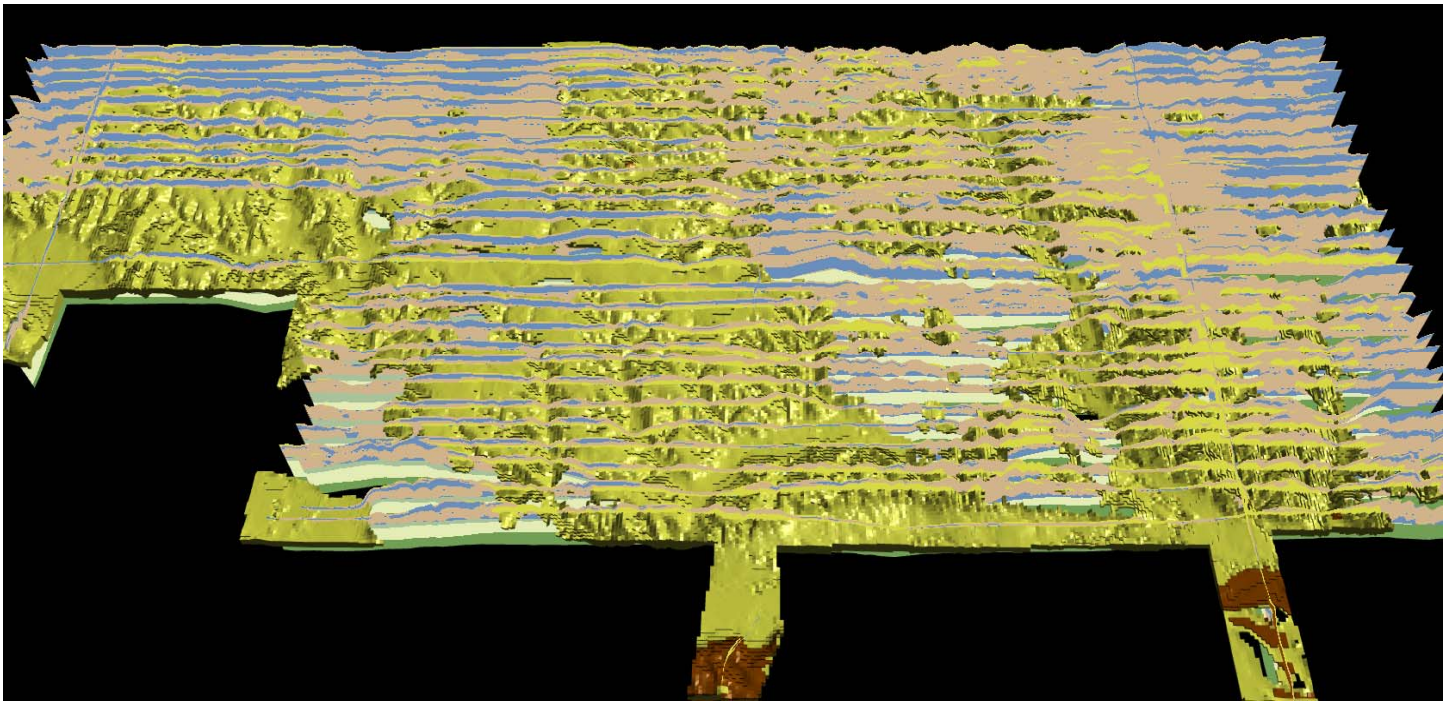
Hydrogeologic Framework of Selected Areas in the Lower Platte North Natural Resources District, Nebraska



***Prepared for*:**

Lower Platte North Natural Resources District

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Wahoo, NE 68066

August 18, 2017

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Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled "*Hydrogeologic Framework of Selected Areas in the Lower Platte North Natural Resources District*". An understanding of the hydrogeological framework in the survey area is desired in order to assist in resource management. AGF entered into an agreement with the Lower Platte North Natural Resources District (LPNNRD) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the LPNNRD 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 LPNNRD area including the SQS#1 and SQS#2 project areas. These flights have been provided as preliminary AEM inversions on July 17-20, 2016 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 ENWRA and LPNNRD assisted in providing information such as power line maps, a test hole database, and related aquifer characteristic studies to AGF.

Upon conclusion of the design process, the SQS#1 flight lines were approximately 14 miles in length (east-west) and 8 miles (north-south) and were separated by approximately 1/3 mile in both north-south directions. SQS#2 flight lines were approximately 23 miles in length (east-west) and 4 miles (north-south) and were separated by approximately 1/3 mile in both east-west directions.

1.4 Within SQS#1 154.5 line-miles (250.2 line-kilometers) and within SQS#2 497.2 line-miles (805.4 line-kilometers) were acquired in the survey areas. Status reports of the flying were provided to the Contract Representative of LPNNRD on a daily basis, including the areas flown, production rates, and flight plan for the following day.

1.5 AGF processed and conducted quality assurance and quality control (QA/QC) procedures on all data collected from the acquisition system. AGF delivered preliminary data and inversions on July 20, 2016.

1.6 AGF inverted the AEM data. These final inverted georeferenced data are delivered to the LPNNRD with this report. After inversion, AGF derived 2D sections, 3D electrical models, and interpreted geologic and hydrogeologic surfaces of the surveyed area.

1.7 AGF is providing a hydrogeologic framework report that includes maps of aquifer(s), maps of aquifer materials relationships to current test holes and production groundwater wells, estimates of water storage capacity, and maps of estimated potential recharge areas. 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. Within SQS#1 survey area there were, 17 CSD holes contained lithology information, 16 holes contained stratigraphic information, and 4 holes contained geophysical information), NE-DNR (A total of 229 registered wells contained usable lithology information) and NOGCC had 5 holes with lithology and 2 with stratigraphy boreholes. Within SQS#2 survey area there were, 17 CSD holes contained lithology information, 9 holes contained stratigraphic information, and 4 holes contained geophysical information), NE-DNR (A total of 859 registered wells contained usable lithology information) and NOGCC had 1 hole with lithology and stratigraphy boreholes.

2.2 Merging 2014 and 2016 AEM Databases - The LPNNRD AEM survey analysis encompassed additional data from AEM surveys conducted in 2014 and 2015 by the ENWRA. The 2014 AEM data contains valuable information that can be utilized in the interpretation of the larger LPNNRD AEM survey area. The 2014 and 2015 AEM data were combined with the 2016 AEM data. This combination did not include reinverting the 2014 and 2015 data, but included merging the 2014 and 2015 inversions into the current database and reinterpretation.

2.3 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 Cretaceous Niobrara (***Kn***), Carlile (***Kc***), Greenhorn limestone and Graneros shale (***Kgg***), and Dakota (***Kd***). The interpretive process benefited from the use of CSD and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary aquifer material mapping are included in the appendices as well as interpretative surface grids.

2.4 Resistivity/Lithology Relationship - Assessment of the sediment character in both the Quaternary aquifer system and the consolidated bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A numerically robust assessment of the resistivity thresholds 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.

2.5 Hydrogeological Framework of the LPNNRD - The AEM reveals considerable variability in the Quaternary deposits across the LPNNRD. The subsurface distribution of materials can be generally characterized in two blocks. These areas include the Quaternary Aquifer Area and the Cretaceous bedrock aquiclude. The ***Q*** aquifer of the SQS#1 survey area is predominantly composed of Quaternary unconsolidated aquifer and a sparse amount of coarse aquifer materials composed of alluvial and glacial sediments. These materials are sitting on varying thickness of ***Kgg*** and ***Kd*** which is the bedrock aquiclude for the SQS#1 survey area. The SQS#1 survey area is within the glacial till area of eastern Nebraska. The bedrock is eroded and has two channels cut into it. A channel trends from west to east along the southern edge of SQS#1 with a larger channel parallel in direction to the first channel approximately 5 miles south. The channels are flanked by three bedrock highs that are in the block area which have an increased

relief of up to approximately 600 feet in elevation. The area is dominated by non-aquifer and marginal materials and water table mostly confined by the overlying glacial till. The thicker sequences of aquifer to coarse aquifer materials lie along the southern edge and northwest corner of the survey area.

The ***Q*** aquifer of the SQS#2 survey area is predominantly composed of Quaternary unconsolidated aquifer and a sparse amount of coarse aquifer materials composed of alluvial and glacial sediments. These materials are sitting on varying thickness of ***Kn, Kc,*** and ***Kgg*** which is the bedrock aquiclude for the SQS#2 survey area. The SQS#2 survey area is within the glacial till area. The bedrock is eroded and has one channel cut into it. A channel trends from west to east through the center of the survey area. The channels are flanked by two bedrock highs that are in the block area which have an increased relief of up to approximately 425 feet in elevation. The area is dominated by non-aquifer and marginal materials and water table mostly confined by the overlying glacial till. The thicker sequences of aquifer to coarse aquifer materials are mostly distributed throughout the survey area.

2.6 Estimation of Aquifer Volume and Water in Storage in the SQS#1 and SQS#2 AEM Survey Areas - Within the SQS#1 survey area non-aquifer material has an estimated volume of 3,932,293acre-ft and contains 1,572,917 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 8,303,004 acre-ft and contains 2,906,051 acre-ft, aquifer material has an estimated volume of 3,466,989 acre-ft and contains an estimated volume of 693,397 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 3,845 acre-ft for a total of 961 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 5,173,326 acre-ft.

Within the SQS#2 survey area non-aquifer material has an estimated volume of 2,885,798 acre-ft and contains 1,154,319 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 8,674,691 acre-ft and contains 3,036,141 acre-ft, aquifer material has an estimated volume of 6,717,815 acre-ft and contains an estimated volume of 1,343,563 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 43,139 acre-ft for a total of 10,784 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 5,544,807 acre-ft.

2.7 Potential Recharge Zones within the SQS#1 and SQS#2 AEM Survey Areas - Within the SQS#1 and SQS#2 survey areas each AEM flight line was interpreted for aquifer material in the first model layer (0 – 10 ft). Areas of coarse aquifer material will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material potentially transmitting slightly less precipitation downward as both units are permeable. The marginal aquifer material has the lowest potential to transmit some water downward and the non-aquifer material will transmit minimal to no water to the groundwater aquifer. Most of the areas are covered in glacial till limiting the amount of recharge. The recharge that does percolate through the first 10 feet needs find a path through any coarse aquifer and aquifer materials to reach the groundwater aquifers.

2.8 Relationship between Registered Wells, Discharge Estimates, and the AEM Results - There is a strong relationship between the distribution of the registered wells from the NEDNR database and the mapped saturated aquifers results from the AEM survey in both SQS#1 And SQS#2. The discharge rates match the aquifer configuration and aquifer materials description well. The highest discharge rates follow the channel along the southern border and the northwest corner of SQS#1 which have the most aquifer and coarse aquifer materials. The medium capacity wells are similarly located in the area. Low capacity wells tend to be in the center of the survey area where the aquifer material and coarse aquifer material are thin to non-existent.

Within SQS#2 the majority of the wells have a medium discharge rate due to most of the aquifer in the area being made up of aquifer material and little coarse aquifer material. The discharge rates match the aquifer configuration and aquifer materials description well. The highest discharge rates are in isolated areas across the survey area. The medium capacity wells are follow the channel in the center of the survey area. Low capacity wells tend to be scattered across the survey area where the aquifer material and coarse aquifer material are thin on non-existent.

2.9 Value of AEM Data Analysis and Images - One of the most important key findings from the LPNNRD AEM investigation is the value-added products resulting from AEM data derived images. There is a step-by-step process involved from flight planning to final images. While the text of the report may not go into detail on each and every data point or every image provided in the appendices, the value to the user is in the final data analysis and associated images. These final interpretive images allow development of science-based decisions for water management by illustrating the spatial relationships of aquifers. These images can help communication to the board and to the general public, the configuration of the aquifers and that those configurations can impact water quantity and quality.

3. Recommendations

Recommendations provided to the LPNNRD 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 LPNNRD about their management challenges.

3.1 **Additional AEM Mapping** - The aquifer maps provided in this report represent the detailed framework developed for the SQS#1 and SQS#2 AEM survey areas. The detail provided in the hydrogeological interpretation of SQS#1 and SQS#2 AEM survey areas allowed for the confident development of the hydrogeologic framework. The interpretations match well with the CSD and NE-DNR test holes. While no additional high resolution AEM information is needed within these survey areas to resolve questions of resource management, it is recommended that additional areas of closely spaced flight lines or "block flights" be collected to develop detailed frameworks in other identified areas of the LPNNRD. The LPNNRD plans to collect additional AEM data in up to four new areas in the district identified in the current Water Sustainability Fund grant application submitted by ENWRA for 2017. This AEM survey will be done in cooperation with the other ENWRA NRDs to get details on the continuous aquifer system that is shared in the area. The line spacing for the block flights should be on the order of 0.25 miles (1,320 ft).

An example of the results from this future survey would be to provide detailed hydrogeologic frameworks similar to what is presented in this report which have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield.

It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of the LPNNRD. This will supply the LPNNRD with information on groundwater flow, aquifer sustainability, and depletion to streams, well interference, groundwater withdrawal, and other management considerations. The LPNNRD's future work will focus on water quantity and the ongoing water quality work in the adjacent areas to determine if additional management is needed. It will also provide locations for new monitoring wells and water level locations.

3.2 **Update the Water Table map** - The groundwater data used in the analyses presented in this report use the CSD 1995 water table map. Additional water level measurement locations would improve the water table map. This is especially true within the SQS water management areas. Additional work would be very useful in advance of new AEM surveys for the district. These water level measurements can be best accomplished doing a synoptic data gathering during the spring over a short time period. Detailed measurements of the transition from the northwest corner of SQS#2 to the rest of that survey area would be a good addition to the network.

3.3 **Siting new test holes and production wells** – The AEM framework maps and profiles provided in this report provide insight 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 LPNNRD area was used in building the framework maps and profiles. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are

sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in optimal locations. The wells could be sited based on the AEM maps to intercept known confined aquifers in areas of water use complaints to the district.

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 with the best aquifer characteristics, saturated thickness, and aquifer interconnection with the least potential for non-point source pollution.

3.4 **Aquifer testing and borehole logging** - Aquifer tests are recommended to improve estimates of aquifer characteristics. 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 tools for aquifer characteristics are highly recommended. The few test holes with geophysical logs in the LPNNRD AEM survey area were inadequate. None were calibrated and several had apparent hardware malfunctions. The borehole geophysical logs provided for this investigation demonstrate that additional calibrated and verified geophysical logs are required in the LPNNRD.

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

3.5 **Recharge Zones** - The LPNNRD hydrogeologic framework in this report provides areas of potential recharge from the ground surface to the groundwater aquifer. These areas are limited, but understanding this complex relationship in other areas of the district is a beneficial activity that can be used for water sustainability estimates. The block flights of AEM data acquisition provide the most detailed information for understanding recharge throughout the LPNNRD. It is recommended that additional AEM data be collected and interpreted utilizing closely-spaced flight lines using an AEM system that has near-surface resolution. It is further recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention in order to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

3.6 **Mapping Well Production Data**- Produce maps of annual well production per year which can be used to make a comparison to the aquifers mapped using AEM. This would provide data to make an analysis of the available water supply and its use. It will also track well performance related

to boundary conditions within the aquifer system. The district has implemented groundwater management in the District and an annual report on well production would give the Board and the public information on changes that are potentially needed for management particularly during periods of drought. This combined with the District water level program can provide improved knowledge on groundwater management.

4. Deliverables

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and ASCII *.xyz
- SCI inversion Geosoft database and ASCII *.xyz
- Borehole Geosoft databases and ASCII *.xyz
- Interpretations Geosoft database and ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView and Geosoft grid files – surface, topo, etc
- 3D fence diagrams of the SQS#1 and SQS#2 AEM survey lines
- 3D voxel models as ASCII *.xyz and *.gdb for the SQS#1 and SQS#2 AEM survey areas

KMZs for LPNNRD SQS#1 and SQS#2 AEM survey flight lines.
Profile Analyst sessions for the Profiles and 3D grids for the SQS#1 and SQS#2 AEM survey area analysis

Table of Contents

1 Introduction 1
1.1 Purpose of Current Project 1
1.2 Background 2
1.3 Description of the LPNNRD AEM Project Area 4
2 Project Area Hydrogeology 8
2.1 Geologic Setting 8
2.1.1 Physiography and Regional Geologic Setting 8
2.1.2 Surficial Geology 8
2.1.3 Cretaceous Geology 12
2.2 LPNNRD AEM Survey Area Hydrogeologic Characteristics in the Quaternary System 13
2.2.1 Soil Characteristics in the LPNNRD AEM Survey Area 20
2.2.2 Aquifer Characteristics 20
2.2.3 Connectivity to Surface Water and to Other Aquifers 25
2.2.4 Water Quality 25
3 Additional Background Information 26
3.1 Borehole Data 26
4 Geophysical Methodology, Acquisition and Processing 31
4.1 Geophysical Methodology 31
4.2 Flight Planning/Utility Mapping 32
4.3 AEM Survey Instrumentation 33
4.4 Data Acquisition 35
4.4.1 Primary Field Compensation 38
4.4.2 Automatic Processing 38
4.4.3 Manual Processing and Laterally-Constrained Inversions 38
4.4.4 Power Line Noise Intensity (PLNI) 41
4.4.5 Magnetic Field Data 46
4.5 Spatially-Constrained Inversion 49
5 AEM Results and Interpretation 55
5.1 Interpretive Process 55
5.1.1 Merge AEM Databases from Different Flights 55
5.1.2 Construct the Project Digital Elevation Model 60

5.1.3 Create Interpretative 2D Profiles 63
5.1.4 Create Interpretative Surface Grids 72
5.1.5 Create 3D Voxel Grids 89
5.2 Resistivity-Lithology Relationship 90
5.2.1 Quaternary Aquifer System 90
5.2.2 Bedrock Resistivity Thresholds 91
5.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs 91
5.3 Hydrogeological Framework of the LPNNRD AEM Survey Area 93
5.3.1 The Quaternary Aquifer within the SQS#1 and SQS#2 AEM Survey Areas 93
5.3.2 The Cretaceous Bedrock Aquiclude 94
5.3.3 SQS#1 AEM Survey Area 103
5.3.4 SQS#2 AEM Survey Area 113
5.4 Estimation of Aquifer Volume and Water in Storage for the LPNNRD SQS#1 and SQS#2 AEM Survey Areas 125
5.5 Recharge Areas within the LPNNRD AEM Survey Area 128
5.5.1 SQS#1 AEM Survey Area 128
5.5.2 SQS#2 AEM Survey Area 128
5.6 Key AEM Findings 134
5.6.1 Boreholes 134
5.6.2 Merging 2014 and 2016 AEM Databases 134
5.6.3 Digitizing Interpreted Geological Contacts 134
5.6.4 Resistivity/Lithology Relationship 134
5.6.5 Hydrogeological Framework of the LPNNRD 134
5.6.6 Estimation of Aquifer Volume and Water in Storage in the SQS#1 and SQS#2 AEM Survey Areas 135
5.6.7 Potential Recharge Zones within the SQS#1 and SQS#2 AEM Survey Areas 135
5.6.8 Relationship between Registered Wells, Discharge Estimates, and the AEM Results 136
5.6.9 Value of AEM Data Analysis and Images 136
5.7 Recommendations 137
5.7.1 Additional AEM Mapping 137
5.7.2 Update the Water Table map 139
5.7.3 Siting new test holes and production wells 139

5.7.4 Aquifer testing and borehole logging 139
5.7.5 Recharge Zones 140
5.7.6 Mapping Well Production Data 140
6 Description of Data Delivered 141
6.1 Tables Describing Included Data Files 141
6.2 Description of Included Google Earth KMZ Data and Profiles 149
6.2.1 Included README for the LPNNRD Interpretation KMZ's 149
6.3 Description of Included Profile Analyst (PA) Session Material 153
7 References 154
Appendix 1. LPNNRD AEM Flight Line 2D Profiles for SQS#1, SQS#2 ..... A1-1
Appendix 2. LPNNRD AEM 3D Fence Diagrams and Voxel Images for SQS#1, SQS#2 ..... A2-1
Appendix 3. Data Deliverables

List of Figures

Figure 1-1. Map of Nebraska counties, indicating the location of the Lower Platte North Natural Resources District (LPNNRD) airborne electromagnetic (AEM) survey with an inset of the project area... 1
Figure 1-2. The LPNNRD AEM survey areas including county lines and major roads (NE 15, 79, 81). Area SQS#1 is to the east of David City and area SQS#2 is to the north of Columbus.. 2
Figure 1-3. Map showing AEM flight lines from 2013, 2014, and 2015 in the vicinity of the 2016 LPNNRD SQS#1 AEM survey 5
Figure 1-4. Map of major river basins within the SQS#1 AEM survey area (NE-DNR, 2016) 6
Figure 1-5. Map of major river basins within the SQS#2 AEM survey area (NE-DNR, 2016) 7
Figure 2-1. Bedrock map of the LPNNRD SQS#1 AEM survey area, modified from Burchett (1986) 9
Figure 2-2. Bedrock map of the LPNNRD SQS#2 AEM survey area, modified from Burchett (1986) 10
Figure 2-3. Geologic time scale with lithostratigraphic sequence underlying Nebraska, modified from Korus and Joeckel (2011). 11
Figure 2-4. Elevation of ground water surface in SQS#1 survey area (CSD, 1995) 14
Figure 2-5. Elevation of ground water surface in SQS#2 survey area (CSD, 1995) 15
Figure 2-6. Generalized hydrogeologic areas within SQS#1 survey area (Olafsen-Lackey et al., 2005a; Summerside et al., 2005a). These maps show generalized hydrologic connections to the streams and rivers 17
Figure 2-7. Generalized hydrogeologic areas within SQS#2 survey area (Olafsen-Lackey et al., 2005a; Summerside et al., 2005a). These maps show generalized hydrologic connections to the streams and rivers 18

Figure 2-8. Specific yield values within the SQS#1 AEM survey area (Olafsen-Lackey et al., 2005b; Summerside et al., 2005b) 21

Figure 2-9. Specific yield values within the SQS#2 AEM survey area (Olafsen-Lackey et al., 2005b; Summerside et al., 2005b) 22

Figure 2-10. Transmissivity values within the SQS#1 AEM survey area (Olafsen-Lackey et al., 2005c; Summerside et al., 2005c) 23

Figure 2-11. Transmissivity values within the SQS#2 AEM survey area (Olafsen-Lackey et al., 2005c; Summerside et al., 2005c) 24

Figure 3-1. Locations of the Nebraska Conservation Survey Division (CSD) boreholes used in this study of the SQS#1 subarea of the LPNNRD AEM survey area including E-logs, "geologs" , lithology logs, and stratigraphic logs and the airborne electromagnetic flight lines 27

Figure 3-2. Locations of the Nebraska Division of Natural Resources Registered wells and the airborne electromagnetic flight lines in the SQS#1 subarea of the LPNNRD AEM survey area 28

Figure 3-3. Locations of Nebraska Oil and Gas Conservation Commission wells (lithology logs and stratigraphic logs) and the AEM flight lines in the SQS#1 subarea of the LPNNRD AEM survey area..... 28

Figure 3-4. Locations of the Nebraska Conservation Survey Division (CSD) boreholes used in this study of the SQS#2 subarea of the LPNNRD AEM survey area including E-logs, "geologs" , lithology logs, and stratigraphic logs and the airborne electromagnetic flight lines 29

Figure 3-5. Locations of the Nebraska Division of Natural Resources Registered wells and the airborne electromagnetic flight lines in the SQS#2 subarea of the LPNNRD AEM survey area 29

Figure 3-6. Locations of Nebraska Oil and Gas Conservation Commission wells (lithology logs and stratigraphic logs) and the AEM flight lines in the SQS#2 subarea of the LPNNRD AEM survey area..... 30

Figure 4-1. Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a) 31

Figure 4-2. A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model. 32

Figure 4-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1..... 34

Figure 4-4. Photo of the SkyTEM304M system in suspension beneath the helicopter..... 34

Figure 4-5. LPNNRD SQS#1 AEM flight lines grouped by acquisition date 36

Figure 4-6. LPNNRD SQS#2 AEM flight lines grouped by acquisition date 36

Figure 4-7. Example locations of electromagnetic coupling with pipelines or power lines. 39

Figure 4-8. A) Example of AEM data from the LPNNRD AEM survey affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing..... 40

Figure 4-9. A) 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. 41

Figure 4-10. Power Line Noise Intensity (PLNI) map of the LPNNRD SQS#1 project area. 42

Figure 4-11. Power Line Noise Intensity (PLNI) map of the LPNNRD SQS#1 project area 43

Figure 4-12. Locations of inverted data along the AEM flight lines in the LPNNRD SQS#1 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix 3\KMZ.. 44

Figure 4-13. Locations of inverted data along the AEM flight lines in the LPNNRD SQS#2 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix 3\KMZ.. 45

Figure 4-14. Magnetic Total Field intensity data for the LPNNRD SQS#1 AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed 46

Figure 4-15. Magnetic Total Field intensity data for the LPNNRD SQS#2 AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed 47

Figure 4-16. USGS magnetic Total Field intensity data for the LPNNRD SQS#1 AEM survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5 mile line spacing and upward continued to a reference elevation of 1000 ft. 48

Figure 4-17. USGS magnetic Total Field intensity data for the LPNNRD SQS#2 AEM survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5 mile line spacing and upward continued to a reference elevation of 1000 ft. 49

Figure 4-18. An example of an AEM profile illustrating increasing model layer thicknesses with depth. . 51

Figure 4-19. Data/model residual histogram for the LPNNRD SQS#1 SCI inversion results 52

Figure 4-20. Data/model residual histogram for the LPNNRD SQS#2 SCI inversion results 52

Figure 4-21. Map of data residuals for the LPNNRD SQS#1 SCI inversion results 53

Figure 4-22. Map of data residuals for the LPNNRD SQS#2 SCI inversion results 54

Figure 5-1. Example of a profile view of a north-south flight line L601402, part of SQS#1 that was combined from the 2015 ENWRA AEM and the 2016 LENRD AEM..... 57

Figure 5-2. Example of a profile view of three east-west lines within SQS#2. The top profile L112101 was collected in 2016 with the SkyTEM304M; the middle profile line L101701 was collected in 2014 with the SkyTEM508; and the bottom profile line L112301 was collected in 2016 with the SkyTEM304M 58

Figure 5-3. A comparison between the southernmost east-west line in the 2016 AEM survey of SQS#1 and the northernmost east-west line in the 2013 AEM survey..... 59

Figure 5-4. Map of the Digital Elevation Model for SQS#1 61

Figure 5-5. Map of the Digital Elevation Model for SQS#2 62

Figure 5-6. 10.5-mile long east-west line L109301 within the SQS#1 survey area..... 65

Figure 5-7. 9.5-mile long north-south line L400301 within the SQS#1 survey area 66

Figure 5-8. 3D fence diagram made up of the SQS#1 2D inverted resistivity earth-model profiles 67

Figure 5-9. 22.5-mile long east-west line L111301 within the SQS#2 AEM survey area 69

Figure 5-10. 11-mile long north-south line L284003 within the SQS#2 AEM survey area 70

Figure 5-11. 3D fence diagram made up of the SQS#2 2D inverted resistivity earth-model profiles 71

Figure 5-12. Map of the elevation of the top of the Cretaceous Niobrara Formation (***Kn***) within the SQS#2 AEM survey area..... 73

Figure 5-13. Map of the elevation of the top of the Cretaceous Carlile Shale (***Kc***) within the SQS#2 AEM survey area 74

Figure 5-14. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***) within the SQS#1 AEM survey area 75

Figure 5-15. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***) within the SQS#2 AEM survey area 76

Figure 5-16. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the SQS#1 AEM survey area 77

Figure 5-17. Map of the elevation of the top of the Cretaceous bedrock within the SQS#1 AEM survey area 79

Figure 5-18. Map of the elevation of the top of the Cretaceous bedrock within the SQS#1 AEM survey area and the area covered by Carney et al. (2014b) 80

Figure 5-19. Map of the elevation of the top of the Cretaceous bedrock within the SQS#2 AEM survey area 81

Figure 5-20. Map of the elevation of the 1995 CSD water table (NE CSD, 1995) within the SQS#1 AEM survey area 83

Figure 5-21. Map of the elevation of the 1995 CSD water table (NE CSD, 1995) within the SQS#2 AEM survey area 84

Figure 5-22. Map of the thickness of the Quaternary (***Q***) within the SQS#1 AEM survey area 85

Figure 5-23. Map of the thickness of the Quaternary (***Q***) within the SQS#2 AEM survey area 86

Figure 5-24. Map of the saturated thickness of the Quaternary (***Q***) within the SQS#1 AEM survey area . 87

Figure 5-25. Map of the saturated thickness of the Quaternary (***Q***) within the SQS#2 AEM survey area . 88

Figure 5-26. Plot displaying the resistivities by major aquifer material color categories (blue- non-aquifer material, tan- marginal aquifer, yellow- aquifer, brown- sand-rich, coarse intervals of the aquifer material) 90

Figure 5-27. Graph of borehole *01-LPN-15* 16-inch normal resistivity log values, 64-inch normal, lateral resistivity log and the inverted airborne electromagnetic resistivity values. Also indicated is the lithology and stratigraphy log from *01-LPN-15* as well as the aquifer material categories 92

Figure 5-28. 3D map looking to the north of the interpreted distributions of aquifer materials within SQS#1 AEM survey area 95

Figure 5-29. 3D map looking to the north of the interpreted distributions of aquifer material within the SQS#2 survey area 96

Figure 5-30. Map of Quaternary material thickness looking to the north within the SQS#1 survey area . 97

Figure 5-31. 3D map looking to the northwest of the interpreted distributions of marginal and non-aquifer materials that accompany the aquifer materials found in the southwest region of SQS#1 98

Figure 5-32. Profile view of line L140601 showing a north-south profile in SQS#1 (north is on the right). There is aquifer and coarse aquifer material on the south separated by marginal and non-aquifer material in the center and the north 99

Figure 5-33. Map of Quaternary material thickness looking to the north within the SQS#2 survey area 100

Figure 5-34. 3D map looking to the northwest of the interpreted distributions of marginal and non-aquifer materials that accompany the aquifer materials found in the northwest region of SQS#2 101

Figure 5-35. Profile view of line L1113901 showing east-west profile in SQS#2 (east is on the right). There is aquifer and coarse aquifer material across the profile separated by marginal and non-aquifer material above and below 102

Figure 5-36. Base of the *Q* aquifer which is the top of the bedrock. Two channels eroded into the bedrock can be seen lying between three bedrock highs 105

Figure 5-37. Voxel of SQS#1 saturated thickness of aquifer (yellow) and coarse aquifer materials (brown) paired with 3D fence diagram of non-aquifer materials (blue) and marginal aquifer (tan) and the bedrock units 106

Figure 5-38. Saturated thickness of all aquifer materials including non-aquifer, marginal aquifer, aquifer, and coarse aquifer in the SQS#1 AEM survey area 107

Figure 5-39. Saturated thickness of just the aquifer and coarse aquifer material in the SQS#1 AEM survey area. Note the thickest sections occupy the channel trending along the center south of SQS#1 survey area. 108

Figure 5-40. Voxel model with a view to the northeast, showing continuous volumes of the four different types of aquifer materials: Non-aquifer materials (blue), marginal aquifer (tan), aquifer (yellow), and coarse aquifer materials (brown) 109

Figure 5-41. Voxel model with a view to the north, showing continuous volumes of the aquifer material and coarse aquifer material: aquifer (yellow), and coarse aquifer materials (brown) 110

Figure 5-42. Voxel model with view to the north, showing continuous volume of aquifer material above and below the water table 111

Figure 5-43. Map showing DNR wells in the vicinity of SQS#1 their water flow discharge capacity overlain on a representation of the thickness of the saturated Quaternary aquifer material. Small blue dots imply low discharge rates (<100 gpm) and large red dots imply higher water discharge rates (>1200 gpm) ... 112

Figure 5-44. Base of the *Q* aquifer which is the top of the bedrock. Two channels eroded into the bedrock can be seen lying between three bedrock highs 115

Figure 5-45. Voxel of SQS#2 saturated thickness of aquifer (yellow) and coarse aquifer materials (brown) paired with 3D fence diagram of non-aquifer materials (blue) and marginal aquifer (tan) and the bedrock units 116

Figure 5-46. Saturated thickness of all aquifer materials including non-aquifer, marginal aquifer, aquifer and coarse aquifer in the SQS#2 AEM survey area 117

Figure 5-47. Saturated thickness of aquifer and coarse aquifer material in the SQS#2 AEM survey area. Note the thickest sections occupy the channel trending along the center of SQS#2 survey area 118

Figure 5-48. Voxel model with a view to the northeast, showing continuous volumes of the four different types of aquifer materials 119

Figure 5-49. Voxel model with a view to the north, showing continuous volumes of the aquifer material and coarse aquifer material 120

Figure 5-50. Voxel model with view to the north, showing continuous volume of aquifer material above and below the water table 121

Figure 5-51. Voxel model with view to the north, showing continuous volumes of coarse aquifer materials below the water table 121

Figure 5-52. Shows profile view of Line L400301 illustrating the differences between small isolated aquifers versus large interconnected aquifers. Note the marginal and non-aquifer materials separating the aquifers along the flight line 123

Figure 5-53. Map showing DNR wells in the vicinity of SQS#2 and their water flow discharge capacity overlain on a representation of the thickness of the saturated Quaternary aquifer material. Small blue dots imply low discharge rates (<100 gpm) and large red dots imply higher water discharge rates (>1200 gpm) 124

Figure 5-54. Map of all aquifer materials for the first 0 to 10 feet displayed over the LPNNRD SQS#1 AEM survey area 130

Figure 5-55. Map of all aquifer materials for the first 0 to 10 feet displayed over the LPNNRD SQS#2 AEM survey area 131

Figure 5-56. Potential aquifer and coarse material recharge zones within the LPNNRD SQS#1 AEM survey area displayed as a kmz in Google Earth 132

Figure 5-57. Potential aquifer and coarse material recharge zones within the LPNNRD SQS#2 AEM survey area displayed as a kmz in Google Earth 133

Figure 5-58. Acquired AEM flight lines in 2016 and proposed flight lines for 2018 138

Figure 6-1. Example Google Earth image for the LPNNRD SQS#1 Interpretation kmz 151

Figure 6-2. Example Google Earth image for the LPNNRD SQS#2 Interpretation kmz 152

List of Tables

Table 2-1. Aquifers in Quaternary and Tertiary Age stratigraphic units. 19

Table 4-1. Positions of instruments on the SkyTEM304M frame, using the center of the frame as the origin, in feet 35

Table 4-2. Positions of corners of the SkyTEM304M transmitter coil, using the center of the frame as the origin in feet 35

Table 4-3. Location of DGPS and magnetic field base station instruments was the Genoa Airport 35

Table 4-4. Thickness and depth to bottom for each layer in the Spatially Constrained inversion (SCI) AEM earth models. The thickness of the model layers increase with depth as the resolution of the AEM technique decreases 50

Table 5-1. Combination of flight lines within the LPNNRD SQS#2 AEM survey area 55

Table 5-2. Combination of 2014 and 2015 AEM data (Carney et al., 2015) flight lines within the 2016 LPNNRD SQS#1 and SQS#2 55

Table 5-3. Estimates of groundwater in storage and extractable water content in all aquifer materials underlying the SQS#1 AEM survey area 127

Table 5-4. Estimates of groundwater in storage and extractable water content in all aquifer materials underlying the SQS#2 AEM survey area 127

Table 6-1. Channel name, description, and units for LPNNRD_SQS1_EM_MAG_v1 and LPNNRD_SQS2_EM_MAG_v1 Geosoft *.gdb and *.xyz with EM, magnetic, DGPS, Inclinometer, altitude, and associated data 143

Table 6-2. Channel name, description, and units for LPN_SQS1_AEM_SCI_Inv_v2 and SPN_SQS2_AEM_SCI_INV_v2 Geosoft gdb and xyz files with EM inversion results 144

Table 6-3. Files containing borehole information for SQS#1 and SQS#2 145

Table 6-4. Channel name, description, and units for borehole collar files 145

Table 6-5. Channel name description and units for borehole data 147

Table 6-6. Channel name description and units for the interpretation results file LPNNRD_SQS1_InterpSurfaces_v1 and LPNNRD_SQS2_InterpSurfaces_v1 “gdb” and “xyz” files 147

Table 6-7. Raw SkyTEM data files 147

Table 6-8. Files containing ESRI ArcView Binary Grids *.flt and Geosoft Grids *.grd (NAD 83 UTM 14 North, feet) 148

Table 6-9. Channel name, description, and units for LPNNRD SQS#1 and SQS#2 AEM survey areas as*.csv and *.gdb 148

Table 6-10. Datamine Discover (formerly pbEncom Discover) PA Session Files 153

List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
A*m^2	Ampere meter squared
AEM	Airborne Electromagnetic
AGF	Aqua Geo Frameworks, LLC
CSD	Conservation and Survey Division
dB/dt	Change in amplitude of magnetic field with time
DEM	Digital Elevation Model
DOI	Depth of Investigation
DGPS	Differential global positioning system
ENWRA	Eastern Nebraska Water Resources Assessment
ft	Feet
Fm	Formation
GIS	Geographic Information System
gpm	Gallons per minute
HEM	Helicopter Electromagnetic
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
Km/km	Kilometers
KMZ/kmz	Keyhole Markup language Zipped file

Kc	Cretaceous Carlile Fm
Kd	Cretaceous Dakota Group
Kgg	Cretaceous Greenhorn/Graneros Fm
Kn	Cretaceous Niobrara Fm
Kp	Cretaceous Pierre Fm
LENRD	Lower Elkhorn Natural Resources District
LPNNRD	Lower Platte North Natural Resources District
LPSNRD	Lower Platte South Natural Resources District
MAG	Magnetic (data); Magnetometer (instrument)
MCG	Minimum curvature gridding
m	Meters
mg/L	Milligrams per liter
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NE-DEQ	Nebraska Department of Environmental Quality
NE-DNR	Nebraska Department of Natural Resources
NMR	Nuclear Magnetic Resonance
NOGCC	Nebraska Oil and Gas Conservation Commission
NRD	Natural Resources Districts
OM	Geosoft Oasis montaj
PFC	Primary Field Compensation
PLNI	Power Line Noise Intensity
Q	Quaternary
Rx	Receiver
SCI	Spatially-Constrained Inversion
STD	Standard Deviation
TEM	Time-Domain Electromagnetic
TDEM	Time-Domain Electromagnetic
TDS	Total dissolved solids
Tx	Transmitter
UNL	University of Nebraska Lincoln
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
XRI	Exploration Resources International

1 Introduction

1.1 Purpose of Current Project

The Lower Platte North Natural Resources District (LPNNRD) desired an improved understanding of the hydrogeologic framework in the LPNNRD within the two Special Quantity Subareas, referred to as SQS#1 and SQS#2 in this report, to provide detailed subsurface information related to the groundwater management (Figure 1-1). This includes detailed information on the subsurface geology to assist in understanding the groundwater quality, surface water/groundwater interaction, amount of groundwater in storage, effects of groundwater pumping in small aquifers and recharge. An airborne electromagnetic (AEM) survey was selected to assist in the development of a 3D hydrogeologic framework of these project areas and recommend future work to enhance groundwater management activities (Figure 1-2).

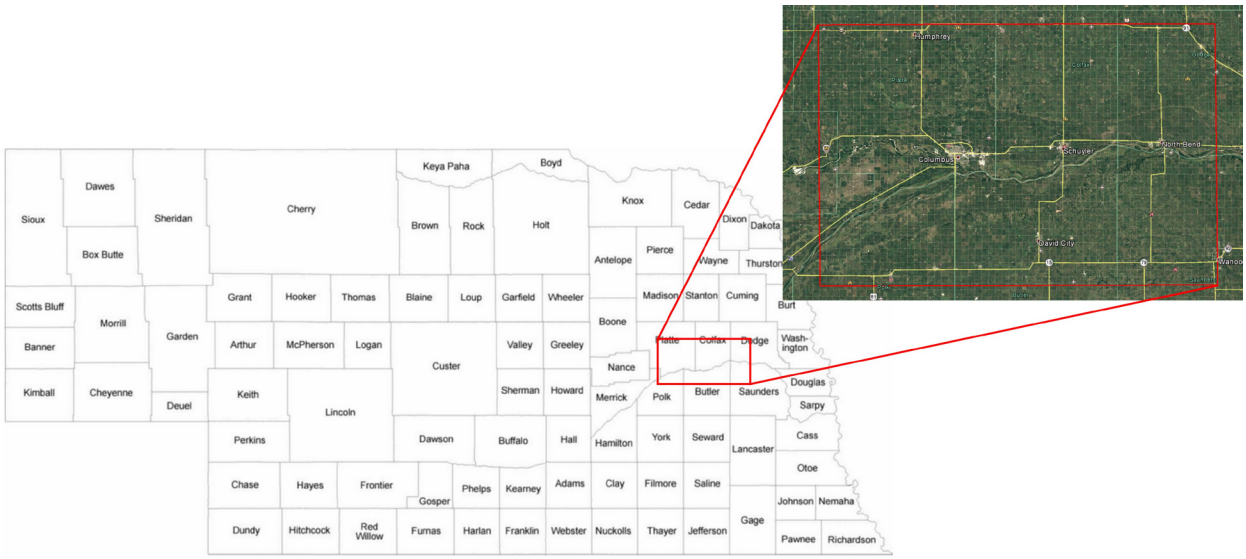


Figure 1-1. Map of Nebraska counties, indicating the location of the Lower Platte North Natural Resources District (LPNNRD) airborne electromagnetic (AEM) survey with an inset of the project area.

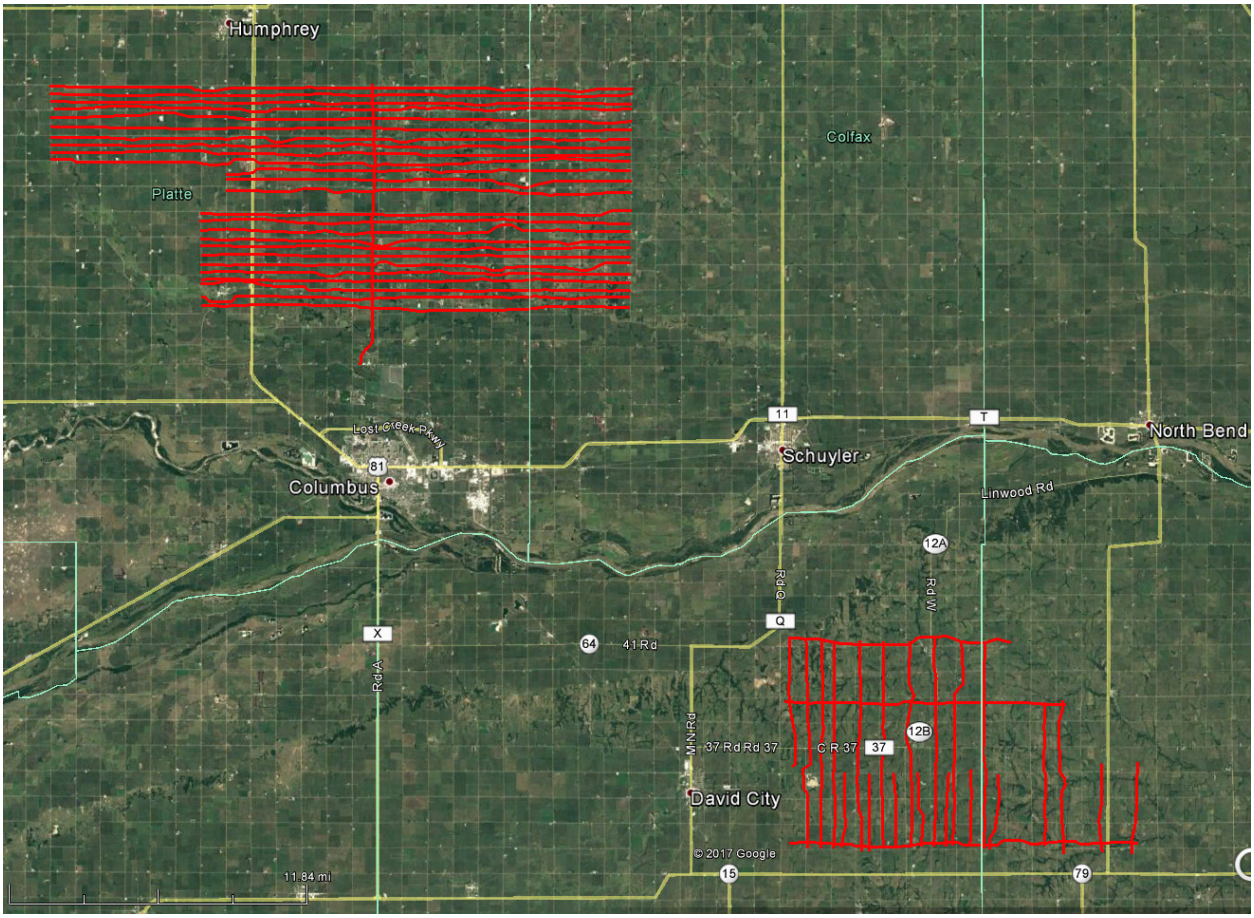


Figure 1-2. The LPNNRD AEM survey areas including county lines and major roads (NE 15, 79, 81). Area SQS#1 is to the east of David City and area SQS#2 is to the north of Columbus.

1.2 Background

In 2008, the LPNNRD declared the portions of the District as Hydrologically Connected Areas (HCAs) which have limited irrigation development allowed every year (LPNNRD, 2017). This determination was based on studies by Nebraska Department of Natural Resources (NE-DNR) and the LPNNRD. The conclusions from these studies indicated that the aquifers appeared to be hydrologically connected to surface water. The report also concluded that the most affected region was considered "fully Appropriated" (LPNNRD, 2017). The LPNNRD also has Restricted Development Areas (RDAs) in Butler, Dodge and Saunders Counties to address quantity management rules of the known aquifers of thin and limited size. Within SQS#1 and SQS#2 management areas the complex geology is related to highly volatile groundwater level changes related to the influence of drought and related increased in groundwater pumping during the irrigation season (LPNNRD, 2017).

Use of AEM technology to map and evaluate groundwater resources has gained momentum over the last 20 years in the United States and abroad. The state of Nebraska has been on the forefront of implementing AEM for water resources management over the last decade with projects across the state in a variety of geologic settings. In recent years, the Eastern Nebraska Water Resources Assessment

(ENWRA) has coordinated efforts between area Natural Resources Districts (NRDs), Nebraska 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, LPNNRD, ENWRA, and CSD are cooperating with AGF because of the shared borders and common groundwater management efforts between these NRDs.

The ENWRA project was formed in 2006 with sponsors from six NRDs (Lewis and Clark, Lower Elkhorn, Papio-Missouri River, Lower Platte North, Lower Platte South, and Nemaha) and cooperating agencies including the CSD and the USGS. The long-term goal of the project is to develop a geologic framework and water budget for the glaciated portion of eastern Nebraska. In March 2007, ENWRA funded a study where AEM methods were implemented by the USGS to characterize the hydrogeologic conditions in the Platte River valley near Ashland, as well as in areas underlain by glacial till near Firth and Oakland, Nebraska (Abraham et al., 2011; Hanson et al., 2012; Korus et al., 2013). In the following years, individual reports utilizing the AEM data collected in 2007 were released by the USGS and CSD. In 2009, a multi-faceted investigation incorporating the 2007 AEM data and 2009 ground-based geophysical techniques was conducted by the USGS to characterize the hydrogeologic setting near Oakland, Nebraska (Abraham et al., 2011). In 2009, the Lower Platte North NRD funded the USGS for the development of a 3D hydrostratigraphic framework of the subsurface near Swedeburg, Nebraska based on an AEM survey (Smith et al., 2009; Divine and Korus, 2013). Also in 2009, the Lower Platte South NRD funded the USGS and CSD for a similar investigation of the hydrostratigraphy near Sprague, Nebraska (Smith et al., 2009; Divine and Korus, 2012). Based on the recommendations of Abraham et al. (2011), in 2013, the Lower Elkhorn NRD funded Exploration Resources International, LLC (XRI) to conduct an AEM survey near the towns of Clarkson and Howells, Nebraska in order to characterize the extent of the Quaternary aquifer beneath the area following the drought of 2012 (Abraham et al., 2013). At the same time the City of Madison also funded XRI for a small scale AEM study in and around the City of Madison (Carney et al., 2014a). Also in 2013, XRI completed an AEM survey covering over 800 line-miles in Butler and Saunders counties northwest of the city of Lincoln, Nebraska (Carney et al., 2014b). This survey, funded by the LPSNRD, revealed buried paleovalley aquifers beneath thick sequences of till. The LPSNRD survey is immediately south of the SQS#1 area. Additionally, intervals of Cretaceous bedrock units were revealed in the survey. The LENRD began to map their district with three-mile AEM grids in the fall of 2014 (Exploration Resources International, 2015). In 2014-2015 the ENWRA funded XRI for a large-scale reconnaissance AEM survey over the glaciated portion of Nebraska, approximately 2,200 line-km of approximately 32 km spaced lines (Abraham et al., 2015; Carney et al., 2015a; Carney et al., 2015b). In 2016, a study led by the CSD showed that the details gained from the AEM survey in around the Firth and Sprague area provided unique details that assisted in the management of the groundwater resources (Korus et al., 2016). In 2017, a study led by AGF provided information to improve the understanding of the hydrogeologic framework including areas of recharge to the aquifer and details for well head protection areas in the Bazile Creek Groundwater Management area (AGF, 2017a). Additionally, in 2017 another study led by AGF provided detailed 3D hydrogeologic framework for the western portions of Sarpy County characterized by eroded Dakota Sandstone aquifers overlain with glacial deposits (AGF, 2017b). Additional studies in the Lower Loup, Lewis and Clark, and Lower Elkhorn NRDs were completed to understand the complex glacial and non-glacial aquifers in their districts (AGF

2017c; AGF, 2017d; AGF, 2017e). Thus, AEM surveys of the glacial terrain of Nebraska have followed a progressive, long-term plan spanning nearly 10 years. This body of work shows continuing advancements in the science and application of AEM to support groundwater management.

In addition to the AEM and Magnetic Total Field data acquired during this investigation, multiple resources were used to develop the presented hydrogeologic framework and subsequent recommendations for potential recharge areas and well locations. Data and findings from previous studies, along with geologic descriptions and geophysical data were utilized to develop the hydrogeologic framework presented herein. A location map showing the LPNNRD survey flight areas and flight lines is presented in Figure 1-2. A Google Earth kmz of the "as-flown" flight lines is included in *Appendix_3_Deliverables\KMZ*. A map showing flight lines from 2013, 2014, and 2015 in the vicinity of the 2016 LPNNRD SQS#1 survey is presented in Figure 1-3.

1.3 Description of the LPNNRD AEM Project Area

The two areas of interest, SQS#1 and SQS#2, in the LPNNRD AEM survey area, are located in east-central Nebraska and encompass approximately 116 and 204 square miles, respectively (Figure 1-4 and Figure 1-5). SQS#1 lies within Butler and Saunders Counties. SQS#2 lies within Colfax and Platte Counties. Precipitation and runoff within SQS#1 and SQS#2 feed into Lower Platte River Basin (NEDNR, 2016): the Lower Platte, and the Middle Platte Basins are in the boundaries of SQS#1 and SQS#2. They sit in distinct groundwater regions; namely, the East Central Dissected Plains and the Nebraska Glacial Drift (Pederson et al., 1986). The towns of Abie and Bruno lie within the SQS#1 AEM survey area. The towns of Platte Center and Tarnov lie within the SQS#2 AEM survey area.

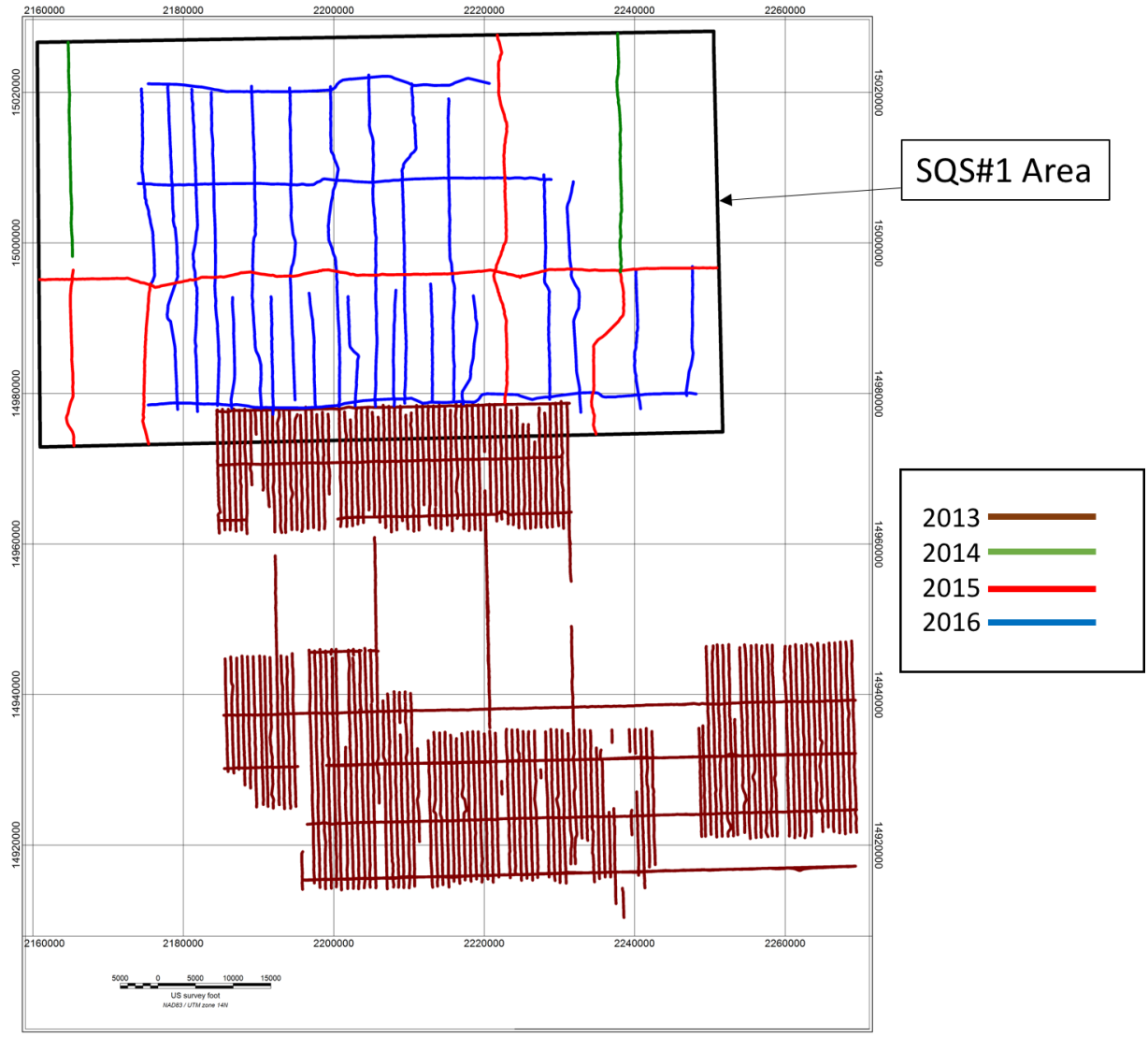


Figure 1-3. Map showing AEM flight lines from 2013, 2014, and 2015 in the vicinity of the 2016 LPNNRD SQS#1 AEM survey.

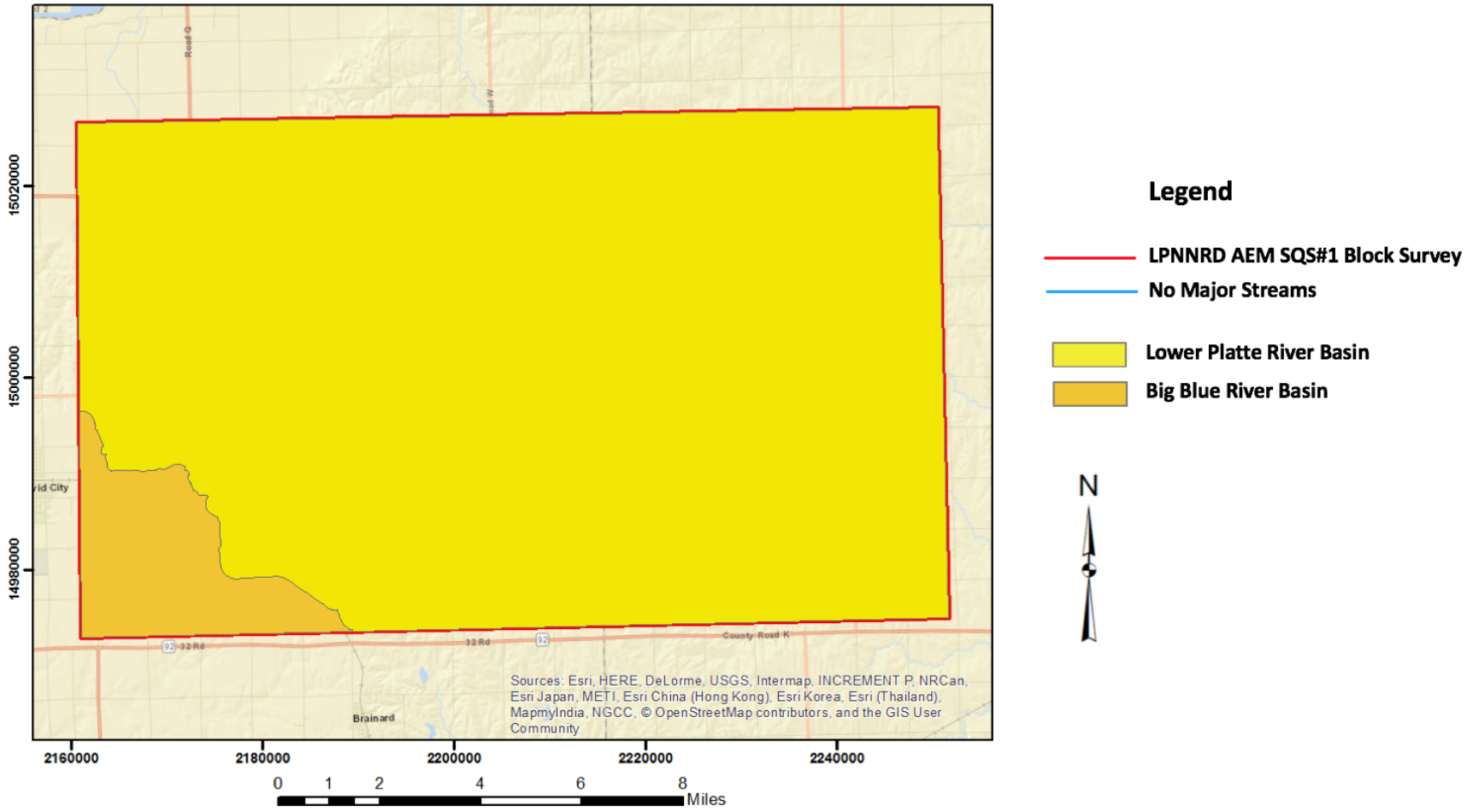


Figure 1-4. Map of major river basins within the SQS#1 AEM survey area (NE-DNR, 2016a).

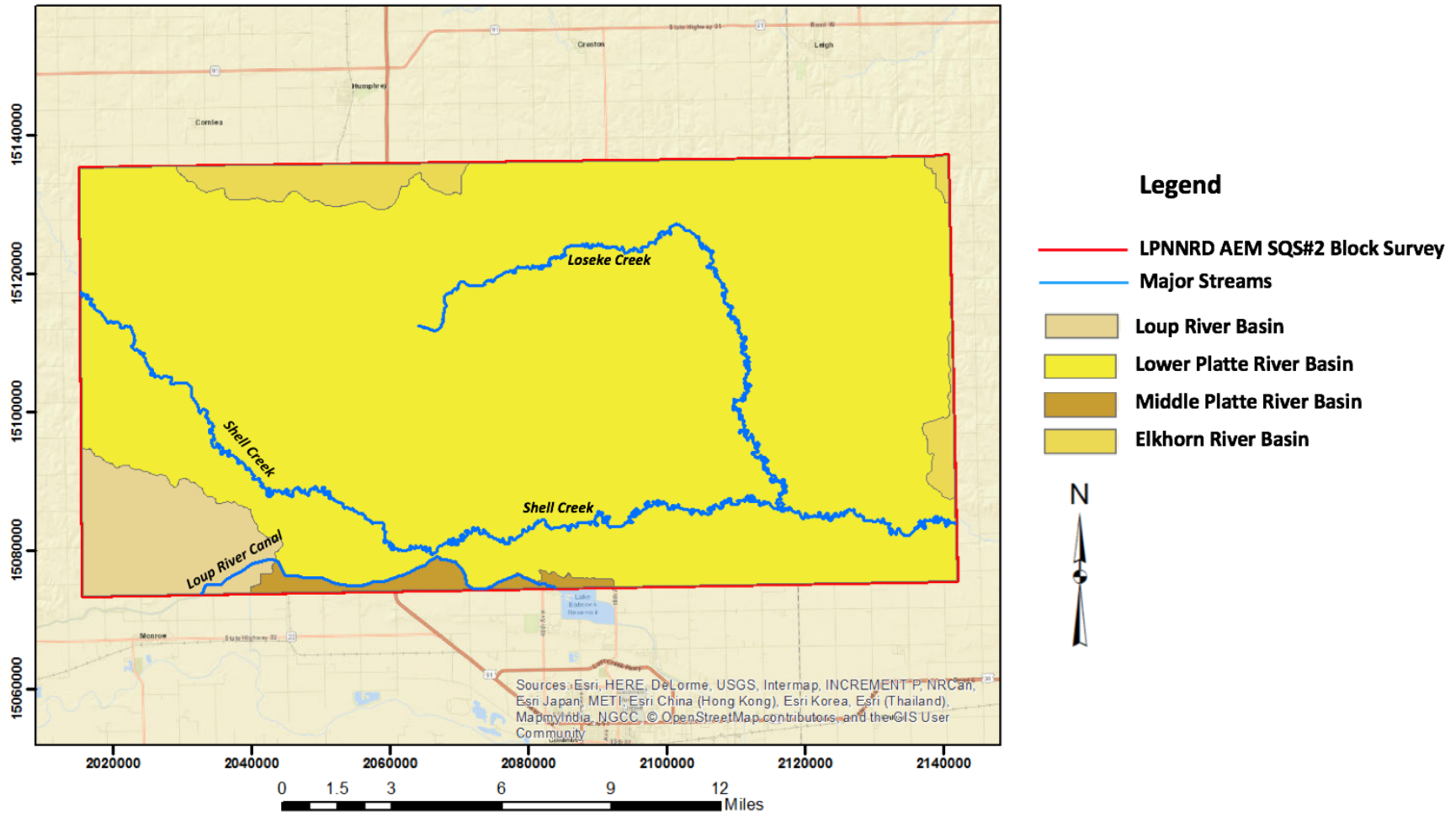


Figure 1-5. Map of major river basins within the SQS#2 AEM survey area (NE-DNR, 2016a).

2 Project Area Hydrogeology

2.1 Geologic Setting

The geology and hydrogeology of the LPNNRD Survey Area and surrounding areas have been studied extensively for over a century with the most recent studies focusing on understanding the hydrogeology of the area related to sustainability of groundwater. Much of the background geology and hydrogeology is present in Carney et al. (2015a) and will not be repeated here in detail. The following sections will include only a brief overview of the geology and hydrogeology of the project area pertinent to the AEM investigation and interpretation analysis. For a more detailed review, the reader is encouraged to explore the background of the region using the references listed. The following narrative is based primarily on the findings from these reports.

2.1.1 Physiography and Regional Geologic Setting

The project area containing SQS#1 and SQS#2 are in east-central Nebraska lie near the towns of Abie and Bruno(SQS#1) and Platte Center and Tarnov (SQS#2). They are within the Valleys, Bluffs and Escarpments, Dissected Plains, Plains, and Rolling Hills topographic regions of Nebraska (CSD, 1951). Bedrock geology in the project area is comprised of consolidated marine sedimentary rocks as presented in Figure 2-1 and Figure 2-2 (from Burchett, 1986). These deposits are not deformed by folding and faulting. The Quaternary (***Q***) sediments in SQS#2 are made up alluvial materials in the west and glacial deposits in the east. Quaternary glacial till covers all SQS#1.

2.1.2 Surficial Geology

The complex Pleistocene and Holocene Quaternary geology in east-central Nebraska consists of sequences of clay, silt, till, sand, and gravel overlying bedrock units. These materials are capped by loess deposits in many locations. Figure 2-3 displays the geologic time scale with CSD's lithostratigraphic sequence that underlies the state of Nebraska (Korus and Joeckel, 2011). The surficial geology of the project area is typical of western mid-continental glaciated areas of North America where buried Quaternary sand and gravel glacial outwash deposits or paleovalleys, comprised of unconsolidated Plio-Pleistocene sand and gravel units, underlie extensive areas of glacial till. In much of northeast Nebraska, glacial till often underlies loess units (e.g., Peoria, Gillman Canyon Formation, and Loveland Loess deposits). Present day surface water systems have incised the loess and till to wide stream valleys in some locations (e.g., Platte River Valley).

CSD test holes and drillers logs obtained from NE-DNR indicate glacial till units are present in the northern portion of the project area. Beneath much of the LPNNRD AEM survey area the surficial deposits consist of Quaternary alluvium composed of inter-bedded gravel, sand, and silt.

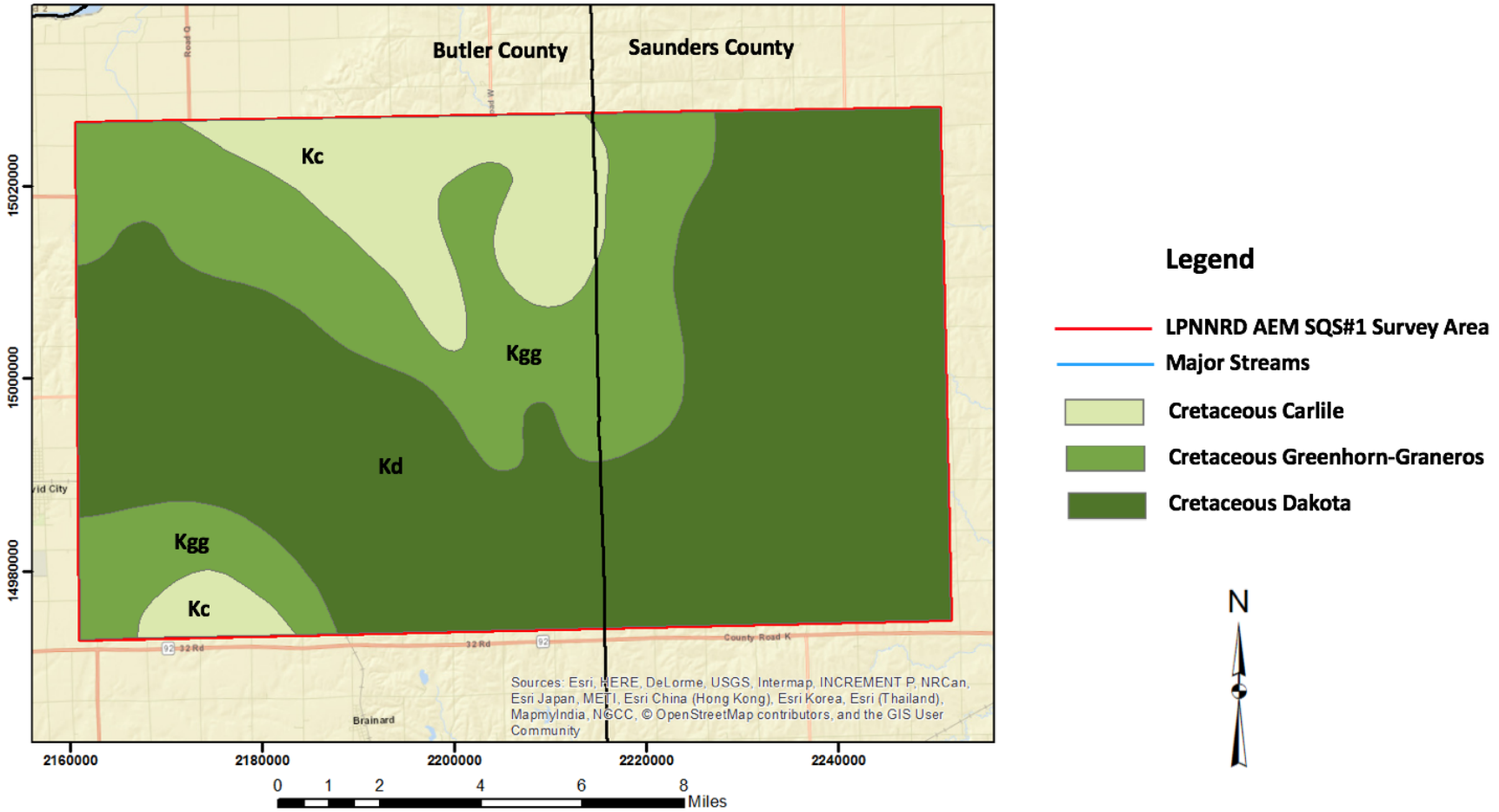


Figure 2-1. Bedrock map of the LPNNRD SQS#1 AEM survey area, modified from Burchett (1986). Projection is NAD83, UTM 14 North (feet).

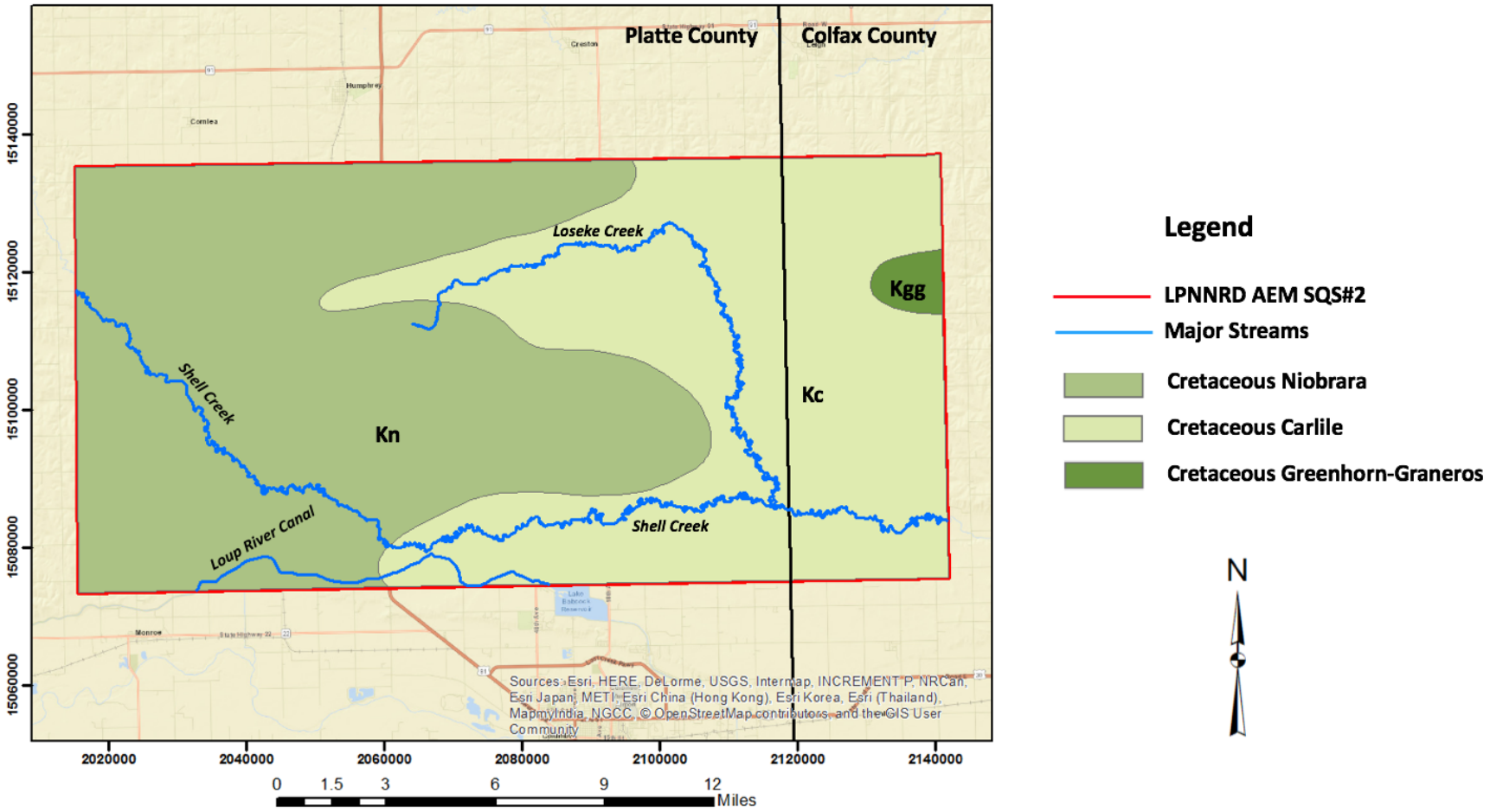


Figure 2-2. Bedrock map of the LPNNRD SQS#2 AEM survey area, modified from Burchett (1986). Projection is NAD83, UTM 14 North (feet).

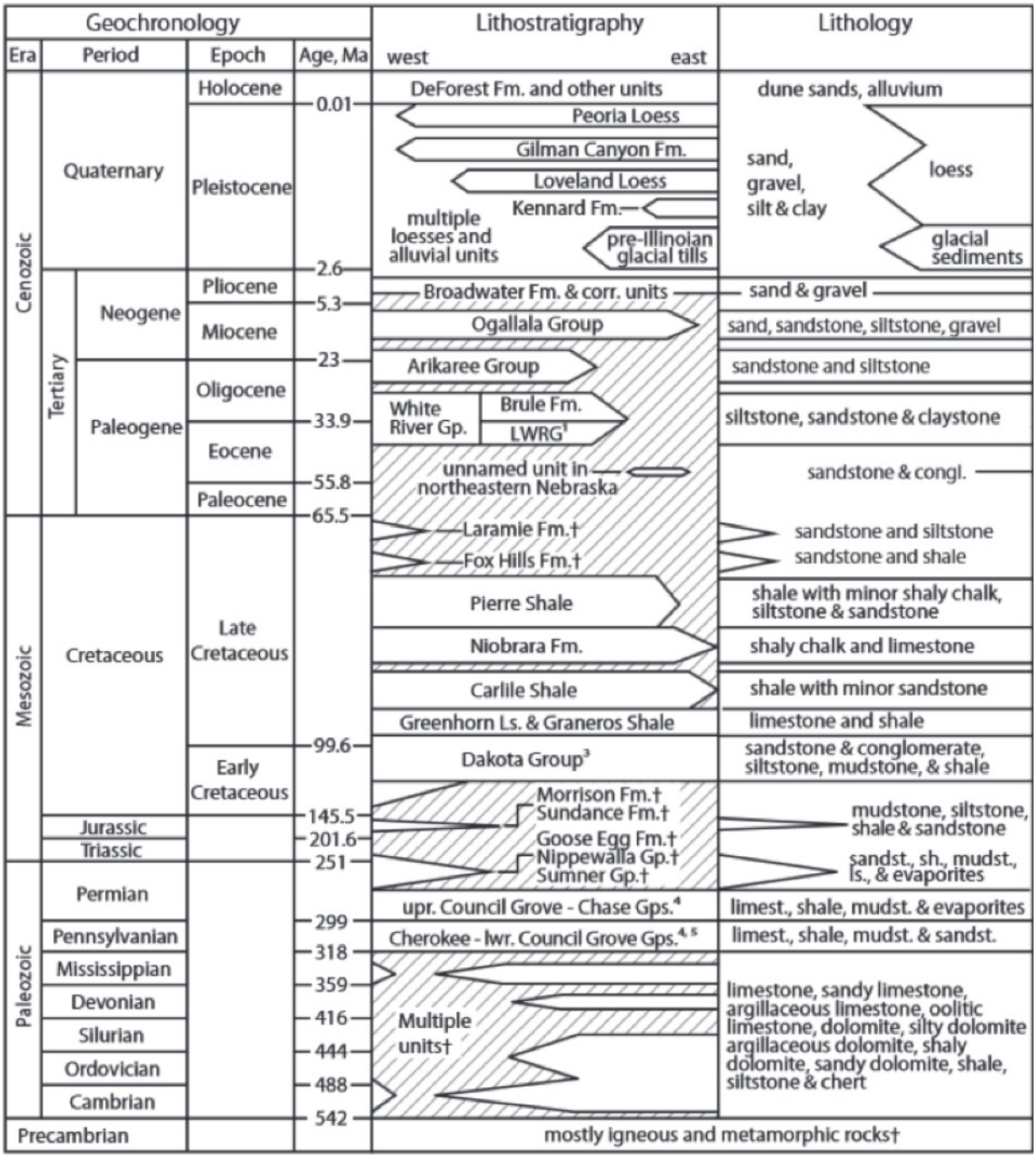


Figure 2-3. Geologic time scale with lithostratigraphic sequence underlying Nebraska, modified from Korus and Joeckel (2011).

2.1.3 Cretaceous Geology

There are deposits within the area from both the Upper and Lower Cretaceous. The Upper Cretaceous bedrock formations are Niobrara Formation (***Kn***), Carlile Shale (***Kc***), and Greenhorn Limestone and Graneros Shale (***Kgg***). Together these formations are comprised of interbedded sandy shales, shales, indurated shaly chalks, and thin layers of bentonite, and limestones (Condra and Reed, 1959; Gutentag et al., 1984). These formations thin and pinch out to the east (Divine, 2012), but where present they act as a lower confining unit to saturated ***Q*** deposits. None of the Upper Cretaceous formations yield beneficial amounts of potable groundwater within the project boundaries. However, in some areas of eastern Nebraska, the ***Kn***, where fractured, is known to yield water for irrigation purposes (Gutentag et al., 1984; Miller and Appel, 1997).

Underlying the Upper Cretaceous formations is the regionally extensive Lower Cretaceous Dakota Group (***Kd***). The ***Kd*** is comprised primarily of massive to interbedded sandstone with ironstone and shale, some argillaceous to slightly sandy (Condra and Reed, 1959). The sandstone in the Dakota Group typically has low permeability and storage compared to the unconsolidated units overlying it. While all the Cretaceous units above occur within the LPNNRD AEM survey area, this report will focus on the ***Kn***, ***Kc,*** ***Kgg***, and ***Kd*** as they directly underlie the Quaternary and Tertiary aquifers. The Cretaceous is underlain by Paleozoic and Precambrian units these units will not be discussed in this report.

2.2 LPNNRD AEM Survey Area Hydrogeologic Characteristics in the Quaternary System

Maps showing the major streams and rivers with the associated basin areas within the LPNNRD AEM survey area are shown in Figure 1-3 and Figure 1-4. SQS#1 has no major streams located within its boundary (Figure 1-3) but it is within the Lower Platte and Big Blue river basins (NE-DNR, 2016). SQS#2 has associated major stream tributaries and canals along with surface water basins (Figure 1-4) that exist between the Loup, Middle Platte, Elkhorn and Lower Platte rivers (NE-DNR, 2016). The largest surface-water system in the project areas is the Lower Platte River (U.S. Geological Survey, 2015) which flows west to east.

The elevation of the water table within the project areas are shown in Figure 2-4 for SQS#1 and Figure 2-5 for SQS#2. The water table maps are from the CSD 1995 water table map (CSD, 1995) and represent the general shape of the water table as 50 foot contours of elevation; actual water levels will likely be somewhat different.

Regional groundwater-flow direction for the project area is predominately from west to east (Figure 2-4 and Figure 2-5). The direction of flow in SQS#2 takes a similar course of the major streams and rivers. In SQS#1 there is a groundwater divide near the town of Bruno with groundwater flow moving from the center of the divide from west to east and from the center of the divide northwest towards the town of Octavia. Within SQS#1 groundwater locally may be hydrologically connected to surface water in some areas. In SQS#2 groundwater levels that are located at shallower depths in the alluvial valleys maybe hydrologically connected to streams. Water levels change with the seasons and typically reach maximum depths from extensive groundwater pumping and usage during the crop growing months. Groundwater levels typically return to shallower, pre-stress levels in the March to June timeframe. Annual depths of drawdown and recharge of aquifers highly depend on the type of aquifer (e.g. confined or unconfined), proximity of the aquifer to the land surface, and the magnitude of stress exhibited on the system during the pumping season, combined with the amount of recharge available to the aquifer. The changes in water levels are more dramatic during time of drought due to the increased demand for irrigation and other uses. In areas where the aquifers are small and disconnected from each other or have no ability to intercept water from streams the greatest drawdowns are seen during drought.

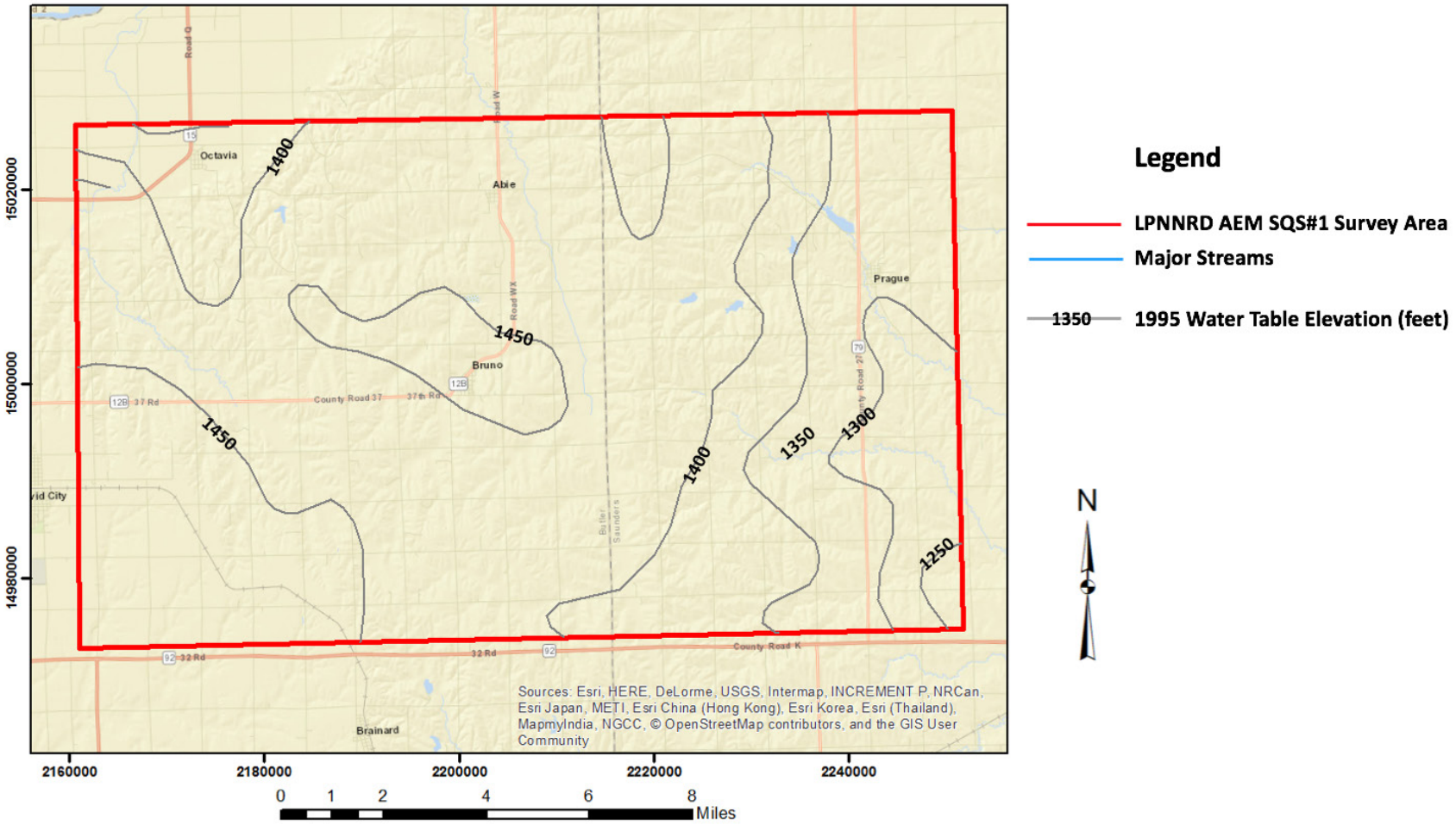


Figure 2-4. Elevation of ground water surface in SQS#1 survey area (CSD, 1995). Projection is NAD83, UTM 14 North (feet).

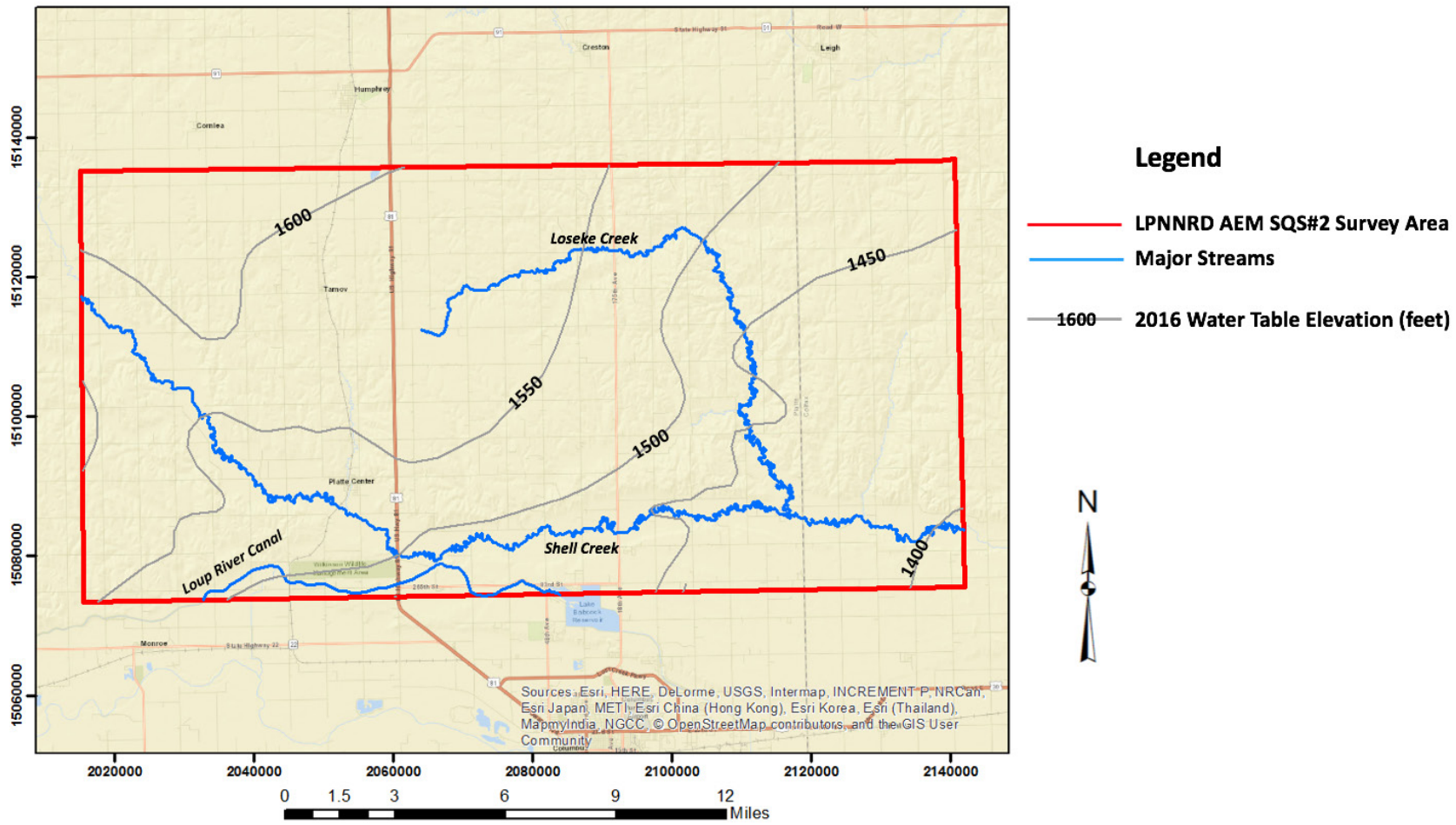


Figure 2-5. Elevation of ground water surface in SQS#2 survey area (CSD, 1995). Projection is NAD83, UTM 14 North (feet).

Groundwater can be confined in aquifers near or beneath glacial till SQS#1 is represented in Figure 2-6 and SQS#2 is represented in Figure 2-7 (CSD, 2017) and typically exhibits more drawdown than groundwater in unconfined systems that are present in alluvial settings. The groundwater system for the LPNNRD AEM survey area is generally under confined conditions.

Potentiometric gradients show groundwater movement from upland areas toward stream valleys. Hilly topography and complex heterogeneity within the glacial-drift terrain can create local flow systems (Gates et al., 2014). Contrasts of hydraulic conductivity within the principal aquifers of eastern Nebraska, can commonly cause significant vertical groundwater flow gradients.

The principal hydrogeologic unit within the LPNNRD AEM survey area is a mix of ***Q*** alluvial and glacial materials that are made up of two parts. The first are saturated alluvial materials that make up the stream-valley (valley fill) aquifers. The second are ***Q*** glacial-drift aquifers which are outwash alluvial and paleo-alluvial or paleo-glacial deposits of Plio-Pleistocene age that underlie till and loess deposits in the uplands in the eastern portion of the project area. Saturated ***Q*** deposits in east-central Nebraska are a complex mixture of unconsolidated, saturated sand, and gravel deposits. These saturated deposits can be confined to unconfined, deep to shallow, and/or regional and local, and, in places, interbedded with glacial till (Miller and Appel, 1997; Flowerday et al, 1998; Stanton et al., 2007). Stream-valley and glacial-drift systems locally can be hydraulically connected with each other.

Table 2-1 contains summary information for each known aquifer units (***Q***) within the area. Included in this table are the geologic system hosting the aquifer, aquifer thickness, and a general discussion regarding the aquifer framework, groundwater flow system characteristics, and aquifer parameters.

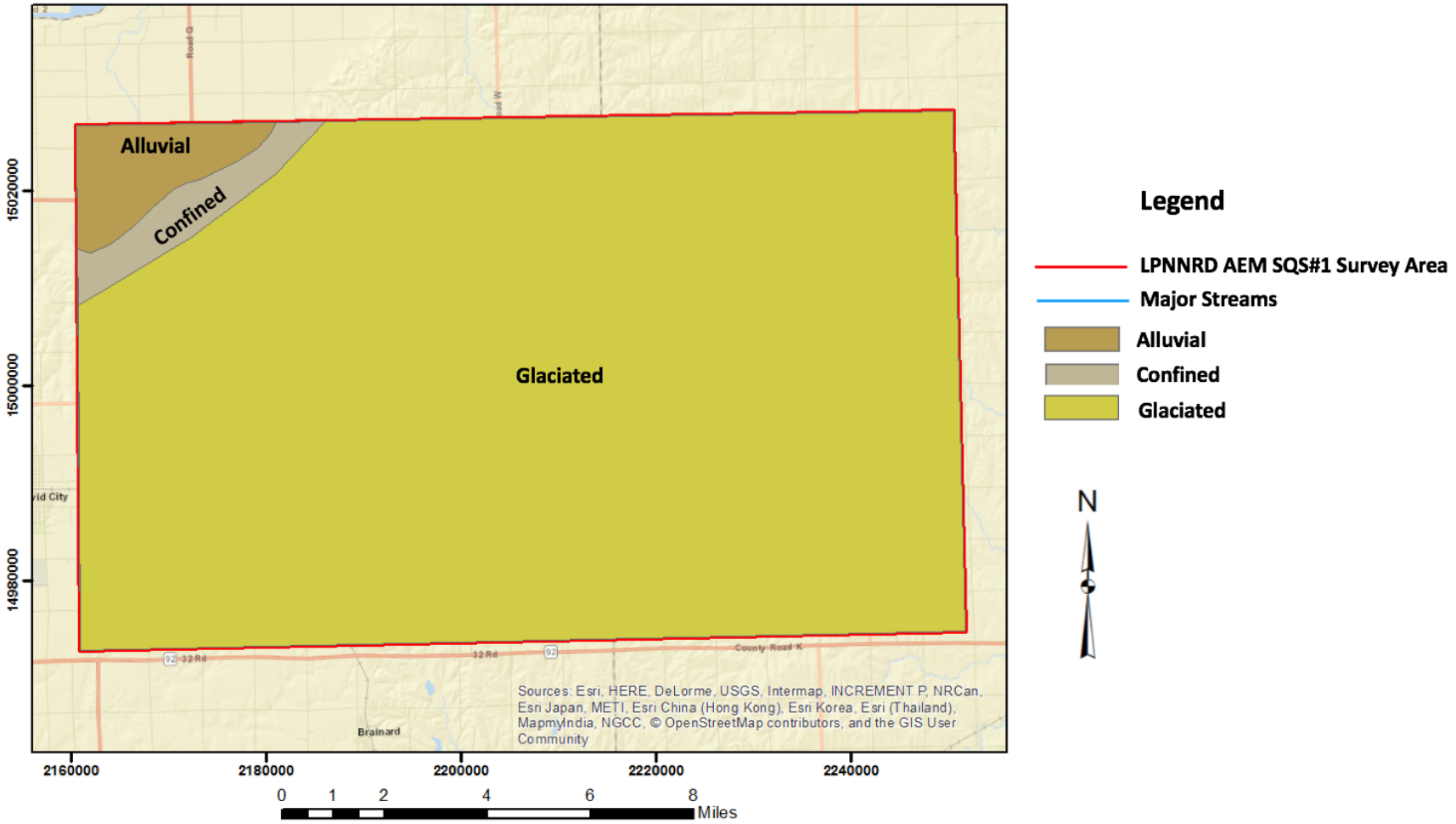


Figure 2-6. Generalized hydrogeologic areas within the SQS#1 survey area (Olafsen-Lackey et al., 2005a; Summerside et al., 2005a). These maps show generalized hydrologic connections to the streams and rivers. Projection is NAD83, UTM 14 North (feet).

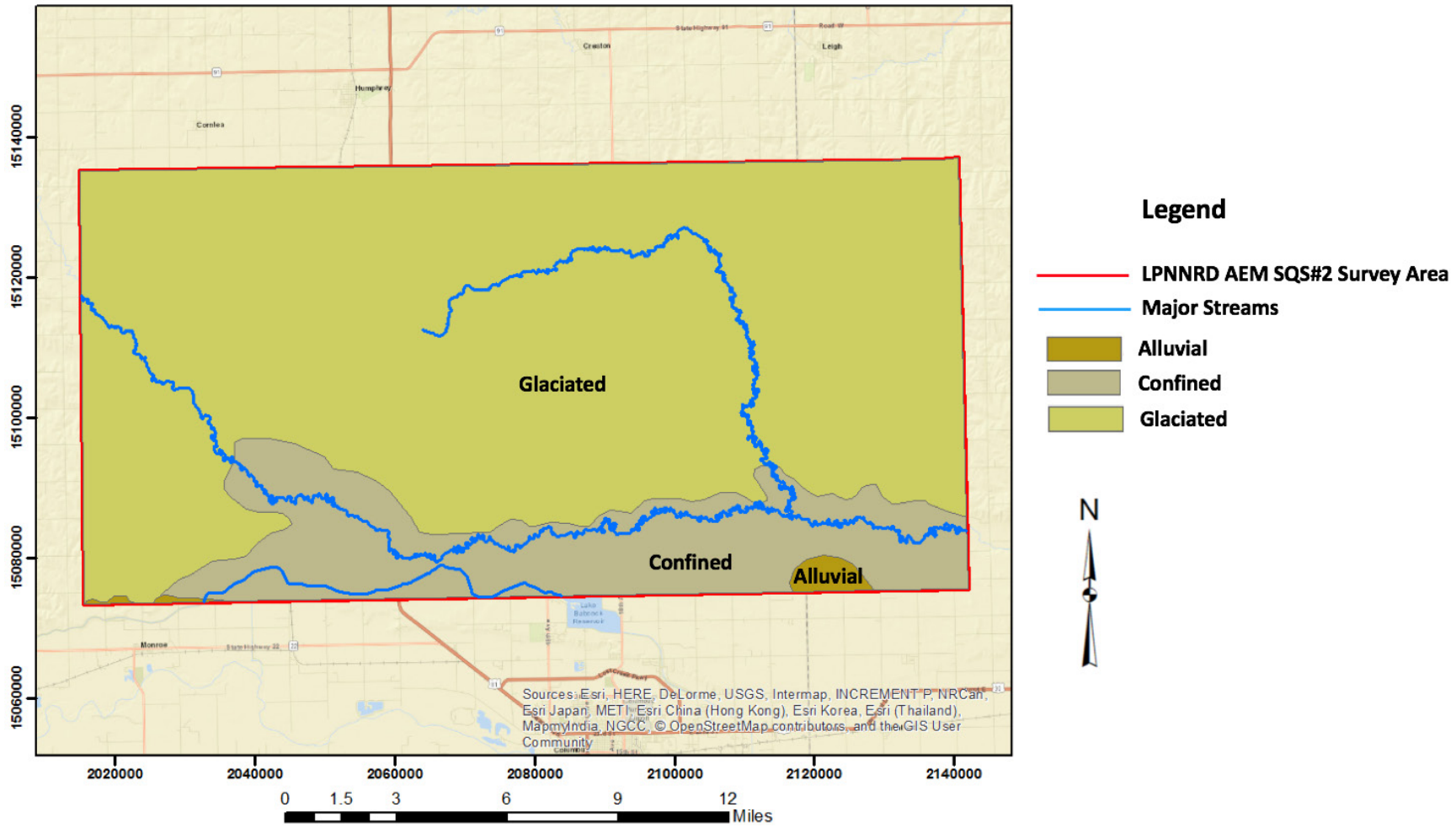


Figure 2-7. Generalized hydrogeologic areas within SQS#2 survey area (Olafsen-Lackey et al., 2005a; Summerside et al., 2005a). These maps show generalized hydrologic connections to the streams and rivers. Projection is NAD83, UTM 14 North (feet).

Table 2-1. Aquifers in Quaternary and Tertiary Age stratigraphic units.

System	Series	Hydrologic unit	Maximum thickness, ft.
Quaternary	Holocene, Pleistocene	Aquifer in undifferentiated alluvial deposits	Generally less than 250 ft
Undifferentiated sand and gravel units in stream-valley systems. Stream-aquifer systems can be intermixed with older glacial sand and gravel making the deposits difficult to distinguish from older glacial outwash. Hydraulic head is typically unconfined. Recharge is principally from local precipitation and surface water canals which can be rapid if the source area is primarily sand and gravel. Wells capable of yielding up to several thousand gallons per minute.			
Quaternary	Holocene, Pleistocene	Aquifer in undifferentiated glacial-drift deposits	Up to ~50 ft
Undifferentiated sand and gravel units in glacial-drift aquifers. Hydraulic head generally under confined conditions, but can be under unconfined conditions elsewhere. Thicknesses of glacial-drift aquifers vary greatly. Comprised largely of sand and gravel from ancestral river channels or glacial outwash that became capped by till or loess. Some paleovalleys several miles wide and tens of miles long. Recharge mostly from precipitation infiltration or inflow from adjacent hydraulically connected aquifers. Wells yields are highly variable; some capable of up to several thousand gallons per minute but vary greatly by location. Isolated aquifers capable of sustaining good quality water only for domestic or stock purposes only.			

2.2.1 Soil Characteristics in the LPNNRD AEM Survey Area

The soils within the LPNNRD AEM survey area, in particular Platte County, are well described by Loerch et al. (1988). These soils consist mostly of well drained soils with some poorly drained soils along the southern edge of the SQS#2. SQS#1 is mostly covered by glacial till and these areas have poor infiltration rates due to the nature of the clays and silts in the till. The sandy classes of soils have the greatest water infiltration rates while the silty to clay rich classes have lesser amounts of infiltration.

2.2.2 Aquifer Characteristics

Specific Yield is an estimate of the percentage of water in an aquifer that will drain under gravity (Heath, 1983). Historic specific yield values in the project area for the aquifer materials ranges from 0.5 to 0.20 based on Figure 2-8 for SQS#1 and Figure 2-9 for SQS#2 from Olafsen-Lackey et al. (2005b) and Summerside et al. (2005b). Specific yields are approximately 0.10 where the aquifer materials are made of mostly silt size particles. Aquifer materials made up of sand and gravel size particles range from approximately 0.10 to 0.25. This work is regional in nature and can change with the addition of aquifer tests to determine aquifer characteristics.

Transmissivity is the capacity of an aquifer to transmit water and is a function of the hydraulic conductivity times the aquifer thickness (Heath, 1983). Historic transmissivity values in the project area for the High Plains aquifer materials range from 20 to 250 thousand gpd/ft based on Figure 2-10 for SQS#1 and Figure 2-11 for SQS#2 (from Olafsen-Lackey et al. (2005c) and Summerside et al. (2005c)). In the SQS#1 survey area approximately half of the area in the central-northeast section is at 20thousand gpd/ft or less indicating the poor transmissivity of the glacial till. This work is regional in nature and can change with the addition of aquifer tests to determine aquifer characteristics.

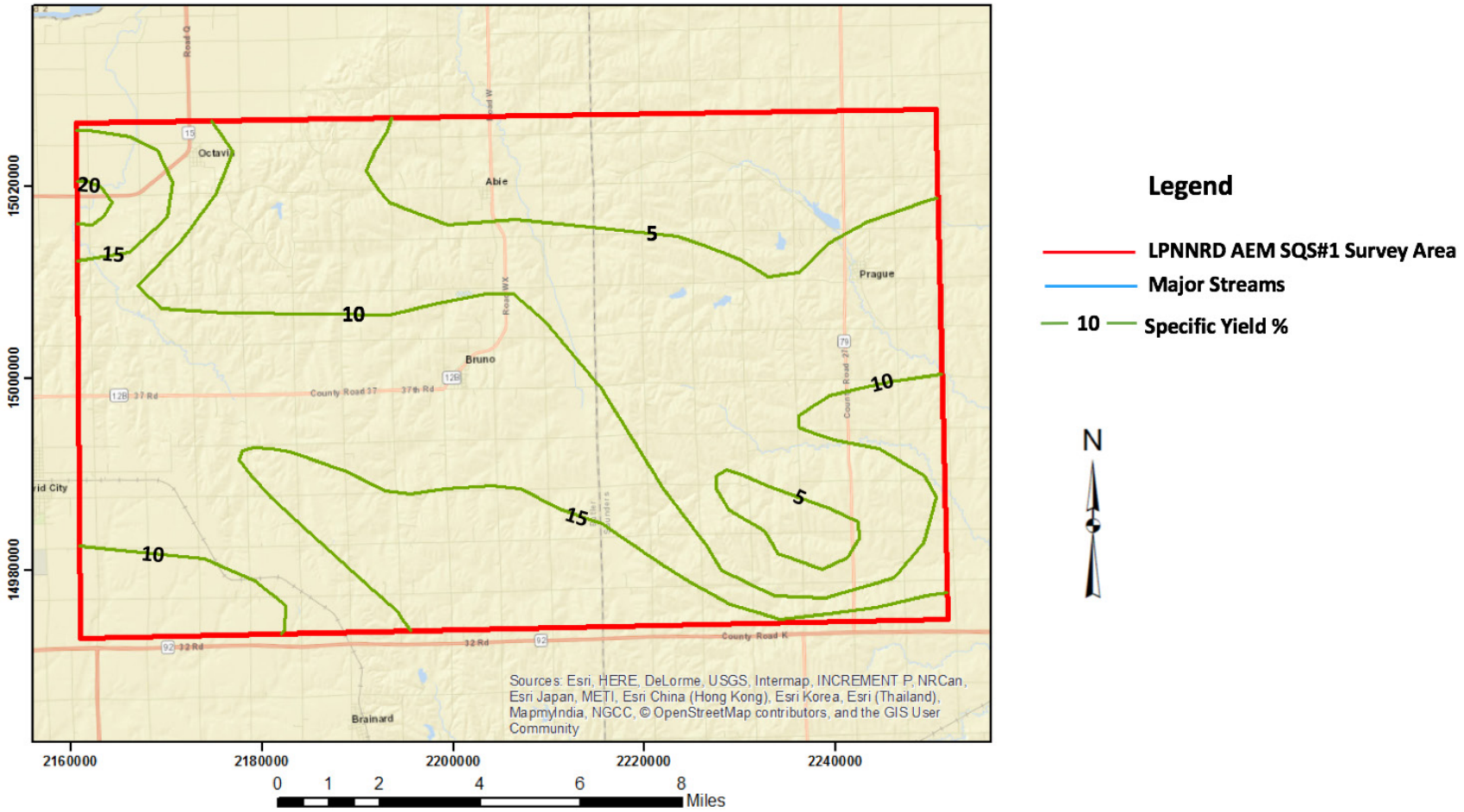


Figure 2-8. Specific yield values within the SQS#1 survey area (Olafsen-Lackey et al., 2005b; Summerside et al., 2005b). Projection is NAD83, UTM 14 North (feet).

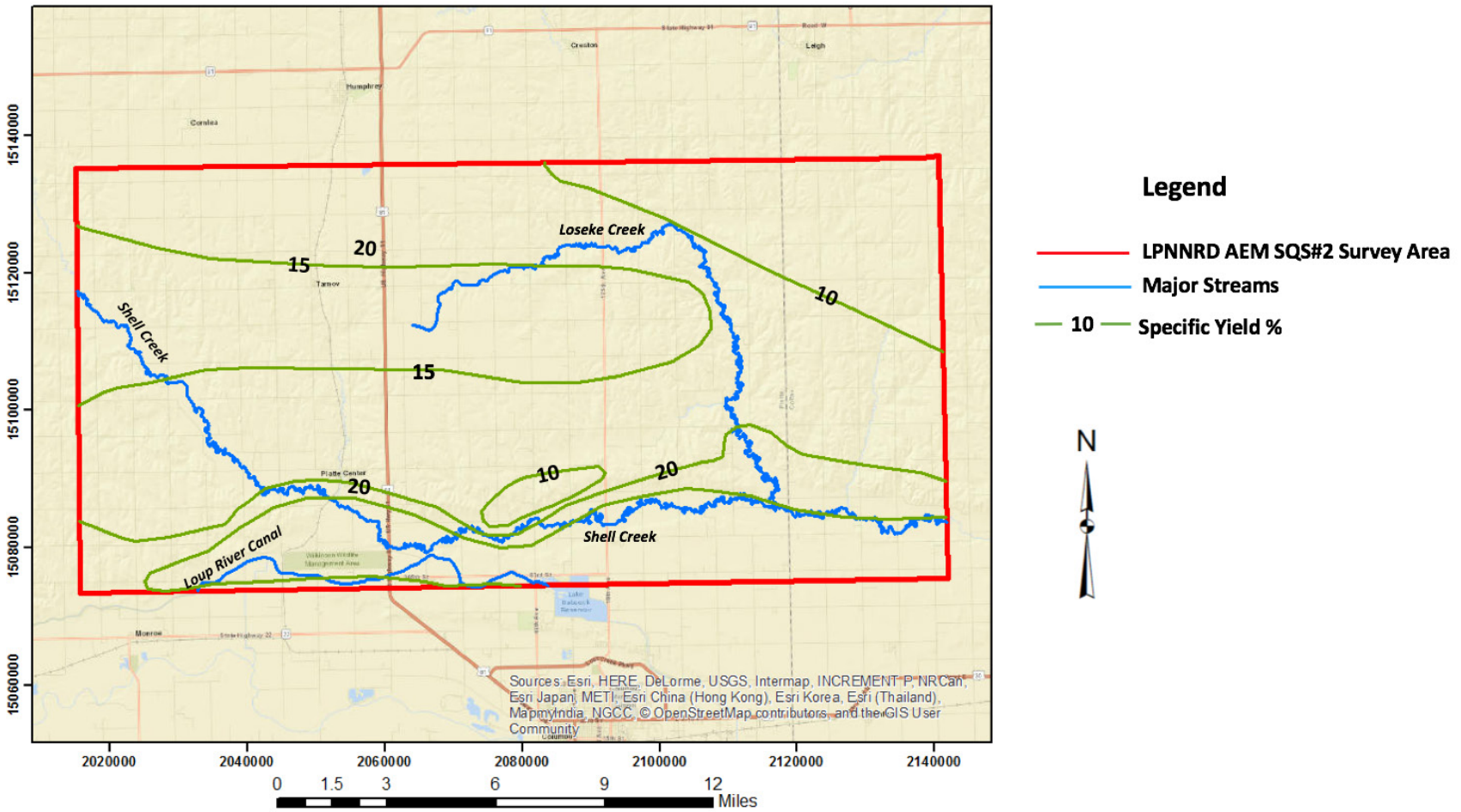


Figure 2-9. Specific yield values within SQS#2 survey area (Olafsen-Lackey et al., 2005b; Summerside et al., 2005b). Projection is NAD83, UTM 14 North (feet).

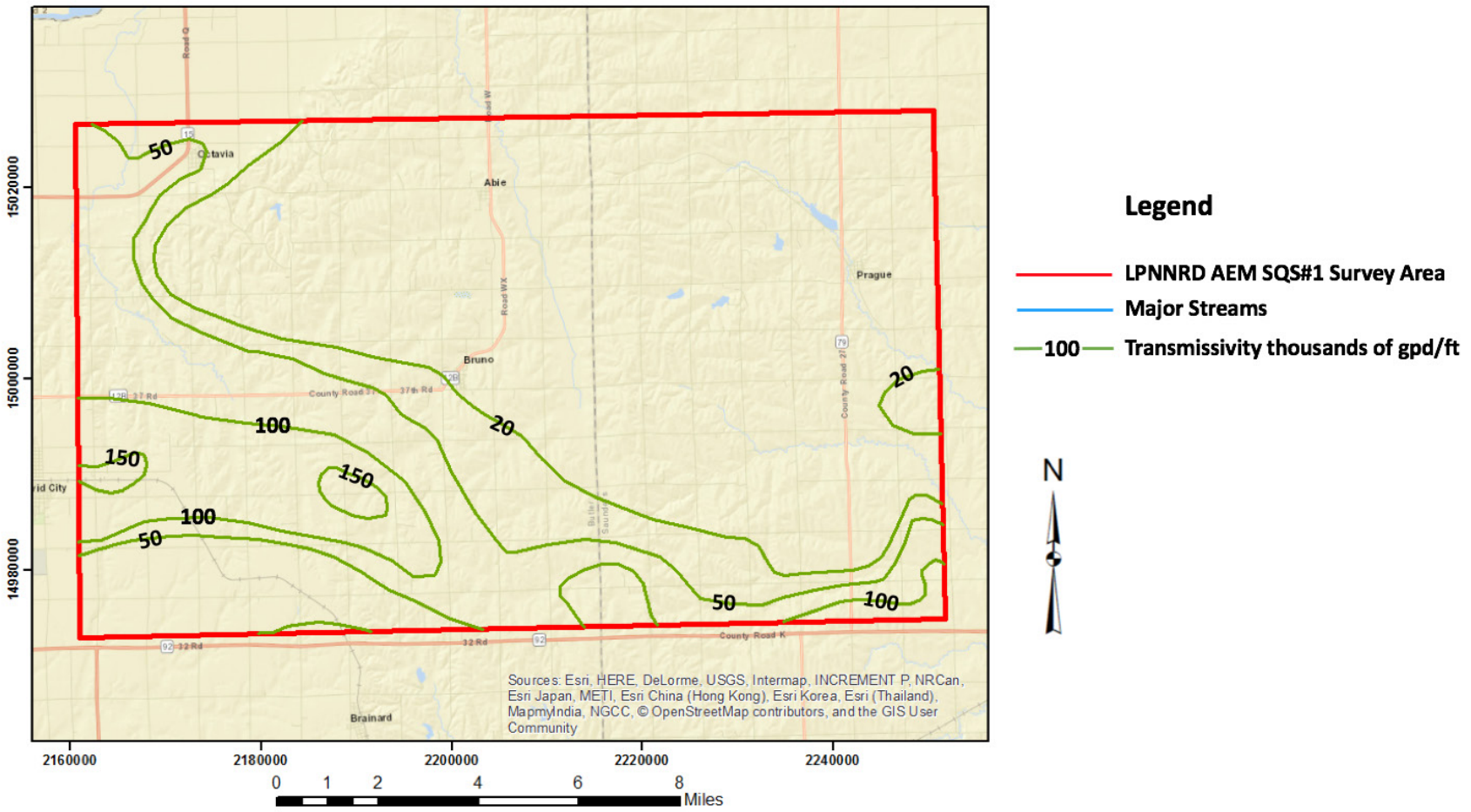


Figure 2-10. Transmissivity values within the SQS#1 survey area (Olafsen-Lackey et al., 2005c; Summerside et al., 2005c). Projection is NAD83, UTM 14 North (feet).

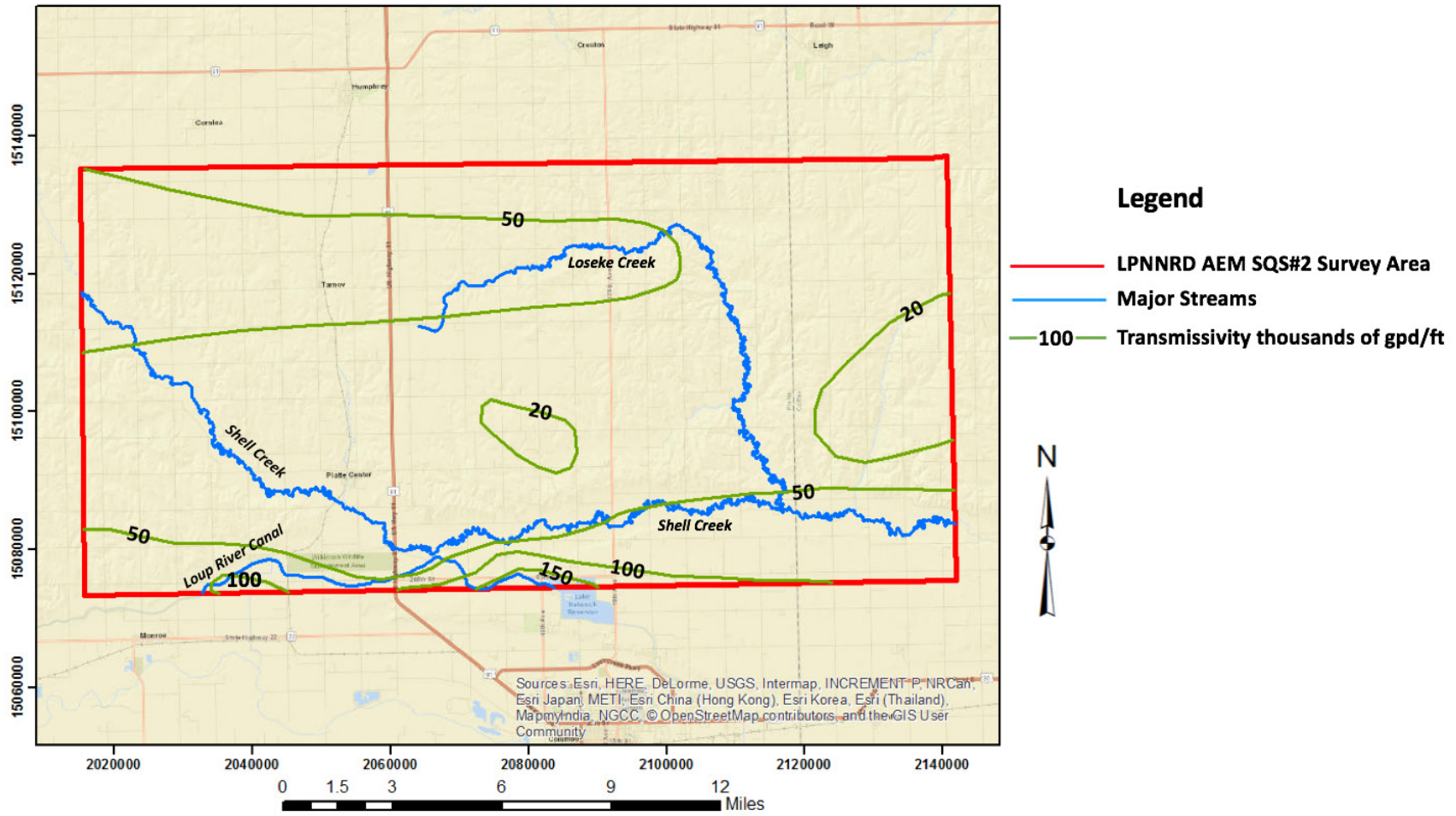


Figure 2-11. Transmissivity values within the SQS#2 survey area (Olafsen-Lackey et al., 2005c; Summerside et al., 2005c). Projection is NAD83, UTM 14 North (feet).

2.2.3 Connectivity to Surface Water and to Other Aquifers

Groundwater flow connectivity to surface water features is largely undocumented. However, Peterson and Strauch (2006) report stream flow measurements at 531 sites conducted in November 2006 in the Elkhorn and Loup River basins and selected streams in the Niobrara and Platte River basins in north-central Nebraska. Most of these sites were located throughout the Elkhorn and Loup River basins, while three are west of the project area. Results at three sites showed stream flow increasing in a downstream direction along Shell Creek indicating surface-water gains to the groundwater system. However, a more detailed review and analysis of the three sites near the project area (which was not a part of the scope of work for this project) would provide a more detailed explanation of these results. It is recognized that there can be strong groundwater-surface water connection along the rivers and streams in the project area.

Locally, ***Q*** deposits are hydrologically connected to shallower aquifers and streams. The deeper aquifers can discharge into the shallow groundwater system or into the streams. The reverse is also true. Detailed studies are not available for precise estimates of groundwater-surface water relationships or where they occur. It is thought that temporal communication changes with increased pumping during the irrigation season (June to September). During this time groundwater gradients change and communication between the two systems can be enhanced. Areal communication is variable as it is possible that a glacial-drift aquifer (such as a paleovalley aquifer) could be in communication with an aquifer or stream at one location and not another.

2.2.4 Water Quality

U.S. Geological Survey Water Supply Paper 2245 provides an historic overview of water quality in the state of Nebraska (Enberg, 1984). Of interest is the map of Total Dissolved Solids (TDS) for the state which shows that the overall groundwater quality for TDS in the LPNNRD AEM survey area ranges from 0 to 750 mg/l. This is important to the AEM survey results because concentrations of TDS above 1500 mg/l can affect the bulk resistivity values impacting the interpretations of the geological materials. There are no water quality samples showing high levels of TDS. Additional detailed information on Water Quality can be found in Carney et al. (2015a).

The LPNNRD has been monitoring groundwater quality across the district with a network of monitoring wells. One of the primary pollutants of concern is nitrate because of its steady rise in concentration to levels above the U.S. Environmental Protection Area (EPA) Maximum Contaminant Level (MCL) of 10 milligrams per liter (mg/L) in certain areas of the district. The entire district was designated a Groundwater Management Area in 1997 (http://www.lpnnrd.org/projects/water/gwma.html).

In 2003 near Bellwood and in 2004 near Richland-Schuyler Phase II groundwater Management Areas were stablished due to increasing nitrate levels.

3 Additional Background Information

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

3.1 Borehole Data

Borehole data for this project consisted of a combination of lithologic, stratigraphic, and downhole geophysical logs. The borehole information was gathered from three sources: 1) CSD Nebraska Statewide Test Hole Database (UNL, 2016) accessed January 28, 2017, which contains information from boreholes drilled between 1930 and 2016 by the CSD and other cooperating agencies.; 2) NE-DNR (Nebraska Department of Natural Resources, 2016b) accessed September 22, 2016; and 3) Nebraska Oil and Gas Conservation Commission (NOGCC, 2017)

The locations of the CSD boreholes utilized in the SQS#1 subarea of the LPNNRD AEM survey are indicated in Figure 3-1. A total of 17 CSD holes contained lithology information, 16 holes contained stratigraphic information, and 4 holes contained geophysical information were within the SQS#1 AEM survey area. The locations of the NE-DNR registered wells used in the SQS#1 AEM survey area are indicated in Figure 3-2. A total of 229 registered wells contained usable lithology information. The locations of the NOGCC wells used in the SQS#1 AEM survey area are indicated in Figure 3-3. Five wells contained lithological information and two of those boreholes contained stratigraphic information.

The locations of the CSD boreholes utilized in the SQS#2 subarea of the LPNNRD AEM survey are indicated in Figure 3-4. A total of 17 CSD holes contained lithology information, 9 holes contained stratigraphic information, and 4 holes contained geophysical information were within the SQS#2 AEM survey area. The locations of the NE-DNR registered wells used in the SQS#2 AEM survey area are indicated in Figure 3-5. A total of 859 registered wells contained usable lithology information. The location of the single NOGCC well used in the SQS#2 AEM survey area is indicated in Figure 3-6. This borehole contained both lithological and stratigraphic information.

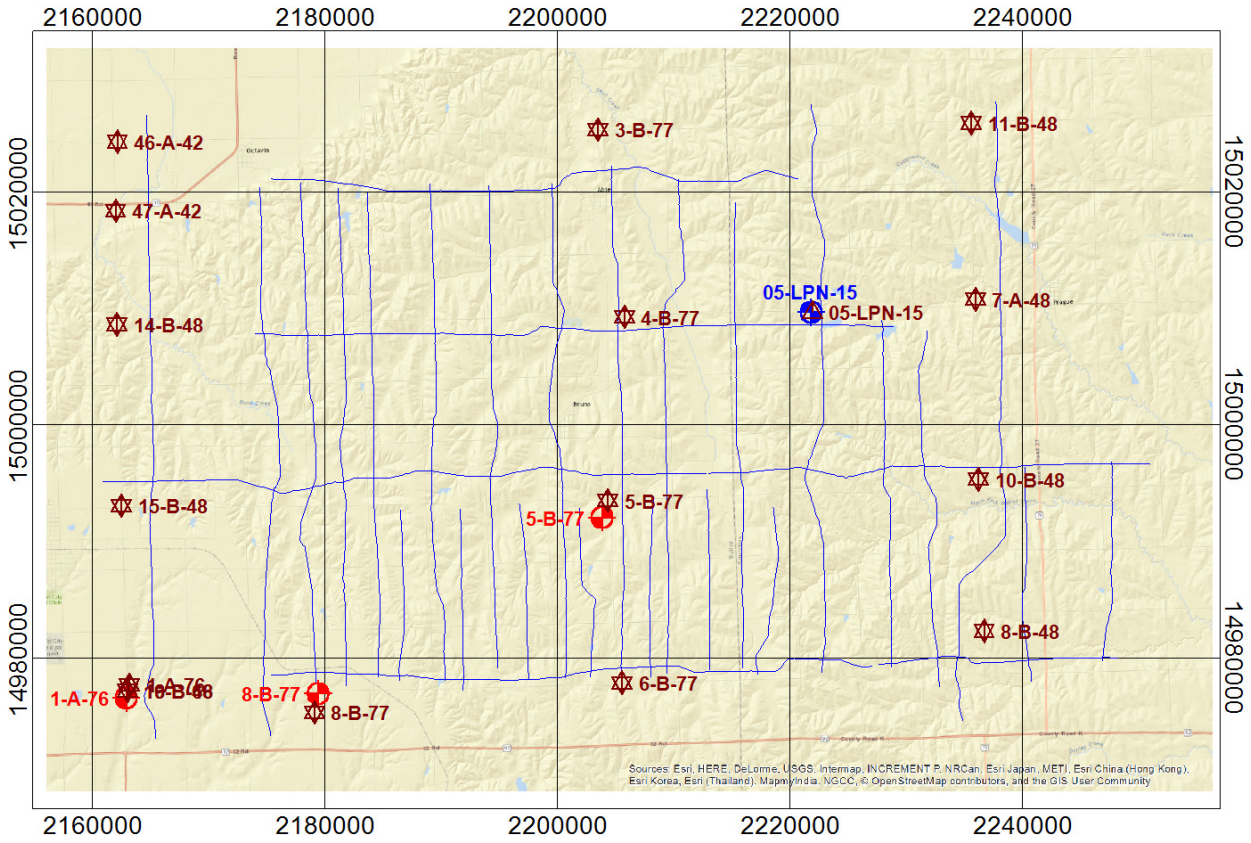


Figure 3-1. Locations of the Nebraska Conservation Survey Division (CSD) boreholes used in this study of the SQS#1 subarea of the LPNNRD AEM survey area including E-logs (red circles), "geologs" (blue circle), lithology logs (upright brown triangles), and stratigraphic logs (inverted brown triangles) and the airborne electromagnetic flight lines (blue lines). Projection is NAD83, UTM 14 North (feet).

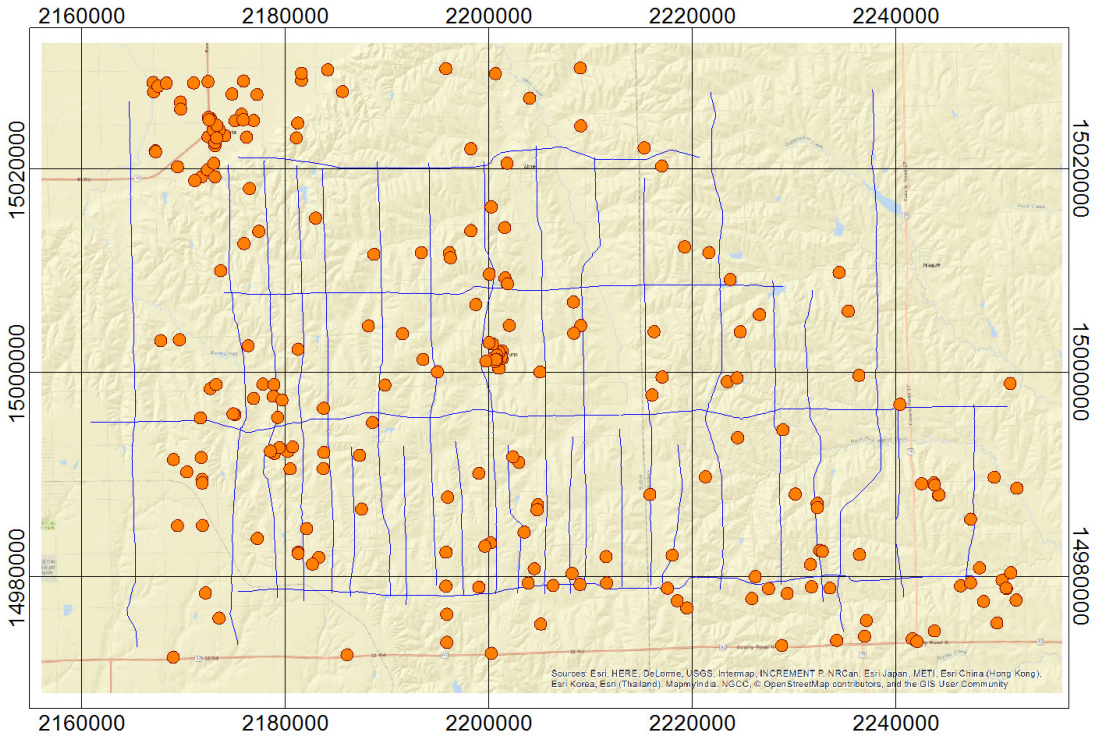


Figure 3-2. Locations of the Nebraska Division of Natural Resources Registered wells (orange dots) and the airborne electromagnetic flight lines (blue lines) in the SQS#1 subarea of the LPNNRD AEM survey area. Projection is NAD83, UTM 14 North (feet).

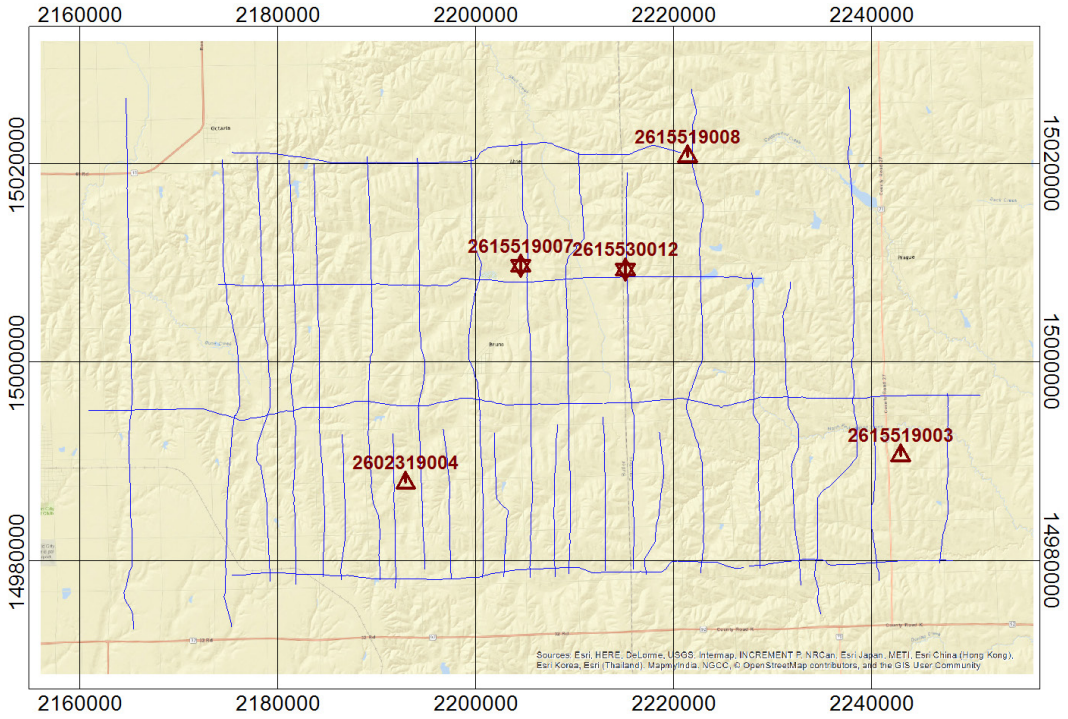


Figure 3-3. Locations of Nebraska Oil and Gas Conservation Commission wells (lithology logs (upright brown triangles) and stratigraphic logs (inverted brown triangles)) and the AEM flight lines (blue lines) in the SQS#1 subarea of the LPNNRD AEM survey area. Projection is NAD83, UTM 14 North (feet).

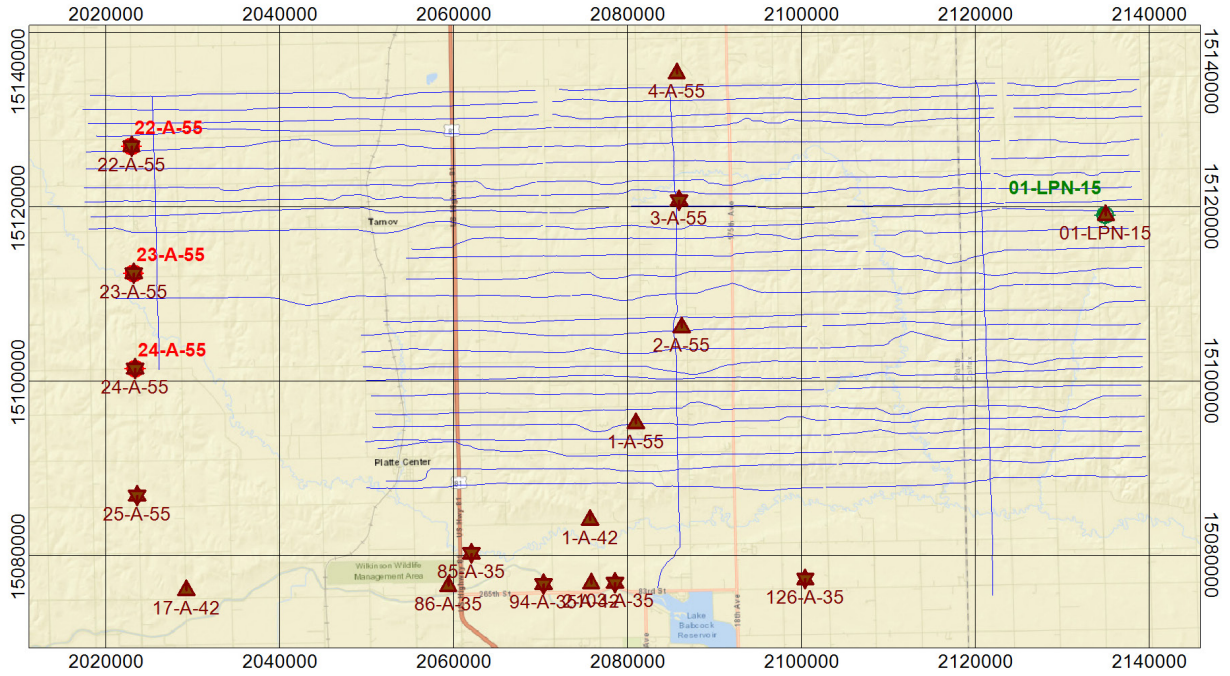


Figure 3-4. Locations of the Nebraska Conservation Survey Division (CSD) boreholes used in this study of the SQS#2 subarea of the LPNNRD AEM survey area including E-logs (red circles), "geologs" (green circle), lithology logs (upright brown triangles), and stratigraphic logs (inverted brown triangles) and the airborne electromagnetic flight lines (blue lines). Projection is NAD83, UTM 14 North (feet).

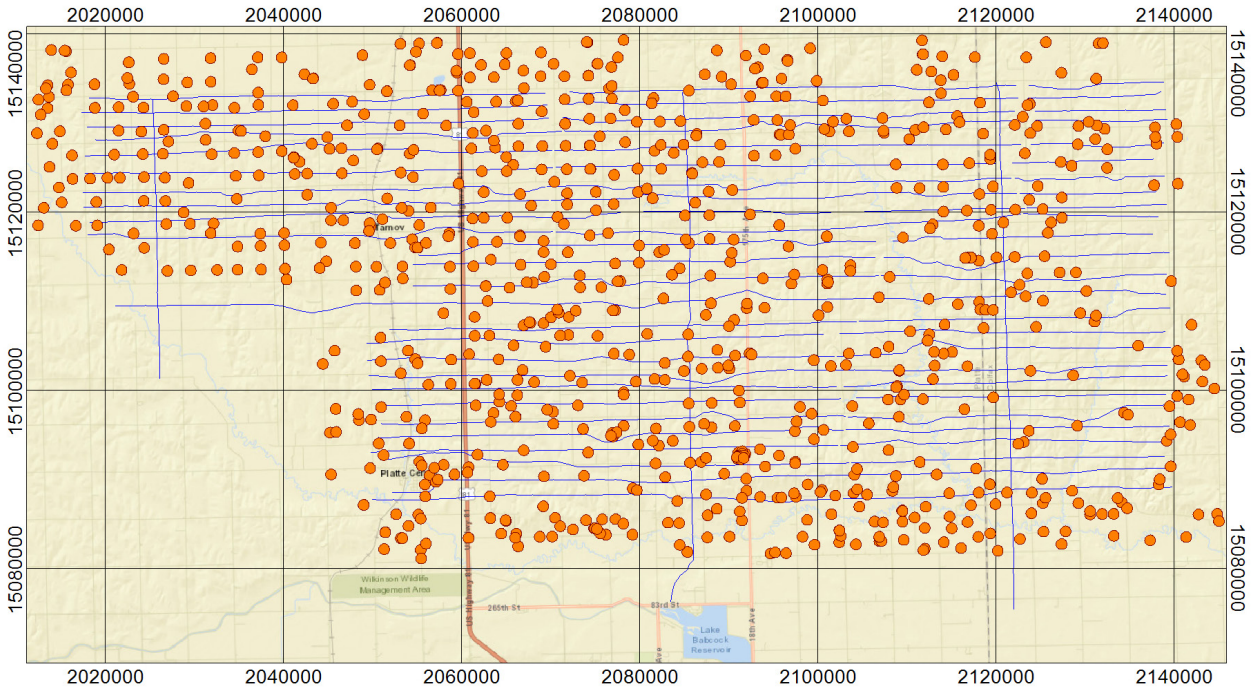


Figure 3-5. Locations of the Nebraska Division of Natural Resources Registered wells (orange dots) and the airborne electromagnetic flight lines (blue lines) in the SQS#2 subarea of the LPNNRD AEM survey area. Projection is NAD83, UTM 14 North (feet).

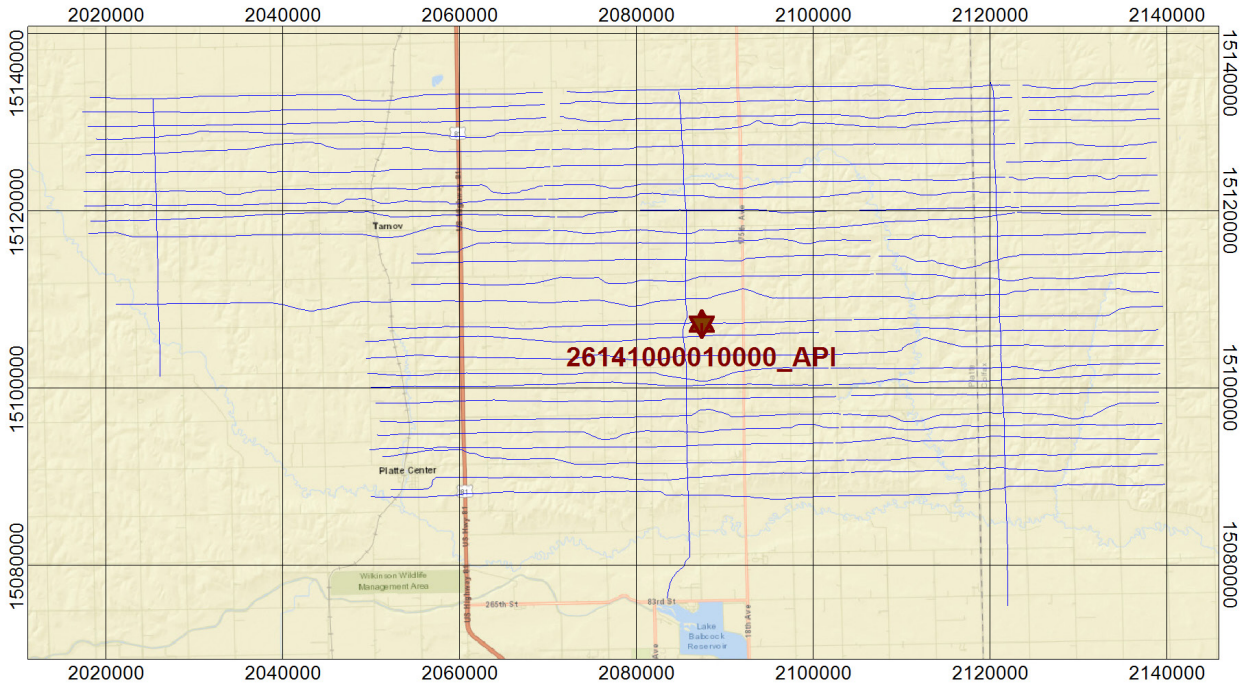


Figure 3-6. Locations of Nebraska Oil and Gas Conservation Commission wells (lithology logs (upright brown triangles) and stratigraphic logs (inverted brown triangles)) and the AEM flight lines (blue lines) in the SQS#2 subarea of the LPNNRD AEM survey area. Projection is NAD83, UTM 14 North (feet)

4 Geophysical Methodology, Acquisition and Processing

4.1 Geophysical Methodology

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

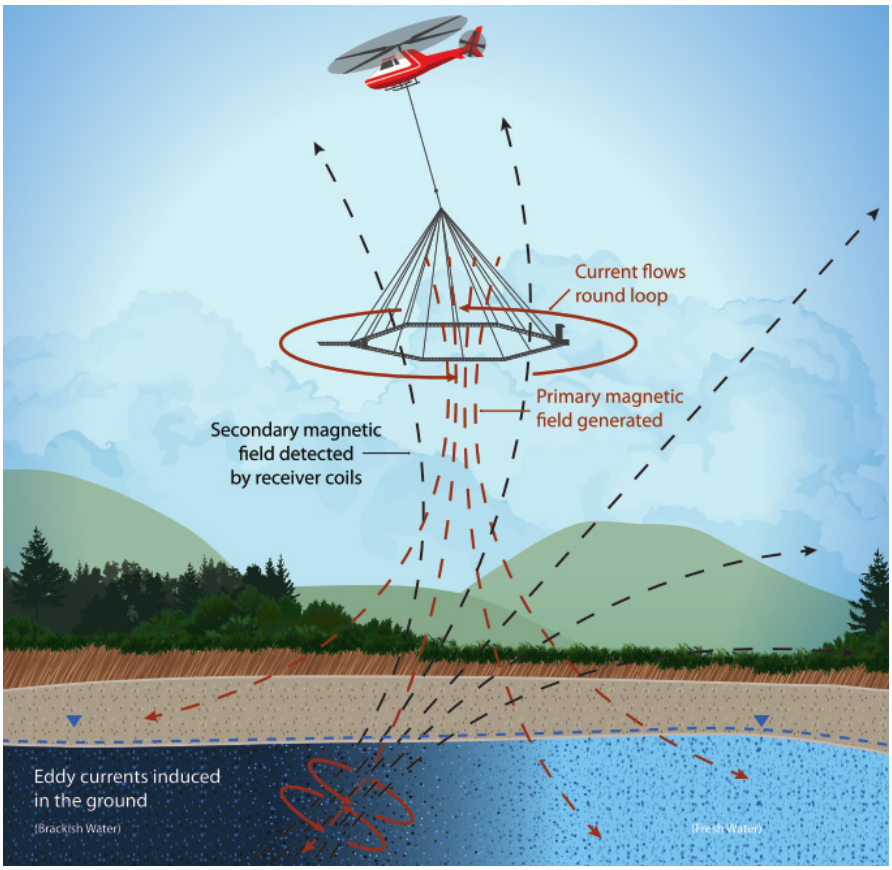
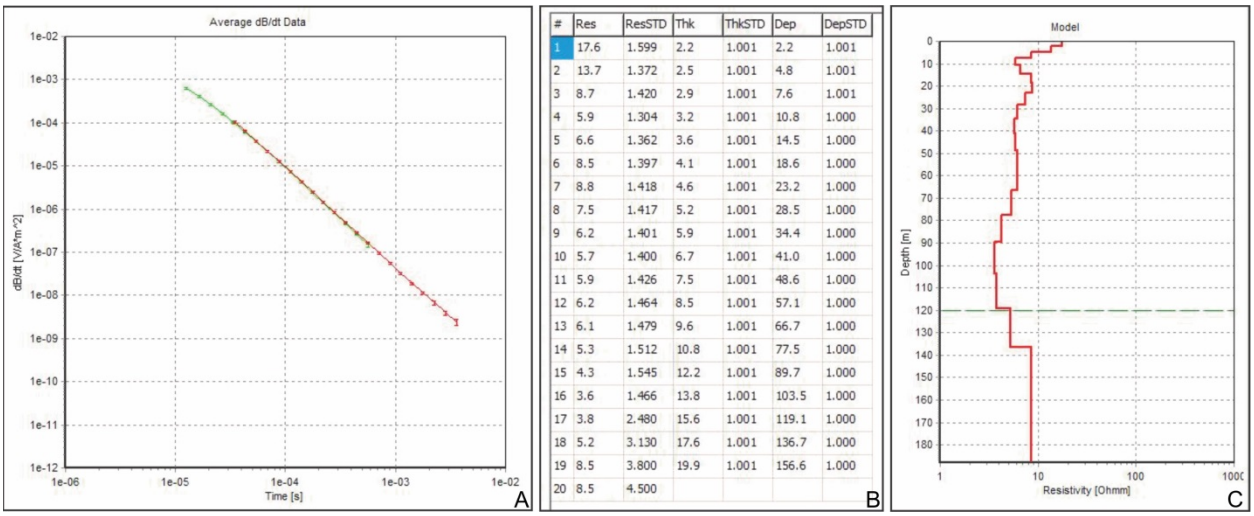


Figure 4-1. Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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 4-2 shows an example of a dual-moment TEM dB/dt sounding curve and the corresponding inverted electrical resistivity model.



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

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

4.2 Flight Planning/Utility Mapping

The primary source of noise in geophysical electromagnetic surveys are other electromagnetic devices that are part of typical municipal utility infrastructure. These include, for example, power lines, railroads, pipelines, and water pumps. Prior to AEM data acquisition in the LPNNRD, 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.

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

At the conclusion of the design process (Figure 1-2), the maximum line length for the SQS#1 AEM survey area was about 14 miles in length, east-west, and about 8 miles in length, north-south, with a minimum line separation of about 0.5 miles (Figure 4-5). About half of the LPNNRD SQS#2 AEM flight lines were approximately 23 miles in length (east-west) and the other half about 17 miles in length. The east-west SQS#2 flight lines were separated by approximately 0.25 miles (Figure 4-6).

4.3 AEM Survey Instrumentation

AEM data were acquired using the SkyTEM304M (304M) airborne electromagnetic system (SkyTem Airborne Surveys Worldwide, 2016). The 304M is a rigid frame, dual-magnetic moment (Low and High) TEM system. The area of the 304M Tx coil is 337 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 120 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 ~160,000 $A*m^2$, respectively.

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

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

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

Dataset, referenced to the North American Vertical Datum of 1988; with feet as the unit of measurement.

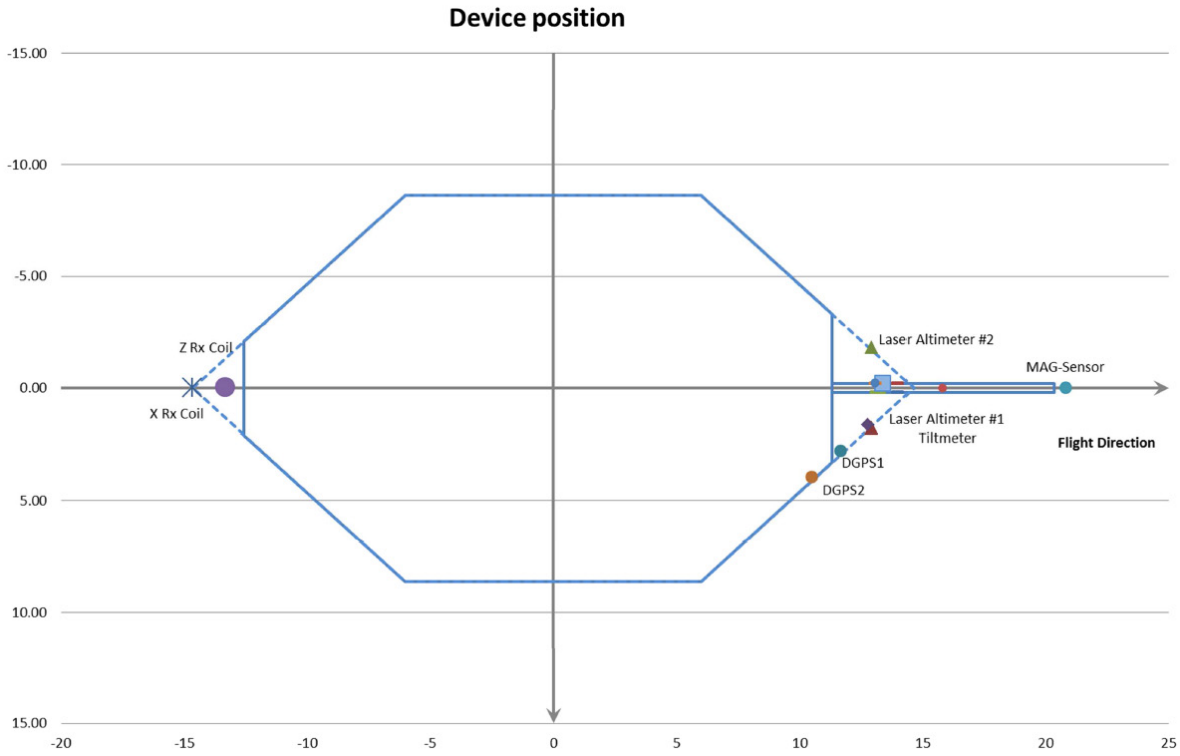


Figure 4-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1.



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

For this project, the 304M was flown at an average speed of 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 AS350BA FX2 helicopter. Figure 4-4 displays a couple of images of the 304M in operation.

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

	DGPS 1	DGPS 2	Inclinometer 1	Inclinometer 2	Altimeter 1	Altimeter 2	Magnetic Sensor	Rx Coil
X	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 4-2: Positions of corners of the SkyTEM304M transmitter coil, using the center of the frame as the origin in feet.

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

Table 4-3: Location of DGPS and magnetic field base station instruments was the Genoa Airport.

Instrument	Easting (ft)	Northing (ft)	UTM Zone
Magnetometer Base Station (Genoa Airport)	1994539	15043449	14 N
DGPS Base Station (Holdrege)	1539670	14686400	14 N

4.4 Data Acquisition

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

For these surveys, installation of the navigational instruments in the helicopter and assembly of the SkyTEM304M system commenced at the beginning of the project. The helicopter and the SkyTEM304M system were located at the Genoa 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 154.5 line-miles (250.2 line-kilometers) were acquired over the LPNNRD SQS#1 AEM survey area and 497.2 line-miles (805.4 line-kilometers) were acquired over the LPNNRD SQS#2 AEM survey area on July 17-20, 2016. The Genoa Municipal airport was used for landing and refueling between production flights. A data acquisition map for SQS#1 is presented in Figure 4-5 with the flight lines grouped by acquisition date and a similar map for the SQS#2 AEM data acquisition is presented in Figure 4-6.

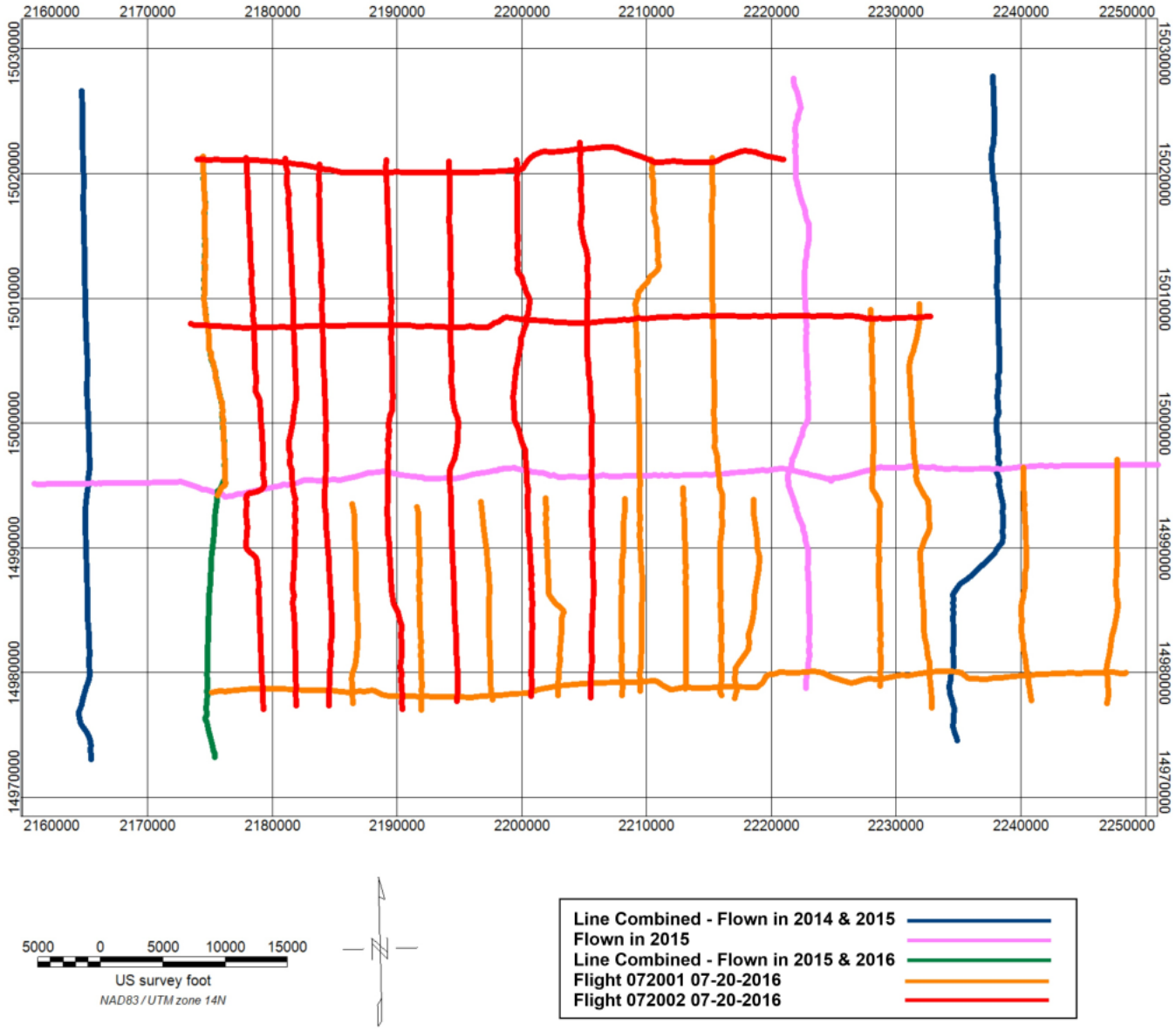


Figure 4-5. LPNNRD SQS#1 AEM flight lines grouped by acquisition date.

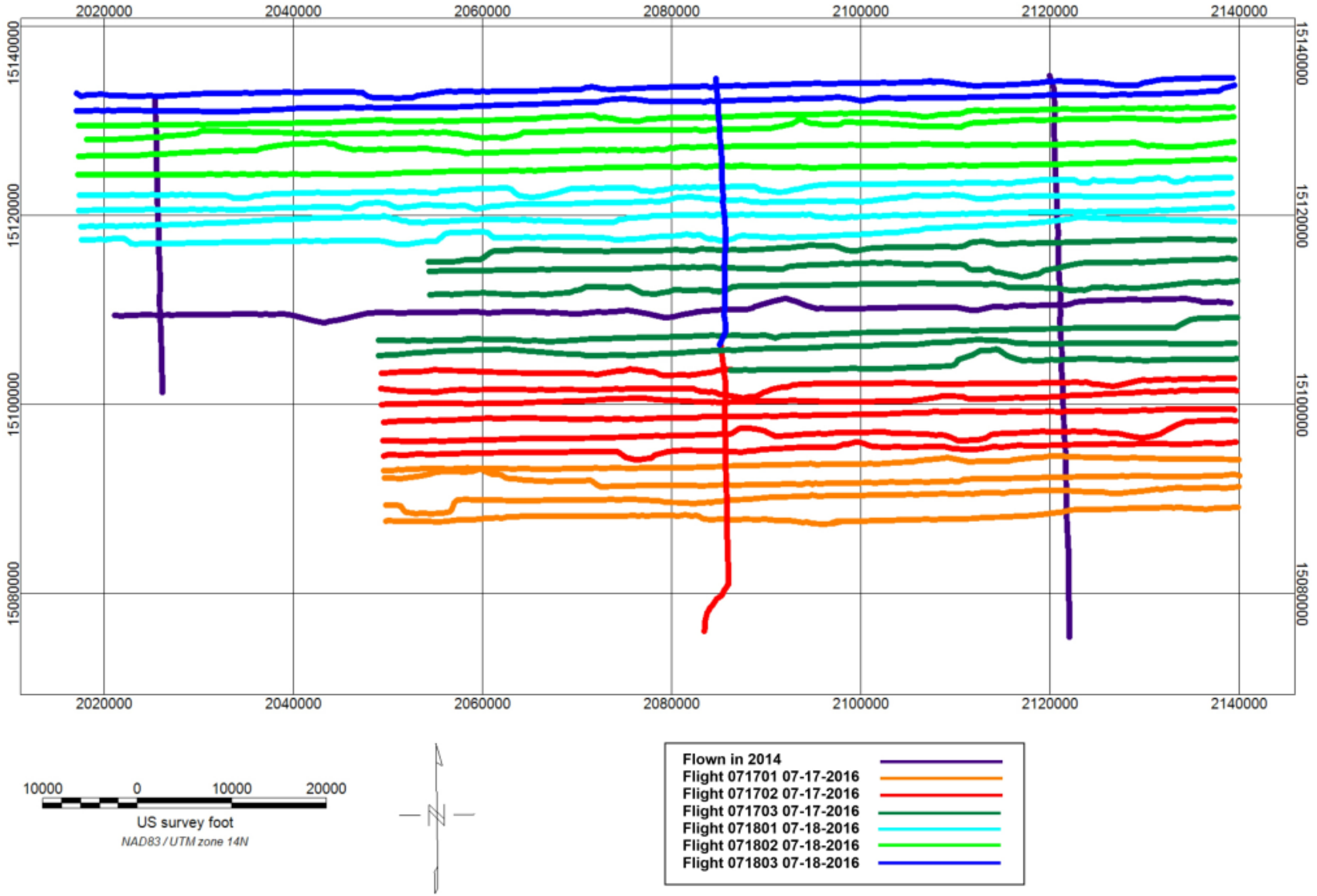


Figure 4-6. LPNNRD SQS#2 AEM flight lines grouped by acquisition date.

4.4.1 Primary Field Compensation

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

4.4.2 Automatic Processing

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

Automatic processing algorithms provided within the Workbench program are initially applied to the AEM data. DGPS locations were filtered using a stepwise, second-order polynomial filter of nine seconds with a beat time of 0.5 seconds, based on flight acquisition parameters. The AEM data are corrected for tilt deviations from level and so filters were also applied to both of the tilt meter readings with a median filter of three seconds and an average filter of two seconds. The altitude data were corrected using a series of two polynomial filters. The lengths of both eighth-order polynomial filters were set to 30 seconds with shift lengths of six (6) 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 8, 10, and 12 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, 12, and 20 seconds. The trapezoid sounding distance was set to 2.5 seconds and the left/right setting, which requires the trapezoid to be complete on both sides, was turned on. The spike factor and minimum number of gates were both set to 25 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

4.4.3 Manual Processing and Laterally-Constrained Inversions

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

The AEM data were then inverted using a Laterally-Constrained Inversion (LCI) algorithm (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, 107.0 line-miles (173.3 line-km) of data were retained for the final inversions for the LPNNRD SQS#1 AEM survey area and 358.7 line-miles (581.1 line-km) of data were retained for the final inversions for the LPNNRD SQS#2 AEM survey area. This amounts to a data retention of 69.3% for SQS#1 and 72.2 % for SQS#2. These high rates are the result of careful flight line planning and design.

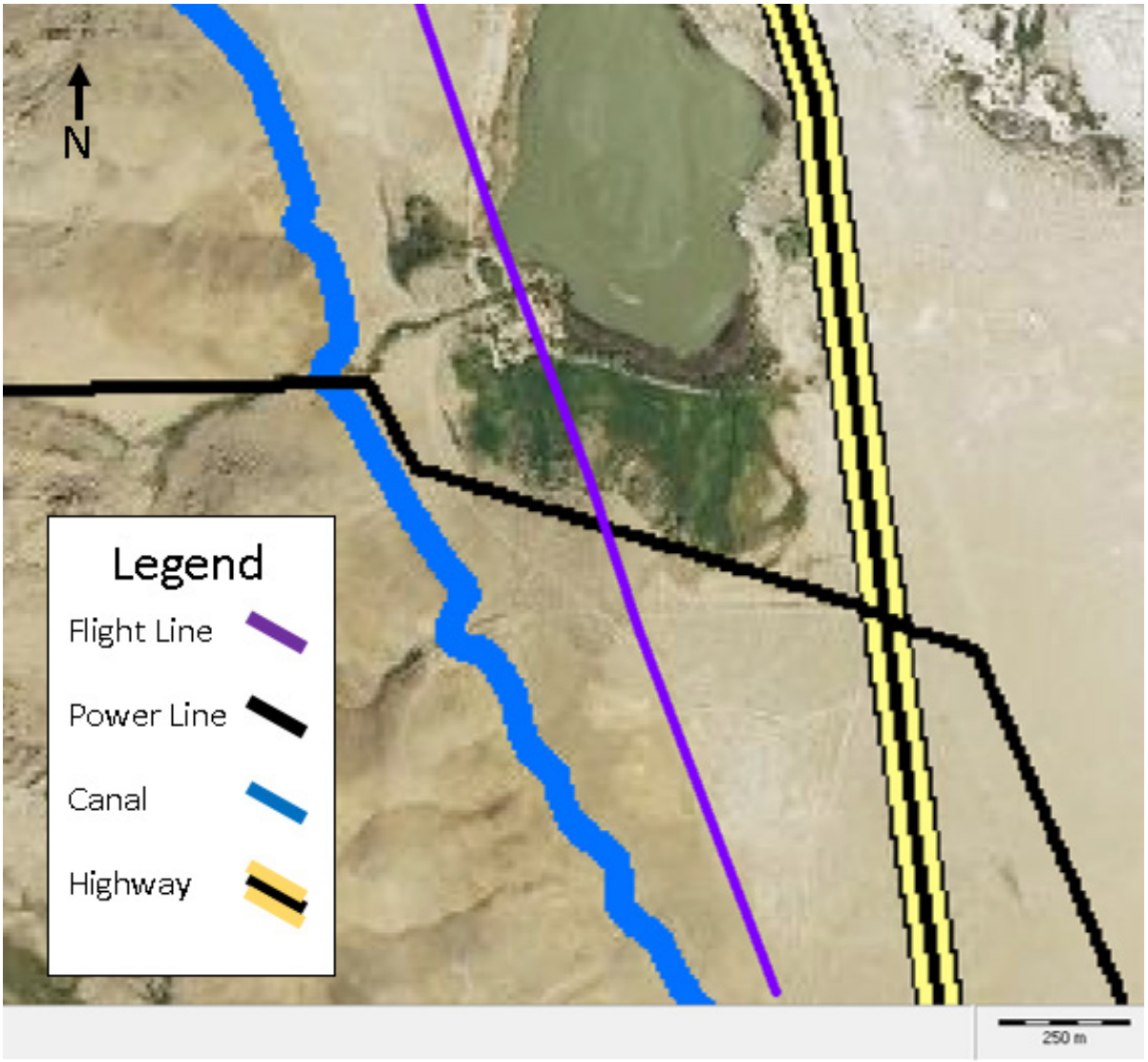


Figure 4-7. Example locations of electromagnetic coupling with pipelines or power lines.

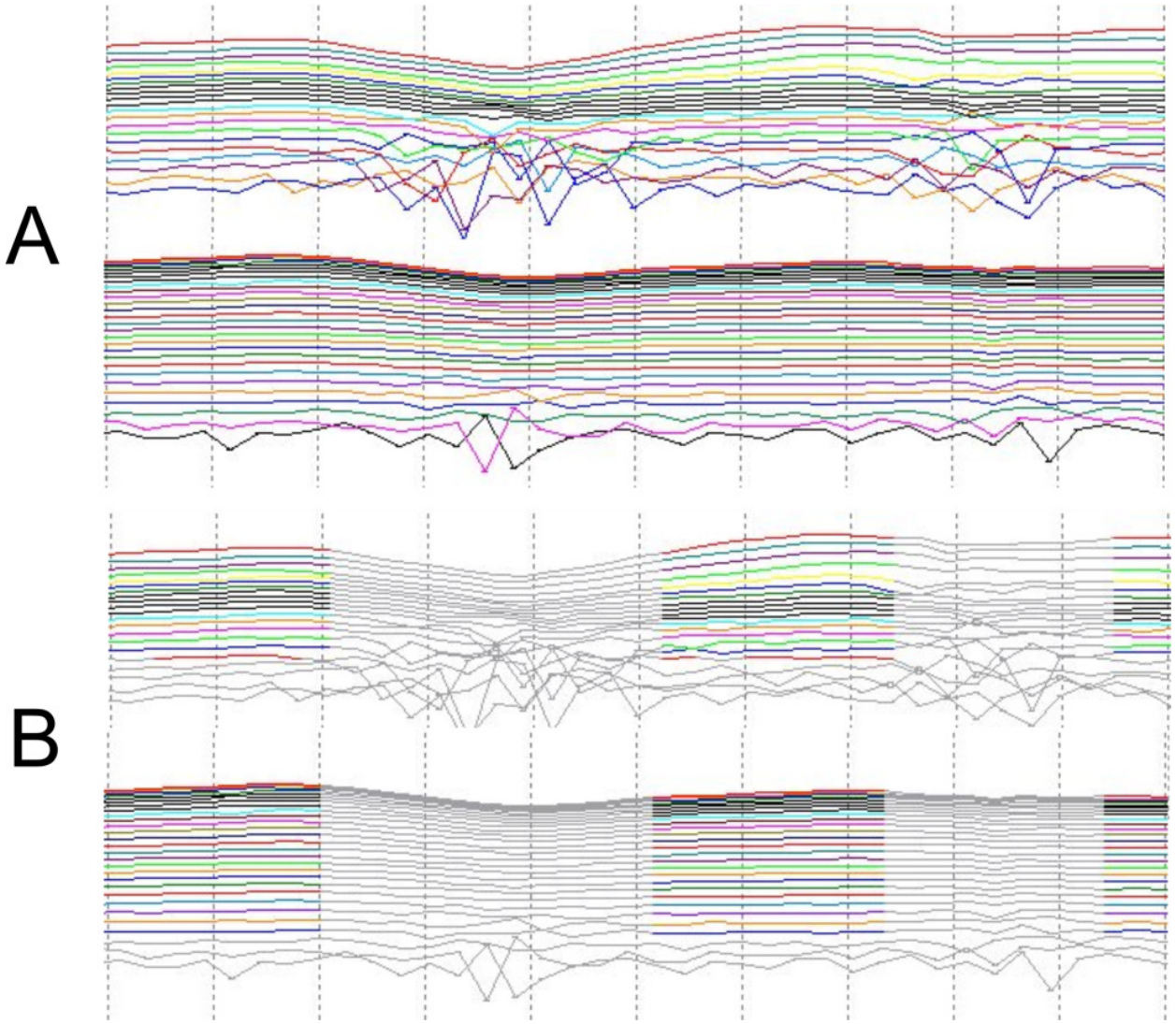


Figure 4-8. A) Example of AEM data from the LPNNRD AEM survey affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

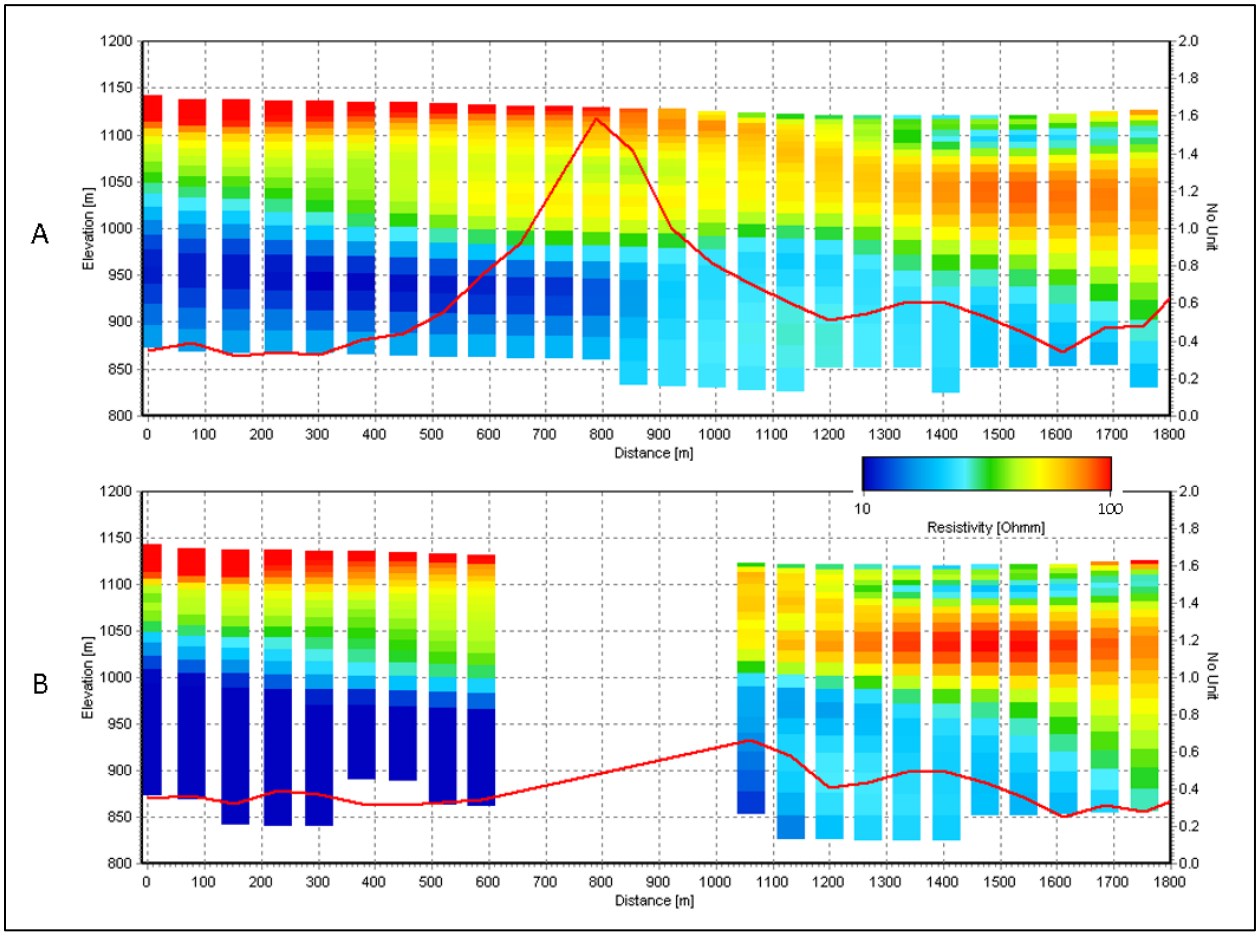


Figure 4-9. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

4.4.4 Power Line Noise Intensity (PLNI)

The Power Line Noise Intensity (PLNI) channel assists in identifying possible sources of noise from power lines. Pipelines, unless they are cathodically-protected, are not mapped by the PLNI. The PLNI is produced by performing a spectral frequency content analysis on the raw received Z-component SkyTEM data. For every Low Moment data block, a Fourier Transform (FT) is performed on the latest usable time gate data. The FT is evaluated at the local power line transmission frequency (60 Hz) yielding the amplitude spectral density of the local power line noise. The PLNI data for the LPNNRD SQS#1 AEM survey are presented in Figure 4-10 and for the SQS#2 AEM survey area are presented in Figure 4-11. The LPNNRD-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 4-12 for SQS#1 and in Figure 4-13 for SQS#2.

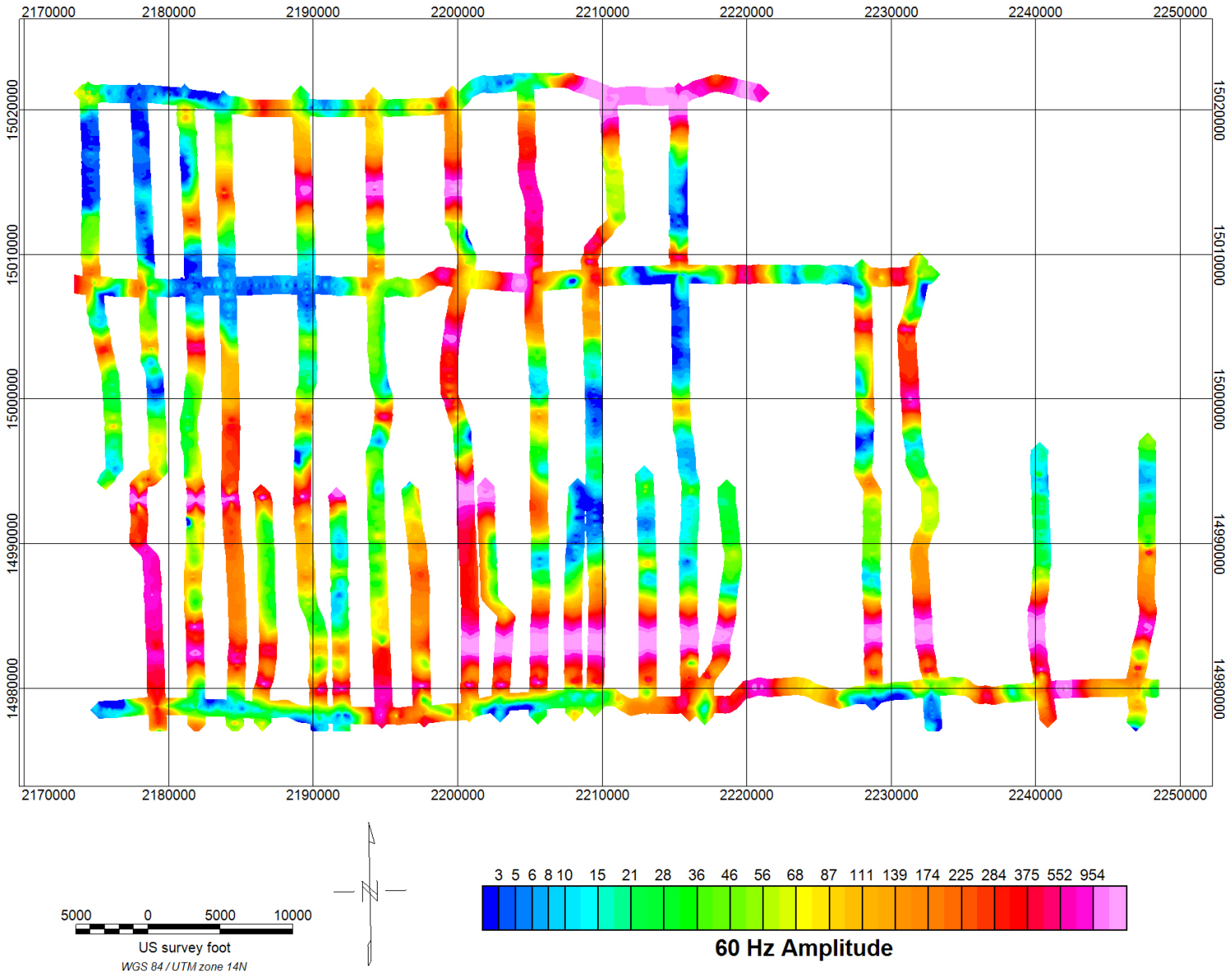


Figure 4-10. Power Line Noise Intensity (PLNI) map of the SQS#1 subarea of the LPNNRD AEM survey area.

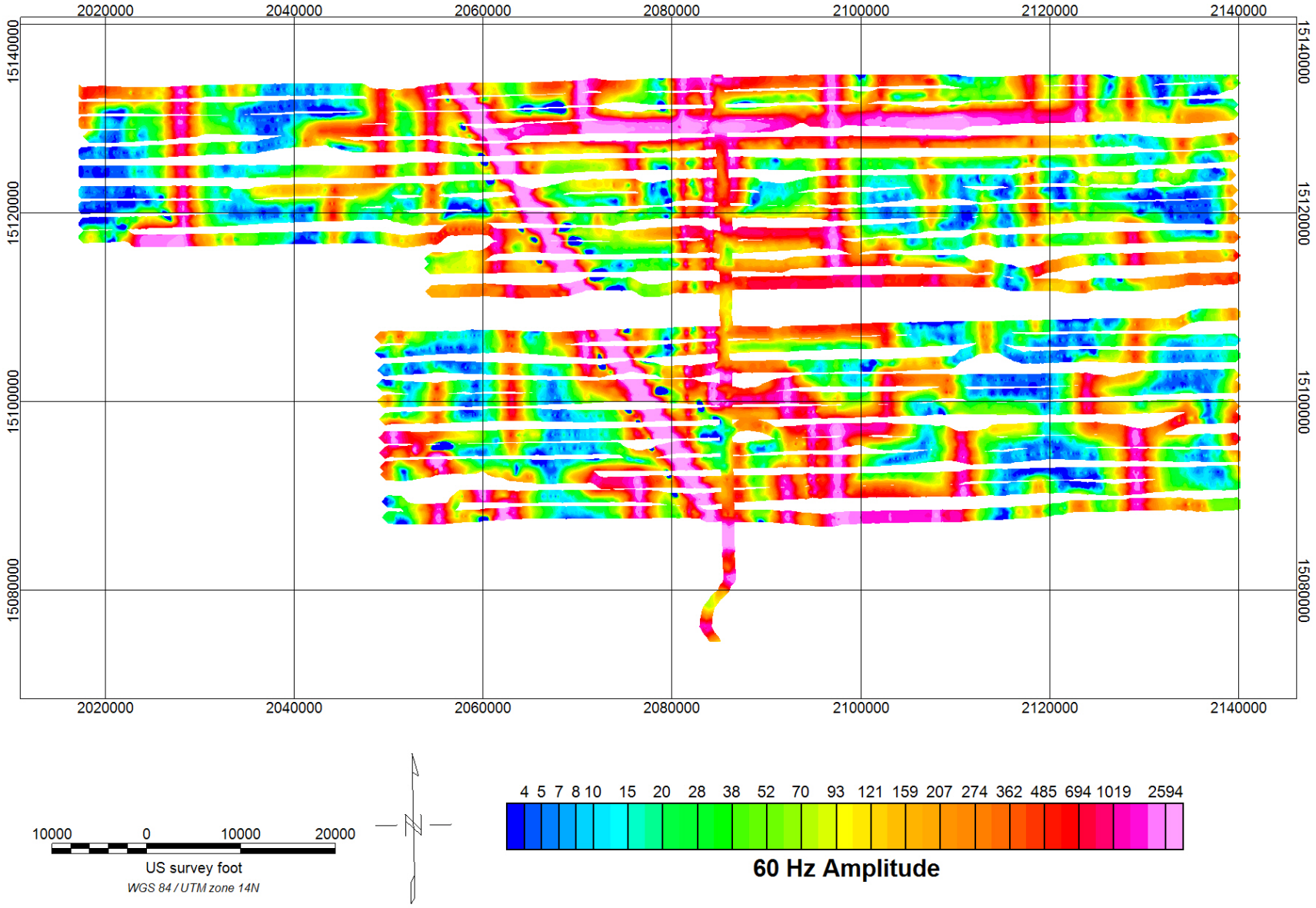


Figure 4-11. Power Line Noise Intensity (PLNI) map of the SQS#2 subarea of the LPNNRD AEM survey area.

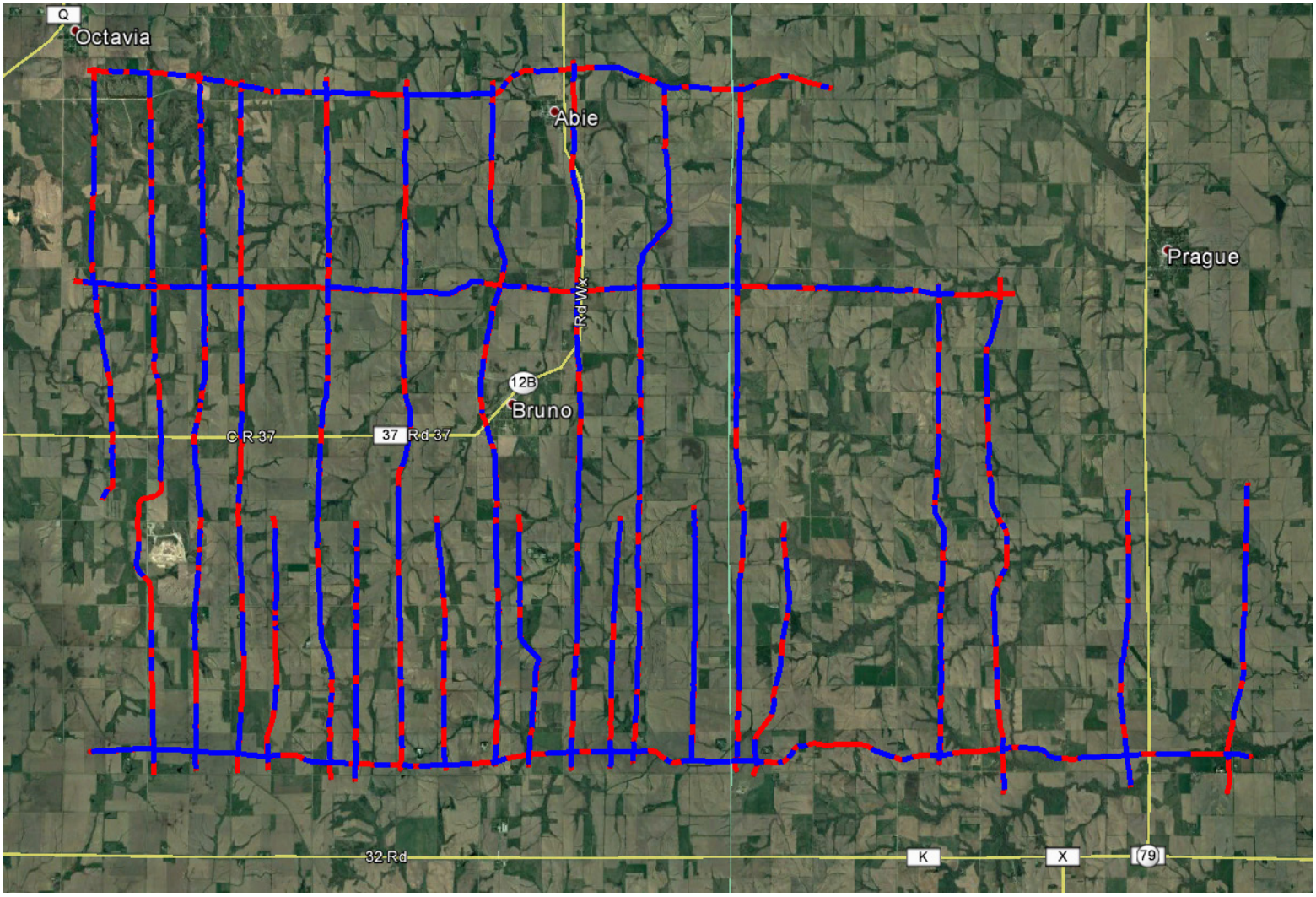


Figure 4-12. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LPNNRD SQS#1 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix_3_Deliverables\KMZ.

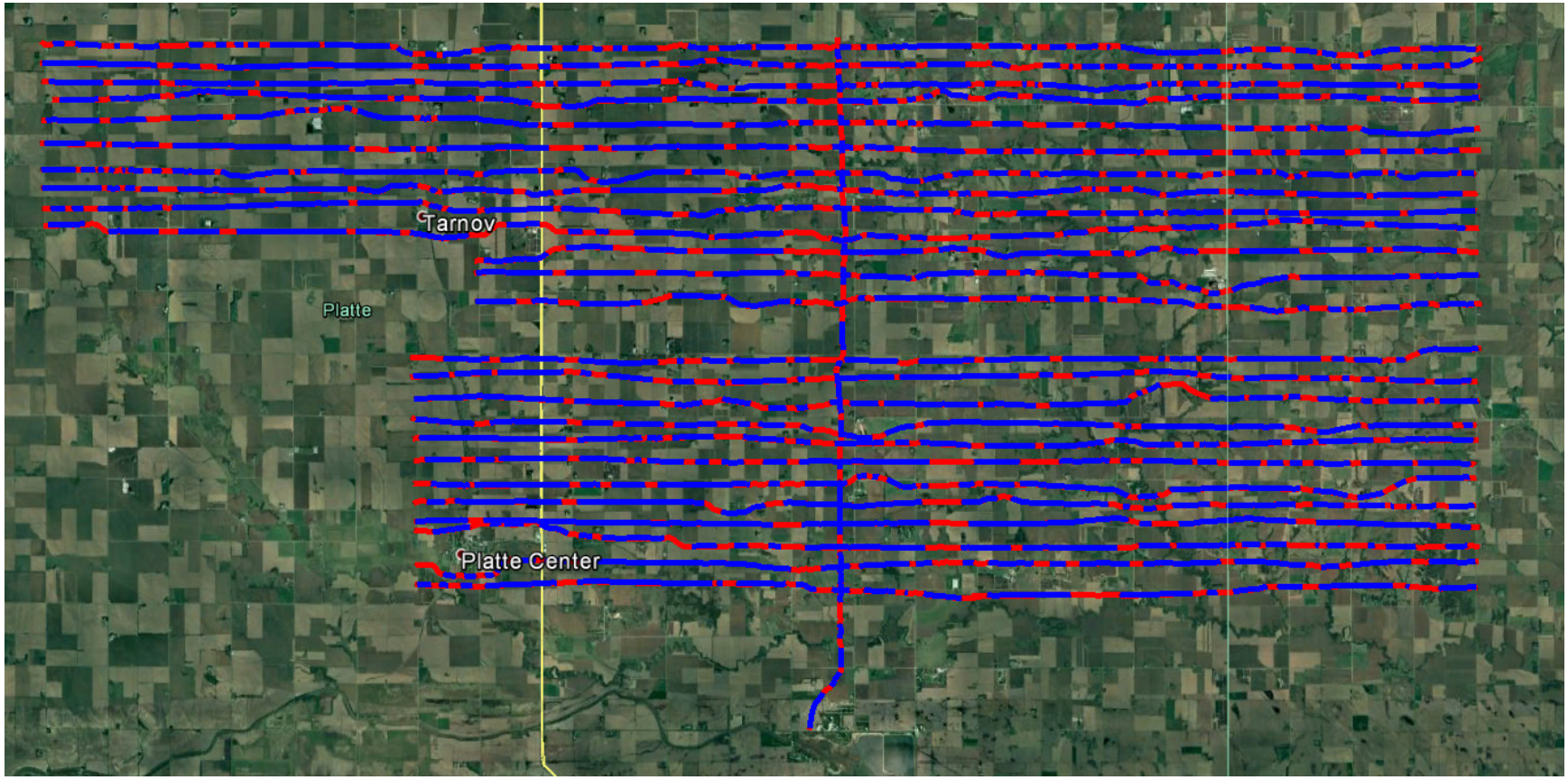


Figure 4-13. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LPNNRD SQS#2 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix_3_Deliverables\KMZ.

4.4.5 Magnetic Field Data

As discussed above, the SkyTEM 304M includes a Total Field magnetometer. The magnetic Total Field data can yield information about infrastructure as well as geology. Figure 4-14 shows the magnetic Total Field intensity data for the LPNNRD SQS#1 AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). A similar map is presented for the SQS#2 AEM survey area in Figure 4-15. These data are used in decoupling efforts.

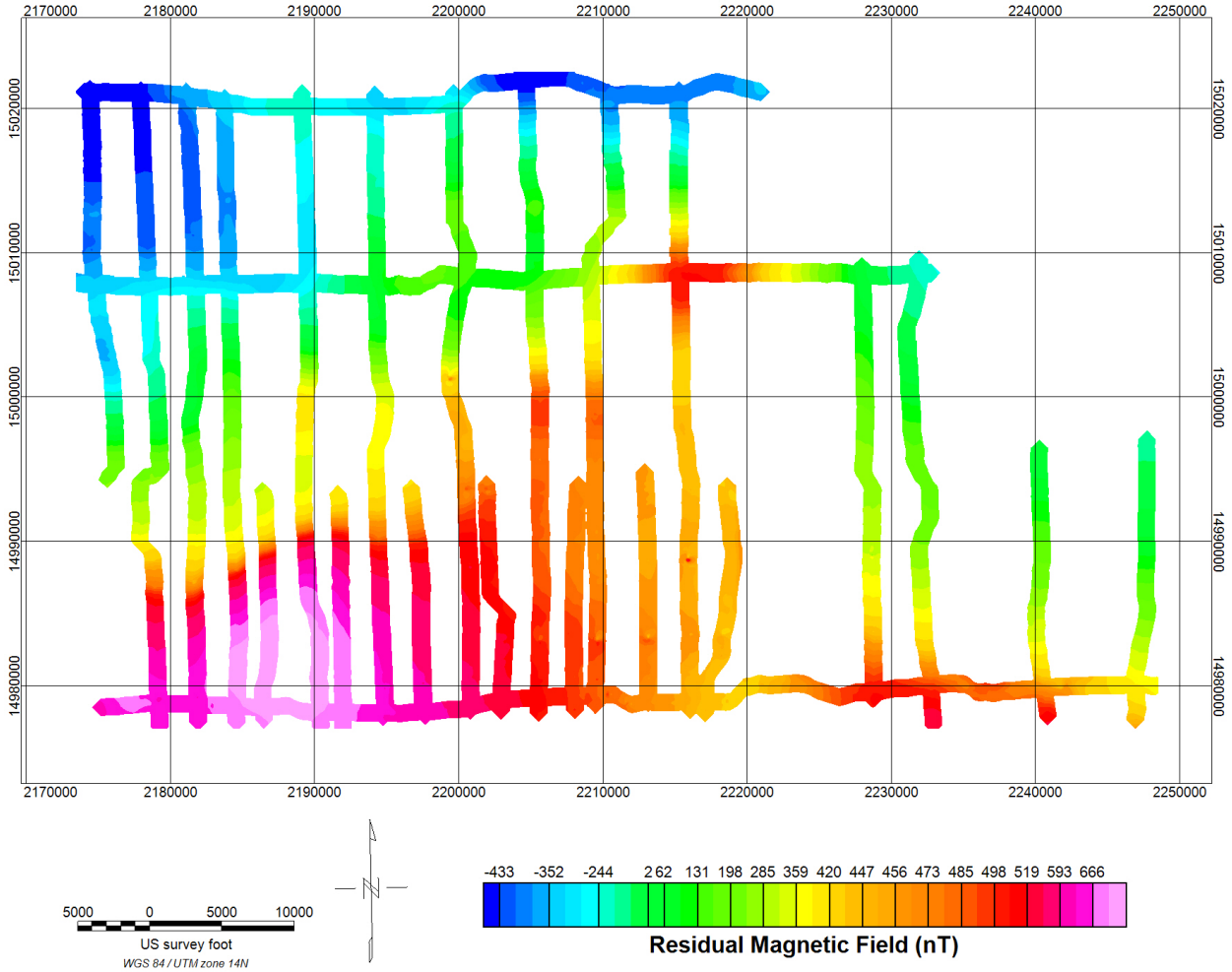


Figure 4-14. Magnetic Total Field intensity data for the LPNNRD SQS#1 AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

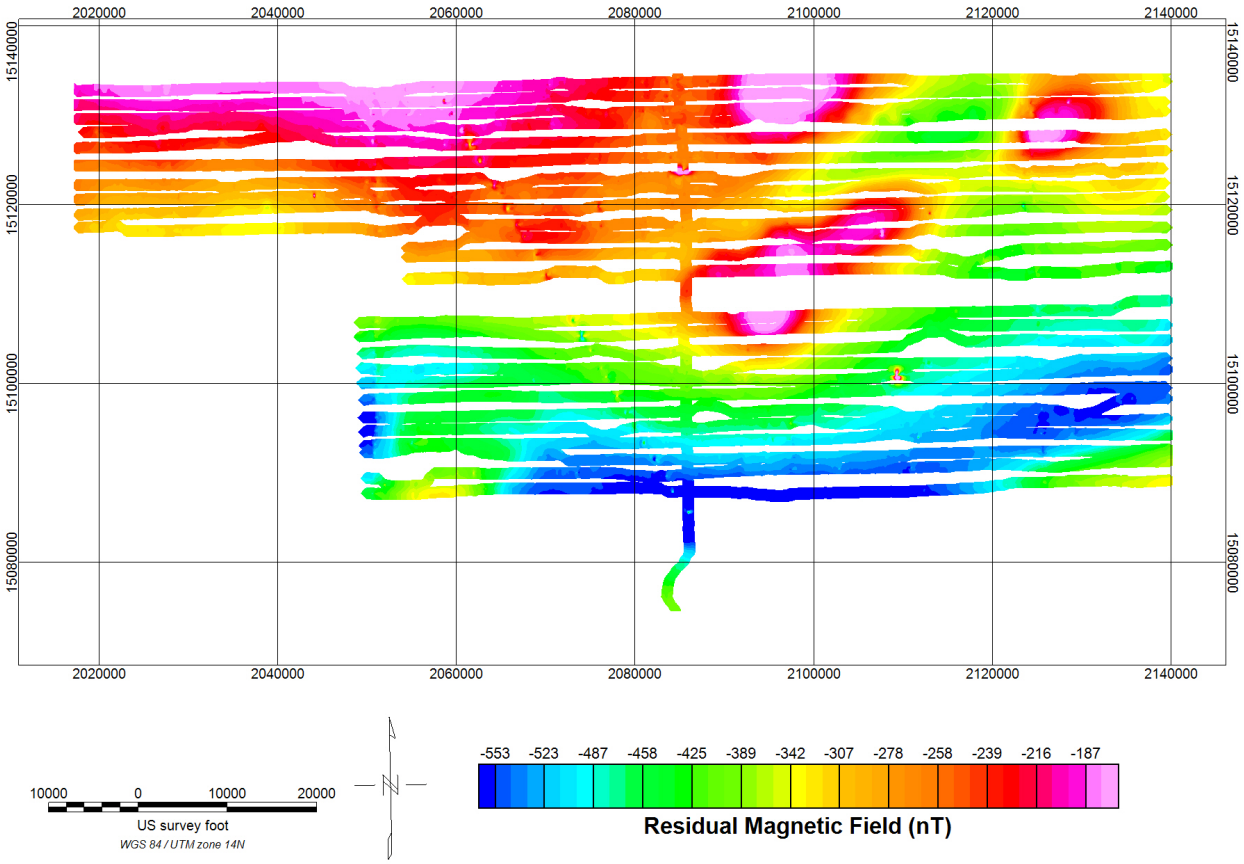


Figure 4-15. Magnetic Total Field intensity data for the LPNNRD SQS#2 AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

For comparison purposes, images of magnetic Total Field data collected by the USGS (Sweeney and Hill, 2005) are presented in Figure 4-16 for SQS#1 and Figure 4-17 for SQS#2. The USGS data were collected over a much larger reconnaissance grid spacing (5 mile line separation) than were collected in the present survey over the LPNNRD and then the USGS data were "upward continued" to a 1000 ft elevation. Even so the comparison between the two data sets are quite good – especially the large high amplitude anomalies in similar positions in each set of images.

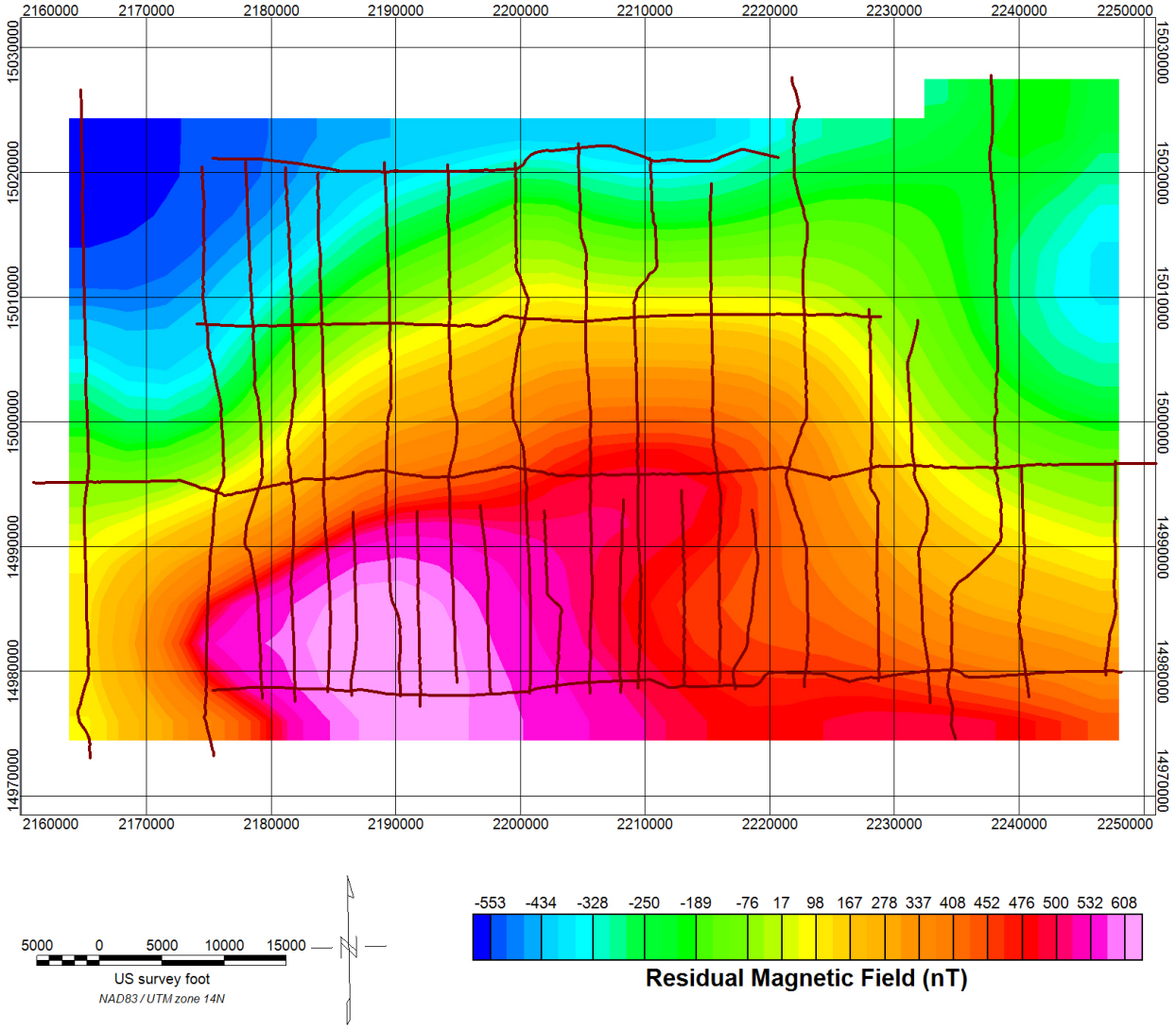


Figure 4-16. USGS magnetic Total Field intensity data for the SQS#1 subarea of the LPNNRD AEM survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5 mile line spacing and upward continued to a reference elevation of 1000 ft.

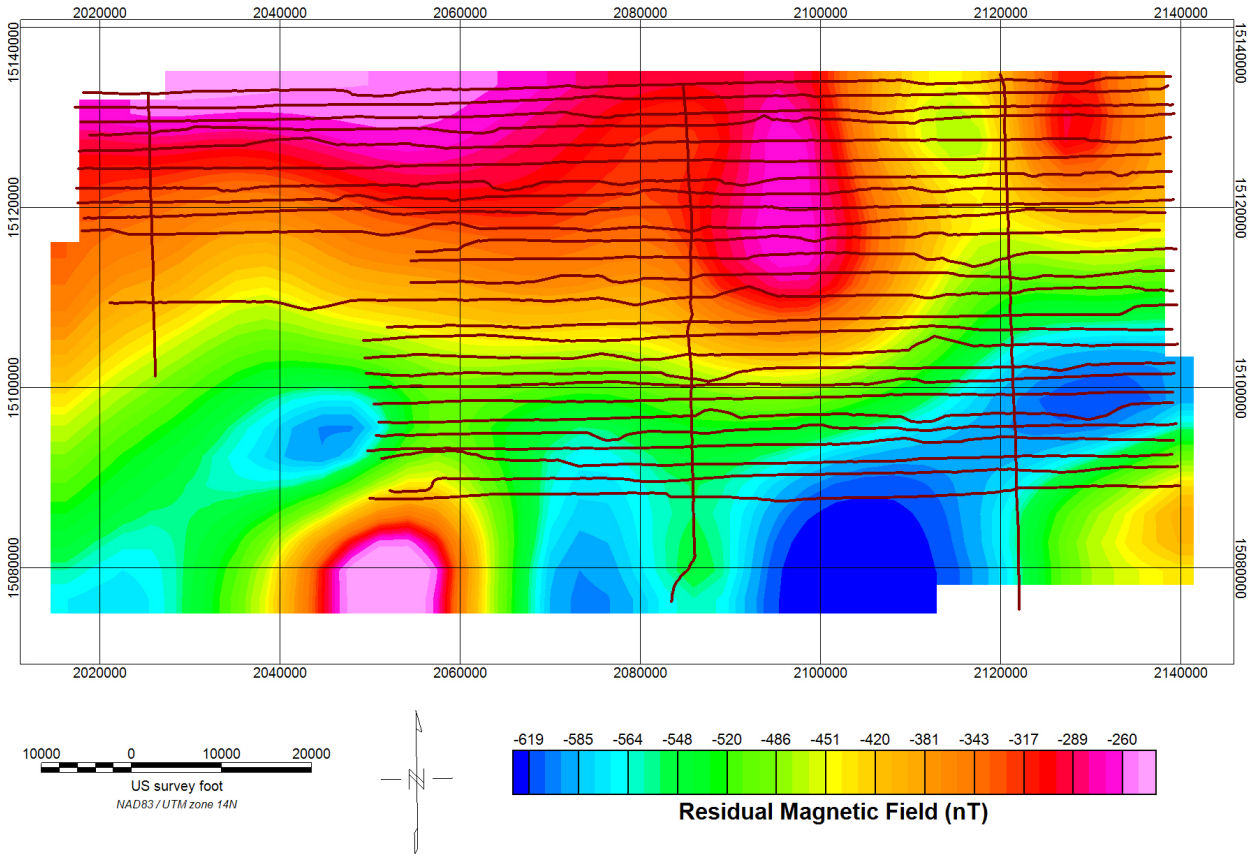


Figure 4-17. USGS magnetic Total Field intensity data for the SQS#2 subarea of the LPNNRD AEM survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5 mile line spacing and upward continued to a reference elevation of 1000 ft.

4.5 Spatially-Constrained Inversion

Following the initial decoupling and LCI analysis, Spatially-Constrained Inversions (SCI) were performed. SCIs use EM data along, and across, flight lines within user-specified distance criteria (Viezzoli et al., 2008).

The LPNNRD AEM data were inverted using SCI smooth models with 29 layers, each with a starting resistivity of 10 Ohm-m (equivalent to a 10 ohm-m halfspace). The thicknesses of the first layers of the models were about 10 ft with the thicknesses of the consecutive layers increasing by a factor of 1.08. The depths to the bottoms of the 28th layers were set to 1,023 ft, with thicknesses up to about 85 ft. The thicknesses of the layers increase with depth (Table 4-4 and Figure 4-18) as the resolution of the technique decreases. The spatial reference distance, ***s***, for the constraints were set to 98 ft with power laws of 0.5. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.7 and 1.6, respectively, for all layers.

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

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

Layer	Depth to Bottom (ft)	Thickness (ft)	Layer	Depth to Bottom (ft)	Thickness (ft)
1	9.8	9.8	16	298.4	31.2
2	20.5	10.6	17	332.1	33.7
3	31.9	11.5	18	368.5	36.4
4	44.3	12.4	19	407.8	39.3
5	57.7	13.4	20	450.3	42.5
6	72.2	14.5	21	496.2	45.9
7	87.8	15.6	22	545.7	49.5
8	104.7	16.9	23	599.2	53.5
9	122.9	18.2	24	657.0	57.8
10	142.5	19.7	25	719.4	62.4
11	163.8	21.2	26	786.8	67.4
12	186.7	22.9	27	859.5	72.8
13	211.5	24.8	28	938.1	78.6
14	238.3	26.8	29	1023.0	84.9
15	267.2	28.9			

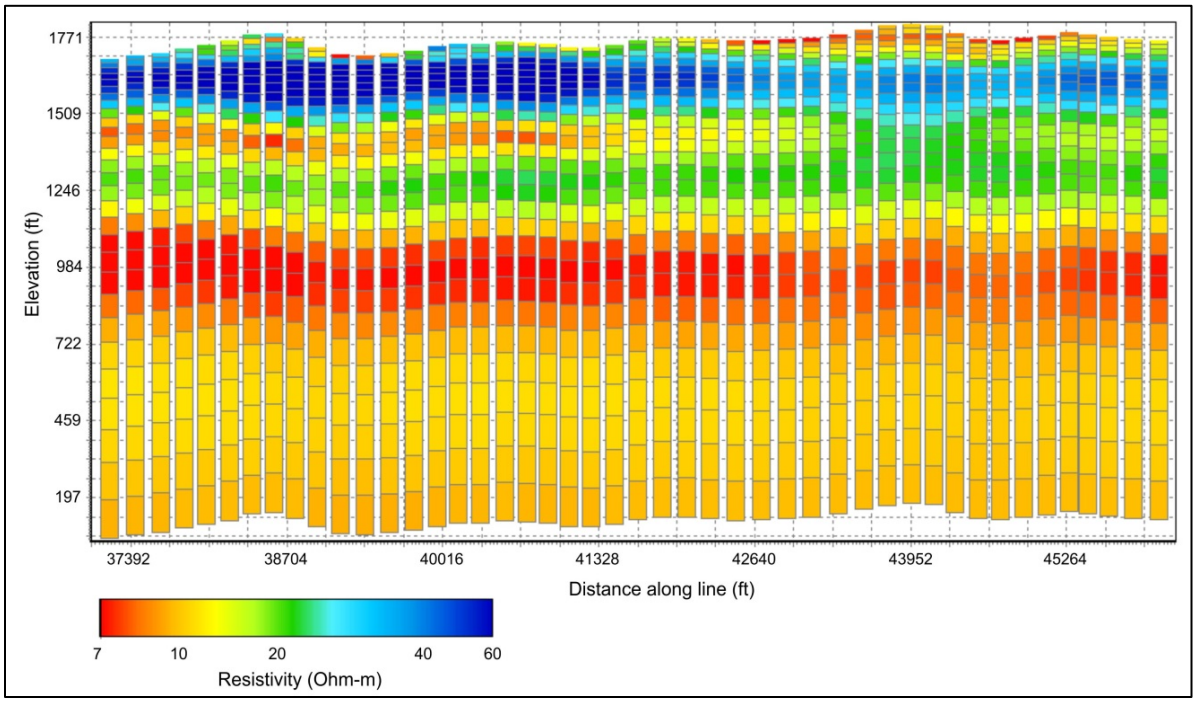


Figure 4-18. An example of an AEM profile illustrating increasing model layer thicknesses with depth.

Figure 4-19 presents a histogram of the LPNNRD SQS#1 SCI inversion data/model residuals and Figure 4-20 presents the histogram of SCI inversion data/model residuals for SQS#2. Maps of data residuals for each AEM study area are presented in Figure 4-21 (SQS#1) and Figure 4-22 (SQS#2).

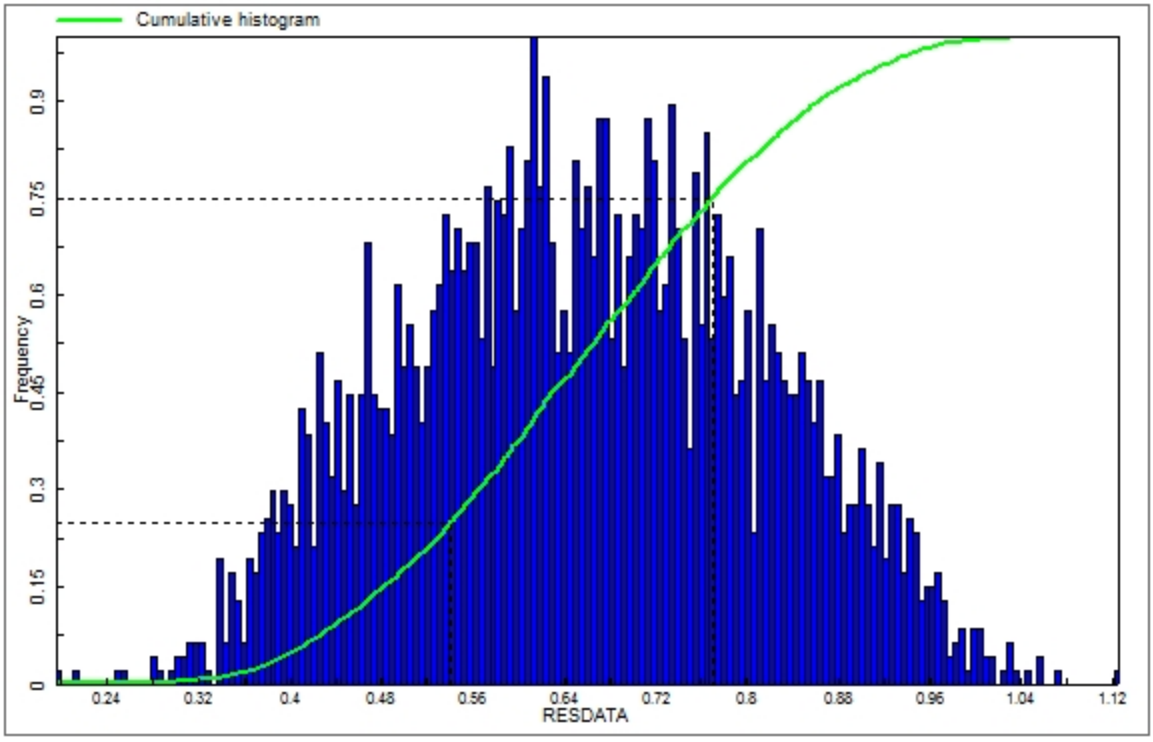


Figure 4-19. Data/model residual histogram for the LPNNRD SQS#1 SCI inversion results.

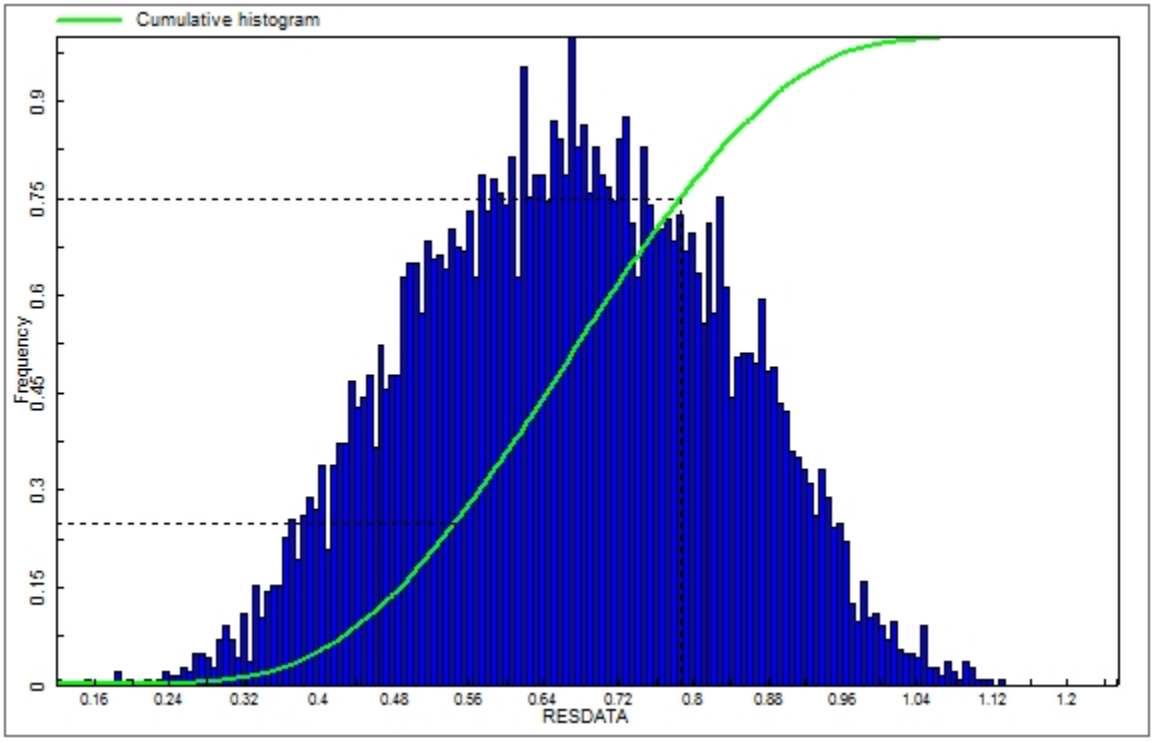


Figure 4-20. Data/model residual histogram for the LPNNRD SQS#2 SCI inversion results.

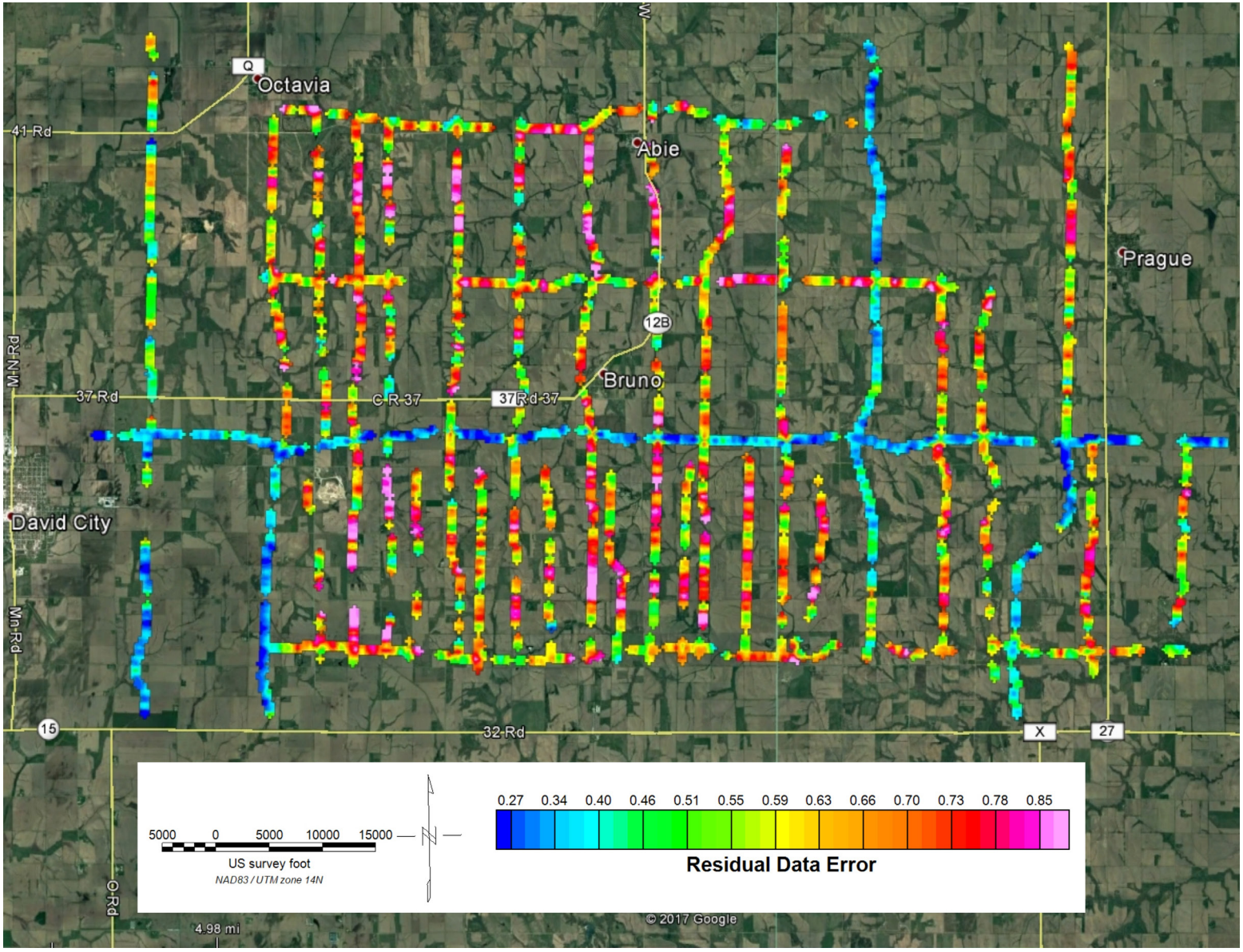


Figure 4-21. Map of data residuals for the LPNNRD SQS#1 SCI inversion results.

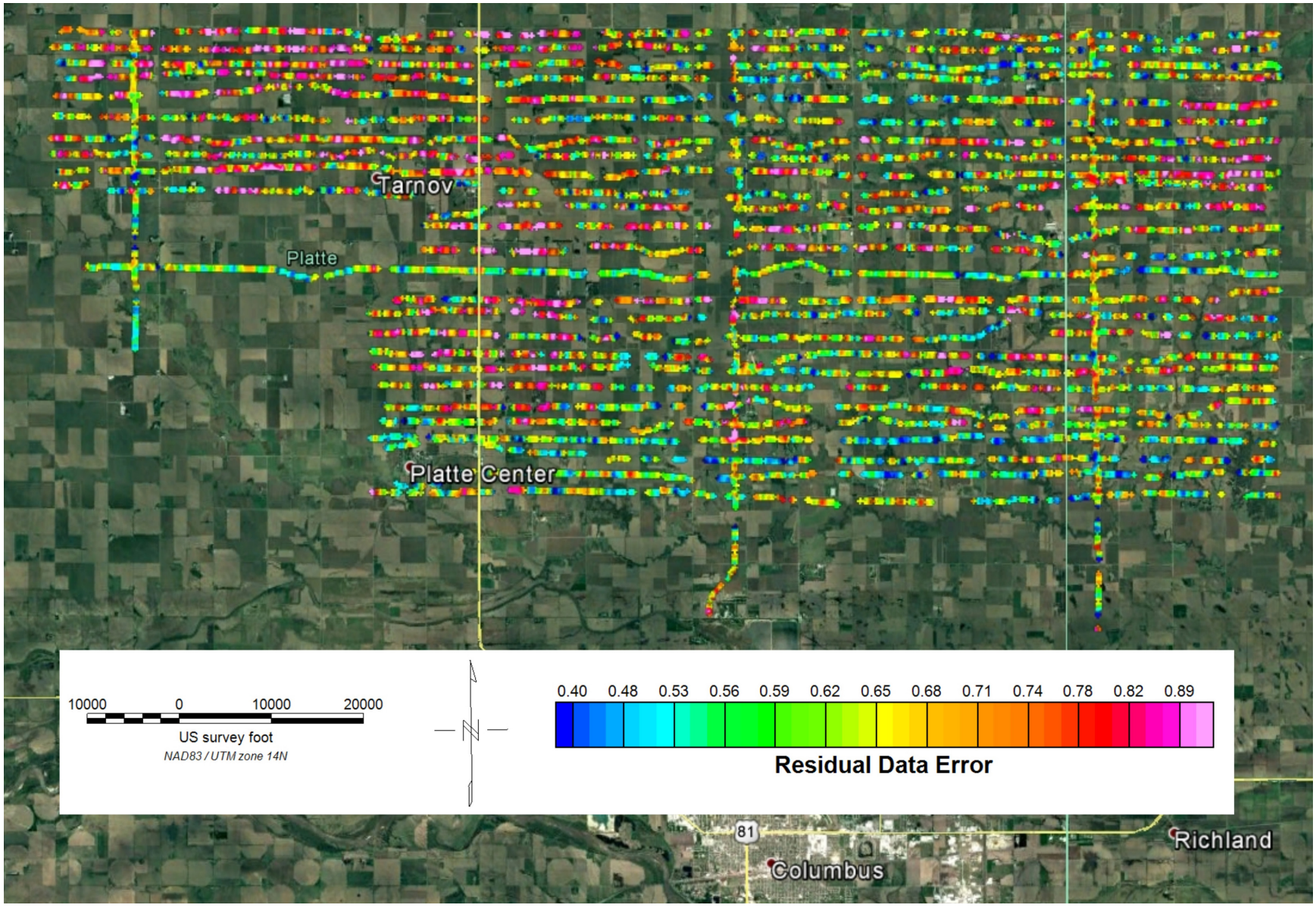


Figure 4-22. Map of data residuals for the LPNNRD SQS#2 SCI inversion results.

5 AEM Results and Interpretation

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

5.1 Interpretive Process

5.1.1 Merge AEM Databases from Different Flights

After the inversion process several short lines were combined to form continuous lines within the SQS#2 AEM survey area. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. Table 5-1 lists the original flown lines and the new combined lines. A portion of the LPNNRD has had AEM data collection before that is summarized in Carney et al (2015b). Table 5-2 lists the lines that were combined with the 2016 data for both SQS#1 and SQS#2.

Table 5-1. Combination of flight lines within the LPNNRD SQS#2 AEM survey area.

Original Source Lines	Direction	New Line
L109701, and L109702	East-West	L219403
L110701, and L110702	East-West	L221403
L111501, and L111502	East-West	L223003
L112701, and L112702	East-West	L225403
L114501, and L114502	East-West	L229003
L125701, and L125702	East-West	L125700
L125901, and L125902	East-West	L125902
L142001, and L142002	North-South	L284003

Table 5-2. Combination of 2014 and 2015 AEM data (Carney et al. 2015b) flight lines within the 2016 LPNNRD SQS#1 and SQS#2.

2016 Lines	2015 Lines	2014 Lines	Area	Direction	New Line
	L400101	L201301	SQS#1	North-South	L601402
	L400501	L201801	SQS#1	North-South	L602302
	L300101		SQS#1	East-West	
L135001	L400201		SQS#1	North-South	L535202
	L400301		SQS#1	North-South	
		L101701	SQS#2	East-West	
		L200401	SQS#2	North-South	
		L201001	SQS#2	North-South	

A comparison of the data collected in 2014, 2015 and 2016 can indicate the stability of the system and the ability of the data to be integrated together. When examining the combination of the two separate data sets that were collected by different systems at different times and inverted separately, it is important to note that both data sets were properly calibrated and any system bias was removed prior to inversion. Inspection of the profiles created from the combined lines displaying inverted resistivity at the same color scale can indicate an issue with calibration and incomplete bias removal. Figure 5-1 is a north-south line within SQS#1 that was combined from the 2016 LENRD SkyTEM 304M AEM inversions (north end) and the 2015 SkyTEM 508 AEM inversions (south end). Inspection of Figure 5-1 shows a small break in the data coverage at the meeting point of the two datasets due to an EM coupling that was removed. However, the resistivity values continue along the line until the top of the ***IP*** is encountered in the 2016 SkyTEM304M inversions. This is due to the differences of the depths of investigation (DOI) of the SkyTEM304M and the SkyTEM 508. The combination of the two datasets indicates that there is no observable bias that was not removed from the data prior to inversion.

An east-west set of lines within SQS#2 is presented in Figure 5-2. Line L101701 (center line) was collected with the SkyTEM508 in 2014. Even though the lines are not directly butted up against each other the comparison of the upper line and the bottom line collected in 2016 and the center line collected in 2014 show good correlations. The center line collected with the SkyTEM 508 illustrates a cleaner bottom of the ***Kc*** then the other two lines due to the increased depth of penetration of the 508 and the increased DOI.

In Figure 5-3 is presented a comparison between the southernmost east-west line in the 2016 AEM survey of SQS#1 and the northernmost east-west line in a 2013 AEM survey (Carney et al., 2014b), the locations of which are displayed in Figure 1-3. Notice that the two sections are very similar and the difference between the DOI (gray dashed lines) for the 2016 AEM survey and the 2013 AEM survey, indicating an improvement in the AEM system hardware and processing.

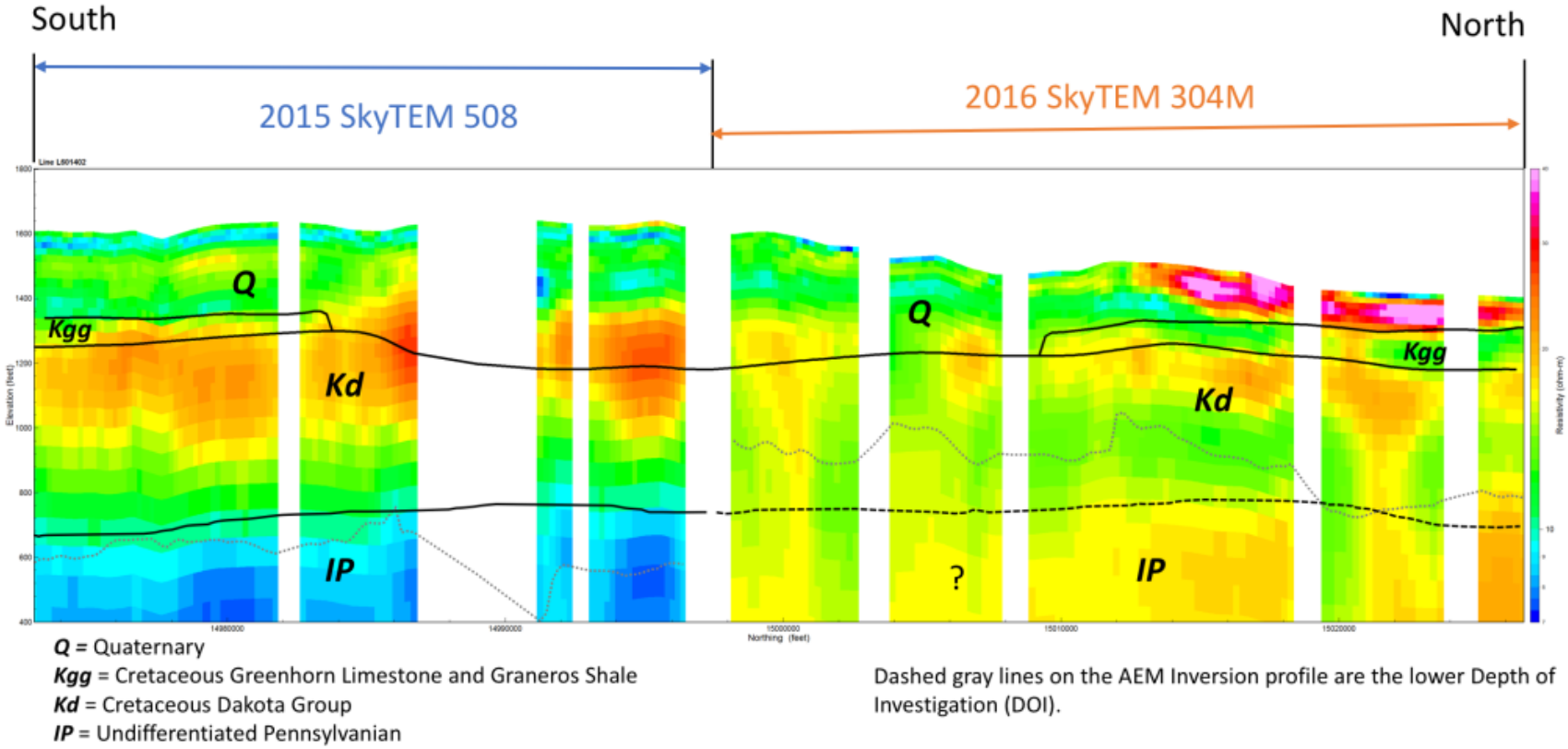


Figure 5-1. Example of a profile view of a north-south flight line L601402, part of SQS#1 that was combined from the 2015 ENWRA AEM and the 2016 LENRD AEM. The 2016 portion is labeled as L299002 within the LENRD. The profile displays the resistivity values of the 2015 ENWRA SkyTEM 508 and the 2016 LENRD SkyTEM 304M inversions. Geological interpretations on the profile include the Quaternary (*Q*), Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*), Cretaceous Dakota Group (*Kd*), and undifferentiated Pennsylvanian (*IP*). The dashed black line shows the inferred location of the *Kd* and *IP* contact in the SkyTEM304M inversions. The dotted gray lines represent the lower depths of investigation (DOI) from the inversions.

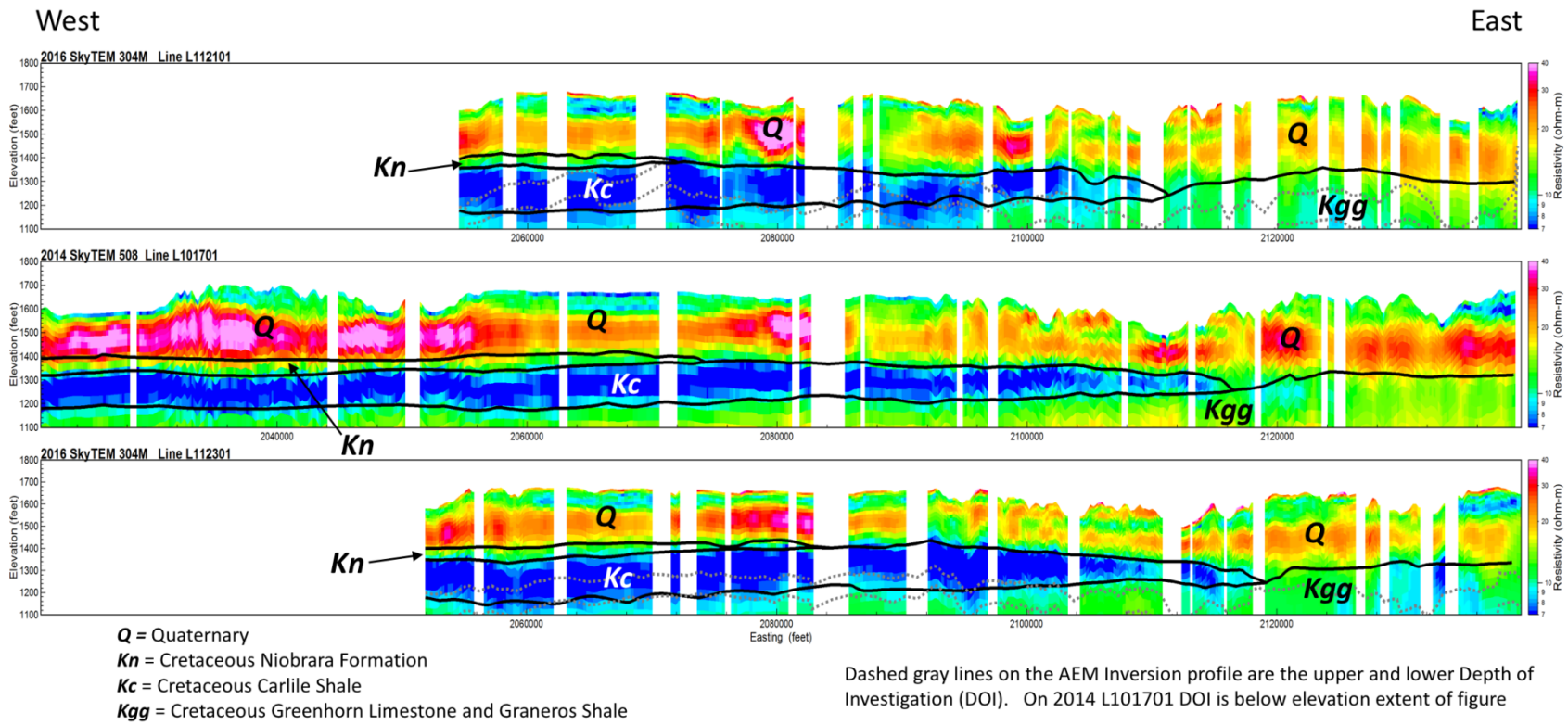


Figure 5-2. Example of a profile view of three east-west lines within SQS#2. The top profile L112101 was collected in 2016 with the SkyTEM304M; the middle profile line L101701 was collected in 2014 with the SkyTEM508; and the bottom profile line L112301 was collected in 2016 with the SkyTEM304M. Geological interpretations on the profile include the Quaternary (*Q*), Cretaceous Niobrara Formations (*Kn*), Cretaceous Carlile Shale (*Kc*), and Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*). The dashed black line shows the inferred location of the *Kd* and *IP* contact in the SkyTEM304M inversions. The dotted gray lines represent the upper and lower depths of investigation (DOI) from the inversions.

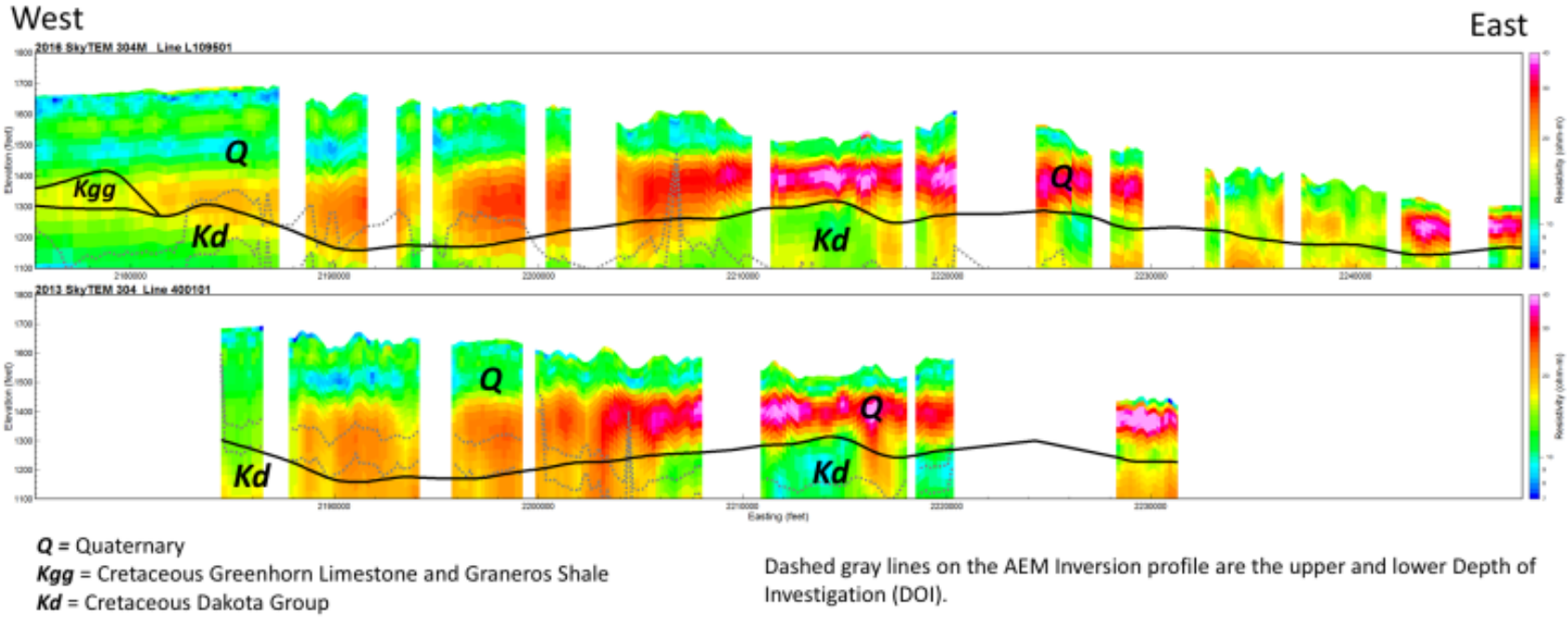


Figure 5-3. A comparison between the southernmost east-west line in the 2016 AEM survey of SQS#1 and the northernmost east-west line in the 2013 AEM survey. Notice that they are very similar and the difference between the DOI for the 2016 AEM survey and the 2013 AEM survey, indicating an improvement in the AEM system hardware and processing.

5.1.2 Construct the Project Digital Elevation Model

To ensure that the elevation used in the project is consistent for all the data sources (i.e. boreholes and AEM), a Digital Elevation Model (DEM) was constructed for the LPNNRD survey. The data were downloaded from the National Elevation dataset (NED) located at the National Map Website (U.S. Geological Survey, 2016) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates are North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88). The 100 ft grid cell size was used throughout the project and resulting products. Figure 5-4 is a map of the DEM of SQS#1 showing a vertical relief of 471.2 ft with a minimum elevation of 1,254.1 ft and a maximum elevation of 1725.3 ft. This DEM was used to reference all elevations within the SQS#1 AEM and borehole datasets. Figure 5-5 is a map of the DEM of SQS#2 showing a vertical relief of 355.8 ft with a minimum elevation of 1391.0 ft and a maximum elevation of 1,746.8 ft. This DEM was used to reference all elevations within the SQS#2 AEM and borehole datasets.

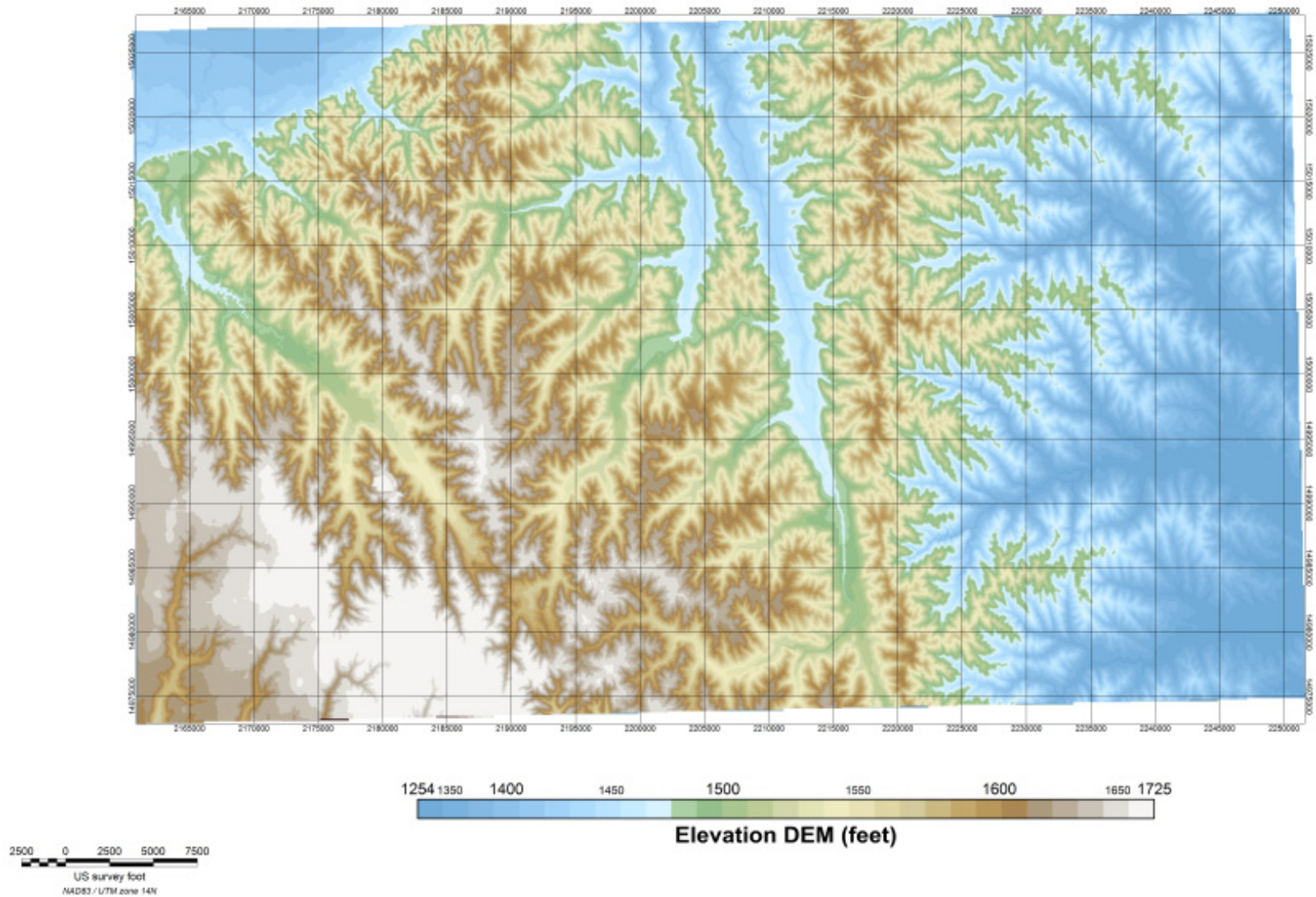


Figure 5-4. Map of the Digital Elevation Model for SQS#1. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2016). North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

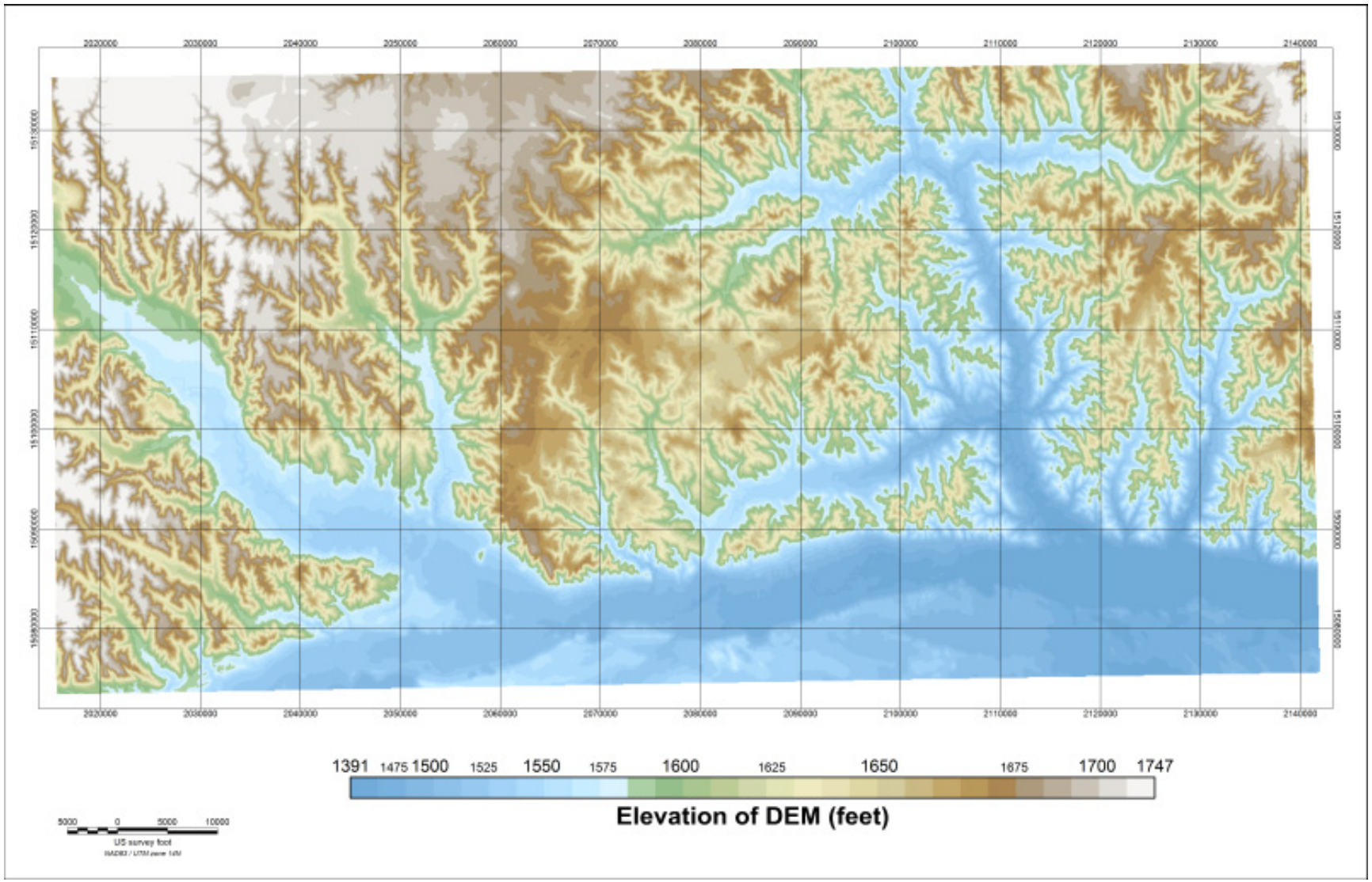


Figure 5-5. Map of the Digital Elevation Model for SQS#2. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2016). North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

5.1.3 Create Interpretative 2D Profiles

After final combination of the AEM data, characterization of the subsurface was performed in cross-section format using Encom PA 2015 (DataminePA, 2017). 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 geological units including: Quaternary (***Q***), the Cretaceous Niobrara Formation (***Kn***), the Cretaceous Carlile Shale (***Kc***), the Cretaceous Greenhorn Limestone and Cretaceous Graneros Shale (***Kgg***), and the Cretaceous Dakota Group (***Kd***). The Pennsylvanian units were not interpreted within the LPNNRD due to the DOI of the 304M. The interpreted geological units included the ***Q***, ***Kn***, ***Kc***, ***Kgg***, and ***Kd*** from the upper surface of the model to the DOI. The interpretive process benefited from the use of CSD, NE-DNR, and NOGCC borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (Burchett, 1986). The interpretation began with picking the ***Kc***, ***Kn***, ***Kgg***, and ***Kd*** contacts. The process was iterative around the eroded units.

The interpretation of the ***Kc*** within the SQS#2 included examining the AEM profile section for a lower electrical resistivity layer that was also indicated in the borehole logs as the base of aquifer. Many of the CSD as well as the NE-DNR borehole logs stop at the ***Kc*** due to that stratigraphic unit not being an aquifer, due to it being composed predominantly of shale containing clay minerals. Many of the CSD boreholes have stratigraphic calls that assist in the location of the ***Kc***. For the profiles, the clipping distance from the flight lines was set independently for the CSD boreholes and for the NE-DNR boreholes. Typically, the CSD clipping distance was set to one mile or 5,280 ft, the NOGCC wells were set to 2.84 miles or 15,000 ft and the NE-DNR boreholes were set to a quarter mile or 1,320 ft. The inversion DOI was also inspected when interpreting the profiles, but was almost always below the top of the ***Kc*** in the SQS#2 flight area.

The top of the ***Kn*** is a much more challenging unit to interpret. This is due to the highly variable resistivity of the ***Kn***. The unit goes from a resistive unit to a conductive unit based on the presence of clay minerals that are within the shale, chalk, and limestone lithologies. The best way to interpret the ***Kn*** unit is to use the boreholes in the area and use the underlining Kc as a guide to the dip of the ***Kn***. Several of the CSD and the NE-DNR holes have shale, chalk, or limestone indicated at the bottom. This provides a clear indication of the ***Kn***. When the CSD holes contain stratigraphic information, that boundary can be confidently interpreted. In some instances, there are no indications of the ***Kn*** at the bottom of the holes. Inspecting the area for the average depth of the NE-DNR holes provides another clue to the positon of the ***Kn*** as many wells stop at the top of the ***Kn***. The ***Kn*** was interpreted only within SQS#2.

The ***Kgg*** can be difficult to detect depending on the depth. The ***Kgg*** is generally a thin unit composed of resistive limestone and conductive shale. When detectable, the resistive limestone of the Greenhorn Limestone is interrupted beneath the ***Kc***. The interpretation of the bottom of the ***Kgg*** is more challenging due to the variable resistivity of the ***Kd*** immediately below the conductive Graneros Shale. When the ***Kd*** contains resistive sands/sandstone, the lower contact of the ***Kgg*** and the top of the ***Kd*** is

identifiable. Deep CSD test holes and very rare deep NE-DNR wells can assist in the verification of the position of the ***Kgg*** and ***Kd***. The ***Kgg*** was interpreted for both SQS#1 and SQS#2.

The ***Kd*** general location is detectable when there are resistive sands/sandstones. Use of general thickness constraints can also assist in the interpretation of the ***Kd*** location. NOGCC wells in the area also provide general stratigraphic control assisting in the location of the geologic units. Within SQS#1 the ***Kd*** is close to the surface and is interpreted with the use of the NE-DNR registered wells.

Figure 5-6 is an approximately 10.5-mile-long east-west line L109301 within SQS#1. This line illustrates the eroded ***Kgg*** overlying the ***Kd***. Two CSD test holes are in the profile on in the center *4-B-77* and one on the eastern end. *05-LPN-15* is on the eastern end of the line shows the stratigraphic section from the ***Kgg*** to the top of the Pennsylvanian. ***Q*** materials overlie the ***Kgg*** throughout the profile. The western end of the ***Q*** material contains large areas of conductive clays with the glacial tills. In the middle of the profile and on the eastern end the ***Q*** materials contain increased amounts of sands as indicated by the increase in resistivity, CSD test holes, and the NE-DNR registered wells.

Figure 5-7 is an approximately 9.5-mile-long North-south line L400301 that is perpendicular to Line L109301 and approximately the location of CSD test hole 05-LPN-15. This line shows the increased ***Q*** resistive zone on the southern end and that the ***Kgg*** is eroded off the southern end. The resistivity of the ***Q*** material indicates a moderately resistive zone in the center of the profile centered on test hole *05-LPN-15*. At the northern end of the line, the ***Q*** material contains large areas of conductive clays with the glacial tills.

A 3D fence diagram of the compiled 2D inverted resistivity earth-model profiles for the SQS#1 AEM survey area is presented in Figure 5-8. The view is to the northwest with a vertical exaggeration is 5. Resistivity and interpretative voxel models can be created from sets of these 3D fence diagrams.

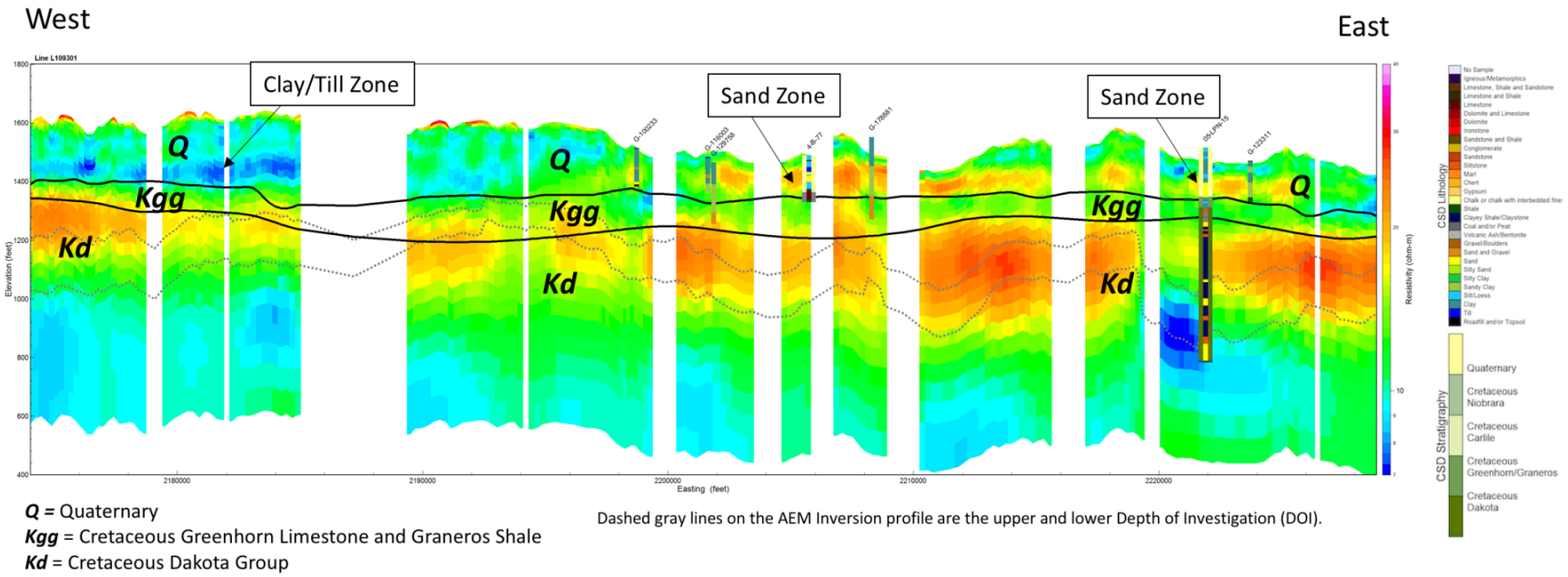


Figure 5-6. 10.5-mile long east-west line L109301 within the SQS#1 survey area. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

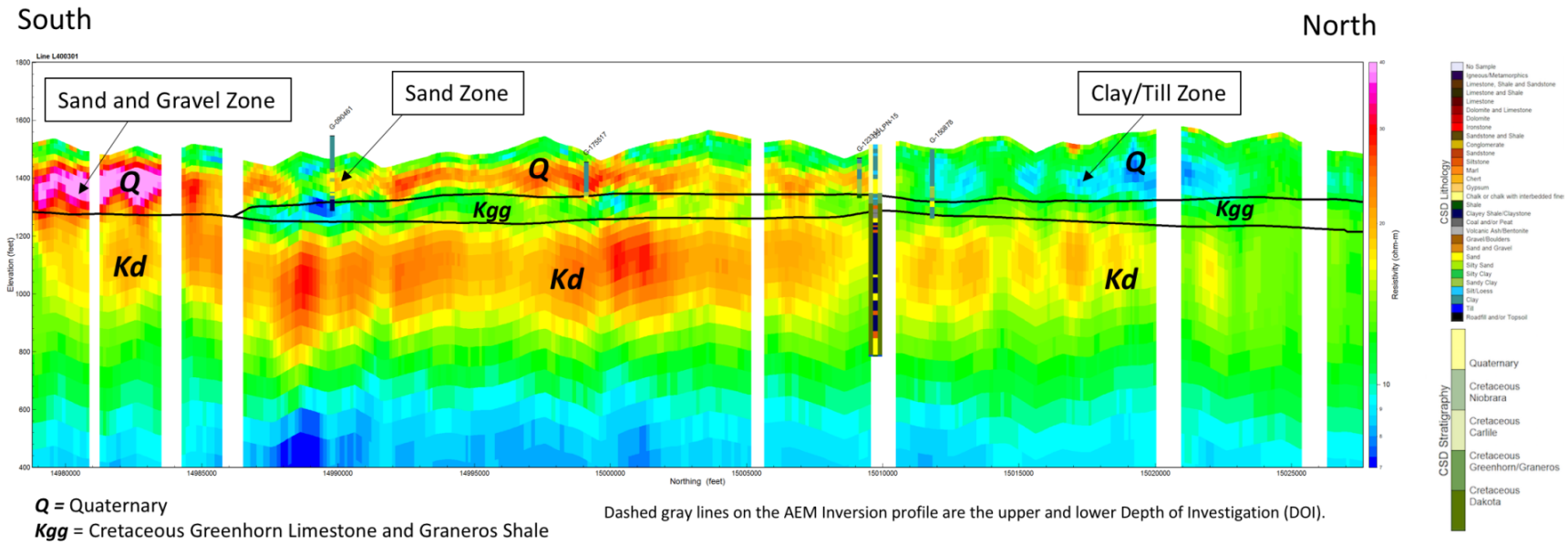


Figure 5-7. 9.5-mile long north-south line L400301 within the SQS#1 survey area. Nebraska CSD and DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

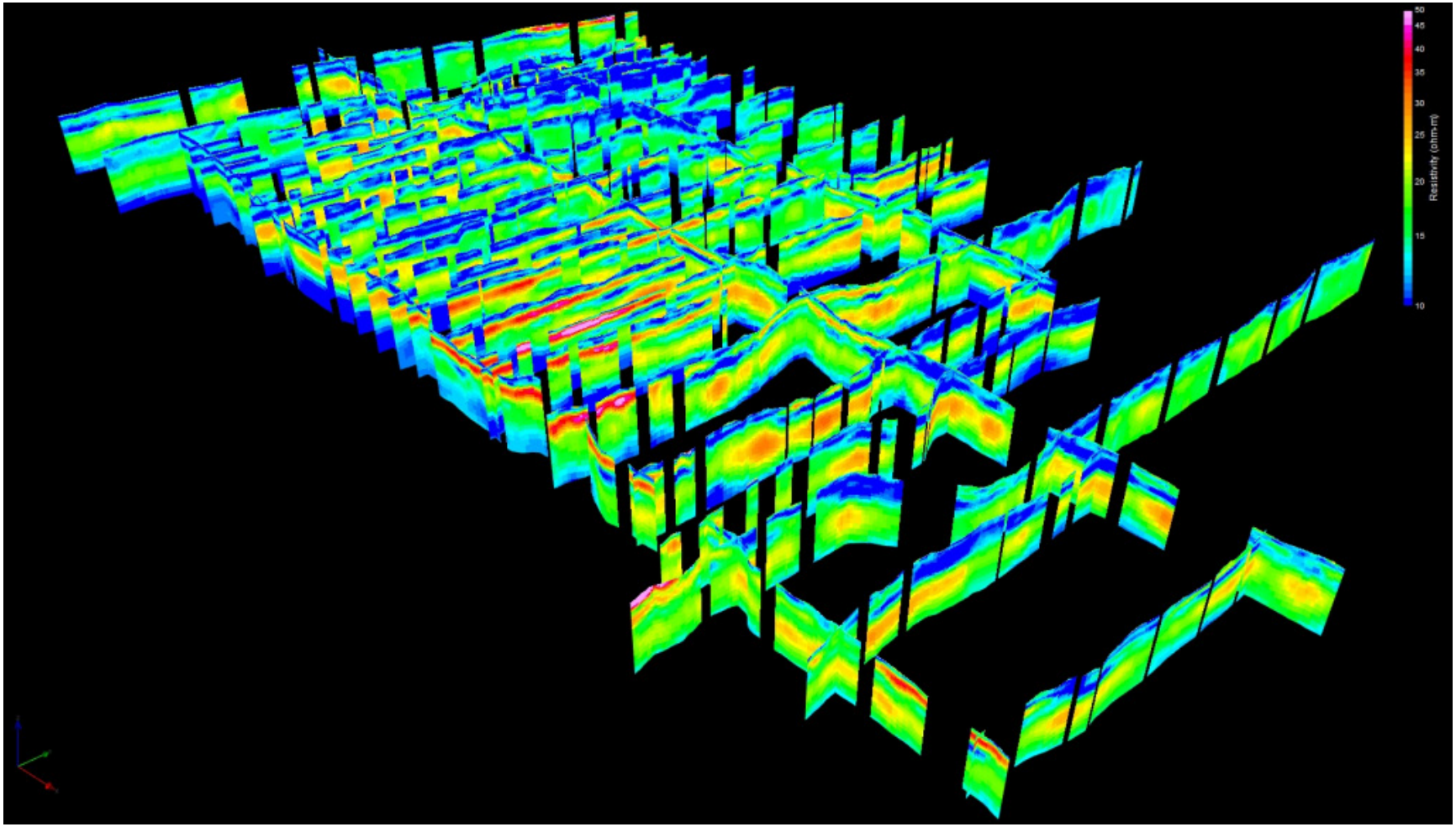


Figure 5-8. 3D fence diagram made up of the SQS#1 2D inverted resistivity earth-model profiles. The view is to the northwest. Vertical exaggeration is x5. Interpretative voxel models can be created from sets of these 3D fence diagrams.

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An approximately 22.5-mile-long east-west line L111301 within the SQS#2 AEM survey area is presented in Figure 5-9. The geological units of ***Kn***, ***Kc***, ***Kgg***, and ***Kd*** are mapped within the profile. The ***Kn*** and the ***Kc*** are dipping to the west and are both eroded off within the profile. The ***Q*** materials sit on the ***Kn***, ***Kc*** and the ***Kgg*** from the west to the east. The detection of the ***Kc*** is easily accomplished by its conductive nature and underlies the ***Kn*** in on the western end of the profile. The top of the ***Kn*** is difficult to interpret and the use of the NE-DNR registered wells are critical. Below the ***Kc*** the ***Kgg*** is detectable on the western end of the profile, but is close to the DOI. As the ***Kc*** is eroded off the ***Kgg*** toward the east, it is difficult to distinguish the ***Kgg*** from the overlying ***Q*** materials and the use of a NE-DNR registered wells is required to determine the contact. At the far eastern end of the profile CSD test hole *01-LPN-15* indicates a thin layer of ***Kc***. The AEM is unable to detect that layer and is not interpreted in the section. *01-LPN-15* also indicates the location of the ***Kd***. However, the contact is subtle and is below the DOI and was not interpreted. Changes in the lithology within the ***Q*** is drastic in some areas and is reflected by the AEM electrical resistivity. Several distinct resistive bodies are indicated from the west to the east. Many of those zones are confirmed by the NE-DNR registered wells.

Figure 5-10 is an approximately 11-mile-long north-south line L284003 within the SQS#2 AEM survey area. Along this profile the eroded ***Kc*** is overlain by the ***Q*** materials. In the center of the profile a deeper eroded area of the ***Kc*** can be detected that is close to eroding through to the underlying ***Kgg***. Within the ***Q*** section of this profile, several discrete bodies of sand are indicated by the resistivity and by the CSD test holes and NE-DNR registered wells.

The above examples illustrate the interpretive process that was used on the profiles provided within this report. Each flight line with interpretation including the Quaternary Aquifer material mapping (Section 5.2.1) are included in *Appendix 1*.

A 3D fence diagram of the compiled 2D inverted resistivity earth-model profiles for the SQS#2 AEM survey area is presented in Figure 5-11. The view is to the northwest with a vertical exaggeration is 10. Resistivity and interpretative voxel models can be created from sets of these 3D fence diagrams.

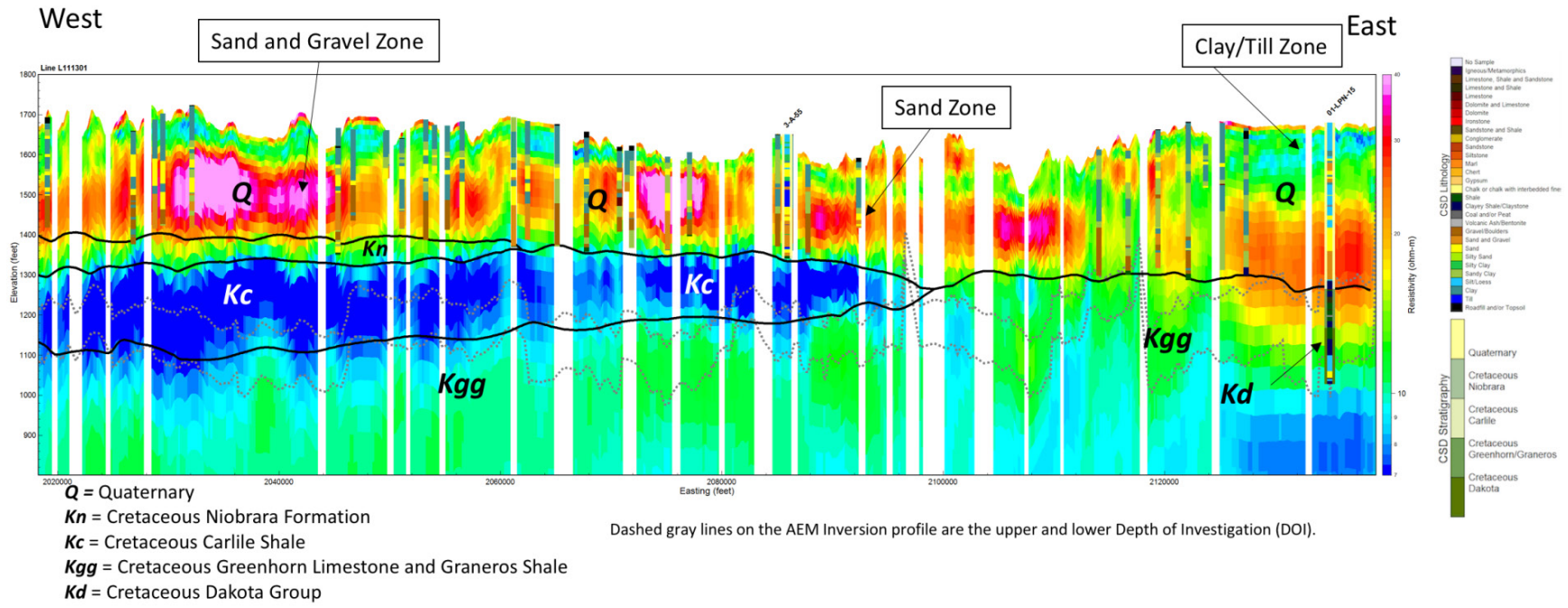


Figure 5-9. 22.5-mile long east-west line L111301 within the SQS#2 AEM survey area. Nebraska CSD and DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

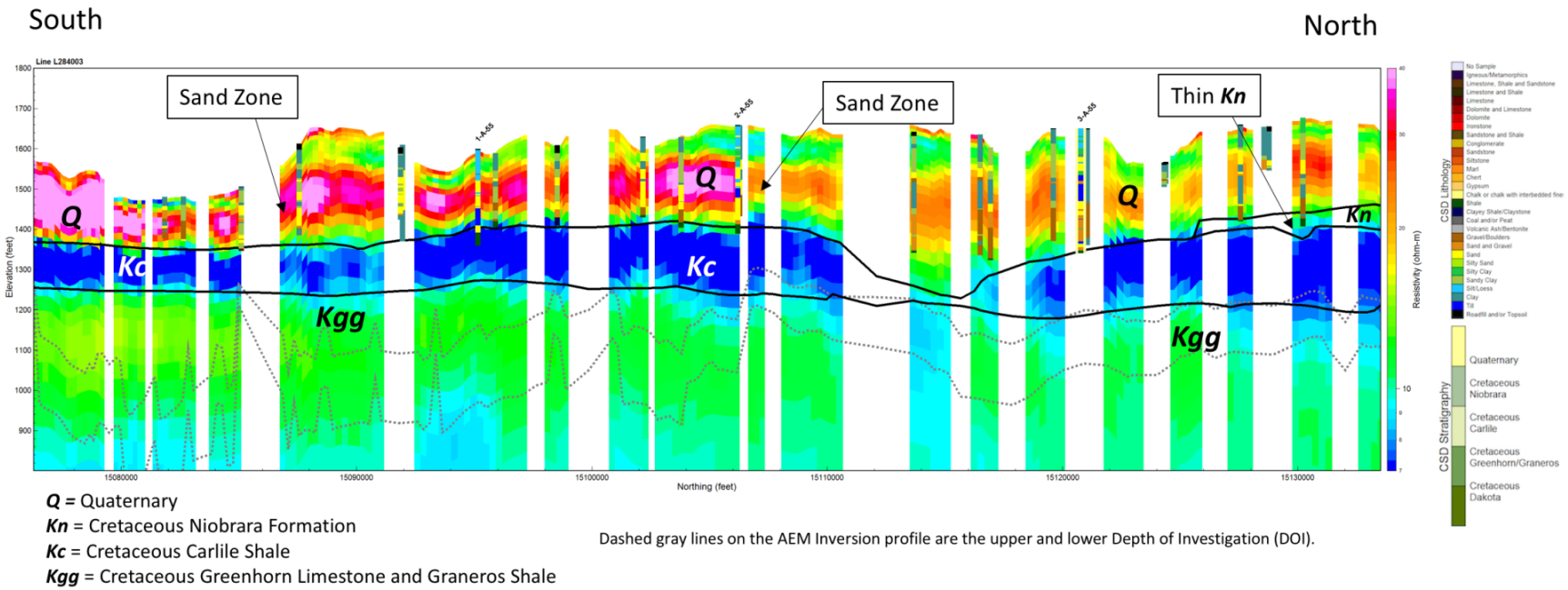


Figure 5-10. 11-mile long north-south line L284003 within the SQS#2 AEM survey area. Nebraska CSD and DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

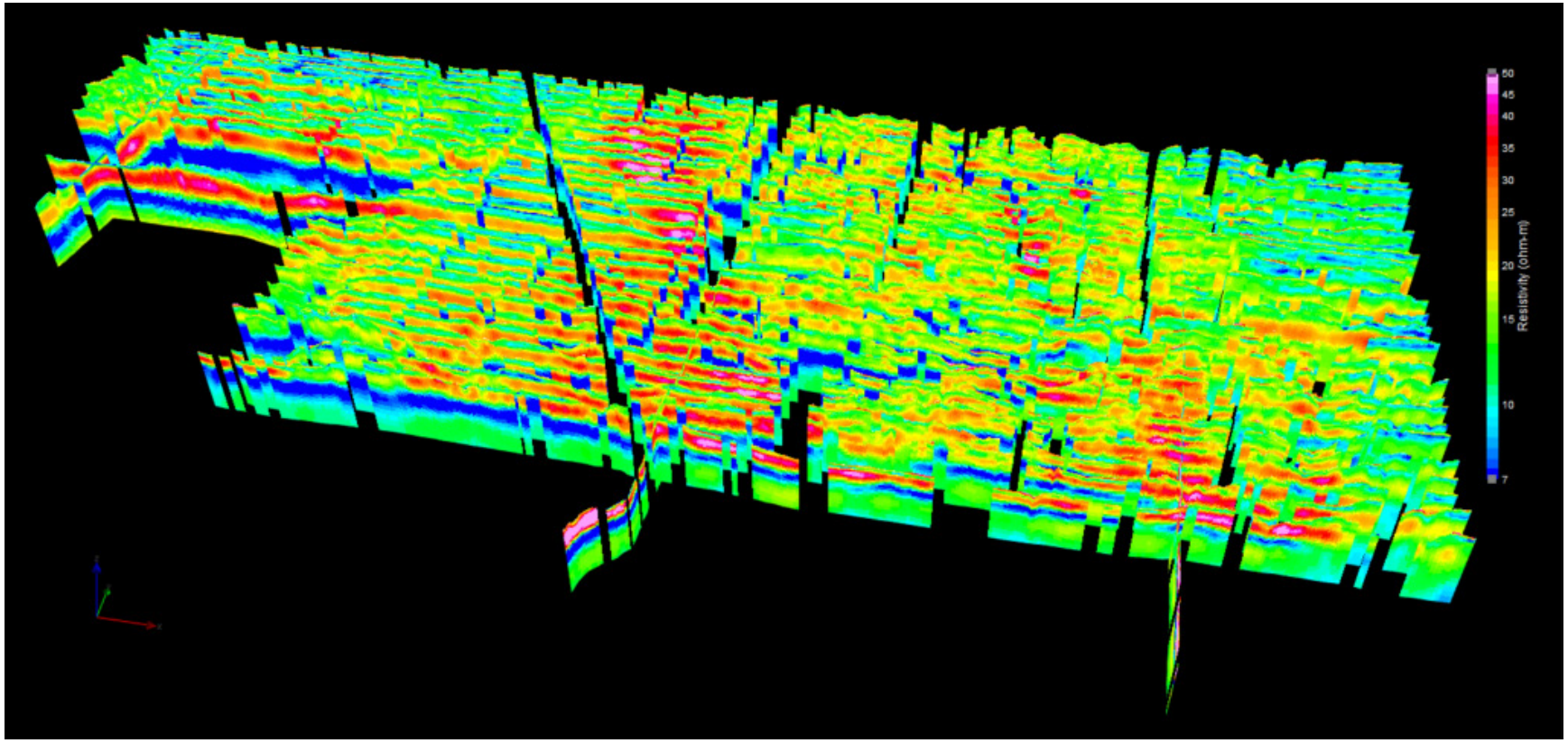


Figure 5-11. 3D fence diagram made up of the SQS#2 2D inverted resistivity earth-model profiles. The view is to the northwest. Vertical exaggeration is x5. Interpretative voxel models can be created from sets of these 3D fence diagrams.

5.1.4 Create Interpretative Surface Grids

SQS#1 and SQS#2 AEM survey area surface grids of geologic formations were also produced. To create these grids, the elevations of the AEM-interpreted top of the formations 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.

For the ***Kn*** top surface within SQS#2 only, 515 AEM picks and four CSD test hole picks were used in the grid using a cell size of approximately 250 feet and the "cells to extend beyond" was set to 10. All other parameters were either set to the default or left blank. The grid was then clipped to the interpreted erosional contact, when appropriate, and then clipped again to the SQS#2 survey area. Figure 5-12 is a map of the elevation of the top of the ***Kn*** within the SQS#2 AEM survey area.

For the SQS#2 ***Kc*** top surface 848 AEM picks and two CSD test hole picks were used in the grid with a cell size of approximately 250 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the interpreted erosional contact and then clipped again to the SQS#2 survey area. Figure 5-13 is a map of the elevation of the top of the ***Kc*** within the SQS#2 survey area.

For the SQS#1 ***Kgg*** top surface 412 AEM picks and seven CSD test hole picks were used in the grid with a cell size of approximately 250 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the SQS#1 survey area. Figure 5-14 is a map of the elevation of the top of the ***Kgg*** within the SQS#1 survey area.

For the SQS#2 ***Kgg*** top surface 709 AEM picks and one CSD test hole pick were used in the grid with a cell size of approximately 250 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the SQS#2 survey area. Figure 5-15 is a map of the elevation of the top of the ***Kgg*** within the SQS#2 survey area.

For the SQS#1 ***Kd*** top surface 476 AEM picks and nine CSD test hole picks were used in the grid with a cell size of approximately 250 feet and the "cells to extend beyond" set to 10. All other parameters were either left as the default or blank. The grid was then clipped to the SQS#1 AEM survey area. Figure 5-16 is a map of the elevation of the top of the Kd within the SQS#1 AEM survey area.

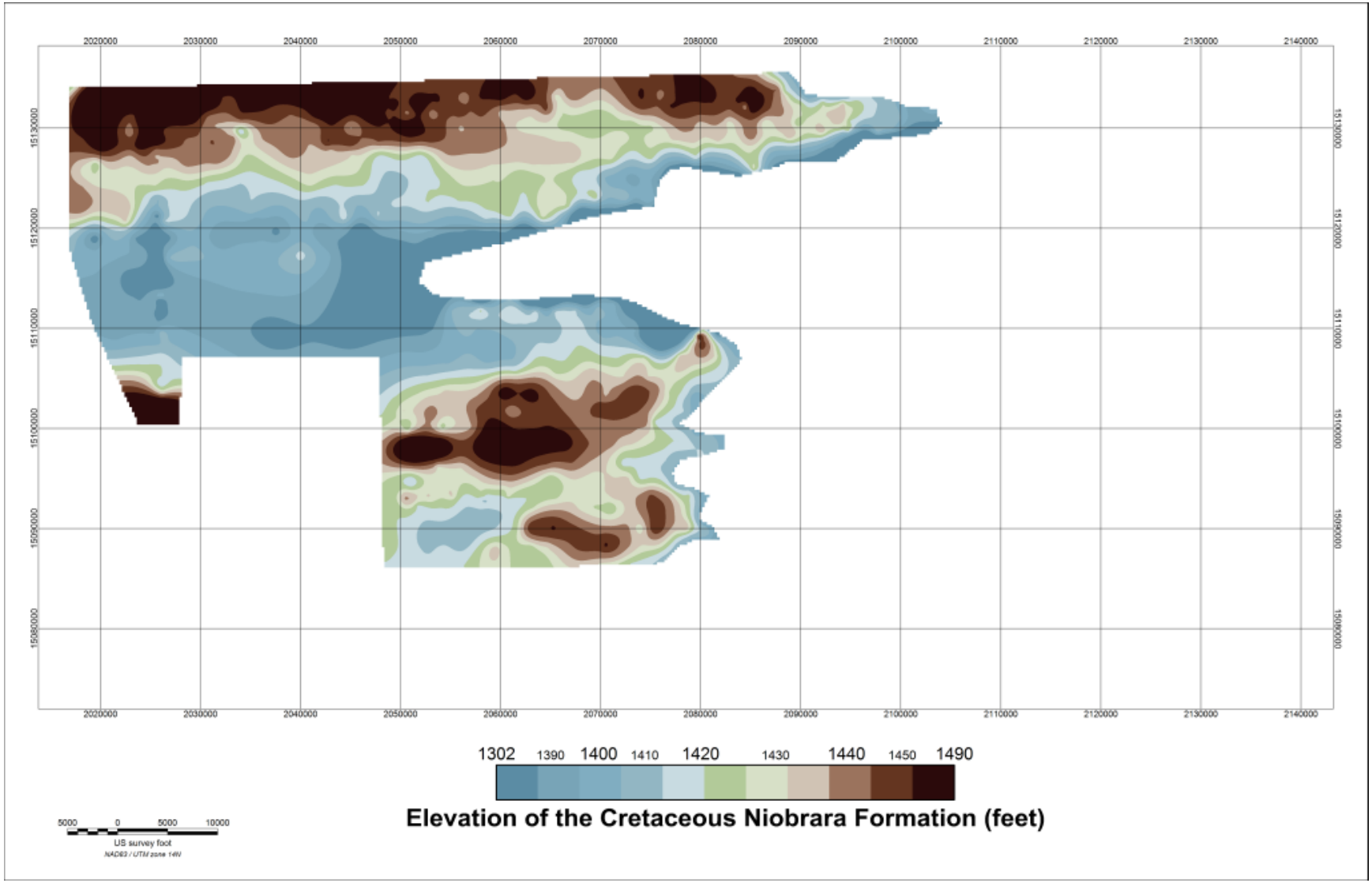


Figure 5-12. Map of the elevation of the top of the Cretaceous Niobrara Formation (*Kn*) within the SQS#2 AEM survey area. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

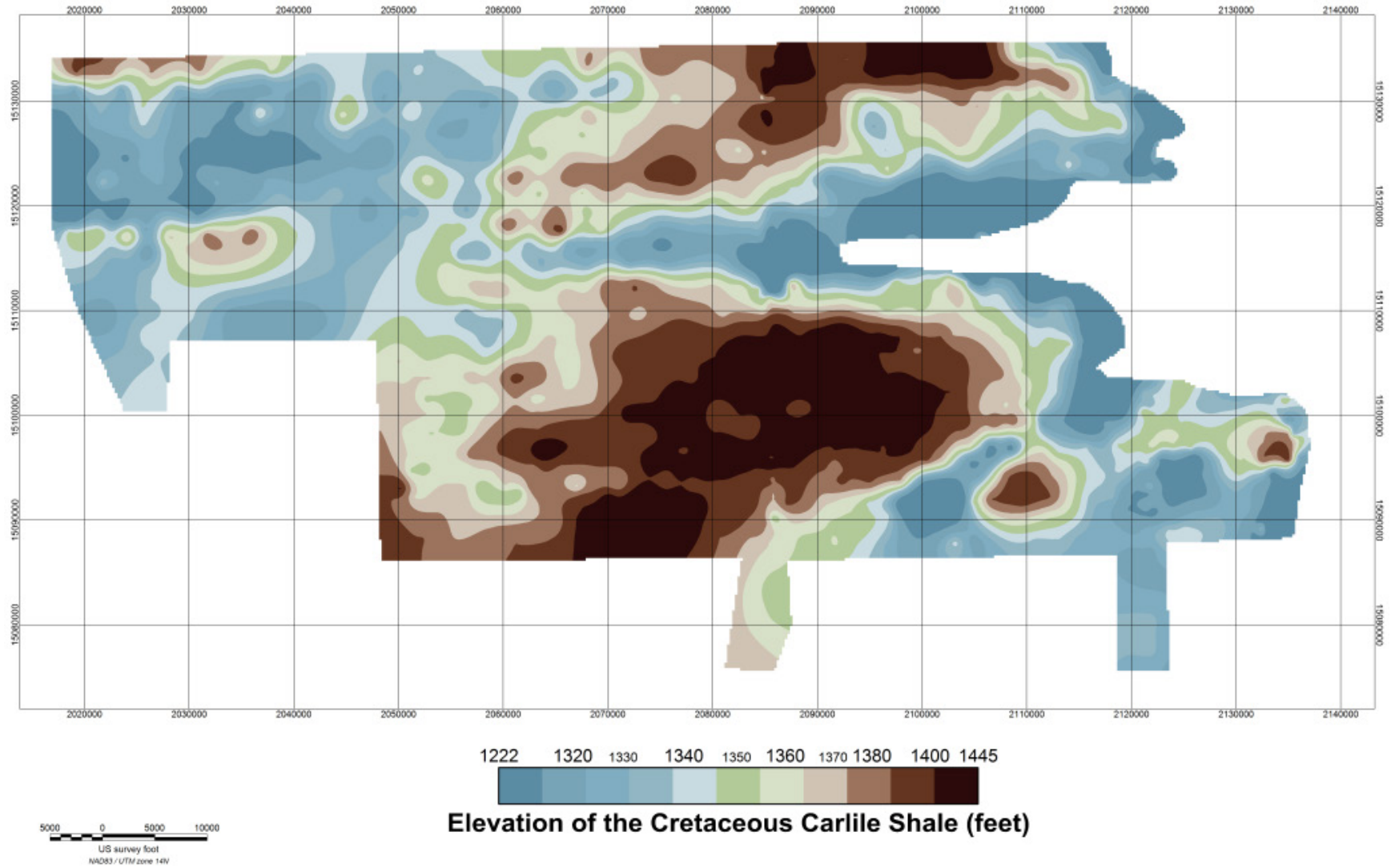


Figure 5-13. Map of the elevation of the top of the Cretaceous Carlile Shale (*Kc*) within the SQS#2 AEM survey area. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

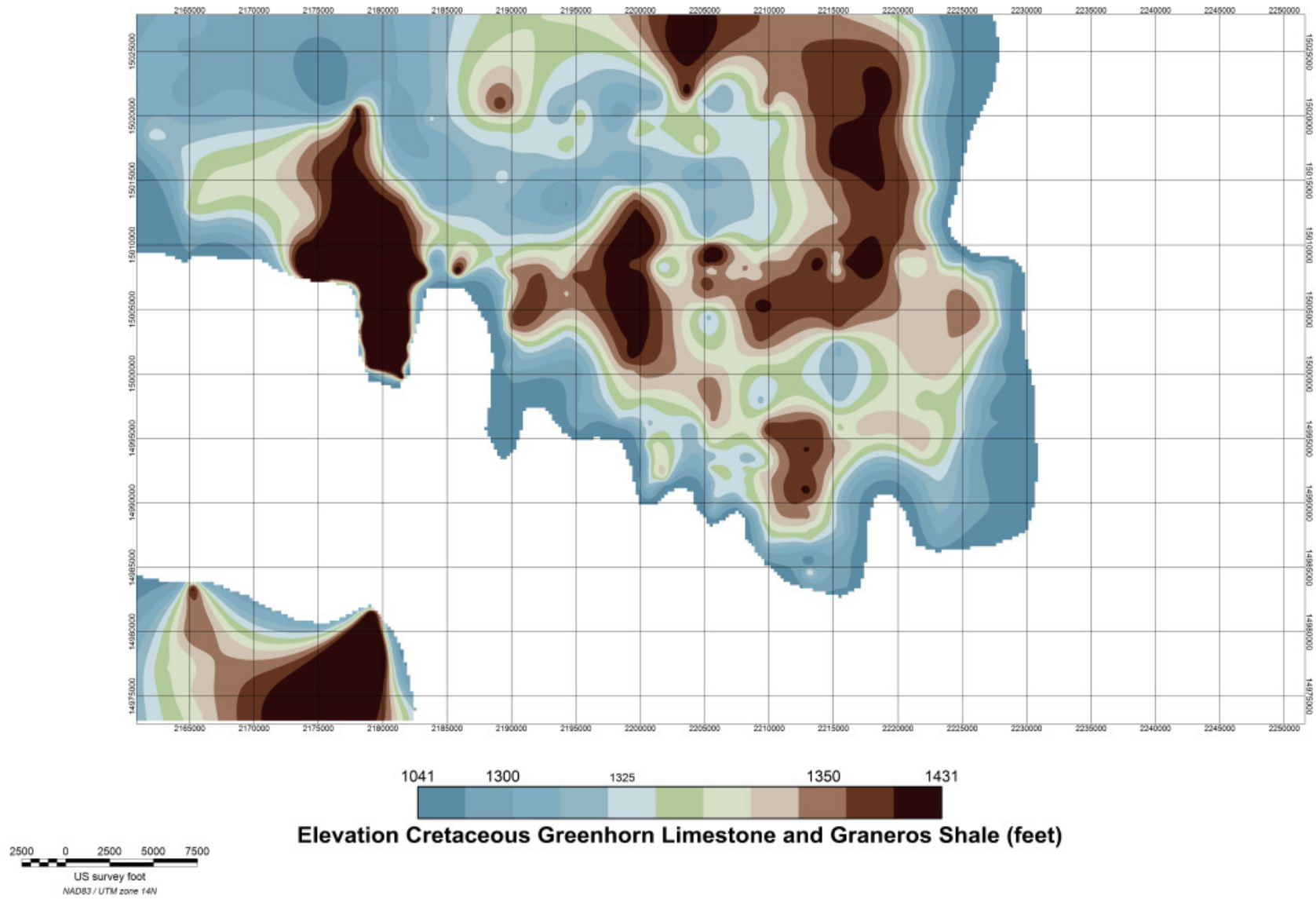


Figure 5-14. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the SQS#1 AEM survey area. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

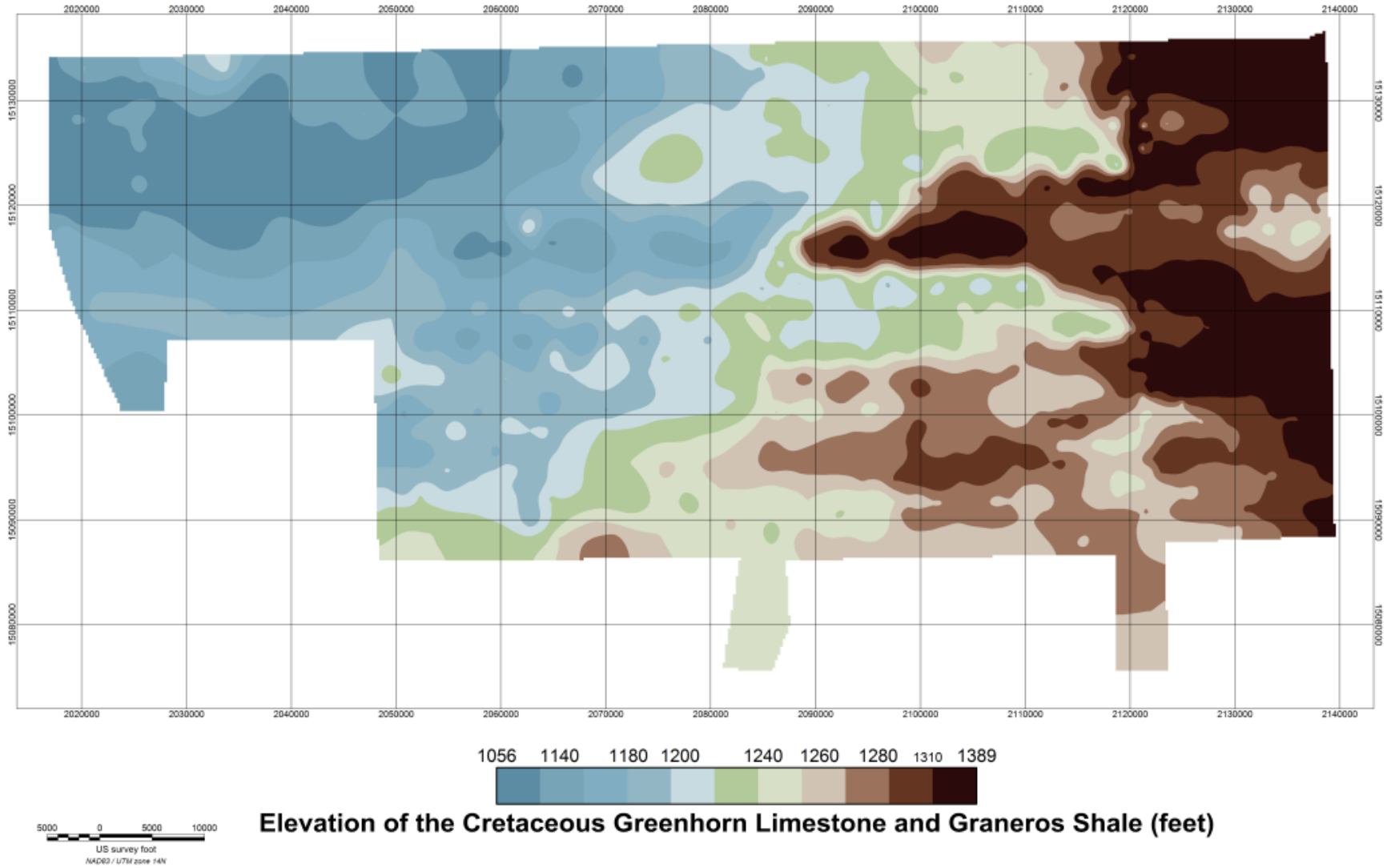


Figure 5-15. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the SQS#2 AEM survey area. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

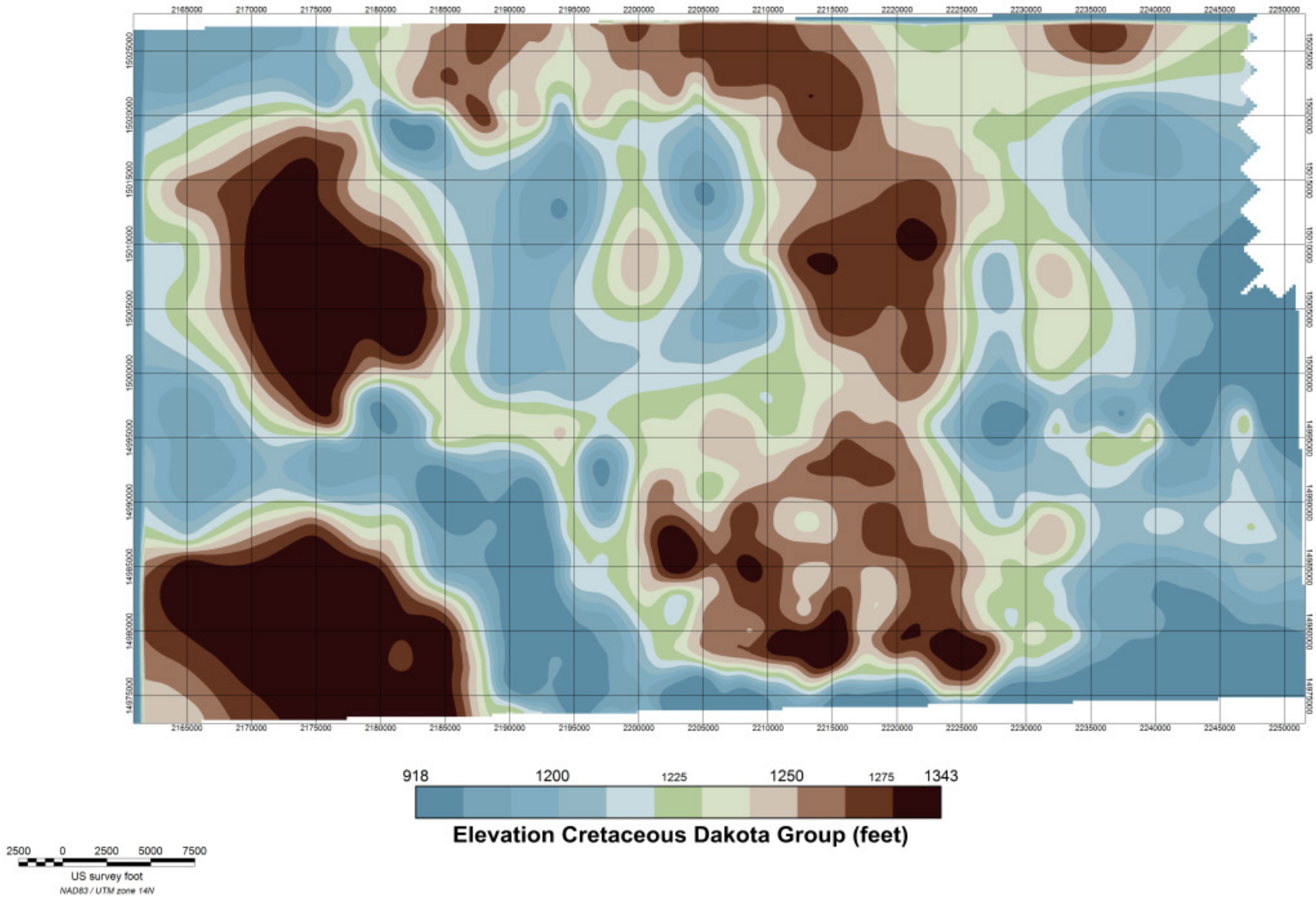


Figure 5-16. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the SQS#1 AEM survey area. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

The Cretaceous bedrock or the base of the Quaternary (***Q***) aquifer within SQS#1 is a combination of the ***Kgg*** and the ***Kd*** surfaces. The Cretaceous bedrock has vertical relief of 512.4 feet, a minimum elevation of 918.3 feet, maximum of 1,430.7 feet, and an average elevation of 1,265.5 feet. Figure 5-17 is a map of the Cretaceous bedrock elevation in SQS#1. The southern end of the SQS#1 survey area within the LPSNRD had AEM data acquired in 2013 (Carney et al. 2014b) This area had a bedrock derived for the area. The bedrock for the Carney et al. 2014b report was used as a constraint on the edges of the SQS#1 bedrock surface. The continuous surface shows a good agreement between the 2016 and 2013 data. Figure 5-18 is a composite grid of the 2013 data from Carney 2014b and the SQS#1 bedrock interpretations.

The Cretaceous bedrock or the base of the Quaternary (Q) aquifer within SQS#2 is a combination of the ***Kn***, ***Kc***, and ***Kgg*** surfaces. The ***Kn*** is the bedrock unit in the west but is eroded and thin. As indicated in Carney et al. (2015b), the ***Kn*** can be a local aquifer when fractured and the fractures have connection to surface water sources. However, in this region it is assumed that the ***Kn*** is a non-aquifer and thus a portion of the base of the aquifer system in the area. Over the center sections of the SQS#2 AEM survey area, the ***Kc*** is the bedrock unit and is eroded to the east. On the eastern side of the SQS#2 survey area the ***Kgg*** is the bedrock unit The Cretaceous bedrock has vertical relief of 424.8 feet, a minimum elevation of 1,063.4 feet, maximum of 1,488.2 feet, and an average elevation of 1,375.6 feet. Figure 5-19 is a map of the Cretaceous bedrock elevation in SQS#2.

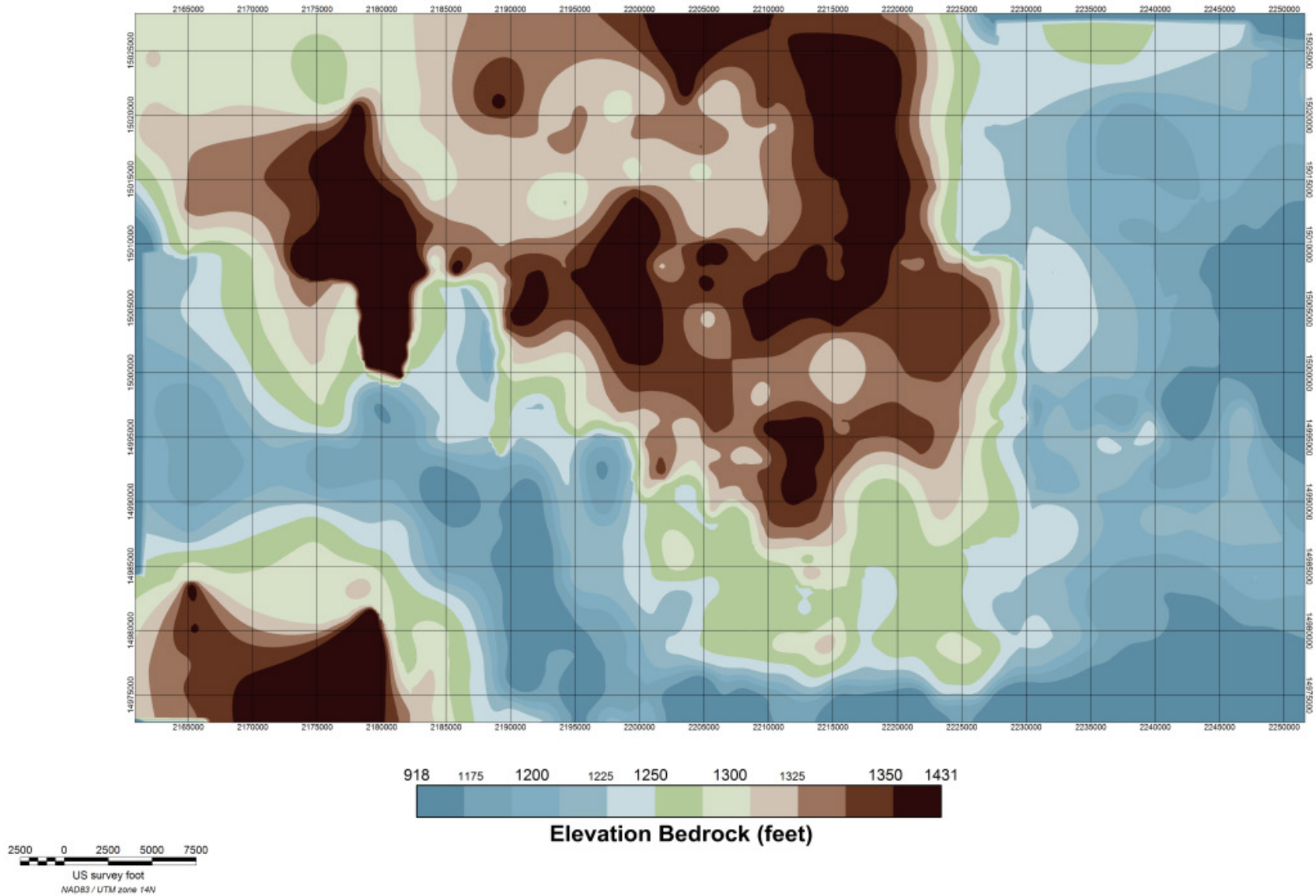


Figure 5-17. Map of the elevation of the top of the Cretaceous bedrock within the SQS#1 AEM survey area. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

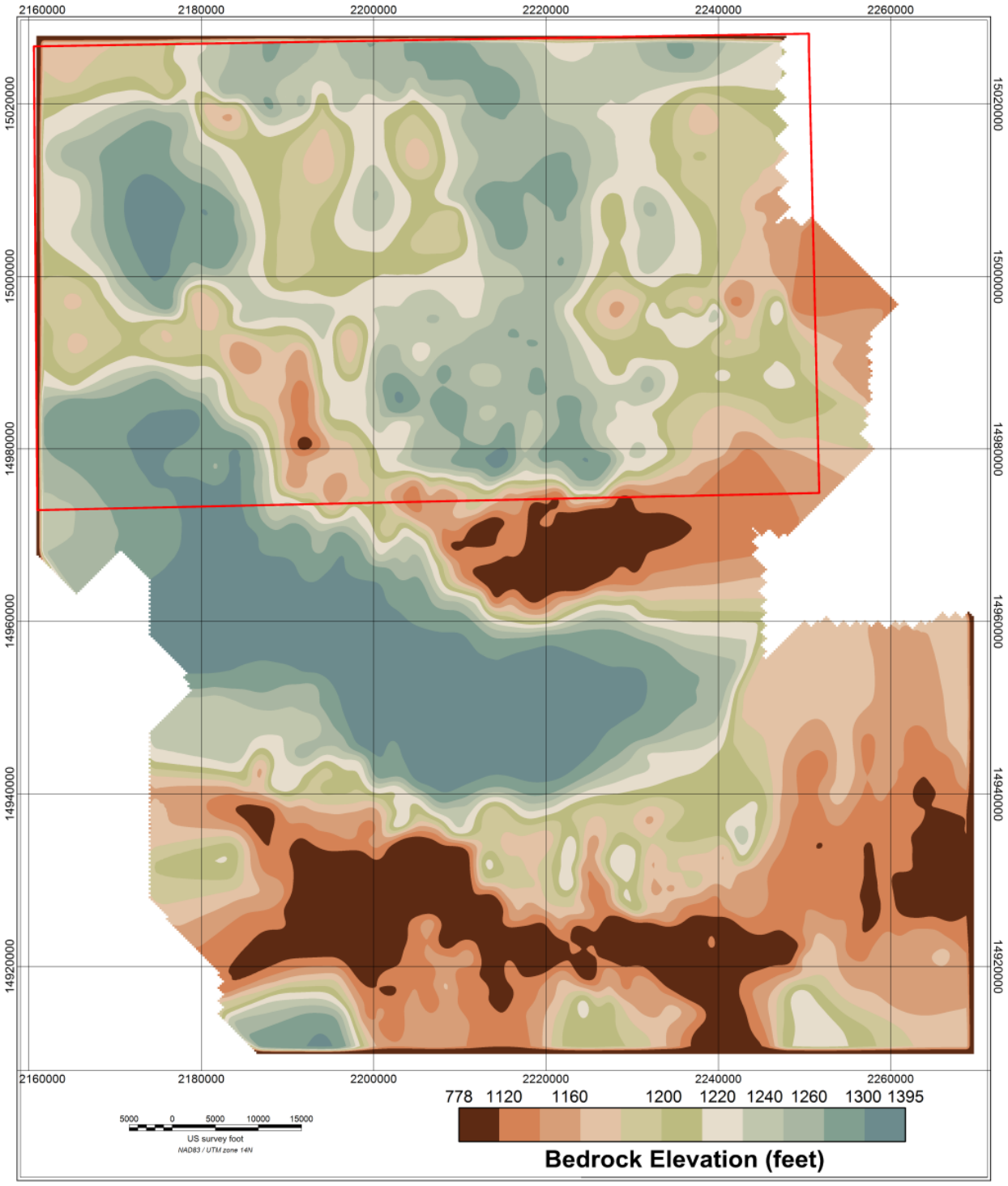


Figure 5-18. Map of the elevation of the top of the Cretaceous bedrock within the SQS#1 AEM survey area (red box) and the area covered by Carney et al. (2014b). The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

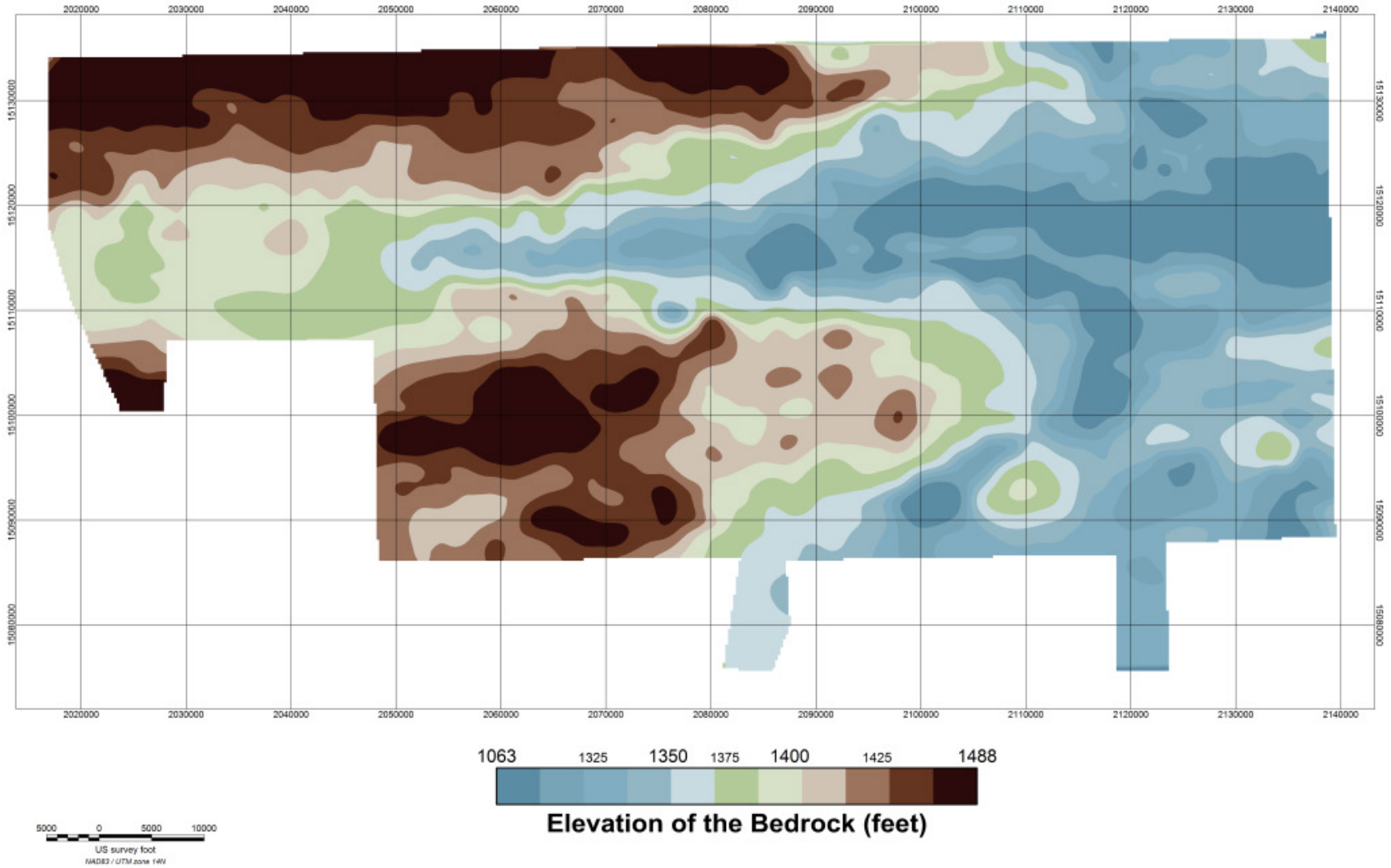


Figure 5-19. Map of the elevation of the top of the Cretaceous bedrock within the SQS#2 AEM survey area. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

Following construction of the Cretaceous bedrock surface, the consolidated and unconsolidated ***Q*** deposits were isolated within the AEM data. The aquifer and non-aquifer materials in the Quaternary system were separated by four major resistivity thresholds. These ranges include less than 12 ohm-m, representing non-aquifer materials ("aquitard"- primarily glacial till, loess), 12-20 ohm-m, representing marginal aquifer deposits with the potential for interlayered silt sand and clay, 20-50 ohm-m of aquifer material containing mostly sand, and an interval of 50 ohm-m or greater, indicating the coarsest, sand and gravel intervals within the aquifer (further discussion regarding the selection of these threshold ranges is provided in the following Section 5.2 regarding the selection of these threshold ranges and in Carney et al. (2015b)). Results of these interpretations can be found in Appendix_1-2D_Profiles.

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 2016 LPNNRD AEM survey, and local conditions likely deviate in areas with variable topography. The water table in the LPNNRD area is close to the surface in some of the areas. To this end 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 of the LENRD AEM survey area. The areas of SQS#1 and SQS#2 were then regridded at 250 feet cell size. 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 SQS#1 and SQS#2 AEM survey areas (Figure 5-20 and Figure 5-21).

Using the bedrock surface and the DEM maps, the thickness of the Quaternary (***Q)*** can be constructed for both the SQS#1 and the SQS#2 areas. For the SQS#1 area the minimum thickness of the ***Q*** was 6.0 feet and the maximum thickness was 653 feet (Figure 5-22). For the SQS#2 area the minimum thickness of the ***Q*** was 68.0 feet and the maximum thickness was 429.9 feet (Figure 5-23).

Using the water table estimates of the saturated Quaternary (***Q***) thickness can also be calculated using the bedrock surface. For the SQS#1 area the minimum thickness of the ***Q*** was 0 feet and a maximum thickness of 458.2 feet (Figure 5-24). For the SQS#2 area the minimum thickness of the ***Q*** was 9.8 feet and a maximum thickness of 232.3 feet (Figure 5-25).

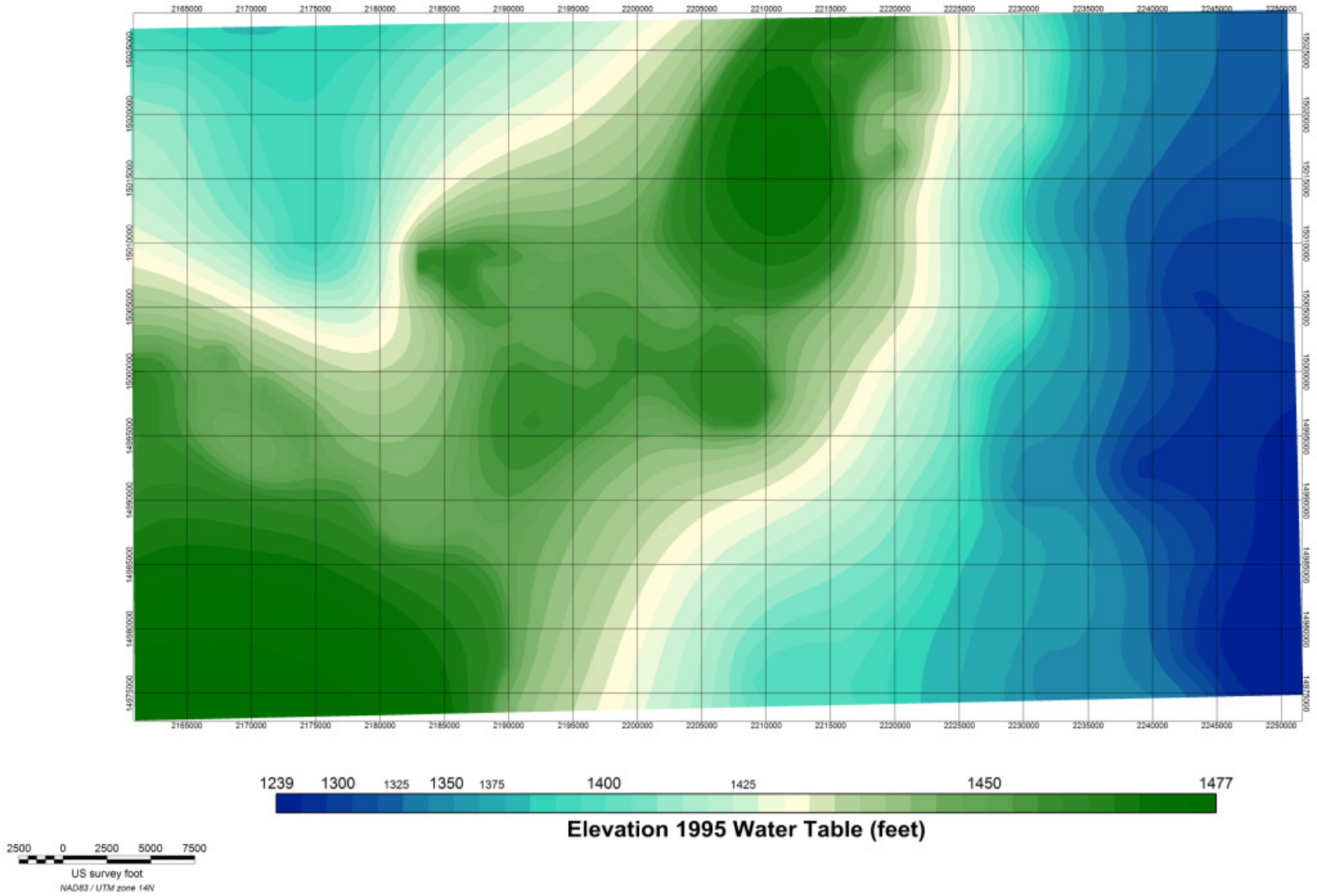


Figure 5-20. Map of the elevation of the 1995 CSD water table (NE CSD, 1995) within the SQS#1 AEM survey area. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

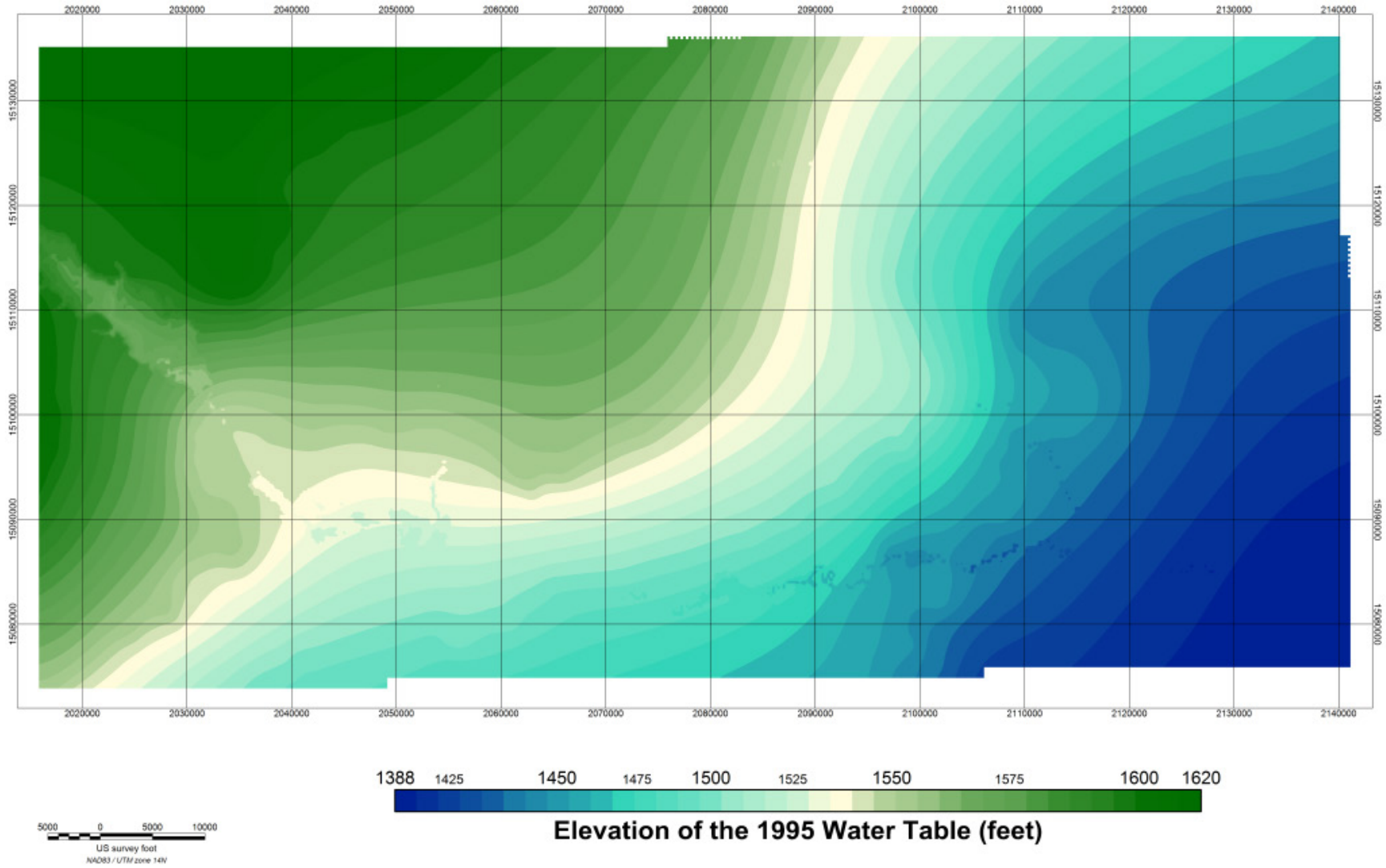


Figure 5-21. Map of the elevation of the 1995 CSD water table (NE CSD, 1995) within the SQS#2 AEM survey area. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

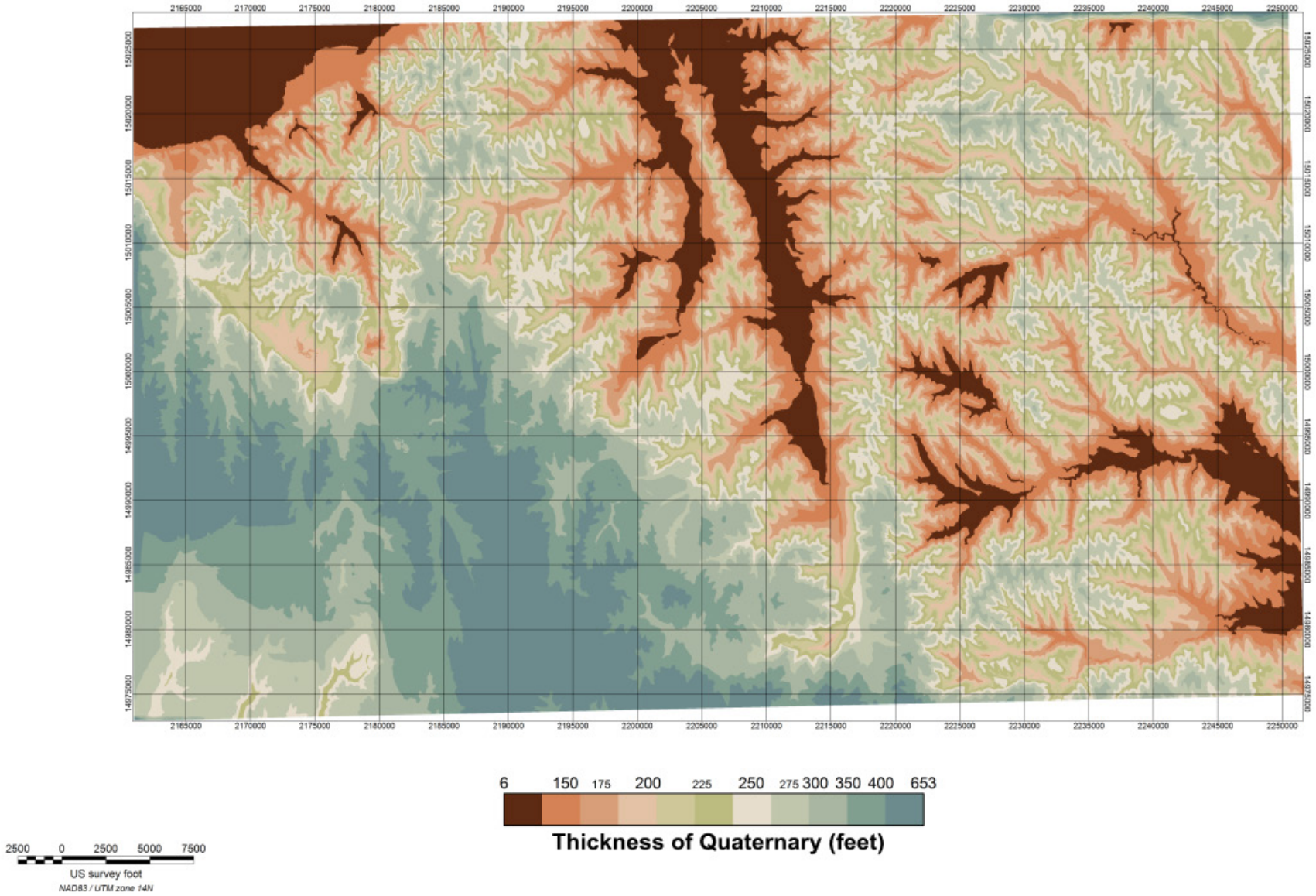


Figure 5-22. Map of the thickness of the Quaternary (*Q*) within the SQS#1 AEM survey area. The projection is NAD83 UTM Zone 14 North, in feet,.

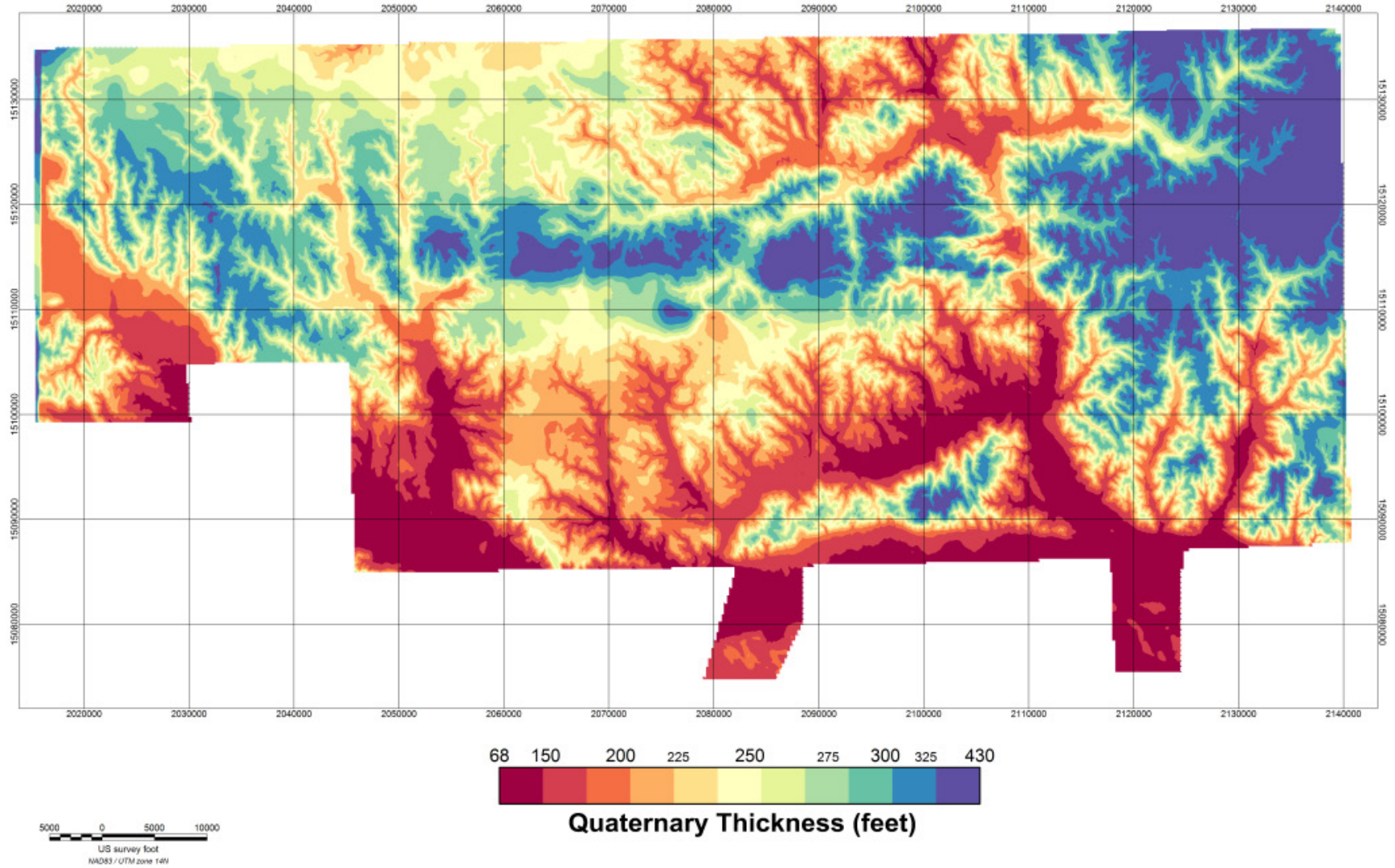


Figure 5-23. Map of the thickness of the Quaternary (*Q*) within the SQS#2 AEM survey area. The projection is NAD83 UTM Zone 14 North.

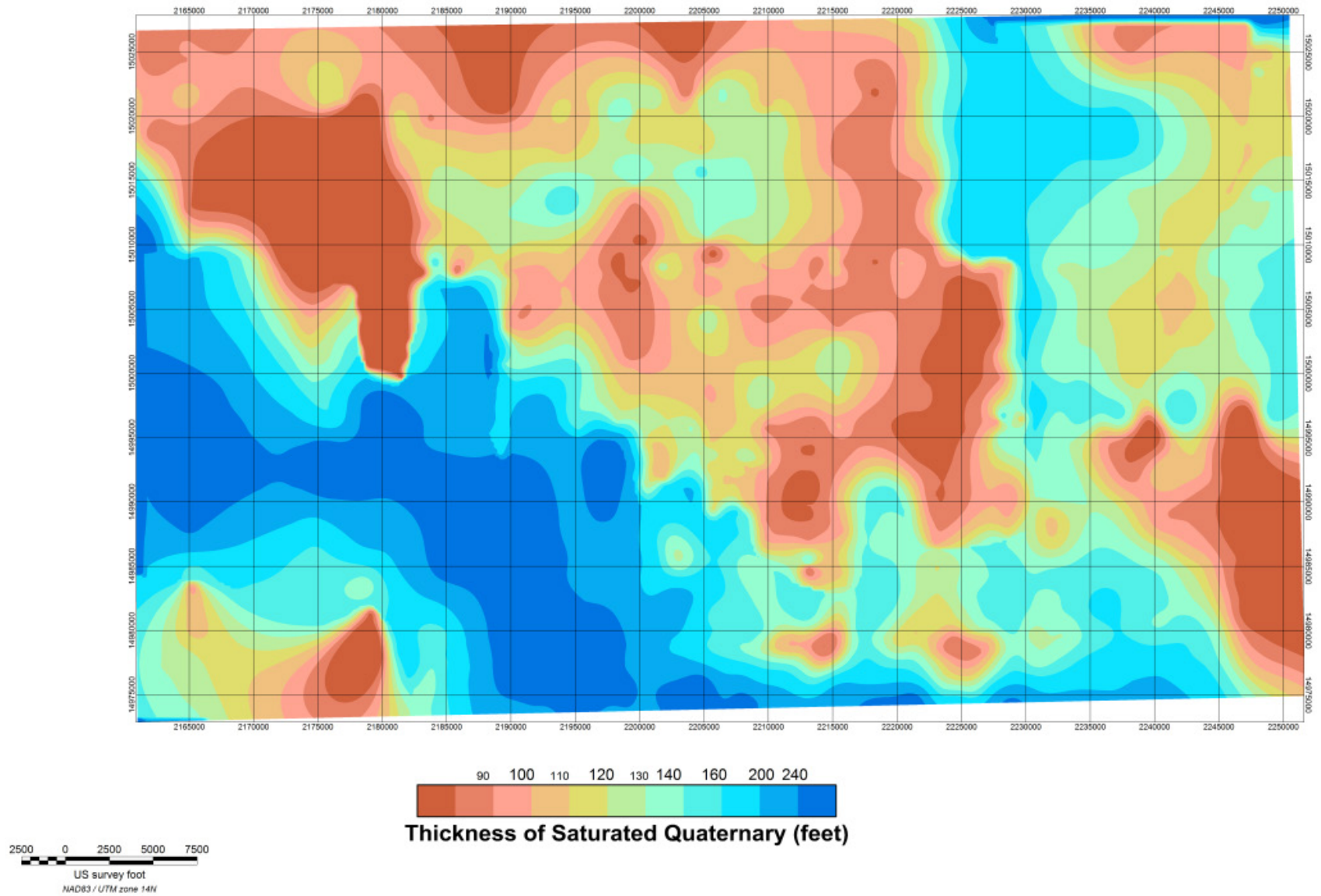


Figure 5-24. Map of the saturated thickness of the Quaternary (*Q*) within the SQS#1 AEM survey area. The projection is NAD83 UTM Zone 14 North.

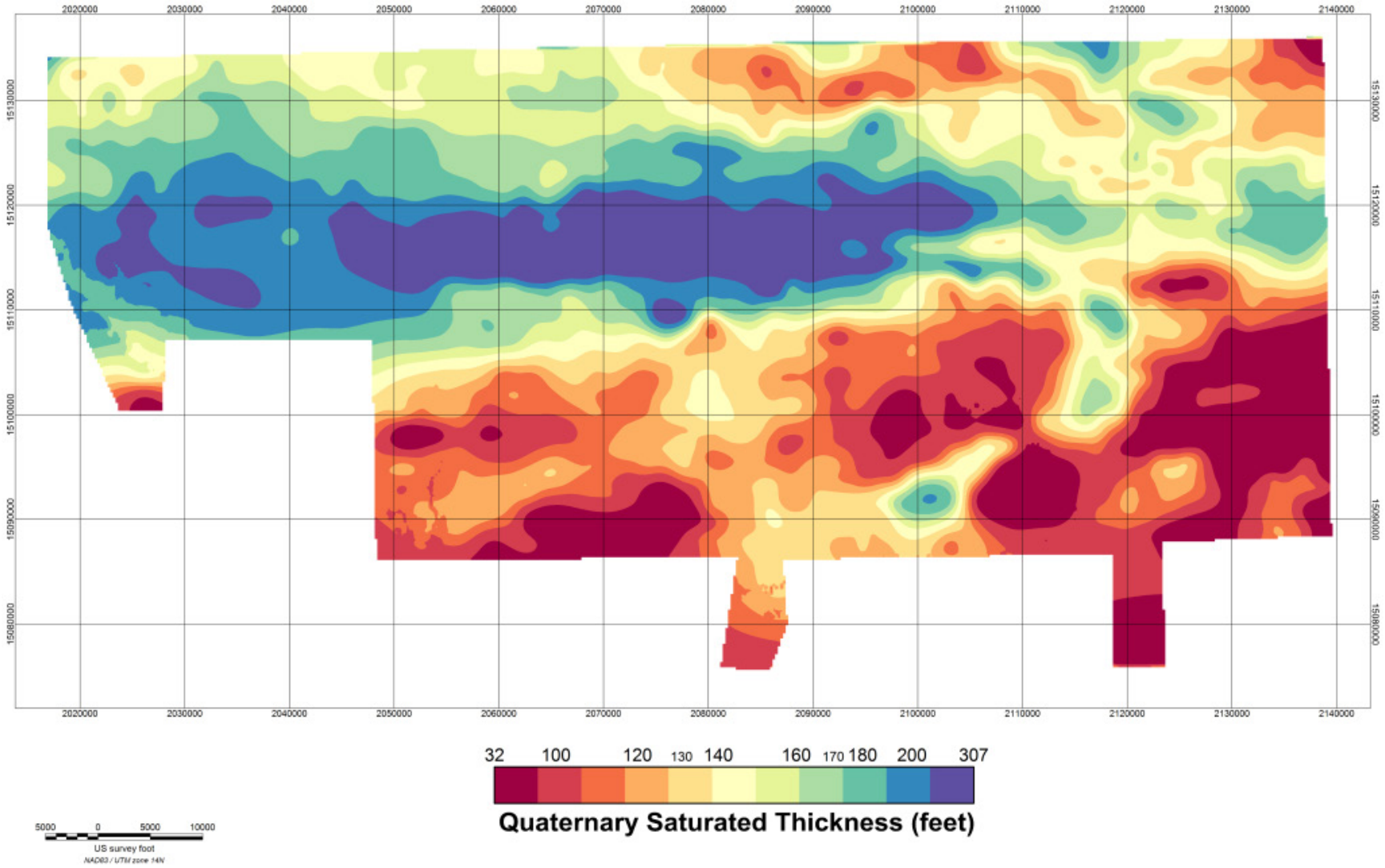


Figure 5-25. Map of the saturated thickness of the Quaternary (*Q*) within the SQS#2 AEM survey area. The projection is NAD83 UTM Zone 14 North.

5.1.5 Create 3D Voxel Grids

A voxel grid was completed for the SQS#1 and the SQS#2 AEM survey areas within the LPNNRD. The voxel grids were made using a 250 ft grid cell size and the model layer thickness (Table 4-4 in the previous section). A minimum curvature method was used within Encom PA (DatamineDiscover, 2017). All layers were referenced to their depth from the surface. After the grid was calculated, the bedrock/base of aquifer system was then truncated/clipped from the voxel grid using the bedrock/base of aquifer grids explained above Section 5.1.4.

The purpose of making the grids is to provide a continuous distribution of the resistivity throughout the survey area that aids in the interpretation of the hydrogeologic framework. However, the interpolation across survey lines can produce data artifacts that are not related to the actual resistivity values. These interpolation artifacts are increased with increased distance between data points, or flight lines. It is important to understand the voxel grids are a model of the 3D distribution of resistivity. The minimum line spacing within the SQS#1 survey area was is 2,640 feet (0.5 mile). The minimum line spacing within the SQS#2 survey area was is 1,320 feet (0.25 mile). Care needs to be taken in not over interpreting areas between the flight lines.

The resulting grids are from the surface down to the bedrock/base of the ***Q*** aquifer system. These grids can be used to explore the distribution of the aquifer materials within the areas in 3D. Specifically, these grids can allow for the calculation of the volume of materials above the bedrock as well as be used to illustrate the surface materials. The grids can be found in *Appendix 3_Deliverables**Voxel*. In order to, calculate the material that is saturated another surface needs to be clipped from the voxel grids. Using the SQS#1 and SQS#2 water table surface, the voxel grids were clipped again from the water table to the surface. These subset voxel grids represent the saturated area from the bedrock/base of aquifer system up to the water table.

The resulting grids are from the surface down to the bedrock/base of the Q aquifer system. These grids can be used to explore the distribution of the aquifer materials within the areas in 3D. Specifically, these grids can allow for the calculation of the volume of materials above the bedrock as well as be used to illustrate the surface materials. The grids can be found in *Appendix 3_Deliverables**Grids*.

5.2 Resistivity-Lithology Relationship

5.2.1 Quaternary Aquifer System

A critical aspect of a geophysical survey, for whatever purpose, is assessing the nature of the material detected by the geophysical method applied in the investigation. Regarding the LPNNRD SQS#1 and SQS#2 AEM survey areas, assessment of the sediment character in the Quaternary aquifer system and the consolidated bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A numerically robust assessment of the resistivity thresholds used to characterize non-aquifer, marginal, and aquifer, including sand-rich intervals was calculated. This allows for the characterization of the ranges of resistivities present in the major geologic units described in this report. It should be noted that this analysis encompasses all Quaternary/Tertiary Ogallala (***Q/To***) aquifer system and bedrock data from the ENWRA project area (Carney et al., 2015b). The original analysis that was completed as part of Carney et al. (2015b) included the overall area of the LPNNRD. 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 the 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 is shown in Figure 5-26.

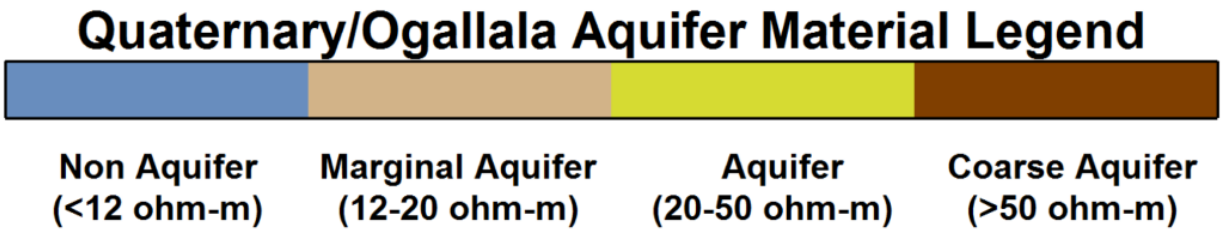


Figure 5-26. Plot displaying the resistivities by major aquifer material color categories (blue- non-aquifer material, tan- marginal aquifer, yellow- aquifer, brown- sand-rich, coarse intervals of the aquifer material).

5.2.2 Bedrock Resistivity Thresholds

The bedrock in the LPNNRD analyzed in this study includes the ***Kn***, ***Kc***, ***Kgg***, and ***Kd***. These were included to demonstrate the overall distribution in resistivity of bedrock materials across the entire LPNNRD. The median resistivity values for each unit are 38 ohm-m for the ***Kn***, 16 ohm-m for the ***Kc*** and the ***Kgg*** lumped together, and the ***Kd*** 35 ohm-m (Carney et al., 2015b). For the ENWRA study the ***Kc*** and the ***Kgg*** were interpreted together. In the present study, the proximity of the ***Kgg*** to the surface allows for a more accurate interpretation. The low resistivity character of 3 to 9 ohm-m for the ***Kc*** made the interpretation of the ***Kc*** relatively straight forward. The ***Kgg*** showed a more resistive character, on the order of 15 ohm-m. The ***Kd*** within the LPNNRD displayed some low resistivities on the order of 9 to 13 ohm-m indicating either clay/shale dominant lithology or the presence of saline waters, mostly in the western portions of the LPNNRD.

5.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs

Of the eight geophysical logs in the areas of SQS#1 and SQS#2 only one log showed calibrated and reliable results 01-LPN-15. The remaining logs showed either log malfunctions or calibrations errors. 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 truth when comparing to AEM inversions that are well calibrated using modern techniques. Throughout much of the geophysical logging at the time it was acquired, the relative deflections of the resistivity measurements were all that was required or expected from a geophysical log. Operators were seldom trained in the proper operation of a calibrated sonde or in the ability to recognize high contact resistance of a cable head. This has led to many geophysical logs that are uncalibrated within the CSD database. Note that these logs still have scientific merit in their ability to relatively indicate an increase or a decrease in the formation resistivity. The logs used herein are for qualitative comparison to the AEM because detailed calibration and corrections would need to be carried out for the resistivity values in the logs to be directly used as numerical constraints in the inversion of the AEM data (Ley-Cooper and Davis, 2010).

Figure 5-27 is a plot of *01-LPN-15* 16-inch short normal, 64-inch long normal, and lateral resistivity log plotted with the inverted AEM resistivity for line L223003. *01-LPN-15* is located 478 feet from line L223003 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the resistivity is reasonable with the AEM indicating a lower overall resistivity in the sand and gravel section of the ***Q*** from approximately 250-390 feet. The shape of the curves shows a good agreement. The lateral log shows resistivities that are anomalously low in the area for the silt rich areas of the ***Q***. The key is that the AEM clearly indicates the marginal aquiver material area of the interbedded sand and silt from approximately 90-225 feet, and the sand and gravel segment from 250-390 feet. A large discrepancy is the area of the ***Kc*** and the ***Kgg***. The ***Kc*** indicated in the log is thin and is deep approximately 400 feet and is not detectable in the AEM contrasted with the ***Kgg***. This was also observed in Carney et al. (2015b). The hydrogeologically important observation is that the bottom of the ***Q*** can be detected and that the bedrock can be interpreted to provide the base of the aquifer.

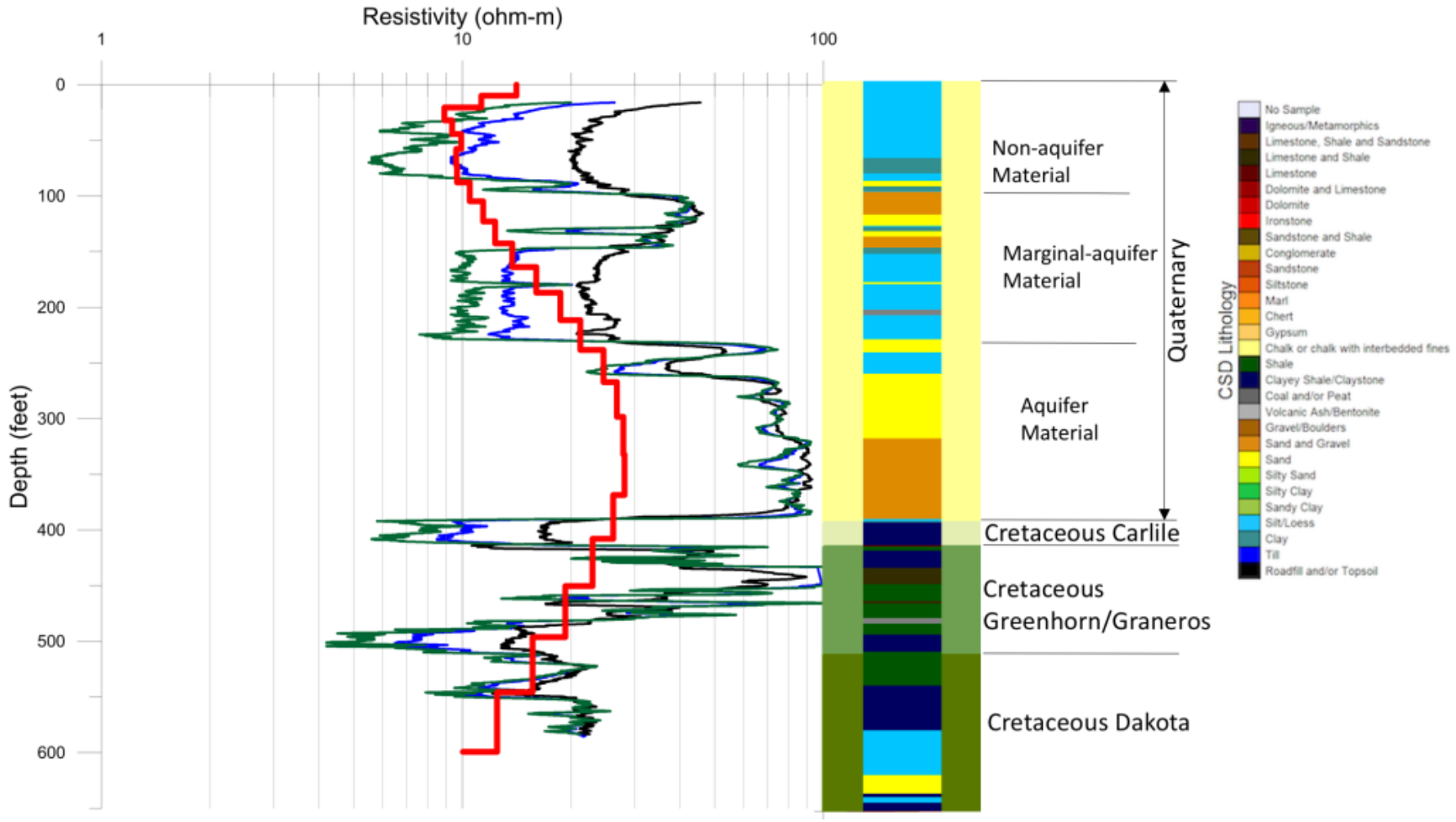


Figure 5-27. Graph of borehole *01-LPN-15* 16-inch normal resistivity log values (blue line), 64-inch normal (black line), lateral resistivity log (green line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *01-LPN-15* as well as the aquifer material categories from the AEM inversion.

5.3 Hydrogeological Framework of the LPNNRD AEM Survey Area

The AEM reveals variability in the Quaternary (***Q***) deposits across the LPNNRD AEM survey area. The ***Q*** makes up the aquifer materials overlying the Cretaceous bedrock units. SQS#1 is shown in Figure 5-28 which displays in 3D the overall distribution of ***Q***, ***Kn***, ***Kc,*** and ***Kgg*** materials (as described in the previous section). SQS#2 is shown in Figure 5-29 which displays in 3D the overall distribution of ***Q***, ***Kgg*** and ***Kd*** materials. The subsurface distribution of ***Q*** materials can be generally characterized into two distinct manners related to the different survey areas.

SQS#1 has limited amounts of aquifer and coarse aquifer materials located to the northwest and along the southern boundary (as observed in the LPSNRD AEM survey conducted in 2013 (Carney et al., 2014b)) overlain by a confining layer made up of marginal to non-aquifer materials. A channel eroded into the bedrock trends from west to east along the southern edge of SQS#1.

SQS#2 has more aquifer and coarse aquifer materials distributed over much of the area, overlain by a confining layer made up of non-aquifer to marginal materials. A channel eroded into the bedrock trends from west to east through the center of SQS#2.

5.3.1 The Quaternary Aquifer within the SQS#1 and SQS#2 AEM Survey Areas

The ***Q*** aquifer of SQS#1 is predominantly composed of Quaternary unconsolidated aquifer (yellow color in Figure 5-28 and Figure 5-29) and some coarse aquifer (brown color in Figure 5-28 and Figure 5-29) materials composed of alluvial, glacial and glacial outwash sediments. Within SQS#1 these materials are sitting on the ***Kgg*** and ***Kd*** which can be the bedrock aquiclude for the area. The maps showing the elevations of the tops of the ***Kgg*** and ***Kd*** for SQS#1 can be found in Figure 5-14 and Figure 5-16, respectively, in Section 5.1.4. The thickness of the ***Q*** materials within SQS#1 range from 6 to 653 feet thick, with the thickest deposits in the southwest quarter (Figure 5-30). These deposits thin to the north and east.

A close up image of the aquifer materials in the southwest corner of SQS#1 is presented in Figure 5-31 showing where it can be heterogeneous in places with a changing mix of all aquifer materials. Most of SQS#1 contains marginal and non-aquifer materials, with the south and northwest corner containing aquifer and some coarse aquifer materials that act as the groundwater supply. The marginal and non-aquifer materials are typically located throughout the ***Q*** deposits and is primarily till made up of non-aquifer material. These layers can locally act as aquicludes and prevent hydrologic connection to a stream, recharge areas, boundary conditions to groundwater flow, or serve as confining units.

A profile view of line L140601, a north-south flight line in SQS#1, is presented in Figure 5-32. All aquifer type materials are indicated along this profile with the center of the profile indicating the positions of marginal and non-aquifer materials that impact the area hydrologically by blocking or inhibiting water movement to and from the surface.

Within SQS#2 the ***Q*** materials are sitting on the ***Kn, Kc,*** and ***Kgg*** which is the bedrock aquiclude for the area, (Figure 5-19, in Section 5.1.4). The thickness of the ***Q*** materials within SQS#2 range from 68 to 430

feet thick, with the thickest deposits in the center to northeast section (Figure 5-33). These deposits thin to the south and west. Most of SQS#2 contains a mix of all aquifer materials, with most of the area containing aquifer and some coarse aquifer materials that act as the groundwater supply. The aquifer and coarse aquifer materials are located throughout most of the survey area and are found layered between basal deposits and near surface deposits made up of marginal aquifer and non-aquifer materials. Marginal aquifer and non-aquifer material can locally act as aquicludes and prevent hydrologic connection to streams, recharge areas, or serve as confining units. An example of this is presented in Figure 5-34 which displays a 3D fence diagram image of several of these layers of marginal (tan color) and non-aquifer (blue color) materials found in the northwest corner of SQS#2.

A profile view of flight line L113901, an east-west line in SQS#2, is presented in Figure 5-35. All aquifer-type materials are indicated along this profile. The labeled tan and blue colors indicate the positions of marginal and non-aquifer materials that impact the area hydrologically by blocking or slowing down water movement to and from the surface. Appendix 1 contains interpreted 2D profiles that illustrate the details of the Quaternary in the LPNNRD AEM survey area. Appendix 2 contains 3D images of the LPNNRD AEM survey area that have been rotated around various angles to allow viewing of the overall distribution of materials.

5.3.2 The Cretaceous Bedrock Aquiclude

The Cretaceous bedrock within SQS#1 is made up of ***Kgg*** on western side and the ***Kd*** on the east. These units make up a continuous surface beneath the Quaternary alluvial sediments that combine to act as an aquiclude restricting groundwater flow across the boundaries. Figure 5-17 in Section 5.1.4 presents an image of the surface of the bedrock. The ***Kd*** can serve as an aquifer in areas of Nebraska; however, no evidence of the ***Kd*** serving as an aquifer exists within the SQS#1 survey area. Immediately to the south of the SQS#1 area in LPSNRD there are productions wells located in the sand/sandstone dominate areas off the ***Kd***.

The Cretaceous bedrock within SQS#2 is made up of the ***Kgg*** on eastern side, ***Kc*** in the center, and ***Kn*** on the west. These units make up a continuous surface beneath the Quaternary alluvial sediments that combine to act as an aquiclude restricting groundwater flow across the boundaries. Figure 5-19 in Section 5.1.4 presents an image of the surface of the bedrock in the SQS#2 AEM survey area. On the western end of the project area the ***Kn*** is thin and lies upon the ***Kc*** which itself thins considerably to the east lying upon the ***Kgg*** which is in contact with the ***Q*** material in some locations.

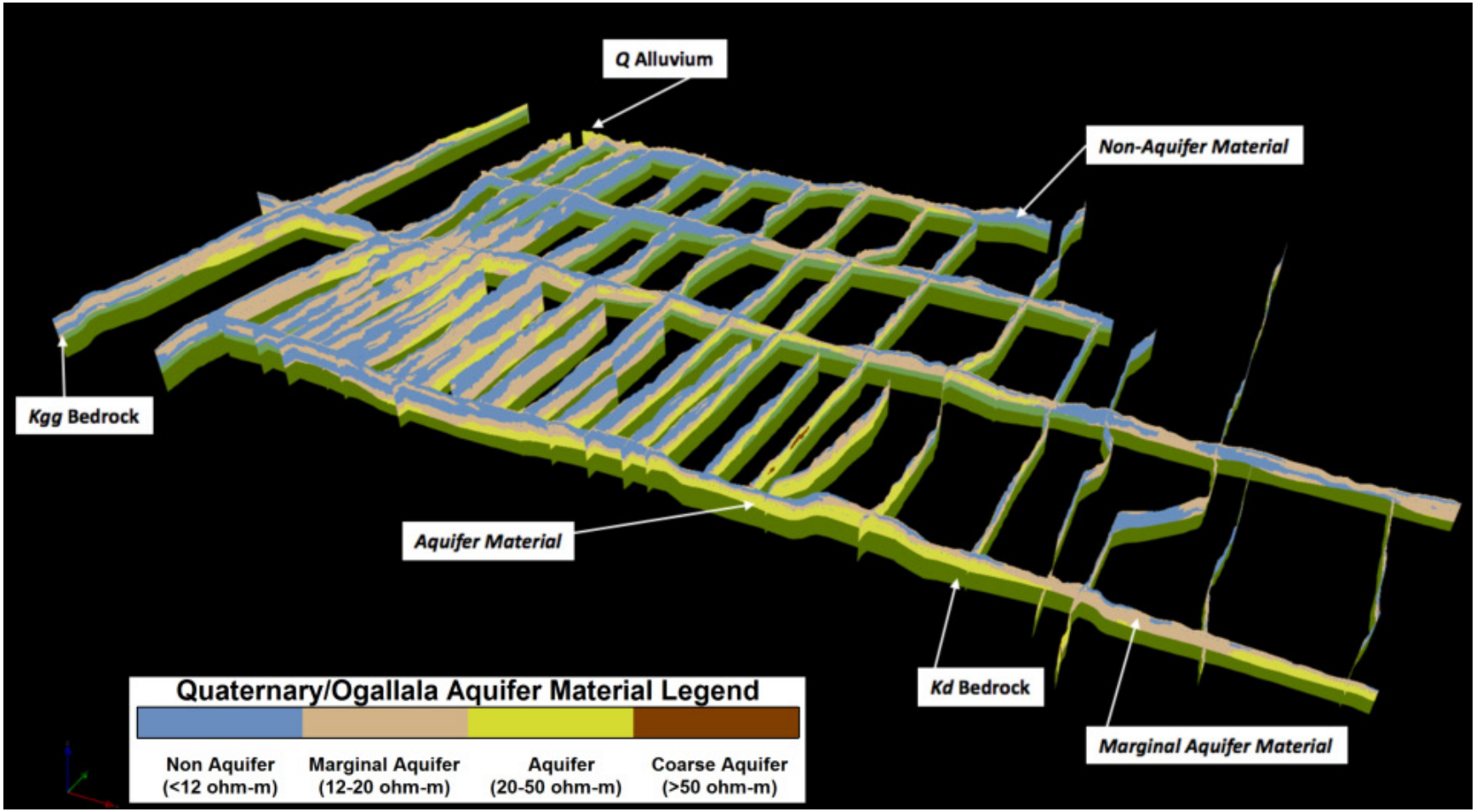


Figure 5-28. 3D map looking to the north of the interpreted distributions of aquifer materials within SQS#1 AEM survey area. Vertical exaggeration is 5x. (*Q*-Quaternary, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale). The image projection is NAD 83, UTM Zone 14 North.

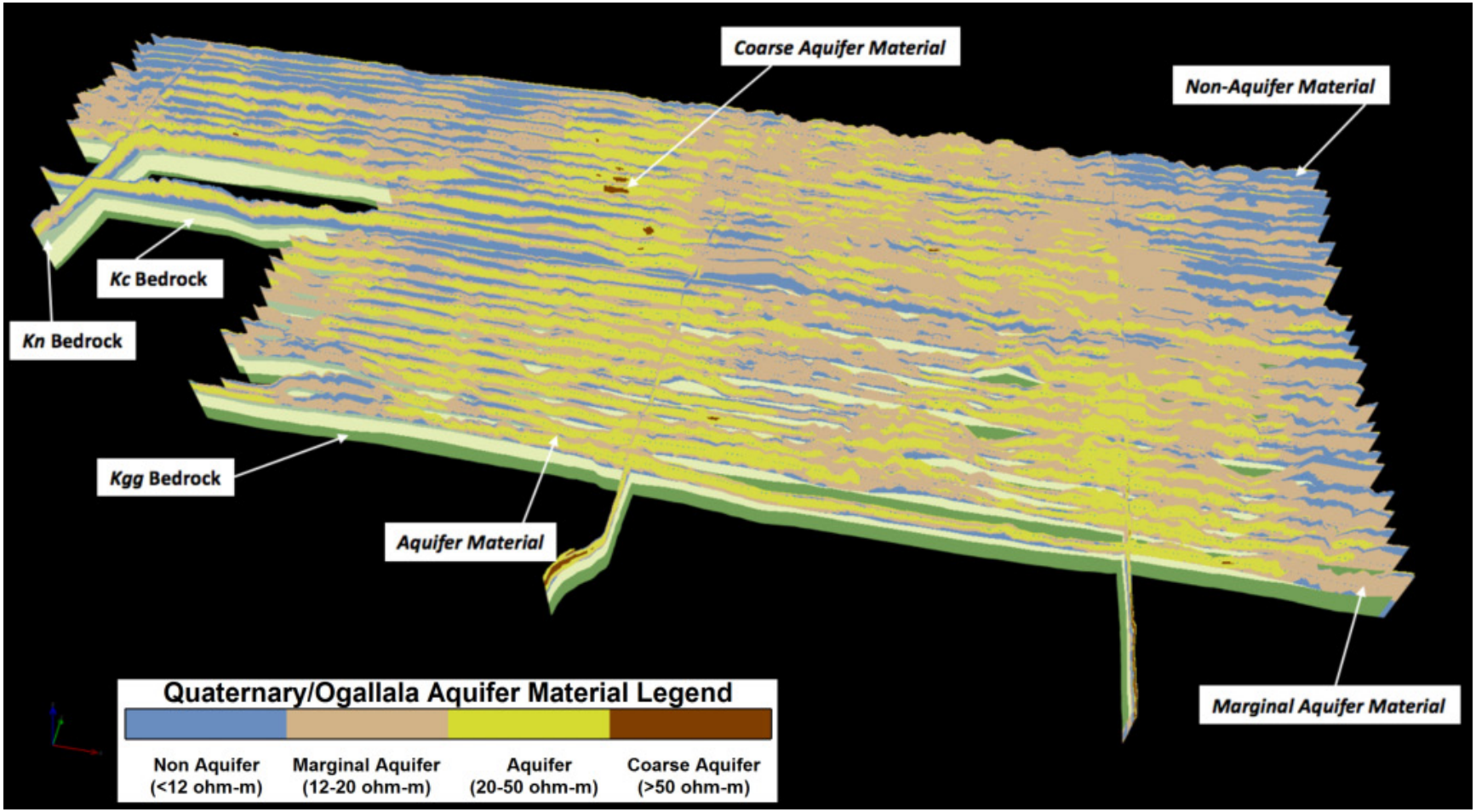


Figure 5-29. 3D map looking to the north of the interpreted distributions of aquifer material within the SQS#2 survey area. Vertical exaggeration is 10x. (*Q*-Quaternary, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale). The image projection is NAD 83, UTM Zone 14 North.

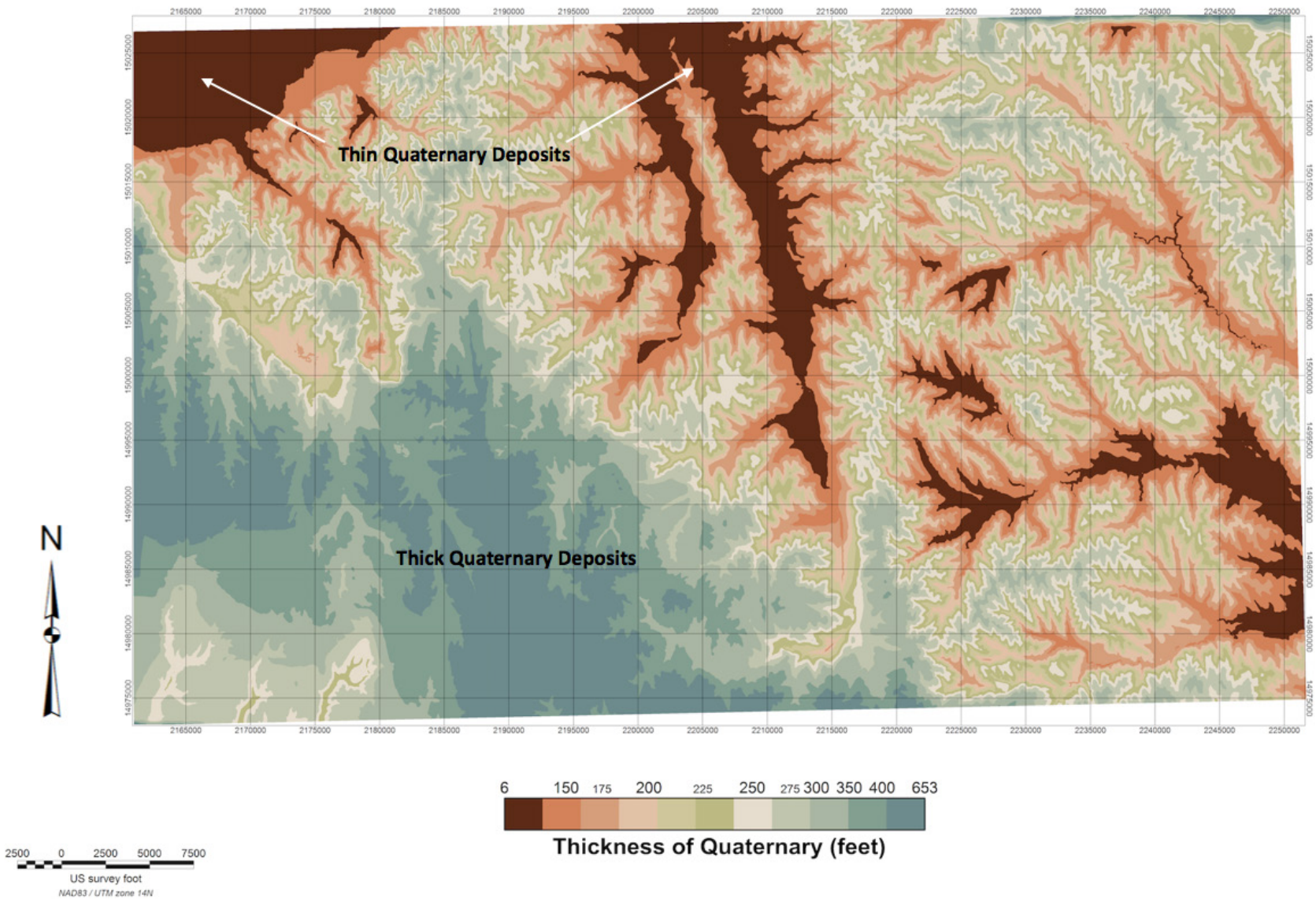


Figure 5-30. Map of Quaternary material thickness looking to the north within the SQS#1 survey area. The image projection is NAD 83, UTM Zone 14 North, feet.

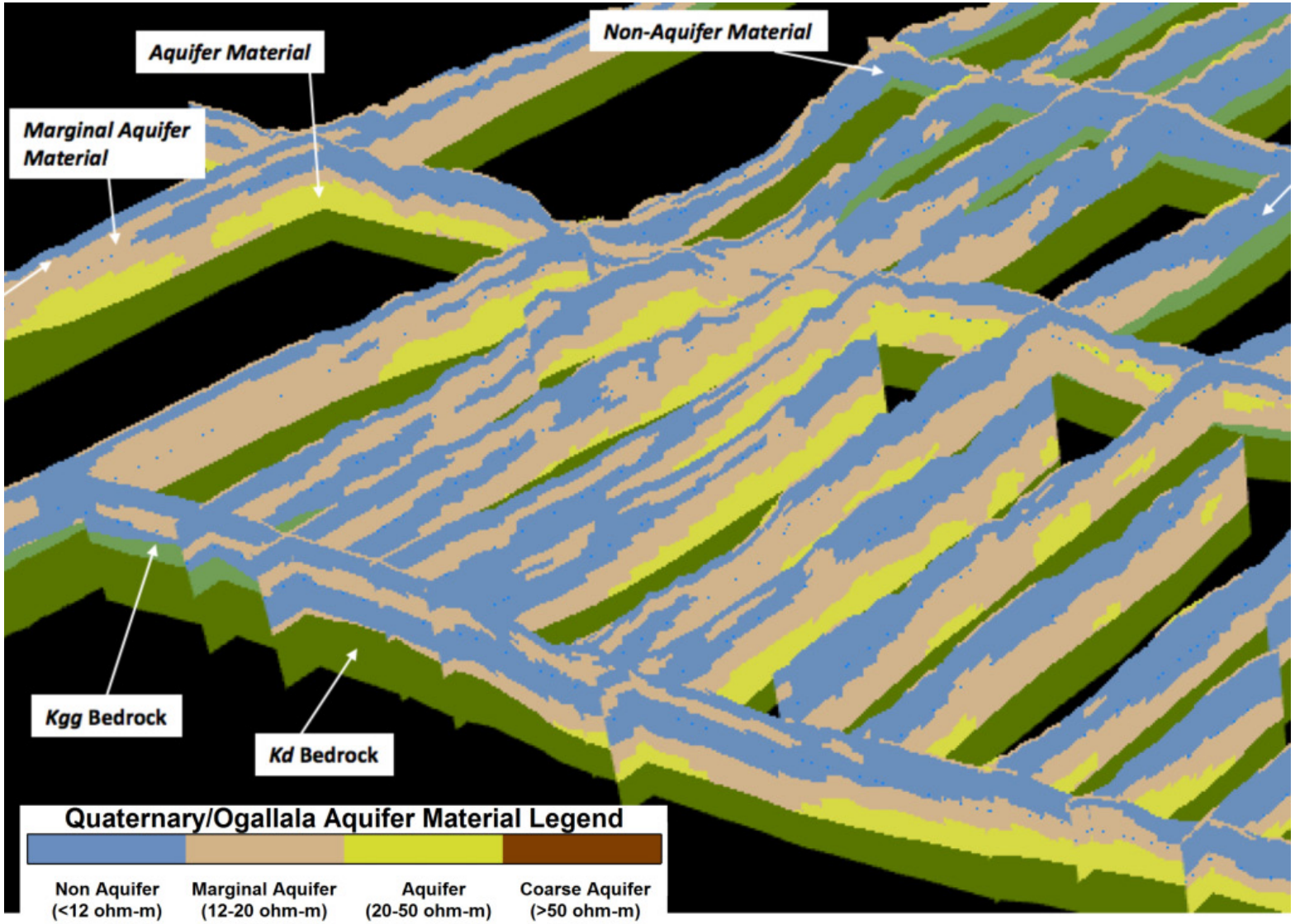


Figure 5-31. 3D map looking to the northwest of the interpreted distributions of marginal and non-aquifer materials that accompany the aquifer materials found in the southwest region of SQS#1. Vertical exaggeration is 5x. (*Q*-Quaternary, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*-Cretaceous Dakota). The image projection is NAD 83, UTM Zone 14 North.

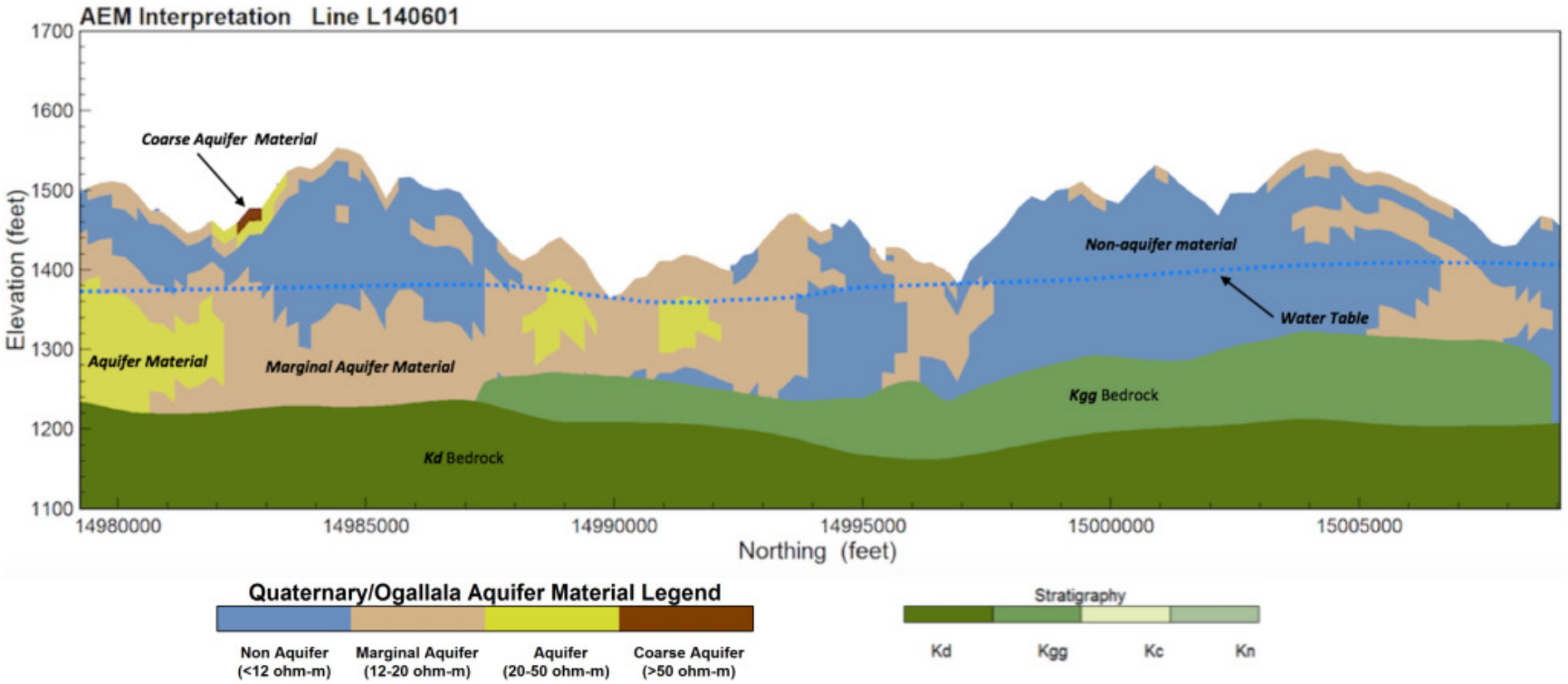


Figure 5-32. Profile view of line L140601 showing a north-south profile in SQS#1 (north is on the right). There is aquifer and coarse aquifer material on the south separated by marginal and non-aquifer material in the center and the north. The water table is represented by the dashed blue line. (*Q*-Quaternary, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*-Cretaceous Dakota). The image projection is NAD 83, UTM Zone 14 North, feet.

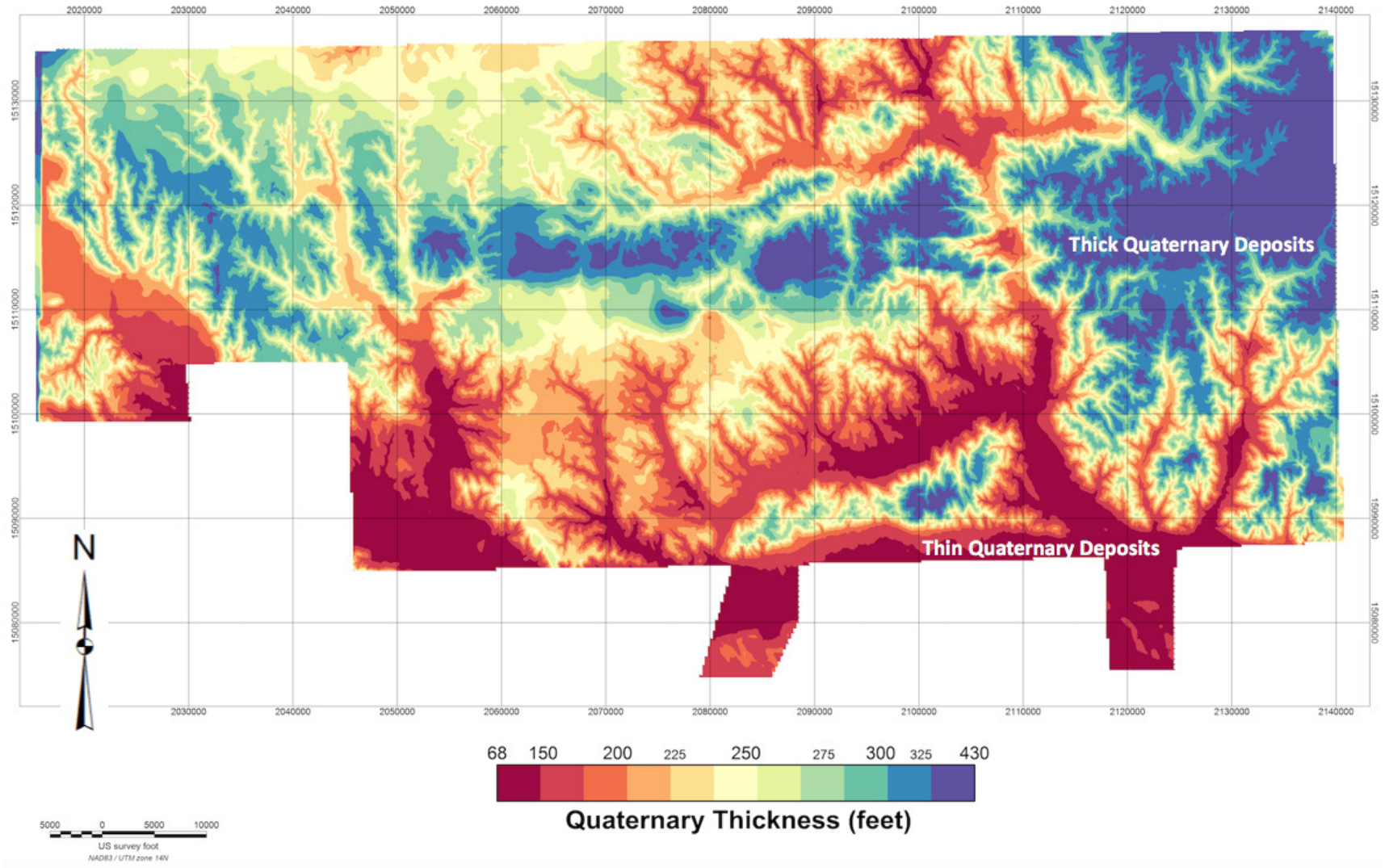


Figure 5-33. Map of Quaternary material thickness looking to the north within the SQS#2 survey area. The image projection is NAD 83, UTM Zone 14 North, feet.

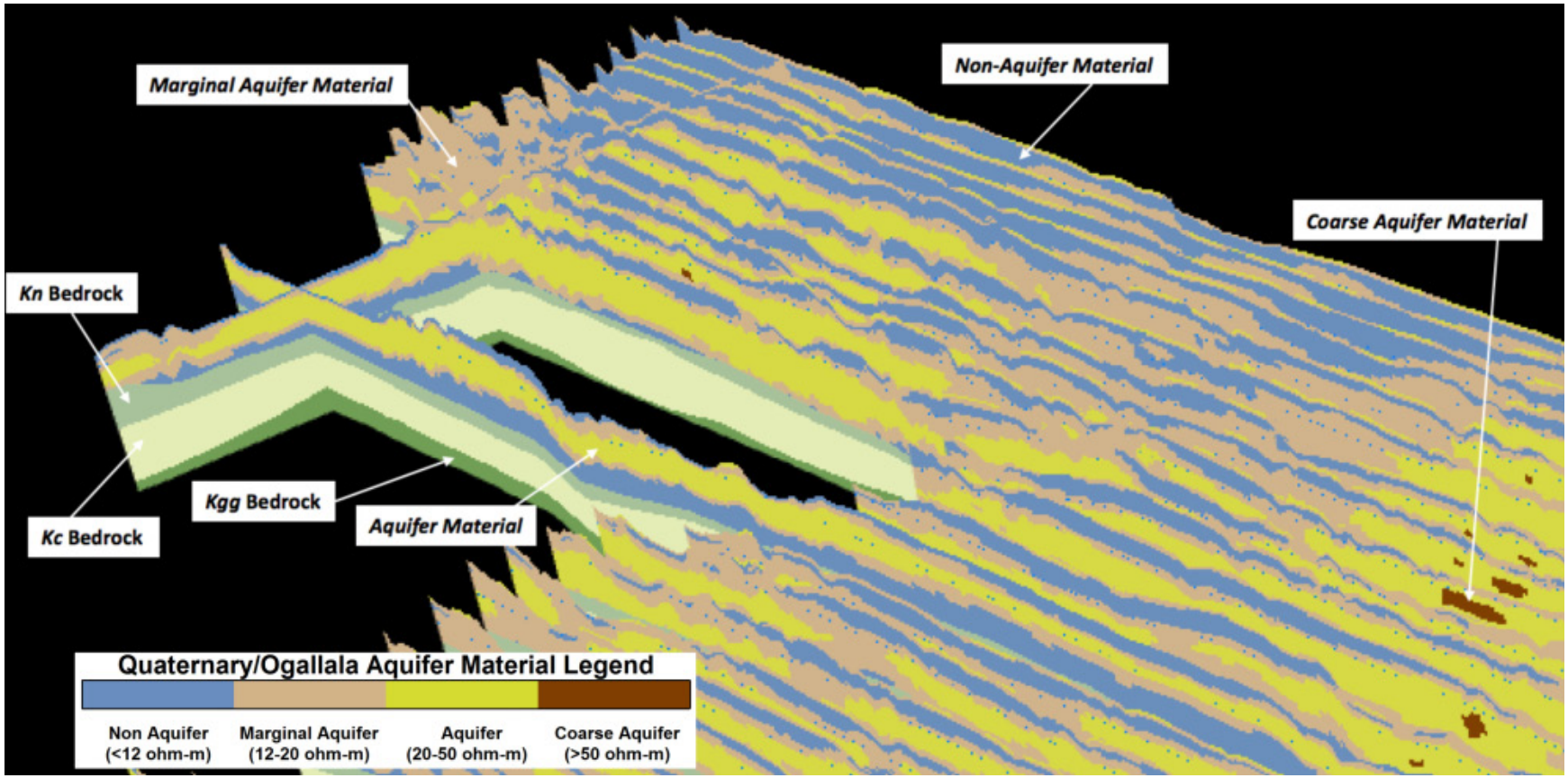


Figure 5-34. 3D map looking to the northwest of the interpreted distributions of marginal and non-aquifer materials that accompany the aquifer materials found in the northwest region of SQS#2. Vertical exaggeration is 5x. (*Q*-Quaternary, Kn- Cretaceous Niobrara, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale). The image projection is NAD 83, UTM Zone 14 North.

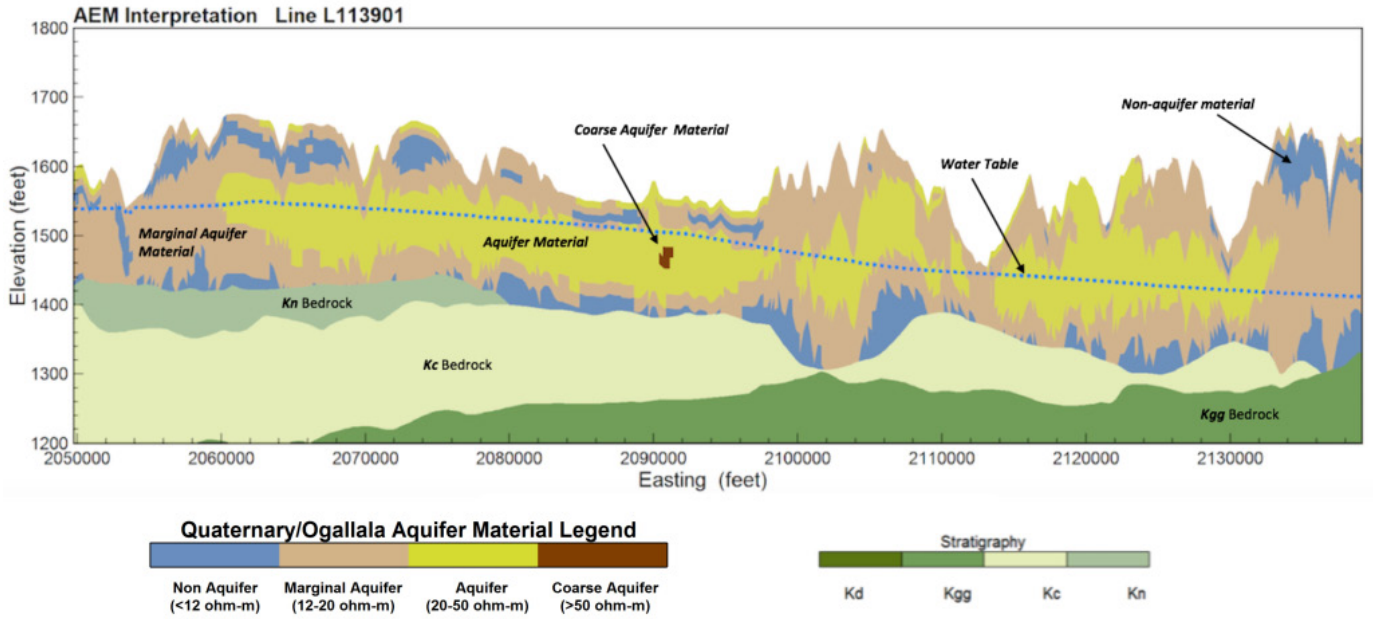


Figure 5-35. Profile view of line L1113901 showing east-west profile in SQS#2 (east is on the right). There is aquifer and coarse aquifer material across the profile separated by marginal and non-aquifer material above and below. The water table is represented by the dashed blue line. (*Q*-Quaternary, Kn- Cretaceous Niobrara, *Kc*-Cretaceous Carlile *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale). The image projection is NAD 83, UTM Zone 14 North, feet.

5.3.3 SQS#1 AEM Survey Area

The SQS#1 AEM survey area is within the Quaternary Aquifer system defined above (Section 5.3.1). In Section 3.1, is a map (Figure 3-1) showing the AEM survey lines included within SQS#1 survey area and the locations the CSD test holes. The area is composed of mostly aquifer materials lying on the ***Kgg*** and ***Kd*** bedrock surface.

Figure 5-36 shows the bedrock configuration within the SQS#1 (red box) and the area to the south (Carney et al., 2014b) which has eroded bedrock with two regional channels cut into it. A channel trends from west to east along the southern edge of SQS#1 with a larger channel parallel in direction to the first approximately 5 miles south (Figure 5-36). The southernmost channel shows the importance of mapping over multiple years and multiple Natural Resources Districts. In this case the channel to the north eventually merges with the southern channel. The channels are flanked by three bedrock highs which have an increased relief of up to ~600 feet in elevation from the bottom of the channels. The thickness of the Quaternary material within the SQS#1 survey area ranges from 6 to 653 feet thick (Figure 5-30). The area is dominated by a mix of all aquifer materials. Figure 5-37 shows a 3D fence diagram of non-aquifer and marginal aquifer materials combined with a voxel model of aquifer and coarse aquifer materials lying on the bedrock units. This allows the reader to understand the relationship between the aquifers and the rest of the hydrogeologic framework by inspection. The percentage of the different aquifer materials are as follows, marginal aquifer (tan) aquifer material makes up the largest percentage of the total at 53%, with aquifer material (yellow) next at 25%, followed by non-aquifer material at 22% (blue) and coarse aquifer material (brown) making up the least at less than 1%. The thicker sequences of aquifer material are along the axis of the channel in the center of the SQS#1 AEM survey area. This material is part of the channel deposits that trend from west to east. When the elevation of the bedrock is subtracted from the elevation of the water table the result is the saturated thickness of the ***Q*** materials in SQS#1 (Figure 5-38). The saturated Q materials (non-aquifer, marginal aquifer, aquifer and coarse aquifer) range in thickness from ~80 feet to 250 feet. The saturated aquifer material and coarse aquifer material are shown in Figure 5-39 which shows the geographically limited areas of the aquifers in SQS#1.

A voxel model showing continuous volumes of the four different types of aquifer materials is presented in Figure 5-40. This shows the abundance of the marginal and non-aquifer materials across the area. The marginal aquifer material (tan) and the non-aquifer material (blue) mantle the surface down to bedrock in many places and is made up of mostly glacial till silts and clays. A voxel model showing continuous volumes of saturated aquifer material and some coarse aquifer material is presented in Figure 5-41. The majority of aquifer material fills the channel along the south-center of the survey area. An image showing aquifer materials below the water table and above the bedrock is presented in Figure 5-42. These materials are the most productive for water wells and have the most transmissivity allowing for the most groundwater flow. Because there are no major streams in SQS#1 there is limited if any aquifer stream interaction.

The SQS#1 AEM survey area has a limited number of DNR registered wells when compared to SQS#2. Figure 5-43 shows the distribution of the wells in the area color coded based on estimated discharge rates in gallons per minute with the range increasing from blue (<100 gpm) to red (>1200 gpm). The DNR well locations are overlain on a representation of the thickness of the saturated ***Q*** aquifer materials, ranging from brown (thinner) to blue (thick). The highest discharge rates follow the channel along the southern border and the Northwest corner of SQS#1. Note that the higher discharge rates (large red circles) are in the vicinity of the areas that the AEM identified as locations of thicker saturated aquifer material, and vice versa with the lower discharge wells. The medium capacity wells are similarly located in the area. Low capacity wells tend to be in the center of the survey area where the aquifer material and coarse aquifer material are thin on non-existent. This information is very useful for the management planning for the district as it is a direct relationship between pump discharge and the AEM mapping.

Individual profiles for the interpreted resistivity sections indicating aquifer materials can be found in Appendix 1 (2D profiles) and Appendix 2 (3D images).

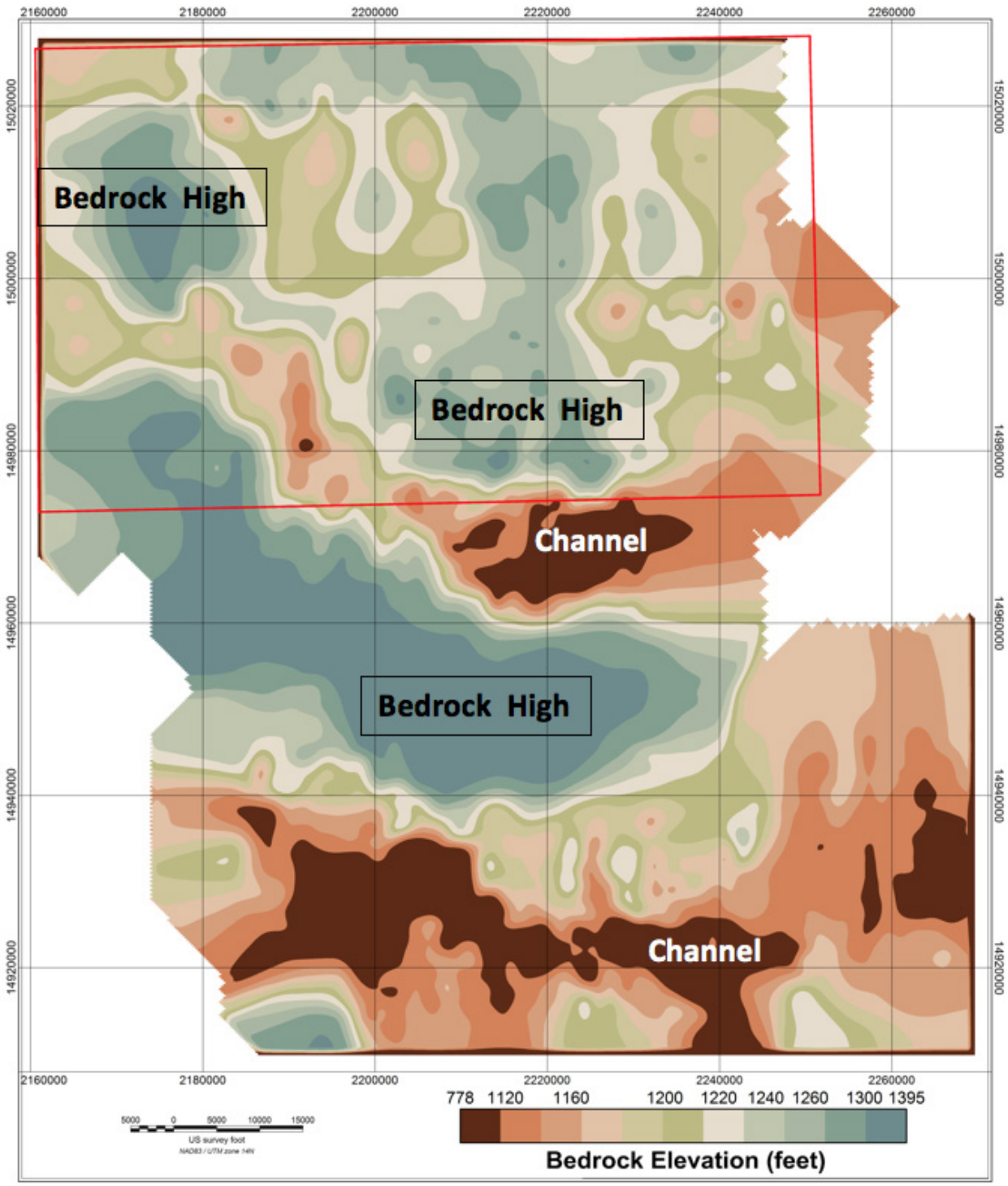


Figure 5-36. Base of the *Q* aquifer which is the top of the bedrock. Two channels eroded into the bedrock can be seen lying between three bedrock highs. Note that only the northern most channel is in the SQS#1 survey area. The image projection is NAD 83, UTM Zone 14 North, feet.

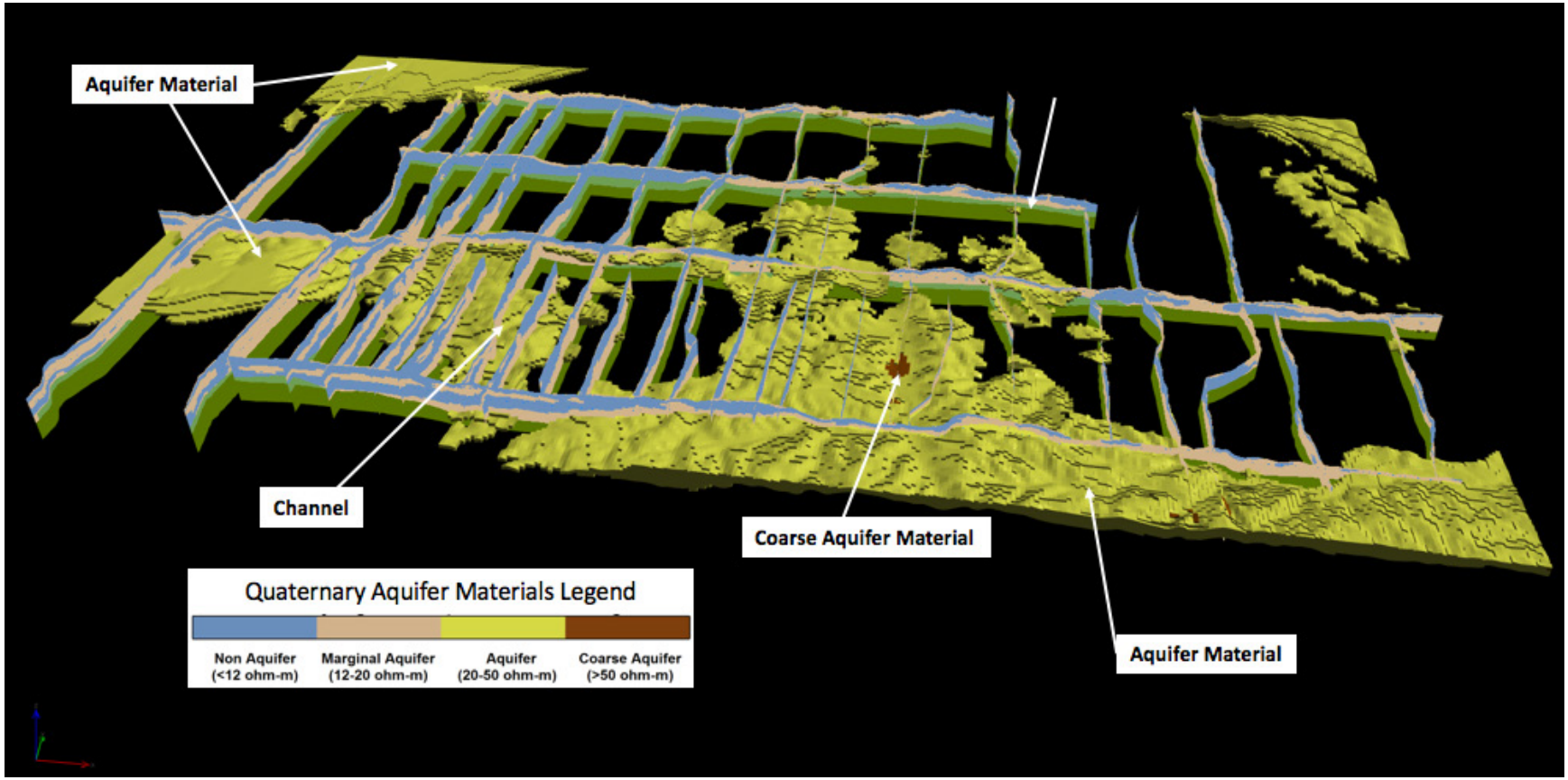


Figure 5-37. Voxel of SQS#1 saturated thickness of aquifer (yellow) and coarse aquifer materials (brown) paired with 3D fence diagram of non-aquifer materials (blue) and marginal aquifer (tan) and the bedrock units. This shows the distribution of the aquifers in the area related to the non-aquifer and marginal aquifer material. The image projection is NAD 83, UTM Zone 14 North.

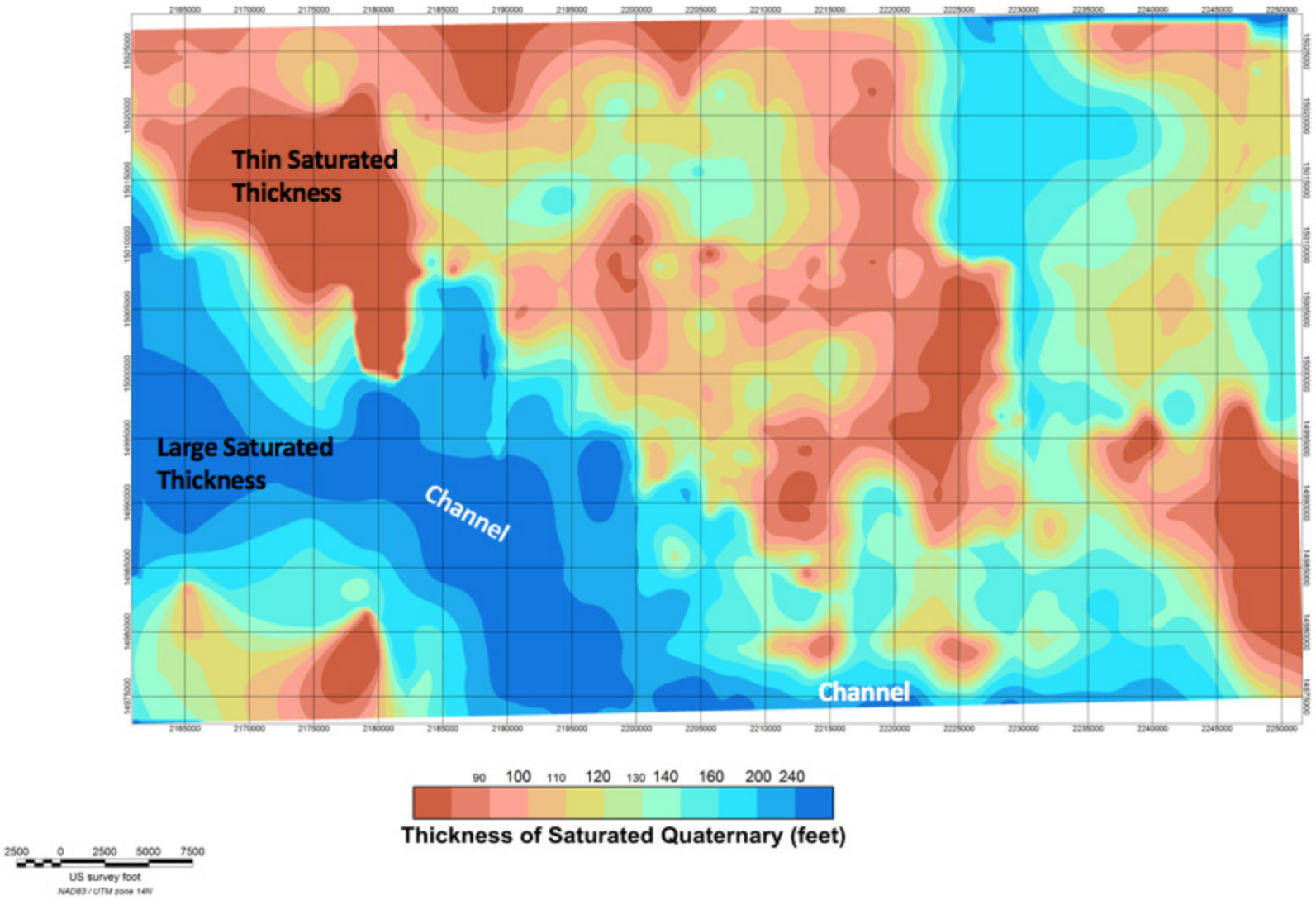


Figure 5-38. Saturated thickness of <u>all</u> aquifer materials including non-aquifer, marginal aquifer, aquifer, and coarse aquifer in the SQS#1 AEM survey area. Note the thickest sections occupy the channel trending along the southern border. The image projection is NAD 83, UTM Zone 14 North, feet.

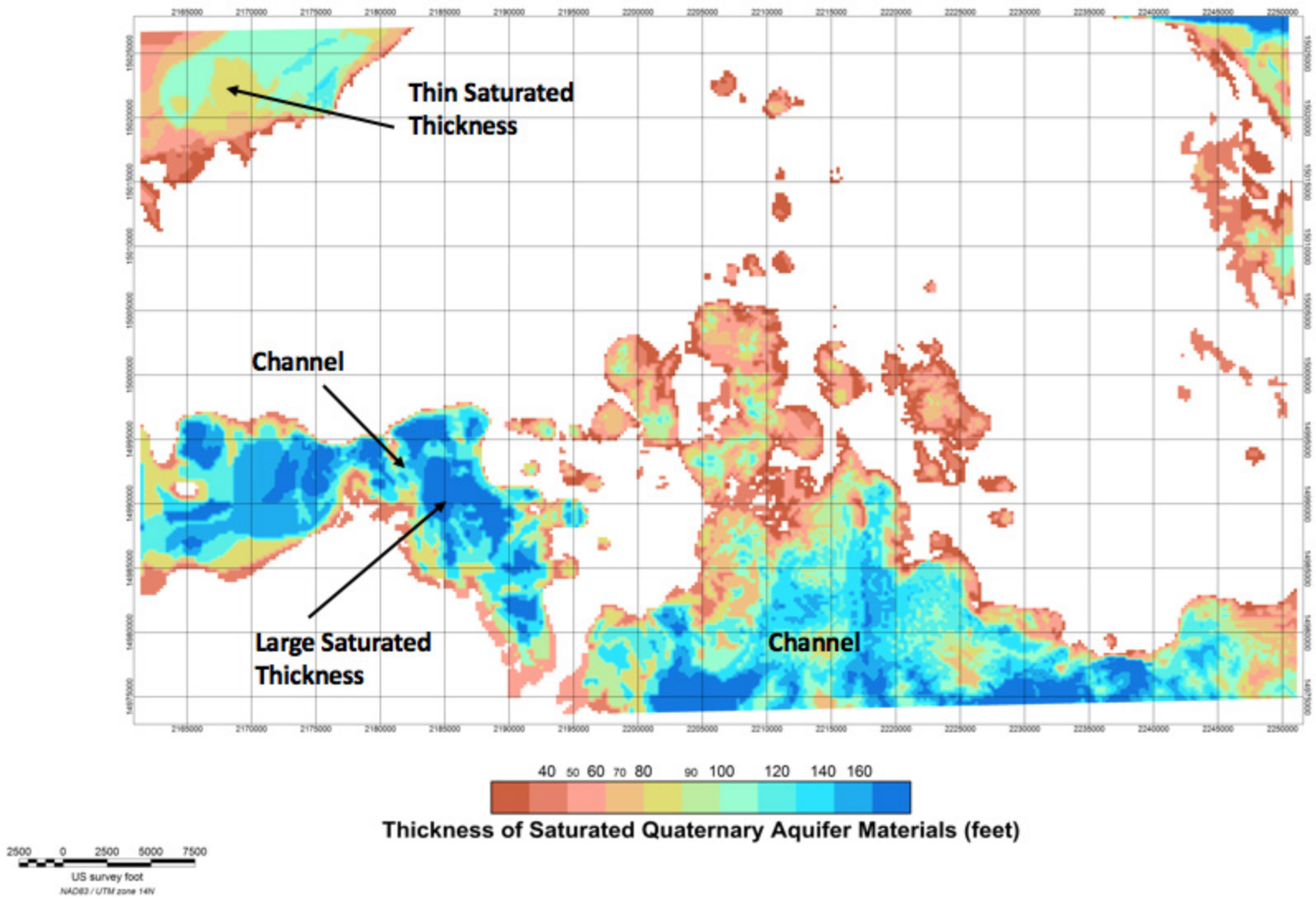


Figure 5-39. Saturated thickness of just the aquifer and coarse aquifer material in the SQS#1 AEM survey area. Note the thickest sections occupy the channel trending along the center south of SQS#1 survey area. There are many disconnected small aquifers in the area, in and around the larger channel aquifers. The image projection is NAD 83, UTM Zone 14 North, feet.

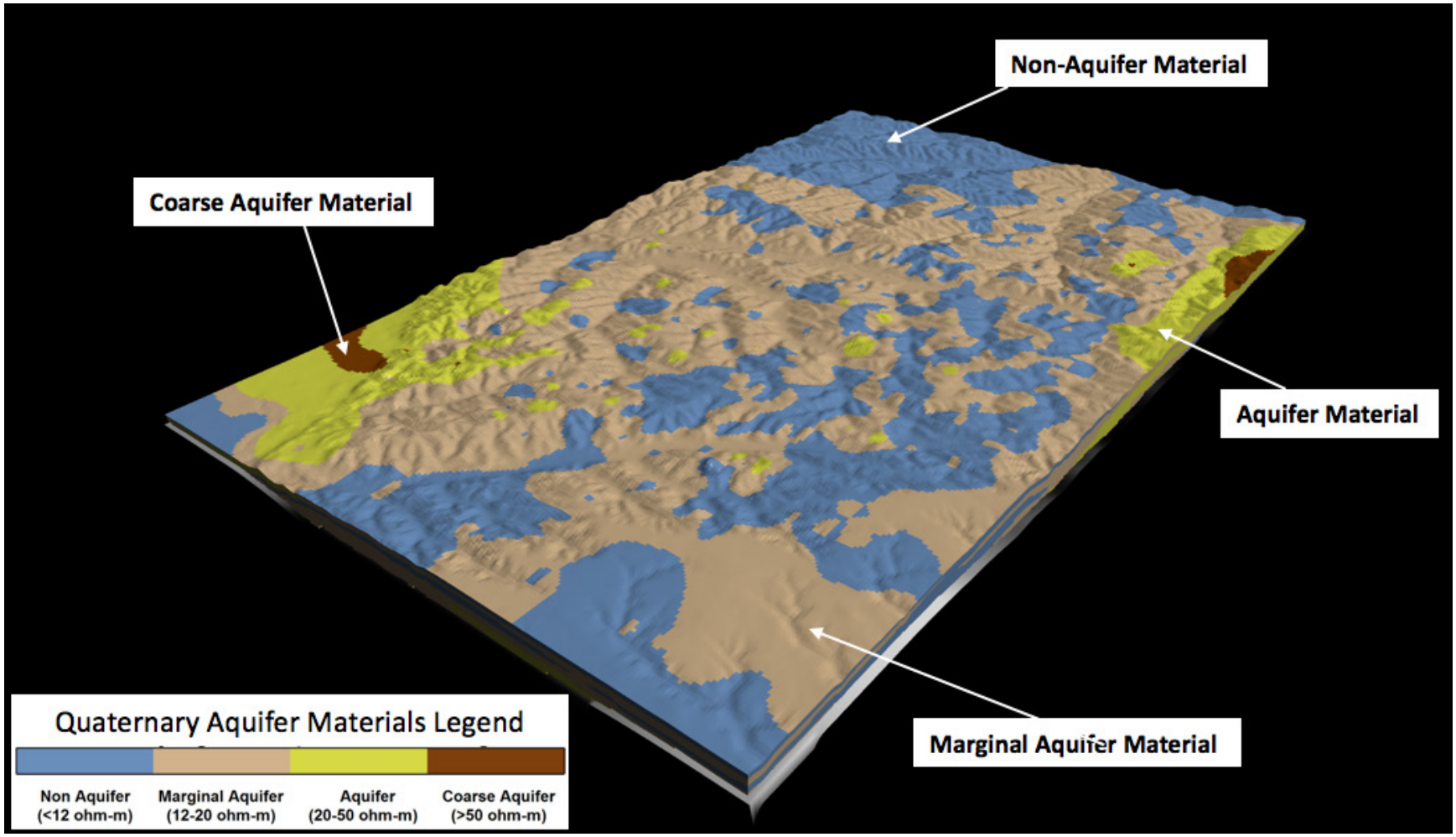


Figure 5-40. Voxel model with a view to the northeast, showing continuous volumes of the four different types of aquifer materials: Non-aquifer materials (blue), marginal aquifer (tan), aquifer (yellow), and coarse aquifer materials (brown). Note the nearly continuous mantle of fine grained marginal and non-aquifer materials across the survey area. S

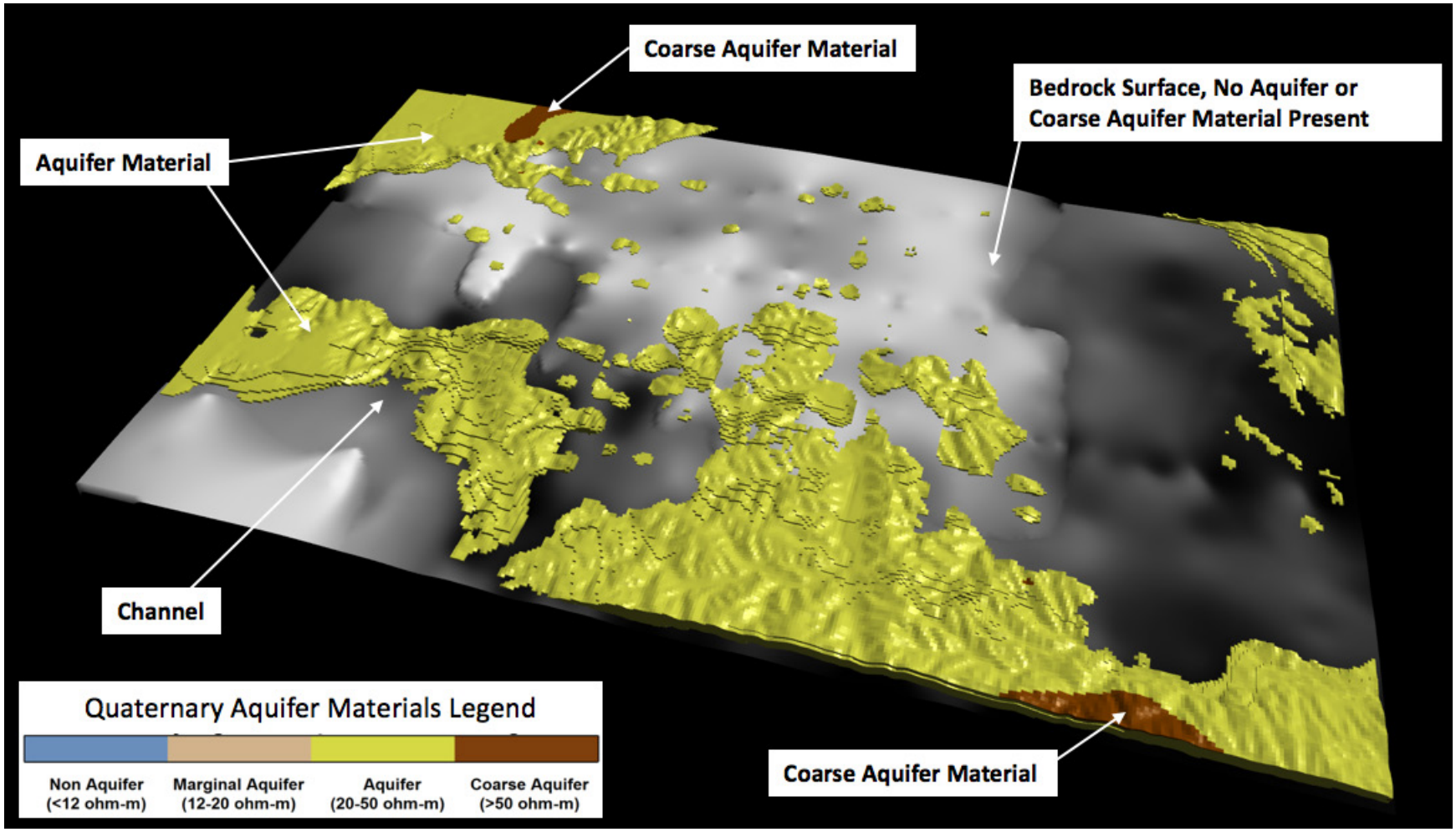


Figure 5-41. Voxel model with a view to the north, showing continuous volumes of the aquifer material and coarse aquifer material: aquifer (yellow), and coarse aquifer materials (brown). Notice the amount of aquifer material that dominate the area. Grey areas are the bedrock surface that is covered in with only marginal and non-marginal materials which are not displayed.

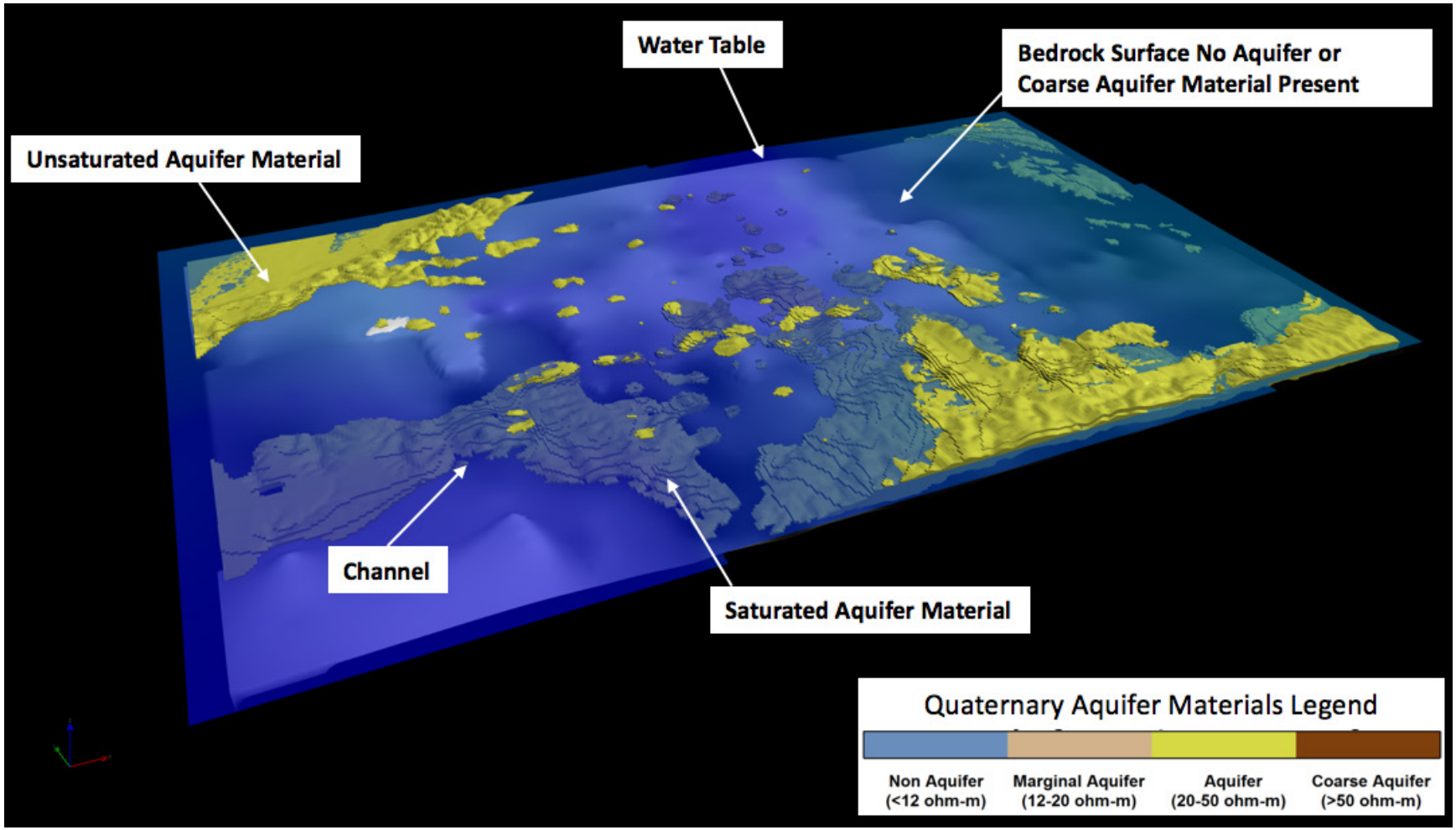


Figure 5-42. Voxel model with view to the north, showing continuous volume of aquifer material above and below the water table: Aquifer material is yellow above water table and shaded blue below the water table. Note the aquifer material filling the channel along the southern boundary of SQS#1.

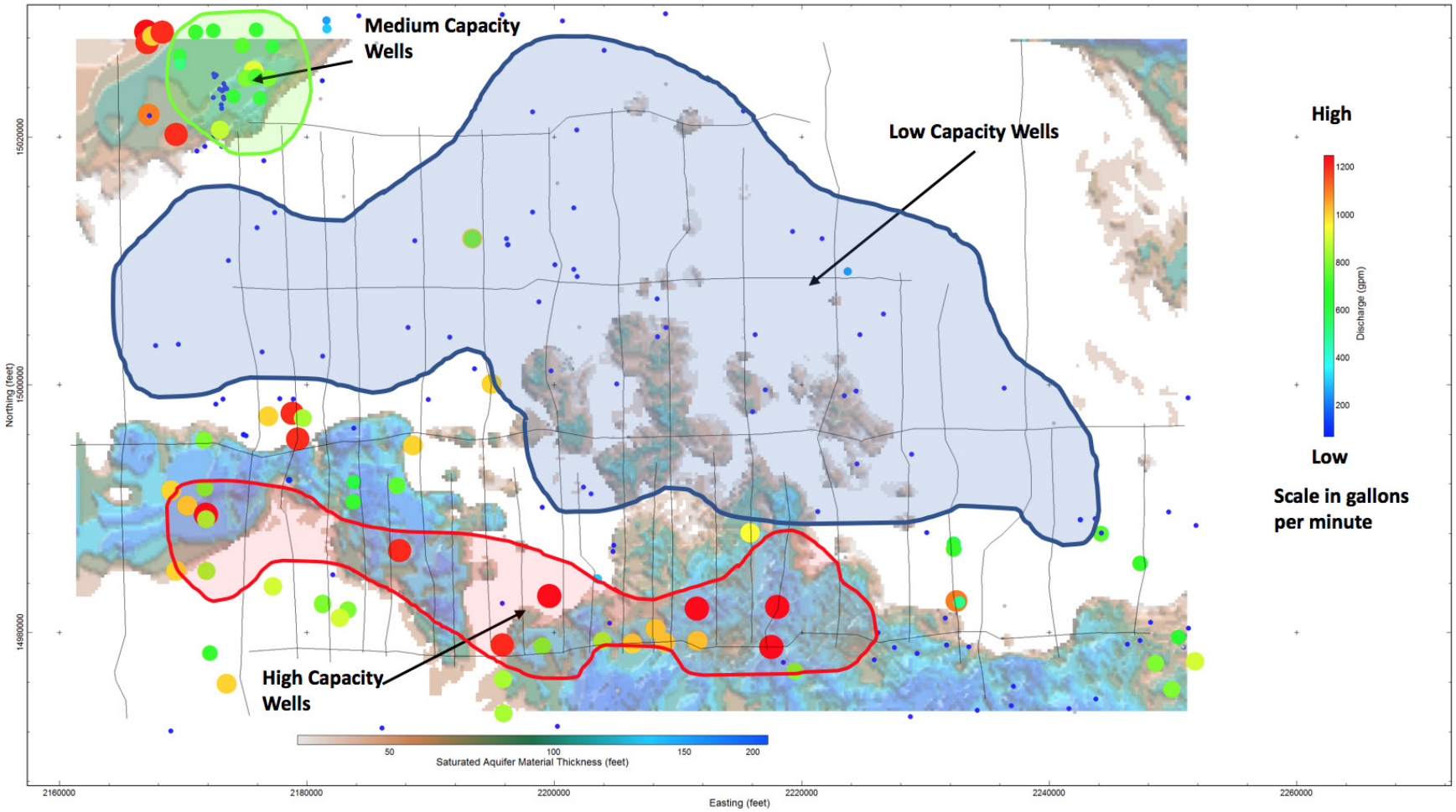


Figure 5-43. Map showing DNR wells in the vicinity of SQS#1 their water flow discharge capacity overlain on a thickness representation of saturated Quaternary aquifer material. Small blue dots imply low discharge rates (<100 gpm) and large red dots imply higher water discharge rates (>1200 gpm). Projection is in NAD83, UTM14 North, feet.

5.3.4 SQS#2 AEM Survey Area

The SQS#2 survey area is within the Quaternary Aquifer system defined above (Section 5.3.1). In Section 3.1, a map showing the AEM survey lines included within SQS#2 survey area and the locations the CSD test holes is presented in Figure 3-1. The area is composed of aquifer materials lying on the ***Kn, Kc*** and ***Kgg*** bedrock surface.

Figure 5-44 shows the bedrock configuration within the SQS#2 which has eroded bedrock with a single regional channel cut into it. The channel trends from west to east along the center of SQS#2 with bedrock highs to the north and the south. The channels are flanked by 2 bedrock highs which have an increased relief of up to approximately 425 feet in elevation from the bottom of the channels. The thickness of the Quaternary material within the SQS#2 survey area ranges from 68 to 430 feet thick (Figure 5-31). The area is dominated by non-aquifer and marginal materials. Figure 5-45 shows a 3D fence diagram of non-aquifer and marginal aquifer materials combined with a voxel model of aquifer and coarse aquifer materials lying on the bedrock units. The percentage of the different aquifer materials are as follows, marginal aquifer (tan) aquifer material makes up the largest percentage of the total at 47%, with aquifer material (yellow) next at 36%, followed by non-aquifer material at 16% (blue) and coarse aquifer material (brown) making up the least at less than 1%. The thicker sequences of aquifer material are to the south and center of the area. This material is part of the channel deposits that trend to the south and east. When the elevation of the bedrock is subtracted from the elevation of the water table the result is the saturated thickness of the ***Q*** materials in SQS#2 (Figure 5-46). The saturated Q materials (non-aquifer, marginal aquifer, aquifer and coarse aquifer) range in thickness from approximately 80 feet to 250 feet. The saturated aquifer material and coarse aquifer material are shown in Figure 5-47 which shows the limited areas of the aquifers in SQS#2. Note that the distribution of the saturated aquifer and coarse aquifer materials is more eve across the area compared to SQS#1.

A voxel model showing continuous volumes of the four different types of aquifer materials is presented in Figure 5-48. This shows the abundance of the marginal and non-aquifer materials across the area. The marginal aquifer material (tan) and the non-aquifer material (blue) mantle the surface down to bedrock in many places and is made up of mostly glacial till silts and clays. A voxel model showing continuous volumes of aquifer material and some coarse aquifer material above the bedrock surface is presented in Figure 5-49. A majority of aquifer material fills the channel along the south edge of survey area. Aquifer materials above and below the water table and above the bedrock is presented in Figure 5-50. As can be observed in the data, not all the aquifers are interconnected with continuous aquifer and coarse aquifer material. They are often separated by non-aquifer and marginal aquifer materials that impede the flow between the adjacent aquifers.

It is important to understand the interconnection between the many aquifers of SQS#2 and its effect on groundwater supply and management. A good example of this is the response of the aquifers to production wells related to aquifer size. Figure 5-51 shows the volumes of the mapped aquifers in SQS#1, the relationship to a small volume aquifer and a production well completed within it shows how the volume of water yielded from the well is very finite (highlighted area in Figure 5-51).

There are no other sources of water to this aquifer except for slow recharge from the marginal and non-aquifer materials surrounding the aquifer. However, when compared to the area on Figure 5-51 of "large interconnected aquifers" you can see that the larger volume of aquifer and coarse aquifer material provides substantially more water to production wells. Figure 5-52 shows a profile view illustrating the same conditions as described for the 3D voxel in Figure 5-51. Again, where the aquifers are small and disconnected, production wells can be impacted by limitations to the rate of flow and water in storage.

Thus, depending on the number of wells, their proximity to each other and aquifer boundaries the large interconnected aquifers have a larger capacity for production wells. To ascertain how much groundwater is available when compared to groundwater demand, a separate study needs to done to evaluate the conditions as the currently exist. It would be helpful to have a map of average well production per well per year that could be compared to the hydrogeologic framework so that one could determine areas that have a need for management based on available water to production wells.

Figure 5-49 is also a voxel model of the volumes of the aquifer materials below the water table. These materials are the most productive for water wells and have the most transmissivity allowing for groundwater flow. These materials are also the most likely to have a hydrologic connection to the streams of the area including Loseke Creek, Loup river Canal, and Shell Creek.

The SQS#2 AEM survey area has a large number of DNR registered wells when compared to SQS#1. Figure 5-53 shows the distribution of the wells in the area color coded based on estimated discharge rates in gallons per minute with range increasing from blue (<100 gpm) to red (>1200 gpm). The DNR well locations are overlain on a representation of the thickness of the saturated ***Q*** aquifer materials, ranging from brown (thinner) to blue (thick). The majority of the wells have a medium discharge rate due to most of the aquifer in the area being made up of aquifer material and little coarse aquifer material. The discharge rates match the aquifer configuration and aquifer materials description well. The highest discharge rates are in isolated areas across the AEM survey area. There are some areas in the SQS#2 AEM survey area that have thick saturated aquifer material but very few wells. These may be good locations for future production well locations. The medium capacity wells are following the channel in the center of the AEM survey area. Low capacity wells tend to be scattered across the survey area where the aquifer material and coarse aquifer material are thin on non-existent.

Individual profiles for the interpreted resistivity sections can be found in Appendix 1 (2D profiles) and Appendix 2 (3D images).

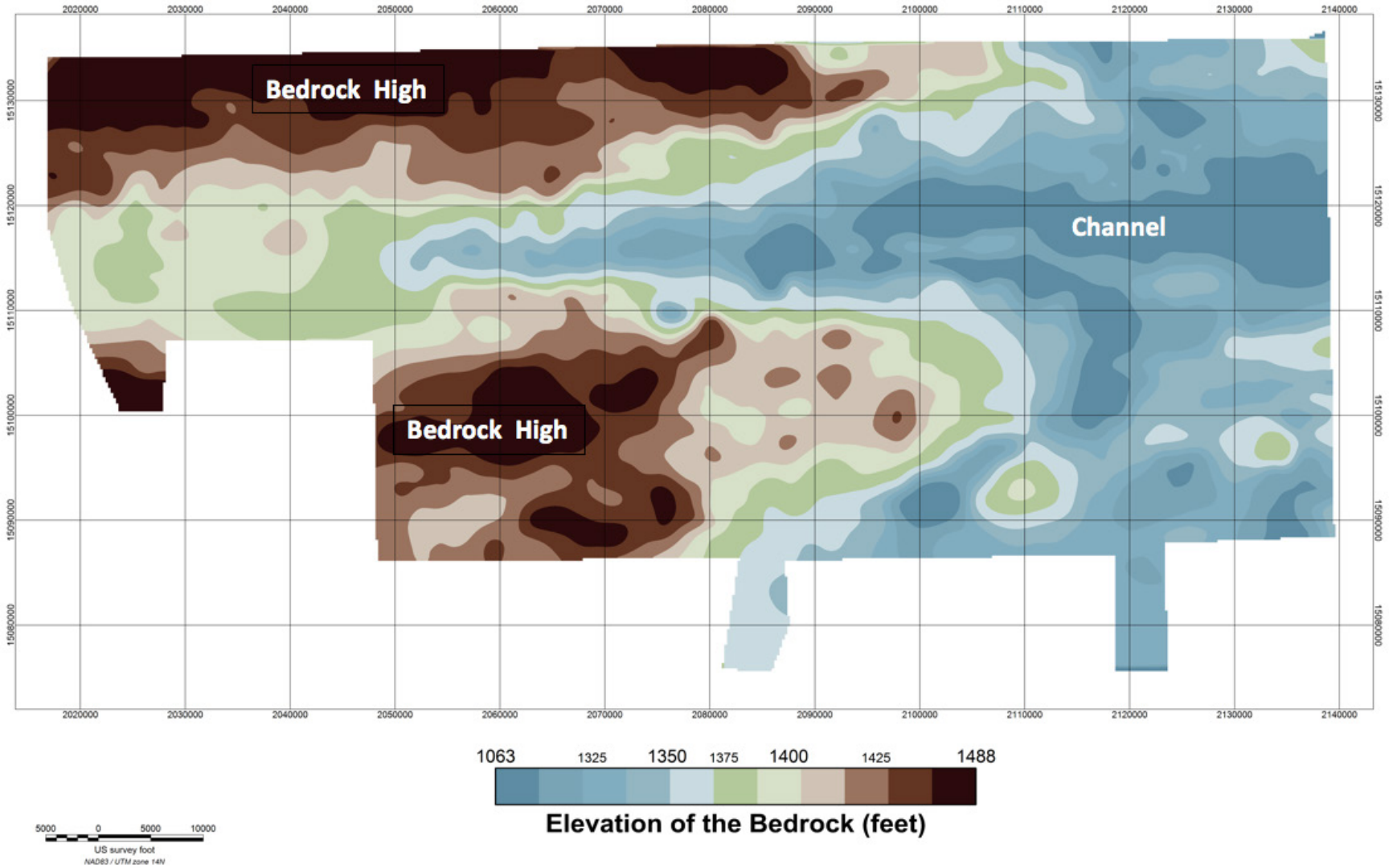


Figure 5-44. Base of the *Q* aquifer which is the top of the bedrock. Two channels eroded into the bedrock can be seen lying between three bedrock highs. Note that only the northern most channel is in the SQS#2 survey area. The image projection is NAD 83, UTM Zone 14 North, feet.

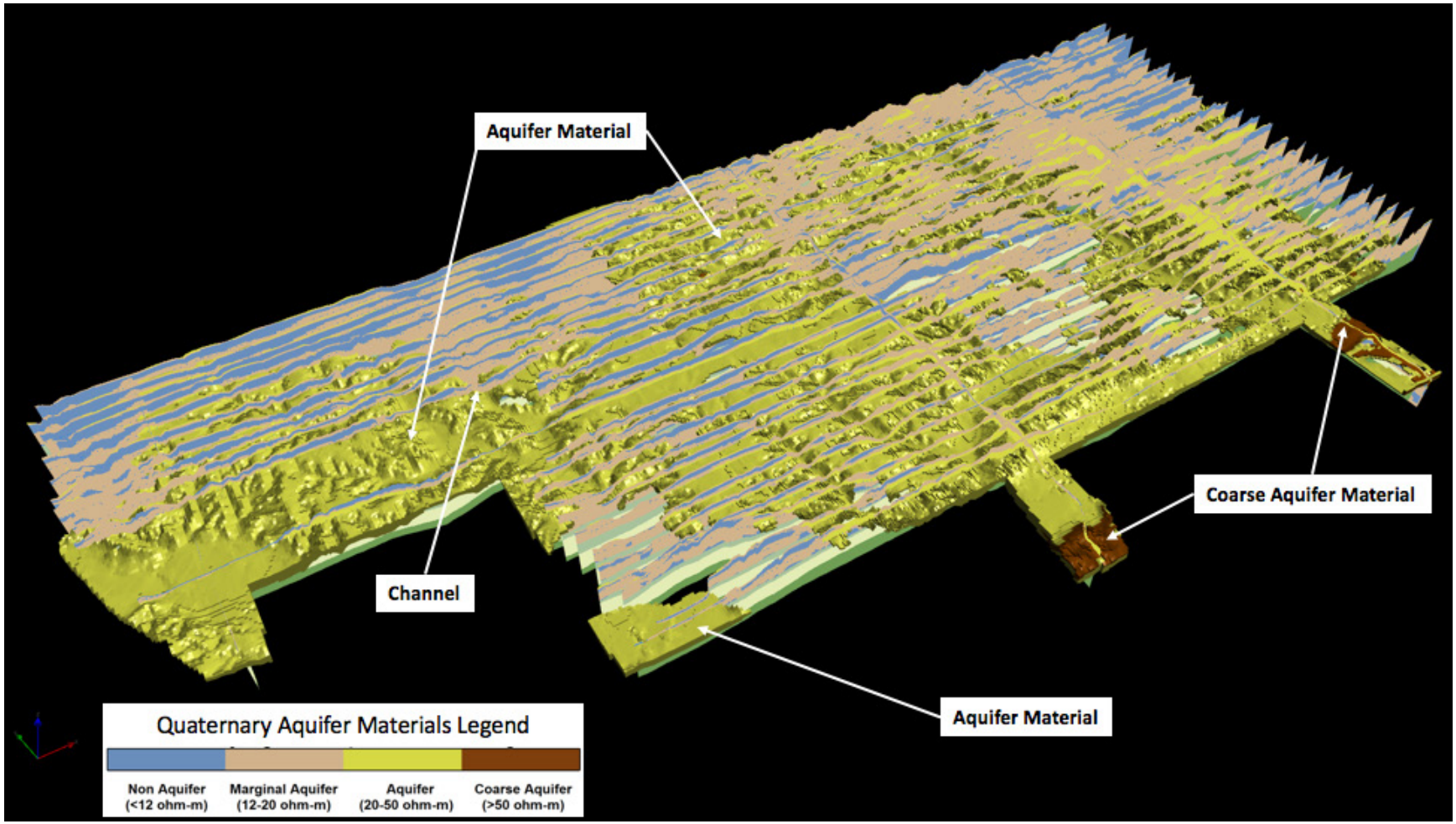


Figure 5-45. Voxel of SQS#2 saturated thickness of aquifer (yellow) and coarse aquifer materials (brown) paired with 3D fence diagram of non-aquifer materials (blue) and marginal aquifer (tan) and the bedrock units. This shows the distribution of the aquifers in the area related to the non-aquifer and marginal aquifer material. The image projection is NAD 83, UTM Zone 14 North.

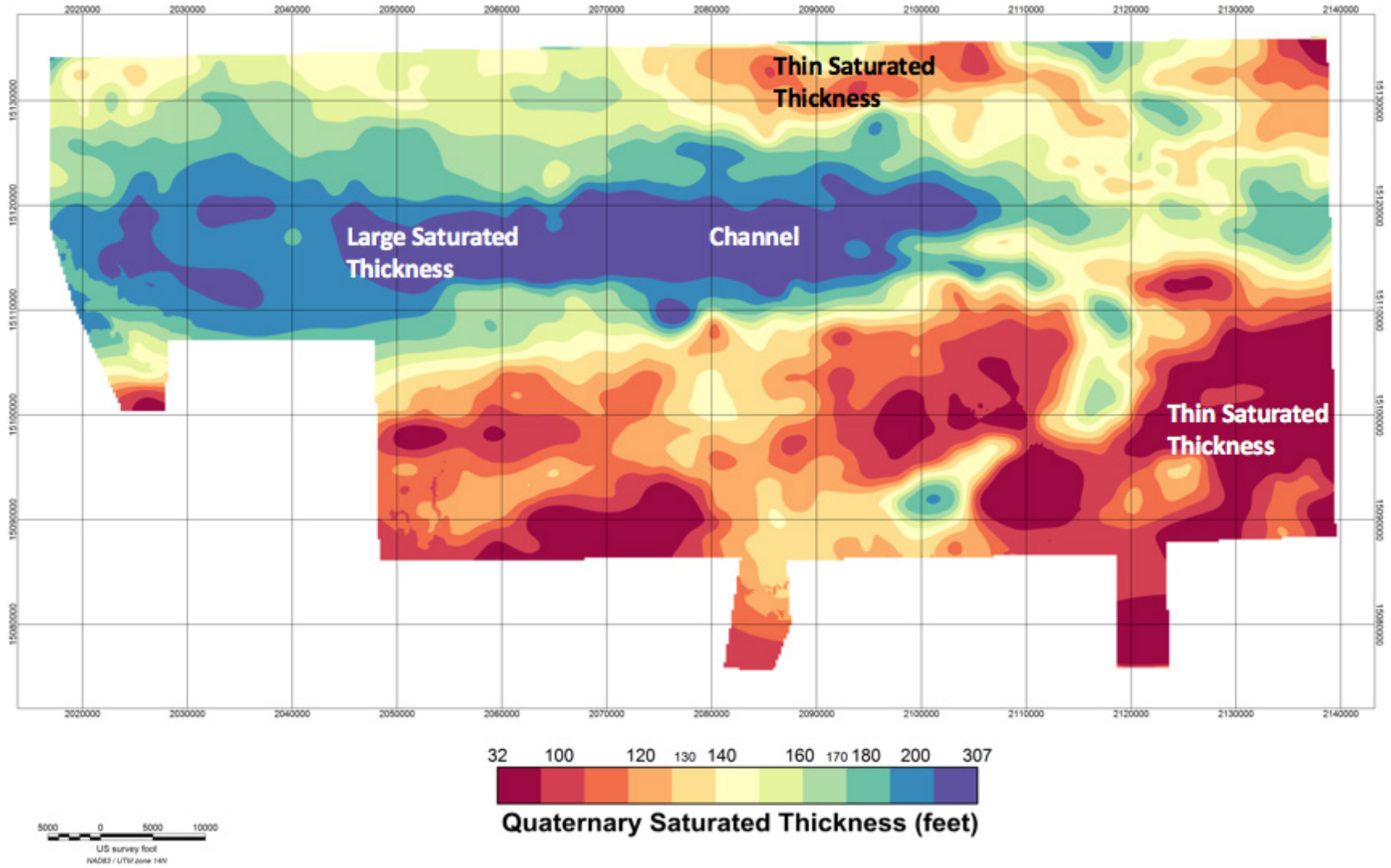


Figure 5-46. Saturated thickness of all aquifer materials including non-aquifer, marginal aquifer, aquifer and coarse aquifer in the SQS#2 AEM survey area. Note the thickest sections occupy the channel trending along the southern border of SQS#2 survey area. The image projection is NAD 83, UTM Zone 14 North, feet.

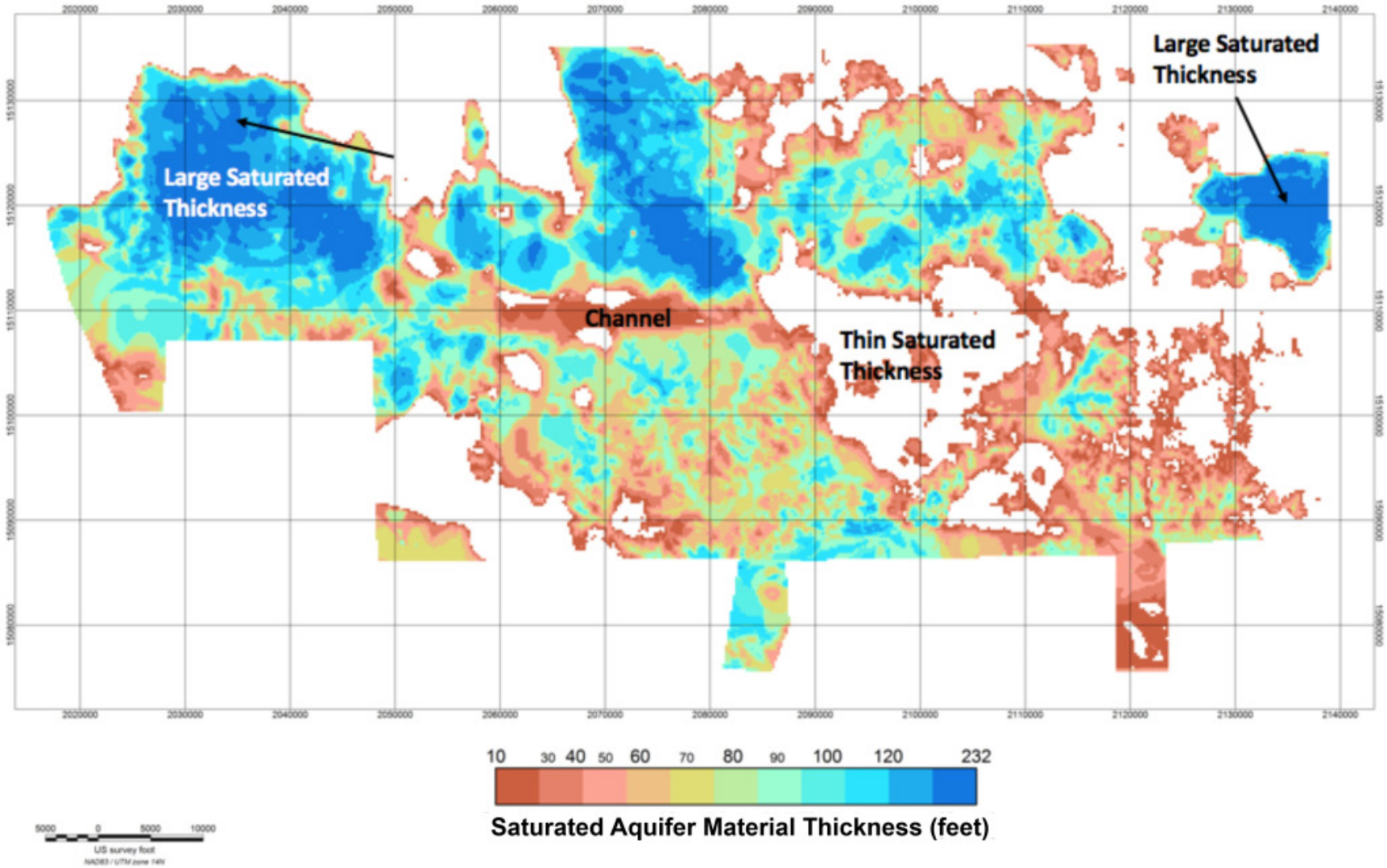


Figure 5-47. Saturated thickness of aquifer and coarse aquifer material in the SQS#2 AEM survey area. Note the thickest sections occupy the channel trending along the center of SQS#2 survey area. There are many disconnected small aquifers in the area in and around the larger channel aquifers. The image projection is NAD 83, UTM Zone 14 North, feet

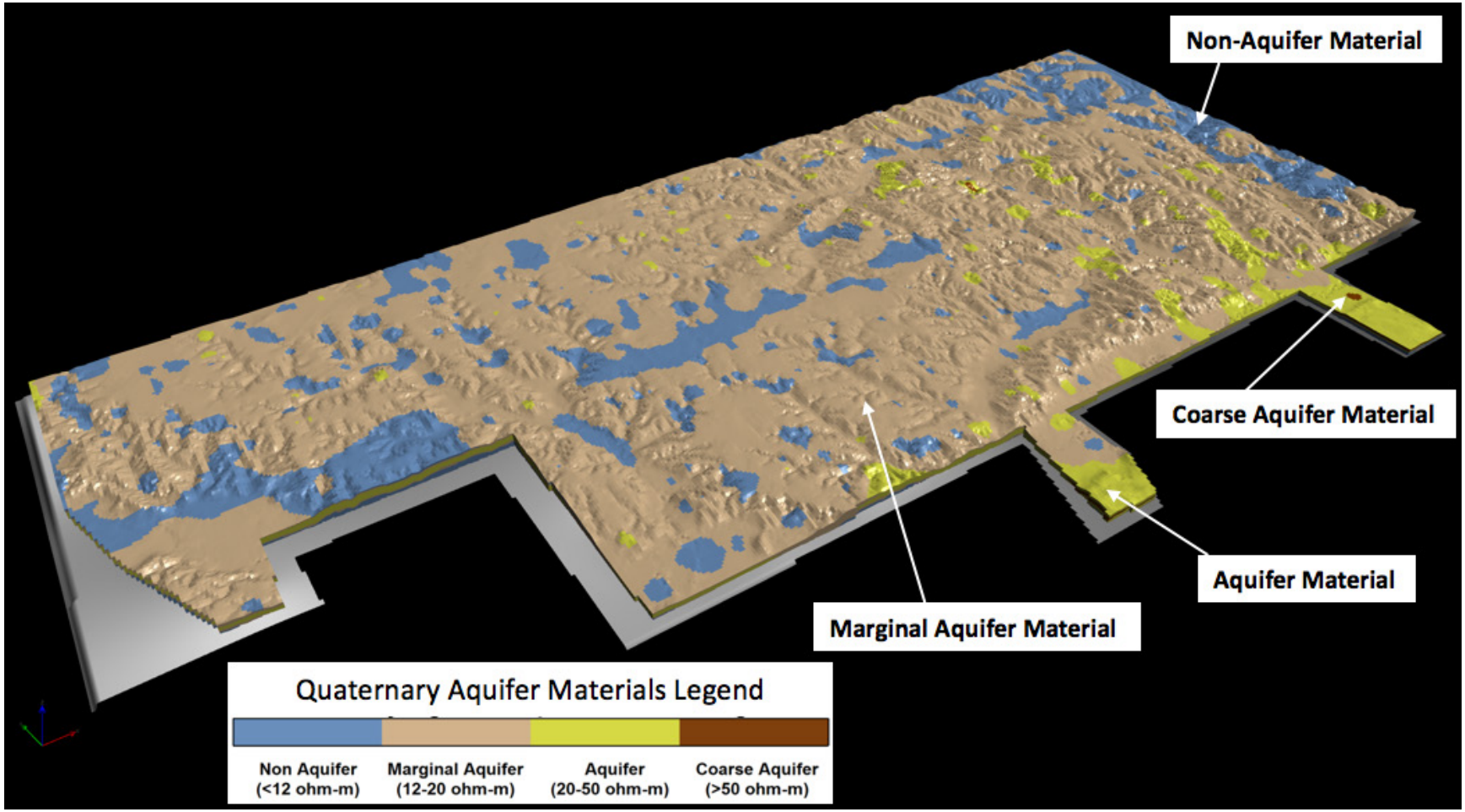


Figure 5-48. Voxel model with a view to the northeast, showing continuous volumes of the four different types of aquifer materials: Non-aquifer materials (blue), marginal aquifer (tan), aquifer (yellow), and coarse aquifer materials (brown). Note the nearly continuous mantle of fine grained marginal and non-aquifer materials across the survey area.

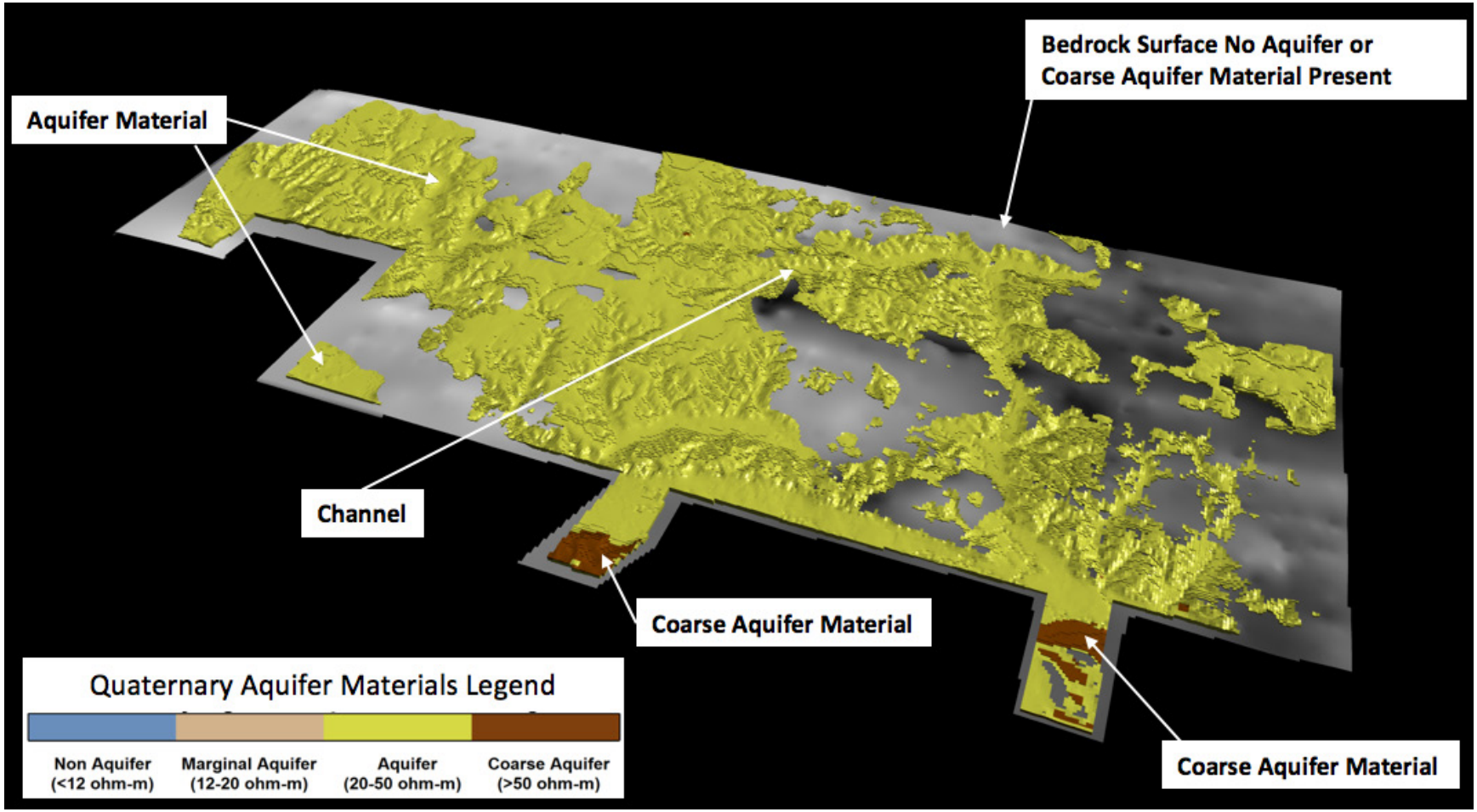


Figure 5-49. Voxel model with a view to the north, showing continuous volumes of the aquifer material and coarse aquifer material: aquifer (yellow), and coarse aquifer materials (brown). Notice the amount of aquifer material that dominate the area. Grey area is the bedrock surface that is covered in with only marginal and non-marginal materials which are not displayed.

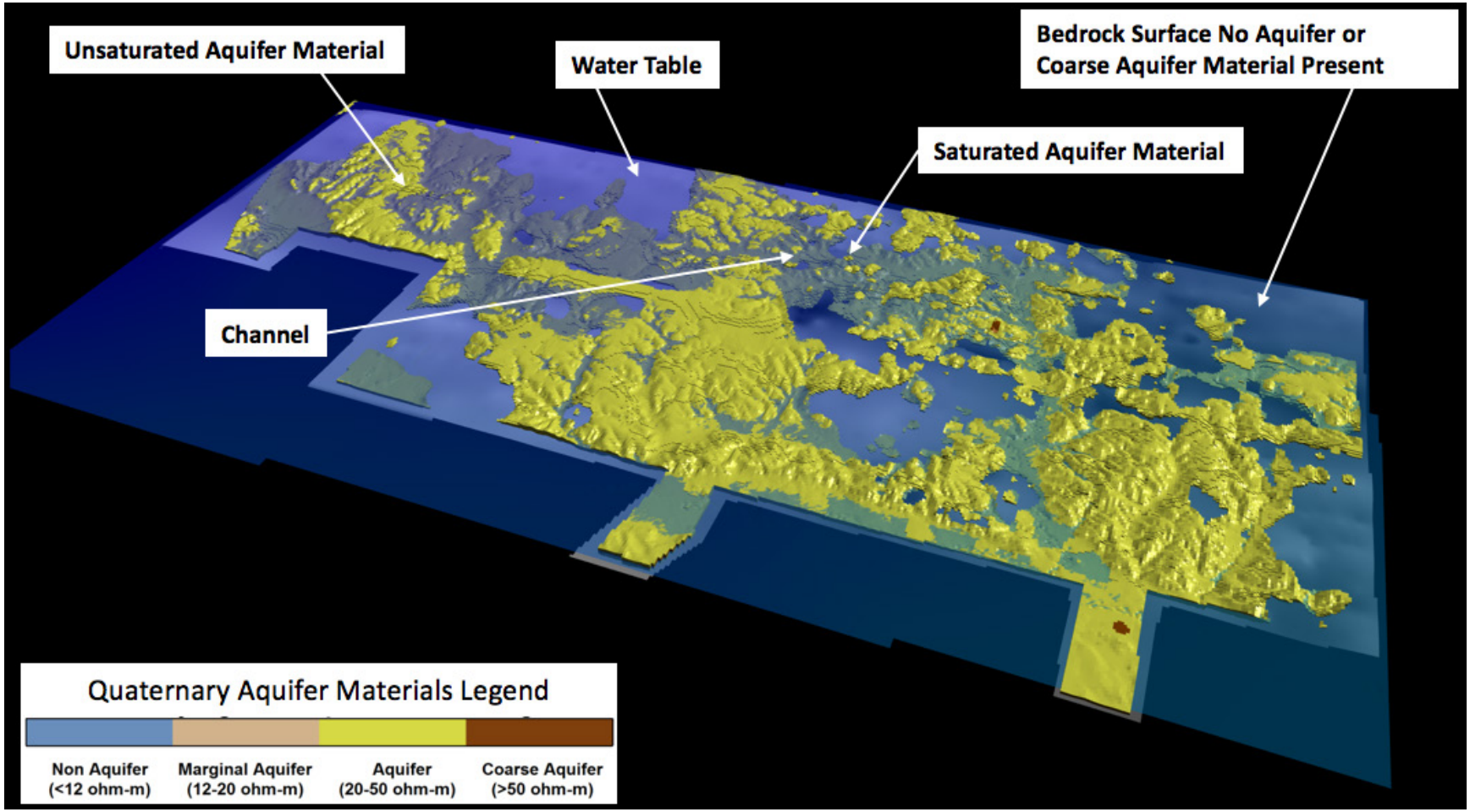


Figure 5-50. Voxel model with view to the north, showing continuous volume of aquifer material above and below the water table: Aquifer material is yellow above water table and shaded blue below the water table. Note the aquifer material filling the channel along the southern boundary of SQS#2.

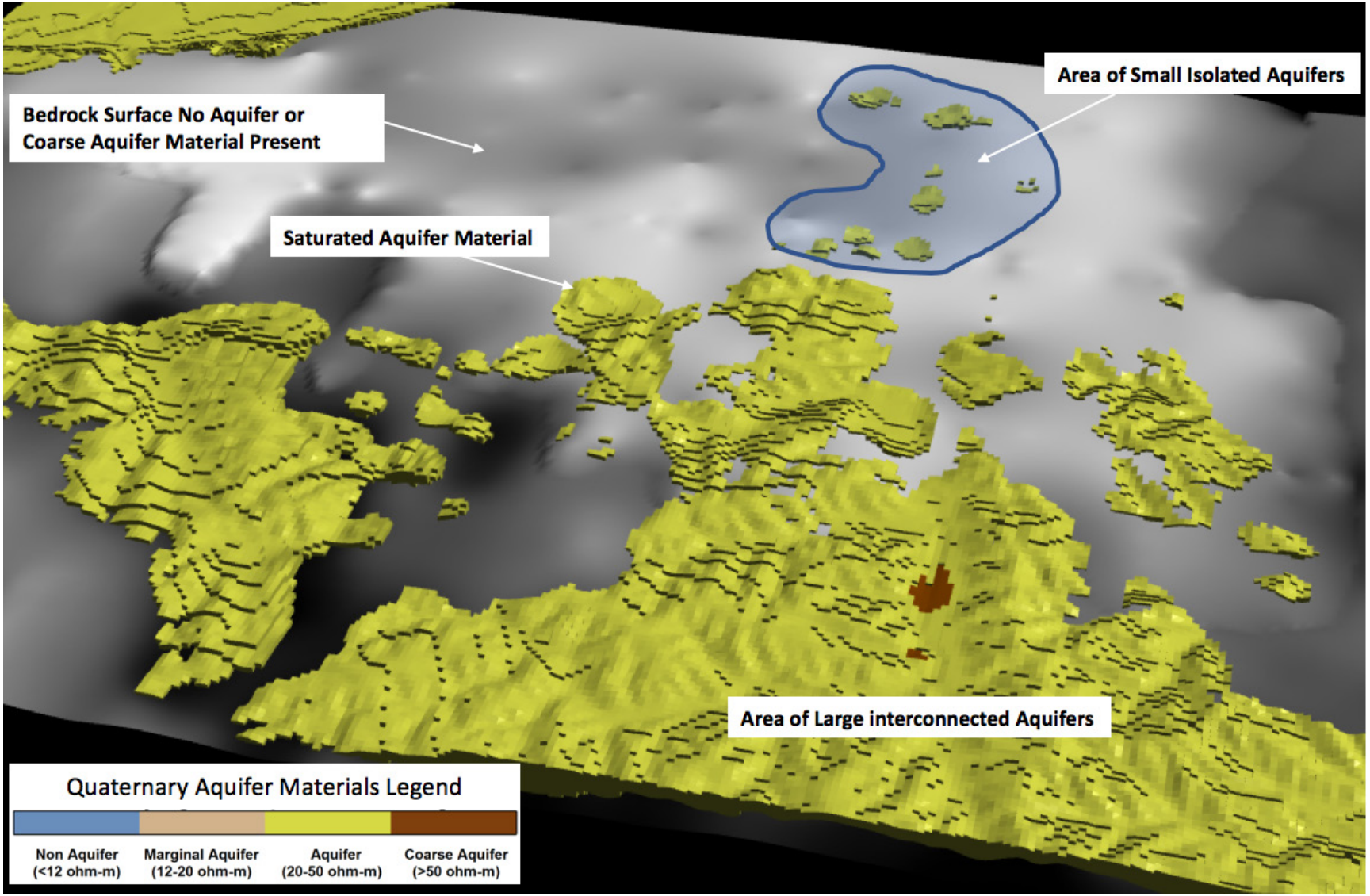


Figure 5-51. Voxel model with view to the north, showing continuous volumes of coarse aquifer materials below the water table. Notice the amount of aquifer and coarse aquifer materials that dominate the area. Also, note the aquifer and coarse aquifer materials missing in parts of the flood plain in the southeast. Streams are represented in their approximate locations.

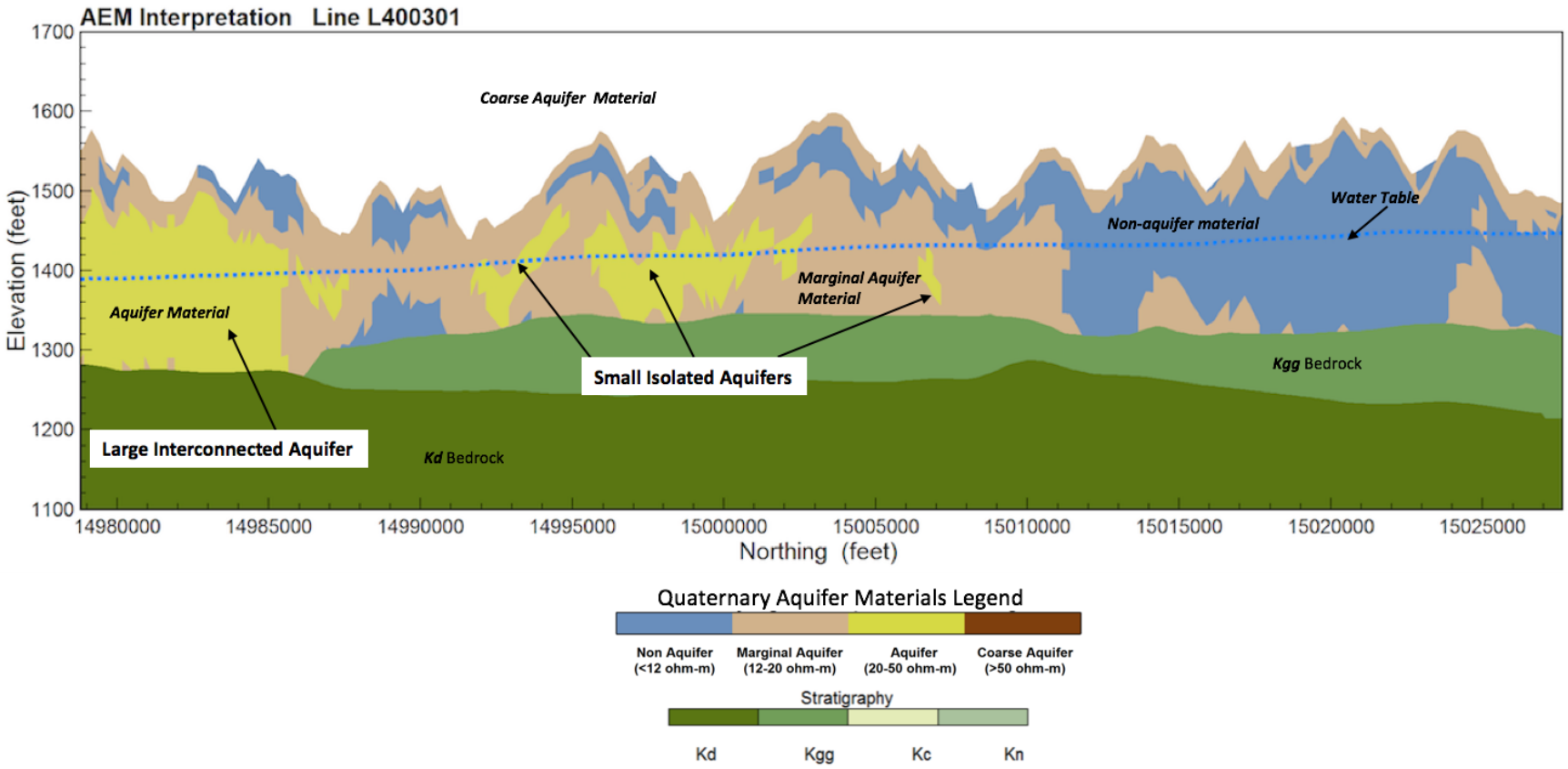


Figure 5-52. Shows profile view of Line L400301 illustrating the differences between small isolated aquifers versus large interconnected aquifers. Note the marginal and non-aquifer materials separating the aquifers along the flight line. Projection is NAD83, UTM 14 North, feet.

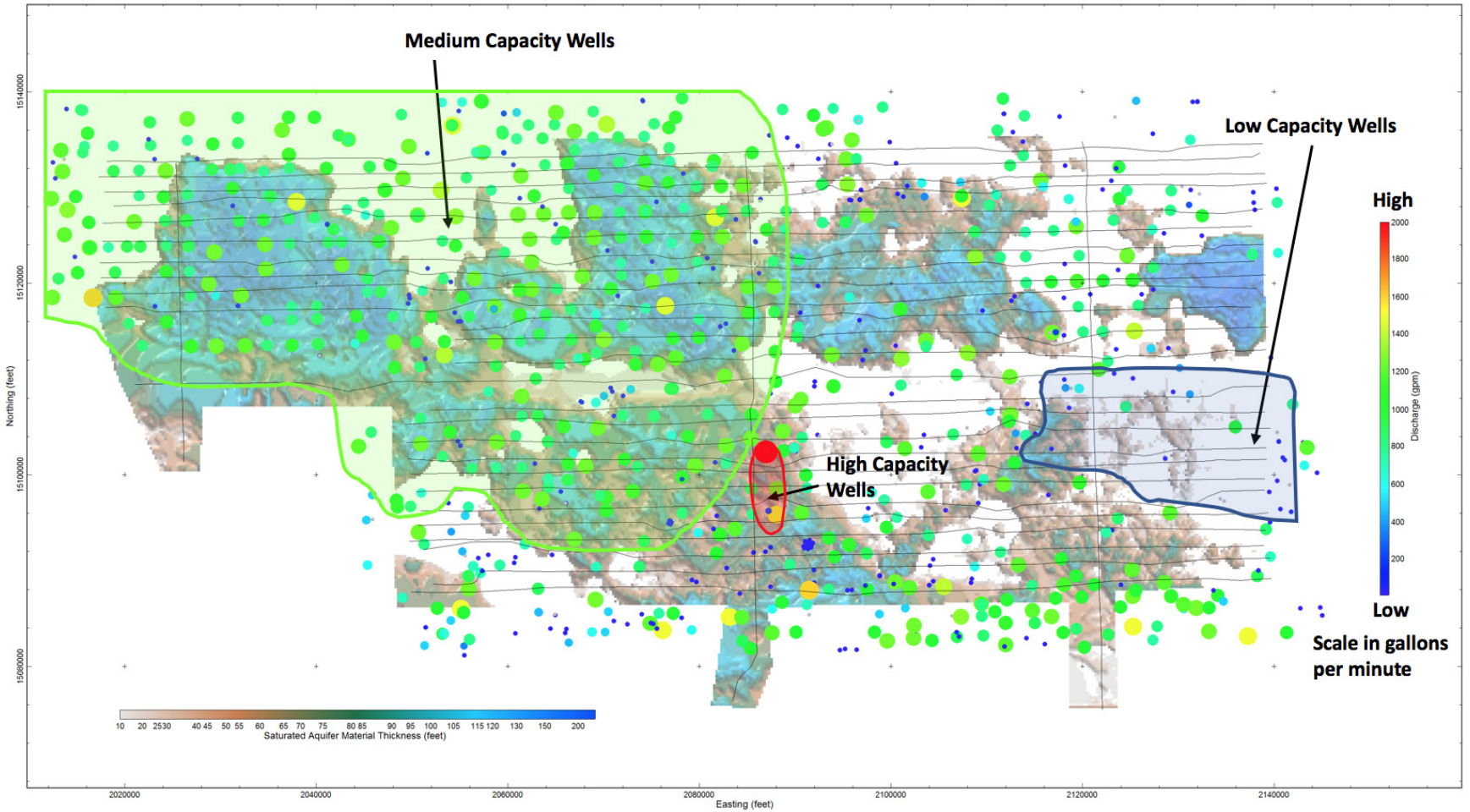


Figure 5-53. Map showing DNR wells in the vicinity of SQS#2 and their water flow discharge capacity overlain on a thickness representation of saturated Quaternary aquifer material. Small blue dots imply low discharge rates (<100 gpm) and larger red dots imply higher water discharge rates (>1200 gpm). The areas of high and low production are indicated. Projection is in NAD83, UTM14 North, feet.

5.4 Estimation of Aquifer Volume and Water in Storage for the LPNNRD SQS#1 and SQS#2 AEM Survey Areas

The 3D digital representation of the subsurface resulting from the AEM method provides users the ability to more accurately estimate total unsaturated and saturated aquifer volume and the amount of extractable water present. The SQS#1 and SQS#2 AEM survey areas were mapped at high resolution for this purpose. Approximately 116 square miles (approximately 74,240 acres) of AEM data were collected were collected in the SQS#1 AEM survey area and interpreted and approximately 204 square miles (approximately 130,560 acres) of AEM data were collected were collected in the SQS#2 AEM survey area and interpreted (Figure 1-2).

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 5.2. Figure 5-26 shows resistivity ranges for interpreted non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. This report provides information on unsaturated and saturated volumes of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials.

Figure 5-37 shows the distribution of the volumes of all saturated Quaternary aquifer materials, including non-aquifer, marginal aquifer, aquifer and coarse aquifer material from the water table down to bedrock, showing the complex nature of the area. Understanding this complexity in the area and within the sedimentary deposits shows that estimated average values for porosity and specific yield are the best values to use in making the following calculations. The area beneath the SQS#1 and SQS#2 AEM survey areas are included in these calculations and are represented in Figure 5-35 and Figure 5-36. Note that the images in these figures were created in Datamine Discover PA (formerly pbEncom PA), version 2015, Release Build 15.0.13 (Datamine Discover, 2017). They can be examined in greater detail by opening the PA sessions provided in *Appendix_3_Deliverables\PA_Sessions*.

All aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material are used for calculating the groundwater in storage volume and the extractable water volumes for the survey area. Reported values of the average porosity for 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 SQS#1 (Figure 2-8) and SQS#2 (Figure 2-9) were selected by estimating values from Olafsen-Lackey (2005b) and personal communication (Susan Olafsen Lackey, January 5, 2017). No aquifer test information was available for this report for the SQS#1 and SQS#2 areas. Estimates of specific yield were made for all aquifer materials. Specific yield for non-aquifer (<12 ohm-m) materials was chosen at 0.02, for marginal aquifer materials (12-20 ohm-m) a value of 0.05 was selected (Heath, 1983). The aquifer material (20-50 ohm-m) ranges from 0.1 to 0.2 with an average of 0.15 (Olafsen-Lackey, 2005). Coarse aquifer materials exist as continuous deposits across 50 percent of the area.

Estimates of specific yield for the coarse aquifer material (>50 ohm-m) ranges from 0.10 to 0.20 with an average of 0.15 (Olafsen-Lackey, 2005b).

Table 5-3 shows the results of calculations for the amount of groundwater in storage in the SQS#1 AEM survey area calculated by volume of all aquifer materials below the water table and then multiplied by the estimated porosity. The following calculation from values in the table shows the non-aquifer material has an estimated volume of **3,932,293** acre-ft and contains **1,572,917** acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of **8,303,004** acre-ft and contains **2,906,051** acre-ft, aquifer material has an estimated volume of **3,466,989** acre-ft and contains an estimated volume of **693,397** acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of **3,845** acre-ft for a total of **961** acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is **5,173,326** acre-ft.

Table 5-4 shows the results of calculations for the amount of groundwater in storage in the SQS#2 AEM survey area calculated by volume of all aquifer materials below the water table then multiplied by the estimated porosity. The following calculation from values in the table shows the non-aquifer material has an estimated volume of **2,885,798** acre-ft and contains **1,154,319** acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of **8,674,691** acre-ft and contains **3,036,141** acre-ft, aquifer material has an estimated volume of **6,717,815** acre-ft and contains an estimated volume of **1,343,563** acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of **43,139** acre-ft for a total of **10,784** acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is **5,544,807** acre-ft.

The estimate of extractable volume of water under SQS#1 is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the SQS#1 AEM survey area will yield approximately **31,458** acre-ft, marginal aquifer materials will yield approximately **145,302** acre-ft, aquifer materials will yield **104,009** acre-ft, and the coarse aquifer material will yield approximately **144** acre-ft. A total of **280,913** acre-ft is available from the combined aquifer and coarse aquifer materials. The estimate of extractable volume of water under SQS#2 is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the SQS#2 AEM survey area will yield approximately **23,086** acre-ft, marginal aquifer materials will yield approximately **151,807** acre-ft, aquifer materials will yield **201,534** acre-ft, and the coarse aquifer material will yield approximately **1,617** acre-ft. A total of **378,044**acre-ft is available from the combined aquifer and coarse aquifer materials.

These estimates are based on the CSD 1995 water table map. Also, these volumetric estimates consider only the volume of water assumed in the pore spaces of the aquifer material defined by the resistivity threshold levels and do not account for the amount of the possible “confined or semi-confined” water under pressure (head above the aquifer). This volume of water would add to the values reported in Table 5-3 and Table 5-4. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed are conservative estimates and the amounts released from the decline in pressure are not considered

Table 5-3. Estimates of groundwater in storage and extractable water content in all aquifer materials underlying the SQS#1 AEM survey 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	171,290,690,625	3,932,293.15	0.40	1,572,917	0.02	31,458
Marginal	361,678,887,500	8,303,004.71	0.35	2,906,051	0.05	145,302
Aquifer	151,022,078,125	3,466,989.84	0.20	693,397	0.15	104,009
Coarse	167,503,125	3,845.34	0.25	961	0.15	144
TOTAL	684,159,159,375	15,706,133		5,173,326		280,913

Table 5-4. Estimates of groundwater in storage and extractable water content in all aquifer materials underlying the SQS#2 AEM survey 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	125,705,382,263	2,885,798.47	0.40	1,154,319	0.02	23,086
Marginal	377,869,543,294	8,674,691.02	0.35	3,036,141	0.05	151,807
Aquifer	292,628,035,588	6,717,815.29	0.20	1,343,563	0.15	201,534
Coarse	1,879,174,113	43,139.90	0.25	10,784	0.15	1,617
TOTAL	798,082,135,256	18,321,444		5,544,807		378,044

5.5 Recharge Areas within the LPNNRD AEM Survey Area

3D representations of the subsurface aquifer materials resulting from the AEM method illustrate areas bedrock up to the land surface for SQS#1 And SQS#2. From these maps a new series of near-surface maps, which includes the interval from 0 to10 feet, were constructed. The interval of 0-10 feet is noteworthy because this is the first layer of the inverted AEM earth model. Remember from the discussion around Table 4-4 that each model layer represents an average of the earth's resistivities within the bounds of each layer, based on the physics behind the electromagnetic exploration technique. These first layer maps show all aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material. These maps indicate the areas at the land surface that can potentially transmit water to the groundwater aquifers in the area. The coarse aquifer and aquifer material transmits the largest volume of water and the non-aquifer and marginal aquifer material being the least able to transmit water. The information from the interpreted aquifer materials maps and the information from Section 2.2.2 provides the basis of the information utilized in this section which is divided into the SQS#1 and SQS#2 survey areas.

5.5.1 SQS#1 AEM Survey Area

The results of the interpretation of the aquifer materials of the LPNNRD Survey Area survey area are explained in detail in Section 5.3. During the SQS#1 survey, approximately 116 square miles (approximately 74,240 acres) of AEM data were collected and interpreted. Each SQS#1 AEM flight line in Figure 4-5 was interpreted for aquifer material in the first model layer (0 – 10 ft) using the colors in the Quaternary/Ogallala Aquifer Material legend in Figure 5-26. Areas of coarse aquifer material (brown) will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material (yellow color) potentially transmitting slightly less precipitation downward as both units are permeable. The marginal aquifer material (tan) has the lowest potential to transmit some water downward and the non-aquifer material (blue) will transmit minimal to no water to the groundwater aquifer.

The flight lines (approximately 1/2 mile apart) illustrate patterns or areas where the potential for recharge can be high and low. Locations where the flight lines intersect and both lines show either aquifer or coarse aquifer material should be considered as higher likelihood for recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true where two flight lines intersect and both lines show non-aquifer or marginal material, those areas will likely not be optimal recharge locations. The area marked "*Low Recharge Area*" in Figure 5-54 shows example areas where recharge is potentially good and potentially poor within SQS#1 being composed of non-aquifer and marginal aquifer material. The coarse aquifer material on the south eastern corner of the SQS#1 area correlates to a similar area in the LPSNRD (Carney et al., 2014b).

5.5.2 SQS#2 AEM Survey Area

The SQS#2 survey area was mapped in similar fashion to SQS#1. During the SQS#2 survey, approximately 204 square miles (approximately 130,560 acres) of AEM data were collected and interpreted. The flight

lines, approximately 1/4 mile apart, within the SQS#2 survey area allowed for nearly continuous mapping of the different aquifer material types. Figure 5-55 is a map displaying all the AEM-inferred aquifer materials in the first model layer, 0 to 10 ft with example areas where recharge is potentially good and potentially poor within SQS#2. There is heterogeneity in the aquifer materials but it is quite easy to identify the areas of aquifer materials that will transmit the most, and the least, amounts of water from the surface down to the groundwater system.

Figure 5-56 and Figure 5-57 are Google Earth images that display the potential recharge based only on the aquifer materials and coarse aquifer materials detected in the near surface in the SQS#1 and SQS#2 AEM survey areas. In these images lighter colors are aquifer materials and darker colors represent coarse aquifer materials.

Most of the SQS#1 and SQS#2 AEM survey areas are covered in low recharge material. However, the aquifer material below the first 10 feet needs to be capable of transmitting recharge water to a lower aquifer. Therefore, inspection of the materials lying below the first 10 feet is important to understand where recharge is effective. These data are included as kmz files in *Appendix_3_Deliverables\KMZ\Recharge.*

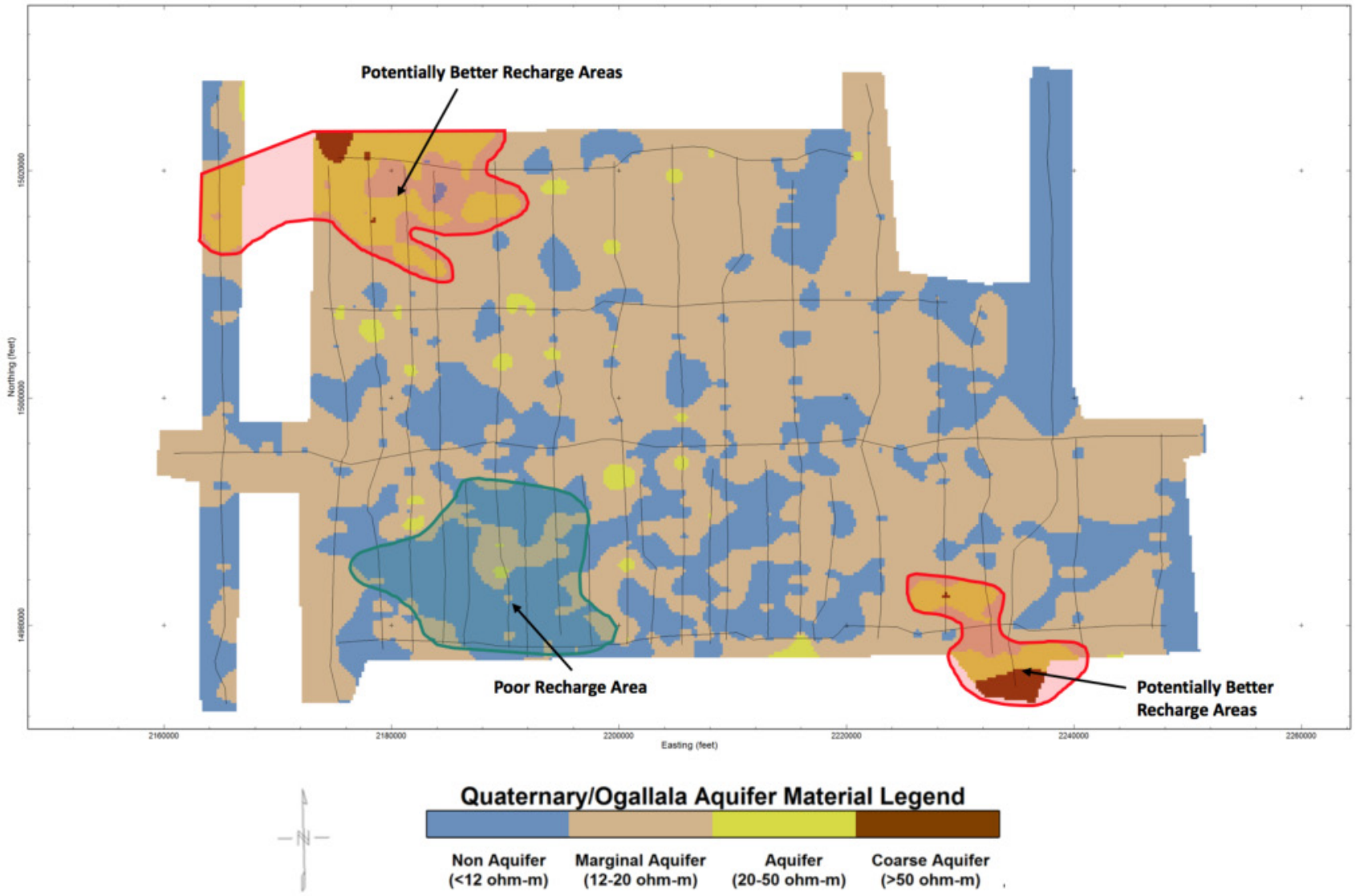


Figure 5-54. Map of all aquifer materials for the first 0 to 10 feet displayed over the LPNNRD SQS#1 AEM survey area. Projection is NAD83, UTM 14 North (feet).

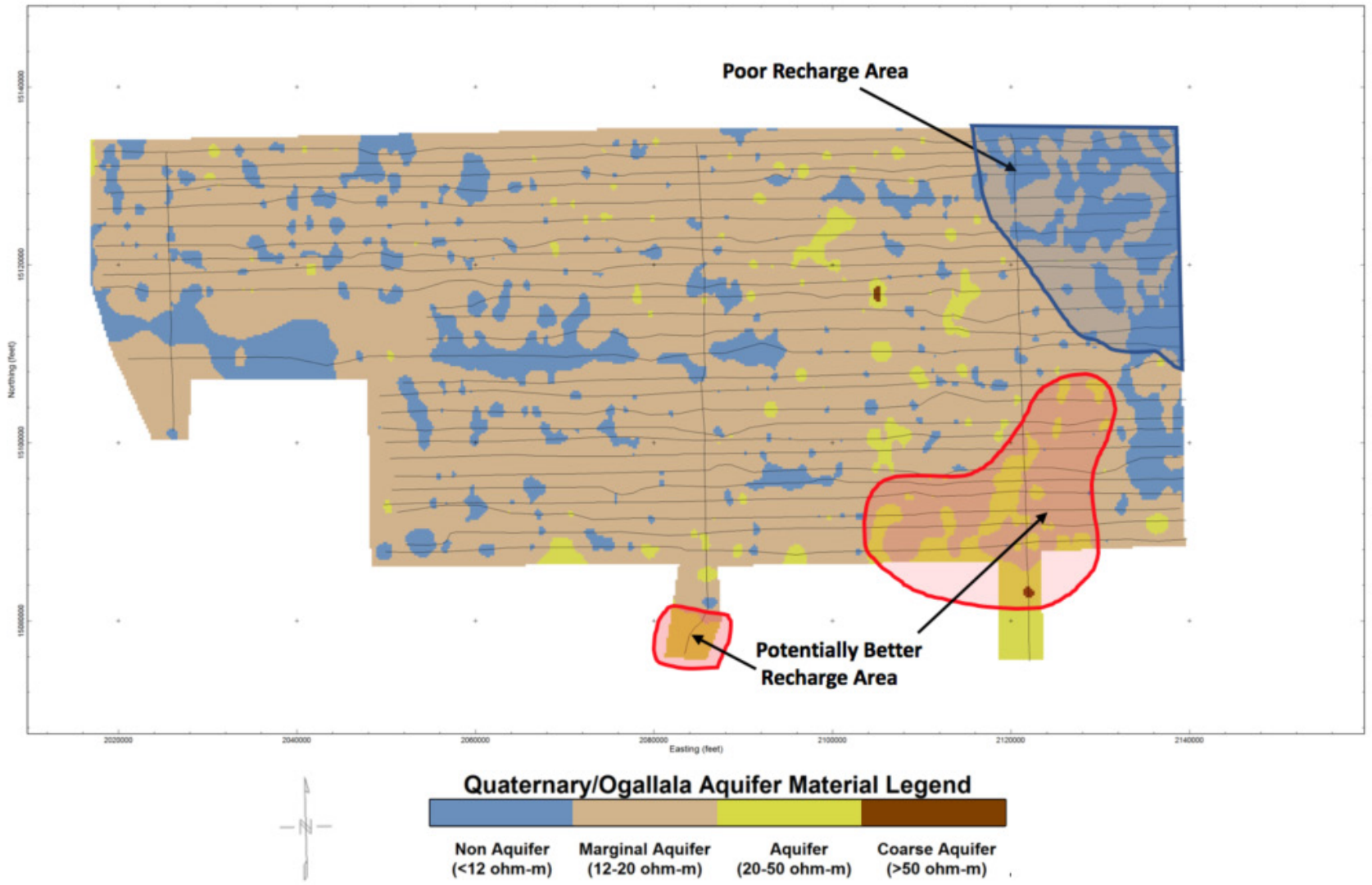


Figure 5-55. Map of all aquifer materials for the first 0 to 10 feet displayed over the LPNNRD SQS#2 AEM survey area. Projection is NAD83, UTM 14 North (feet).

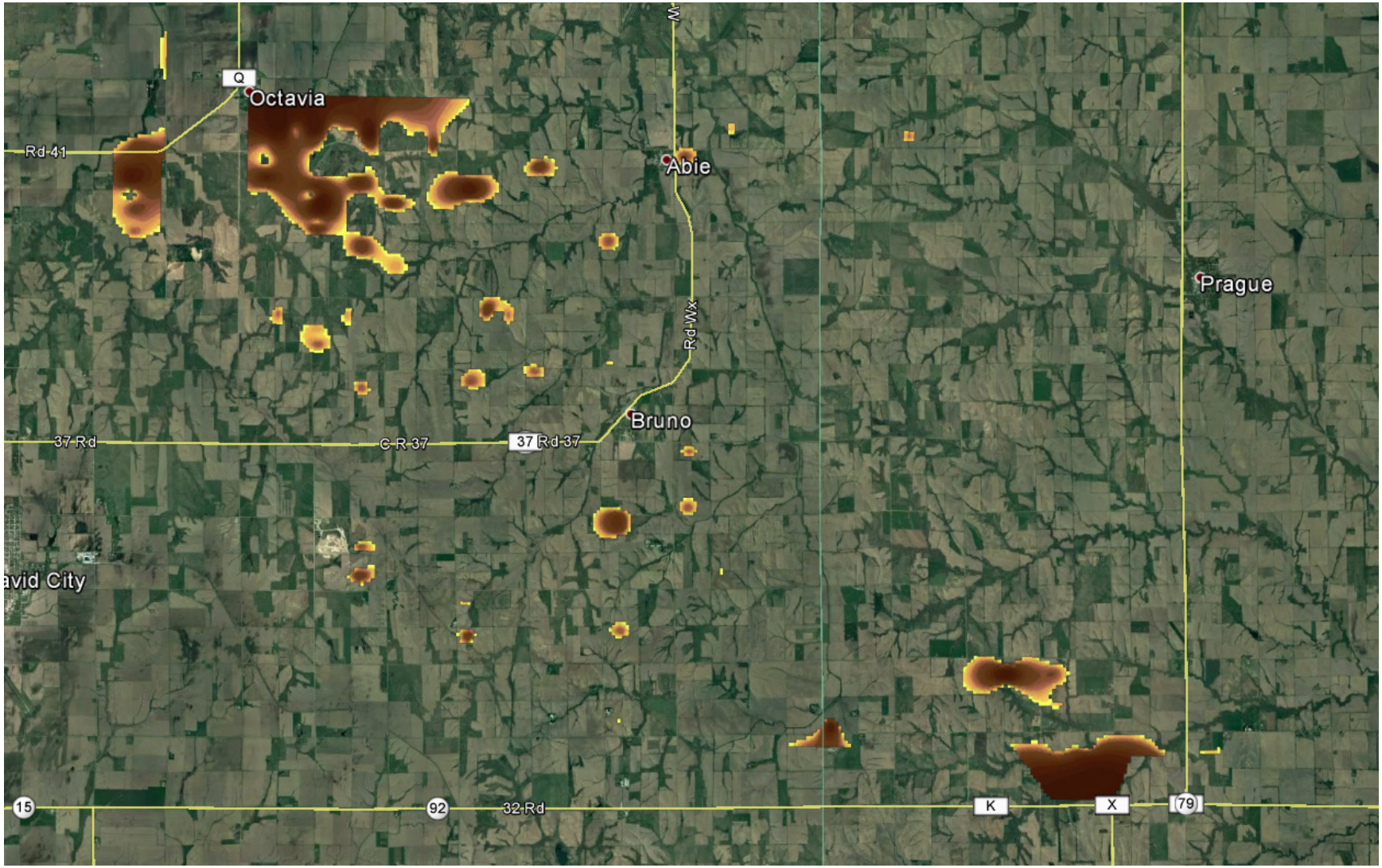


Figure 5-56. Potential aquifer and coarse material recharge zones within the LPNNRD SQS#1 AEM survey area displayed as a kmz in Google Earth. This kmz is included as a deliverable in Appendix_3_Deliverables\KMZ\Recharge.

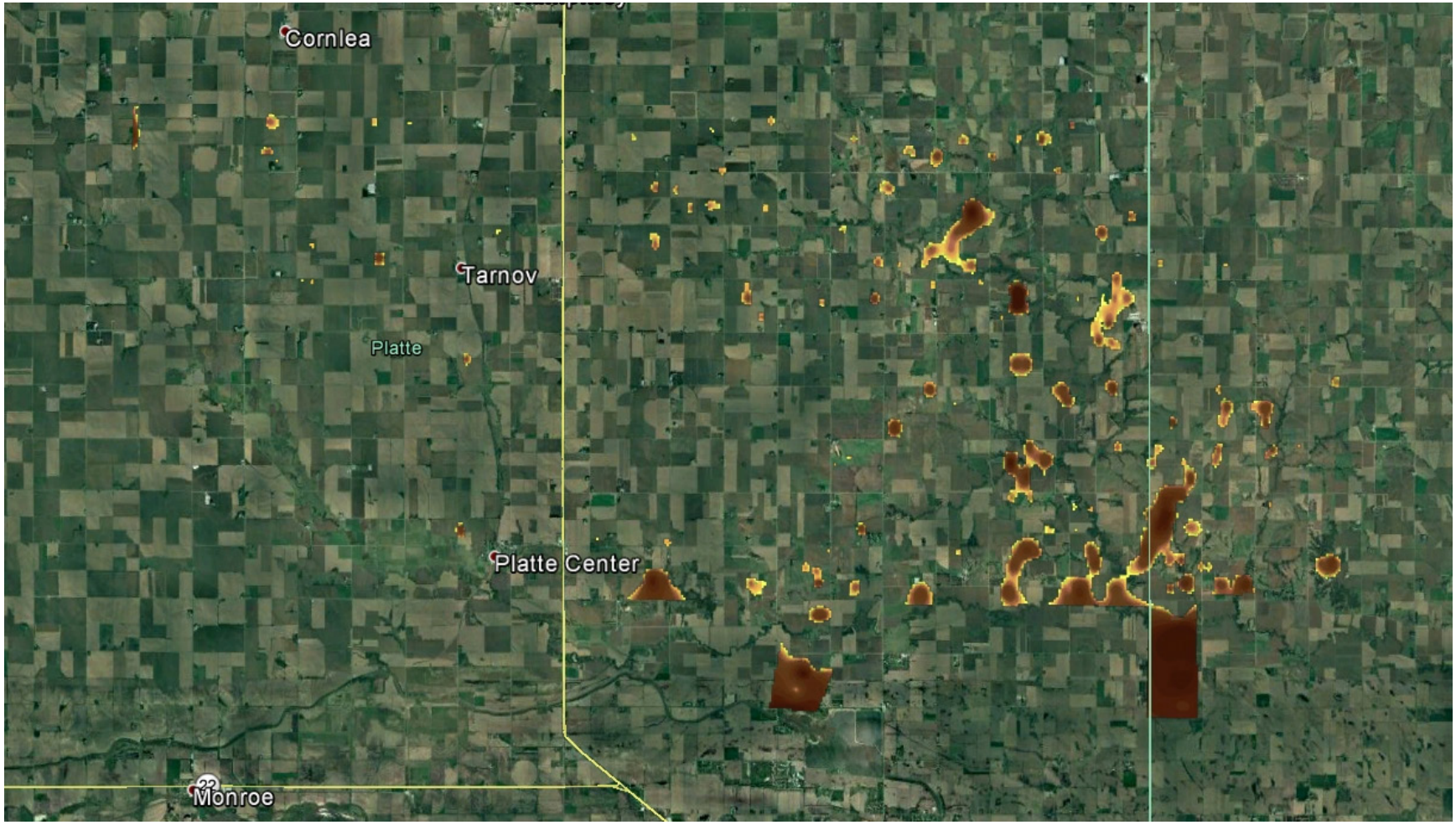


Figure 5-57. Potential aquifer and coarse material recharge zones within the LPNNRD SQS#2 AEM survey area displayed as a kmz in Google Earth. This kmz is included as a deliverable in Appendix_3_Deliverables\KMZ\Recharge.

5.6 Key AEM Findings

5.6.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results. Within SQS#1 survey area there were, 17 CSD holes contained lithology information, 16 holes contained stratigraphic information, and 4 holes contained geophysical information), NE-DNR (A total of 229 registered wells contained usable lithology information) and NOGCC had 5 holes with lithology and 2 with stratigraphy boreholes. Within SQS#2 survey area there were, 17 CSD holes contained lithology information, 9 holes contained stratigraphic information, and 4 holes contained geophysical information), NE-DNR (A total of 859 registered wells contained usable lithology information) and NOGCC had 1 hole with lithology and stratigraphy boreholes.

5.6.2 Merging 2014 and 2016 AEM Databases

The LPNNRD AEM survey analysis encompassed additional data from AEM surveys conducted in 2014 and 2015 by the ENWRA. The 2014 AEM data contains valuable information that can be utilized in the interpretation of the larger LPNNRD AEM survey area. The 2014 and 2015 AEM data were combined with the 2016 AEM data. This combination did not include reinverting the 2014 and 2015 data, but included merging the 2014 and 2015 inversions into the current database and reinterpretation.

5.6.3 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 Cretaceous Niobrara (***Kn***), Carlile (***Kc***), Greenhorn limestone and Graneros shale (***Kgg***), and Dakota (***Kd***). The interpretive process benefited from the use of CSD and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary aquifer material mapping are included in the appendices as well as interpretative surface grids.

5.6.4 Resistivity/Lithology Relationship

Assessment of the sediment character in both the Quaternary aquifer system and the consolidated bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A numerically robust assessment of the resistivity thresholds 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.

5.6.5 Hydrogeological Framework of the LPNNRD

The AEM reveals considerable variability in the Quaternary deposits across the LPNNRD. The subsurface distribution of materials can be generally characterized in two blocks. These areas include the Quaternary Aquifer Area and the Cretaceous bedrock aquiclude. The ***Q*** aquifer of the SQS#1 survey area is predominantly composed of Quaternary unconsolidated aquifer and a sparse amount of coarse aquifer materials composed of alluvial and glacial sediments. These

materials are sitting on varying thickness of ***Kgg*** and ***Kd*** which is the bedrock aquiclude for the SQS#1 survey area. The SQS#1 survey area is within the glacial till area of eastern Nebraska. The bedrock is eroded and has two channels cut into it. A channel trends from west to east along the southern edge of SQS#1 with a larger channel parallel in direction to the first channel approximately 5 miles south. The channels are flanked by three bedrock highs that are in the block area which have an increased relief of up to approximately 600 feet in elevation. The area is dominated by non-aquifer and marginal materials and water table mostly confined by the overlying glacial till. The thicker sequences of aquifer to coarse aquifer materials lie along the southern edge and northwest corner of the survey area.

The ***Q*** aquifer of the SQS#2 survey area is predominantly composed of Quaternary unconsolidated aquifer and a sparse amount of coarse aquifer materials composed of alluvial and glacial sediments. These materials are sitting on varying thickness of ***Kn, Kc,*** and ***Kgg*** which is the bedrock aquiclude for the SQS#2 survey area. The SQS#2 survey area is within the glacial till area. The bedrock is eroded and has one channel cut into it. A channel trends from west to east through the center of the survey area. The channels are flanked by two bedrock highs that are in the block area which have an increased relief of up to approximately 425 feet in elevation. The area is dominated by non-aquifer and marginal materials and water table mostly confined by the overlying glacial till. The thicker sequences of aquifer to coarse aquifer materials are mostly distributed throughout the survey area.

5.6.6 Estimation of Aquifer Volume and Water in Storage in the SQS#1 and SQS#2 AEM Survey Areas

Within the SQS#1 survey area non-aquifer material has an estimated volume of **3,932,293**acre-ft and contains **1,572,917** acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of **8,303,004** acre-ft and contains **2,906,051** acre-ft, aquifer material has an estimated volume of **3,466,989** acre-ft and contains an estimated volume of **693,397** acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of **3,845** acre-ft for a total of **961** acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is **5,173,326** acre-ft.

Within the SQS#2 survey area non-aquifer material has an estimated volume of **2,885,798** acre-ft and contains **1,154,319** acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of **8,674,691** acre-ft and contains **3,036,141** acre-ft, aquifer material has an estimated volume of **6,717,815** acre-ft and contains an estimated volume of **1,343,563** acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of **43,139** acre-ft for a total of **10,784** acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is **5,544,807** acre-ft.

5.6.7 Potential Recharge Zones within the SQS#1 and SQS#2 AEM Survey Areas

Within the SQS#1 and SQS#2 survey areas each AEM flight line was interpreted for aquifer material in the first model layer (0 – 10 ft). Areas of coarse aquifer material will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material potentially transmitting slightly less precipitation downward as both units are permeable. The marginal aquifer material has the lowest potential to transmit some water downward and the non-aquifer material will transmit minimal to no water to the groundwater aquifer. Most of the areas are covered in glacial till limiting the amount of recharge. The

recharge that does percolate through the first 10 feet needs find a path through any coarse aquifer and aquifer materials to reach the groundwater aquifers.

5.6.8 Relationship between Registered Wells, Discharge Estimates, and the AEM Results

There is a strong relationship between the distribution of the registered wells from the NEDNR database and the mapped saturated aquifers results from the AEM survey in both SQS#1 And SQS#2. The discharge rates match the aquifer configuration and aquifer materials description well. The highest discharge rates follow the channel along the southern border and the northwest corner of SQS#1 which have the most aquifer and coarse aquifer materials. The medium capacity wells are similarly located in the area. Low capacity wells tend to be in the center of the survey area where the aquifer material and coarse aquifer material are thin to non-existent.

Within SQS#2 the majority of the wells have a medium discharge rate due to most of the aquifer in the area being made up of aquifer material and little coarse aquifer material. The discharge rates match the aquifer configuration and aquifer materials description well. The highest discharge rates are in isolated areas across the survey area. The medium capacity wells are follow the channel in the center of the survey area. Low capacity wells tend to be scattered across the survey area where the aquifer material and coarse aquifer material are thin on non-existent.

5.6.9 Value of AEM Data Analysis and Images

One of the most important key findings from the LPNNRD AEM investigation is the value-added products resulting from AEM data derived images. There is a step-by-step process involved from flight planning to final images. While the text of the report may not go into detail on each and every data point or every image provided in the appendices, the value to the user is in the final data analysis and associated images. These final interpretive images allow development of science-based decisions for water management by illustrating the spatial relationships of aquifers. These images can help communication to the board and to the general public, the configuration of the aquifers and that those configurations can impact water quantity and quality.

5.7 Recommendations

Recommendations provided to the LPNNRD 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 LPNNRD about their management challenges.

5.7.1 Additional AEM Mapping

The aquifer maps provided in this report represent the detailed framework developed for the SQS#1 and SQS#2 AEM survey areas. The detail provided in the hydrogeological interpretation of SQS#1 and SQS#2 AEM survey areas allowed for the confident development of the hydrogeologic framework. The interpretations match well with the CSD and NE-DNR test holes. While no additional high resolution AEM information is needed within these survey areas to resolve questions of resource management, it is recommended that additional areas of closely spaced flight lines or "block flights" be collected to develop detailed frameworks in other identified areas of the LPNNRD. The LPNNRD plans to collect additional AEM data in up to four new areas (Figure 5-58) in the district identified in the current Water Sustainability Fund grant application submitted by ENWRA for 2017. This AEM survey will be done in cooperation with the other ENWRA NRDs to get details on the continuous aquifer system that is shared in the area. The line spacing for the block flights should be on the order of 0.25 miles (1,320 ft).

An example of the results from this future survey would be to provide detailed hydrogeologic frameworks similar to what is presented in this report which have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield (Section 5-4).

It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of the LPNNRD. This will supply the LPNNRD with information on groundwater flow, aquifer sustainability, and depletion to streams, well interference, groundwater withdrawal, and other management considerations. The LPNNRD's future work will focus on water quantity and the ongoing water quality work in the adjacent areas to determine if additional management is needed. It will also provide locations for new monitoring wells and water level locations.

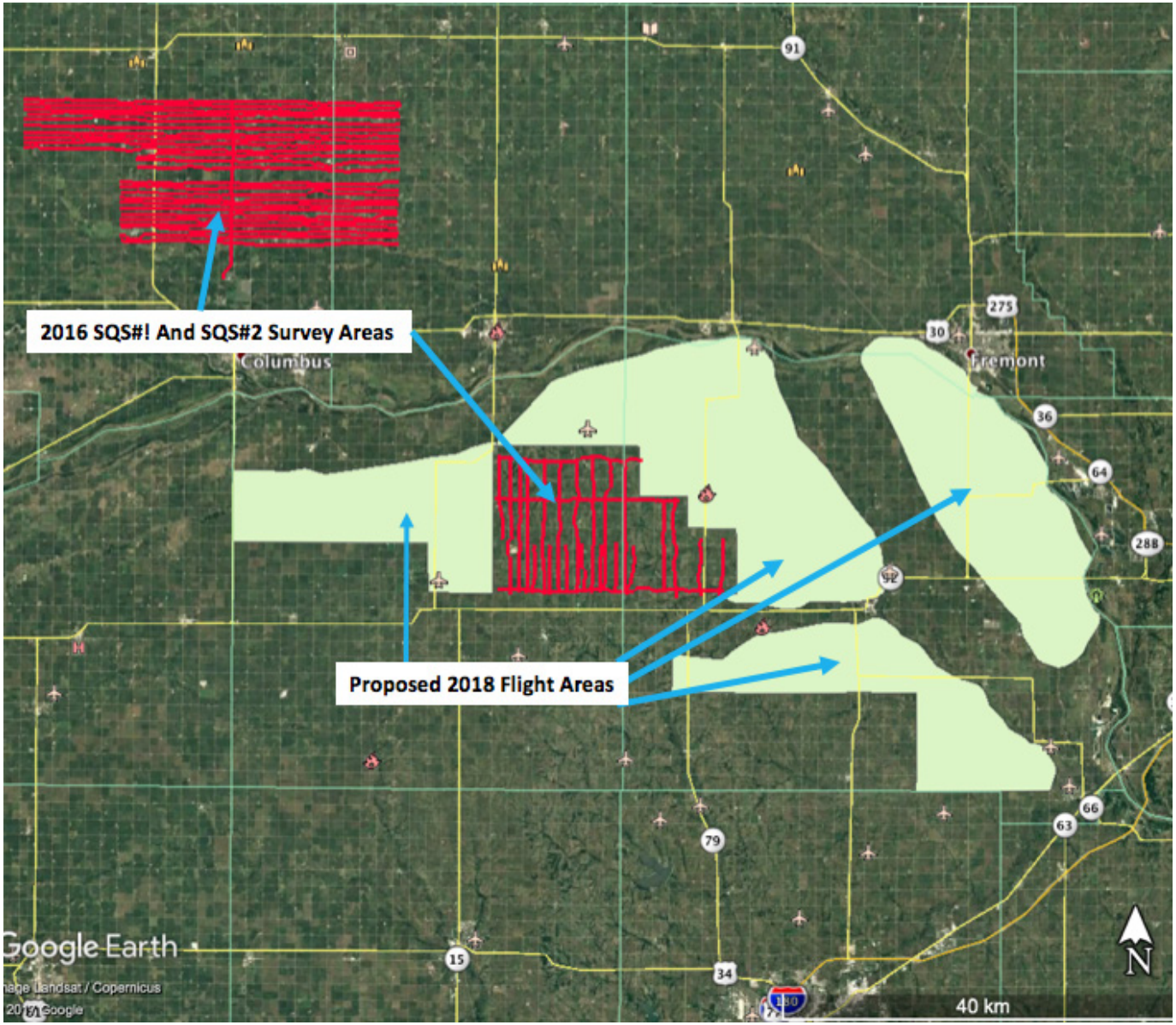


Figure 5-58. Acquired AEM flight lines in 2016 and proposed flight lines for 2018.

5.7.2 Update the Water Table map

The groundwater data used in the analyses presented in this report use the CSD 1995 water table map. Additional water level measurement locations would improve the water table map. This is especially true within the SQS water management areas. Additional work would be very useful in advance of new AEM surveys for the district. These water level measurements can be best accomplished doing a synoptic data gathering during the spring over a short time period. Detailed measurements of the transition from the northwest corner of SQS#2 to the rest of that survey area would be a good addition to the network.

5.7.3 Siting new test holes and production wells

The AEM framework maps and profiles provided in this report provide insight 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 LPNNRD area was used in building the framework maps and profiles. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in optimal locations. The wells could be sited based on the AEM maps to intercept known confined aquifers in areas of water use complaints to the district.

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 with the best aquifer characteristics, saturated thickness, and aquifer interconnection with the least potential for non-point source pollution.

5.7.4 Aquifer testing and borehole logging

Aquifer tests are recommended to improve estimates of aquifer characteristics. 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 tools for aquifer characteristics are highly recommended. The few test holes with geophysical logs in the LPNNRD AEM survey area were inadequate. None were calibrated and several had apparent hardware malfunctions. The borehole geophysical logs provided for this investigation demonstrate that additional calibrated and verified geophysical logs are required in the LPNNRD.

Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailed aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR). This is a quick and effective way to characterize porosity and water

content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth. This is very cost effective when compared to traditional aquifer tests.

5.7.5 Recharge Zones

The LPNNRD hydrogeologic framework in this report provides areas of potential recharge from the ground surface to the groundwater aquifer. These areas are limited, but understanding this complex relationship in other areas of the district is a beneficial activity that can be used for water sustainability estimates. The block flights of AEM data acquisition provide the most detailed information for understanding recharge throughout the LPNNRD. It is recommended that additional AEM data be collected and interpreted utilizing closely-spaced flight lines using an AEM system that has near-surface resolution. It is further recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention in order to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

5.7.6 Mapping Well Production Data

Produce maps of annual well production per year which can be used to make a comparison to the aquifers mapped using AEM. This would provide data to make an analysis of the available water supply and its use. It will also track well performance related to boundary conditions within the aquifer system. The district has implemented groundwater management in the District and an annual report on well production would give the Board and the public information on changes that are potentially needed for management particularly during periods of drought. This combined with the District water level program can provide improved knowledge on groundwater management.

6 Description of Data Delivered

6.1 Tables Describing Included Data Files

Table 6-1 describes the data columns in the ASCII *.xyz files LPNNRD_SQS#1_EM_MAG_v1.xyz and LPNNRD_SQS#2_EM_MAG_v1.xyz as well as the Geosoft database files LPNNRD_SQS#1_EM_MAG_v1.gdb and LPNNRD_SQS#2_EM_MAG_v1.gdb. These files contain the electromagnetic raw data, plus the magnetic and navigational data, as supplied directly from SkyTEM.

The result of the SCI is included in LPN_SQS1_AEM_SCI_INV_v2.gdb and LPN_SQS2_AEM_SCI_INV_v2.gdb files and LPN_SQS1_AEM_SCI_INV_v2.xyz and LPN_SQS2_AEM_SCI_INV_v2.xyz and the data columns of these databases are described in Table 6-2.

The borehole data used to constrain the SCI inversion and to assist in the interpretation of the inversion results for SQS#1 and SQS#2 are included in the files listed in Table 6-3. Each type of borehole information has both a collar file containing the location of each of the wells, and a second file containing the borehole data for the individual wells. The data column descriptions for the collar files are listed in Table 6-4. Table 6-5 describes the channels in all the borehole data files as well as indicates which type of data contains each channel.

The various interpretation results are included in data files LPNNRD_SQS1_InterpSurfaces_v1 and LPNNRD_SQS2_InterpSurfaces_v1 in gdb and ASCII xyz formats. Table 6-6 describes the data columns of those files.

Table 6-7 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, eight (8) flights were required to acquire the LPNNRD AEM data (SQS#1 - Figure 4-5 and SQS#2 - Figure 4-6). Grouped by flight date, there are four (4) data flies included in Appendix_3_Deliverables\Raw_Data for each flight. These files have extensions of “*.sps” and “*.skb”. The “*.sps” files include navigation and DGPS location data and the “*.skb” files include the raw AEM data that have been PFC-corrections (discussed in section 4.4.1). Two additional files are used for all the flights. These are the system description and specifications file (with the extension “*.gex”) in the GEO subdirectory and the ‘mask’ file (with the extension “*.lin”), in the MASK subdirectory, which correlates the flight dates, flight numbers, and assigned line numbers.

ESRI Arc View Binary Grids and equivalent Geosoft grids of the surfaces that were used in the interpretation (DEM, water table) and derived from the interpretation (top of geological units) of the AEM and borehole are listed in Table 6-8. And stored in Appendix 3_Deliverables\Grids.

Voxel grids were completed for each of the LPNNRD SQS#1 and SQS#2 AEM survey areas. The voxel grid was made using a 250 ft grid cell size and the model layer thickness (Table 4-4). The voxel grid was clipped below the bedrock surf ace interpreted from the AEM and the boreholes as detailed in Section 5.2.3. Table 6-9 is a list of the channel names in both ASCII *.xyz and Geosoft *.gdb format for the *SQS1_Voxel_Final and SQS2_Voxel_Final* *.csv and *.gdb files.

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and ASCII *.xyz
- SCI inversion Geosoft database and ASCII *.xyz
- Borehole Geosoft databases and ASCII *.xyz
- Interpretations Geosoft database and ASCII *.xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView and Geosoft grid files – surface, topo, etc
- 3D fence diagrams of the SQS#1 and SQS#2 AEM survey lines.
- 3D voxel models as ASCII *.xyz and *.gdb for the SQS#1 and SQS#2 AEM survey areas

KMZs for LPNNRD SQS#1 and SQS#2 AEM survey flight lines (Discussed in Section 6.2)

Profile Analyst sessions for the Profiles and 3D grids for the SQS#1 and SQS#2 AEM survey area analysis. (Discussed in Section 6.3)

Table 6-1: Channel name, description, and units for LPNNRD_SQS1_EM_MAG_v1 and LPNNRD_SQS2_EM_MAG_v1 Geosoft *.gdb and *.xyz with EM, magnetic, DGPS, Inclinometer, altitude, and associated data.

Parameter	Description	Unit
Fid	Unique Fiducial Number	
Line	Line Number	
Flight	Name of Flight	yyyymmdd.ff
DateTime	DateTime Format	Decimal days
Date	DateTime Format	yyyymmdd
Time	Time UTC	hhmmss.sss
AngleX	Angle (in flight direction)	Degrees
AngleY	Angle (perpendicular to flight direction)	Degrees
Height	Filtered Height Measurement	Meters [m]
Lon	Longitude, WGS84	Decimal Degrees
Lat	Latitude, WGS84	Decimal Degrees
E_m	Easting, NAD83 UTM Zone 14N	Meters [m]
N_m	Northing, NAD83 UTM Zone 14N	Meters [m]
DEM_m	Digital Elevation	Meters [m]
Alt	DGPS Altitude above sea level	Meters [m]
GDSpeed	Ground Speed	Kilometers/hour [km/h]
Curr_LM	Current, Low Moment	Amps [A]
Curr_HM	Current, High Moment	Amps [A]
LMZ_G01 [Gates 0-27]	Normalized (PFC-Corrected) Low Moment Z-RxCoil value	pV/(m^4*A)
HMZ_G01 [Gates 0-36]	Normalized (PFC-Corrected) High Moment Z-RxCoil value	pV/(m^4*A)
LMX_G01 [Gates 0-27]	Normalized (PFC-Corrected) Low Moment X-RxCoil value	pV/(m^4*A)
HMX_G01 [Gates 0-36]	Normalized (PFC-Corrected) High Moment X-RxCoil value	pV/(m^4*A)
_60Hz_IntenSity	Power Line Noise Intensity monitor	
Bmag_f	Raw Base Station Mag Data filtered	nanoTesla [nT]
Diurnal	Diurnal Mag Data	nanoTesla [nT]
MA1_orig	Raw Mag Data	nanoTesla [nT]
Mag_fil	Mag filtered	nanoTesla [nT]
Mag_CD	Mag Data Corrected for Diurnal Drift	nanoTesla [nT]
RMF	Residual Magnetic Field	nanoTesla [nT]
IGRF	International Geomagnetic Reference Field	nanoTesla [nT]
X_ft	Easting, NAD83 UTM Zone 14N	Feet [ft]
Y_ft	Northing, NAD83 UTM Zone 14N	Feet [ft]
Z_ft	Elevation, 100 ft grid of NED DEM NAVD88	Feet [ft]

Table 6-2: Channel name, description, and units for LPN_SQS1_AEM_SCI_Inv_v2 and SPN_SQS2_AEM_SCI_INV_v2 Geosoft gdb and xyz files with EM inversion results.

Parameter	Description	Unit
LINE	Line Number	Feet [ft]
X_FT	Easting NAD83, UTM Zone 14	Feet [ft]
Y_FT	Northing NAD83, UTM Zone 14	Feet [ft]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
X_M	Easting NAD83, UTM Zone 14	Meters [m]
Y_M	Northing NAD83, UTM Zone 14	Meters [m]
DEM_M	DEM from survey	Meters [m]
FID	Unique Fiducial Number	
TIME	Date Time Format	Decimal days
ALT_M	Altitude of system above ground	Meters [m]
INVALT	Inverted Altitude of system above ground	Meters [m]
INVALTSTD	Inverted Altitude Standard Deviation of system above ground	Meters [m]
DELTAALT	Change in Altitude of system above ground	Meters [m]
RESDATA	Residual of individual sounding	
RESTOTAL	Total residual for inverted section	
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]
RHO_I_0 THROUGH RHO_I_28	Inverted resistivity of each later	Ohm-m
RHO_STD_0 THROUGH RHO_STD_28	Inverted resistivity standard deviation	
SIGMA_I_0 THROUGH SIGMA_I_28	Conductivity	S/m
DEP_TOP_0_FT THROUGH DEP_TOP_28_FT	Depth to the top of individual layers	Feet [ft]
DEP_BOT_0_FT THROUGH DEP_BOT_28_FT	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT THROUGH THK_28_FT	Thickness of individual layers	Feet [ft]
DEP_TOP_0_M THROUGH DEP_TOP_28_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_M THROUGH DEP_BOT_28_M	Depth to the bottom of individual layers	Meters [m]
THK_0_M THROUGH THK_28_M	Thickness of individual layers	Meters [m]

Table 6-3: Files containing borehole information for SQS#1 and SQS#2

Database (*.xyz, *.gdb)	Description
LPN_SQS[1,2]_CSD_Elog_Collar	Geophysical ELogs from CSD registered wells within the LPNNRD SQS#1 and SQS#2 AEM survey area
LPN_SQS[1,2]_CSD_Elog_Data	
LPN_SQS[1,2]_CSD_Geolog_Collar	Recent geophysical logs from CSD registered wells within the LPNNRD SQS#1 and SQS#2 AEM survey area
LPN_SQS[1,2]_CSD_Geolog_Data	
LPN_SQS[1,2]_CSD_Lith_Collar	Lithology logs from CSD registered wells within the LPNNRD SQS#1 and SQS#2 AEM survey area
LPN_SQS[1,2]_CSD_Lith_Data	
LPN_SQS[1,2]_CSD_Strat_Collar	Stratigraphic logs from CSD registered wells within the LPNNRD SQS#1 and SQS#2 AEM survey area
LPN_SQS[1,2]_CSD_Strat_Data	
LPN_SQS[1,2]_DNR_Lith_Collar	Lithology logs from NE-DNR registered wells within the LPNNRD SQS#1 and SQS#2 AEM survey area
LPN_SQS[1,2]_DNR_Lith_Data	
LPN_SQS[1,2]_OG_Lith_Collar	Lithology data from wells from the Nebraska Oil and Gas Conservation Commission within the LPNNRD SQS#1 and SQS#2 AEM survey area
LPN_SQS[1,2]_OG_Lith_Data	
LPN_SQS[1,2]_OG_Strat_Collar	Stratigraphy data from wells from the Nebraska Oil and Gas Conservation Commission within the LPNNRD SQS#1 and SQS#2 AEM survey area
LPN_SQS[1,2]_OG_Strat_Data	

Table 6-4: Channel name, description, and units for collar files.

Parameter	Description	Unit
DH_Hole	Name of individual boreholes	
DH_East	Easting of boreholes, NAD83, UTM Zone 14	Feet [ft]
DH_North	Northing of boreholes, NAD83, UTM Zone 14	Feet [ft]
DH_RL	Elevation of top of borehole	Feet [ft]
DH_Dip	Dip of borehole	Degrees
DH_Azimuth	Azimuth of borehole	Degrees
DH_Top	Depth to top of borehole	Feet [ft]
DH_Bottom	Depth to bottom of borehole	Feet [ft]
DH_ZMin	Minimum elevation in borehole	Feet [ft]
DH_ZMax	Maximum elevation in borehole	Feet [ft]

Table 6-5: Channel name description and units for borehole data.

Parameter	Description	Unit	Type of Log
DH_East	Easting of boreholes, NAD83, UTM Zone 14	Feet [ft]	All
DH_North	Northing of boreholes, NAD83, UTM Zone 14	Feet [ft]	All
DH_RL	Elevation of top of borehole	Feet [ft]	All
DH_From	End of interval	Feet[ft]	Strat, Lith
DH_To	Start of interval	Feet [ft]	Strat, Lith
DH_Strat_Code	Code used to indicate type of stratigraphy		Strat
DH_Soil_Code	Code used to indicate type of lithology		Lith
DH_Lith_Number	1 of 30 numbers assigned to reference lithology		
Lithcode	Lithology description associated with 30 categories		
StratCode	Formation designation (e.g. "***Q***", "***Kd***")		
DH_Description/DH_Des	Description of stratigraphy or lithology		Strat, Lith
DH_Depth	Depth	Feet [ft]	GP
DH_SP	Self Potential	milliVolt [mV]	GP, E, Geo
DH_SN	Short Normal Resistivity	Ohm-m	GP
DH_SFL	Spherically Focus Log	Ohm-m]	GP
DH_ILD	Induction Log Deep	Siemens/m [S/m]	GP
DH_ILM	Induction Log Medium	Siemens/m [S/m]	GP
DH_LAT	Laterolog	Ohm-m	GP
DH_Res	Resistivity	Ohm-m	Constrain, E
DH_Nat_Gam	Natural Gamma	Counts	Geo
DH_Res_SnglPt	Resistivity Single Point	Ohm-m	Geo
DH_Res_16	Resistivity 16in	Ohm-m	Geo
DH_Res_64	Resistivity 64in	Ohm-m	Geo
DH_Res_Lat	Res Laterolog	Ohm-m	Geo
DH_SP_Cond	Self Potential Induction	milliVolt [mV]	Geo
DH_Res_FL	Resistivity of the fluid	Ohm-m	Geo
DH_Tmp_FL	Temperature of the fluid	Degrees F	Geo
DH_Del_Tmp	Change in temperature of the fluid	Degrees F	Geo

Table 6-6: Channel name description and units for the interpretation results file LPNNRD_SQS1_InterpSurfaces_v1 and LPNNRD_SQS2_InterpSurfaces_v1 "gdb" and "xyz" files.

Parameter	Description	Unit
East_ft	Easting NAD83, UTM Zone 14	Feet [ft]
North_ft	Northing NAD83, UTM Zone 14	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
RHO[0] through RHO[28]	Array of Inverted model resistivities of each later	Ohm-m
RESDATA	Inversion model residuals of each individual sounding	
DEP_TOP[0] through DEP_TOP[28]	Depth to the top of individual layers	Feet [ft]
DEP_BOT[0] through DEP_BOT[28]	Depth to the bottom of individual layers	Feet [ft]
DOI_UPPER	More conservative estimate of DOI from Workbench	Feet [ft]
DOI_LOWER	Less conservative estimate of DOI from Workbench	Feet [ft]
WaterTable_2016	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
AquiferTyp[0] through AquiferTyp[28]	Array of Aquifer Material types: 0 - Bedrock; 1 - Non-Aquifer Material; 2 - Marginal Aquifer Material; 3 - Aquifer Material; 4 - Coarse Aquifer Material	Integer Array
Top_AqMat1	Elevation of top of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Bot_AqMat1	Elevation of bottom of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Top_AqMat2	Elevation of top of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Bot_AqMat2	Elevation of bottom of lower Aquifer Material (20 - 50 ohm-m), if present	Feet [ft]
Top_Coarse_AqMat	Elevation of top of Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bot_Coarse_AqMat	Elevation of bottom of Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bedrock	Elevation of interpreted bedrock surface	Feet [ft]
Kn	Elevation of the top of the Cretaceous Niobrara Formation.	Feet [ft]
Kc	Elevation of the top of the Cretaceous Carlile Shale.	Feet [ft]
Kgg	Elevation of the top of the Cretaceous Greenhorn-Graneros Shale	Feet [ft]
Kd	Elevation of the top of the Cretaceous Dakota Formation.	Feet [ft]

Table 6-7: 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	20160815_337m2_Cal_DualWaveform_60Hz.gex	304M System Description
Mask	LPNNRD_Linefile.lin	Production file listing dates, flights, and assigned line numbers

Table 6-8. Files containing ESRI ArcView Binary Grids *.flt and Geosoft Grids *.grd (NAD 83 UTM 14 North, feet)

Grid File Name	Description	Grid Cell Size (feet)
SQS1_1995WT_elevation SQS2_1995WT_elevation	Grids of the 1995 water table elevation; (feet) in the LPNNRD SQS1 and SQS2 AEM survey area.	250
SQS1_Bedrock_elevation SQS2_Bedrock_final	Grids of the top of the Bedrock composed of either ***Kc*** or ***Kd*** and ***Kgg***; NAVD88 (feet) LPNNRD Survey Area	250
SQS1_DEM SQS2_DEM	Grids of the Digital Elevation Models (DEM) downloaded from the National Elevation Dataset (NED) August 2016 NAVD88 (feet)	100
SQS2_Kn_elevation	Grid of the top of the ***Kn*** elevation NAVD88 (feet) LPNNRD SQS2 AEM survey area	250
SQS2_Kc_elevation	Grid of the top of the ***Kc*** elevation NAVD88 (feet) LPNNRD SQS2 AEM survey area	250
SQS1_Kgg_elevation SQS2_Kgg_elevation	Grids of the top of the ***Kgg*** elevation (NAVD88 feet) LPNNRD SQS1 and SQS2 survey areas	250
SQS1_Kd_elevation	Grid of the top of the ***Kd*** elevation NAVD88 (feet) in the LPNNRD SQS1 AEM survey area	500
SQS1_layer1 SQS2_layer1	Grids of the top layer of the AEM model 0-10 feet in depth resistivity (ohm-m)	100
SQS1_Q_AquiferMaterial_Saturatedthickness SQS2_Q_AquiferMaterial_Saturatedthickness	Grids of the thickness of the saturated Quaternary Aquifer Material within the LPNNRD SQS1 and SQS2 AEM survey areas (feet)	100
SQS1_Q_Saturatedthickness SQS2_Q_Saturatedthickness	Grids of the thickness of the saturated Quaternary material; (feet)	100
SQS1_Q_thickness SQS2_Q_thickness.	Grids of the thickness of the Quaternary material within the LPNNRD SQS1 and SQS2 AEM survey areas (feet)	100

Table 6-9. Channel name, description, and units for LPNNRD SQS#1 and SQS#2 AEM survey areas as*.csv and *.gdb.

Parameter	Description	Unit
X	Easting NAD83, UTM Zone 14	Feet [ft]
Y	Northing NAD83, UTM Zone 14	Feet [ft]
Z	Elevation of Voxel Node	
Resistivity	Voxel cell resistivity value	Ohm-m
Elevation	Ground Surface Elevation NAVD 88 100 ft grid	Feet [ft]

6.2 Description of Included Google Earth KMZ Data and Profiles

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

KMZ files of the potential recharge zones in the SQS#1 and SQS#2 areas are included in the folder "*Appendix_3_Deliverables\KMZ\LPNNRD_Recharge*"

Unique KMZ files were created for each individual flight line in 10-mile segments or shorter. Within these specialized KMZ files, the AEM flight line is shown as well as place marks at each location where there are interpreted geologic results. The attribute data for each unique place mark contains location information plus the elevations of tops and bottoms of aquifer material and coarse aquifer material as well as bedrock, the water table (1995), and the elevations of the tops of the Cretaceous Carlile, Greenhorn and Graneros, and Dakota formations. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\LPNNRD_Prof* folder. Also in this folder are "*GoogleE_Readme_SQS1.pdf*" and "*GoogleE_Readme_SQS2.pdf*" files that provide instructions in regards to the "*Settings*" changes that need to be made in Google Earth, and how to use the KMZ files in Google Earth including a legend of what attributes are displayed when an AEM sounding location is clicked. One of these files is repeated below as a convenience. An example of the SQS#1 KMZ is presented in Figure 6-1 and for the SQS#2 area in Figure 6-2.

6.2.1 Included README for the LPNNRD Interpretation KMZ's

README for:

LPNNRD_SQS1_Interpretation_v1.kmz

Data Files - Please copy the folder *LPNNRD_Prof* to your C:\ drive. Do not rename any of the files or directories 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 *LPNNRD_SQS1_Interpretation_v1.kmz* file within the folder named *LPNNRD_Prof* 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, UTM 14N, in feet

North (ft) – Northing coordinate in NAD83, UTM 14N, in feet

Elevation (ft) – DEM elevation in feet

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

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

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

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

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

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

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

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

(In SQS#2 Only) Elevation Kn (ft) – Elevation of Cretaceous Niobrara Fm, in feet

(In SQS#2 Only) Elevation Kc (ft) – Elevation of Cretaceous Carlile Fm, in feet

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

(In SQS#1 Only) Elevation Kd (ft) – Elevation of Top of Cretaceous Dakota Group, in feet

Profile – Link to Interpreted AEM profile images

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

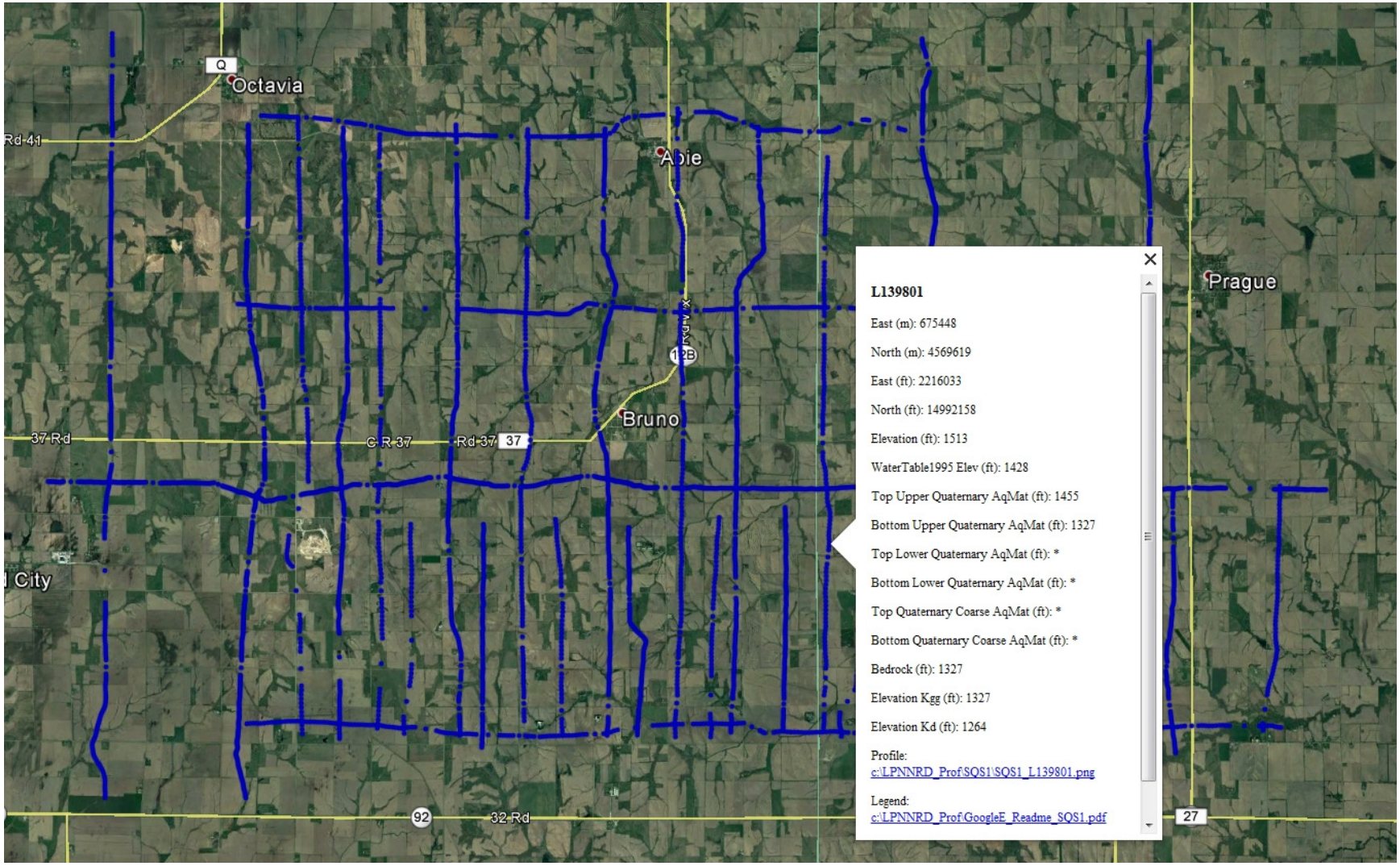


Figure 6-1. Example Google Earth image for the LPNNRD SQS#1 Interpretation kmz.

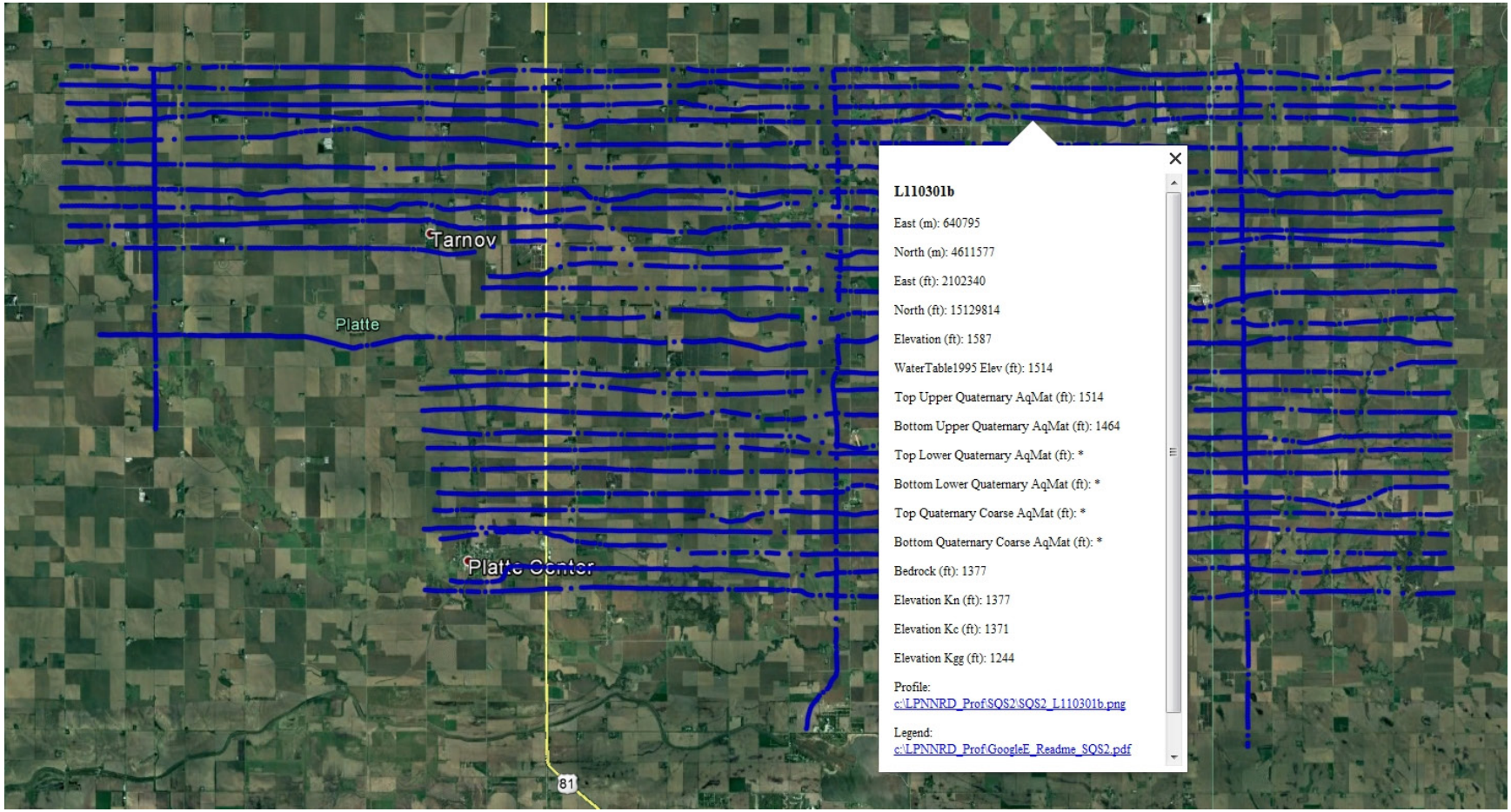


Figure 6-2. Example Google Earth image for the LPNNRD SQS#2 Interpretation kmz.

6.3 Description of Included Profile Analyst (PA) Session Material

As discussed above Datamine Discover PA Version 2015 Release Build 15.0.13 (dataminediscover, 2017) was used to create the 3D volumes and the profiles used in the interpretation within this report. In order to allow the future use of the information imported into the PA platform, PA Session Package files were created and are included within this report. A free viewer is available from the Datamine Discover PA website: http://support.dataminesoftware.com/software-downloads/

The files located in the Appendix_3_Deliverables\PA_Sessions need to be unzipped and copied to a directory and then the Session file needs to be opened within Discover PA. Details on the function of Discover PA can be accessed from the pbEncom website and the help functions within Discover PA. The session files that are included with the project deliverables are summarized in Table 6-10.

Table 6-10. Datamine Discover (formerly pbEncom Discover) PA Session Files

Area Covered	View Format	File name
SQS1 2D Profiles	**2D**	**PA_package_SQS1_profiles**
SQS1 3D Voxel Images, Fence Diagrams	**3D**	**SQS1_voxel_PA_Packed**
SQS2 2D Profiles	**2D**	**PA_package_SQS2_profiles**
SQS2 3D Voxel Images, Fence Diagrams	**3D**	**SQS2_voxel_PA_Packed**

7 References

Abraham, J. D., Bedrosian, P.A., Asch, T.H., Ball, L.B., Cannia, J. C., Phillips, J.D., and S. Olafsen-Lackey. 2011. Evaluation of Geophysical Techniques for the Detection of Paleochannels in the Oakland Area of Eastern Nebraska as Part of the Eastern Nebraska Water Resource Assessment. U.S. Geological Survey Scientific Investigations Report 2011-5228. https://pubs.usgs.gov/sir/2011/5228/ (accessed on January 9, 2017).

Abraham, J. D., Carney, C.P., and J. C. Cannia. 2013. Data Report on Mapping the Hydrogeology of the Clarkson Area within the Lower Elkhorn Natural Resources District Using an Airborne Electromagnetic Survey. Project findings report prepared for the Lower Elkhorn Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.lenrd.org/latest-news/2014/5/15/report-on-airborne-electromagnetic-aem-survey-in-the-clarkso.html (accessed on January 9, 2017).

Abraham, J.D., Cannia, J.C., Cameron, K., and Asch T.H. 2015. Watershed scale characterization of glacial and bedrock aquifers in eastern Nebraska, NovCare 2015, Lawrence, KS, May 19-21.

AGF, 2017a, Mapping the Hydrogeology of the Bazile Groundwater Management Area with Airborne Electromagnetics Surveys, Prepared for Bazile Groundwater Management Area Project (Lewis and Clark Natural Resources District, Lower Elkhorn Natural Resources District, Lower Niobrara Natural Resources District, and Upper Elkhorn Natural Resources District): by Aqua Geo Frameworks, LLC, Mitchell, Nebraska.

AGF, 2017b, Hydrogeologic Framework of Selected Area in Sarpy County, Nebraska, Prepared for the Papio-Missouri River Natural Resources District: by Aqua Geo Frameworks, LLC, Mitchell, Nebraska.

AGF, 2017c, Hydrogeologic Framework of Selected Areas in Lower Loup Natural Resources District, Nebraska, Prepared for the Lower Loup Natural Resources District: by Aqua Geo Frameworks, LLC, Mitchell, Nebraska.

AGF, 2017d, Hydrogeologic Framework of Selected Area in Lewis & Clark Natural Resources District, Nebraska, Prepared for the Lewis & Clark Natural Resources District: by Aqua Geo Frameworks, LLC, Mitchell, Nebraska.

AGF, 2017e, Hydrogeologic Framework of Selected Areas in Lower Elkhorn Natural Resources District, Prepared for the Lower Elkhorn Natural Resources District: by Aqua Geo Frameworks, LLC, Mitchell, Nebraska.

Asch, T.H., Abraham, J.D., and Irons, T., 2015, "A discussion on depth of investigation in geophysics and AEM inversion results", Presented at the Society of Exploration Geophysicists Annual Meeting, New Orleans.

Burchett, R. R., 1986, Bedrock geology of Nebraska. University of Nebraska-Lincoln, School of Natural Resources.

Carney, C.P, Abraham, J.D., and Cannia, J.C. 2014a. Data report on mapping the hydrogeology near the City of Madison, Nebraska using an airborne electromagnetic survey: Prepared for the City of Madison by Exploration Resources International Geophysics LLC, Vicksburg, MS.

Carney, C. P., Pierce, K.S., Abraham, J.D., Steele, G.V., Genco, A.G., and Cannia, J.C., 2014b, "Hydrogeologic Assessment and Framework Development of the Aquifers beneath the Brainard-Valparaiso Area of the Lower Platte South Natural Resources District in Eastern Nebraska." Prepared for the Lower Platte South Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.lpsnrd.org/Programs/gwaem.htm (accessed on January 9, 2017).

Carney, C.P., Abraham, J.D., Cannia, J.C., and Steele, G.V., 2015a, Final Report on Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for the Eastern Nebraska Water Resources Assessment – Volume I, including the Lewis and Clark, Lower Elkhorn, and Papio-Missouri River Natural Resources Districts: Prepared for the Eastern Nebraska Water Resources Assessment (ENWRA) by Exploration Resources International Geophysics LLC, Vicksburg, MS., http://www.enwra.org/aem%20data%20download.html (accessed on January 9, 2017).

Carney, C.P., Abraham, J.D., Cannia, J.C., and Steele, G.V. 2015b. Final Report on Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for the Eastern Nebraska Water Resources Assessment – Volume II, including the Lower Platte North, Lower Platte South, and Nemaha Natural Resources Districts: Prepared for the Eastern Nebraska Water Resources Assessment (ENWRA) by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.enwra.org/aem%20data%20download.html (accessed on January 9, 2017).

Christensen, N. B., J. E. Reid, and M. Halkjaer, 2009, "Fast, laterally smooth inversion of airborne time-domain elecromagnetic data." *Near Surface Geophysics* 599-612.

Christiansen, A. V., and E. Auken, 2012, "A global measure for depth of investigation." *Geophysics,Vol. 77, No. 4* WB171-177.

Condra, G. E., and Reed, C. E., 1959. The geological section of Nebraska with current revisions by C.E. Reed: Nebraska Geological Survey Bulletin, University of Nebraska-Lincoln, Conservation and Survey Division.

dataminediscover, 2017, Datamine Discover Profile Analyst, available on the world-wide web at: https://www.dataminediscover.com/discover.

Divine, D. P., 2012, Geologic cross section across eastern Nebraska from Pierce County to Dakota County, Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Correlations and Cross Sections, Issue 18.2.

Divine, D. P. and J. T. Korus, 2012, Eastern Water Resources Assessment. Three-dimensional Hydrostratigraphy of the Sprague Nebraska Area: Results from Helicopter Electromagnetic (HEM) Mapping in the Eastern Nebraska Water Resources Assessment (ENWRA), Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, http://www.enwra.org/media/2012ENWRA_Sprague_final.pdf (accessed Jan 8, 2015).

Divine, D.P. and Korus, J.T., 2013, Three-dimensional hydrostratigraphy of the Swedeburg, Nebraska Area: Results from Helicopter Electromagnetic (HEM) Mapping for the Eastern Nebraska Water Resources Assessment (ENWRA) Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Conservation

Bulletin (New Series), Link to PDF file: http://enwra.org/media/2013SwedeburgFINAL.pdf (accessed January 9, 2017)

Exploration Resources International (XRI), 2015, Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for Selected Sites in the Lower Elkhorn Natural Resources District. Project findings report prepared for the Lower Elkhorn Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.enwra.org/LENRD2014AEMDataDownload.html (accessed January 9, 2017)

Flowerday, C. A., R. D. Kuzelka, and D. T. Pederson, 1998, The groundwater atlas of Nebraska. Resorce Atlas No. 4A, Lincoln, Nebraska: Conservation and Survey Division, School of Natural Resoirces, Institute of Agriculture and Natural Resoruces, University of Nebraska-Lincoln.

Foged, Nikolaj, Esben Auken, Anders Vest Christiansen, and Kurt Ingvard Sorensen, 2013, "Test-site calibration and validation of airborne and ground based TEM systems." *Geophysics* 78, No.2: E95-E106.

Freeze, R.A. and J.A. Cherry, 1979, "Groundwater": Published by Prentice Hall, New Jersey, ISBN 0-13-365312-9.

Gates, J. B., G. V. Steele, P. Nasta, and J. Szilagyi, 2014, "Lithologic influenes on groundwater recharge through incised glacial till from profile to regional scales: Evidence from glaciated Eastern Nebraska." Water Resources 50, 466-481.

Gutentag, E. D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B. 1984. Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B.

Hanson, P. R., Korus, J.T., and D. P. Divine. 2012. Three-dimensional hydrostratigraphy of the Platte River Valley near Ashland, Nebraska: Results from helicopter electromagnetic mapping in the Eastern Nebraska Water Resources Assessment. Bulletin 2, Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and National Resources, University of Nebraska-Lincoln. Link to PDF file: http://enwra.org/media/Ashland_ENWRA_Bull_2_2012_small.pdf (accessed January 9, 2017).

Heath, R.C., 1983. Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220, 86p, http://pubs.er.usgs.gov/publication/wsp2220 (accessed Jan 8, 2017)

HydroGeophysics Group, Aarhus University, 2010, "Validation of the SkyTEM system at the extended TEM test site." Aarhus, Denmark.

HydroGeophysics Group, Aarhus University, 2011, "Guide for processing and inversion of SkyTEM data in Aarhus Workbench, Version 2.0."

Korus, J.T., and R. M. Joeckel. 2011. Generalized geologic and hydrostratigraphic framework of Nebraska 2011, version 2. Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Korus, J.T., 2012, Geologic cross section across eastern Nebraska from Thurston County to Pawnee County. Conservation and Survey Division, School of Natural Resources Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Korus, J. T., Divine, D. P., Hanson, P.R., and J. S. Dillon, 2012, Three geologic cross sections across portions of eastern Nebraska showing Quaternary lithologic units and stratigraphy of uppermost

bedrock. Correlations and Cross Sections, Conservation and Survey Division School of Natural Resources, University of Nebraska-Lincoln.

Korus, J.T., Joeckel, R.M. and Divine, D.P. 2013. Three-dimensional hydrostratigraphy of the Firth, Nebraska Area: Results from Helicopter Electromagnetic (HEM) mapping in the Eastern Nebraska Water Resources Assessment (ENWRA). Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Conservation Bulletin 3 (New Series).

Korus, J. T., Joeckel, R. M., Divine, D. P. and Abraham, J. D. 2016. Three-dimensional architecture and hydrostratigraphy of cross-cutting buried valleys using airborne electromagnetics, glaciated Central Lowlands, Nebraska, USA. Sedimentology. doi:10.1111/sed.12314

Ley-Cooper, Y. and Davis, A., 2010. Can a borehole conductivity log discredit a whole AEM survey?: *in* Extended abstracts of the Australian Society of Exploration Geophysicists Annual meeting Aug 20-24, Sydney, Australia.

Loerch, C., Hammond, C. L., Bartlett, P., Young, P., Newton, K. and Zuccolo, R., 1988. Soil Survey of Platte County, Nebraska. Natural Resources and Conservation Service, U.S. Department of Agriculture.

Lower Platte North Natural Resources District, 2017, Groundwater Management, http://www.lpnnrd.org/projects/water/gwma.html.

Miller, J. A., and C. L. Appel, 1997, Ground water atlas of the United States; Segment 3 Kansas, Missouri, and Nebraska. Hydraulic Atlas 730D, U.S. Geological Survey. https://pubs.er.usgs.gov/publication/ha730D (accessed January 9, 2017). .

Nebraska Conservation and Survey Division, University of Nebraska-Lincoln, 1951, Topographic Regions of Nebraska. [Online] Available at: http://snr.unl.edu/data/geographygis/geology.aspx (accessed December 22, 2016)

Nebraska Conservation and Survey Division, 1995. Configuration of the water table in 1995. Institute of Agriculture & Natural Resources, University of Nebraska-Lincoln. Online GIS data set at accessed June 10, 2015 http://csd.unl.edu/general/gis-datasets.asp.

Nebraska Conservation and Survey Division, University of Nebraska-Lincoln, 2017, Till map for Nebraska 2017. http://snr.unl.edu/data/geographygis/geology.aspx (accessed July 30, 2017).

Nebraska Department of Natural Resources (NEDNR), 2016a, National Hydrographic Dataset, http://www.dnr.ne.gov/surface-water-data (accessed November 29, 2016).

Nebraska Department of Natural Resources. 2016b. Registered Groundwater Wells Data Retrieval. http://dnr.ne.gov/gwr/groundwaterwelldata (accessed September 22, 2016)

NOGCC - Nebraska Oil and Gas Conservation Commission, 2017, Data and Publications website, http://www.nogcc.ne.gov/NOGCCPublications.aspx (accessed March 6, 2017).

Olafsen-Lackey, S. 2005a. Generalized Hydrogeologic Areas of the Principal Aquifer, Fremont and Omaha Quadrangles, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Olafsen-Lackey, S. 2005b. Specific Yield of the Principal Aquifer, Fremont and Omaha Quadrangles, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Olafsen-Lackey, S. 2005c. Transmissivity of the Principal Aquifer, Fremont and Omaha Quadrangles, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Pederson, D., Kuzelka, B., and Flowerday, C., 1986. The Groundwater Atlas of Nebraska. Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. http://nlc1.nlc.state.ne.us/epubs/U2375/X001.0004-1986.pdf (accessed on February 22, 2017).

Peterson, S. M., Strauch, K.R., 2007, Streamflow measurements in North-Central Nebraska, November 2006, U.S. Geological Survey Data Series 332.

Schamper, C., Auken, E., and Sorensen, K., 2014, *Coil response inversion for very early time modelling of helicopter-borne time-domain electromagnetic data and mapping of near-surface Geologic Layers.* European Association of Geoscientistis & Engineers, Geophysical Prospecting.

SkyTEM Airborne Surveys Worldwide, 2012, "SkyTEM survey: Mary Creek Canada data report." Beder, Denmark.

SkyTem Airborne Surveys Worldwide, 2016, SkyTEM304M, http://skytem.com/system-specifications/ (accessed January 9, 2016)

Smith, B.D., Abraham, J.D., Cannia, J.C., Minsley, B.J., Ball, L.B., Steele, G.V., and Deszcz-Pan, M., 2009, Helicopter Electromagnetic Geophysical Survey Data, Swedeburg and Sprague Areas, Eastern Nebraska: U.S. Geological Survey Open-File Report 2010-1288. Link to PDF file: https://pubs.usgs.gov/of/2010/1288/downloads/REPORT/ofr_2010_1288_v1_2.pdf (accessed January 9, 2017)

Stanton, J.S., Steele, G.V., and Vogel, J.R. 2007, Occurrence of agricultural chemicals in shallow ground water and the unstaturated zone, northeast Nebraska glacial till, Scientific Investigations Report 2002-04, U.S. Geological Survey. Link to PDF file: . https://pubs.usgs.gov/sir/2007/5228/pdf/sir2007-5228.pdf (accessed January 9, 2017)

Summerside, S., Meyers, W. 2005a, Generalized Hydrogeologic Areas of the Principal Aquifer, Lincoln and Nebraska City quadrangles, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Summerside, S., Meyers, W. 2005b, Specific Yield of the Principal Aquifer, Lincoln and Nebraska City quadrangles, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Summerside, S., Meyers, W. 2005c, Transmissivity of the Principal Aquifer, Lincoln and Nebraska City quadrangles, Nebraska: Open File Report-71, Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln.

Sweeney, R. E., and Hill, P.L, 2005, Nebraska, Kansas, and Oklahoma Aeromagnetic and Gravity Maps and Data: A Web Site for Distribution of Data: U.S. geological Survey Data Series 138, 2005. https://pubs.usgs.gov/ds/2005/138/neksok.html. (accessed January 9, 2017)

United States Department of Agriculture, 2014. USDA Natural Resources Conservation Service. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/oh/technical/dma/gis/?cid=nrcs144p2_029531 (accessed January 9, 2017).

University of Nebraska-Lincoln (UNL) School of Natural Resources. 2016. Nebraska statewide test-hole database. http://snr.unl.edu/data/geologysoils/NebraskaTestHole/NebraskaTestHoleIntro.asp (accessed April 22, 2016).

U.S. Geological Survey (USGS). Water. https://water.usgs.gov/edu/earthgwaquifer.html (accessed January 9, 2017)

U.S. Geological Survey, 2015, USGS surface-water data for Nebraska. http://waterdata.usgs.gov/ne/nwis/sw/ (accessed January 8, 2017).

U.S. Geological Survey (USGS), 2016, The National Map, 2016, 3DEP products and services: The National Map, 3D Elevation Program Web page, http://nationalmap.gov/3DEP/3dep_prodserv.html (accessed May 26, 2016)

Viezzoli, A., A. V. Christiansen, E. Auken, and K. Sorensen, 2008, "Quasi-3D modeling of airborne TEM data by spatially constrainted inversion." *Geophysics Vol. 73 No. 3* F105-F11