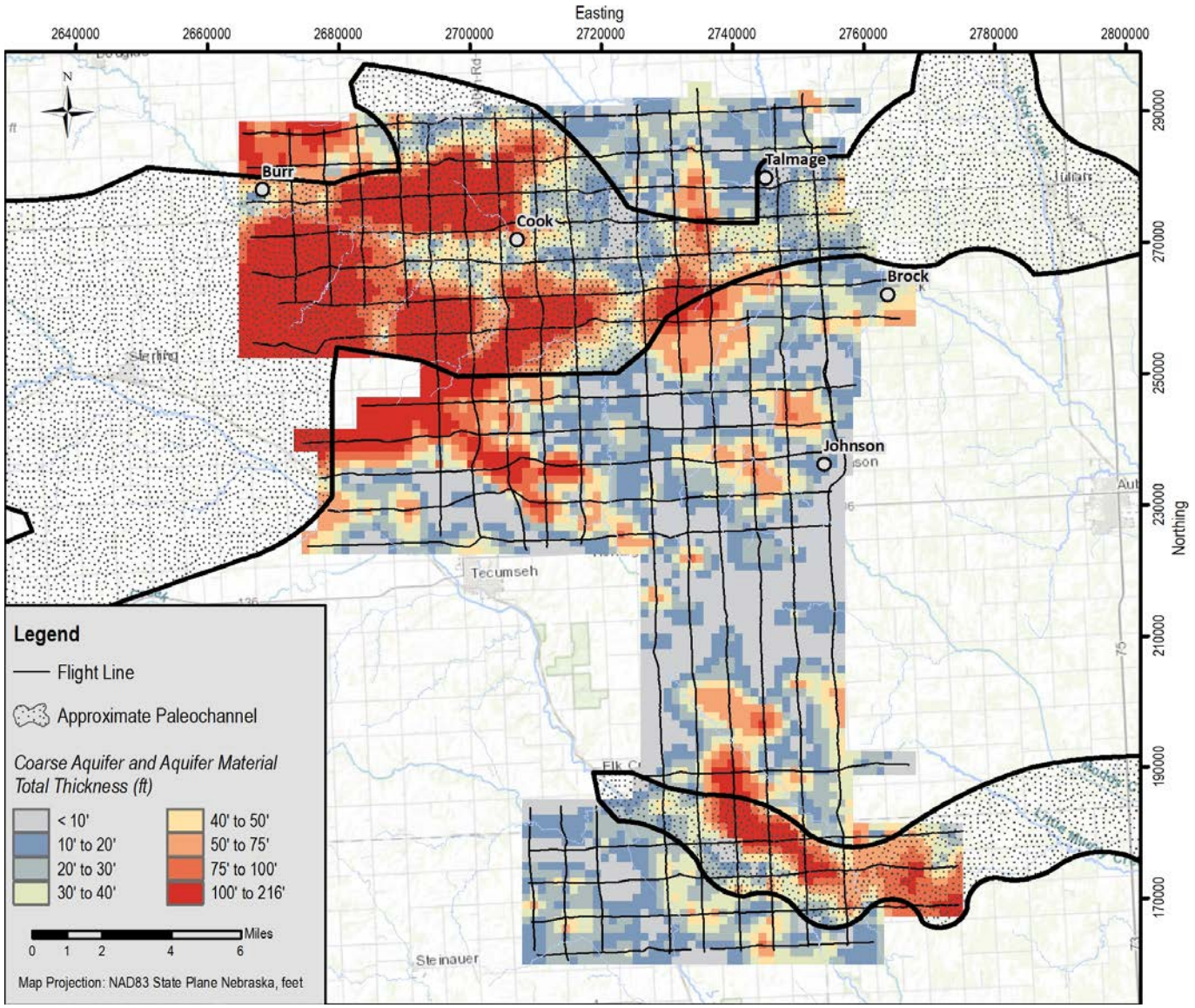


Figure 3-34. Map of the total thickness of the aquifer and coarse aquifer material thickness NNRD Reconnaissance survey area compared to the paleochannels from Korus et al. (2013). The projection is NAD83 State Plane Nebraska (feet).

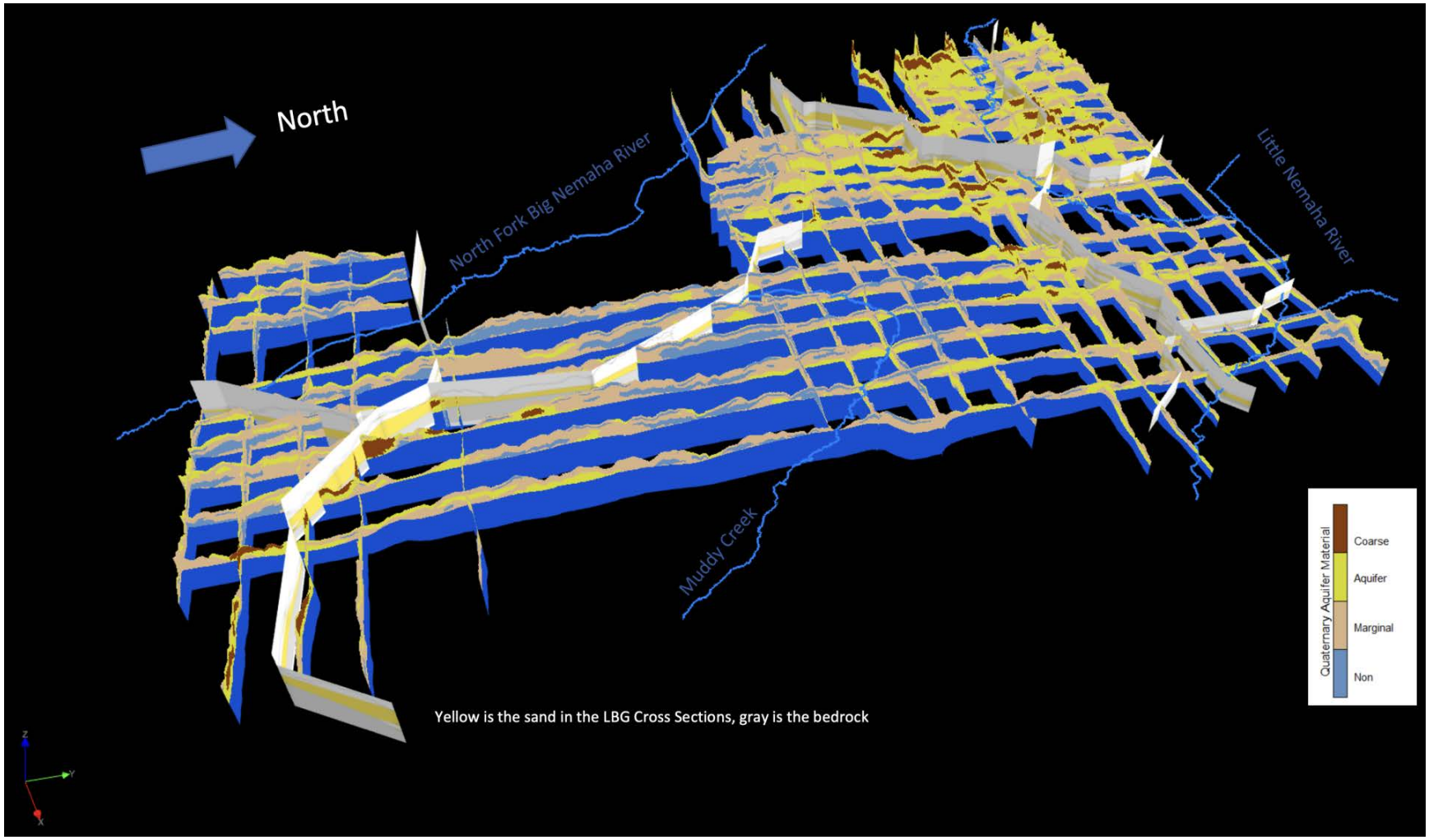


Figure 3-35. 3D Fence diagram of the NNRD Reconnaissance lines and the LBG cross sections looking to the southwest. Blue area in the fence diagrams is the undifferentiated Pennsylvanian. Vertical exaggeration 15x.

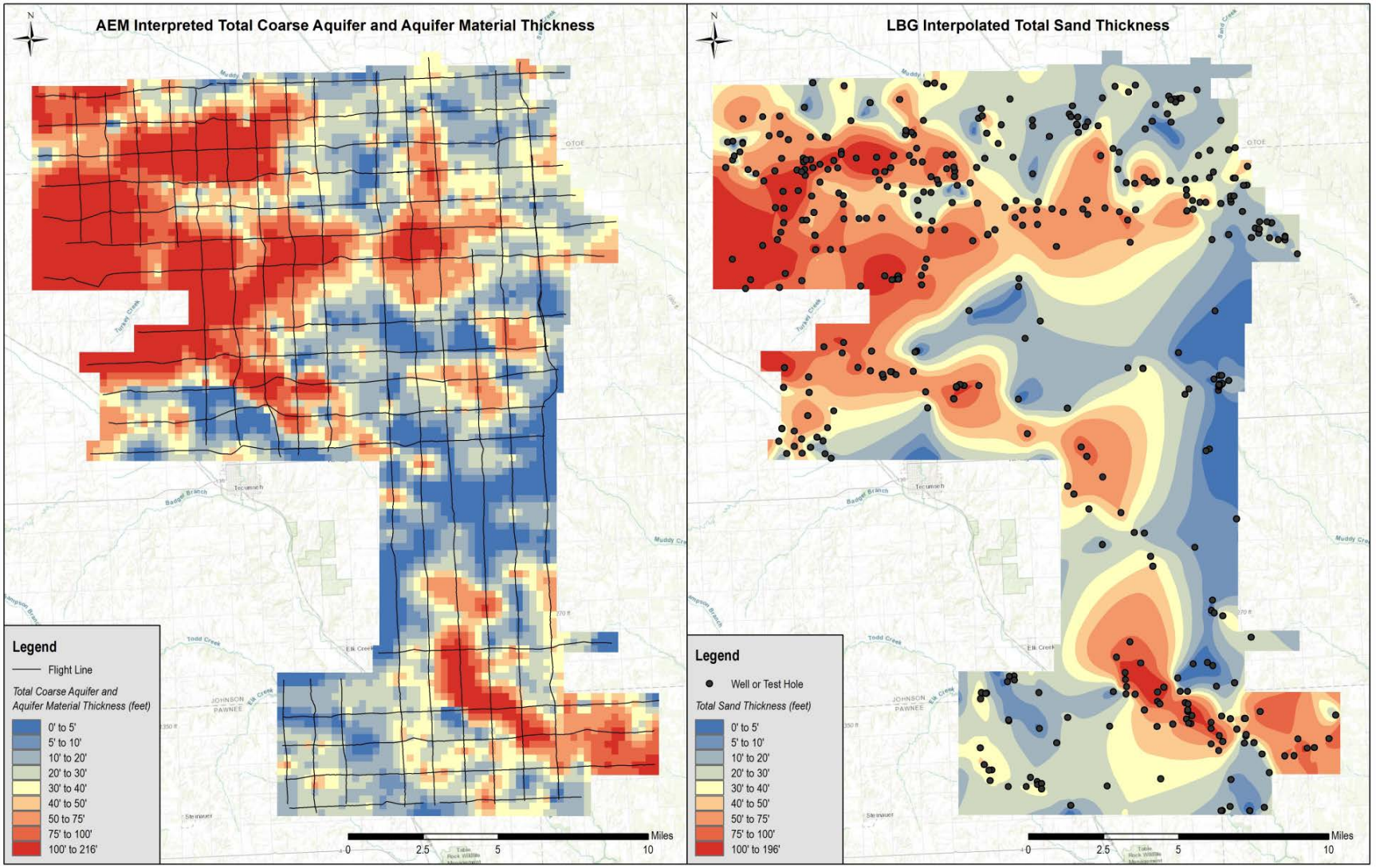


Figure 3-36. Comparison of the total thickness of the aquifer and coarse aquifer materials thickness from the AEM (flight lines are black lines) versus LBG total sand thickness derived from boreholes (black dots). The projection is NAD83 State Plane Nebraska (feet).

Examining the 3D fence diagrams provides a spatial understanding of the distribution of aquifer materials within the NNRD Reconnaissance survey area. Figure 3-37 is a 3D fence diagram looking to the southeast. The figure includes the surface of the undifferentiated Pennsylvanian as well as some of the major streams and the NE-DNR registered wells as well as the CSD test holes displaying the lithology. The AEM aquifer material classifications illuminate the areas of the main aquifers with the yellow and brown colors of the aquifer and coarse aquifer materials, respectively. The boreholes also provide additional evidence as the area of sand and sand and gravel are shown as yellow and orange, respectively. In areas where there are no paleochannels the dominant aquifer material type is marginal (tan areas). Non-aquifer materials do exist in the area and occupy the center of the survey area. These areas have few to no boreholes. It is important to note that the marginal aquifer areas may have wells that produce, just at a lower rate due to the interlayered nature of the marginal materials that contain large portions of silt and clay, but may also contain thin layers of sand and gravel and/or sandy clay. Discussion on the materials that were found to be within the marginal aquifer materials resistivity range can be found in Carney et al. (2015b).

In some areas of the survey the paleochannels are discrete and have very sharp transitions from non-aquifer and marginal aquifer materials to aquifer and coarse aquifer materials. East-west line L100201 (Figure 3-38) is in the southern portion of the NNRD Reconnaissance survey area (just south of the Richardson County Line) and illustrates the discrete nature of the paleochannel deposits. In the center of Line L100201 a paleochannel is detected by the AEM as well as by NE-DNR registered wells and CSD test holes. This geometry provides for sharp flow boundaries within the aquifer system.

East-west line L102400 (Figure 3-39), south of Burr and Talmage and north of Cook, Nebraska, also displays a paleochannel system in the center portion of the line. It is not as sharp as the example from L100201 but exhibits a discrete deposit. This deposit also shows some layering within the aquifer materials that maybe related to the lower aquifer materials being from pre-glacial deposits. Specifically, around NE-DNR registered well *G-031091*.

North-south line 201701 (Figure 3-40), east of Talmage and west of Johnson, Nebraska, illustrates the bedrock high in the center portion of the NNRD Reconnaissance lines. On the southern end of the survey line a paleochannel is visible. Toward the north on the north side of the bedrock high there is a deposit of aquifer materials that is above the 1995 CSD water table.

Using the interpretive surfaces and grids that were produced as described above, an enhanced understanding of the hydrogeological framework of the NNRD Reconnaissance survey area can be achieved. Figure 3-41 is the total thickness of the aquifer and coarse aquifer materials. The locations of the paleochannels can be readily identified. When the 1995 CSD water table is used to separate the unsaturated (Figure 3-42) from the saturated (Figure 3-43), the paleochannel systems are not as apparent in the unsaturated aquifer and coarse aquifer thickness. However, much of that is due to post-glacial erosional processes. These unsaturated areas may provide areas of future groundwater storage through the use of MAR. The saturated thickness of the aquifer and coarse aquifer materials illustrates the area of the most productive aquifers in the area. The thickness of the non-aquifer materials (Figure

3-44) shows the areas in the center portion of the Reconnaissance lines over the bedrock high that have the most clay. Other areas between the paleochannels are observable.

As indicated above by using the saturated thickness of the aquifer and coarse aquifer material and an estimate of the hydraulic conductivity, an estimate of the transmissivity can be developed (Figure 3-45). These values compare relatively well with the LBG values derived from using the specific capacitance. The coarsest and thickest areas of the saturated paleochannel have the highest transmissivity values. It is important to also note that the values in Figure 3-45 only used the thickness of the aquifer and coarse aquifer materials. However, this provides an additional view of the possible transmissivity of the materials within the area of the Reconnaissance lines.

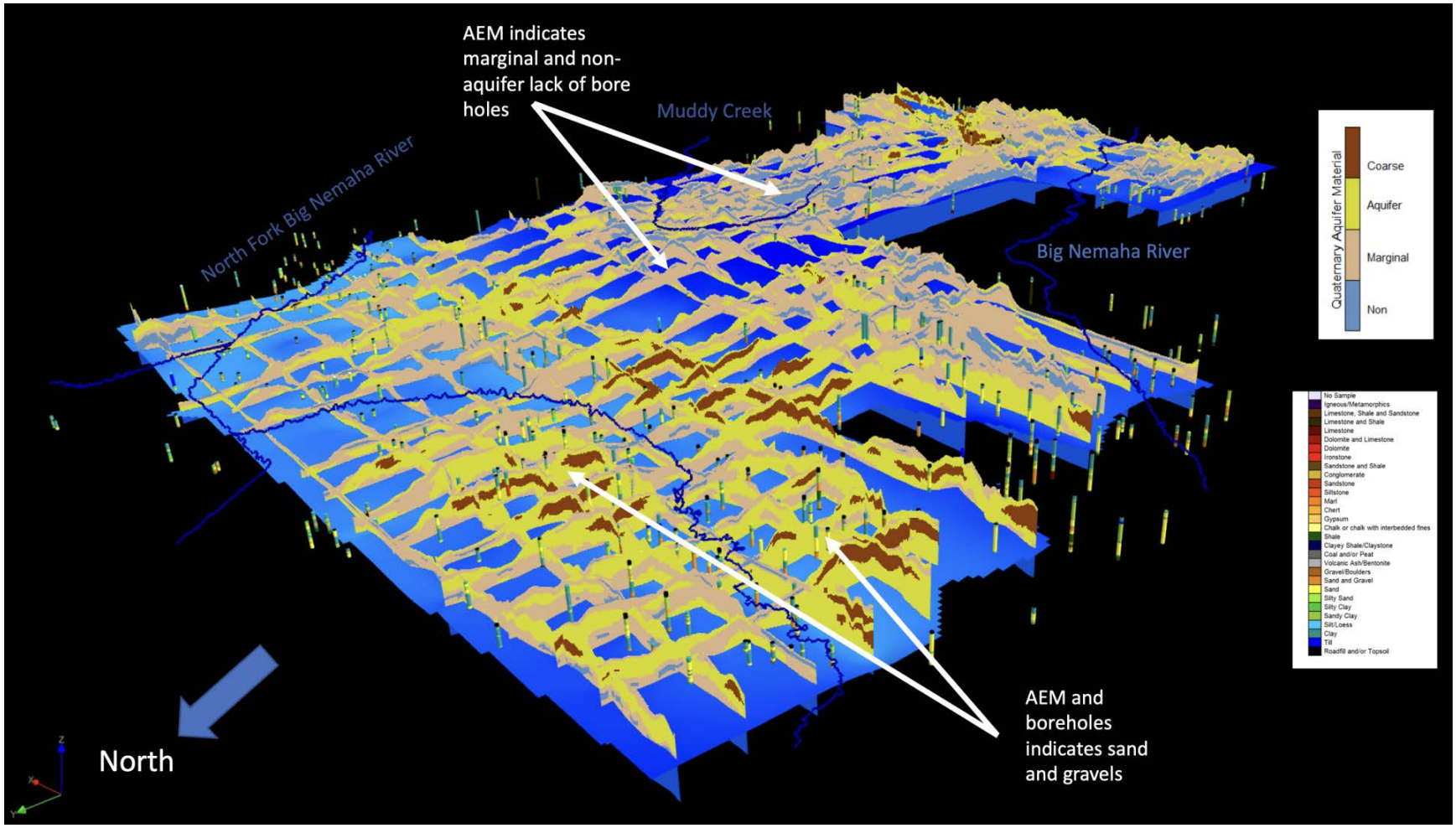


Figure 3-37. 3D fence diagram of the NNRD Reconnaissance lines and borehole lithology looking to the southeast. Blue surface is the undifferentiated Pennsylvanian (*IP*). Vertical exaggeration 15x.

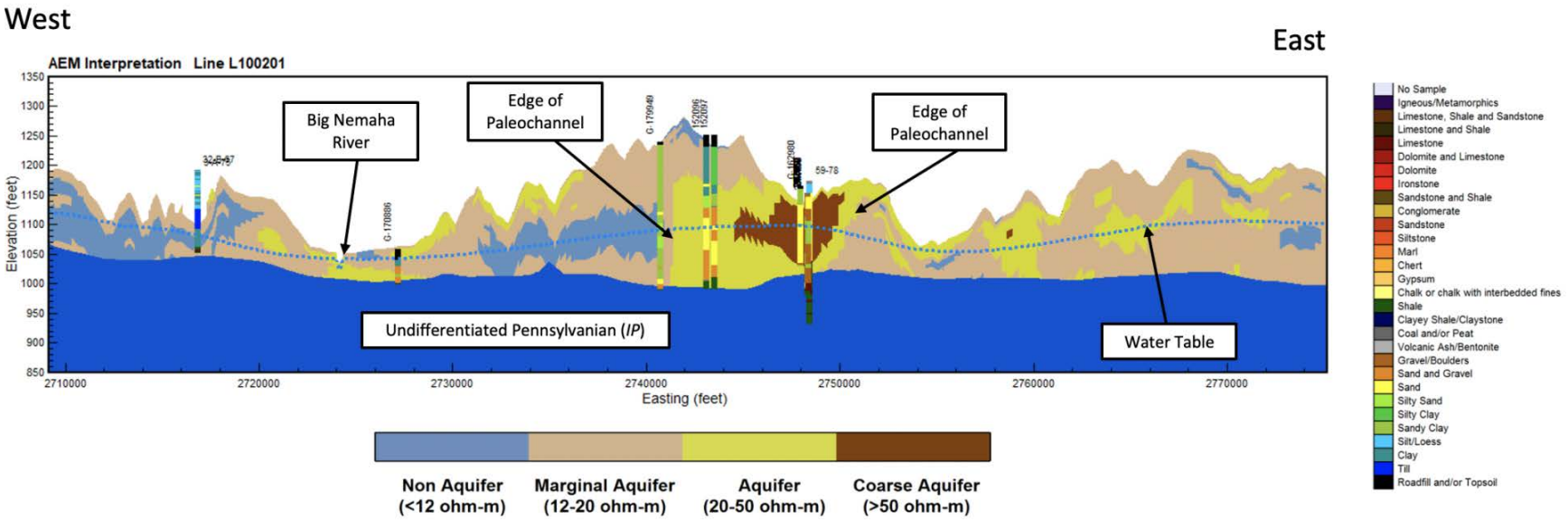


Figure 3-38. East-west Line L100201. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. The CSD 1995 water table is indicated with a dashed blue line.

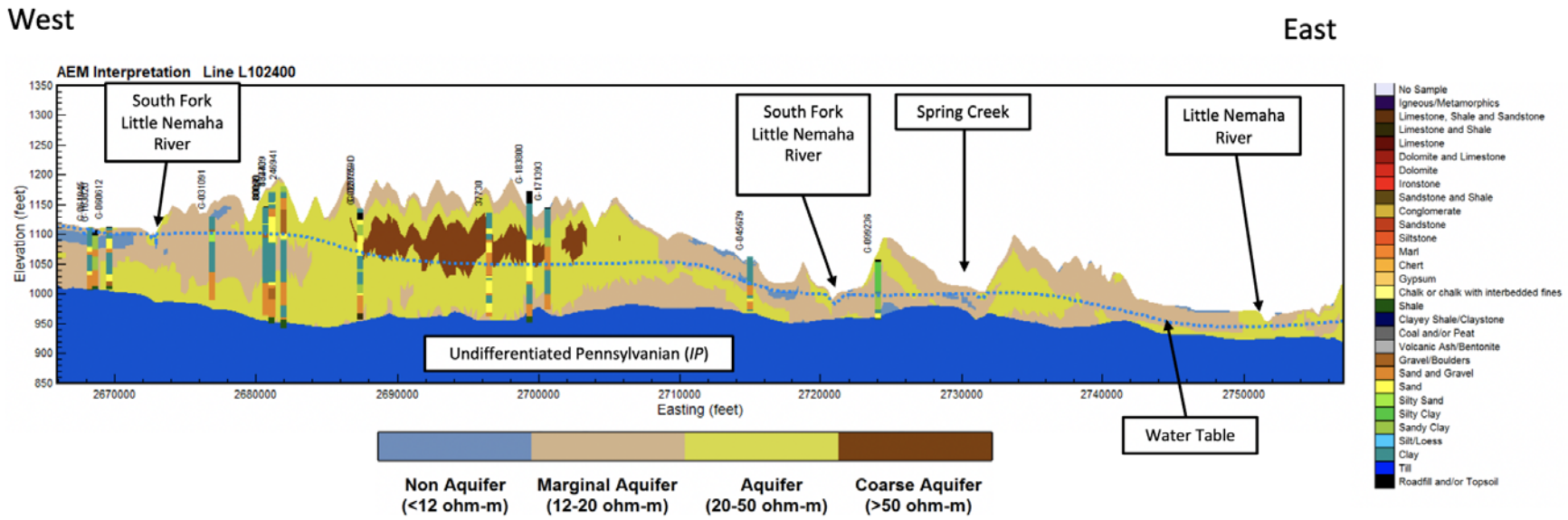


Figure 3-39. East-west Line L102400. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. The CSD 1995 water table is indicated with a dashed blue line.

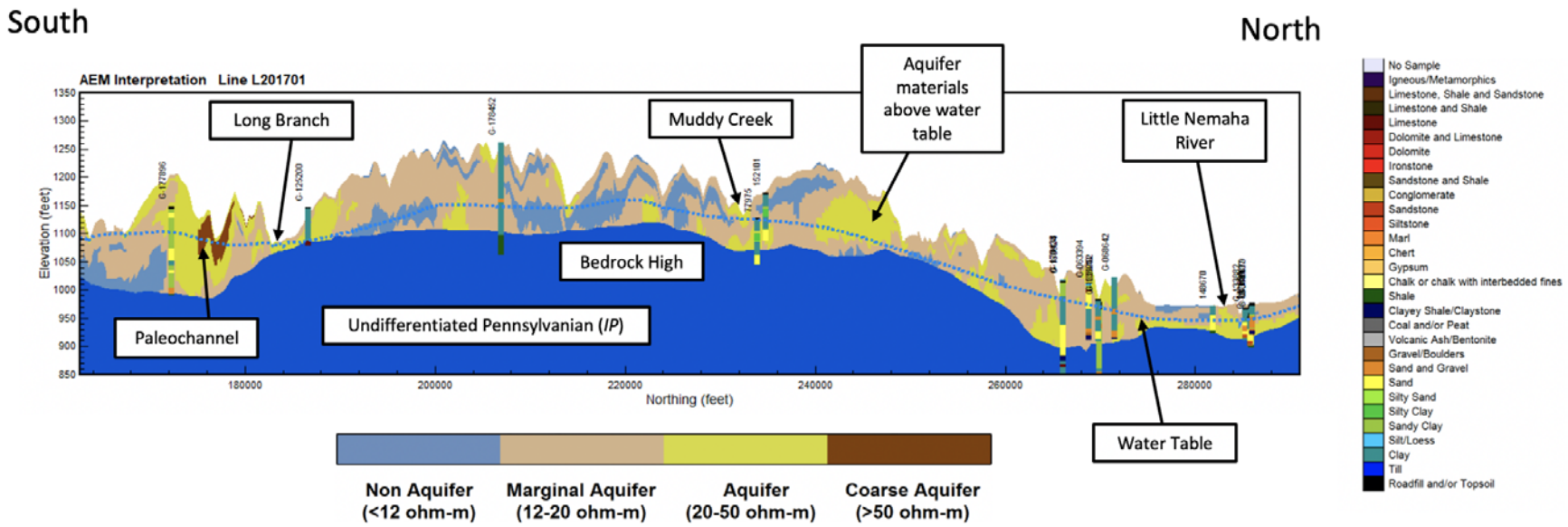


Figure 3-40. North-south Line L201701. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top undifferentiated Pennsylvanian (*IP*) is indicated by the blue area. The CSD 1995 water table is indicated with a dashed blue line.

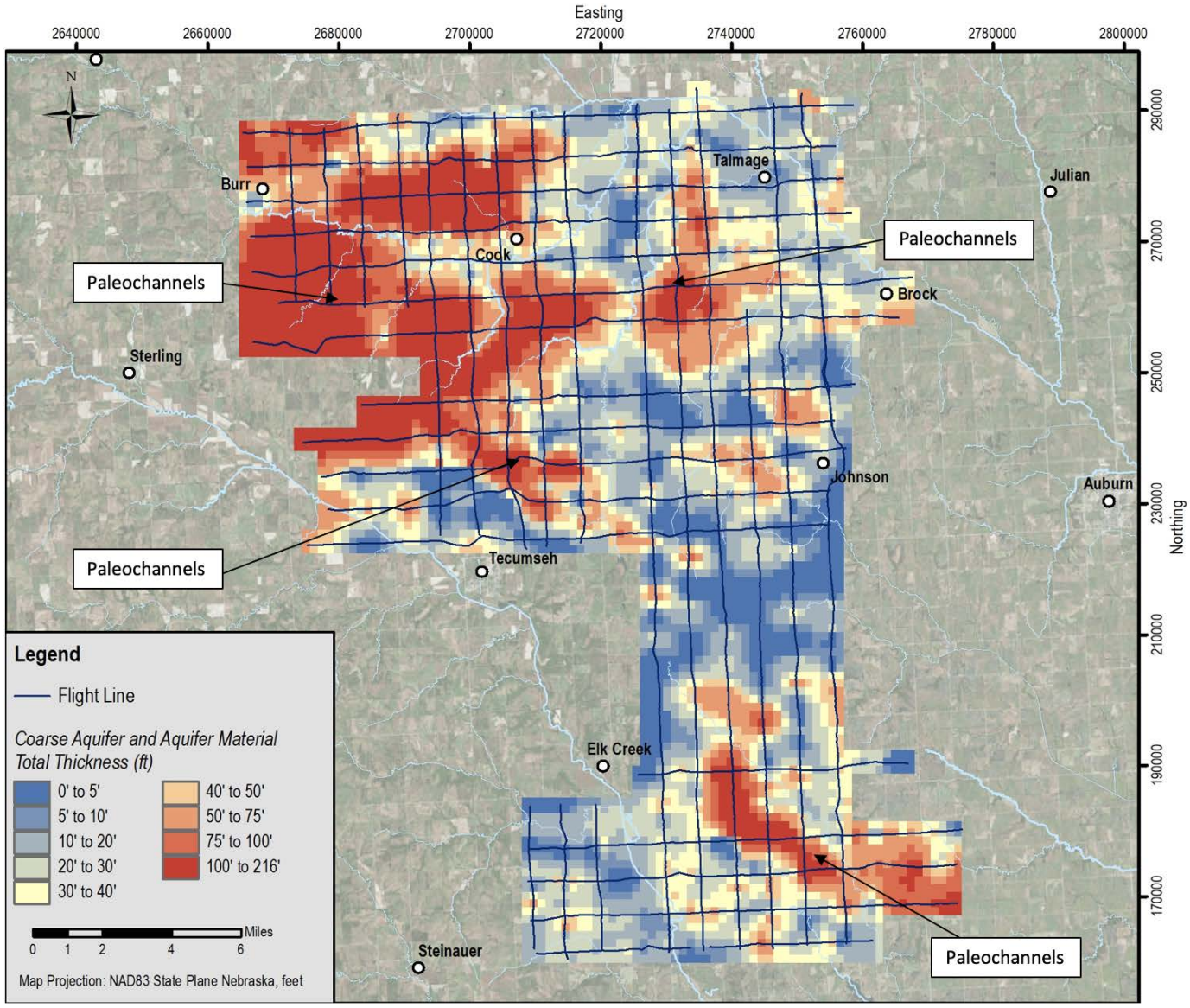


Figure 3-41. Map of the total thickness of Aquifer Material and Coarse Aquifer material within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

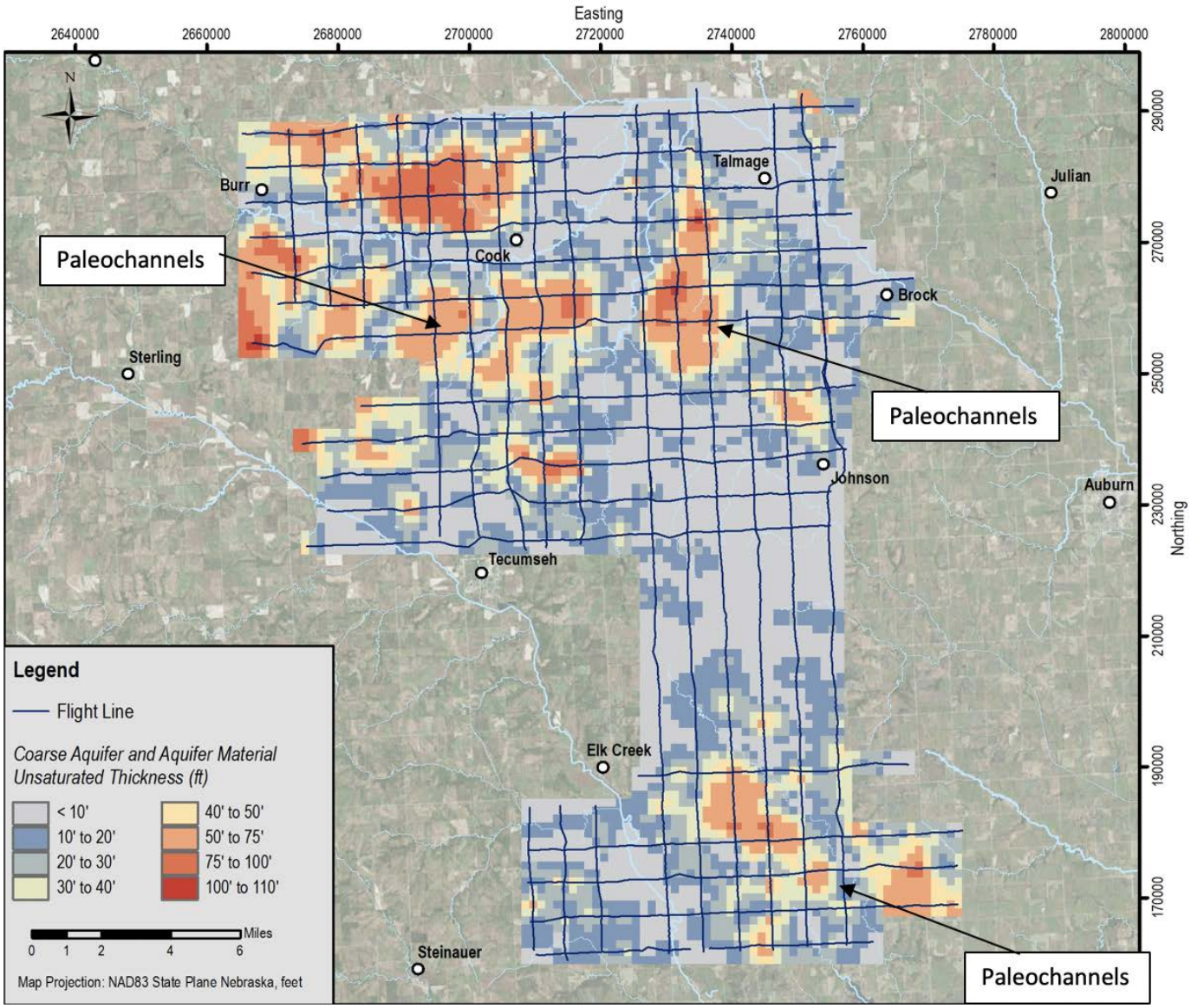


Figure 3-42. Map of the unsaturated thickness of Aquifer Material and Coarse Aquifer material within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

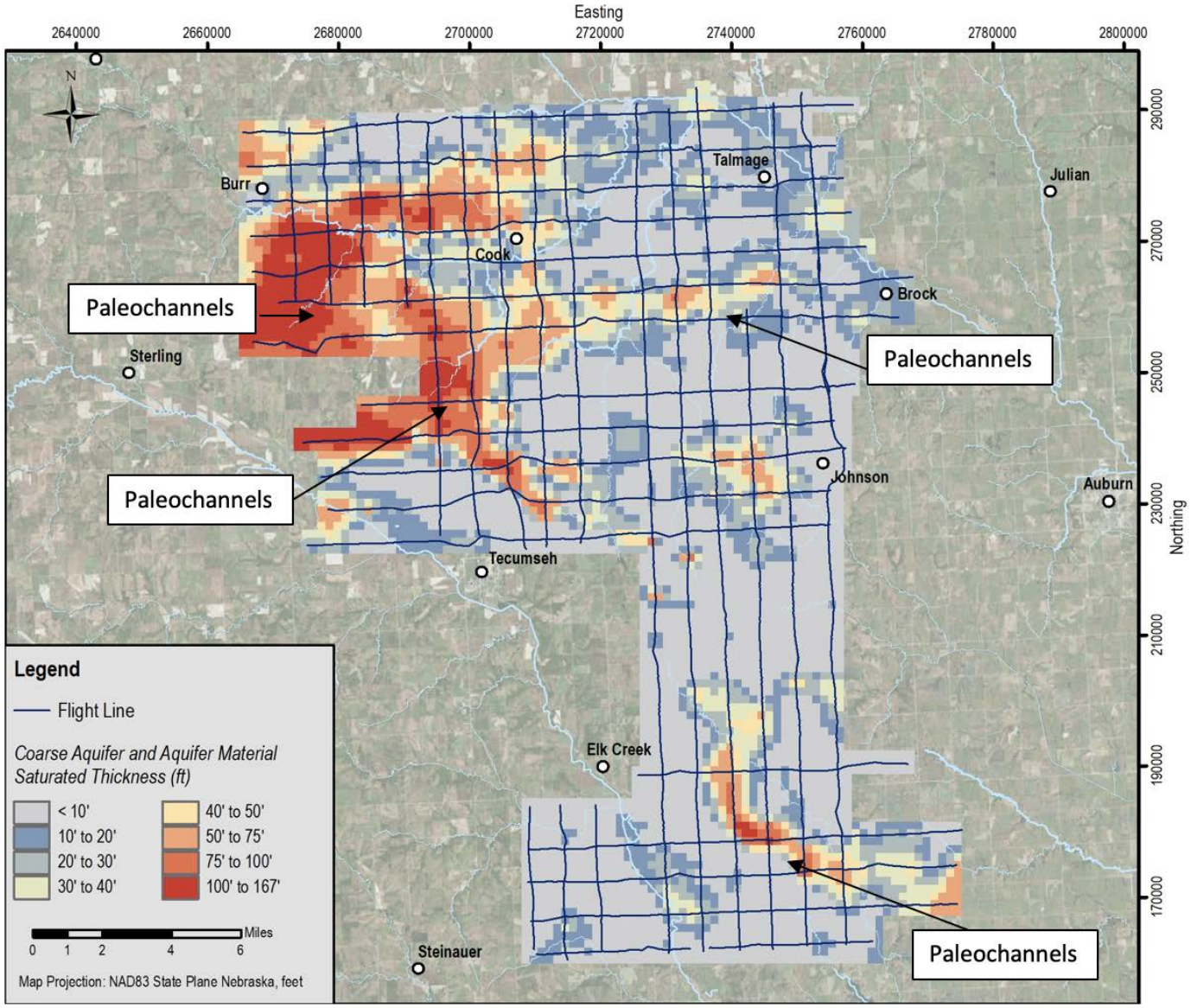


Figure 3-43. Map of the saturated thickness of Aquifer Material and Coarse Aquifer material within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

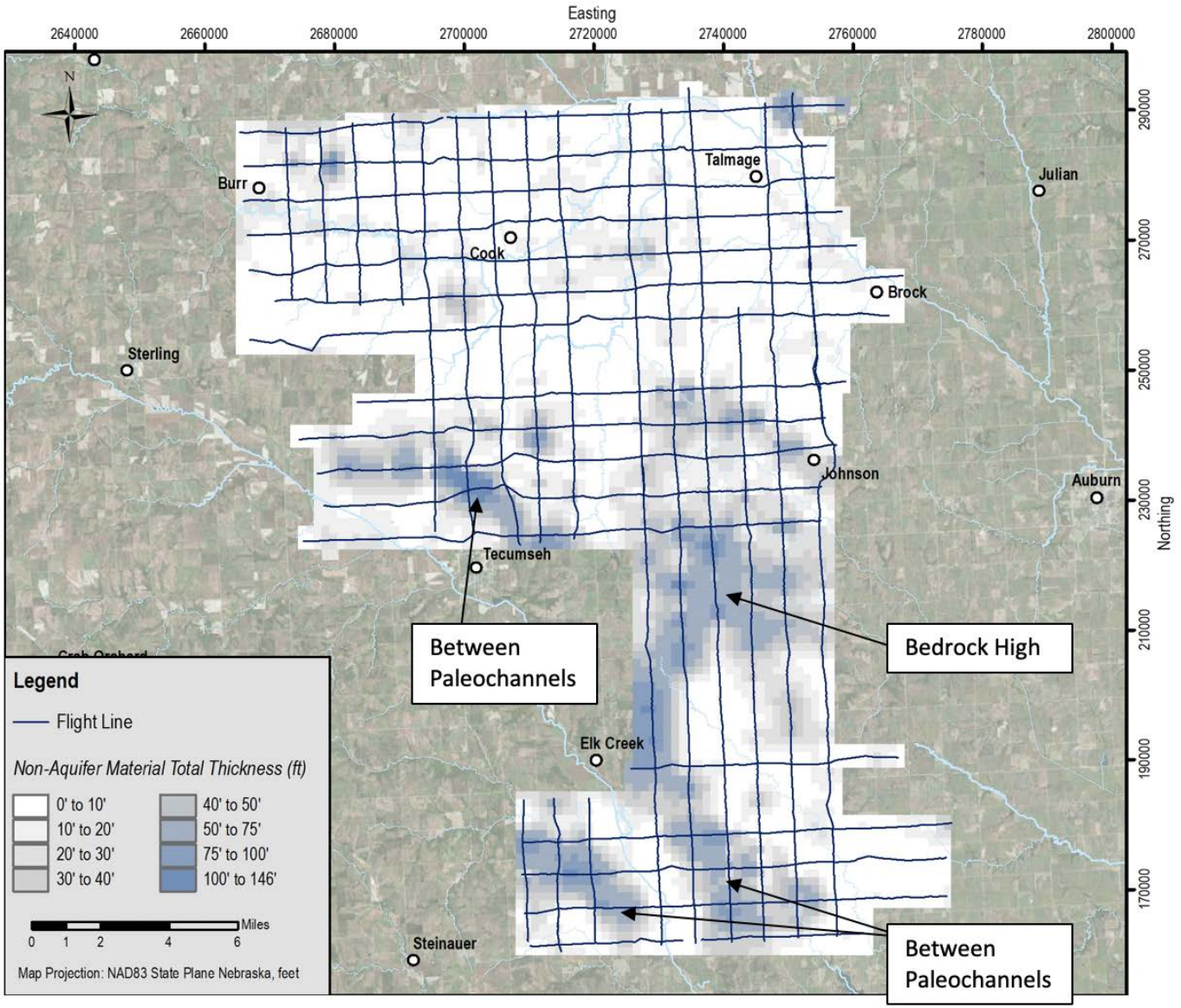


Figure 3-44. Map of the total thickness of Non-Aquifer material within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

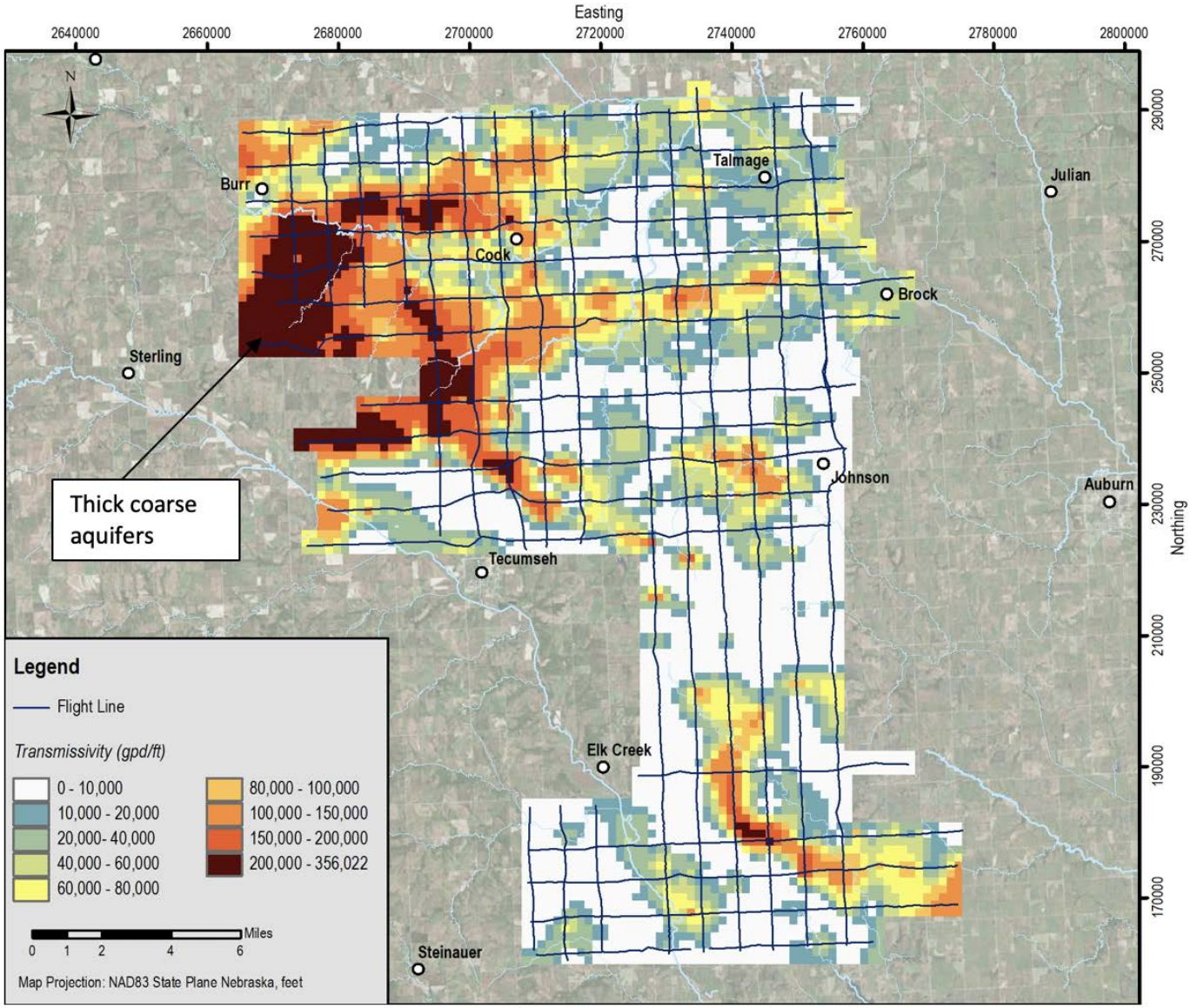


Figure 3-45. Map of the estimated transmissivity within the 2018 NNRD Reconnaissance survey area. Flight lines are indicated by the blue lines. The projection is NAD83 State Plane Nebraska (feet).

3.3.2 Hydrogeologic Framework of the Shubert Block Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material in the Shubert survey area. The term "unconsolidated" material refers to the Quaternary (***Q***) alluvial silt, sand, and gravel as well as loess and glacial till that overly the Pennsylvanian bedrock. The unconsolidated material in the Shubert Block survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material. The material classifications and associated colors correspond to the resistivity ranges described in Section 3.1.5, *Resistivity-Lithology Relationship*. Figure 3-46 displays a 3D fence diagram of the flight lines and the interpreted hydrostratigraphic profiles of the Shubert Block survey area looking to the northwest. Generally, the northern portion of the survey area, with the exception of the area just north of the town of Shubert, displays a consistent non-aquifer material layer separating layers of marginal aquifer material. There are no flight lines directly within the town of Shubert due to FAA restrictions. The boreholes in the area indicate silty clay and sandy clay in much of the area with only thick layers of sand and sand and gravel in the basal areas above the bedrock. In the southeastern portion the material is made up of nearly all marginal aquifer with the exception of isolated bodies of aquifer and non-aquifer materials at near surface elevations. There is a possible channel deposit at the very southwestern portion of the survey area, identified by a layer of aquifer material overlain by coarse aquifer material. A more detailed description of the hydrogeologic framework AEM interpretation is given in later sections.

As indicated above the total thickness of the unconsolidated material (Figure 3-47) was gridded by subtracting the bedrock elevation from the ground surface elevation. The bedrock underlying the unconsolidated material is generally highest in elevation in the northeast/east-central area and lowest in elevation in the southeastern corner of the survey area (Figure 3-48). The bedrock low in the southeastern corner underlies an area with a topographically higher elevation and, therefore, correlates to a high unconsolidated material thickness where it is almost 250 ft thick. The higher bedrock elevations, as observed in the northeast corner, do not necessarily have an immediate correlation to a lower unconsolidated material thickness, but rather the topography, where recent streams have incised the Quaternary deposits, does have an observable influence on the overall thicknesses as observed along Sardine Creek in the south-central portion of the survey area.

The 1995 CSD water table surface elevation was converted to a gridded dataset (Figure 3-49) and incorporated into the interpreted AEM hydrostratigraphic profiles. Generally, the water table surface conforms to the topography of the Shubert Block survey area where the elevation is shallow within the drainage valleys. The presence of drainage valleys in the survey area is due to the area being geographically located between the Missouri River to the east and Muddy Creek to the west with Sardine Creek, a tributary to Muddy Creek, flowing from approximately the center of the survey area to the south. The depth to water table ranges from 0 ft, along the Sardine Creek drainage area, to approximately 150 ft below ground surface along the north, east, and west-central portions of the survey area. The water table surface is found within non-aquifer materials predominantly in the northern portion of the survey area, indicating confined or semi-confined aquifer conditions.

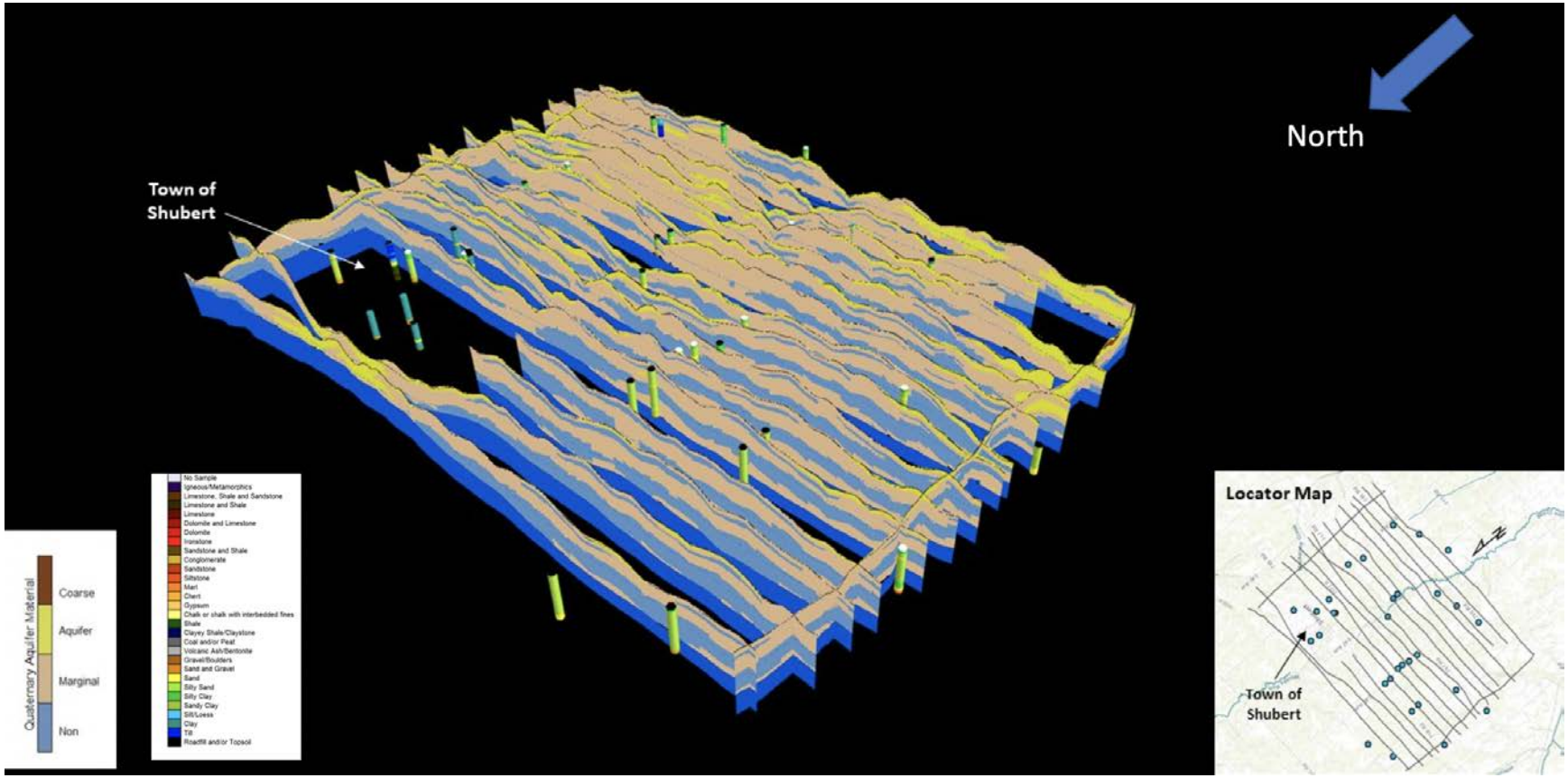


Figure 3-46. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Shubert Block survey area. NE-DNR and CSD boreholes are colored by lithology. Vertical exaggeration 7x.

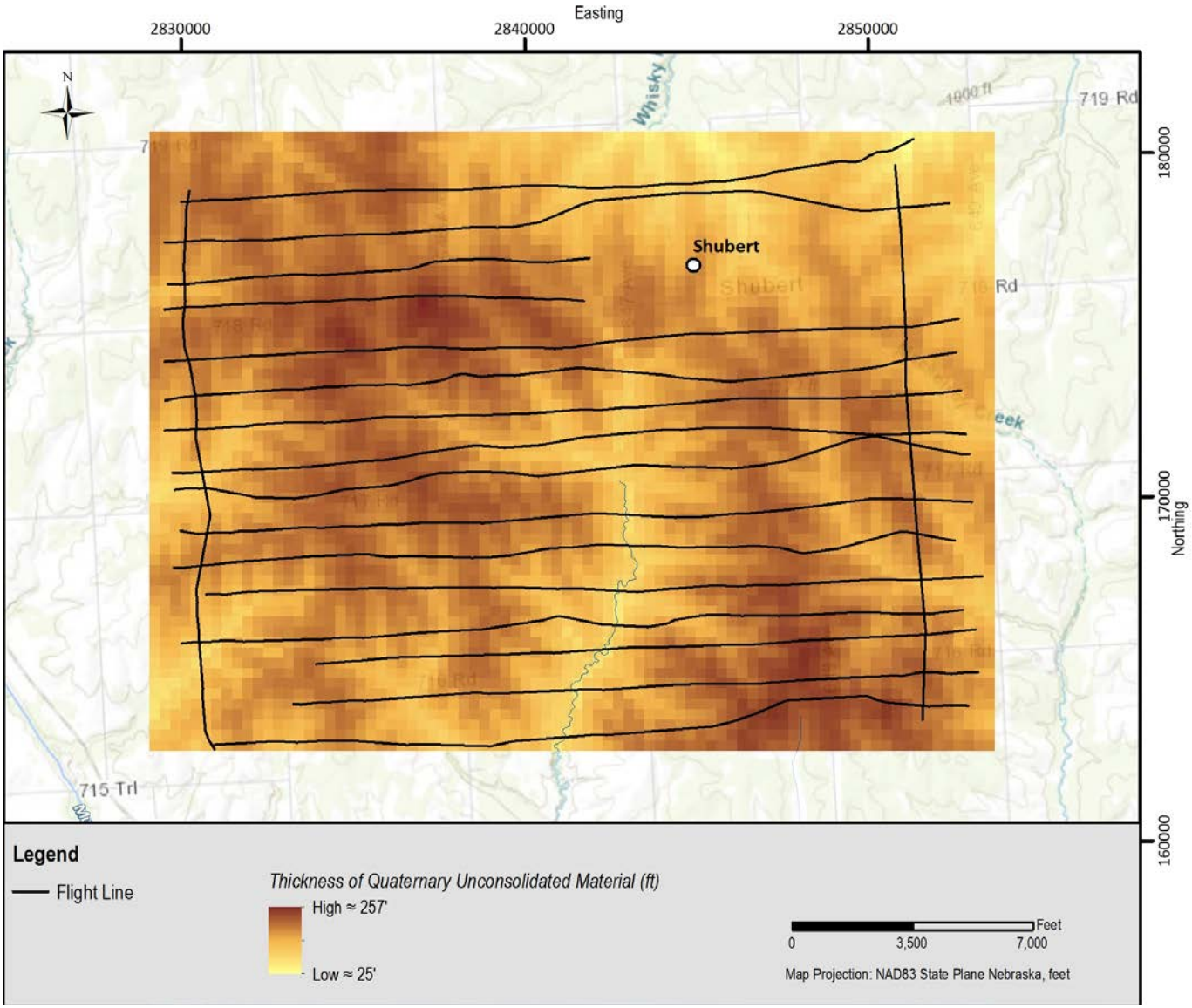


Figure 3-47. Map of the total thickness of Quaternary deposits within the 2018 Shubert Block. Flight lines are indicated by black lines. The projection is NAD83 State Plane Nebraska (feet).

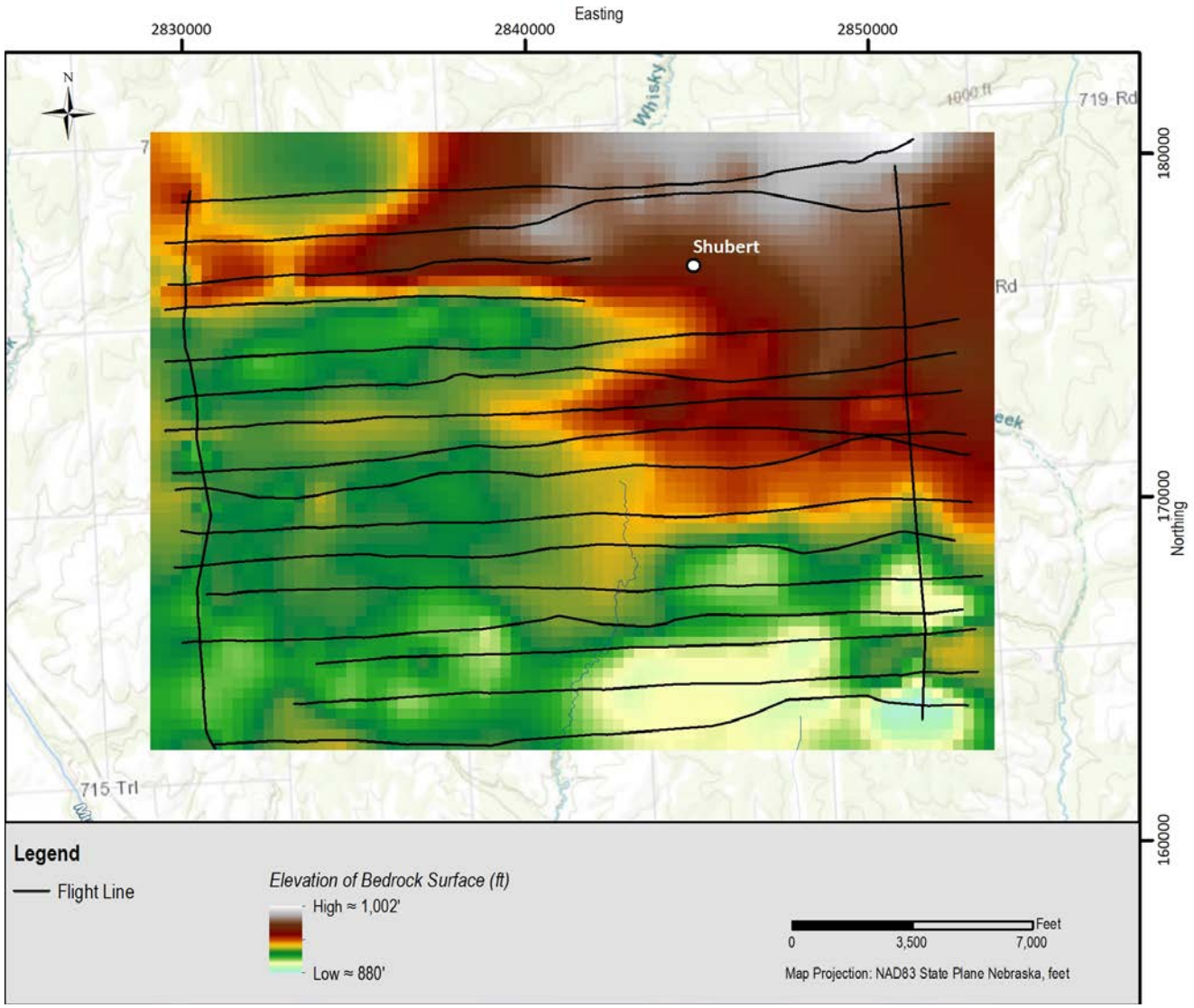


Figure 3-48. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the NNRD Shubert Block from the 2018 AEM survey. 2018 flight lines are indicated by the black lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

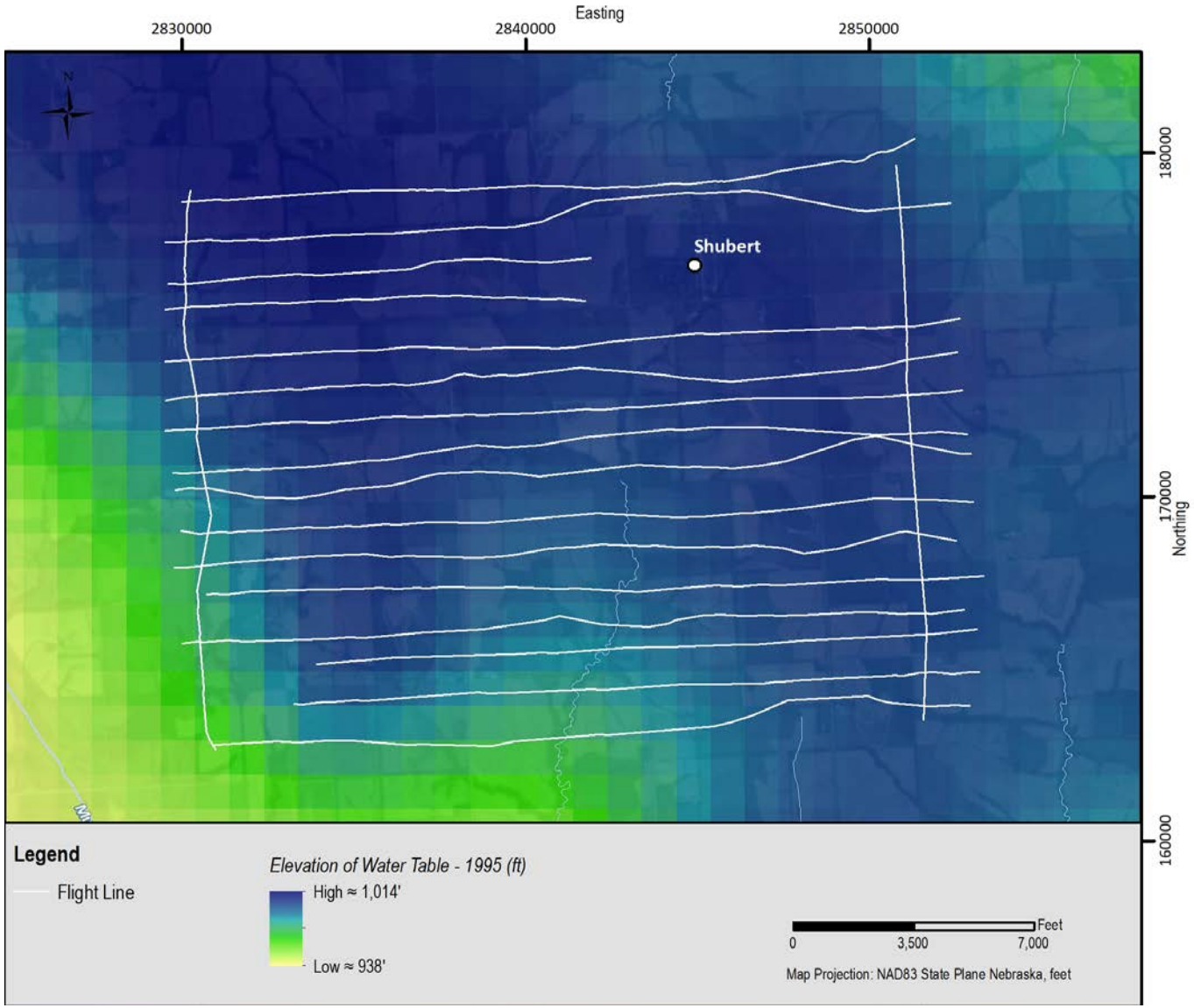


Figure 3-49. Map of the 1995 CSD water table elevation within the 2018 NNRD Shubert Block. White lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

The bedrock elevation was subtracted from the gridded 1995 CSD water table surface elevation to obtain a total saturated thickness of unconsolidated material (Figure 3-50). Areas where there are low total saturated thickness values generally correlate to locations of bedrock highs where the water level gets to within at least 30 feet of the bedrock surface. And, bedrock low elevations are associated with high saturated thickness where the water level elevation may be over 100 feet above the bedrock surface as seen in the southeast corner of the survey area.

3.3.2.1 Extent of Water-Bearing Unconsolidated Materials (Marginal Aquifer, Aquifer Material, and Coarse Aquifer Material)

The aquifer materials in the Shubert Block survey area are identified as marginal aquifer, aquifer material, and coarse aquifer materials. The total thickness of these materials range from less than 10' in the northeast corner, to over 200' in areas between drainage valleys where the topographic elevation is highest (Figure 3-51) The saturated materials, or those materials below the water table, are predominantly made up of marginal aquifer materials, consisting of silt, loess, till, clay, and/or sandy clay, with lesser amounts of aquifer and coarse aquifer material. The cumulative thickness of each of these materials was extracted from below the water table to calculate the total saturated thickness (Figure 3-52). The areas of extensive saturated thickness generally correspond to bedrock lows where there is little to no non-aquifer material below the water table. This scenario is most apparent in the southeastern portion of the survey area at the most eastern extent of flight line 102101 (Figure 3-53). Where there are areas of bedrock highs and/or areas where there is a relatively thick layer of non-aquifer material below the water table, the saturated thickness is lowest. This scenario is apparent in the north-central portion of the Shubert Block survey area along flight line 100601 (Figure 3-54). Areas of moderate thickness of saturated materials (approximately 50 ft to 75 ft thick) can be seen along flight line 101501 where marginal aquifer material makes up the predominant material type and only a small basal layer of non-aquifer material overlies the bedrock (Figure 3-55).

Coarse aquifer and aquifer materials, materials usually associated with the principal aquifer in northeastern Nebraska (Carney et al., 2015b), are not extensive within the survey area, especially in the saturated zone. Figure 3-56 displays this scenario clearly where only small, isolated bodies of coarse aquifer and aquifer saturated materials exist. The thickest saturated material is located adjacent to and just east of Sardine Creek in the south-central region of the survey area. The profile for flight line 101701 (Figure 3-57), running west to east across Sardine Creek, shows a small lens of aquifer material overlain by marginal aquifer material within the saturated zone. This isolated body is over 60 ft thick, however, the majority of the rest of the isolated saturated bodies are less than 40 ft thick.

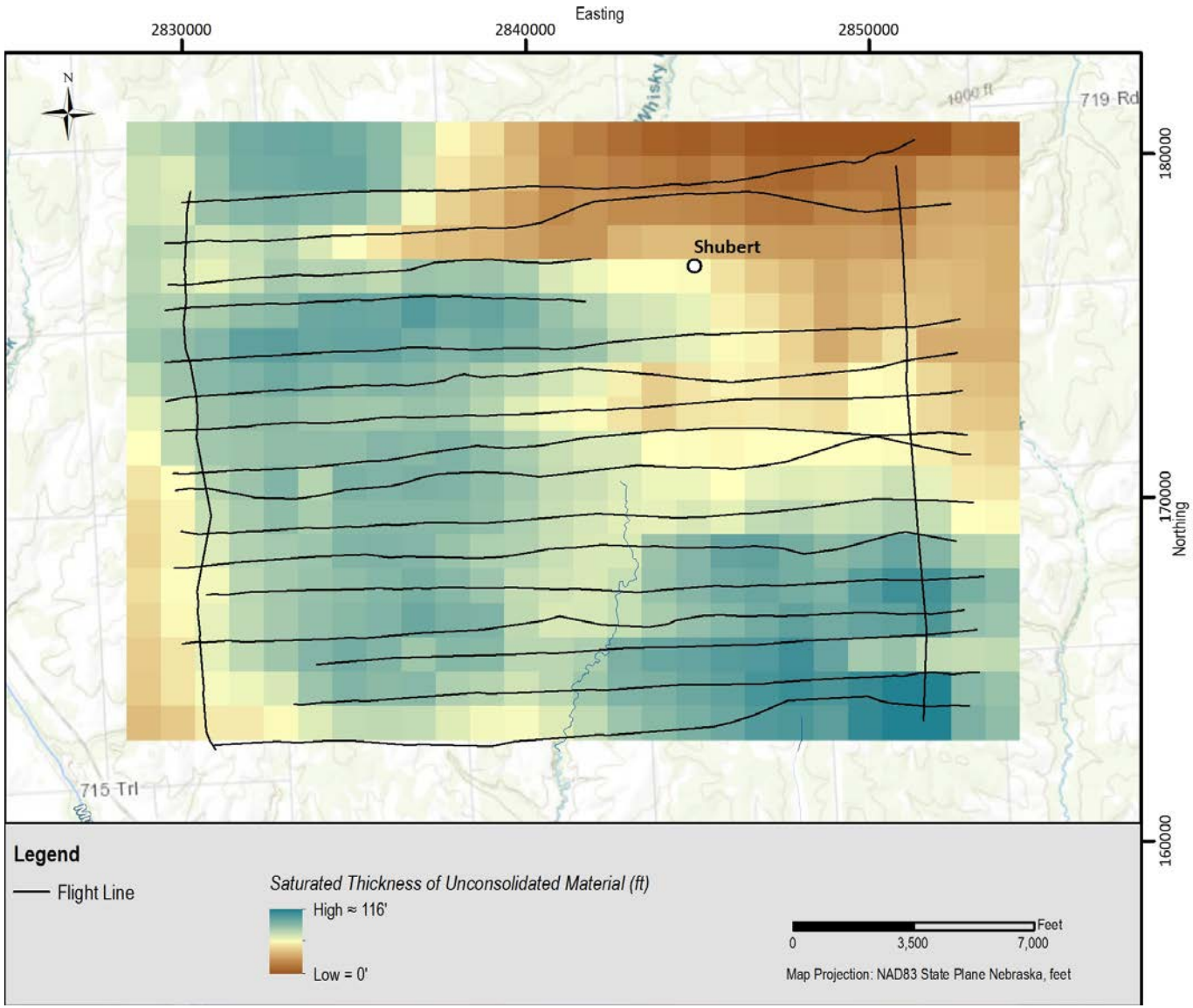


Figure 3-50. Map of the saturated thickness of Quaternary deposits within the 2018 Shubert Block survey area. Flight lines are indicated by black lines. The projection is NAD83 State Plane Nebraska (feet).

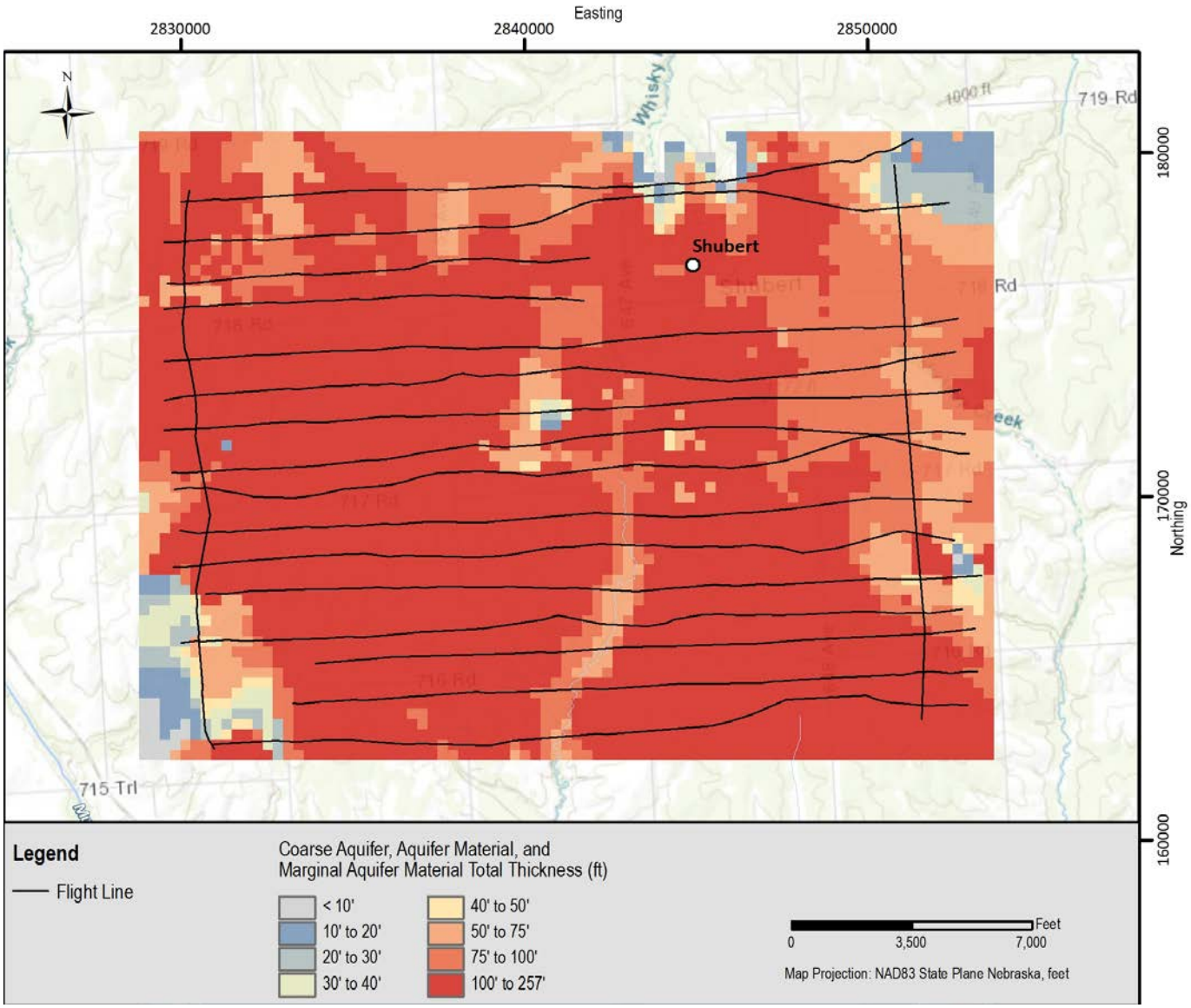


Figure 3-51. Map of the total thickness of Marginal Aquifer, Aquifer Material, and Coarse Aquifer materials within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

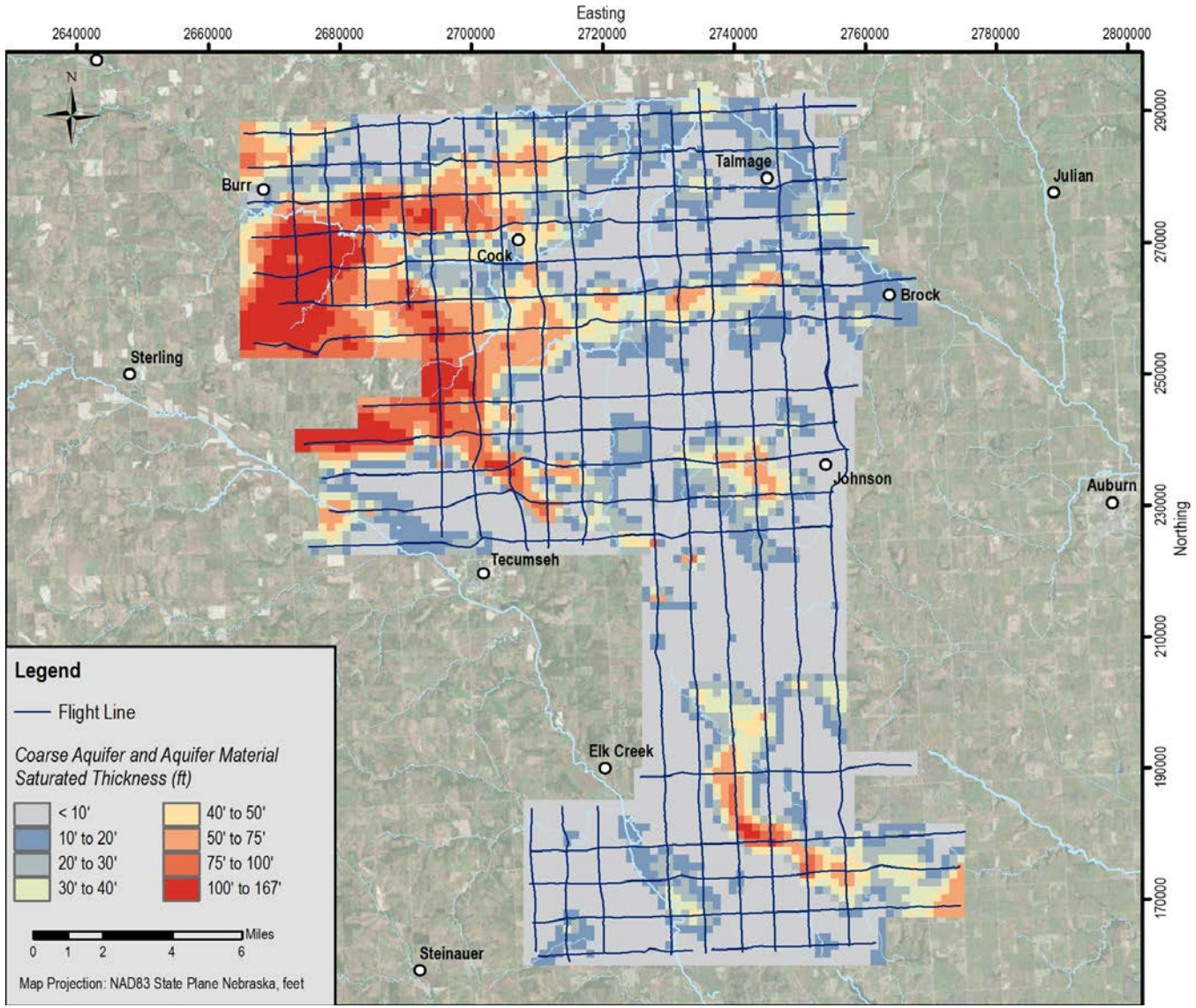


Figure 3-52. Map of the saturated thickness of Marginal Aquifer, Aquifer Material, and Coarse Aquifer materials within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

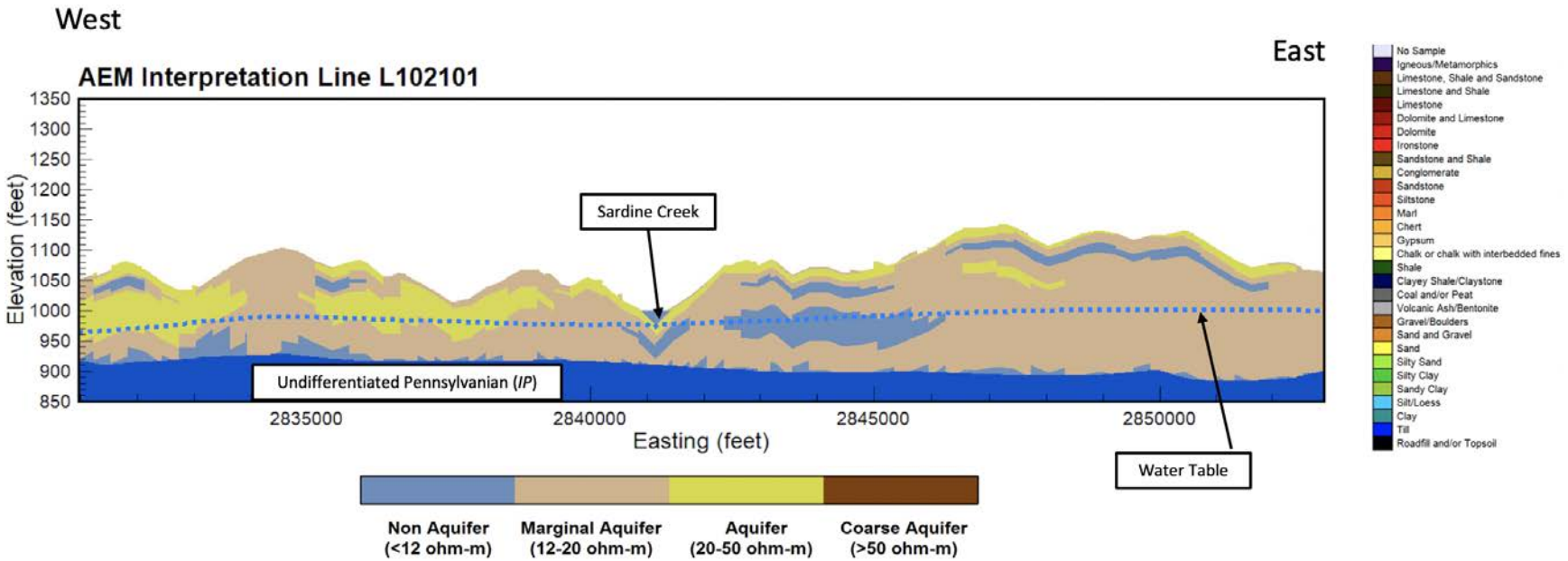


Figure 3-53. Interpreted AEM Profile for east-west line L102101 within the Shubert Block. Blue area indicates undifferentiated Pennsylvanian. 1995 CSD water table is indicated by the dashed blue line.

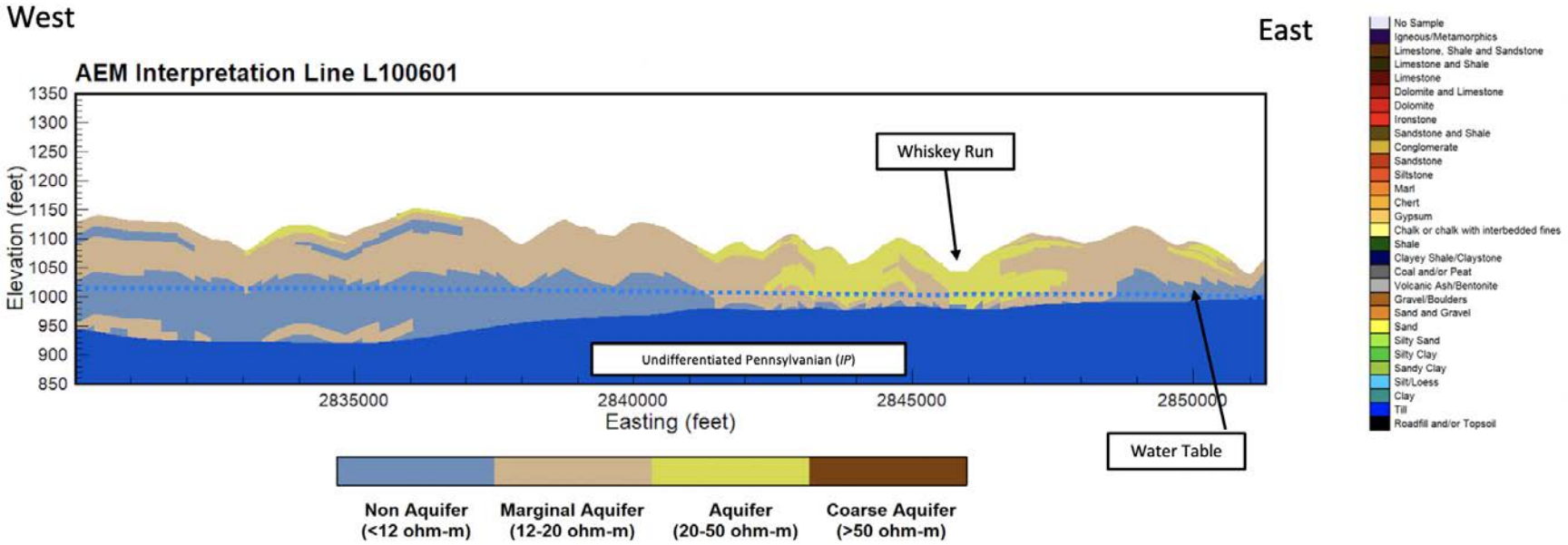


Figure 3-54. Interpreted AEM Profile for east-west line L100601 within the Shubert Block. Blue area indicates undifferentiated Pennsylvanian. 1995 CSD water table is indicated by the dashed blue line.

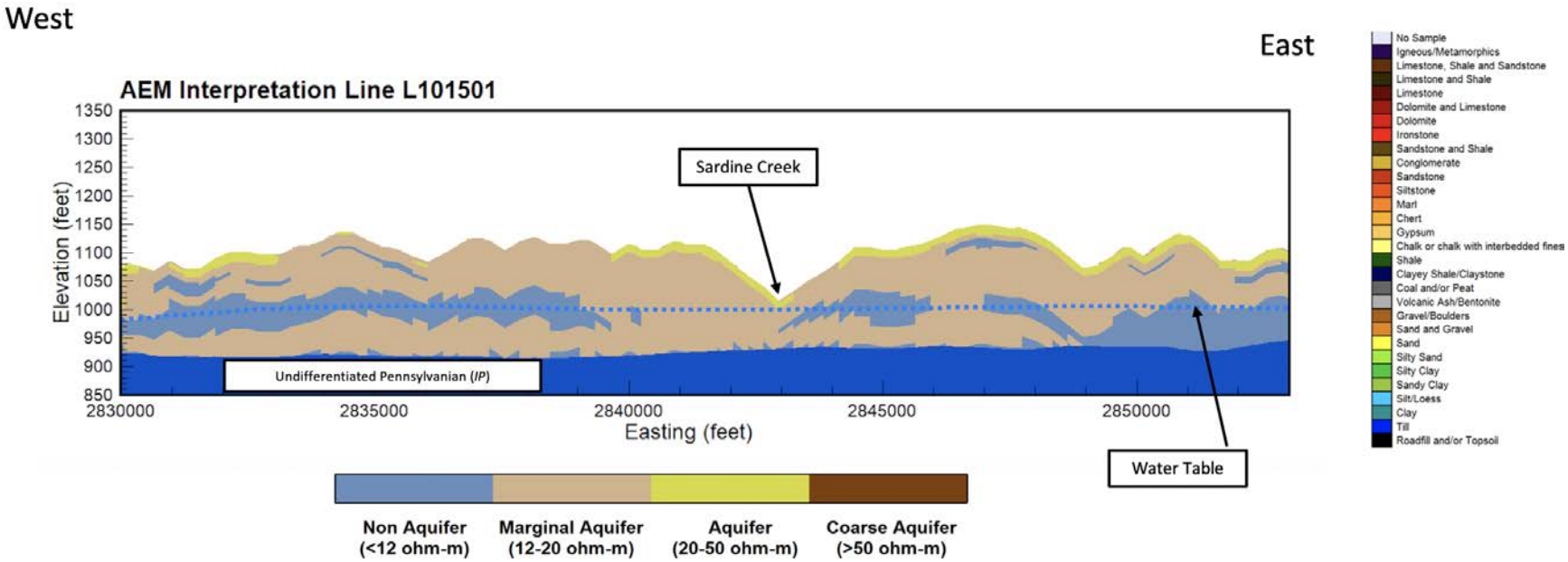


Figure 3-55. Interpreted AEM Profile for east-west line L101501 within the Shubert Block. Blue area indicates undifferentiated Pennsylvanian. 1995 CSD water table is indicated by the dashed blue line.

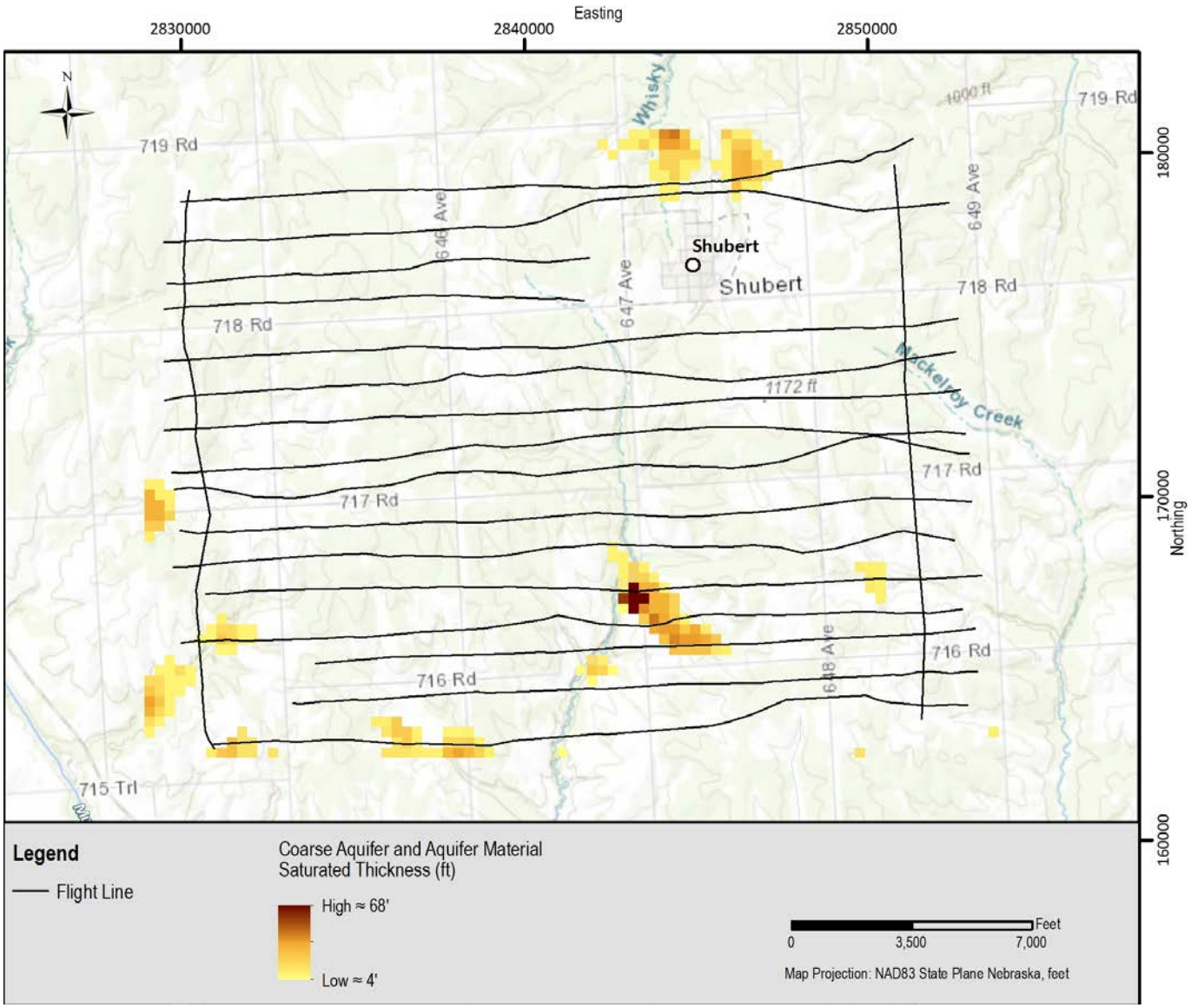


Figure 3-56. Map of the saturated thickness of Aquifer Material, and Coarse Aquifer materials within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

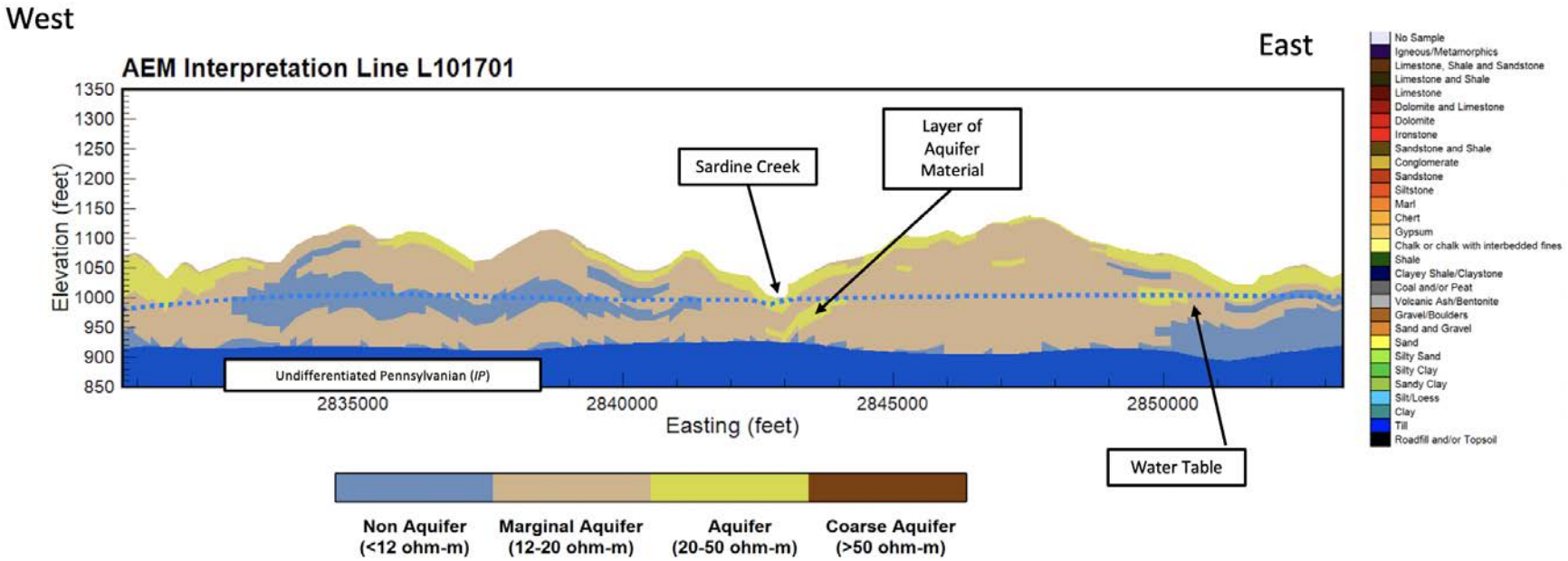


Figure 3-57. Interpreted AEM Profile for east-west line L101701 within the Shubert Block. Blue area indicates undifferentiated Pennsylvanian. 1995 CSD water table is indicated by the dashed blue line.

3.3.2.2 *Extent of Unsaturated Unconsolidated Materials (Marginal Aquifer, Aquifer Material, and Coarse Aquifer Material)*

The unsaturated extent of marginal aquifer, aquifer material, and coarse aquifer materials is notable because the thickness often exceeds the saturated thickness within the Shubert Block survey area with the thickest areas outside of the current drainage valleys (Figure 3-58). However, the unsaturated marginal, aquifer, and coarse materials are often found at ground surface specifically just north of the town of Shubert, and within the drainage valley of Sardine Creek. These areas of unsaturated zones may have potential for managed aquifer recharge. However, other key factors, including soil type, slope, vegetation, and land use practices may influence recharge management.

3.3.2.3 *Extent of Non-Aquifer Material*

Non-aquifer material is made up of low-permeable clay and silt and is persistent throughout much of the Shubert Block survey area. This material may act as a confining layer to lower aquifer material as well as cause water to accumulate above due to its lower permeability, ultimately creating perched water with potential benefit to low-capacity water needs. The extent and thickness of non-aquifer material can be seen in Figure 3-59. The most extensive bodies of non-aquifer material exist in the northwest and east-central portions of the survey area where, in some cases, it makes up over half of all unconsolidated material. These areas may experience slower recharge rates due to lower overall permeability. The area where non-aquifer material is thinnest is to the south where in some areas only a basal layer overlaying the bedrock is interpreted.

3.3.2.4 *Wide Range of Well Capacity*

It has been observed that specific capacity of wells within the Shubert Block survey area, defined as pumping rate (Q) divided by water level drawdown (s), varies considerably over small distances. Considering that errors and inconsistency in how pumping rates and/or drawdown may originally be recorded, Figure 3-60 shows a comparison of saturated material (coarse aquifer, aquifer, and marginal aquifer materials only) to wells with available specific capacity data. Overall, there is a general correlation between higher specific capacity values, in this case > 3.0 gpm/ft, and larger saturated thickness. Of course, exceptions exist as seen at wells *G-095440* and *G-167161* where specific capacity values are 2.3 gpm/ft and 2.1 gpm/ft, respectively, but saturated thickness at those locations is over 100 ft. Some of the variability in specific capacity values could partly be explained by the variability in unconsolidated materials in which the wells are screened into as well as overlain by. Figure 3-61 displays a 3D fence diagram of the AEM interpreted hydrostratigraphic profiles within a portion of the Shubert Block survey area. Included in the figure is a cross-section developed by LBG (2015) that extends from well *G-139660* in the southern portion of the survey area north to wells *G-118974* and *G-112180*. The area depicted as sand and gravel on the LBG cross-section (very light yellow) is the interval that the wells are screened within. In this same interval the AEM data show that the majority of the material is considered marginal aquifer (tan) predominantly overlain by a relatively thick, continuous layer of non-aquifer material (light blue).

The non-aquifer material layer bisects thick layers of marginal aquifer material from the most northern wells on the cross-section line shown in Figure 3-61 (*G-118974* and *G-112180*) to just north of well *G-*

177145. South of well *G-177145* the non-aquifer material has thinned to a layer predominantly in the unsaturated zone. Further south to well *G-139660*, the non-aquifer material is almost non-existent. The thick non-aquifer, low-permeable layer as well as the composition of the materials in which the wells are screened (marginal aquifer) could explain the poor recovery responses described in the LBG report (LBG, 2015) in the wells depicted on Figure 3-61**.**

There is also a noticeable difference between the saturated material type in the north-northwest and the southeast of the survey area. Figure 3-46 displays this comparison well. The north-northwest region of the survey area is predominantly comprised of a relatively continuous non-aquifer layer in the saturated zone. Moving south-southeast, that continuous layer appears to bisect a thick layer of marginal aquifer material as it generally increases in elevation into the unsaturated zone until it is very thin to non-existent in the southeast corner. This variability is related to the complex Quaternary deposits of buried pre-glacial alluvium underlying areas of glacial till, however, a trend of upward elevation and thinning of finer materials to the southeast is evident.

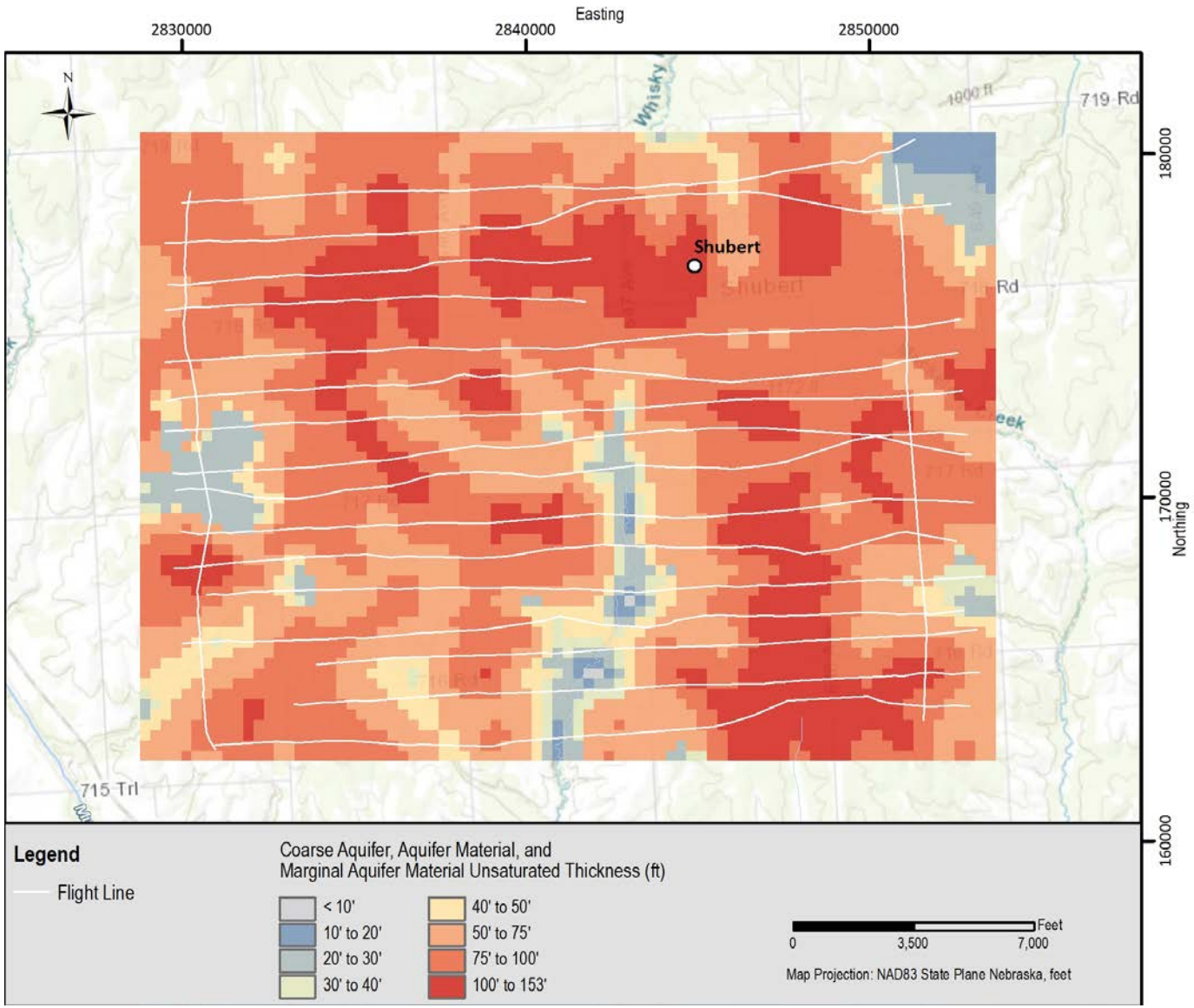


Figure 3-58. Map of the unsaturated thickness of Marginal Aquifer, Aquifer Material, and Coarse Aquifer materials within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

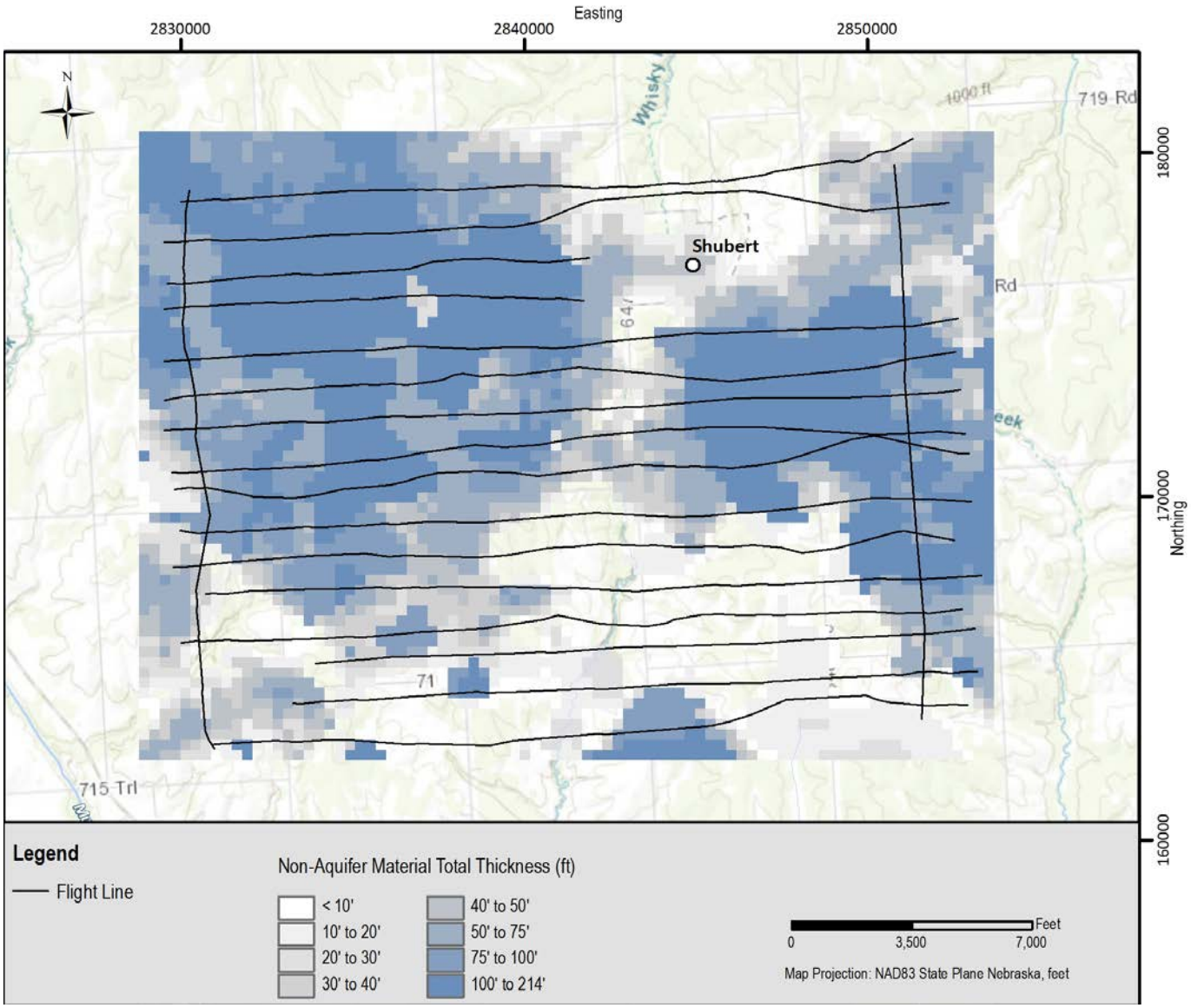


Figure 3-59. Map of the Non-Aquifer materials within the 2018 Shubert Block survey area. Black lines indicated flight lines. The projection is NAD83 State Plane Nebraska (feet).

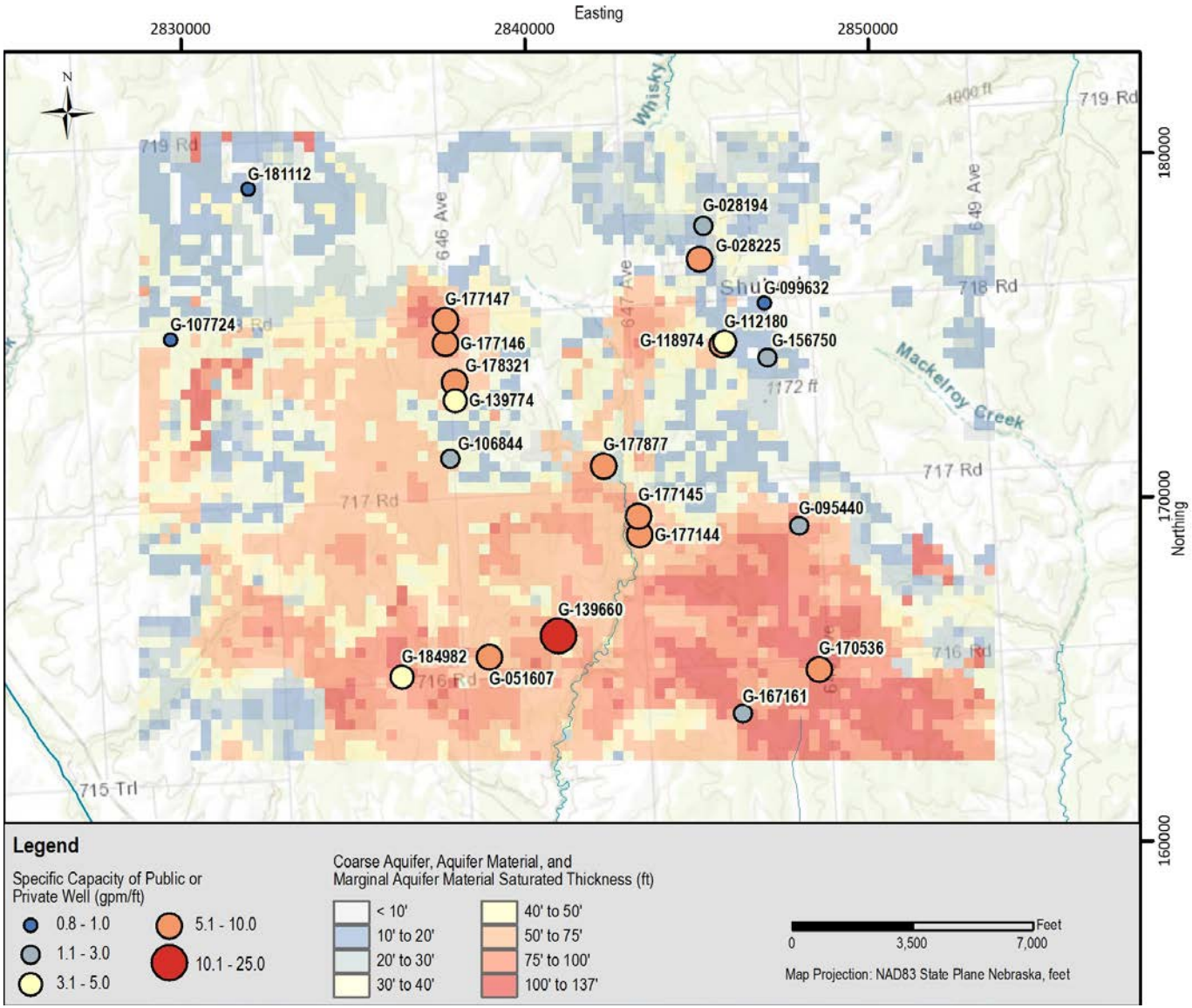


Figure 3-60. Map of the specific capacity of public or private wells compared to the saturated thickness of Coarse Aquifer, Aquifer Material, and Marginal Aquifer materials within the 2018 Shubert Block survey area. The projection is NAD83 State Plane Nebraska (feet).

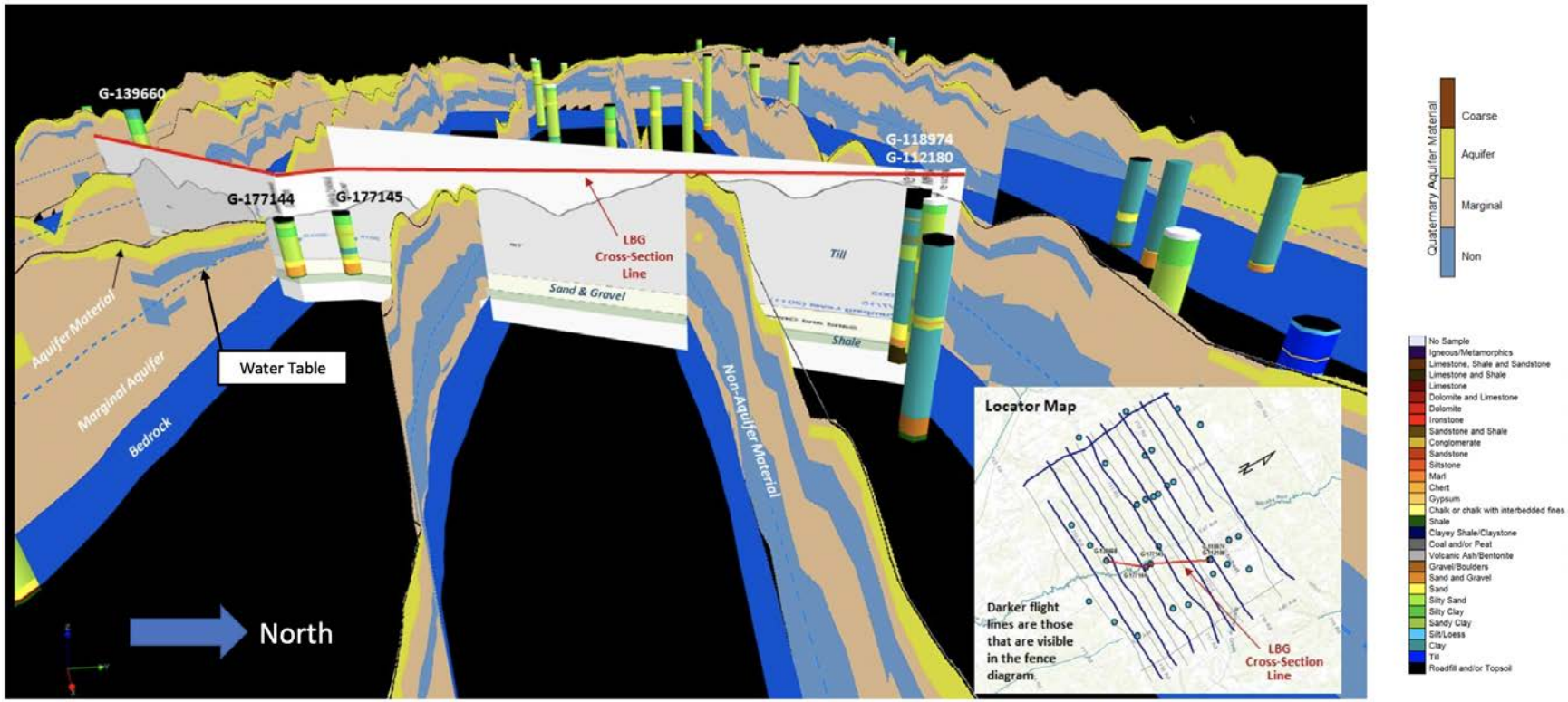


Figure 3-61. 3D fence diagram of interpreted AEM hydrostratigraphic profiles including a cross-section developed by LBG (2015) within a portion of the 2018 Shubert Block survey area. CSD and NE-DNR boreholes are colored by lithology. 1995 CSD water table is indicated by dashed blue line. Blue areas at on the profiles are the undifferentiated Pennsylvanian. Vertical exaggeration is 7x.

3.3.2.5 *Shubert Block Estimates of Aquifer Volumes and Yield*

All aquifer materials within the ***Q*** 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.

Table 3-2 has the calculations for groundwater in storage for the ***Q*** materials when fully saturated for the Shubert Block. Table 3-3 has the calculations for groundwater in storage for the ***Q*** materials when using the 1995 CSD Water Table for the Shubert Block.

Table 3-2. Fully saturated Quaternary aquifer materials underlying the Shubert 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	21,987,278,946	504,760	0.4	201,904	0.02	4,038
Marginal	45,901,187,303	1,053,749	0.35	368,812	0.05	18,441
Aquifer	6,252,544,377	143,539	0.2	28,708	0.22	6,316
Coarse Aquifer	107,972,789	2,479	0.25	620	0.19	118
TOTAL	74,248,983,414	1,704,526		600,044		28,912

Table 3-3. 1995 CSD water table saturated Quaternary aquifer materials underlying the Shubert 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	14,762,147,945	338,893	0.4	135,557	0.02	2,711
Marginal	17,252,029,481	396,053	0.35	138,619	0.05	6,931
Aquifer	311,663,921	7,155	0.2	1,431	0.22	315
Coarse Aquifer	2,140,853	49	0.25	12	0.19	2
TOTAL	32,327,982,198	742,150		275,619		9,959

3.4 Recharge Areas in the NNRD AEM Survey Area

3D representations of the subsurface resulting from AEM investigations illustrate areas of aquifer materials from the bedrock up to the land surface. A new 40-layer model (previous work used a 30-layer model) was developed for the layer inversions and interpretations for the NNRD. From these interpretations a new series of near-surface maps were constructed that include the intervals from 0 to 3.28 ft (1 m), 3.28 ft to 6.89 ft (1 m to 2.1 m), and 6.89 to 10.83 ft (2.1 m to 3.3 m), these intervals cover the first model layer from the original 30 model layer which went from 0 to 10 feet (about 3 m). The three intervals listed are noteworthy because they cover the 3 layers from the land surface downward of the inverted AEM earth model. Remember from the discussion around Table 2-3, that each model layer represents an average of the earth's resistivities within those depths, based on the physics of the electromagnetic exploration technique. The first layer through the third layer maps show all aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material and indicate the areas at the land surface that can potentially transmit water to the groundwater aquifers in the area. The coarse aquifer material can transmit the largest volume of water and the non-aquifer material being the least able to transmit water. By viewing layers 1 through 3 an understanding of the heterogeneity of the aquifer materials and their distribution can be achieved. There is not always a direct path downwards to the aquifer from the land surface. Often there is no path available for the water to move through.

The results of the interpretation of the aquifer materials of the NNRD AEM survey area are explained in detail in Section 3.3.1 and Section 3.3.2. The interpreted aquifer materials for the first three model layers are presented in a series of figures of the NNRD Reconnaissance survey area and the Shubert Block area as a color from the ***Q*** material legend (Figure 3-16). Areas of coarse aquifer material (brown colored material) will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material (yellow colored material) potentially transmitting slightly less precipitation downward as both units are permeable and transmissive. The marginal aquifer material (tan colored material) has a low potential to transmit some water downward and the non-aquifer material (blue colored material) will transmit minimal to no water to the groundwater aquifer.

However, since the amount of slope of the land surface plays a large role in the amount of residence time that water will spend in an area, the greater the length of time spent at a location, the greater the amount of infiltration potential. The greatest possibility for recharge in the NNRD AEM survey area is the alluvial valley floor and the creek beds that have aquifer and coarse aquifer materials are near the land surface. On the table lands, the best possible location for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands with little relief in elevation with a pathway of similar materials down to the saturated aquifer at depth. The profile in Figure 3-40 in Section 3.3.1 provides an example of this with the paleochannel on the south and also over Long Branch Creek near the south end of the profile L201701. Note the ***Q*** marginal and non-aquifer materials covering most of the bedrock high between Long Branch Creek and the Little Nemaha River showing an area of poor recharge.

Figure 3-62, Figure 3-63, and Figure 3-64 show 2D surface maps of the first, second, and third layers of the AEM model as a distribution of aquifer materials along the reconnaissance lines. There are contour lines in 20-foot intervals showing the thickness of the unsaturated unconsolidated materials in the NNRD Reconnaissance AEM survey area. It should be noted that the maps are interpolated across ~1-mile intervals between flight lines. Figure 3-65 is a map of the average material type Non-Aquifer, Marginal Aquifer, Aquifer, and Coarse Aquifer materials from 0 to 10.83 ft (3.3 m).

Figure 3-66, Figure 3-67, and Figure 3-68 show 2D surface maps of the first, second, and third layers of the AEM model as a distribution of aquifer materials for the Shubert Block area. Figure 3-69 is a map of the average material type Non-Aquifer, Marginal Aquifer, Aquifer, and Coarse Aquifer materials from 0 to 10.83 ft (3.3 m). These maps show a similar heterogeneity in material type and distribution as the Reconnaissance line coverages. However, there is little recharge into the Shubert Block due to there being a preponderance of non-aquifer and marginal aquifer materials between the land surface and the saturated aquifer and coarse aquifer materials near the base of the ***Q***. Figure 3-46 is a 3D fence diagram of the Shubert Block illustrating the lack of aquifer and coarse aquifer materials.

Separate Google Earth kmz's of the NNRD and Shubert Block recharge materials and locations are presented in Figure 3-70. A zoomed-in version of the Shubert Block is presented in Figure 3-71. These kmzs' are included in Appendix 3-Deliverables\KMZ\Recharge.

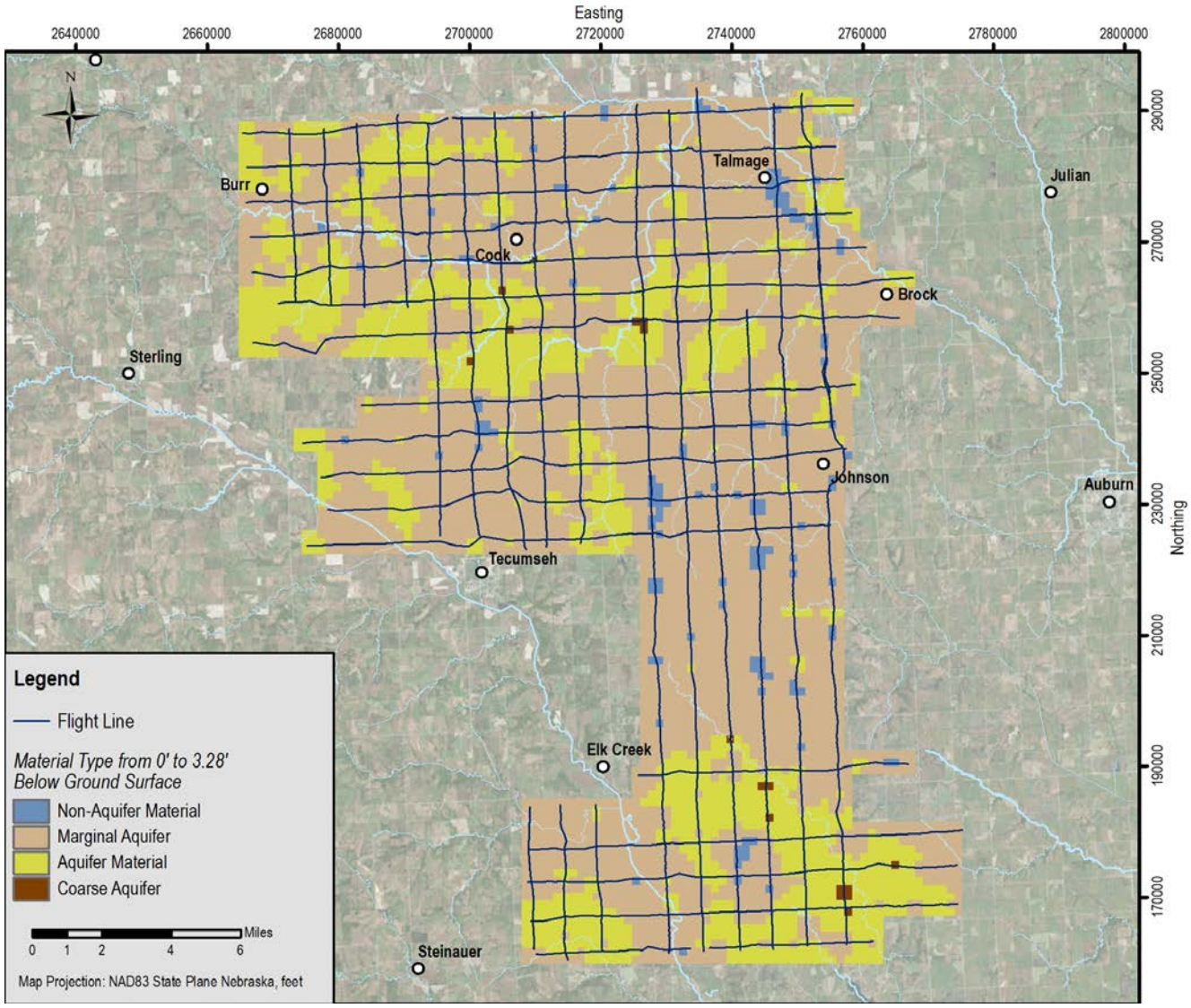


Figure 3-62. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 0' to 3.28' below ground surface within the 2018 NNRD Reconnaissance AEM survey area. Blue lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet).

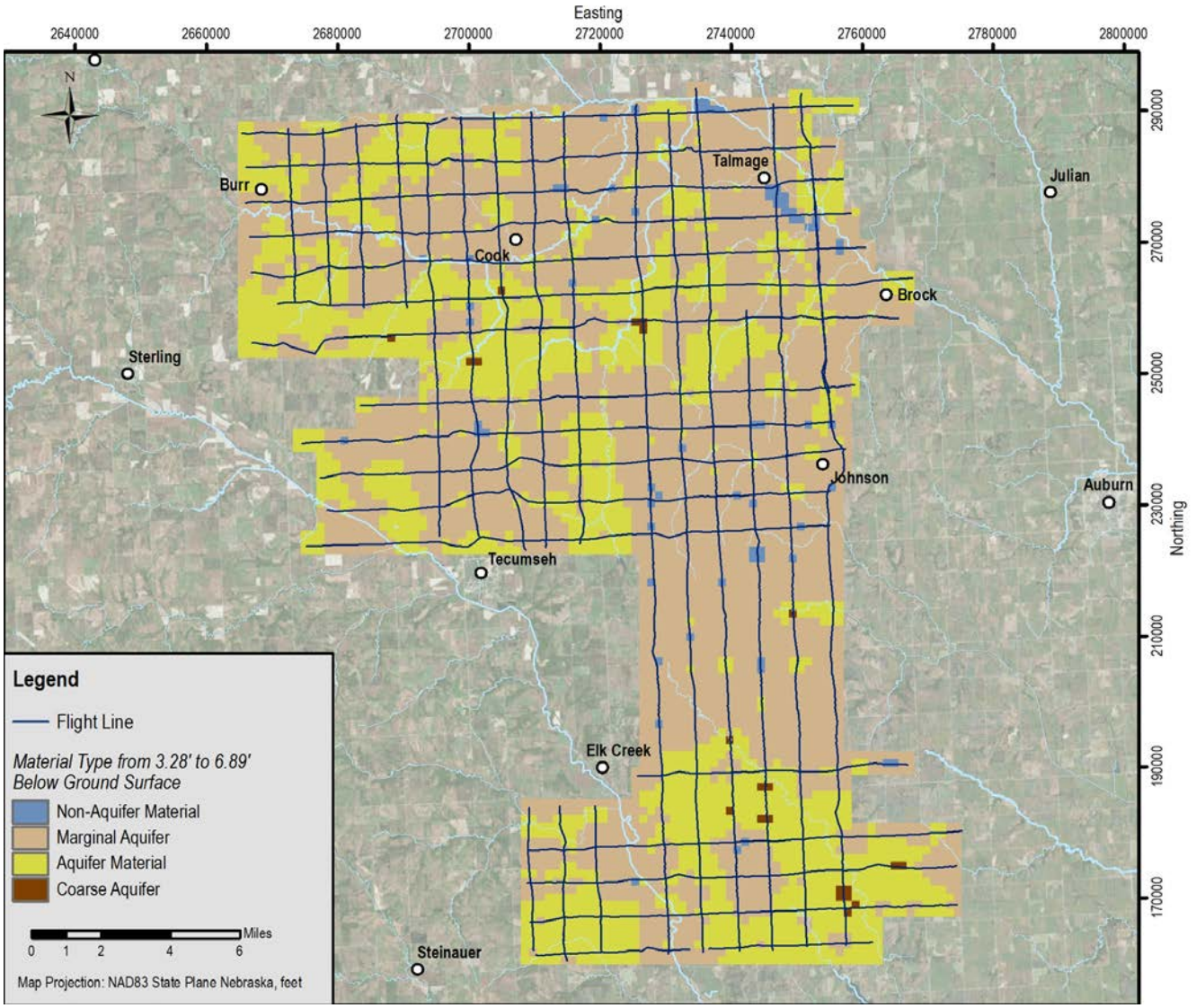


Figure 3-63. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 3.28' to 6.89' below ground surface within the 2018 NNRD Reconnaissance survey area. Blue lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet).

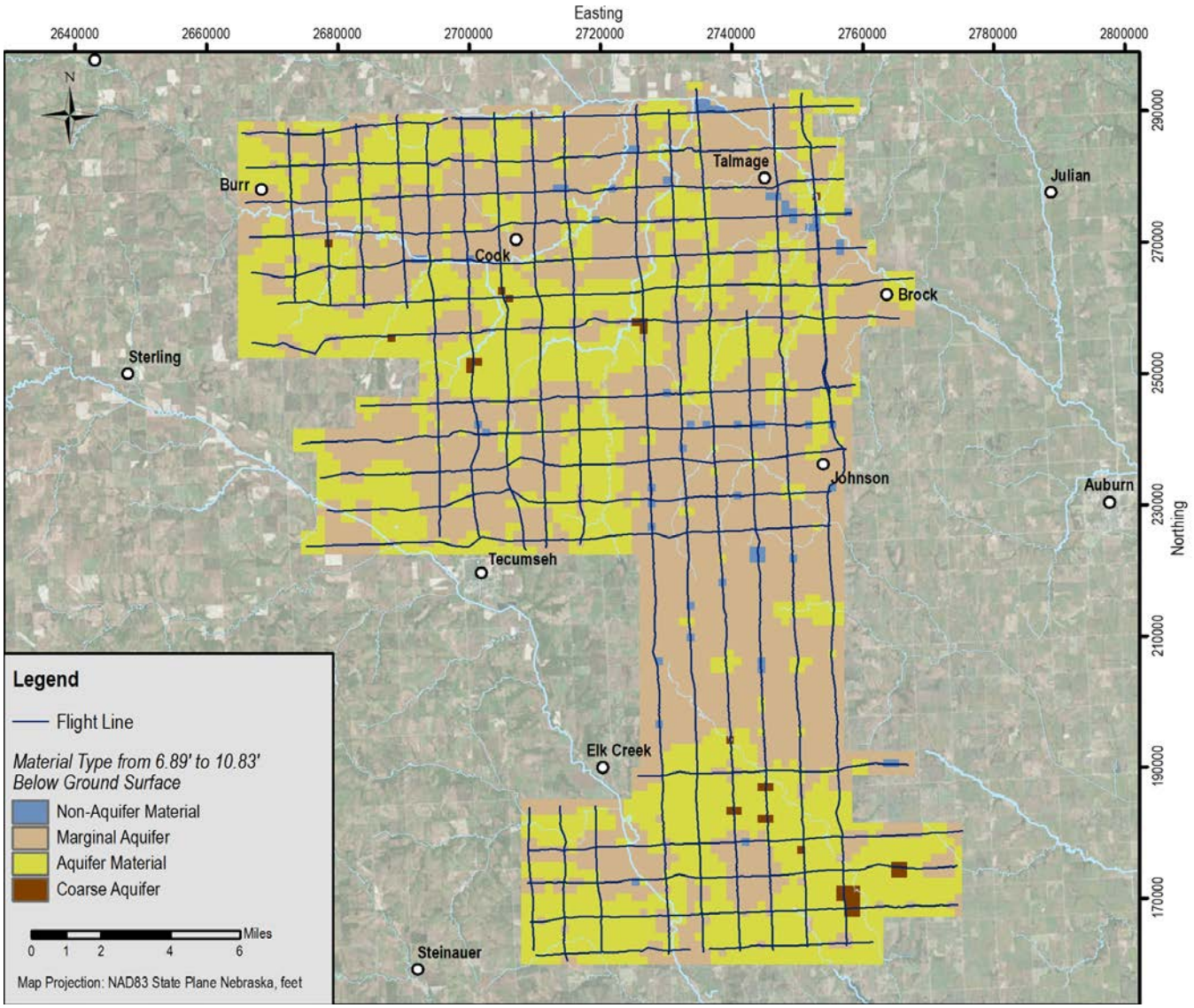


Figure 3-64. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 6.89' to 10.83' below ground surface within the 2018 NNRD Reconnaissance survey area. The projection is NAD83 State Plane Nebraska (feet).

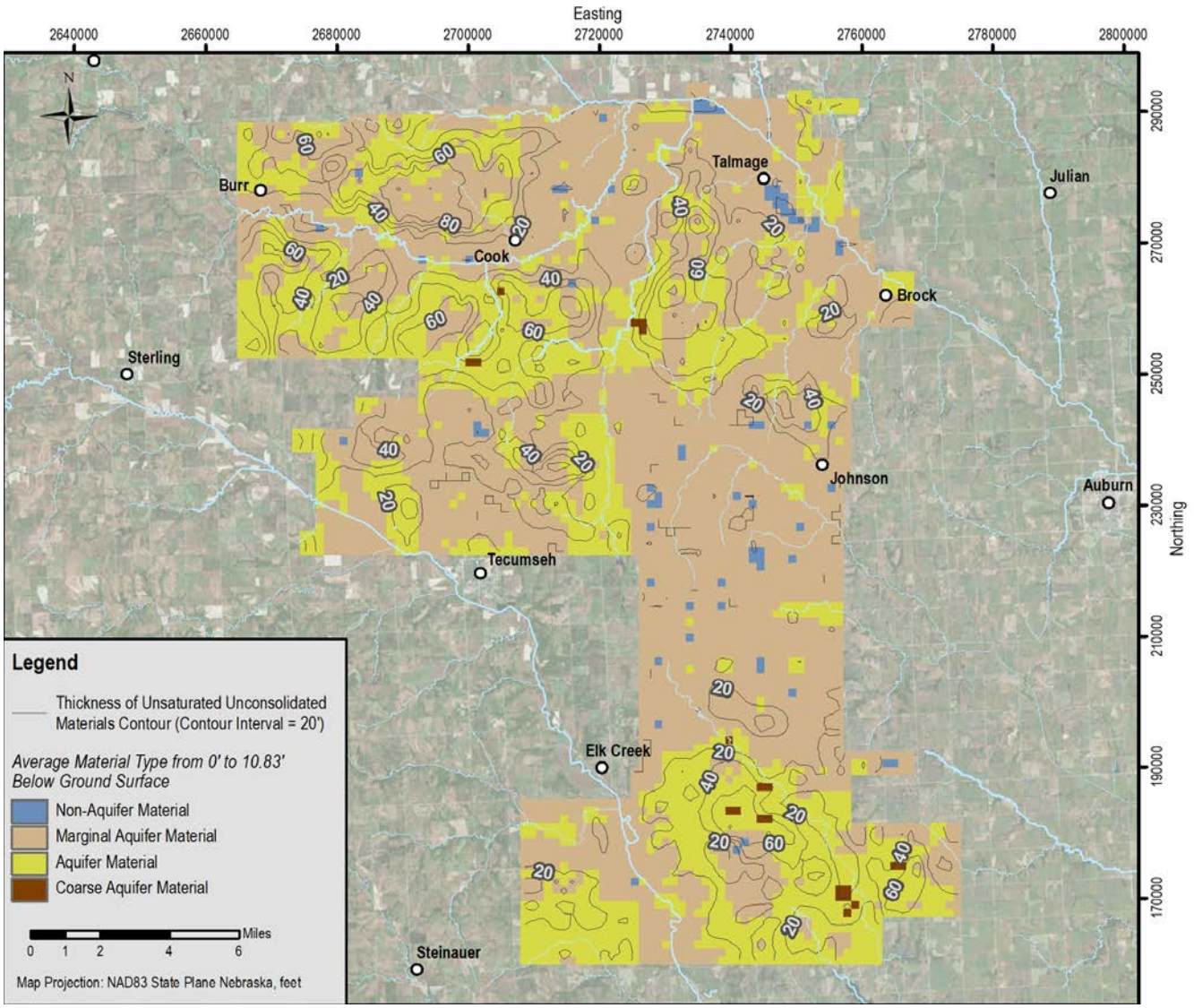


Figure 3-65. Map of the average material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 0' to 10.83' below ground surface with the thickness of unsaturated unconsolidated contours (black lines) of equal thickness within the 2018 NNRD Reconnaissance survey area. The projection is NAD83 State Plane Nebraska (feet).

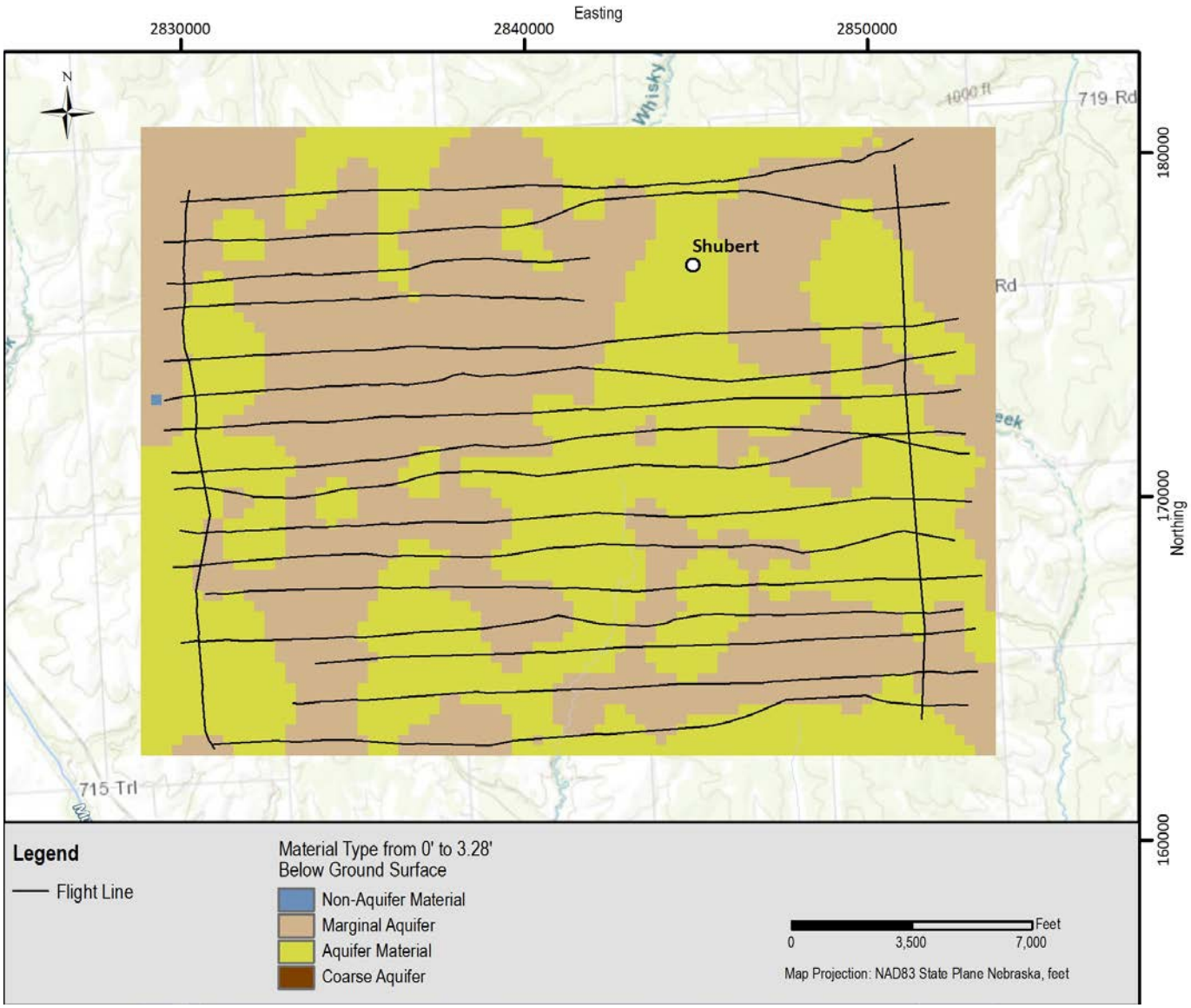


Figure 3-66. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 0' to 3.28' below ground surface within the 2018 NNRD Shubert Block area. Blue lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet).

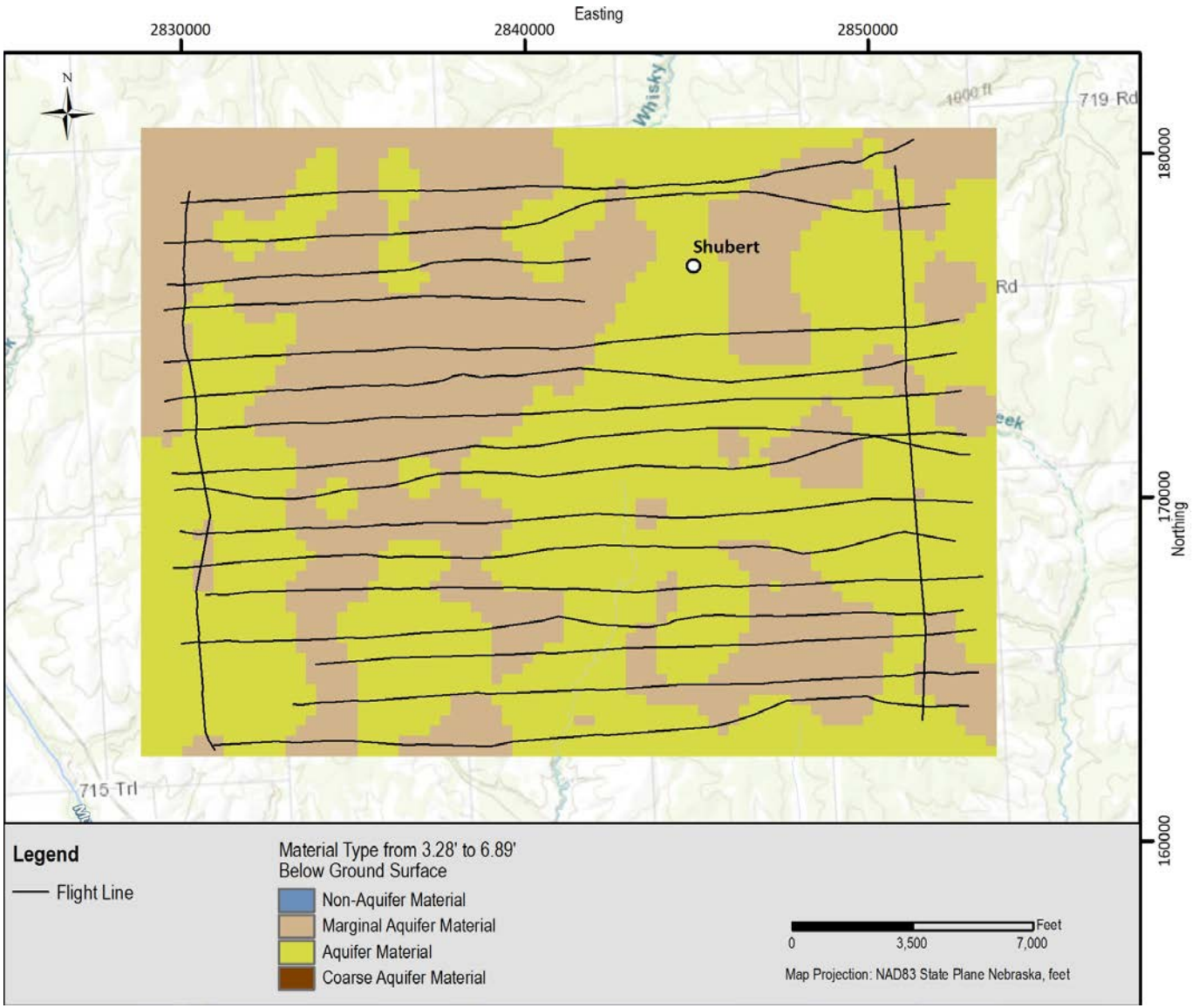


Figure 3-67. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 3.28' to 6.89' below ground surface within the 2018 NNRD Shubert Block area. Blue lines indicate flight lines. The projection is NAD83 State Plane Nebraska (feet).

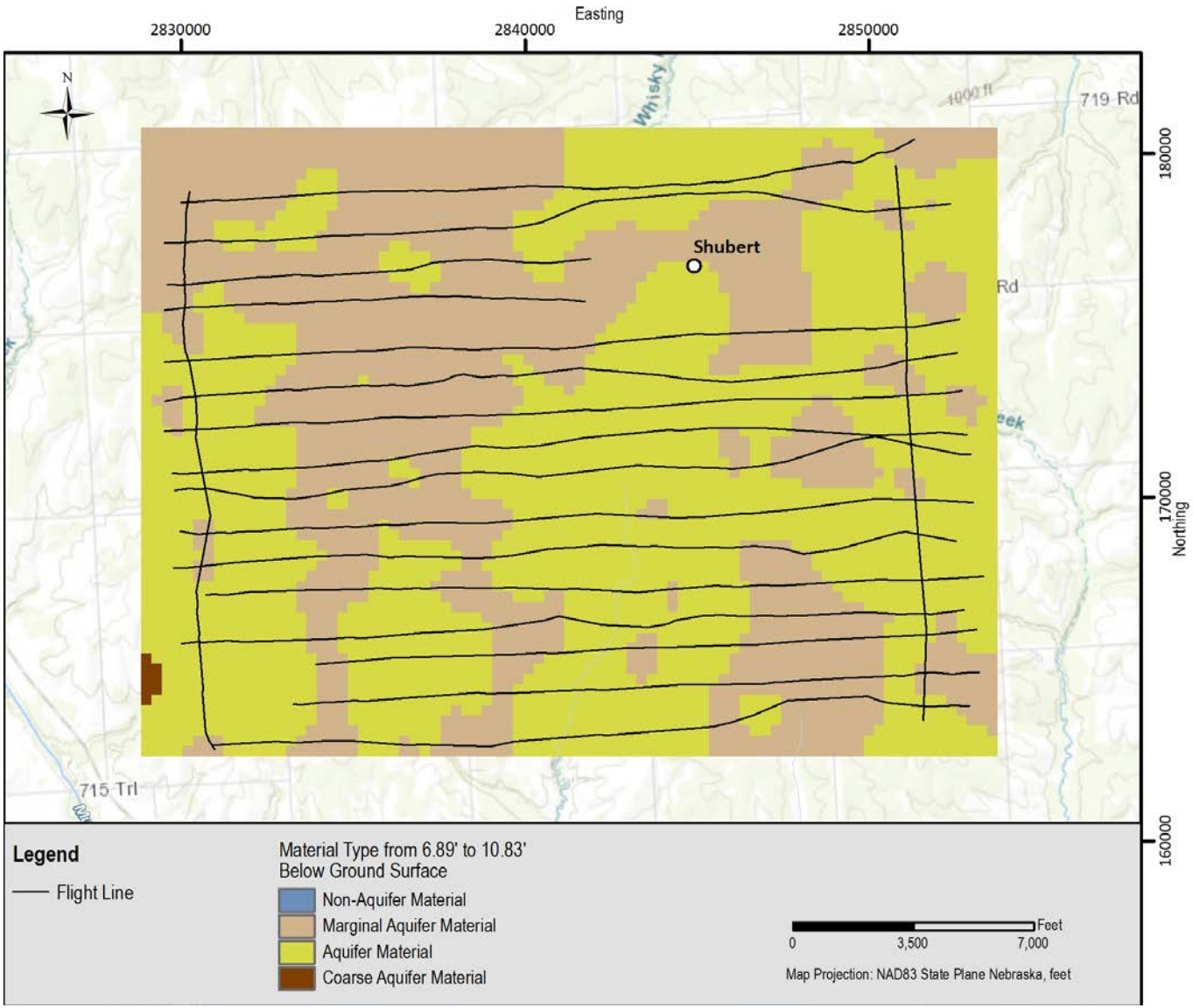


Figure 3-68. Map of the material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 6.89' to 10.83' below ground surface within the 2018 NNRD Shubert Block area. The projection is NAD83 State Plane Nebraska (feet).

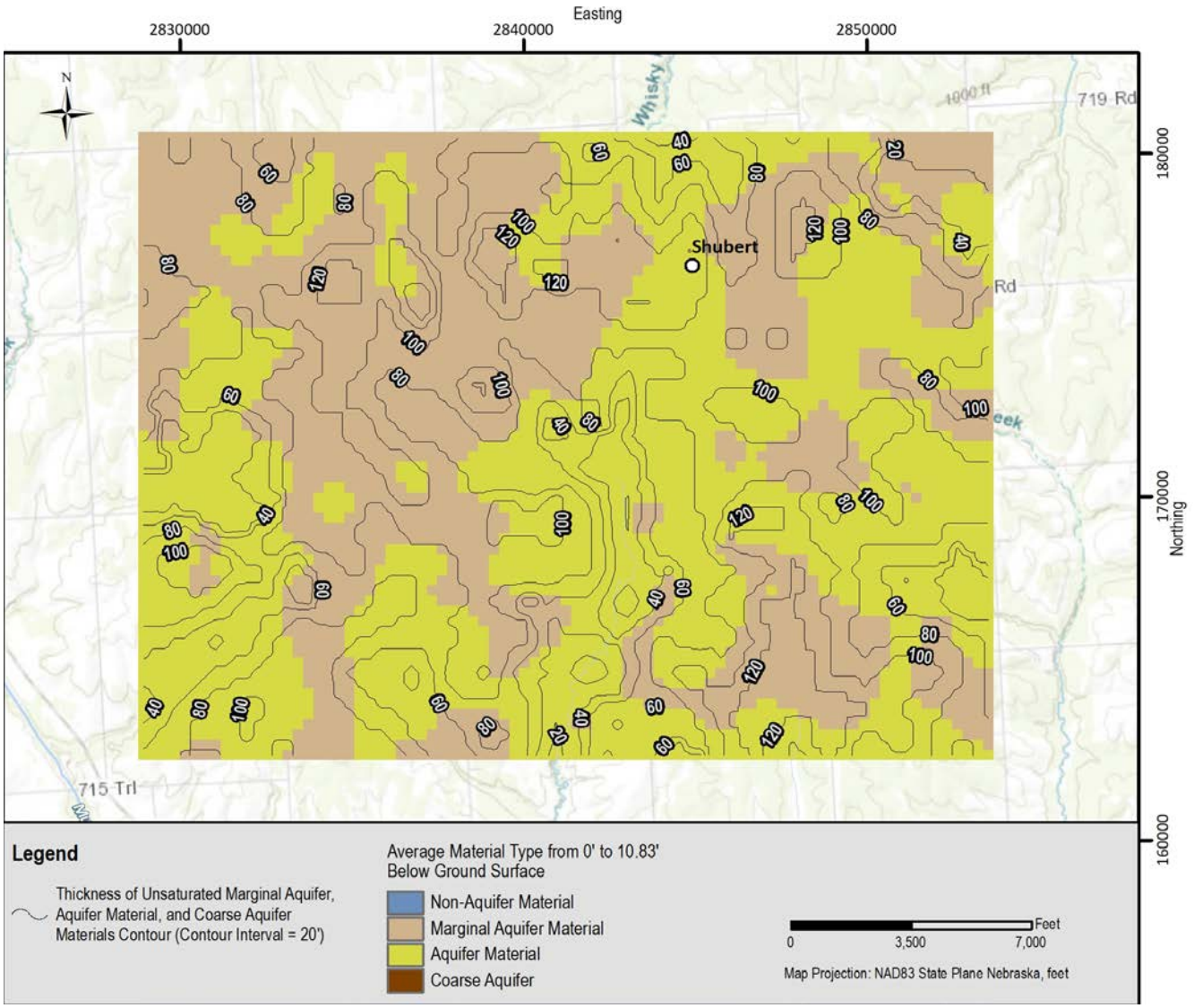


Figure 3-69. Map of the average material type (Non-Aquifer, Marginal Aquifer, Aquifer Material, or Coarse Aquifer) from 0' to 10.83' below ground surface with the thickness of unsaturated unconsolidated contours (black lines) of equal thickness within the 2018 NNRD Shubert Block area. The projection is NAD83 State Plane Nebraska (feet).

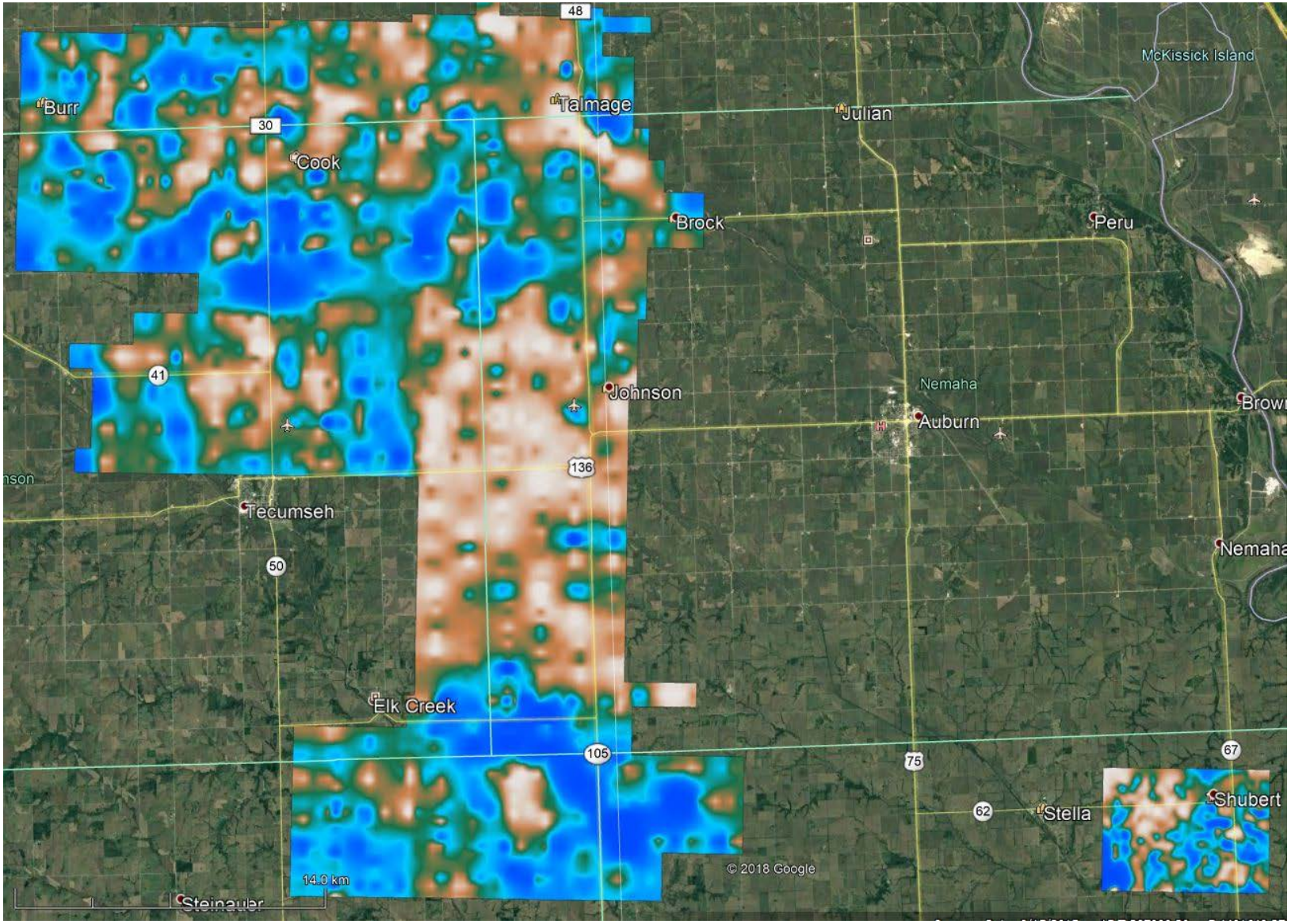


Figure 3-70. Google Earth image of the NNRD Reconnaissance and Shubert Block recharge potential. Darker blue areas have the greater potential for recharge. These datasets are included as Google Earth KMZ's in Appendix 3 – Deliverables\KMZ\Recharge.

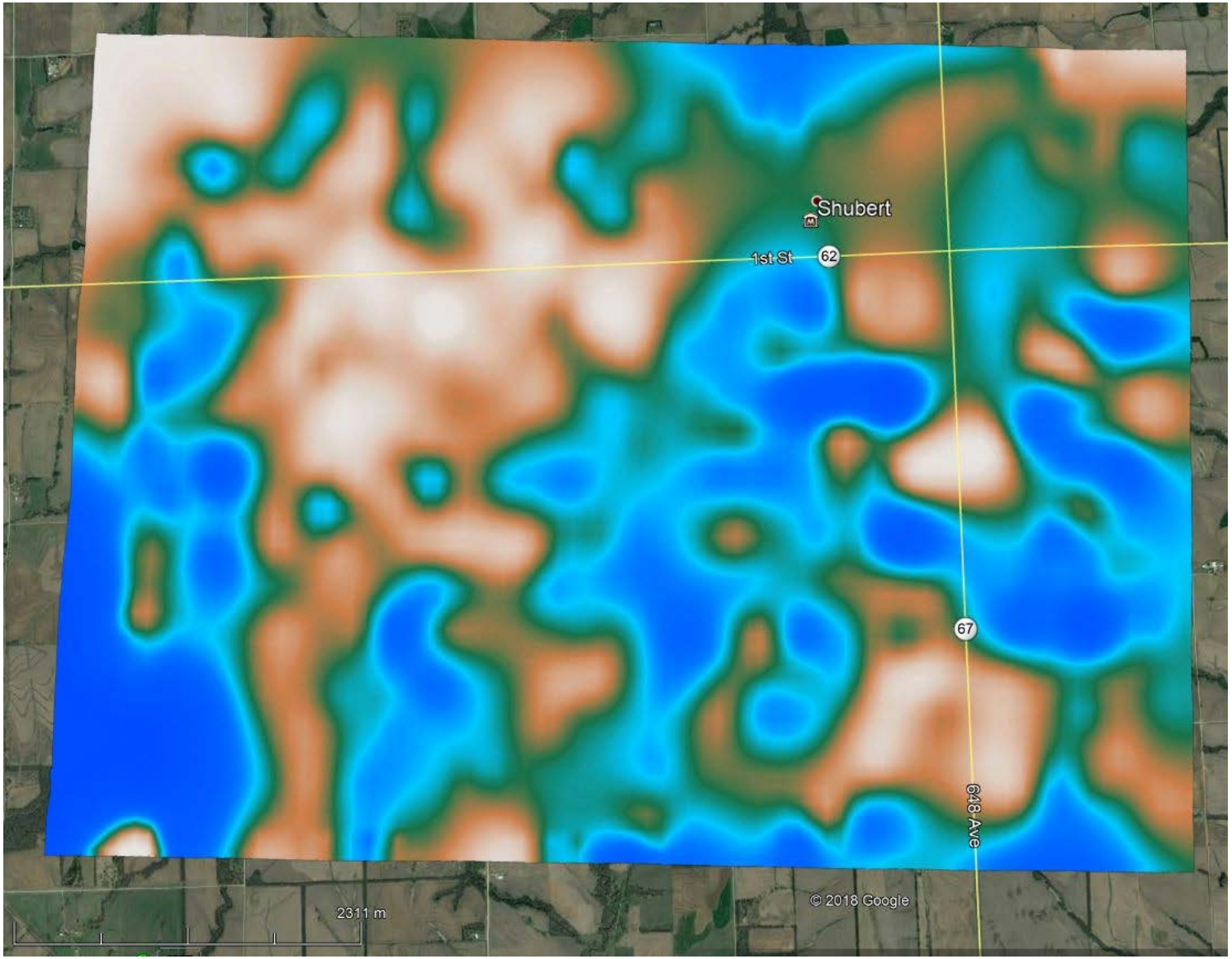


Figure 3-71. Zoomed in view of the Shubert Block recharge potential Google Earth kmz presented in Figure 3-70. Darker blue areas have the greater potential for recharge.

3.5 Key AEM Findings

3.5.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results and was important for all areas in the NNRD. The top of the undifferentiated Pennsylvanian (***IP***) was a challenging unit to interpret due to the highly variable resistivity of the ***IP***. This unit when compared to the Quaternary (***Q***) often 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 Nebraska Department of Natural Resources (NE-DNR) registered wells. Very rarely inconsistencies are encountered in the oldest of the Conservations and Survey Division (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 bedrock surface as developed by Leggette, Brashears, and Graham (LBG) (LBG, 2017) was used as a guide for the interpretation of the ***IP*** in areas of low electrical resistivity contrast and no boreholes. As in all surveys of this nature the use of boreholes with AEM needs to be approached in a thoughtful and considered manner as to the value of information from an individual borehole.

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)*** and undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, , Nebraska Oil and Gas Conservation Commission (NEOGCC), and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary aquifer material mapping are included in the appendices as well as interpretative surface grids. The known differences between the parameters of the 2015 AEM survey and 2018 AEM survey, 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, model layer parameters, and lithologic nomenclature.

3.5.3 Resistivity/Lithology Relationship

Assessment of the sediment character in the Quaternary 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.

3.5.4 Hydrogeological Framework of the NNRD

The 2018 NNRD AEM survey reveals variability in the Quaternary (***Q***) deposits across the NNRD AEM survey area. The ***Q*** make up the aquifer materials overlying the undifferentiated Pennsylvanian (***IP***) bedrock units. In the north and south parts of the AEM survey area, the aquifer material and coarse aquifer material exist in paleochannels which are separated by ***Q*** deposits which consist of predominantly marginal to non-aquifer materials which are glacial till and loess and which can be more than 200 feet thick. ***Q*** aquifer and coarse aquifer materials are thick in the northwest part of the survey area. The Shubert Block flight area has very little aquifer and coarse aquifer material. Estimates of the groundwater in storage within the Shubert Block of aquifer material below the 1995 CSD water table elevation is 1,431 acre-ft and coarse aquifer material is 12 acre-ft. The amount of extractable groundwater from aquifer material is 315 acre-ft and coarse aquifer material is 2 acre-ft. The main aquifer material type in the Shubert Block is marginal aquifer materials. This material is composed of thin sand and gravel layers with silty sand, silty clay, and sandy clay. While these materials will produce water the yields and specific capacity will be reduced. The total estimate of the groundwater in storage below the 1995 water table is 275,619 acre-ft with 9,959 acre-ft extractable, demonstrating the impact of the fine grained materials on the overall extractable groundwater.

3.5.5 Potential Recharge Zones within the NNRD AEM Survey Area

The use of block flights in Shubert area 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 showing 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. The area throughout the Shubert Block has potential recharge that is limited in extent. The groundwater in storage and potential yield from the aquifer has been calculated for the Shubert Block area. It supports the determination that low rates of recharge are available.

Within the Reconnaissance area the highest rate of recharge can be expected in the northwest area of the survey area due to the presence of aquifer and coarse aquifer materials from land surface down to the water table. Areas with aquifer and coarse aquifer materials at the surface can also become conduits for infiltration of nitrates into the groundwater system. These areas exist in the northwest section of the survey area where the reconnaissance lines are the basis for this determination. It should be noted that in these areas the results shown in the recharge maps are based on more interpolation between data points and less actual AEM data. A potential solution for any nonpoint source water quality contamination is adding additional fresh surface water as recharge to select areas of rangeland that can dilute any potential nitrate contaminant problem occurring from cropland. Additional work can be done to identify where the best locations are for these type of management efforts. A new feature for mapping

recharge areas is the addition of the new 40-layer model for data analysis. This improves the recharge estimates by expanding the number of layers in the near surface providing a better estimate for the aquifer materials present. This allows for more accurate representation of the aquifer materials in the first 10 feet from the land surface downward.

3.6 Recommendations

Recommendations provided to the NNRD 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 NNRD about their management challenges.

3.6.1 Integration of 2007-2018 AEM Hydrogeological Investigations

The NNRD has acquired AEM data from 2007, 2015, and 2018 with three different AEM systems and contractors performing the work including USGS, XRI Geophysics and AGF with oversight from the ENWRA and the NNRD. With the completion of this current study there needs to be additional work done to bring all the work from previous years together in one seamless package using the same parameters such as the three different geographic projections NAD83 Zone 14N (meters), NAD83 Zone 14N (feet), and NAD83 Sate Plane Nebraska (feet), model layering structure, and hydrologic nomenclature. Recent communication with NNRD 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. 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 NNRD.

3.6.2 Additional AEM Mapping

The hydrogeologic maps provided in this report represent the completed hydrogeologic framework developed for the NNRD at reconnaissance level with approximately 1-mile spacing between flight lines. The Shubert Block flight area is the only exception to this flight line spacing which is about 0.1 to 0.25 miles (200 m to over 300 m). The first AEM project for the District was done in 2007 in the Firth Block that was collected with dense flight lines over a limited area. In 2015 AEM data was collected at an approximately 20-mile grid spacing. The interpretations match well with the CSD and NE-DNR test holes. The 2018 AEM project for NNRD selected areas for a hydrogeologic framework map to support groundwater models, selection of rural water supply well locations, locating water quality monitoring wells, determining the potential for areas make decisions about irrigation development and management policy, and selecting MAR or ASR locations. It is highly recommended that additional AEM data be collected and analyzed within the area of the Nemaha River basin northwest of the 2018 flights to complete the reconnaissance flights at 1-mile separation and addition of selected areas of block flights where detailed information is needed for decisions related to groundwater management. This information will strengthen the knowledge base of the important aquifer areas of the district.

Most importantly it will provide information including the geographic distribution of amount of groundwater in storage, recharge areas, susceptibility to groundwater contamination and hydrologic connection to the streams in the block flight areas, within the NNRD that can be selected for current and future water development impacts.

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. The areas of glacial till and loess covering the parts 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. Use of the data collected in this survey and future surveys will provide the best possible water table and conditions map for the district.

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 NNRD area was used in building the framework maps and profiles. Additional information from previous groundwater reports were helpful in this work. 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 with minimal sedimentary boundary conditions. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the NNRD.

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 NNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer in Shubert 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 Shubert Block which utilized closely-spaced flight lines using an AEM system that has good near-surface resolution in areas identified by the NNRD 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. This information can and has been used in Nebraska to improve Well Head Protection Areas by refining the estimated travel time estimates and the boundary areas.

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 NNRD 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 NNRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the NNRD for storage and release of water for stream flow and other uses.

3.6.8 Updating previous groundwater reports and Groundwater Management Plans

The groundwater report from LBG Hydrogeologic Assessment Report (LBG, 2017) should be updated with the AEM information which make it a more comprehensive publication. It should be noted that AGF conferred with LBG on some aspects of their report for this project. Future AEM work should be included in their report in order to achieve similar results. Should future AEM work be completed the results from that effort will help guide the future groundwater management plans for the district. The addition of estimates of groundwater in storage, recharge areas, hydrologic connection to streams and consideration of managed aquifer recharge sites will greatly improve and groundwater management plan.

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, nine (9) flights were required to acquire the NNRD 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 NNRD2018_EM_MAG_AUX.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 NNRD2018_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 NNRD2018_Recon_InterpSurfaces.xyz and ShubertBlk_InterpSurfaces.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 Shubert Block is described in Table 4-7. The voxel grid is presented as an xyz file, *NNRD_Shubert_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 Shubert Block ***Q*** *.csv
- 2D profiles and 3D fence diagrams of the AEM survey inversion results

KMZs for NNRD 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	20180613_446_NE304_NNRD.lin	Production file listing dates, flights, and assigned line numbers

Table 4-2: Channel name, description, and units for NNRD2018_EM_MAG_AUX.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	$pV/(m^4*A)$
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	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_Cor	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 NNRD2018_AEM_SCI_INV_v1.xyz with EM inversion results.

/Parameter	Description	Unit
LINE	Line Number	
Easting_SP83FT	Easting NAD83, Nebraska State Plane	Feet (ft)
Northing_ SP83FT	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_M	Inverted Altitude of system above ground	Meters [m]
INVALTSTD	Inverted Altitude Standard Deviation of system above ground	Meters [m]
DELTAALT	Change in Altitude of system above ground	Meters [m]
RESDATA	Residual of individual sounding	
RESTOTAL	Total residual for inverted section	
RHO_I_0 THROUGH RHO_I_38	Inverted resistivity of each layer	Ohm-m
RHO_STD	Inverted resistivity error per layer	
SIGMA_I_0 THROUGH SIGMA_I_39	Conductivity	S/m
DEP_TOP_0_FT THROUGH DEP_TOP_38_FT	Depth to the top of individual layers	Feet [ft]
DEP_BOT_0_FT THROUGH DEP_BOT_38_FT	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT THROUGH THK_38_FT	Thickness of individual layers	Feet [ft]
DEP_TOP_0_M THROUGH DEP_TOP_38_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_M THROUGH DEP_BOT_38_M	Depth to the bottom of individual layers	Meters [m]
THK_0_M THROUGH THK_38_M	Thickness of individual layers	Meters [m]
DOI_UPPER_FT	More conservative estimate of DOI	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI	Feet [ft]
DOI_UPPER_M	More conservative estimate of DOI	Meters [m]
DOI_LOWER_M	Less conservative estimate of DOI	Meters [m]

Table 4-4. Channel name description and units for the interpretation results files NNRD2018_Recon_InterpSurfaces.xyz and ShubertBlk_InterpSurfaces.xyz.

Parameter	Description	Unit
LINE	Line Number	
East_M	Easting NAD83, UTM Zone 14N	Meters (m)
North_M	Northing NAD83, UTM Zone 14N	Meters (m)
East_ft	Easting NAD83, Nebraska State Plane	Feet [ft]
North_ft	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
RHO[0] through RHO[38]	Array of Inverted model resistivities of each layer	Ohm-m
RHO_STD[0] through RHO_STD[38]	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 [38]	Depth to the top of 39 individual layers	Feet [ft]
DEP_BOT_FT [0] through DEP_BOT_FT [38]	Depth to the bottom of 39 individual layers	Feet [ft]
DOI_UPPER_FT	More conservative estimate of DOI from Workbench	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI from Workbench	Feet [ft]
WaterTable1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
AquiferTyp[0] through AquiferTyp[38]	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_NonAq1	Elevation of top of upper Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Bot_NonAq1	Elevation of bottom of upper Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Thk_NonAq1	Thickness of upper Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Top_NonAq2	Elevation of top of middle Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Bot_NonAq2	Elevation of bottom of middle Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Thk_NonAq2	Thickness of middle Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Top_NonAq3	Elevation of top of lower Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Bot_NonAq3	Elevation of bottom of lower Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Thk_NonAq3	Thickness of lower Non-Aquifer Material (<12 ohm-m)	Feet [ft]
Top_MargAq1	Elevation of top of upper Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
Bot_MargAq1	Elevation of bottom of upper Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
Top_MargAq2	Elevation of top of lower Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
Bot_MargAq2	Elevation of bottom of lower Marginal-Aquifer Material (12 - 20 ohm-m)	Feet [ft]
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]
Thk_AqMat1	Thickness 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]
Thk_AqMat2	Thickness of middle Aquifer Material (20 - 50 ohm-m), if present	

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]
Thk_AqMat3	Thickness 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]
Thk_Coarse_AqMat1	Thickness 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]
Thk_Coarse_AqMat2	Thickness of Lower Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bedrock	Elevation of interpreted bedrock surface	Feet [ft]
IP	Elevation of the top of the Undifferentiated Pennsylvanian.	Feet [ft]
LBG_Bedrock	Elevation of interpreted bedrock surface received from LBG (2015)	Feet [ft]

Table 4-5. NNRD Inversion Model Structure with DEM and Layer Top-, Bottom-, and Mid-points in Depth and Elevation plus Inverted Cell Resistivities (*NNRD_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)
NNRD_Recon_DEM	Digital Elevation Model (ground surface elevation) (NAVD88 feet) of the 2018 NNRD survey area, NAD 83State Plane Nebraska, feet	100
NNRD_Shubert_DEM	Digital Elevation Model (ground surface elevation) (NAVD88 feet) of the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	100
NNRD_Recon_BedrockEle	Elevation (NAVD88 feet) of the top of the undifferentiated Pennsylvanian (***IP***) for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	500
NNRD_Shubert_BedrockEle	Elevation (NAVD88 feet) of the top of the undifferentiated Pennsylvanian (***IP***) for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Recon_WT1995	Elevation (NAVD88 feet) of the water table (1995) for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1000
NNRD_Shubert_WT1995	Elevation (NAVD88 feet) of the water table (1995) for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	1000
NNRD_Recon_QTotalThick	Total thickness (feet) of the unconsolidated Quaternary deposits for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	500
NNRD_Shubert_QTotalThick	Total thickness (feet) of the unconsolidated Quaternary deposits for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Recon_SatThick_All	Saturated thickness (feet) of the unconsolidated Quaternary deposits for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	100
NNRD_Shubert_SatThick_All	Saturated thickness (feet) of the unconsolidated Quaternary deposits for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	100
NNRD_Recon_TotThick_AMCA	Total thickness (feet) of aquifer material and coarse aquifer material for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200
NNRD_Recon_SatThick_AMCA	Saturated thickness (feet) of aquifer material and coarse aquifer material for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200

NNRD_Recon_UnSatThick_AMCA	Unsaturated thickness (feet) of aquifer material and coarse aquifer material for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200
NNRD_Recon_TotalThick_NA	Total thickness (feet) of non-aquifer material for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200
NNRD_Recon_Transmissivity	Estimated transmissivity (gpd/ft) for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200
NNRD_Recon_RHO0	Material type (non-aquifer, marginal aquifer, aquifer, or coarse aquifer) from 0'-3.281' below ground surface for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200
NNRD_Recon_RHO1	Material type (non-aquifer, marginal aquifer, aquifer, or coarse aquifer) from 3.281'-6.8901' below ground surface for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200
NNRD_Recon_RHO2	Material type (non-aquifer, marginal aquifer, aquifer, or coarse aquifer) from 6.8901'-10.8273' below ground surface for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200
NNRD_Recon_RHO_Average	Average material type (non-aquifer, marginal aquifer, aquifer, or coarse aquifer) from 0'-10.8273' below ground surface for the 2018 NNRD survey area, NAD83 State Plane Nebraska, feet	1,200
NNRD_Shubert_TotThick_MAAMCA	Total thickness (feet) of marginal aquifer, aquifer material, and coarse aquifer material for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Shubert_SatThick_MAAMCA	Saturated thickness (feet) of marginal aquifer, aquifer material, and coarse aquifer material for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Shubert_UnsatThick_MAAMCA	Unsaturated thickness (feet) of marginal aquifer, aquifer material, and coarse aquifer material for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Shubert_Total_NA	Total thickness (feet) of non-aquifer material for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Shubert_SatThickAMCA	Saturated thickness (feet) of aquifer material and coarse aquifer material for	300

	the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, ft	
NNRD_Shubert_L0	Material type (non-aquifer, marginal aquifer, aquifer, or coarse aquifer) from 0'-3.281' below ground surface for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Shubert_L1	Material type (non-aquifer, marginal aquifer, aquifer, or coarse aquifer) from 3.281'-6.8901' below ground surface for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Shubert_L2	Material type (non-aquifer, marginal aquifer, aquifer, or coarse aquifer) from 6.8901'-10.8273' below ground surface for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300
NNRD_Shubert_L0-2_Ave	Average material type (non-aquifer, marginal aquifer, aquifer, or coarse aquifer) from 0'-10.8273' below ground surface for the 2018 NNRD Shubert block survey area, NAD83 State Plane Nebraska, feet	300

Table 4-7. Channel name, description, and units for NNRD_Shubert_voxel.xyz.

Parameter	Description	Unit
X	Easting NAD83, State Plane Nebraska	feet [ft]
Y	Northing NAD83, State Plane Nebraska	feet [ft]
Z	Depth of Voxel Node	feet [ft]
Elevation	Surface 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 as well as bedrock and the 1995 water table. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\Interpretation\NNRD18_Profiles*" folder. In this folder is a "*GoogleE_Readme.pdf*" file that provides 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 NNRD GoogleE_Readme.pdf file is repeated below as a convenience. An example of the NNRD interpretation KMZ for the Reconnaissance lines is presented in Figure 4-1 and one for the Shubert Block is in Figure 4-2.

4.2.1 Included README for the NNRD Interpretation KMZ's

README for:

2018_NNRD_Reconnaissance_Interpretation.kmz

2018_NNRD_Shubert_Block_Area_Interpretation.kmz

Data Files - Please copy the folder *NNRD18_Profiles* to your C:\ drive. Do not rename any of the images within the folder.

Google Earth Instructions:

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

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

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

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

STEP 5: The *2018_NNRD_Reconnaissance_Interpretation.kmz* and *2018_NNRD_Shubert_Block_Area_Interpretation.kmz* files within the folder named *NNRD18_Profiles* can now be opened and viewed in Google Earth.

Data:

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

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

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

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

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

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

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

Profile – Link to Interpreted AEM profile images

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

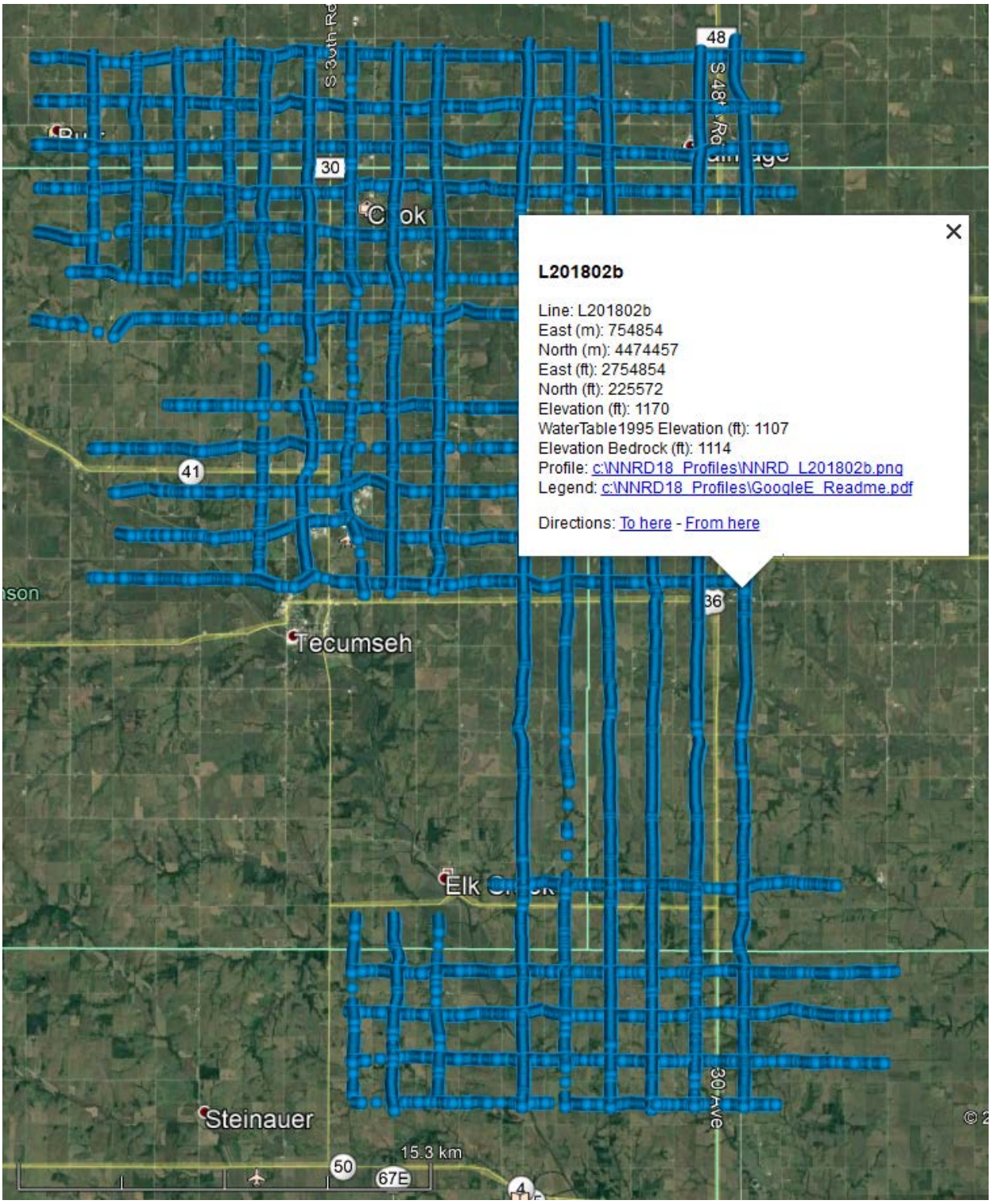


Figure 4-1. Example Google Earth image for the NNRD Reconnaissance interpretation kmz.

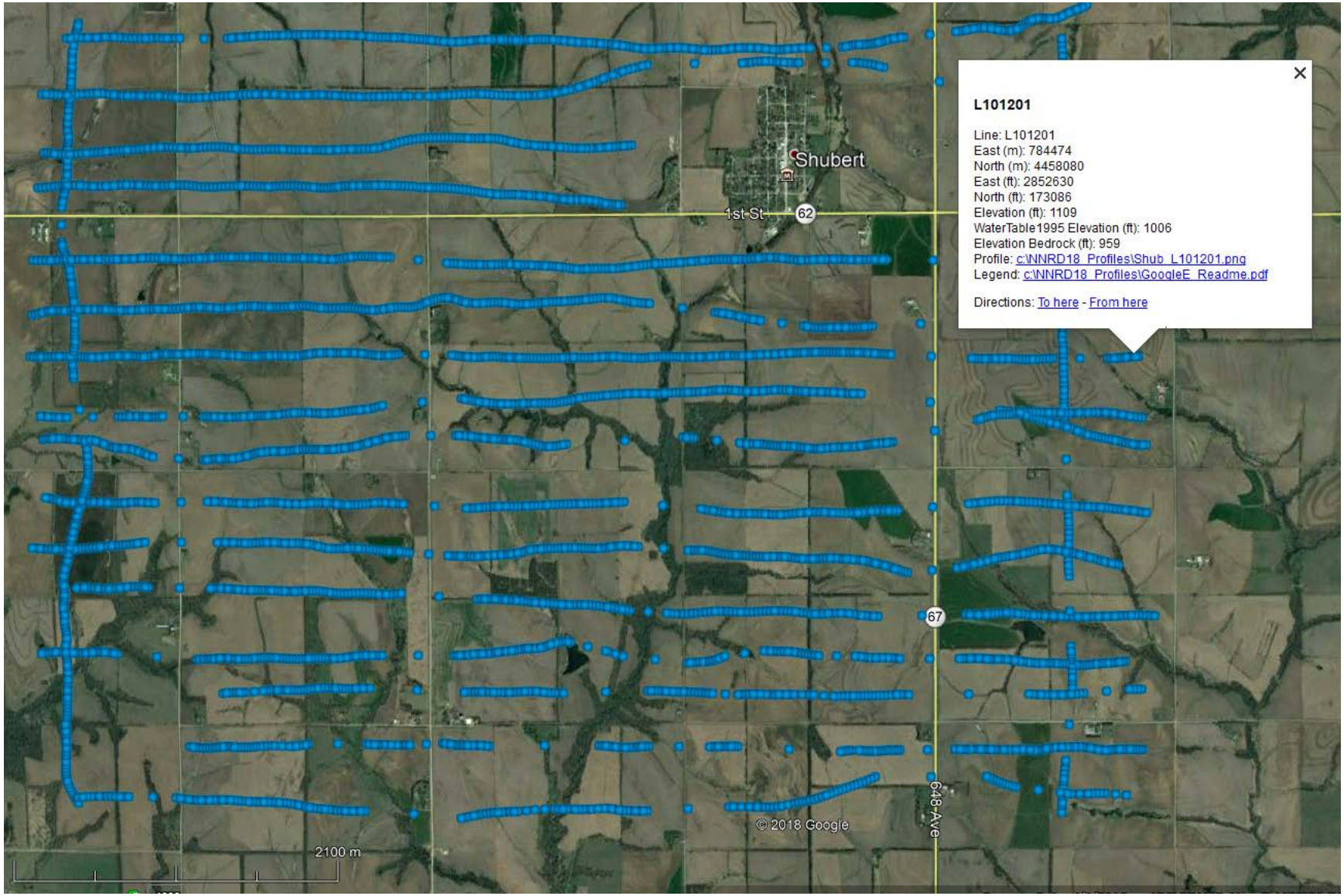


Figure 4-2. Example Google Earth image for the Shubert Block area interpretation kmz.

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