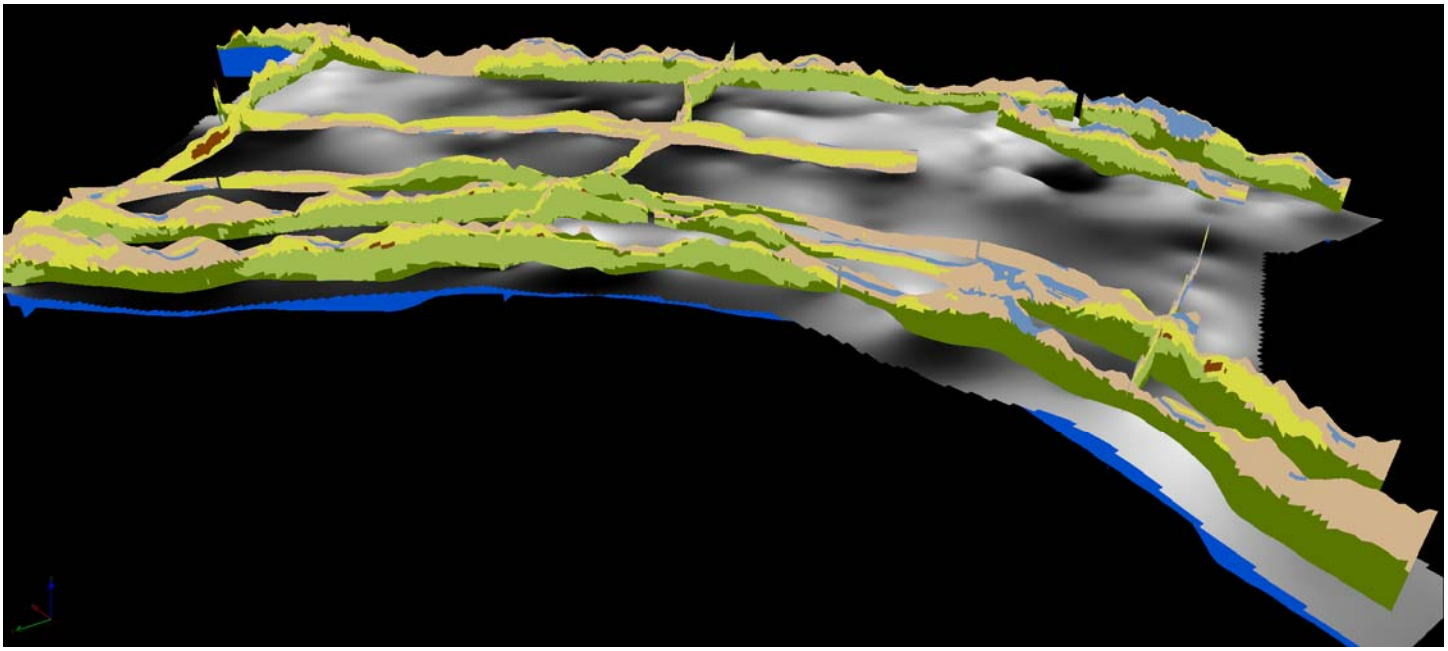
Hydrogeologic Framework of Selected Areas in the Lower Platte South Natural Resources District, Nebraska



***Prepared for*:**

Lower Platte South Natural Resources District

3125 Portia St
Lincoln, NE 68521

November 10, 2017

Aqua Geo Frameworks, LLC.

November 10, 2017

Hydrogeologic Framework of Selected Areas in the Lower Platte South Natural Resources District

Prepared for the:

Lower Platte South Natural Resources District
3125 Portia St
Lincoln, NE 68521

Submitted by:

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

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

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

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







Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled "*Hydrogeologic Framework of Selected Areas in the Lower Platte South 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 South Natural Resources District (LPSNRD) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the LPSNRD project areas 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 LPSNRD area including the Lower Salt Creek, Waverly, Cass County Rural Water District #2 (CCRWD2), Eagle, Elmwood, Otoe County Rural Water District #3 (OCRWD3), Weeping Water, Cass County Rural Water District #1/ Sanitary Improvement District #1 (CCRWD1/SD1), and Union project areas including several reconnaissance lines. These flights have been provided as preliminary AEM inversions on July 29 to August 3, 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 LPSNRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies to AGF.

Upon conclusion of the design process, the LPSNRD flight lines were arranged as five (5) block areas connected by reconnaissance lines and one larger reconnaissance flight area (Lower Salt Creek). The flight blocks varied in size from a low of approximately 2.25 miles on along east-west lines by up to 5.5 miles in north-south directions. The lines in the flight blocks were separated by approximately 0.2 miles (200 m) in both north-south directions and east-west directions with occasional tie lines. The reconnaissance flight lines varied from approximately 20 miles in length across the LPSNRD to about 8 miles in the area of the Lower Salt Creek reconnaissance flight area.

1.4 Across the LPSNRD, approximately 693.4 line-miles (1,123.3 line-km) were acquired in the survey areas. Status reports of the flying were provided to the Contract Representative of LPSNRD 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 August 3, 2016.

1.6 AGF inverted the AEM data. Approximately 539.3 line-miles (873.7 line-km) were retained for inversion (77.8%, a high rate of retention). These final inverted georeferenced data are delivered to the LPSNRD 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. A total of 78 CSD holes contained lithology information, 72 holes contained stratigraphic information, 49 holes contained geophysical log information from the "ELog" database, and 8 contained geophysical log information from the "GeoLog" database in the LPSNRD AEM survey area. There were also 352 DNR lithology logs that were part of the data delivery from the ENWRA Volume II report (Carney et al., 2015c) as well as 752 more recent DNR lithology logs. The well data correlated well with the AEM and provided control to allow hydrogeological interpretations.

2.2 Merging 2015 and 2016 AEM Databases - The LPSNRD AEM survey area analysis encompassed an additional 51.7 line-miles (83.8 line-km) of AEM data collected in 2015 in the LPSNRD area. The 2015 AEM data contains valuable information that can be utilized in the interpretation of the larger LPSNRD AEM survey data. The 2015 AEM results were combined with the 2016 AEM data. Note that this combination did not include reinverting the 2015 data, but rather included merging the 2015 inversion results into the 2016 database and interpretation. The 2015 data correlated and merged well with the 2016 AEM. The systems were both stable and the inversions were well executed.

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***), Cretaceous Dakota (***Kd***), and undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD and NE-DNR. Surface grids of the interpreted geologic formations were then produced and it was found that the AEM allowed interpretation of the geological contacts. Each flight line profile with interpretation including Quaternary aquifer material mapping and Cretaceous Dakota sandstone/sand dominant zones are included as appendices as well as the interpretative surface grids.

2.4 Resistivity/Lithology Relationship - Assessment of the sediment character in both the ***Q*** and the ***Kd*** aquifer systems was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. For the ***Q*** aquifer systems, 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). A similar process was applied to the ***Kd*** and a resistivity threshold of 27 ohm-m was determined to separate sandstone/sand dominant zones from shale/clay dominant zones. 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 LPSNRD - The AEM reveals considerable variability

in the ***Q***, ***Kd***, and undifferentiated ***IP*** deposits across LPSNRD AEM survey area. The subsurface distribution of materials can generally be characterized into four somewhat overlapping, but distinct, areas with smaller localized depositional features distributed at various locations within the survey area. These include the Quaternary alluvium in a limited area, Quaternary glacial deposits that cover most of the project area, the ***IP*** bedrock area where the ***Kd*** is eroded off, and the ***Kd*** bedrock area which occurs mostly in the west and is eroded away in the east. The ***Q*** alluvium aquifer area of the LPSNRD AEM survey area is predominantly composed of unconsolidated aquifer and coarse aquifer materials composed of alluvial sediments. The alluvial sediments also contain marginal aquifer and non-aquifer materials but they are isolated and limited in geographic area. Most alluvial materials lie in the Platte River plain, the Missouri River plain, the North Fork of the Nemaha River, Salt Creek and Weeping Water Creek and are saturated from the near surface down. The ***Q*** alluvium overlies the ***IP*** in many areas along the listed streams. The ***Kd*** can act both as an aquifer and an aquiclude. Water from the alluvium or ***Kd*** can move between the units. The coarse aquifer and aquifer materials are most likely to have this connection and interaction.

The ***Q*** glacial deposits covering much of the LPSNRD AEM survey area vary in thickness but in general reach a maximum thickness of greater than 150 feet. These materials are a combination of tills and outwash deposits. They lie unconformably upon the ***Kd*** and ***IP***.

The ***Kd*** bedrock unit is located mostly in the western end of the survey area although there are additional erosional remnants in the central-eastern regions. The ***Kd*** is characterized by a combination of sandstone/sand dominant and shale/clay dominant units. The sandstone/sand dominant part of the ***Kd*** is an important aquifer where saturated. It can also be hydrologically connected to the Quaternary aquifer materials and Streams. The ***Kd*** shale/clay dominant materials are considered an aquiclude which acts as a boundary condition to groundwater flow. The ***Kd*** is mostly covered by a small amount of ***Q*** alluvium and mostly covered by ***Q*** glacial materials. There are areas of some ***Kd*** outcrops along the streams of the survey area.

2.6 Estimation of Aquifer Volume and Water in Storage in the LPSNRD AEM Survey Area - Estimations were calculated for both ***Q*** and ***Kd*** aquifer materials for 5 CWSPA locations. A 3D representation of the subsurface derived from the AEM imaging provides users the ability to more accurately identify the total unsaturated and saturated aquifer volumes for the ***Q*** and the ***Kd***. The saturated zones of the ***Q*** and ***Kd*** materials can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present. Block flights were flown near five towns within the LPSNRD for understanding the hydrogeology near the Community Water System Protection Areas (CWSPAs). The CWSPA mapped were near the towns of Eagle, Elmwood, Union, Waverly and Weeping Water where AEM data was collected and interpreted (Figure 1-2). The amount of groundwater in storage for each location is: Eagle, ***Q*** material is 65,497 acre-ft and ***Kd*** is 400,695 acre-ft, Elmwood, ***Q*** material is 32,201 acre-ft and ***Kd*** is 77,445 acre-ft, Union, ***Q*** material is 159,116 acre-ft, Waverly, ***Q*** material is 30,320 acre-ft and ***Kd*** is 267,030 acre-ft and Weeping Water, ***Q*** material is 46,852 acre-ft and ***Kd*** is 163,562 acre-ft.

2.7 Potential Recharge Zones within the LPSNRD AEM Survey Areas - 3D representations of the subsurface resulting from the LPSNRD AEM investigation illustrate areas of aquifer materials from the bedrock up to the land surface. From these interpretations a series of near-surface maps were constructed to display the ***Q*** aquifer materials in the first 10 ft. These indicate that while there is some heterogeneity in the aquifer materials, it is easy to identify the areas of

aquifer materials that will transmit the most (aquifer and coarse aquifer materials), and the least (non-aquifer and marginal aquifer materials), amounts of water from the surface down to the groundwater system. The greatest possibility for recharge in the LPSNRD AEM survey area is the Platte River and Missouri River alluvial valley floor and the creek beds that have aquifer and coarse aquifer materials are near the land surface. On the table lands, the best possible location for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands with little relief in elevation with a pathway of similar materials down to the saturated aquifer at depth. Since most of the LPSNRD is covered in glacial sediments the pathways for recharge from the land surface to the saturated aquifers tend to be limited in most areas, the best locations are Waverly, Union flight blocks.

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 the LPSNRD. The discharge rates match the aquifer configuration and aquifer materials description well.

2.9 Value of AEM Data Analysis and Images - One of the most important key findings from the LPSNRD 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 LPSNRD 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 LPSNRD about their management challenges.

3.1 **Additional AEM Mapping** - The aquifer maps provided in this report represent the detailed framework developed for the LPSNRD AEM survey area. The detail provided in the hydrogeological interpretation of the LPSNRD AEM survey area allowed for confident development of hydrogeologic framework. The interpretations match well the CSD and NE-DNR test holes. If additional high resolution information is needed within LPSNRD to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or “block flights” be collected to develop detailed frameworks.

It should be noted that the ability to effectively map erosional remnants of the ***Kd*** can only happen with block flights. Thus, if ***Kd*** remnants are suspected and are targets of interest within an area designated for investigation, then block flights are required for effective characterization.

For example, the detailed hydrogeologic frameworks presented in this report have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield for 5 CWSPAs. It was noted that the edges of the CWSPA flight blocks often terminated with geological features important to understanding the amount of groundwater in storage and hydrologic connection to the surrounding area extend beyond the flight area boundary. It is recommended that additional

closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of LPSNRD. This will supply the LPSNRD with information on aquifer sustainability, depletion to streams, well interference, groundwater withdrawal, and other management considerations.

3.2 **Update the Water Table map** - The groundwater data used in the analyses presented in this report use the 1995 CSD water table data. 22 years is a long time in the evolution of a groundwater system and, in many areas, the water table used for this report was found not to be inconsistent with other recent borehole data.

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 LPSNRD AEM survey area was used in building the framework maps and profiles. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in optimal locations.

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

3.4 **Aquifer testing and borehole logging** - Additional aquifer tests are recommended to improve estimates of aquifer characteristics. No aquifer properties were available outside the larger cities in the survey area. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. The few test holes with geophysical logs in the LPSNRD AEM survey 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 LPSNRD.

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 LPSNRD AEM survey hydrogeologic framework provides areas of recharge from the ground surface to the groundwater aquifer. The block flights of AEM data acquisition provide the most detailed information for understanding recharge throughout the LPSNRD AEM survey area. It is recommended that additional AEM data be collected and interpreted along the reconnaissance lines in promising locations 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 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 LPSNRD AEM survey lines
- 3D voxel models as ASCII *.xyz and *.gdb for the LPSNRD AEM survey area

KMZs for LPSNRD AEM survey flight lines.
Profile Analyst sessions for the Profiles and 3D grids for the LPSNRD AEM survey area analysis

Table of Contents

1 Introduction 1
1.1 Purpose of Current Project 1
1.2 Background 3
1.3 Description of the LPSNRD AEM Project Area 5
2 Project Area Hydrogeology 7
2.1 Geologic Setting 7
2.1.1 Surficial Geology 7
2.1.2 Cretaceous Geology 10
2.2 LPSNRD AEM Survey Area Hydrogeologic Characteristics in the Quaternary and Cretaceous Dakota Systems 10
2.2.1 Quaternary 10
2.2.2 Cretaceous Dakota 19
3 Additional Background Information 21
3.1 Borehole Data 21
4 Geophysical Methodology, Acquisition and Processing 29
4.1 Geophysical Methodology 29
4.2 Flight Planning/Utility Mapping 30
4.3 AEM Survey Instrumentation 31
4.4 Data Acquisition 33
4.4.1 Primary Field Compensation 35
4.4.2 Automatic Processing 35
4.4.3 Manual Processing and Laterally-Constrained Inversions 35
4.4.4 Power Line Noise Intensity (PLNI) 38
4.4.5 Magnetic Field Data 41
4.5 Spatially-Constrained Inversion 42
5 AEM Results and Interpretation 46
5.1 Interpretive Process 46
5.1.1 Merge AEM Databases from Different Flights 46
5.1.2 Construct the Project Digital Elevation Model 47
5.1.3 Interpretative 2D Profiles 51
5.1.4 Create Interpretative Surface Grids 58

5.1.5 Create 3D Interpretative Voxel Grids 67
5.2 Resistivity-Lithology Relationship 71
5.2.1 Quaternary Aquifer System 71
5.2.2 Bedrock Resistivity Thresholds 72
5.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs 76
5.3 Hydrogeological Framework of the LPSNRD AEM Survey Area 83
5.3.1 The Quaternary Alluvium and Glacial Aquifer Areas 83
5.3.2 The Cretaceous Dakota Group 94
5.3.3 The IP Bedrock Area 96
5.3.4 Hydrogeology of the AEM Block Flight Areas 96
5.4 Estimation of Aquifer Volume and Water in Storage for the LPSNRD AEM Block Flight Survey Areas 127
5.4.1 Eagle 128
5.4.2 Elmwood 131
5.4.3 Union 133
5.4.4 Waverly 133
5.4.5 Weeping Water 135
5.5 Recharge Areas within the LPSNRD AEM Survey Area 139
5.6 Key AEM Findings 150
5.6.1 Boreholes 150
5.6.2 Merging 2015 and 2016 AEM Databases 150
5.6.3 Digitizing Interpreted Geological Contacts 150
5.6.4 Resistivity/Lithology Relationship 150
5.6.5 Hydrogeological Framework of the LPSNRD AEM Survey Area 150
5.6.6 Estimation of Aquifer Volume and Water in Storage in the LPSNRD AEM Survey Areas 151
5.6.7 Potential Recharge Zones within the LPSNRD AEM Survey Area 152
5.6.8 Relationship between Registered Wells, Discharge Estimates, and the AEM Results 152
5.6.9 Value of AEM Data Analysis and Images 152
5.7 Recommendations 153
5.7.1 Additional AEM Mapping 153
5.7.2 Update the Water Table map 153
5.7.3 Siting new test holes and production wells 153

5.7.4 Aquifer testing and borehole logging 154
5.7.5 Recharge Zones 154
5.7.6 Mapping Well Production Data 154
6 Description of Data Delivered 155
6.1 Tables Describing Included Data Files 155
6.2 Description of Included Google Earth KMZ Data and Profiles 164
6.2.1 Included README for the LPSNRD Interpretation KMZ's 164
6.3 Description of Included Profile Analyst (PA) Session Material 167
7 References 168
Appendix 1. LPSNRD AEM Flight Line 2D Profiles A1-1
Appendix 2. LPSNRD AEM 3D Fence Diagrams and Voxel Images A2-1
Appendix 3. Data Deliverables

List of Figures

Figure 1-1. Map of Nebraska counties, indicating the location of the Lower Platte South Natural Resources District (LPSNRD) airborne electromagnetic (AEM) survey with an inset of the project area. 1
Figure 1-2. The LPSNRD AEM survey areas east of Lincoln including county lines and major roads (NE 30, 4, 63). CCRWD2 stands for Cass County Rural Water District #2, CRWD3 stands for County Rural Water District #3, CCRWD1 stands for Cass County Rural Water District #2, and SID1 stands for Sanitary Improvement District #1. 2
Figure 1-3. Map of major river basins within the LPSNRD AEM survey area 6
Figure 2-1. Bedrock map of LPSNRD AEM survey area, Nebraska 8
Figure 2-2. Geologic time scale with lithostratigraphic sequence underlying Nebraska 9
Figure 2-3. Map displaying the major streams and rivers within the AEM survey area. The surface water divide point between the towns of Alvo and Murray. 11
Figure 2-4. Elevation of groundwater surface in the LPSNRD AEM survey area. The groundwater elevation contours show groundwater flow direction towards the Platte River, Salt Creek, Weeping Water Creek and North Fork of the Nemaha River 12
Figure 2-5. Generalized Hydrogeologic Areas within the LPSNRD AEM survey area 15
Figure 2-6. Glacial Till within the LPSNRD AEM survey area 16
Figure 2-7. Specific yield values within the LPSNRD AEM survey area 17
Figure 2-8. Transmissivity values within the LPSNRD AEM survey area 18
Figure 3-1. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in this study of the LPSNRD AEM survey area 22

Figure 3-2. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Lower Salt Creek area of the LPSNRD AEM survey 23

Figure 3-3. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Eagle block subarea of the LPSNRD AEM survey area 24

Figure 3-4. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Elmwood block subarea of the LPSNRD AEM survey area..... 25

Figure 3-5. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Union block subarea of the LPSNRD AEM survey area 26

Figure 3-6. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Waverly block subarea of the LPSNRD AEM survey area 27

Figure 3-7. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Weeping Water block of the LPSNRD AEM survey area 28

Figure 4-1. Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a) 29

Figure 4-2. A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model. 30

Figure 4-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1..... 32

Figure 4-4. Photo of the SkyTEM304M system in suspension beneath the helicopter..... 32

Figure 4-5. LPSNRD AEM flight lines grouped by acquisition date 34

Figure 4-6. Example locations of electromagnetic coupling with pipelines or power lines 36

Figure 4-7. Example of AEM data from the LPSNRD 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..... 37

Figure 4-8. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed 38

Figure 4-9. Power Line Noise Intensity (PLNI) map of the LPSNRD AEM survey area 39

Figure 4-10. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LPSNRD AEM survey area. Where blue lines are not present indicates decoupled (removed) data..... 40

Figure 4-11. Magnetic Total Field intensity data for the LPSNRD AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed 41

Figure 4-12. USGS magnetic Total Field intensity data for the LPSNRD 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..... 42

Figure 4-13. An example of an AEM profile illustrating increasing model layer thicknesses with depth.. 43

Figure 4-14. Data/model residual histogram for the LPSNRD SCI inversion results..... 44

Figure 4-15. Map of data residuals for the LPSNRD SCI inversion results 45

Figure 5-1. Example of a profile view of a three north-south flight lines within the Waverly Block. The top profile L177001 (western-most) was collected in 2016 with the SkyTEM304M; the middle profile line L200801 was collected in 2015 with the SkyTEM508; and the bottom profile line L177401 (easternmost) was collected in 2016 with the SkyTEM304M 48

Figure 5-2. Example of a profile view of a three east-west lines within the Waverly Block. The top profile L286402 (northernmost) was collected in 2016 with the SkyTEM304M; the middle profile line L100702 was collected in 2015 with the SkyTEM508; and the bottom profile line L431906 (southernmost) was collected in 2016 with the SkyTEM304M 49

Figure 5-3. Map of the Digital Elevation Model for the 2016 LPSNRD AEM survey area 50

Figure 5-4. Selected profile from the LPSNRD AEM dataset showing the full depth of the AEM inversions and the changes in the resistivity structure below the undifferentiated Pennsylvanian contact..... 52

Figure 5-5. 19.7-mile long east-west line L100702. The upper map is the location of the flight line as a red line on the Bedrock Geology Map (Burchett, 1986)..... 54

Figure 5-6. 6.6-mile long east-west line L341803. The upper map is the location of the flight line as a red line on the Bedrock Geology Map (Burchett, 1986). The profile shows CSD (within one mile) and Nebraska DNR borehole (within ½ mile) lithology and stratigraphy logs are indicated on the AEM inverted earth models 55

Figure 5-7. 4.4-mile long north-south line L180401. The upper map is the location of the flight line as a red line on the Bedrock Geology Map (Burchett, 1986)..... 56

Figure 5-8. 5.7-mile-long east-west line L147501..... 57

Figure 5-9. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the Waverly Block..... 59

Figure 5-10. Map of the elevation of the top of the undifferentiated Pennsylvanian (***IP***) within the Union Block..... 60

Figure 5-11. Map of the elevation of the top of the bedrock in the Lower Salt Creek Block composed of the Cretaceous Dakota Group (***Kd***) and the undifferentiated Pennsylvanian (***IP***) 61

Figure 5-12. Map of the Quaternary thickness in the Eagle Block..... 63

Figure 5-13. Map of the Cretaceous Dakota Group (***Kd***) thickness in the Waverly Block 64

Figure 5-14. Map of the elevation of the 1995 CSD water table (NE CSD, 1995) within the LPSNRD AEM survey area..... 65

Figure 5-15. Map of the saturated thickness of the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) within the Elmwood Block 66

Figure 5-16. Map of the saturated Quaternary (***Q***) aquifer material thickness of the Union Block..... 68

Figure 5-17. Map of the saturated Cretaceous Dakota Group (***Kd***) sand/sandstone dominant thickness of the Waverly Block 69

Figure 5-18. Map of the surface layer interpreted Quaternary aquifer materials for the Waverly Block . 70

Figure 5-19. 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)..... 71

Figure 5-20. Box and whiskers plot of the resistivity distribution of the Tertiary, Cretaceous, and Paleozoic bedrock units discussed in the interpretation of the AEM data 74

Figure 5-21. Box and whisker plot for the major lithologic texture categories within the ***Kd*** from CSD E-logs located across the entire ENWRA project area 75

Figure 5-22. Plot displaying the relation between resistivities and Cretaceous Dakota Group (***Kd***) clay/shale dominant (<27 ohm-m) and the sand/sandstone dominant (>27 ohm-m) 75

Figure 5-23. Graph of the *3-SC-08* 16-inch normal resistivity log values, 64-inch normal, lateral resistivity log and the inverted airborne electromagnetic resistivity values 77

Figure 5-24. Graph of the *11-A-61* 16-inch normal resistivity log values and the inverted airborne electromagnetic resistivity values 78

Figure 5-25. Graph of the 11-79 16-inch normal resistivity log values and the inverted airborne electromagnetic resistivity values 80

Figure 5-26. Graph of the 12-79 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values 81

Figure 5-27. Graph of the 31-79 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values 82

Figure 5-28. 3D fence diagram showing the reconnaissance flight lines, looking to the north of the interpreted distributions of aquifer material within the LPSNRD AEM survey area 84

Figure 5-29. 3D fence diagram of the reconnaissance flight lines, looking to the north of the four distinct areas, Quaternary alluvium (***Q***), Quaternary (***Q***) glacial, Cretaceous Dakota (***Kd***) bedrock and undifferentiated Pennsylvanian bedrock (***IP***) within the LPSNRD AEM survey area 85

Figure 5-30. 3D fence diagram of the reconnaissance flight lines, looking to the north showing the approximate locations of the Quaternary (***Q***) alluvium lying on the Cretaceous Dakota bedrock (***Kd***) and undifferentiated Pennsylvanian bedrock (***IP***) within the LPSNRD AEM survey area 86

Figure 5-31. 3D fence diagram of the reconnaissance flight lines, looking to the northwest showing the approximate locations of the Quaternary (***Q***) alluvium lying on the undifferentiated Pennsylvanian bedrock (***IP***) along Salt Creek 87

Figure 5-32. Profile L170201 showing the north-south flight line near the west end of the Salt Creek AEM survey area 88

Figure 5-33. Profile L171201 showing the north-south flight line from the uplands to the south to the Platte River valley 90

Figure 5-34. 3D fence diagram showing the reconnaissance flight lines looking to the northeast showing distribution and thickness of Quaternary (***Q***) glacial material 91

Figure 5-35. Profile L145101 oriented southeast-northwest from the uplands to the Platte River valley. This shows the complex geology of the Quaternary (***Q***) deposits which are variable in thickness deposited above the undifferentiated Pennsylvanian (***IP***) contact 92

Figure 5-36. Profile L144701 oriented southwest-northeast in the uplands near Elmwood 93

Figure 5-37. Profile L341002 oriented southeast-northwest between Waverly and Greenwood 95

Figure 5-38. 3D fence diagram showing the Eagle block flight lines looking to the east showing distribution and thickness of Quaternary (***Q***) glacial material and Cretaceous Dakota (***Kd***) materials 97

Figure 5-39. Profile L184201, oriented north, is south of Eagle 98

Figure 5-40. Elevation map of the undifferentiated Pennsylvanian (***IP***) bedrock surface which is considered the base of aquifer 99

Figure 5-41. Specific yield values within the LPSNRD AEM survey area 100

Figure 5-42. Comparison of discharge values from individual well locations compared to saturated thickness of the Quaternary aquifer (***Q***) and the Cretaceous Dakota sandstone/sand dominant material (***Kd***) 101

Figure 5-43. 3D fence diagram showing the Elmwood block flight lines looking to the east showing distribution and thickness of Quaternary (***Q***) glacial material and Cretaceous Dakota (***Kd***) materials ... 103

Figure 5-44. Profile L184201, oriented north-south, is west of Elmwood 104

Figure 5-45. Elevation map of the undifferentiated Pennsylvanian bed (***IP***) rock surface which is considered the base of aquifer 105

Figure 5-46. Specific yield values within the LPSNRD AEM survey area 106

Figure 5-47. Comparison of discharge values from individual well locations compared to saturated thickness of the Quaternary aquifer (***Q***) shown in grey tones and the Cretaceous Dakota sandstone/sand dominant material (***Kd***) 107

Figure 5-48. 3D fence diagram showing the Union block flight lines looking to the northwest showing distribution and thickness of Quaternary (***Q***) glacial material 109

Figure 5-49. Profile L147701, oriented east-west, is north of Union 110

Figure 5-50. Map of the elevation of the top of the undifferentiated Pennsylvanian (IP) bedrock within the Union block flight area 111

Figure 5-51. Specific yield values within the Union block flight area 112

Figure 5-52. Transmissivity values within the Union block flight area 113

Figure 5-53. Comparison of discharge values from individual well locations compared to saturated thickness of the Quaternary aquifer (***Q***) 114

Figure 5-54. 3D fence diagram showing the Waverly block flight lines looking to the east showing distribution and thickness of Quaternary (***Q***) glacial material and Cretaceous Dakota (***Kd***) materials ... 116

Figure 5-55. Profile L174201, oriented north-south, near the center of the Waverly block 117

Figure 5-56. Map of the elevation of the top of the undifferentiated Pennsylvanian (***IP***) bedrock within the Waverly AEM block flight area 118

Figure 5-57. Specific yield values within the Waverly AEM block flight area which average approximately 15% 119

Figure 5-58. Comparison of discharge values from individual well locations compared to saturated thickness of the Quaternary aquifer (***Q***) and the Cretaceous Dakota sandstone/sand dominant material (***Kd***) 120

Figure 5-59. 3D fence diagram showing the Weeping Water block flight lines looking to the east showing distribution and thickness of Quaternary (***Q***) glacial material and Cretaceous Dakota (***Kd***) materials ... 122

Figure 5-60. Profile L188801, oriented north-south, is north of Manley 123

Figure 5-61. Map of the elevation of the top of the undifferentiated Pennsylvanian (***IP***) bedrock within the Weeping Water AEM block flight area 124

Figure 5-62. Specific yield values within the Weeping Water AEM block flight area 125

Figure 5-63. Comparison of discharge values (color and size) from individual well locations (NEDNR, 2016b) compared to saturated thickness of the Quaternary aquifer (***Q***) shown in grey tones and the Cretaceous Dakota sandstone/sand dominant material (***Kd***) shown in color tones. 126

Figure 5-64. Map of all aquifer materials for the first 0 to 10 feet displayed over the Eagle block flight AEM survey area 140

Figure 5-65. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Eagle AEM block flight survey area 141

Figure 5-66. Map of all aquifer materials for the first 0 to 10 feet displayed over the Elmwood AEM block flight survey area 142

Figure 5-67. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Elmwood AEM block flight survey area 143

Figure 5-68. Map of all aquifer materials for the first 0 to 10 feet displayed over the Union AEM block flight survey area 144

Figure 5-69. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Union AEM block flight survey area 145

Figure 5-70. Map of all aquifer materials for the first 0 to 10 feet displayed over the Waverly AEM block flight survey area 146

Figure 5-71. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Waverly AEM block flight survey area 147

Figure 5-72. Map of all aquifer materials for the first 0 to 10 feet displayed over the Weeping Water AEM block flight survey area 148

Figure 5-73. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Weeping Water AEM block flight survey area 149

Figure 6-1. Example Google Earth image for the LPSNRD Interpretation kmz 166

List of Tables

Table 2-1. Aquifers in Quaternary and Tertiary Age stratigraphic units. 14

Table 2-2. Aquifer Characteristics for the Cretaceous Dakota (***Kd***) Fm 20

Table 4-1. Positions of instruments on the SkyTEM304M frame, using the center of the frame as the origin, in feet 33

Table 4-2. Positions of corners of the SkyTEM304M transmitter coil, using the center of the frame as the origin in feet 33

Table 4-3. Location of DGPS and magnetic field base station instruments was the Plattsmouth Airport . 33

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 43

Table 5-1. Combination of flight lines within the LPSNRD AEM survey area 46

Table 5-2. Combination of 2015 AEM data flight lines within the 2016 LPSNRD AEM dataset 46

Table 5-3. Saturated ***Q*** aquifer materials underlying the Eagle AEM block flight survey area 130

Table 5-4. Saturated ***Kd*** aquifer materials underlying the Eagle AEM block flight survey area 130

Table 5-5. Saturated ***Q*** aquifer materials underlying the Elmwood block flight AEM survey area 132

Table 5-6. Saturated ***Kd*** aquifer materials underlying the Elmwood block flight AEM survey area 132

Table 5-7. Saturated ***Q*** aquifer materials underlying the Union block flight AEM survey area 134

Table 5-8. Saturated ***Q*** aquifer materials underlying the Waverly AEM block flight survey area 136

Table 5-9. Saturated ***Kd*** aquifer materials underlying the Waverly block flight survey area 136

Table 5-10. Saturated ***Q*** aquifer materials underlying the Weeping Water AEM block flight survey area 138

Table 5-11. Saturated ***Kd*** aquifer materials underlying the Weeping Water AEM block flight survey area 138

Table 6-1. Channel name, description, and units for LPSNRD_EM_MAG_v1 Geosoft *.gdb and *.xyz with EM, magnetic, DGPS, Inclinometer, altitude, and associated data 157

Table 6-2. Channel name, description, and units for LPSNRD_AEM_SCI_Inv_v1 Geosoft gdb and xyz files with EM inversion results 158

Table 6-3. Files containing borehole information for the LPSNRD AEM survey 159

Table 6-4. Channel name, description, and units for borehole collar files 159

Table 6-5. Channel name description and units for borehole data 160

Table 6-6. Raw SkyTEM data files 160

Table 6-7. Channel name description and units for the interpretation results file LPSNRD_InterpSurfaces_v1 “gdb” and “xyz” files 161

Table 6-8. Files containing ESRI ArcView Binary Grids *.flt and Geosoft Grids *.grd (NAD 83 UTM 14 North, feet) 162

Table 6-9. Channel name, description, and units for for EagleVoxel, ElmwoodVoxel, UnionVoxel, WaverlyVoxel, and WeepingWaterVoxel Blocks as*.xyz and *.gdb 163

Table 6-10. Datamine Discover (formerly pbEncom Discover) PA Session Files 167

List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
$A*m^2$	Ampere meter squared
AEM	Airborne Electromagnetic
AGF	Aqua Geo Frameworks, LLC
CCRWD1	Cass County Rural Water District #1
CCRWD2	Cass County Rural Water District #2
cm	Centimeter
CSD	Conservation and Survey Division
CWSPAs	Community Water System Protection Areas
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
ft/day	foot per day
ft^2/day	Square feet per day
Fm	Geological Formation
FT	Fourier Transform
GIS	Geographic Information System
GP	Geological Group
gpd/ft	Gallon per day per foot
gpm	Gallons per minute
GWRs	Ground Water Reservoirs
HEM	Helicopter Electromagnetic
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
IMP	Integrated Management Plan
Km/km	Kilometers
KMZ/kmz	Keyhole Markup language Zipped file
Kd	Cretaceous Dakota Group
LCI	Laterally-Constrained Inversion
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
µS/cm	Micro-Siemens per centimeter
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NED	National Elevation Dataset
NE-DEQ	Nebraska Department of Environmental Quality
NE-DNR	Nebraska Department of Natural Resources

NMR	Nuclear Magnetic Resonance
NRD	Natural Resources Districts
nT	Nano-Tesla
OM	Geosoft Oasis montaj
Ohm-m	Ohm-meter
OCRWD3	Otoe County Rural Water District #3
IP	Undifferentiated Pennsylvania aged rocks
PA	Profile Analyst
Pd	Pennsylvanian Douglas Group
PFC	Primary Field Compensation
Pkc	Pennsylvanian Kansas City Group
Pl	Pennsylvanian Lansing Group
PLNI	Power Line Noise Intensity
LPSNRD	Lower Platte South Natural Resources District
Ps	Pennsylvanian Shawnee Group Pennsylvanian
Pw	Wabaunsee Group
Q	Quaternary
RA	Remaining Area
Rx	Receiver
SCI	Spatially-Constrained Inversion
SD1	Sanitary Improvement District #1
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 South Natural Resources District (LPSNRD) desires an improved understanding of the hydrogeologic framework to provide detailed subsurface information related to 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. Detailed information was also desired for the ten Community Water System Protection Areas (CWSPAs; equivalent to state-designated Well Head Protection Areas (WHPAs)) for the towns/systems of Alvo, Cass County Rural Water District #1 South, Cass County Rural Water District #2, Cass County Sanitary Improvement District #1/Lake Waconda, Eagle, Elmwood, Otoe County Rural Water District #3, Waverly, Weeping Water, and Union. Also, additional information for the lower portion of Salt Creek was needed to increase the District's understanding of the hydrologic connection between ground and surface water in that area to support implementation of LPSNRD's Integrated Management Plan (IMP). 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). For the remainder of the report the individual flight blocks indicated on Figure 1-2 will be referred to as the following: Waverly area as the Waverly Block; Lower Salt Creek - Greenwood as the Salt Creek Block; Cass County Rural Water District #2, Alvo Community Water System Protection Areas, and Eagle Community Water System Protection Areas as the Eagle Block; Elmwood Community Water System Protection Area as the Elmwood Block; Otoe County Rural Water District # 3, Weeping Water as the Weeping Water Block; and Cass County Rural Water District #1 South/Sanitary District #1/ Lake Waconda and Union Community Water System Protection Area as the Union Block.

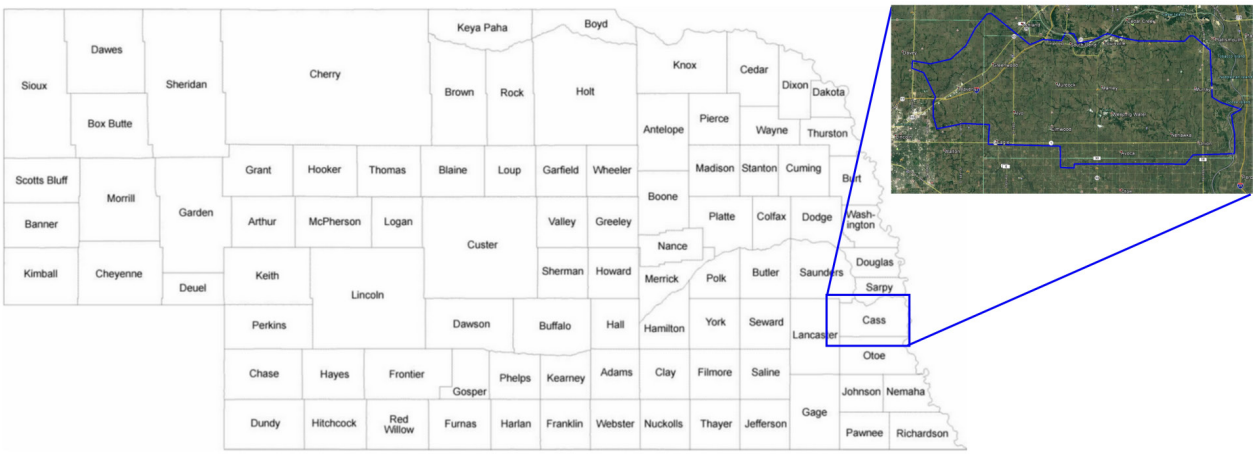


Figure 1-1. Map of Nebraska counties, indicating the location of the Lower Platte South Natural Resources District (LPSNRD) airborne electromagnetic (AEM) survey with an inset of the project area. The survey area is outlined in blue.

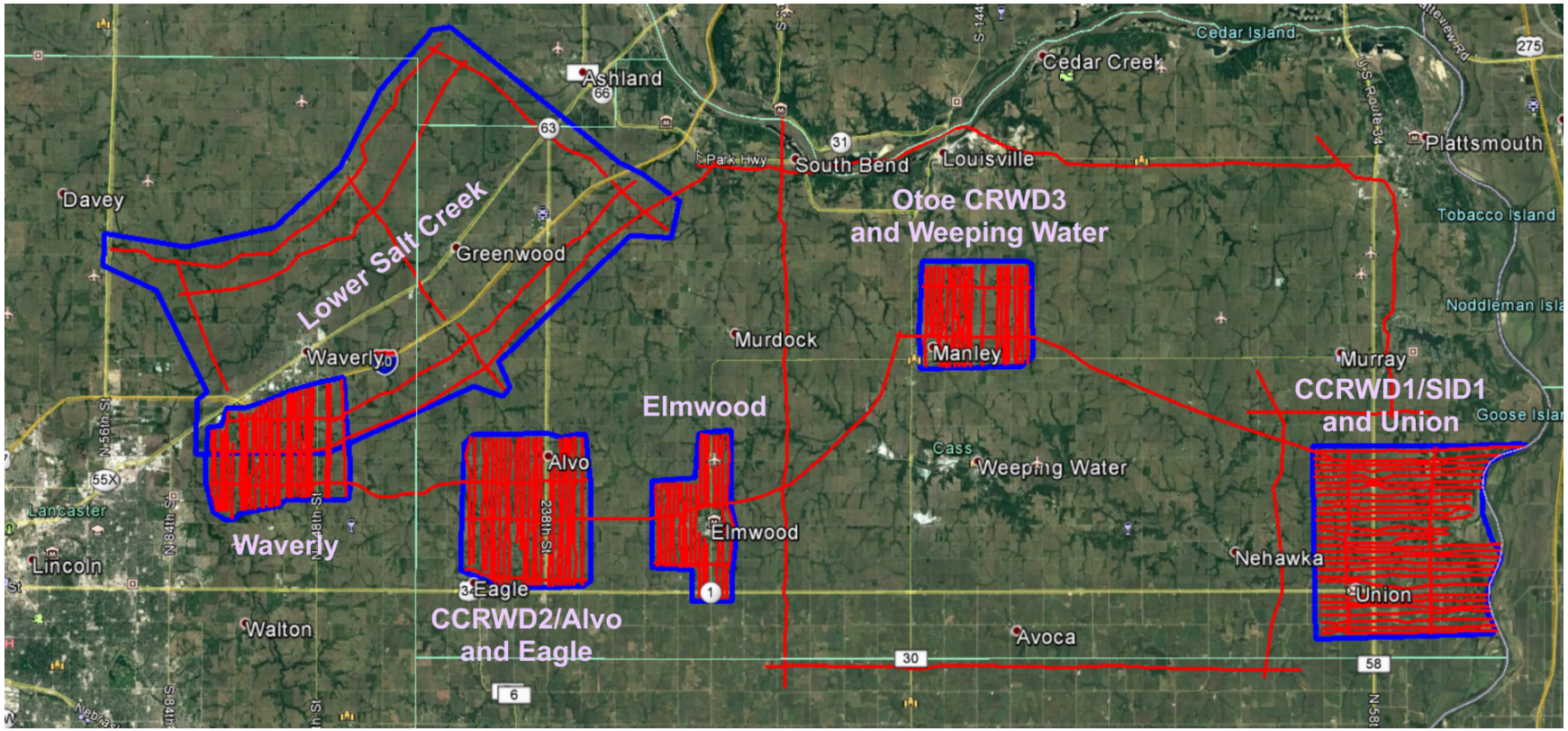


Figure 1-2. The LPSNRD AEM survey areas east of Lincoln including county lines and major roads (NE 30, 4, 63). CCRWD2 stands for Cass County Rural Water District #2, CRWD3 stands for County Rural Water District #3, CCRWD1 stands for Cass County Rural Water District #2, and SID1 stands for Sanitary Improvement District #1. The interpretation block boundaries are outlined in blue.

1.2 Background

In 1995, the LPSNRD declared the entire District as Phase I for ground water quality and quantity, which implemented basic programs such as well permitting, cost-sharing on best management practices, and information and education programs (LPSNRD, 1995). This determination was based on a variety of studies by the LPSNRD, the U.S. Geological Survey (USGS), and private consultants. The conclusions from these studies indicated that the LPSNRD is underlain by several different and separate aquifer units, referred to in the Plan as Ground Water Reservoirs (GWRs), and designated these as specific areas of management for ground water quality and quantity. In addition, the Plan identified the CWSPAs surrounding approximately 30 communities in the LPSNRD as areas of management. The remainder of the LPSNRD was designated as the Remaining Area (RA), where ground water availability is highly variable and aquifer units must be managed on a case-by-case basis. The plan also directed that areas of management needed to be managed for both quality and quantity. Subsequent studies by the LPSNRD and private consultants delineated areas where ground water quality, particularly from nitrate contamination, was a concern, and these areas were designated as Phase II quality management areas, mostly in the early 2000s. In Phase II areas, additional requirements such as certification training for individuals applying nitrogen fertilizer are instituted. In the eastern portion of the LPSNRD, these included the Lower Salt Creek GWR, and the Otoe County Rural Water District #3/Weeping Water and Union CWSPAs. In addition, historically high nitrate levels in the Elmwood CWSPA resulted in a Phase III ground water quality management area designation; Phase III requirements include additional measures such as required soil sampling and restrictions on fertilizer application timing. The other CWSPAs in the eastern portion of the LPSNRD (Waverly, Alvo/Cass County Rural Water District #2, Eagle, and Cass County Rural Water District #1 South/Sanitary District #1/ Lake Waconda), although not designated as Phase II or III management areas, are characterized in most cases by limited aquifer units which increase their vulnerability to ground water quality and quantity problems. As a result of these concerns, all these areas were mapped during the 2016 AEM investigation.

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), the Nebraska Conservation and Survey Division (CSD), the 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, LPSNRD, ENWRA, and CSD are working in cooperating along 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 South NRD funded the USGS and the CSD 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 loess and/or till. 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 (Carney et al., 2015a). 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., 2015b, Carney et al., 2015c). 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). The Lower Platte North NRD (LPNNRD) report was completed in August 2017 and was designed to support groundwater management efforts in the district (AGF, 2017f). This study bordered the survey area of 2013 LPSNRD study and showed the paleovalley indicated in the 2013 survey continues into the LPNNRD. 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 technology and application of AEM to support groundwater management.

In addition to the AEM and Magnetic Total Field data were 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 LPSNRD 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*.

1.3 Description of the LPSNRD AEM Project Area

The areas of interest in the LPSNRD AEM survey area for the 10 CWSPAs described above includes approximately 70 square miles. The area encompassed by the reconnaissance lines near the CWSPAs and additional transect lines along Lower Salt Creek, is approximately 472 square miles (Figure 1-1). The survey area lies within Cass, Lancaster, and Otoe Counties. The survey area is part of three distinct ground water regions: the Platte River Valley, the Missouri River Lowlands, and the Nebraska Glacial Drift (Pederson et al., 1986). The geologic history of these ground water regions accounts for the great complexity and heterogeneity of the unsaturated zone, aquifer units, and bedrock in this part of eastern Nebraska. Figure 1-3 shows the major streams and the associated river basins. AEM is one tool which has the capacity to gather great amounts of data about such a complex geologic setting.

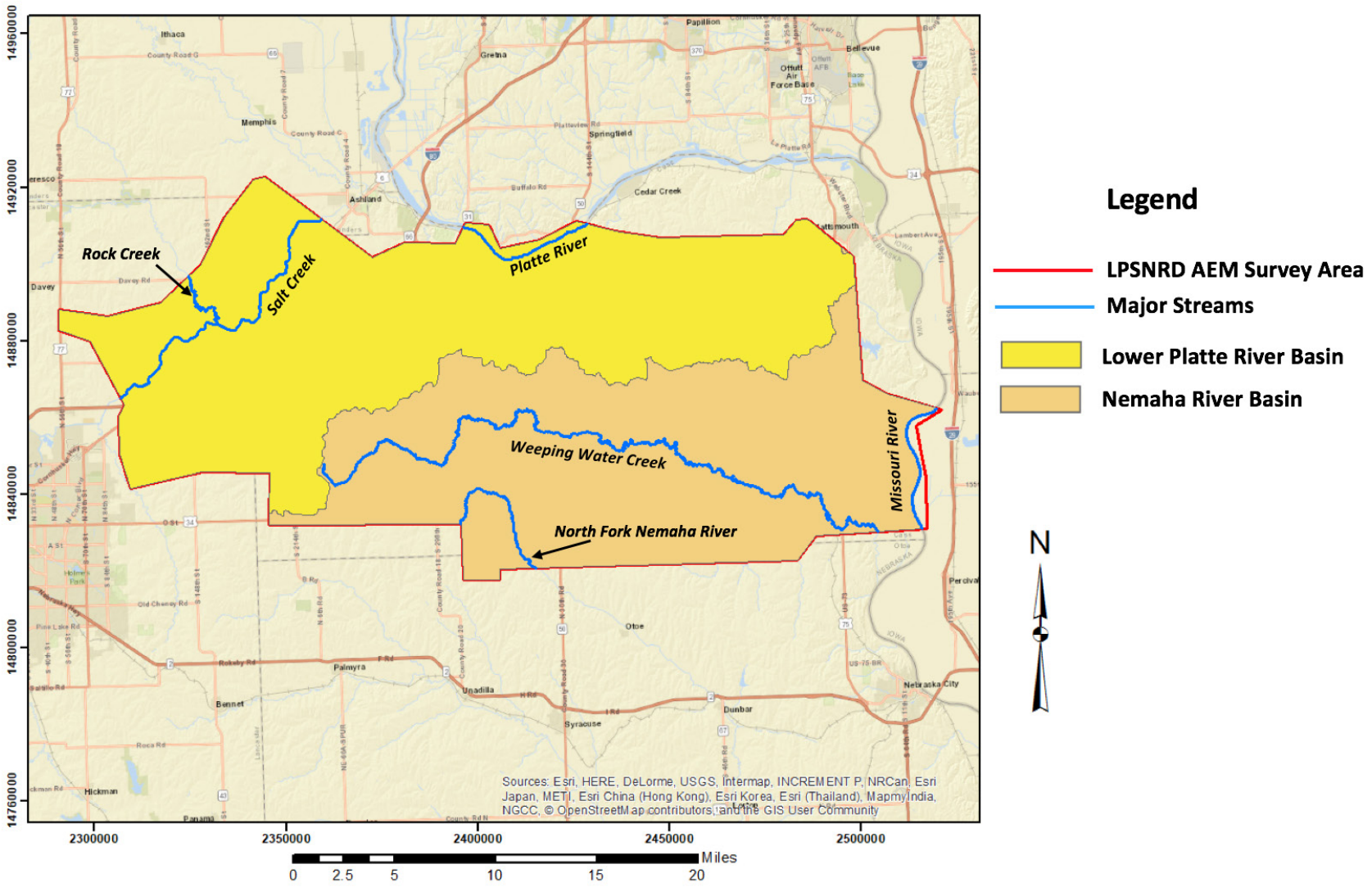


Figure 1-3. Map of major river basins within the LPSNRD AEM survey area (NE-DNR, 2016a). The surface water divide point is between Weeping Water Creek and the Platte River. The map projection is NAD1983, UTM zone 14 N feet.

2 Project Area Hydrogeology

2.1 Geologic Setting

Surface geologic exposures in LPSNRD consist, generally, of soil, loess, glacial till and alluvium (clay, silt, sand, and gravel) as well as areas of bedrock outcrop of shale, sandstone, and limestone. Bedrock formations include the Cretaceous Dakota (***Kd***) formation (sandstone, sand, clay, shale) or Pennsylvanian (***IP***) age limestones and shales composed of several formations and groups (Figure 2-1). A geologic map showing the outcrops that are mapped in the project area can be found in Burchett (1982). These bedrock outcrops are made up of Cretaceous Dakota materials and Pennsylvanian age materials, these outcrop exposures are mostly along incised stream valleys or areas eroded by Pleistocene glaciation. The Quaternary (***Q***)-aged materials are less than 1.7 million years old. These unconsolidated materials lay on consolidated/semi-consolidated bedrock that consists of sedimentary rocks of Cretaceous and Pennsylvanian age. These bedrock units may outcrop along valley sides and other various places in the county. The Cretaceous-age rocks consist primarily of sandstone and shale and are 66 to 138 million years old. The Pennsylvanian-aged rocks range from 290 to 300 million years old. Unexposed older sedimentary rocks of Mississippian, Devonian, Ordovician, and Cambrian ages consisting mostly of dolomite, limestone, shale, and sandstone occur in the subsurface of the LPSNRD AEM survey area. The basement units consist of metamorphic rocks (gabbro or basalt) (Korus and Joeckel, 2011).

Structurally, the survey area lies within the Eastern Nebraska Uplift. There is one structural high in the survey area. A northern extension of the Humbolt Fault Zone cuts across the eastern part of Cass and Otoe Counties with the Union Fault cutting across the southeast corner of Cass and Northeast corner of Otoe Counties (Burchett, 1981).

The Cretaceous deposits are not deformed by folding and faulting, but are heavily eroded. Outcrops of these rocks are present in the project area within the valleys along the north and west areas of the project area.

2.1.1 Surficial Geology

The complex Pleistocene and Holocene Quaternary geology in eastern 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 2-2 (Korus & Joeckel, 2011) displays the geologic time scale with the NE-CSD's lithostratigraphic sequence that underlies the state of Nebraska. The surficial geology of the project area is typical of western mid-continental glaciated areas of North America where buried ***Q*** sand and gravel glacial outwash deposits or paleovalleys, comprised of unconsolidated Plio-Pleistocene sand and gravel units, underlie extensive areas of glacial till.

CSD test holes and drillers logs obtained from NE-DNR indicate glacial till units are prevalent across most of the project area. These deposits are thick north and south of the Weeping Water Creek channel. There is a channel between the two large ***Kd*** deposits seen in Figure 2-1 and another channel between the ***Kd*** between the LPSNRD and Sarpy County to the north of the Platte River.

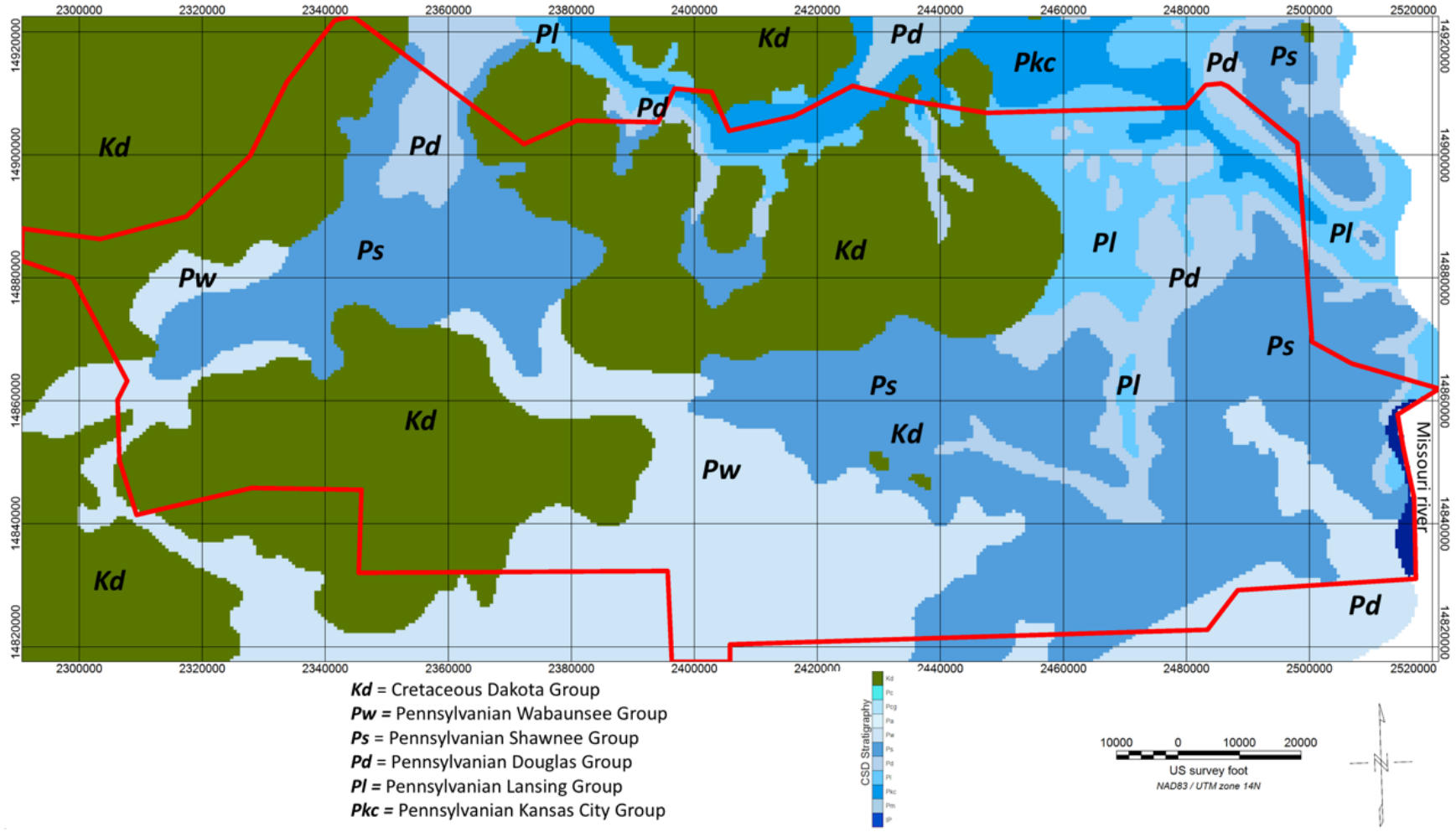


Figure 2-1. Bedrock map of LPSNRD AEM survey area (red polygon), Nebraska, modified from Burchett (1986). Projection is NAD83, UTM 14 North (feet).

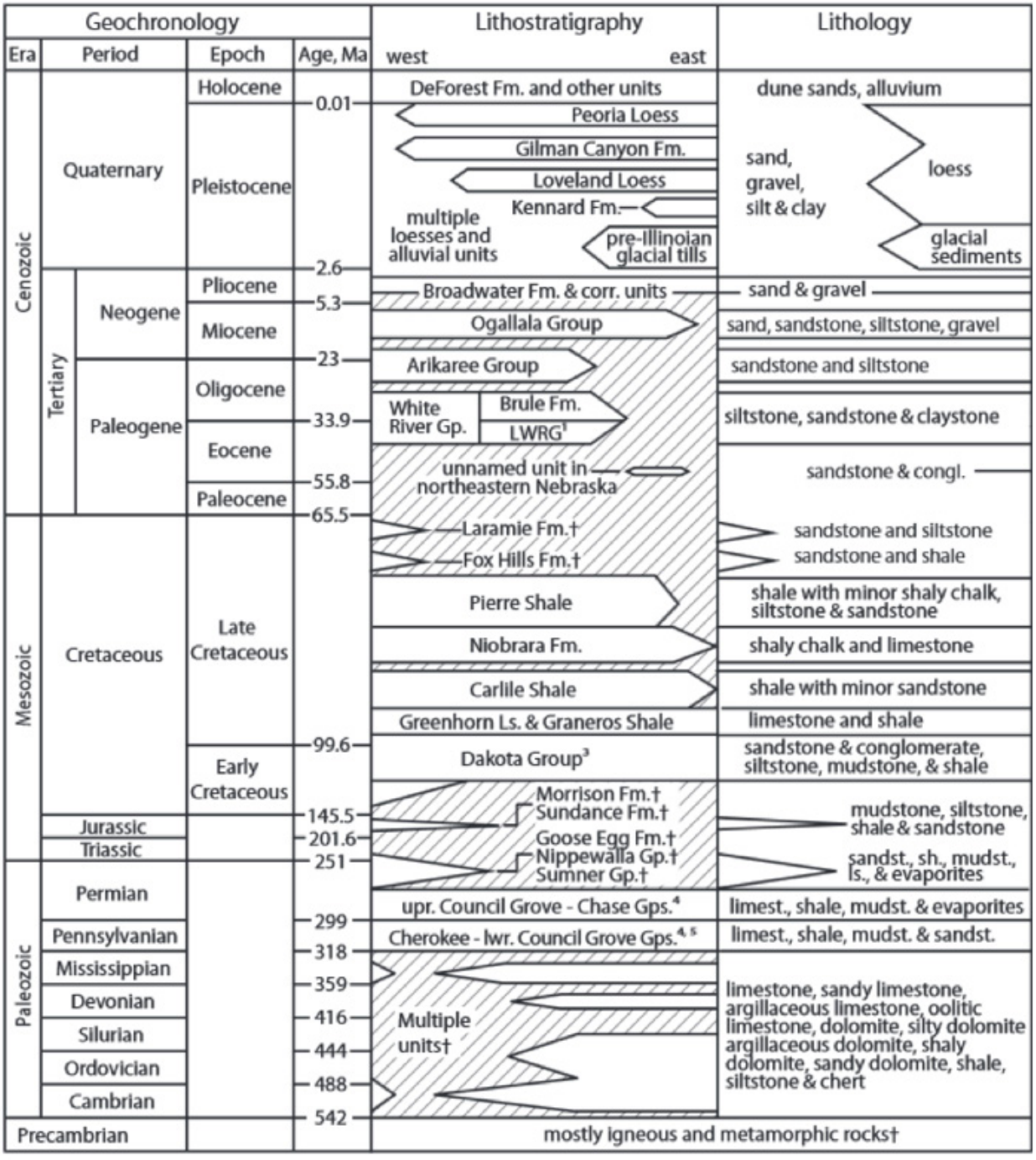


Figure 2-2. Geologic time scale with lithostratigraphic sequence underlying Nebraska, modified from Korus and Joeckel (2011).

2.1.2 Cretaceous Geology

There are deposits within the area from the Lower Cretaceous Dakota Group (***Kd)***. The ***Kd*** lies upon the ***IP*** bedrock. Figure 2-1 shows the highly-eroded nature of the ***Kd*** which has left erosional remnants of the formation, one near Alvo to the west and one near Manley, south of the Platte River. Figure 2-1 shows the bedrock is made up of the ***Kd*** lying upon the ***IP*** (Burchett et al., 1975). As seen on the map, the ***Kd*** sandstones can form a resistive erosional area. These two large sections of ***Kd*** make up the bulk of the remaining formation in the LPSNRD AEM survey area. The ***Kd*** is comprised primarily of massive to interbedded sandstone/sand with ironstone and shale, some zones are argillaceous to slightly sandy shale (Condra and Reed, 1959). The sandstone in the Dakota Group typically has low permeability and storage compared to unconsolidated sand and gravel units overlying it.

2.2 LPSNRD AEM Survey Area Hydrogeologic Characteristics in the Quaternary and Cretaceous Dakota Systems

2.2.1 Quaternary

A map showing the major streams and rivers within the project area is shown in Figure 2-3. Two surface water divides exist between the Nemaha and Platte Rivers with both draining into the Missouri River with the divide runs roughly parallel from the southwest corner to the northeast corner of the project area. The largest surface-water system in the project area is the Missouri River (NEDNR, 2016c) which flows along the eastern border of the project area. The next most important drainages are the Platte River, the North Fork Nemaha Rivers, Salt Creek, Weeping Water Creek, and Rock Creek.

The overall elevation of the water table within the project area is shown in Figure 2-4. It was derived from the 1995 CSD statewide map (Nebraska CSD, 1995) and represents the general shape of the groundwater surface; actual water levels will be different. The contour interval is 50 feet. There is a groundwater high at approximately 1250 feet elevation near the town of Alvo and extends eastward towards the town of Murray. The area north of the high moves toward Salt Creek and the Platte River. The groundwater to the south moves toward Weeping Water Creek and the North Fork of the Nemaha River.

Groundwater locally can be hydraulically connected to surface water. Groundwater levels are located at shallower depths in the alluvial valleys and typically deeper under glaciated areas. Groundwater levels can be affected by the amount of groundwater withdrawal which is generally highest in warm weather months and typically return to shallower, pre-stress levels in the March to June timeframe. Annual depths of drawdown and recharge of aquifers are highly dependent on the type of aquifer (e.g., confined, semi-confined, or unconfined), proximity of the aquifer to the land surface, and the magnitude of stress exhibited on the system during the pumping season, combined with the amount of recharge available to the aquifer.

Groundwater under confined systems, such as in some of the aquifers beneath glacial till or clay layers, typically exhibits more drawdown than groundwater in unconfined systems that are present in alluvial settings.

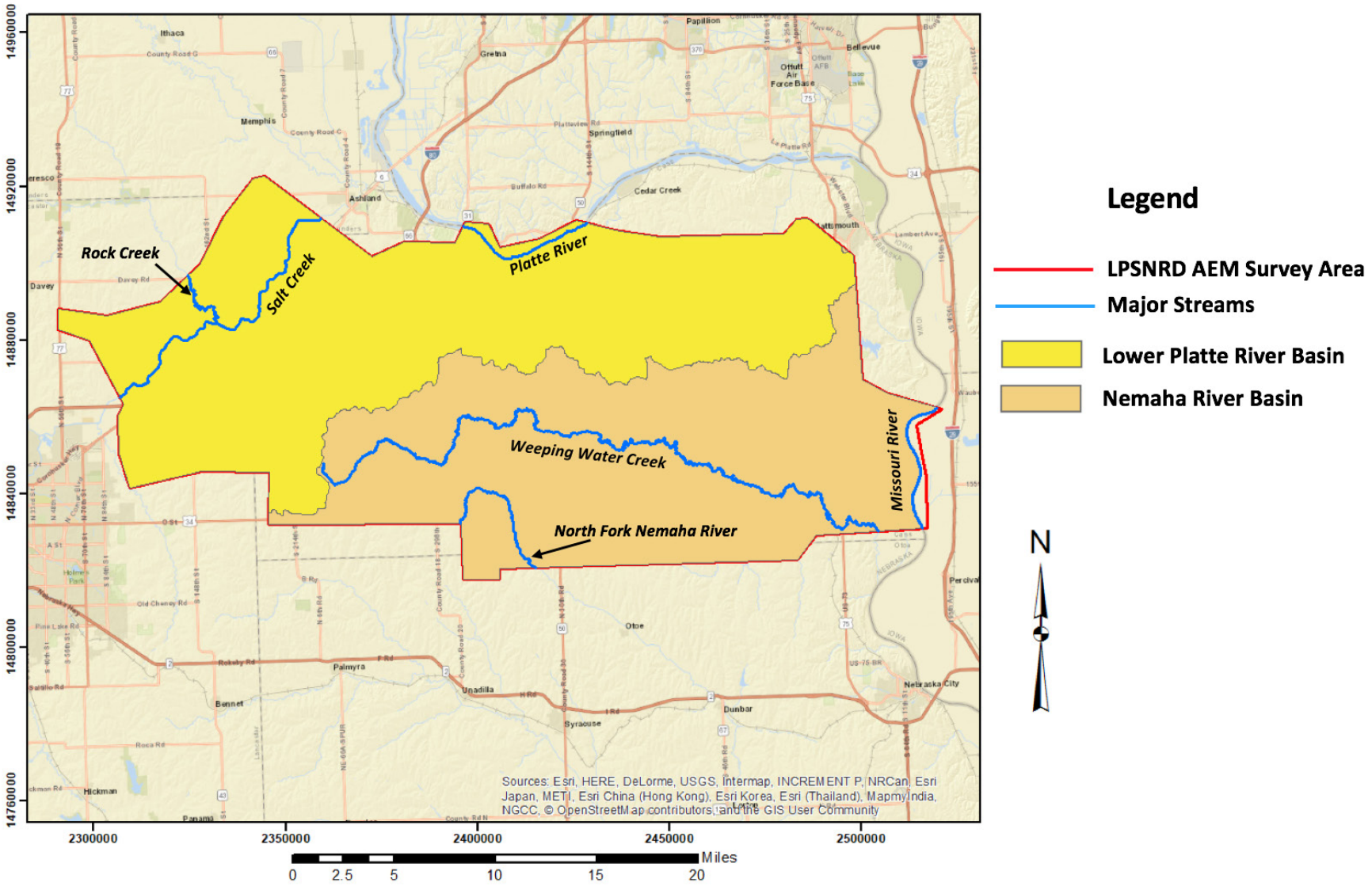


Figure 2-3. Map displaying the major streams and rivers within the AEM survey area. The surface water divide point is between Weeping Water Creek and the Platte River. Projection is NAD83, UTM 14 North (feet). (NE-DNR, 2016c).

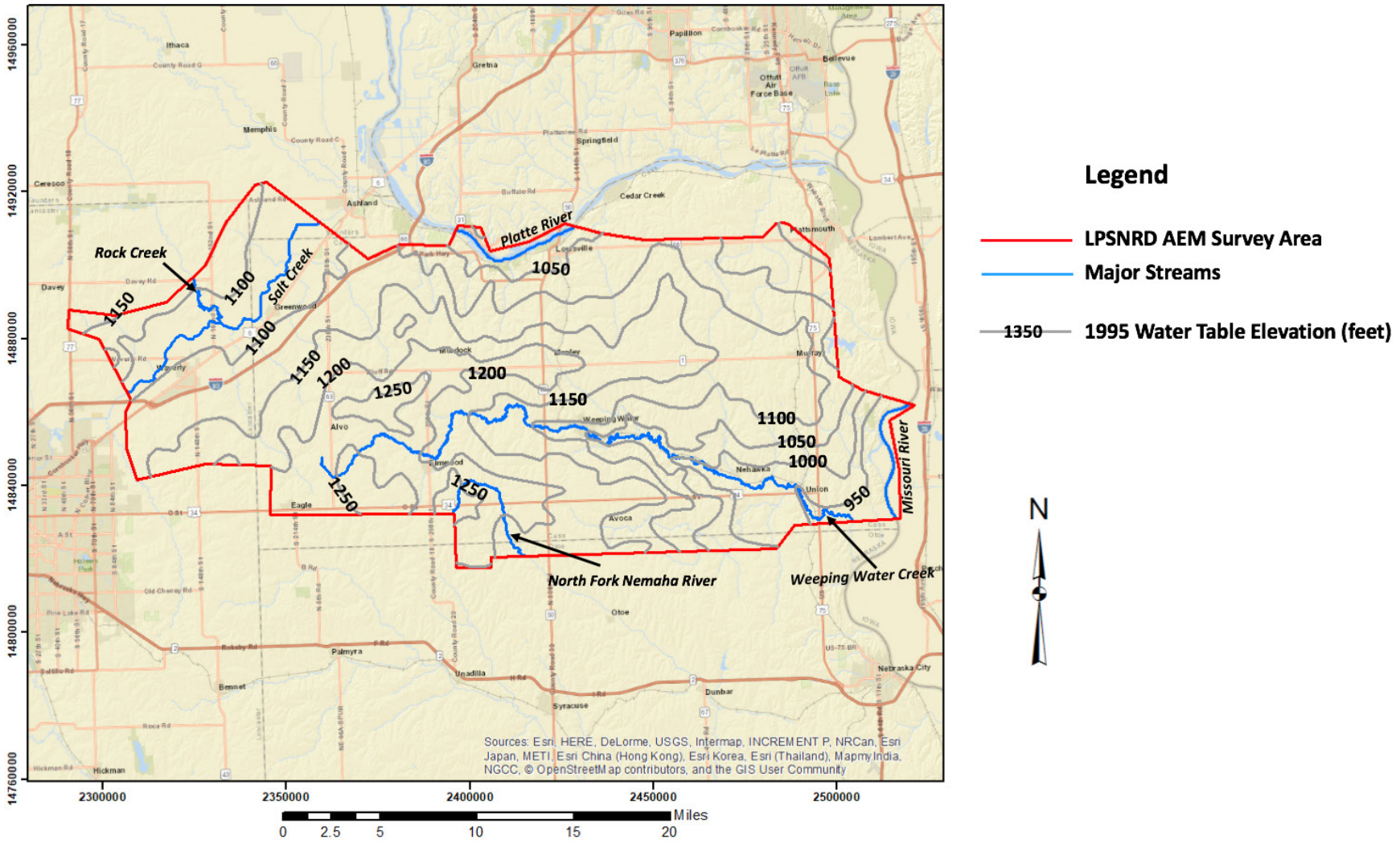


Figure 2-4. Elevation of groundwater surface in the LPSNRD AEM survey area. The groundwater elevation contours show groundwater flow direction towards the Platte River, Salt Creek, Weeping Water Creek and North Fork of the Nemaha River (NE-CSD, 1995). Projection is NAD83, UTM 14 North (feet).

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.

There are two principal ***Q*** hydrogeologic units within the LPSNRD AEM survey area. The first are saturated alluvial deposits and the second are the glacial drift deposits. These aquifers are considered one unit for this report. Saturated ***Q*** alluvial deposits in eastern 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. Stream-valley and glacial-drift systems locally can be hydraulically connected with other, similar systems. The 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 project area.

Table 2-1 contains summary information for each known aquifer (***Q*** through ***Kd***) within the area (adapted from Carney et al., 2015c) including the geologic system hosting the aquifer, aquifer thickness, and a general discussion regarding the aquifer framework, groundwater flow system characteristics, and aquifer parameters.

2.2.1.1 Aquifer Characteristics

A CSD map of the Generalized Hydrogeologic Areas in Figure 2-5 shows the aquifer characteristics classes in the project area (Summerside and Meyers, 2005a). The aquifer characteristic areas present are alluvial aquifer (Platte and Missouri Rivers), confined and glaciated. The glaciated area is the largest within the LPSNRD survey area with the confined aquifer along Salt Creek being next in geographic size and the Platte River alluvial aquifer along with the Missouri River alluvial aquifer. These maps were produced to show a general understanding of the aquifers and their hydrologic connections to the streams and rivers. The alluvial aquifers have the greatest hydrologic connection, the glacial aquifers have limited hydrologic connection where the coarse-grained portions of the glacial materials are in contact with the streams and rivers, and the confined aquifers which have no connection to surface water. Glacial Till covers most of LPSNRD AEM survey area limiting the amount of recharge to the groundwater system and acting as a confining layer (NE-CSD, 2009) (Figure 2-6).

Historic specific yield values in the project area (Figure 2-7) for the ***Q*** materials range from less than 0.05 to 0.20 based on Summerside and Meyers (2005b). As noted on the map in Figure 2-7, there are extensive areas with the aquifer being absent or very thin in the upland areas. Specific yields are approximately less than 0.05 where the aquifer materials are made of mostly silt size particles. Specific yields from aquifer materials made up of sand and gravel size particles range from approximately 0.10 to 0.20. This work is regional in nature and is used in calculations for this report in later sections.

Lower and upper ranges of transmissivity were reported between 20 to 200 gpd/ft in Summerside and Meyers (2005c). As noted on the map in Figure 2-8, there are extensive areas with the aquifer being absent or very thin in the upland areas. Overall, most transmissivity values within the project area likely

range from 20 thousand gallons per day per foot (gpd/ft) in wells open to the ***Q*** uplands glacial aquifer materials and up to 200 thousand gpd/ft in wells screened in ***Q*** alluvium and glacial-drift sand and gravel.

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

System	Series	Hydrologic unit	Maximum thickness (ft)
Quaternary	Holocene, Pleistocene	Aquifer in undifferentiated alluvial deposits	Generally less than 100 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 is rapid if the source area is primarily sand and gravel. Wells can yield up to several thousand gpm.			
Quaternary	Holocene, Pleistocene	Aquifer in undifferentiated glacial-drift deposits	Up to 300 ft
Undifferentiated sand and gravel units in glacial-drift aquifers. Hydraulic head under confined conditions and unconfined conditions. Thickness 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. Recharge mostly from precipitation infiltration or inflow from adjacent hydraulically connected aquifers. Well yields are highly variable; some capable of greater than a thousand gallons per minute but vary greatly by location. Isolated aquifers are capable of sustaining potable quality water for domestic or stock purposes.			
Cretaceous	Lower	Aquifer in sandstone/sand of the ***Kd***	Total thickness variable. Up to 300 ft in the project area
Locally, the ***Kd*** serves as an aquifer or as a confining unit. The aquifer is generally located in loosely-cemented, medium- to fine-grained sandstone/sand. Hydraulic head typically confined with local unconfined conditions encountered. Groundwater is often potable in eastern part of the state, where the ***Kd*** underlies saturated Quaternary deposits. Where ***Kd*** units lie within near proximity to the land surface, recharge is primarily from local precipitation, otherwise largely from inflow from adjacent hydrologically-connected aquifers. ***Kd*** Sandstones/sand can produce potable water to irrigation and municipal wells with variable yields.			

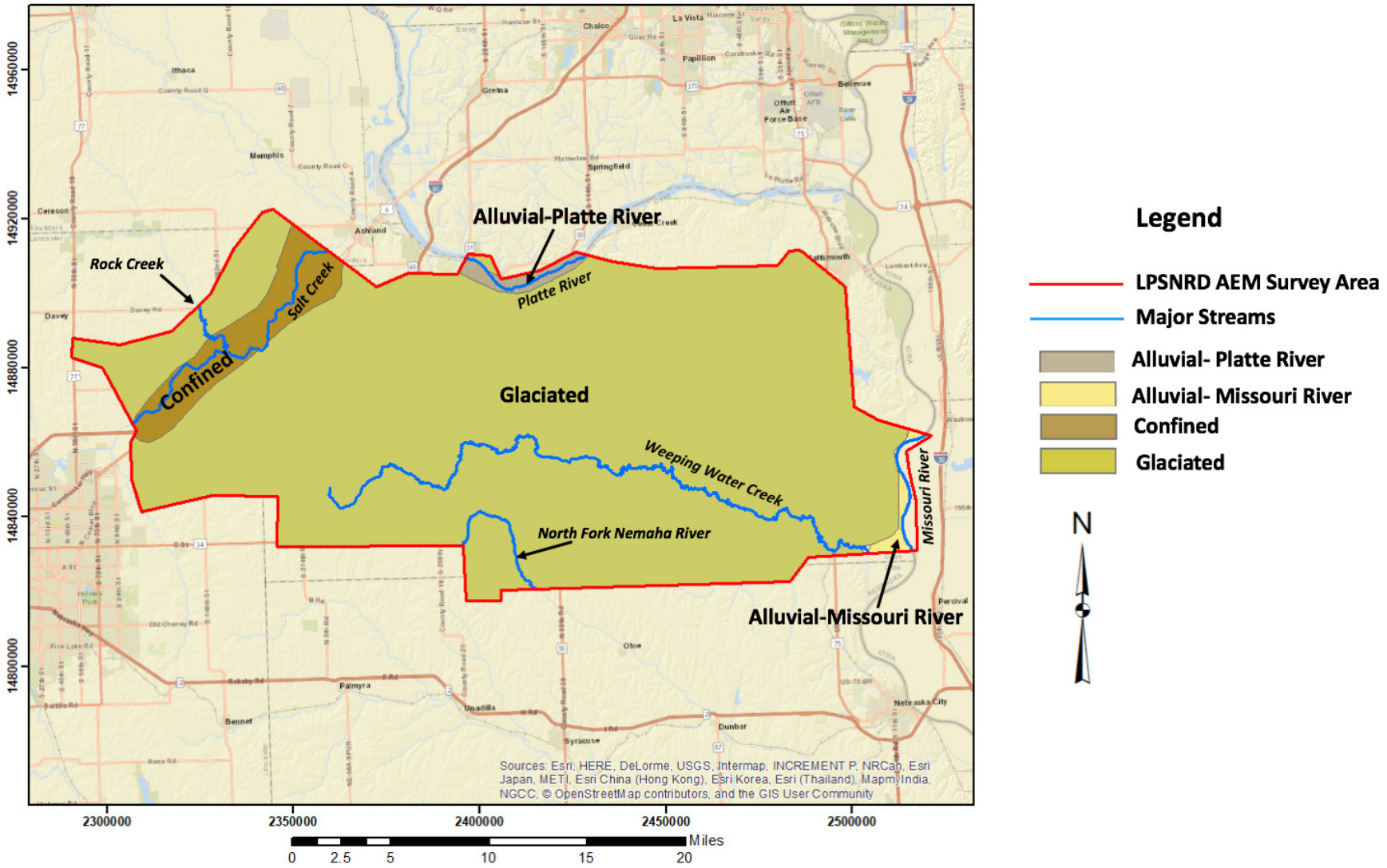


Figure 2-5. Generalized Hydrogeologic Areas within the LPSNRD AEM survey area (Summerside and Meyers, 2005a). This map show generalized hydrologic connections to the streams and rivers. Projection is NAD83, UTM 14 North (feet).

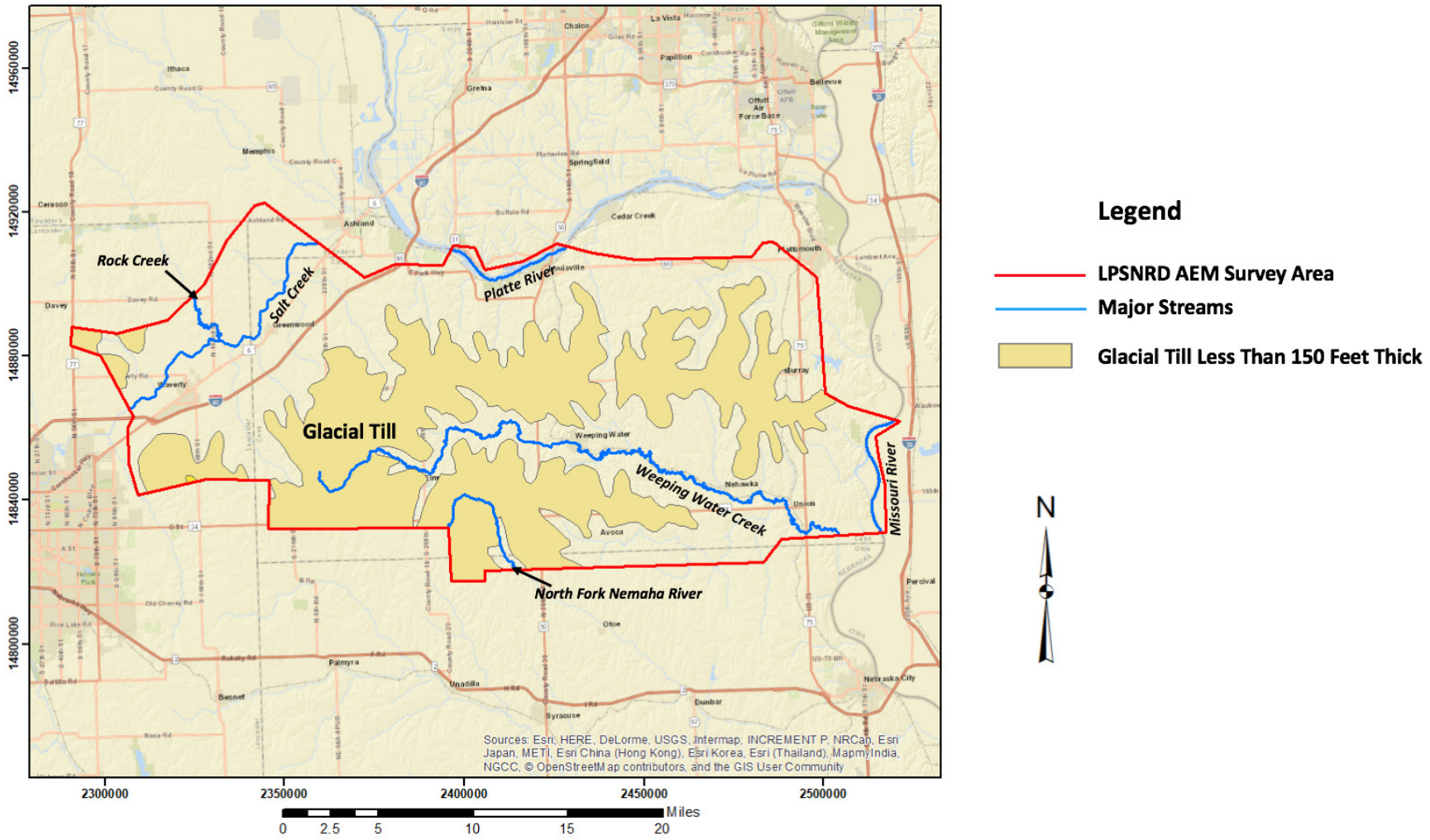


Figure 2-6. Glacial Till within the LPSNRD AEM survey area (Nebraska Conservation and Survey Division, 2009). This map shows glacial till cover less than 150 feet thick. Projection is NAD83, UTM 14 North (feet).

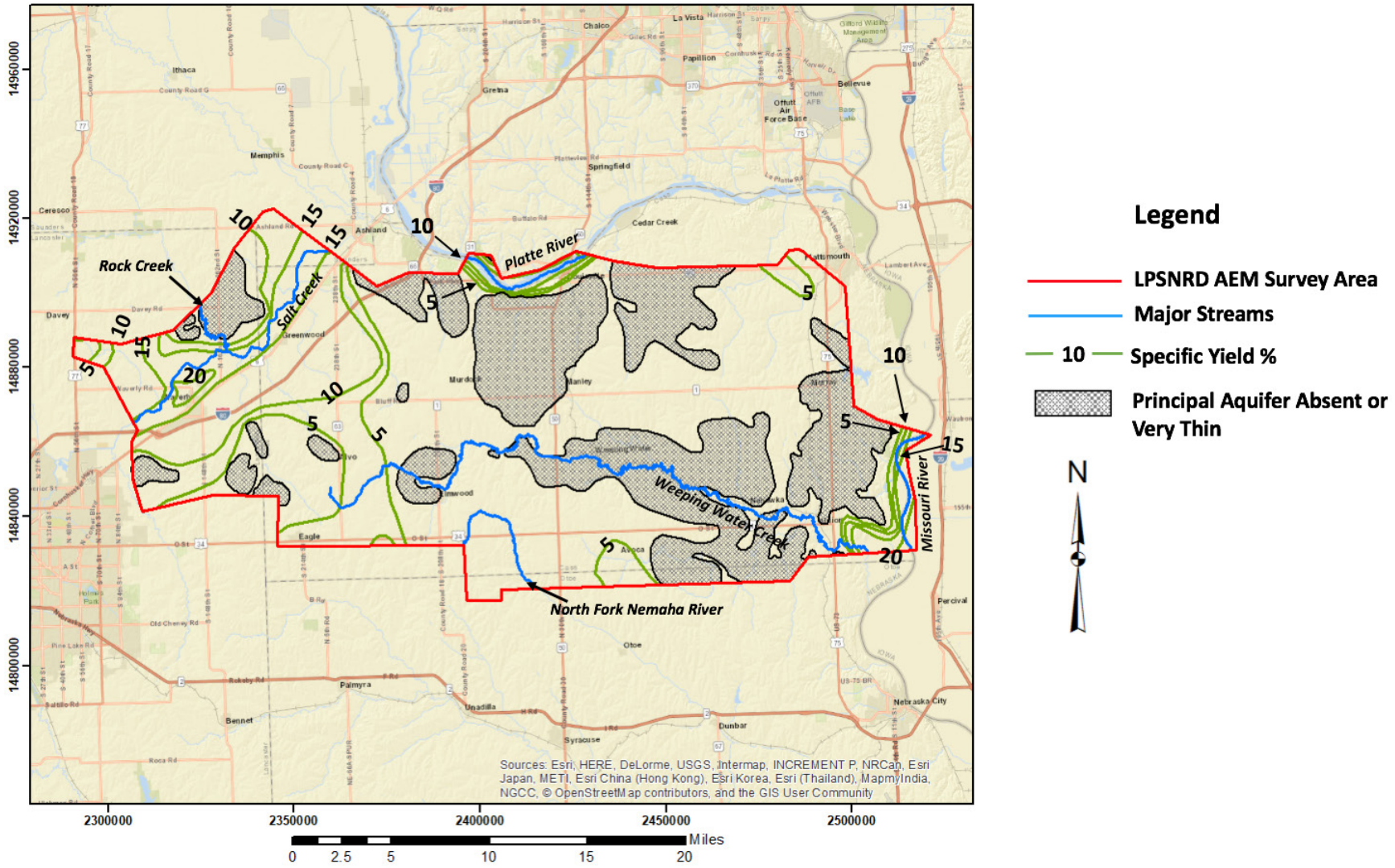


Figure 2-7. Specific yield values within the LPSNRD AEM survey area (Summerside and Meyers, 2005b). Note the large areas of the uplands that have aquifer materials that are absent or very thin. Projection is NAD83, UTM 14 North (feet).

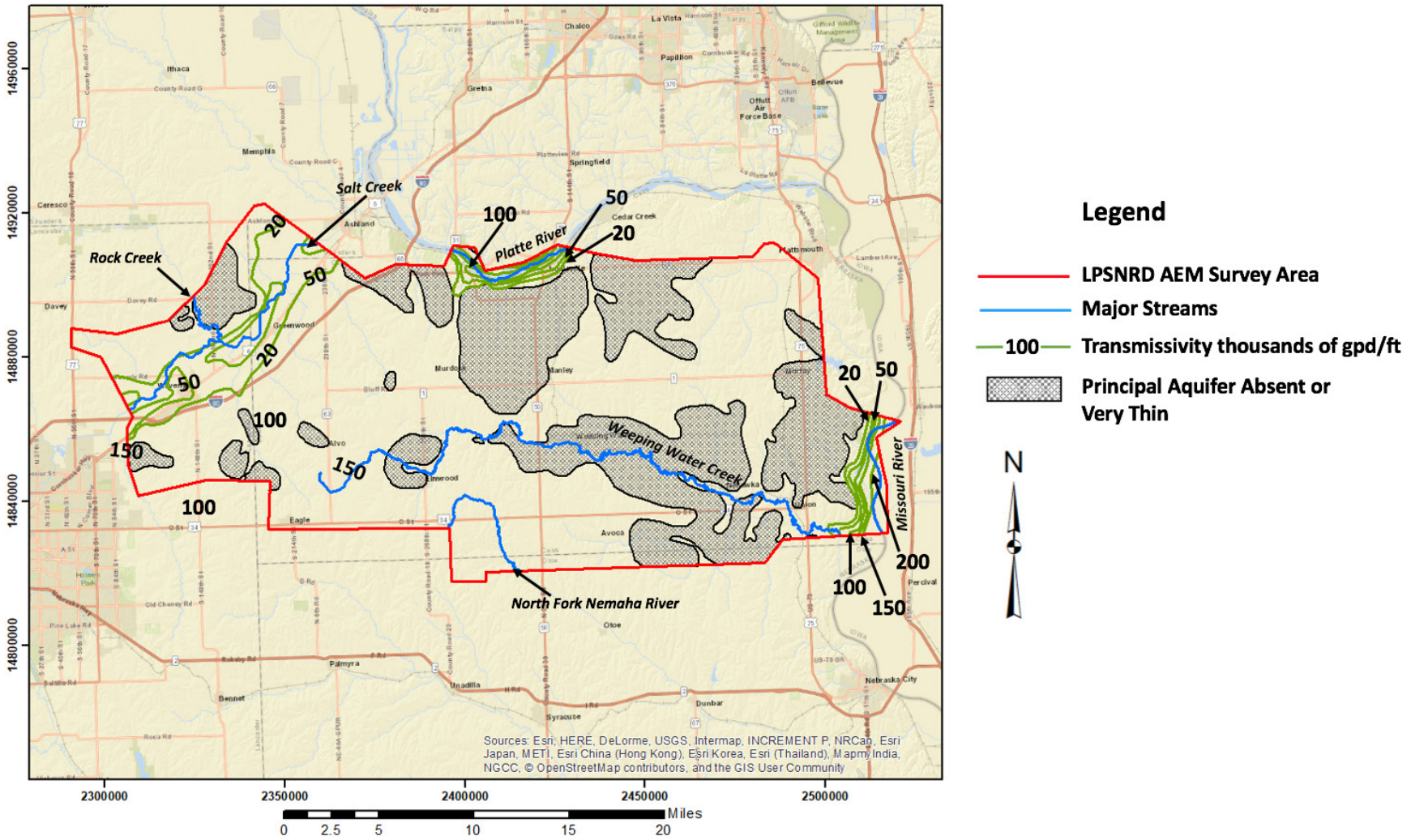


Figure 2-8. Transmissivity values within the LPSNRD AEM survey area (Summerside and Meyers, 2005c). Note the large areas of the uplands that have aquifer materials that are absent or very thin. Projection is NAD83, UTM 14 North (feet).

.

2.2.1.2 *Connectivity to Surface Water*

Groundwater flow connectivity to surface water features is largely undocumented in the LPSNRD AEM survey area. However, there appears to be possible connections along the streams shown in Figure 2-3. It can be safely assumed that there is a strong connection to the streams and the alluvium that the stream lies upon. Often stream flow measurements indicate changes in flow due to contributions from base flow or losses from the stream to the groundwater system are completed to assess this potential. There were no records found in this area to indicate these conditions.

2.2.1.3 *Connectivity to other Aquifers*

Locally, ***Q*** and ***Kd*** deposits can be hydraulically connected to each other and are treated as a single source of groundwater where they are both saturated and are hydrologically connected. These systems can be hydrologically connected to the streams and rivers. 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 understood 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. There is limited connection from the glacial aquifers to the streams when tills or clays are present.

2.2.1.4 *Water Quality Quaternary*

The USGS water quality database reported water quality results from groundwater samples that included specific conductance in microsiemens per centimeter (µS/cm) as part of the field parameters collected during sampling events (USGS, 2017a). The samples from these wells were analyzed for major ions and other constituents including specific conductance. Specific conductance is an indicator of saline water. None of the groundwater wells sampled have records that are within the AEM survey area. With the AEM system used in this survey, it is not possible to discern the differences between the clay-containing material and variations in the specific conductance of the fresh water. In any case, there is no direct evidence of saline groundwater, or brackish groundwater, present in this survey area (USGS, 2015; USGS, 2017b; USGS, Water).

2.2.2 *Cretaceous Dakota*

The ***Kd*** in the LPSNRD AEM survey area which is adjacent to the LPSNRD AEM survey area contains resistive discontinuous eroded surfaces (AGF, 2017b). In certain areas where the ***Kd*** is dominated by sandstone/sand, it is an important aquifer. In other areas where the ***Kd*** is dominated by shale/clay, it acts as an aquitard. Nearly all information on the ***Kd*** is from borehole lithology logs along with limited outcrops in the project area. Most of the aquifer characteristic information for the project area comes from O'Connor (1987), with limited information from the USGS on selected wells in the LPSNRD. Specific yield for the ***Kd*** aquifer materials can only be provided by generic published results. However, O'Connor

(1987), made some estimates on specific capacity, hydraulic conductivity, and transmissivity for three high capacity wells which can be used as examples for this survey. These are presented in Table 2-2.

Table 2-2. Aquifer Characteristics for the Cretaceous Dakota (*Kd*) Fm (O'Connor, 1987)

Well Location: Section-Township-Range	Discharge Rate	Specific Capacity Gpm/ft	Hydraulic Conductivity ft/d	Transmissivity ft^2/day
NE $^1/_4$, S18-T14N-R12E	1,800	74	300	21,500
NW$^1/_4$, NE $^1/_4$, S35-T14N-R10E	400	26.7	110	7440
NE ¼, SW ¼, S 18-T13N-R12E	1,000	13.5	62	3,720

Water quality in the ***Kd*** is assumed to be similar to ***Q*** values (O'Connor, 1987) with the wells tested in LPSNRD for total dissolved solids being less than 500 mg/l or 782 µS/cm.

3 Additional Background Information

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

3.1 Borehole Data

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

The locations of all of the boreholes utilized in the LPSNRD AEM survey are indicated in Figure 3-1. A total of 78 CSD holes contained lithology information, 72 holes contained stratigraphic information, 49 holes contained geophysical log information from the "ELog" database, and 8 contained geophysical log information from the "GeoLog" database in the LPSNRD AEM survey area. There were also 352 DNR lithology logs that were part of the data delivery from the ENWRA Volume II report (Carney et al., 2015c) (locations indicated as "DNR Lithologic Logs (2015)" in the figure legends) as well as 752 additional DNR lithology logs added to encompass this LPSNRD AEM survey area.

A map showing all the borehole used for the whole of the LPSNRD AEM investigation is presented in Figure 3-1. Figure 3-2 presents the boreholes used in the Lower Salt Creek AEM reconnaissance survey area and the boreholes used in the Eagle, Elmwood, Union, Waverly, and Weeping Water block survey areas are presented in Figure 3-3, Figure 3-4, Figure 3-5, Figure 3-6, and Figure 3-7, respectively

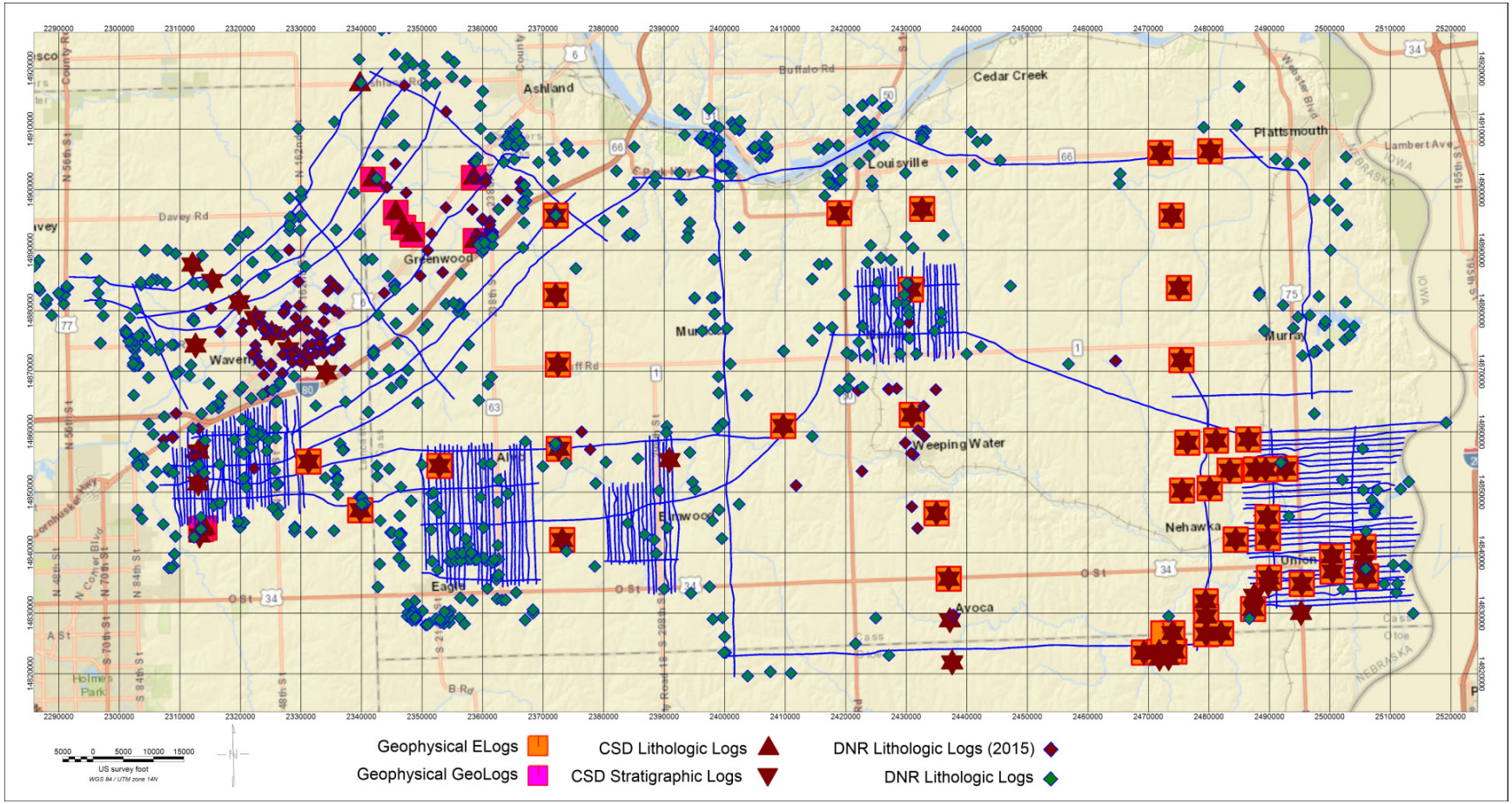


Figure 3-1. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in this study of the LPSNRD AEM survey area. The blue lines are the AEM flight lines. Projection is NAD83, UTM 14 North (feet).

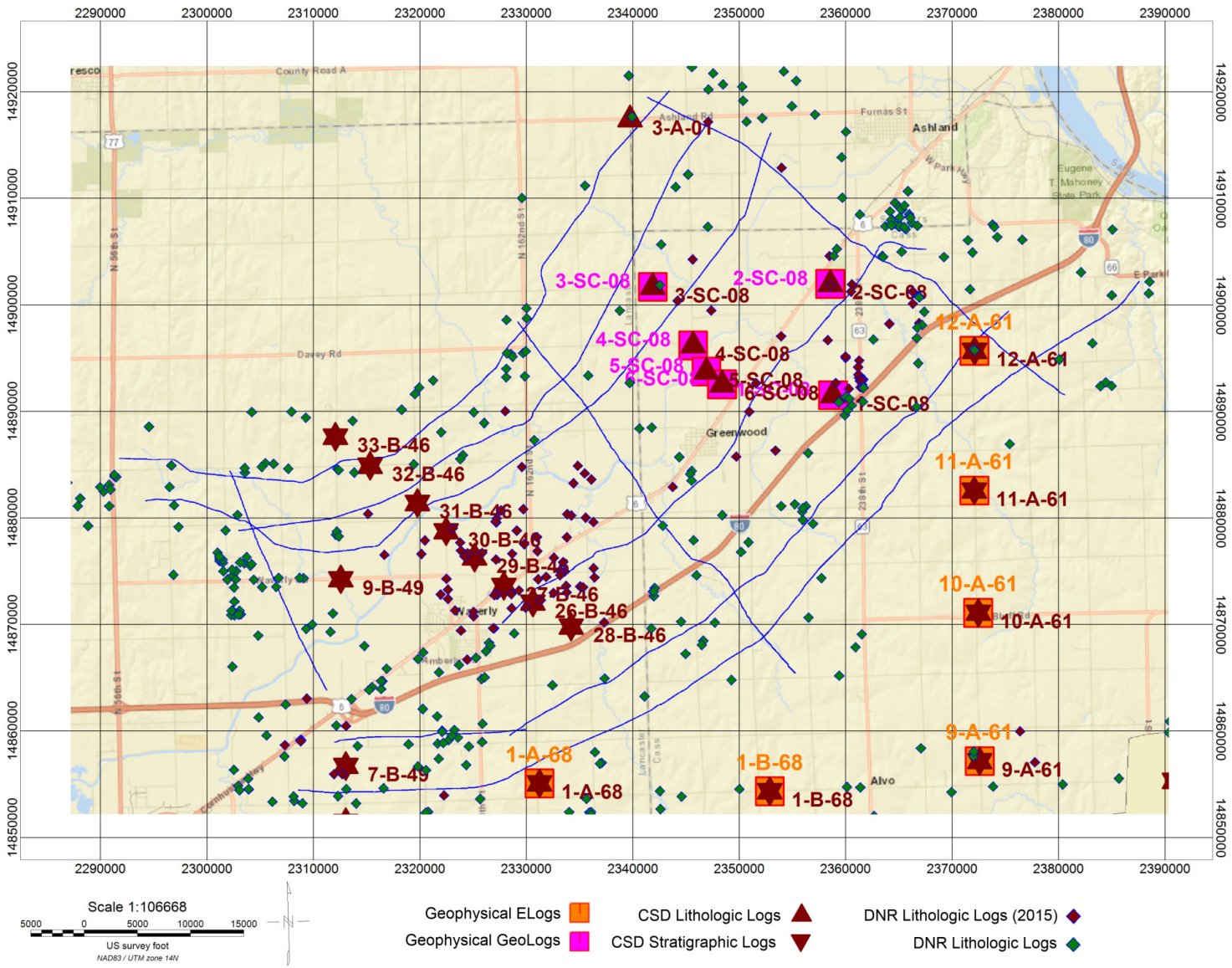


Figure 3-2. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Lower Salt Creek area of the LPSNRD AEM survey. The blue lines are the AEM flight lines.

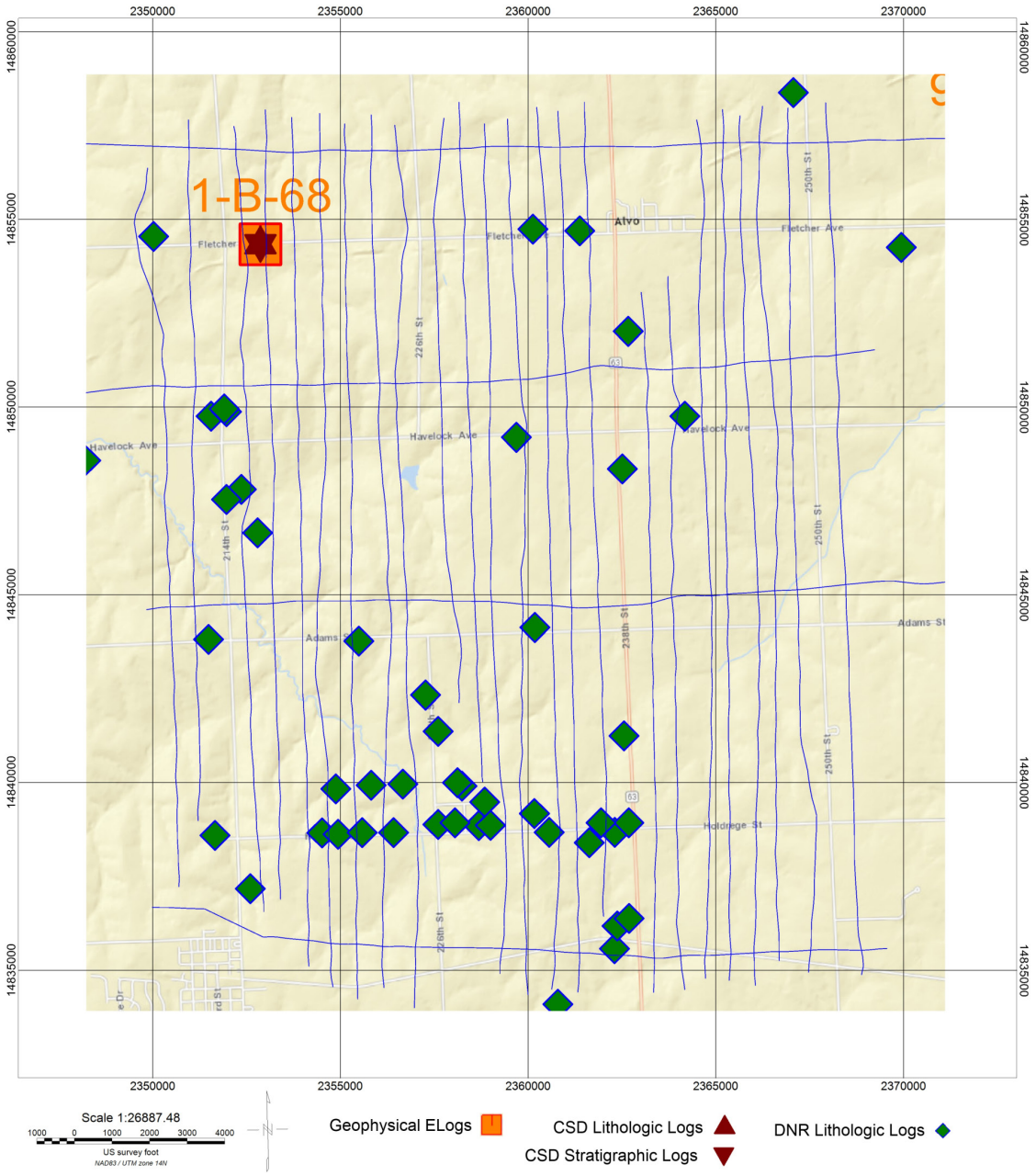


Figure 3-3. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Eagle block subarea of the LPSNRD AEM survey area. The blue lines are the AEM flight lines. Projection is NAD83, UTM 14 North (feet).

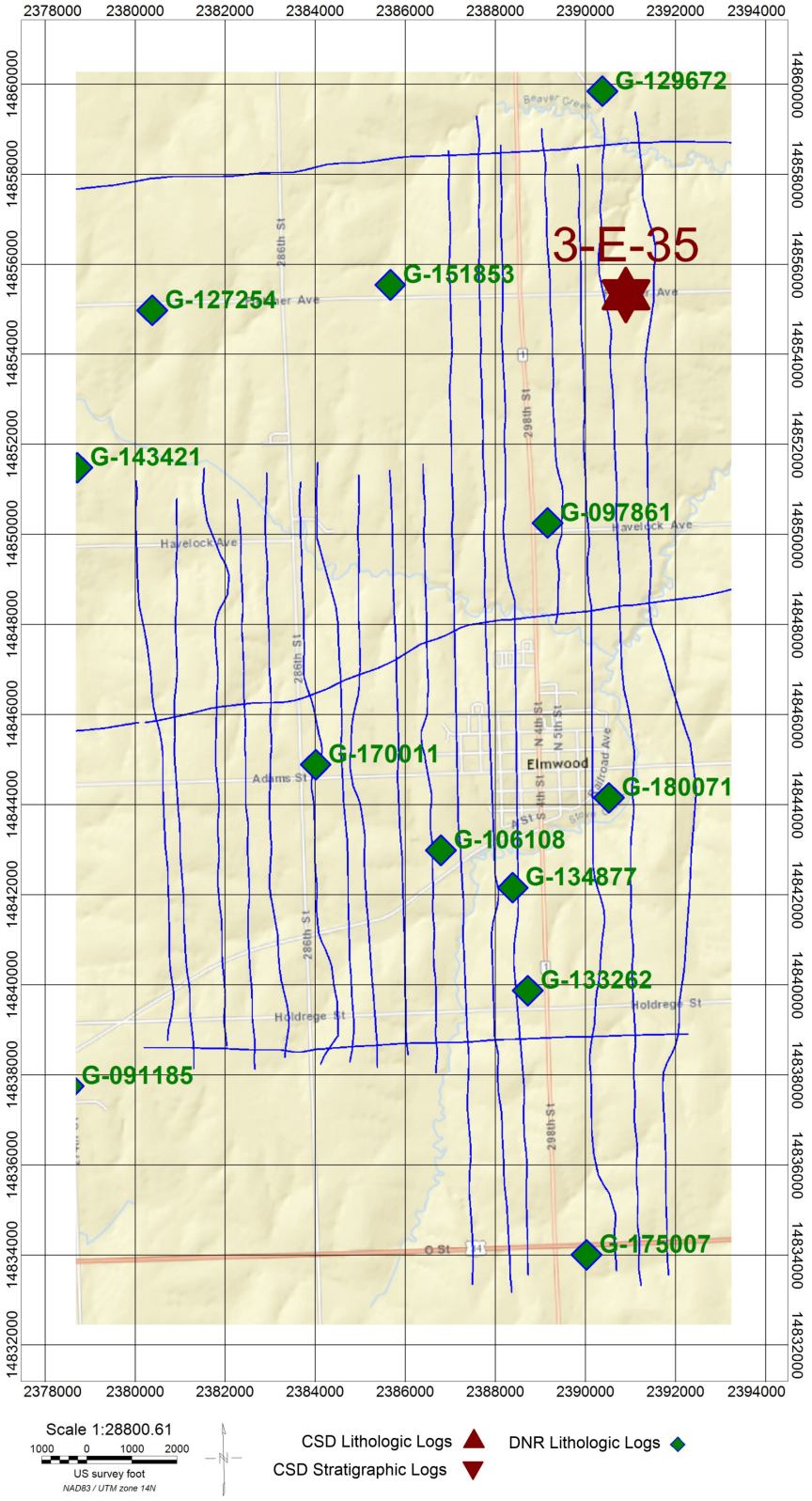


Figure 3-4. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Elmwood block subarea of the LPSNRD AEM survey area. The blue lines are the AEM flight lines. Projection is NAD83, UTM 14 North (feet).

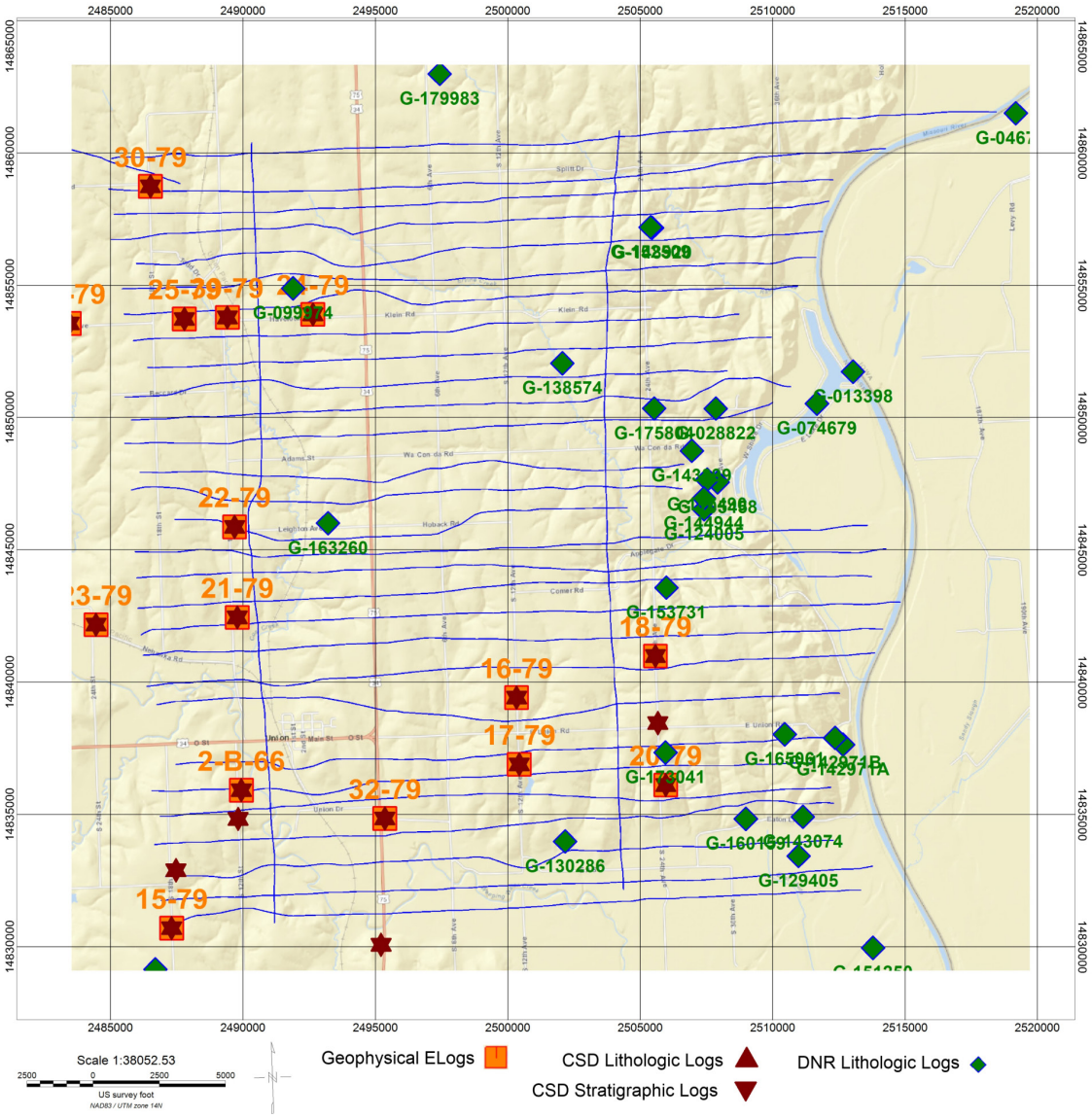


Figure 3-5. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Union block subarea of the LPSNRD AEM survey area. The blue lines are the AEM flight lines. Projection is NAD83, UTM 14 North (feet).

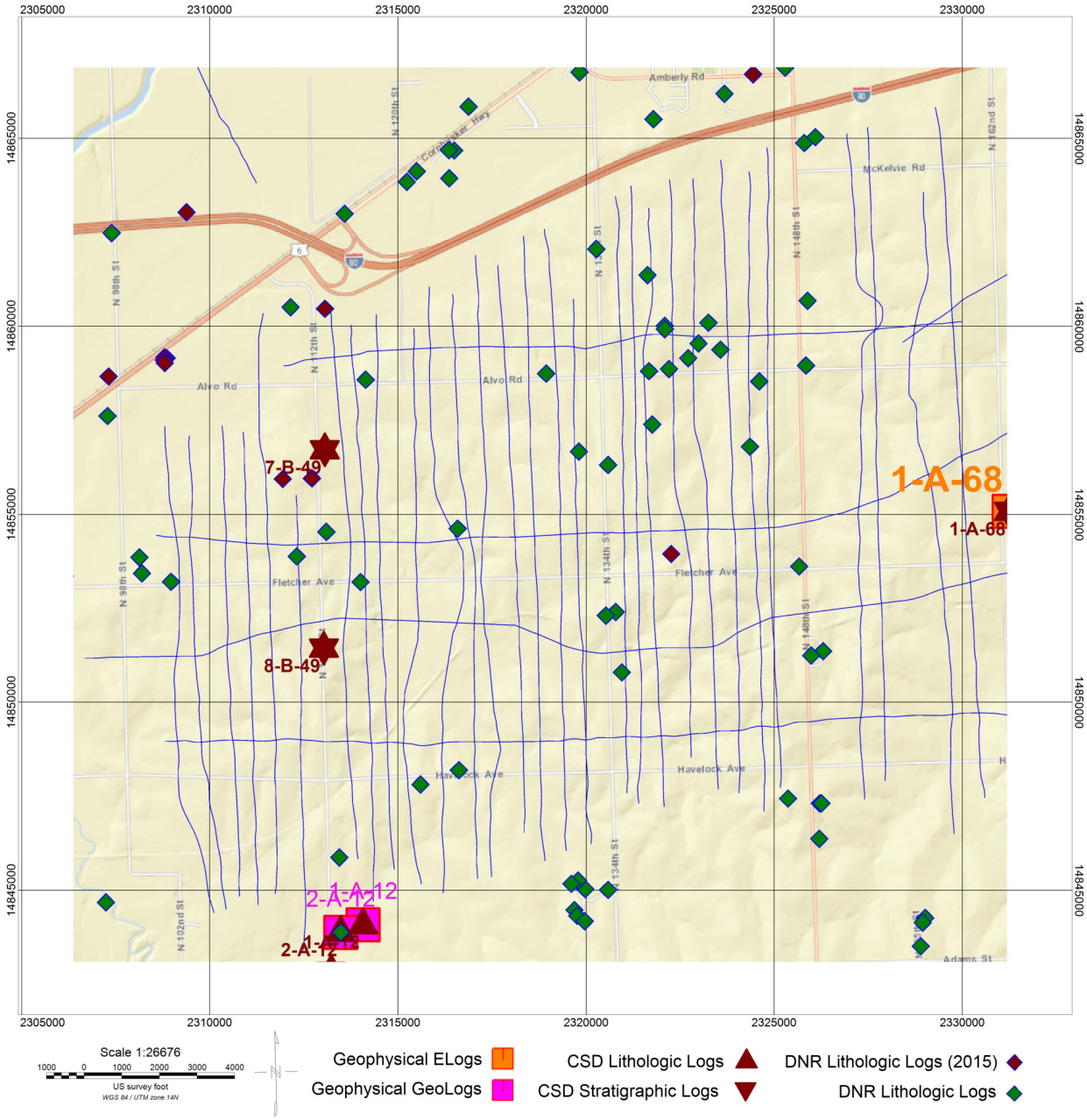


Figure 3-6. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Waverly block subarea of the LPSNRD AEM survey area. The blue lines are the AEM flight lines. Projection is NAD83, UTM 14 North (feet).

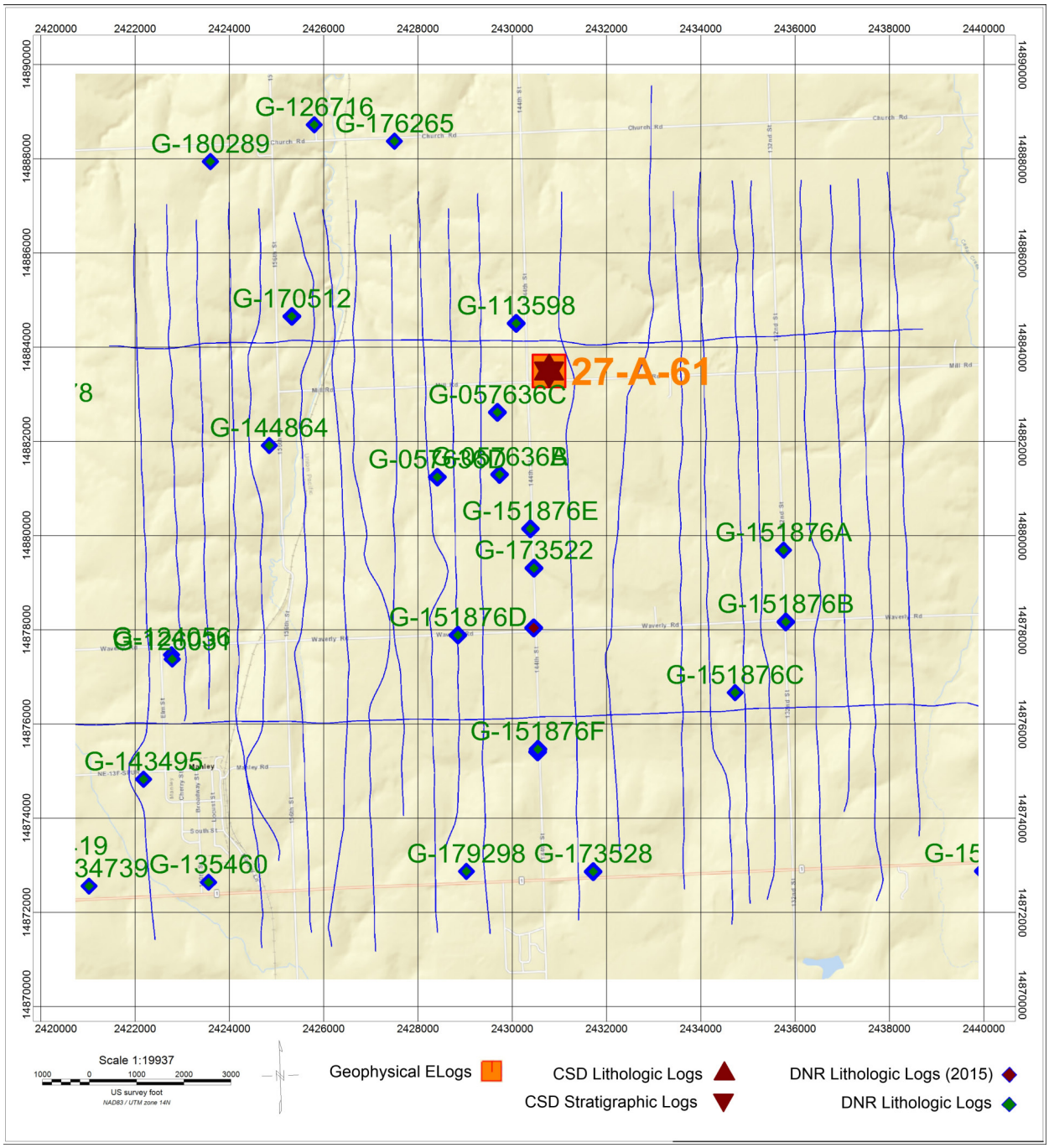


Figure 3-7. Locations of the Nebraska Conservation Survey Division (CSD) and Department of Natural Resources (DNR) boreholes used in the Weeping Water block subarea of the LPSNRD AEM survey area. The blue lines are the AEM flight lines. Projection is NAD83, UTM 14 North (feet).

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.

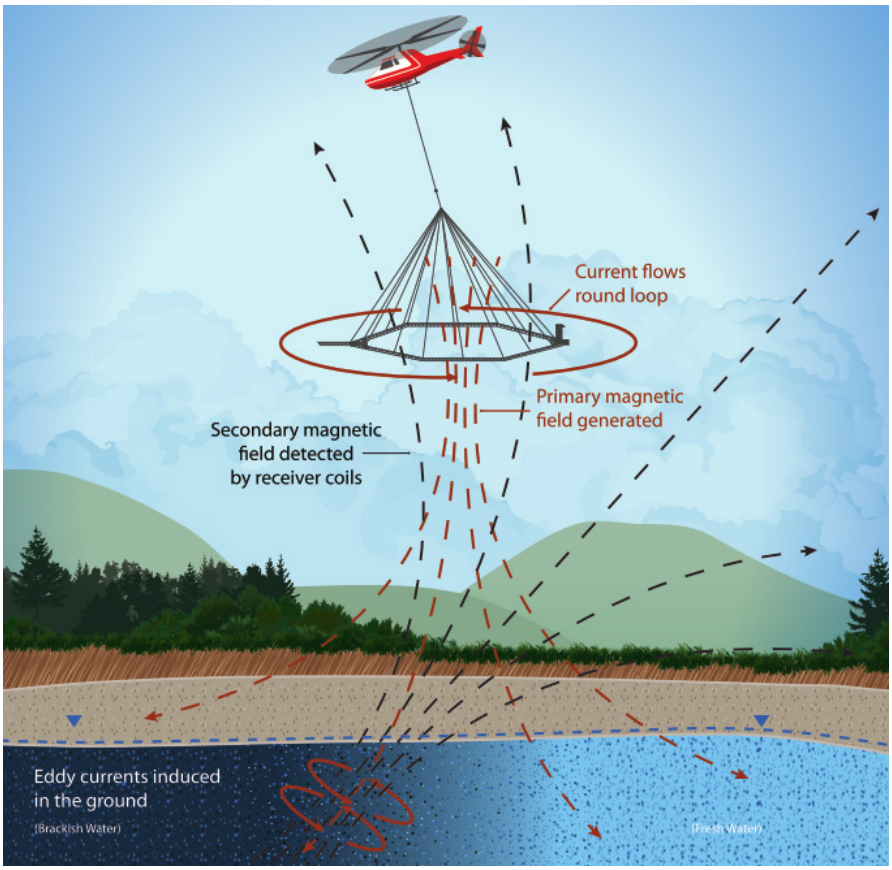


Figure 4-1. Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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 time-varying EM field, which also begins to decay, is generated within the subsurface. The decaying secondary EM field generates a current in a receiver (Rx) coil, per Ampere's Law. This current is measured at several different moments in time (each moment being within a time band called a "gate"). From the induced current, the time rate of decay of the magnetic field, B, is determined (dB/dt). When

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

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

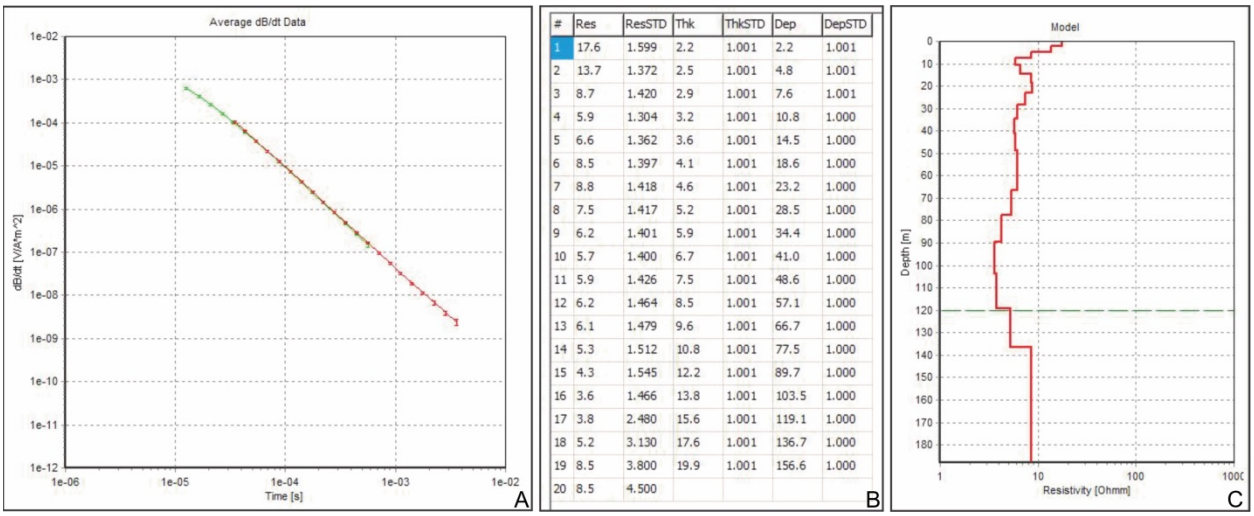


Figure 4-2. A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model.

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 LPSNRD, 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 Waverly AEM block survey area was about 3.5 miles in length in both east-west and north-south directions, for the Eagle AEM block survey area the flight lines were about 3.5 miles east-west and 4.5 north-south, for the Elmwood AEM survey block, the east-west flight lines were about 2.25 miles in length and just less than 5 miles in the north-south direction. The east-west lines in the Weeping Water AEM survey block were about 3.25 miles in length and the north-south flight lines were about 3 miles in length. The Union AEM block survey flight lines were about 5.5 miles in both north-south and east-west direction. The Lower Salt Creek southwest-northeast reconnaissance flight lines were on the order of 11.6 miles to 18 miles in length and the northwest-southeast ties lines ranged from about 4.5 miles to over 9 miles in length. The other reconnaissance AEM flight lines varied from about 16 miles (east-west) to over 31 miles (north-south) in length.

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.

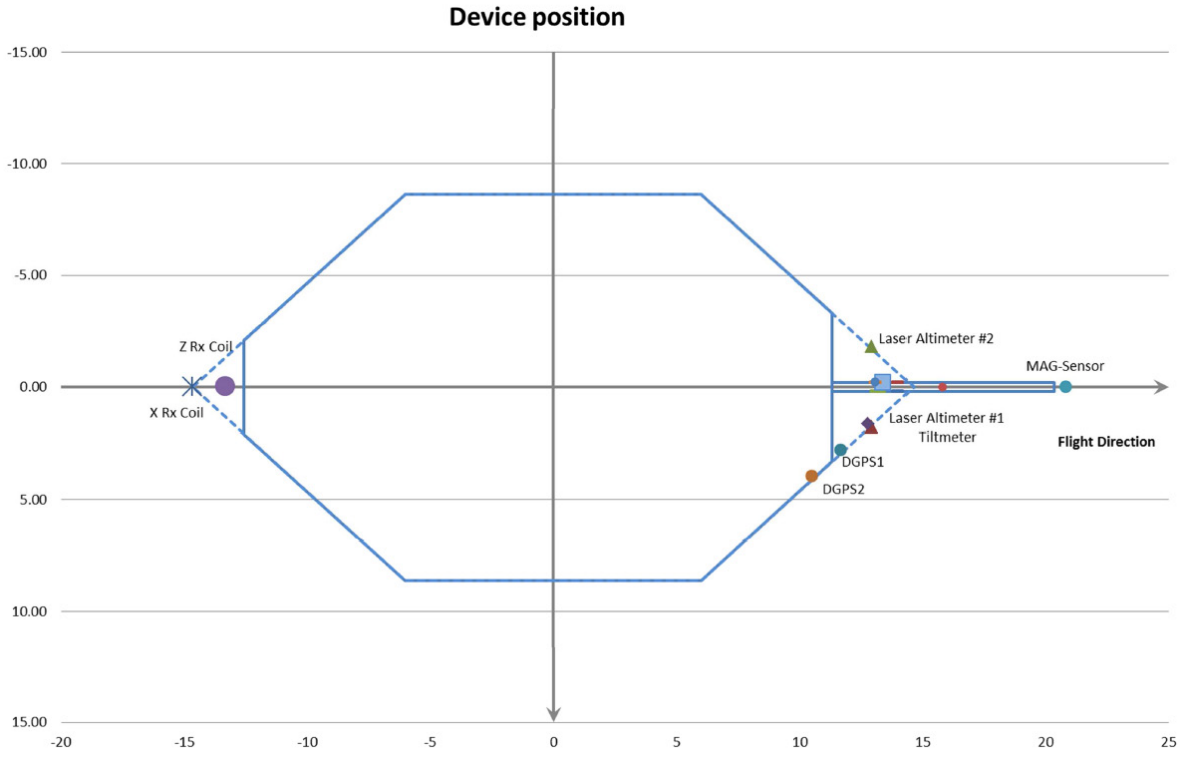


Figure 4-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1.



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 Plattsmouth Airport.

Instrument	Easting (ft)	Northing (ft)	UTM Zone
Magnetometer Base Station	2492414	14887427	14 N
DGPS Base Station (NEOM)	2443445	14982206	14 N
DGPS Base Station (NEDR)	2448843	14820844	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 another project which began in Ogallala, Nebraska. The helicopter and the SkyTEM304M system were located at the Plattsmouth 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.

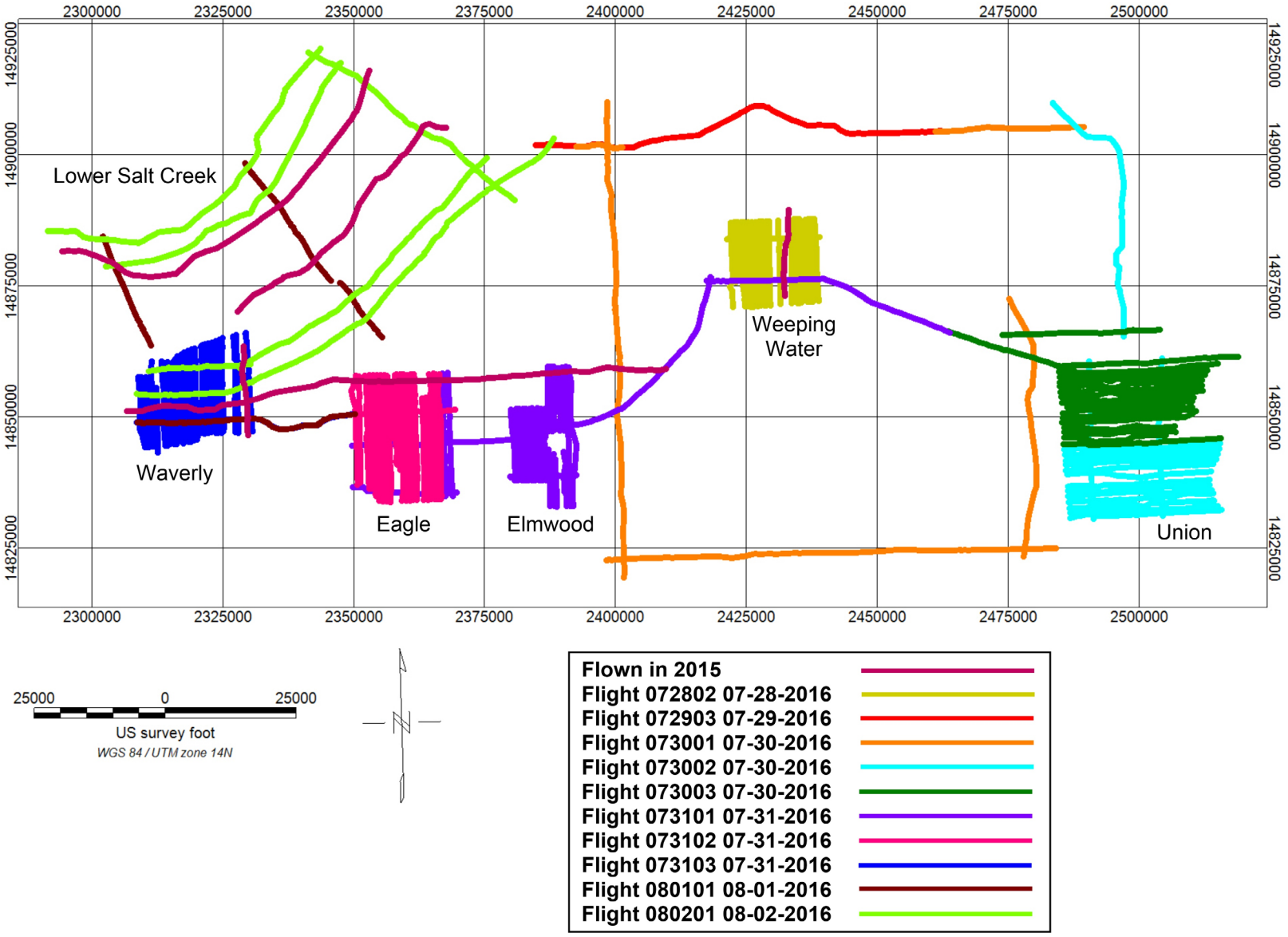


Figure 4-5. LPSNRD AEM flight lines grouped by acquisition date.

Approximately 693.4 line-miles (1,123.3 line-kilometers) were acquired over the LPSNRD AEM survey area on July 28-August 2, 2016 (Figure 4-5). The Plattsmouth Municipal airport was used for landing and refueling between production flights.

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 (Christensen et al., 2009; HydroGeophysics Group Aarhus University, 2011). The profile and depth slices were examined, and any remaining electromagnetic couplings were masked out of the data set.

After final processing, 539.3 line-miles (873.3 line-km) of data were retained for the final inversions for the LPSNRD AEM survey area. This amounts to a data retention of 77.8%. These high rates are the result of careful flight line planning and design.

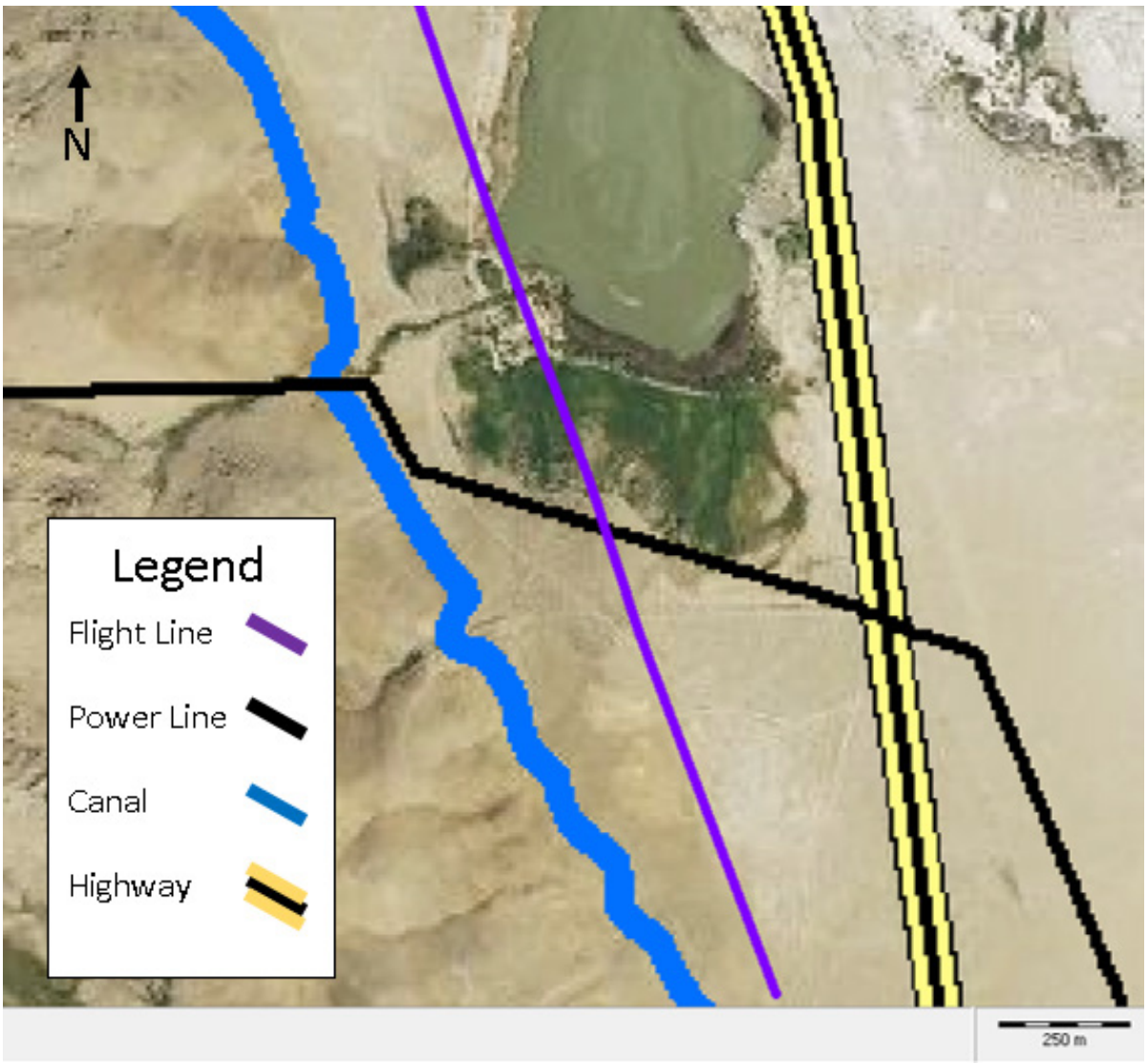


Figure 4-6. Example locations of electromagnetic coupling with pipelines or power lines.

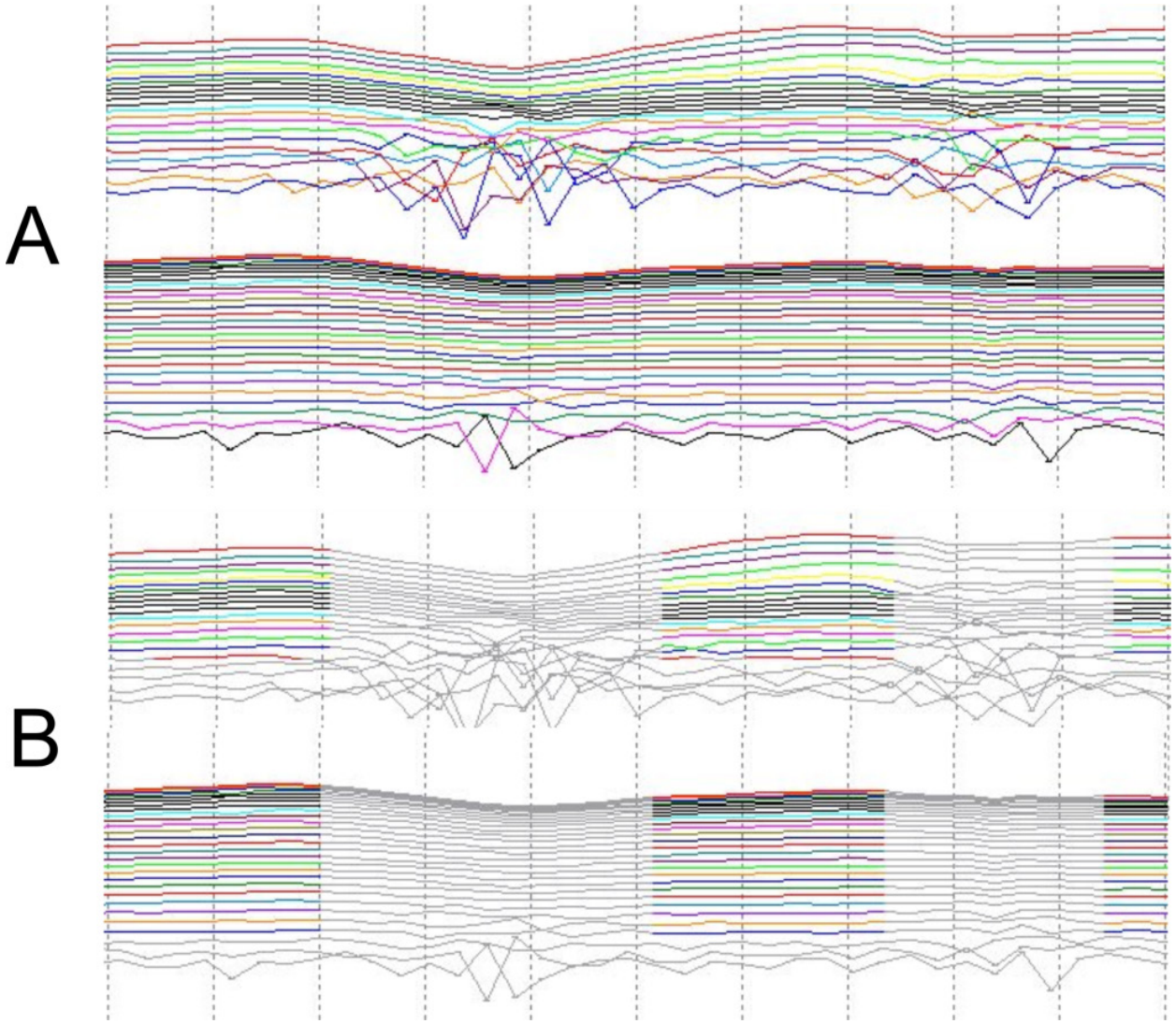


Figure 4-7. Example of AEM data affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

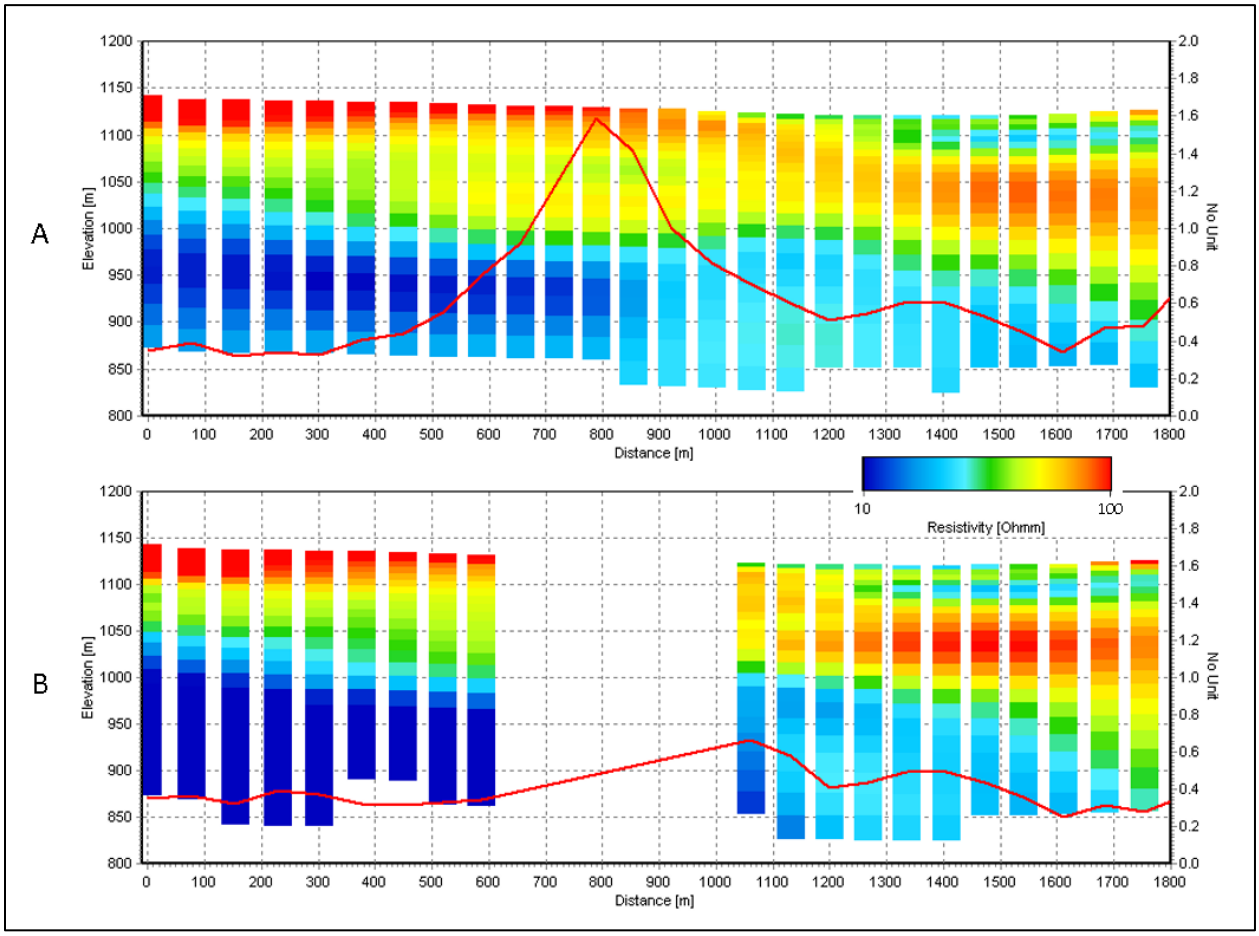


Figure 4-8. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

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 LPSNRD AEM survey are presented in Figure 4-9. The LPSNRD-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 4-10.

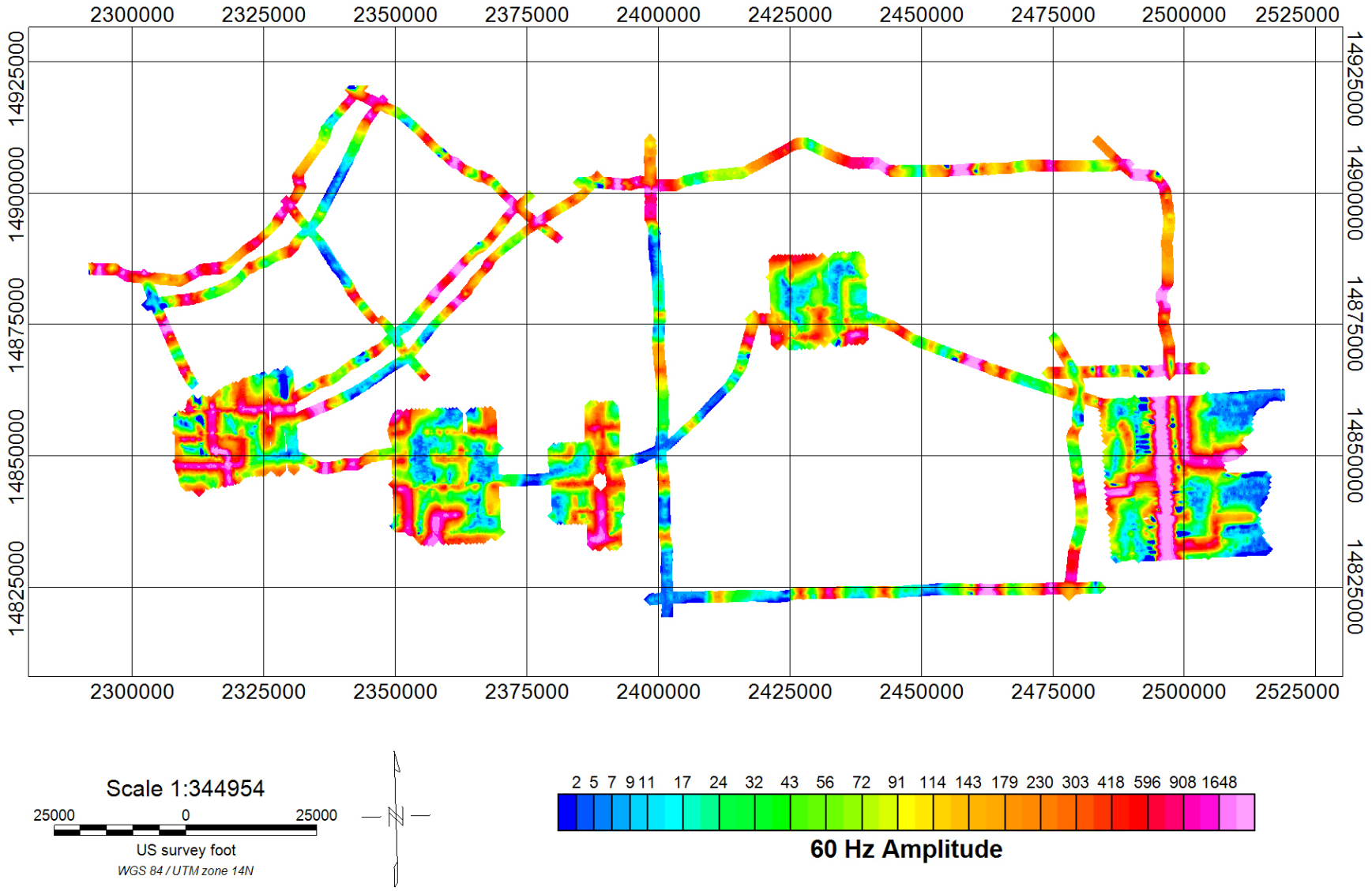


Figure 4-9. Power Line Noise Intensity (PLNI) map of the LPSNRD AEM survey area.

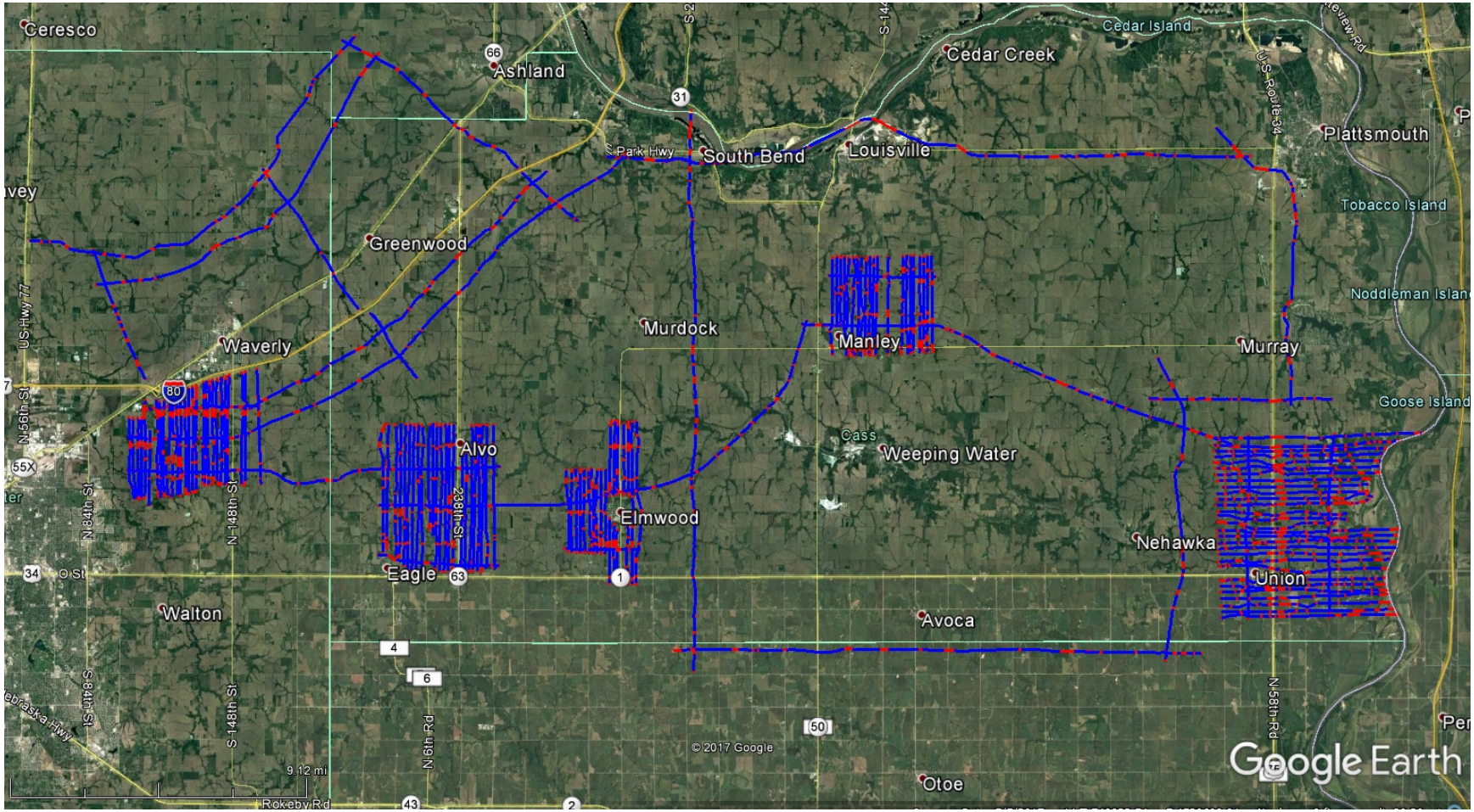


Figure 4-10. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LPSNRD AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix_3_Deliverables\KMZ.

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 4-11 shows the magnetic Total Field intensity data for the LPSNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). These data are used in decoupling efforts.

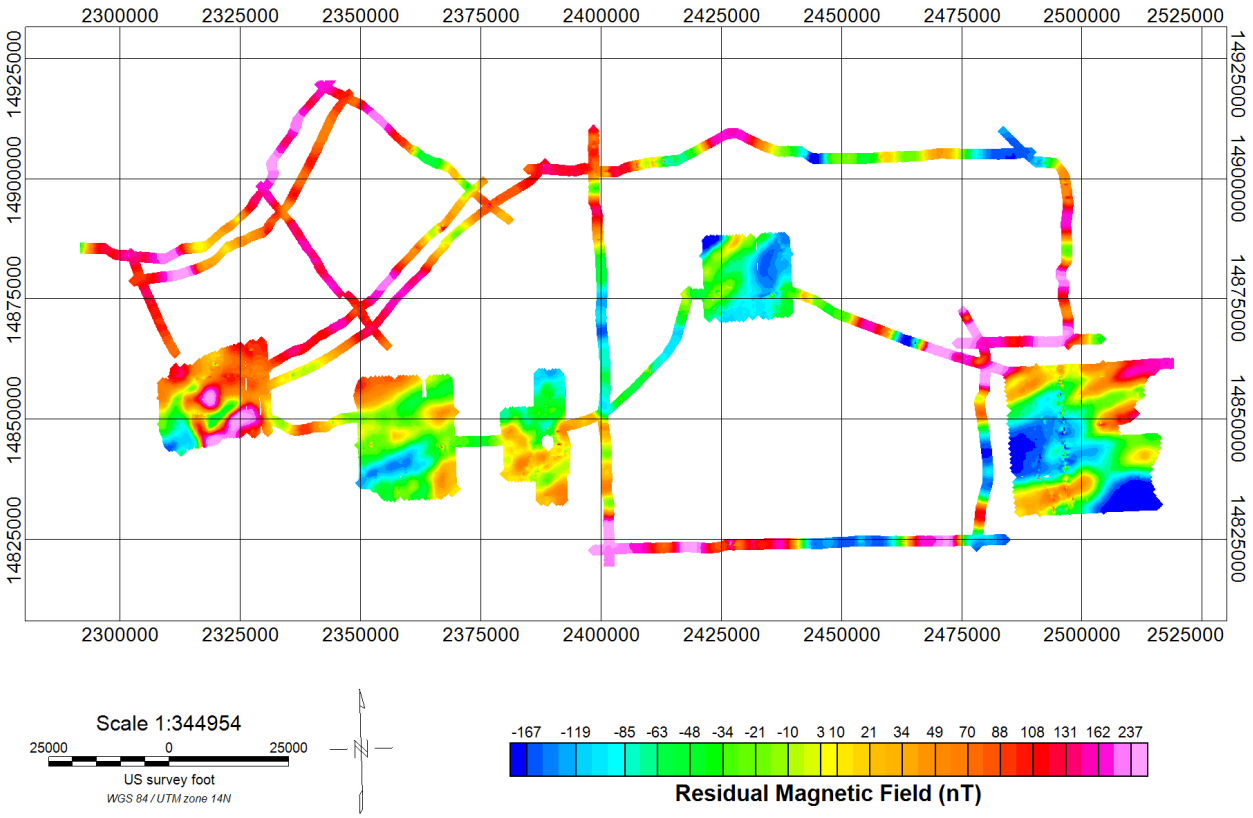


Figure 4-11. Magnetic Total Field intensity data for the LPSNRD AEM survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed. There is noise in the Union Block in the north-south direction along a powerline that can be observed in the PLNI image (Figure 4-9) and in the data As-Flown-Retained image (Figure 4-10).

For comparison purposes, images of magnetic Total Field data collected by the USGS (Sweeney and Hill, 2005) are presented in Figure 4-12 for the LPSNRD AEM survey area. 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 LPSNRD 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.

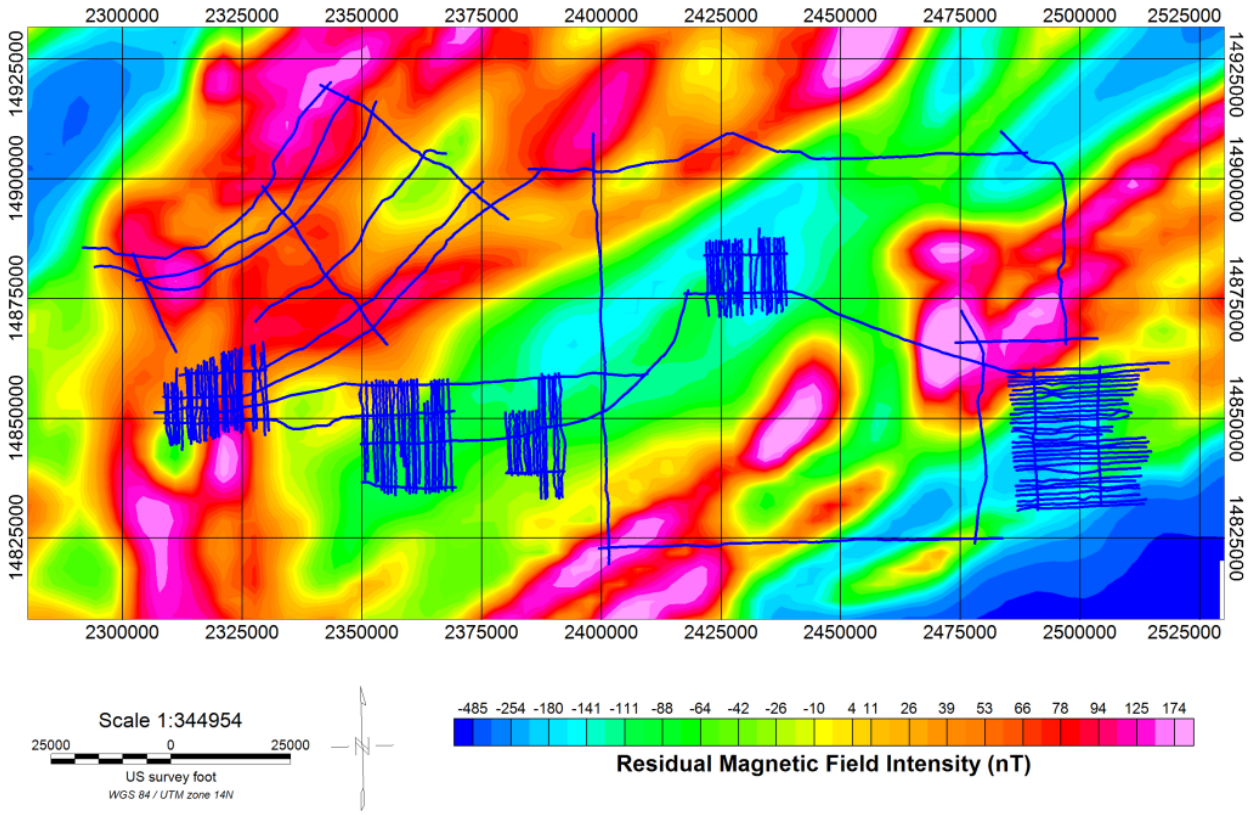


Figure 4-12. USGS magnetic Total Field intensity data for the LPSNRD AEM survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5-mile line spacing and upward continued to a reference elevation of 1000 ft. The AEM survey lines are marked in blue.

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 LPSNRD 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 4-13) 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			

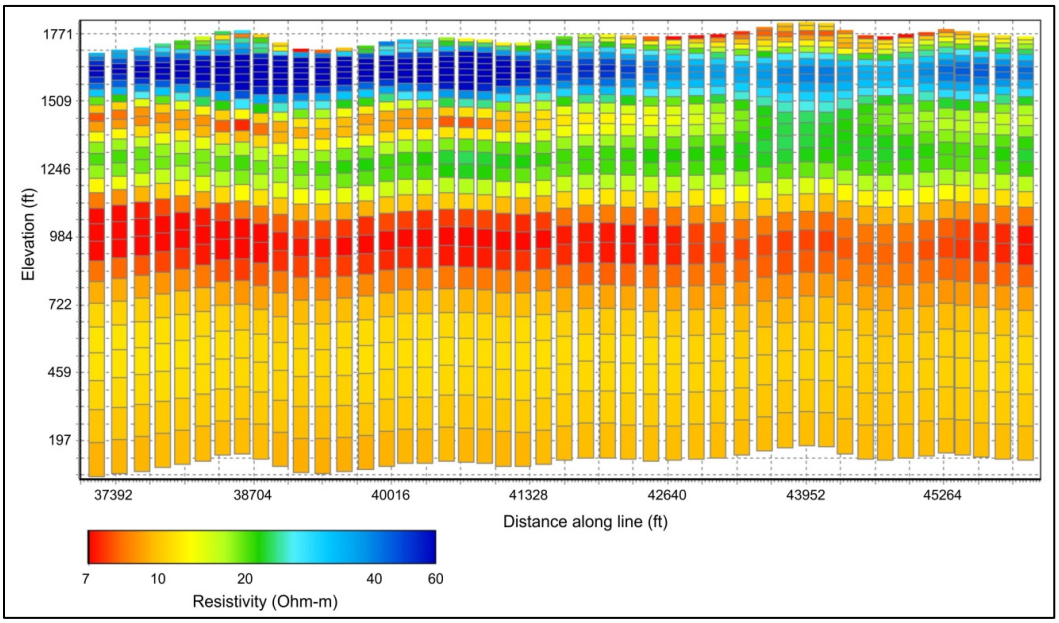


Figure 4-13. An example of an AEM profile illustrating increasing model layer thicknesses with depth.

Figure 4-14 presents a histogram of the LPSNRD SCI inversion data/model residuals. Maps of data residuals for the AEM study area are presented in Figure 4-15.

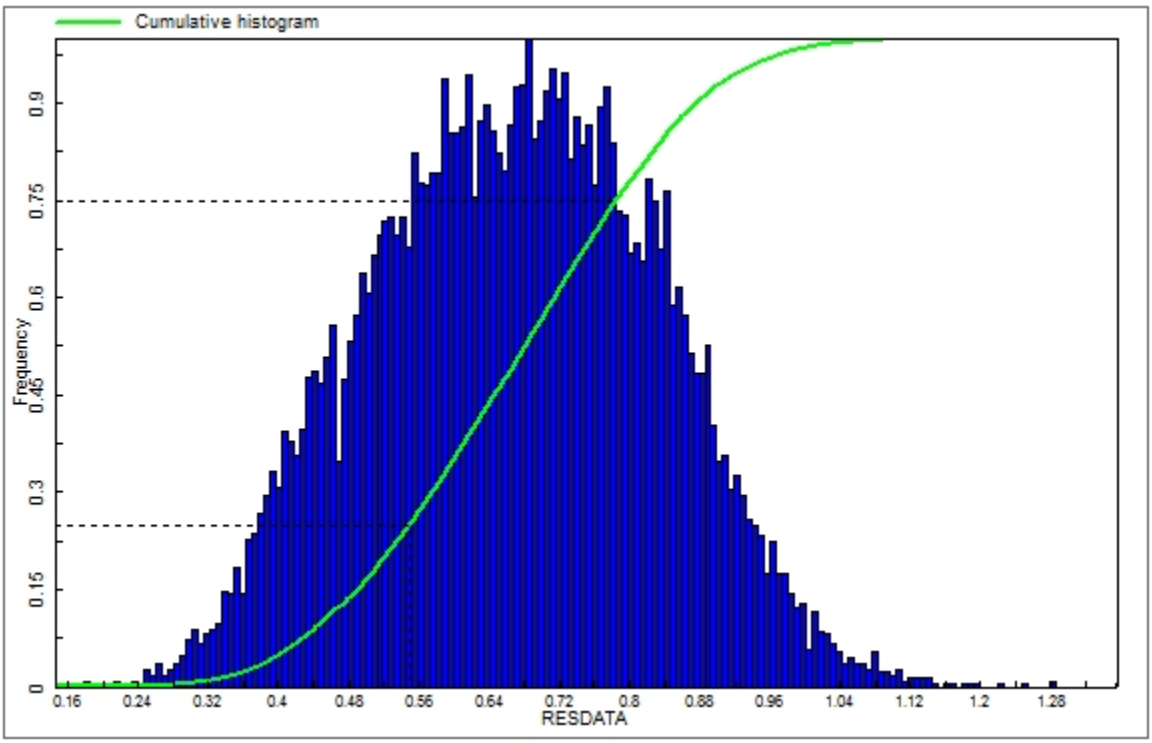


Figure 4-14. Data/model residual histogram for the LPSNRD SCI inversion results.

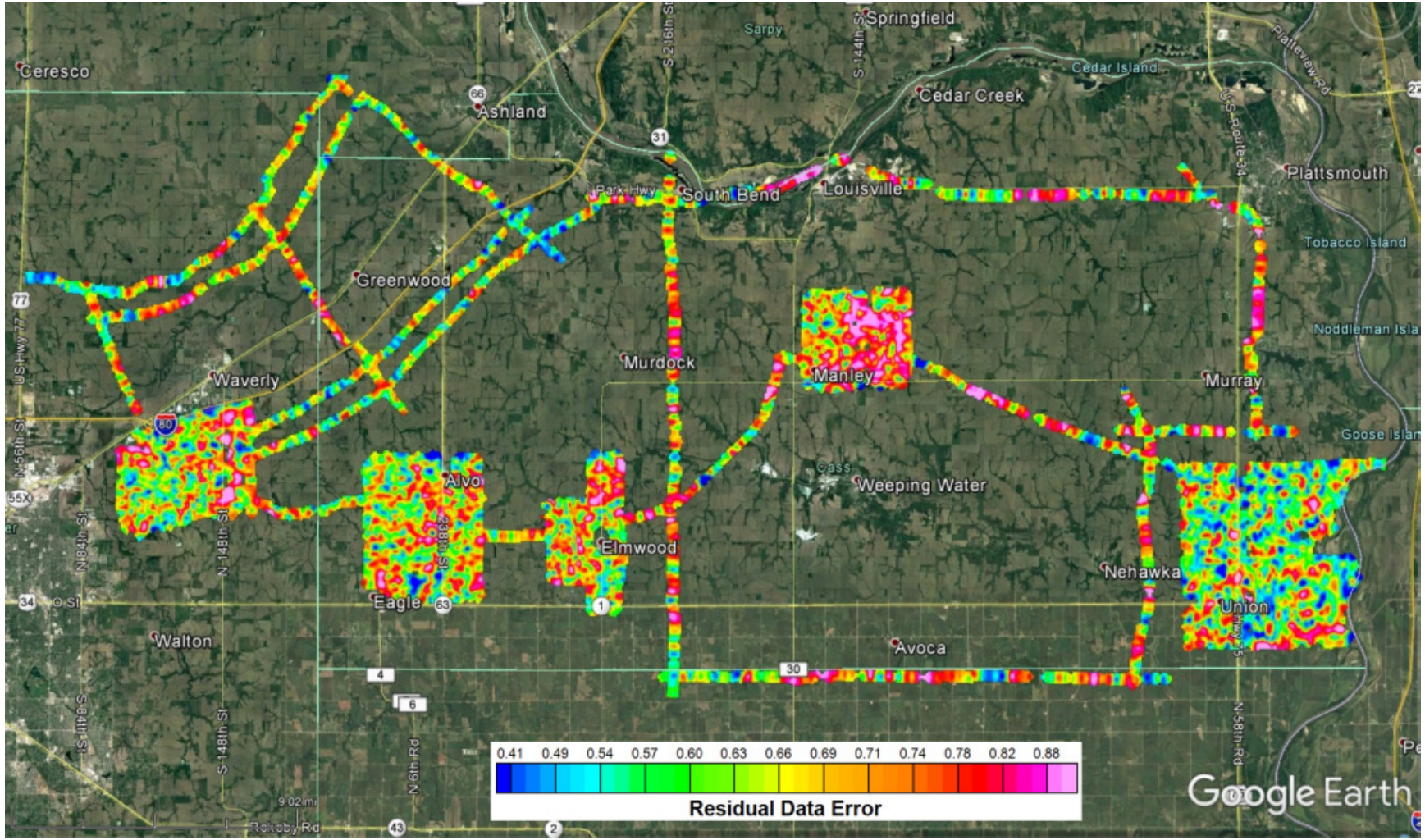


Figure 4-15. Map of data residuals for the LPSNRD SCI inversion results.

5 AEM Results and Interpretation

This section provides the details on the process involved in the interpretation of the LPSNRD 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 LPSNRD 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. Two lines were deleted due to repeats within the data set, L142902 and L170602. A portion of the LPSNRD has had previous AEM data collection summarized in Carney et al (2015c). Table 5-2 lists the 2015 SkyTEM508 AEM flight lines that were combined with the LPSNRD 2016 AEM dataset. A total of approximately 51.7 line miles (83.8 line-km) from the 2015 survey were added to the merged 2015-2016 data set. Figure 4-5 shows the 2015 data in relation to the 2016 survey.

Table 5-1. Combination of flight lines within LPSNRD

Original Source Lines	Direction	New Line
L142901, and L142903	East-West	L285804
L142701, and L143701	East-West	L286402
L143902, L143903, and L144101	East-West	L431906
L170401, and L170601	Southeast-Northwest	L341002
L170801, and L171001	Southeast-Northwest	L341803
L184401, and L185801	North-South	L390202
L184601, and L186001	North-South	L390602
L184801, and L186201	North-South	L391002
L185201, and L186401	North-South	L391602

Table 5-2. Combination of 2015 AEM data (Carney et al. 2015c) within the 2016 LPSNRD AEM dataset

2015 Lines	Area	Direction
L100301	Salt Creek Block	Curved Southwest to Northeast
L100401	Salt Creek Block	Curved Southwest to Northeast
L100702	Waverly, Eagle, and Elmwood Blocks	East-West
L200801	Waverly Block	North-South
L201101	Weeping Water Block	North-South

A comparison of the data collected in 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 set of three parallel north-south line within the Waverly Block displaying two outer lines from the 2016 LPSNRD SkyTEM 304M AEM inversions and the center line from 2015 SkyTEM 508 AEM inversions. Inspecting Figure 5-1, the resistivity values continue along the same trend. The combination of the two datasets indicates that there is no observable bias that was not removed from the data prior to inversion. Figure 5-2 is a set of three parallel east-west lines within the Waverly Block. Line L100702 (center line) was collected with the SkyTEM508 in 2015. Even though the lines are not directly up against each other the comparison of the upper line and the bottom line collected in 2016 and the center line collected in 2015 show good spatial correlations.

5.1.2 Construct the Project Digital Elevation Model

To ensure that the elevation used in the project is constant for all the data sources (i.e. boreholes and AEM) a Digital Elevation Model (DEM) was constructed for the LPSNRD survey. The data was 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 5-3 is a map of the DEM of the LPSNRD 2016 Survey area showing a vertical relief of 451 ft with a minimum elevation of 923 ft and a maximum elevation of 1,374 ft. This DEM was used to reference all elevations within the LPSNRD AEM and borehole datasets. A subset DEM was constructed for each of the six survey blocks (Eagle, Elmwood, Salt Creek, Union, Waverly and Weeping Water (Section 1-1)) and can be found in *Appendix 2-Interpretive surfaces*.

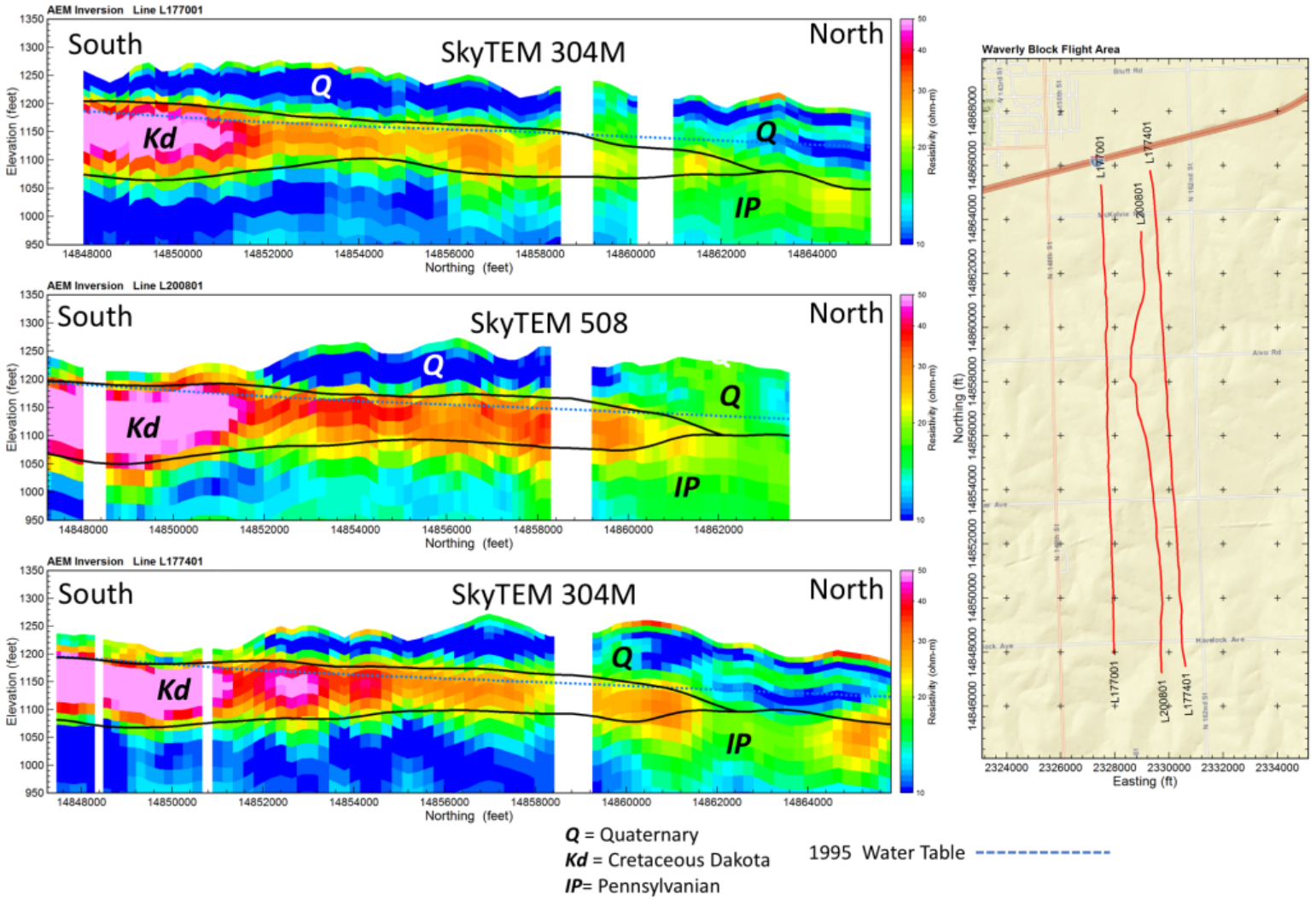


Figure 5-1. Example of a profile view of a three north-south flight lines within the Waverly Block. The top profile L177001 (western-most) was collected in 2016 with the SkyTEM304M; the middle profile line L200801 was collected in 2015 with the SkyTEM508; and the bottom profile line L177401 (easternmost) was collected in 2016 with the SkyTEM304M. Geological interpretations on the profile include the Quaternary (*Q*), Cretaceous Dakota (*Kd*), and the undifferentiated Pennsylvanian (*IP*). The black line indicates the interpreted contact of the *Q* and *Kd* as well as the *Kd* and *IP*. The 1995 Conservation and Survey Division Water Table is indicated as a dashed blue line (NE CSD, 1995).

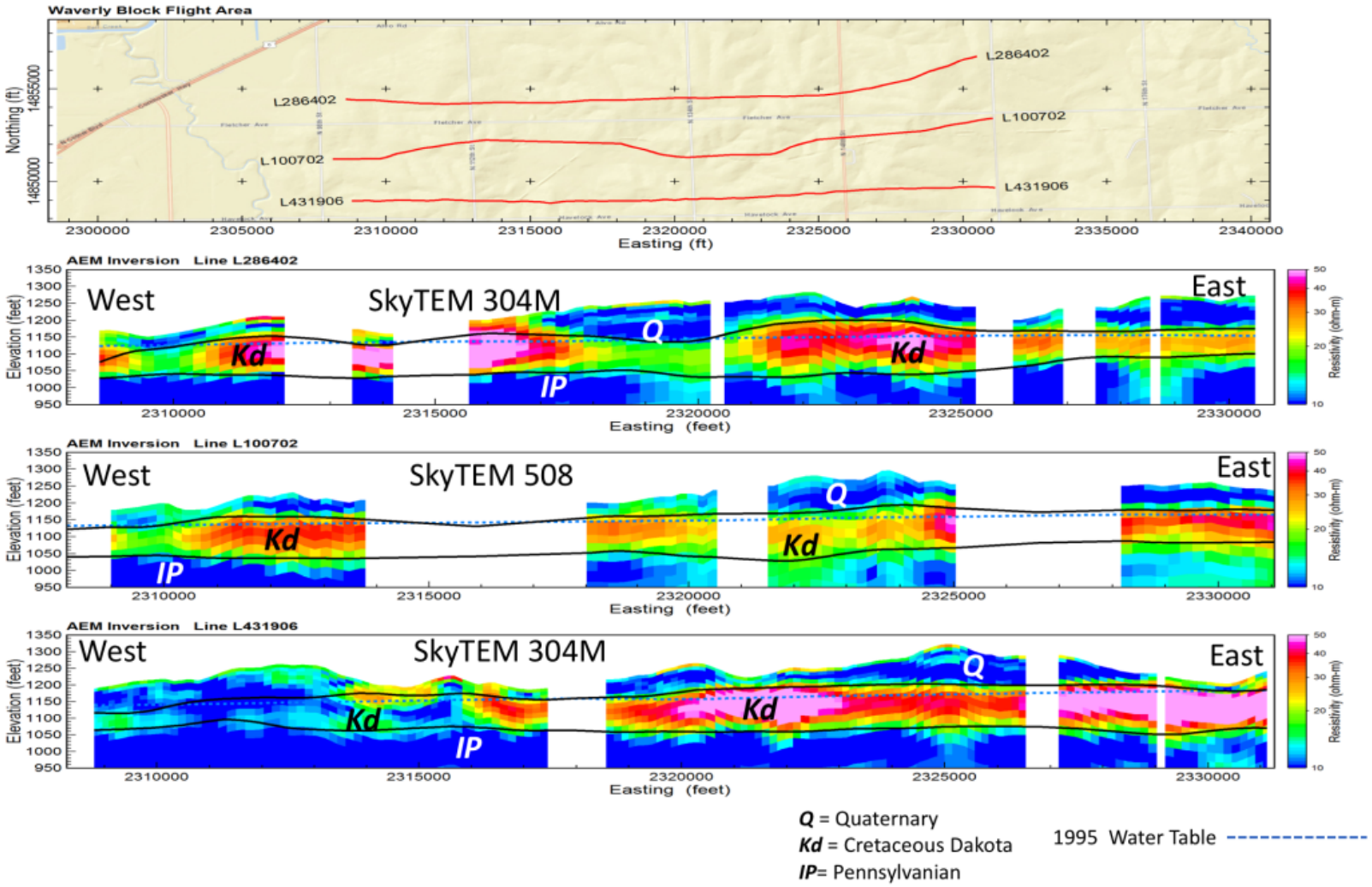


Figure 5-2. Example of a profile view of a three east-west lines within the Waverly Block. The top profile L286402 (northernmost) was collected in 2016 with the SkyTEM304M; the middle profile line L100702 was collected in 2015 with the SkyTEM508; and the bottom profile line L431906 (southernmost) was collected in 2016 with the SkyTEM304M. Geological interpretations on the profile include the Quaternary (*Q*), Cretaceous Dakota (*Kd*), and the undifferentiated Pennsylvanian (*IP*). The black line indicates the interpreted contact of the *Q* and *Kd* as well as the *Kd* and *IP*. The 1995 Conservation and Survey Division Water Table is indicated as a dashed blue line (NE CSD, 1995).

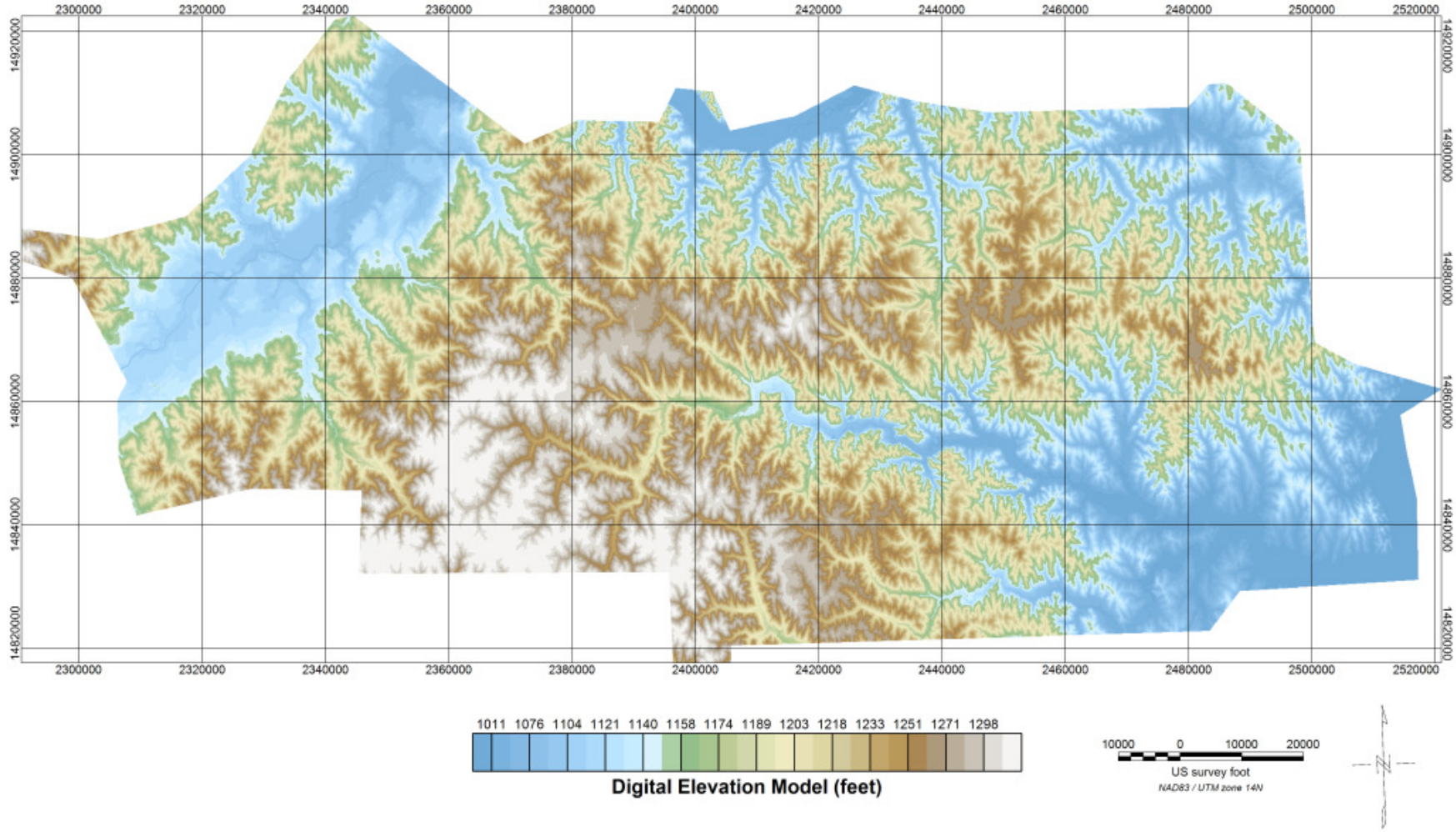


Figure 5-3. Map of the Digital Elevation Model for the 2016 LPSNRD AEM survey area. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2016). North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

5.1.3 Interpretative 2D Profiles

After final combination of the AEM data, characterization of the subsurface was performed in cross-section format using Encom PA (DatamineDiscover, 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 Dakota Group (***Kd***), and the top of the undifferentiated Pennsylvanian (***IP***) units. While there is much detail in the AEM of the Pennsylvanian and lower units no attempt was made at the interpretation of the units nor the obvious structure in those units. Figure 5-4 is a cross section displaying the changes that are observable in the ***IP*** units within the LPSNRD data set. The interpreted geological units included the ***Q*** and ***Kd*** from the upper surface of the model to the top of the ***IP***. The Depth of Investigation (DOI) for the 2015 and 2016 AEM datasets was below the top of the ***IP*** in all locations. Due to the need to focus on the units above the ***IP***, the profiles have had the maximum depth set to zoom into the ***Q*** and ***Kd*** units of interest in the hydrogeological framework. The interpretive process benefited from the use of CSD and NE-DNR borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map and bedrock configuration maps (Burchett, 1982; Burchett, 1983; Burchett, 1986). The interpretation began with picking the ***IP***, ***Kd*** and ***Q*** contacts. The process was iterative around the eroded segments of the ***Kd***.

The interpretation of the top of the ***IP*** within the LPSNRD included examining the AEM profile section for a typically lower electrical resistivity layer that was also indicated in the NE-DNR borehole logs as the base of aquifer or a limestone lithology. Many of the CSD as well as the NE-DNR borehole logs stop at the ***IP*** due to that stratigraphic unit not being an aquifer, due to it being composed predominantly of interbedded limestone and shale. Many of the CSD boreholes have stratigraphic calls that assist in the location of the ***IP***. 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, and the NE-DNR boreholes were set to between a quarter mile and half mile or 1,340-2,640 ft. In some areas, the changes in resistivity between the ***IP*** and either the ***Q*** and/or ***Kd*** were very subtle. In these areas, the basic trend of the unit was interpolated from areas where boreholes confirmed the presence of the ***IP***.

The top of the ***Kd*** is a much more challenging unit to interpret when there are sandy/resistive ***Q*** materials. This is due to the highly variable resistivity of the ***Kd*** and the ***Q***. The key to unraveling these stratigraphic boundaries lies in the use of the CSD and NE-NDR boreholes. Where present, the CSD stratigraphy is invaluable and provides a clear indication of the location of the top of the ***Kd***. Using the NE-DNR wells requires inspection of the lithology looking for indications of shale and sandstone in the lithology. These are clear indications of the ***Kd*** and not ***Q*** sediments. Care needs to be taken as many areas of the ***Kd*** contain sand, and not sandstone. Using the projection of the interpretive picks of the surrounding areas assists in the interpretation of the location of the ***Kd***. Also, in much of the LPSNRD, the ***Q*** sediments are composed of fine grained till, clay, and silt and form an electrically conductive layer over the generally more resistive ***Kd***.

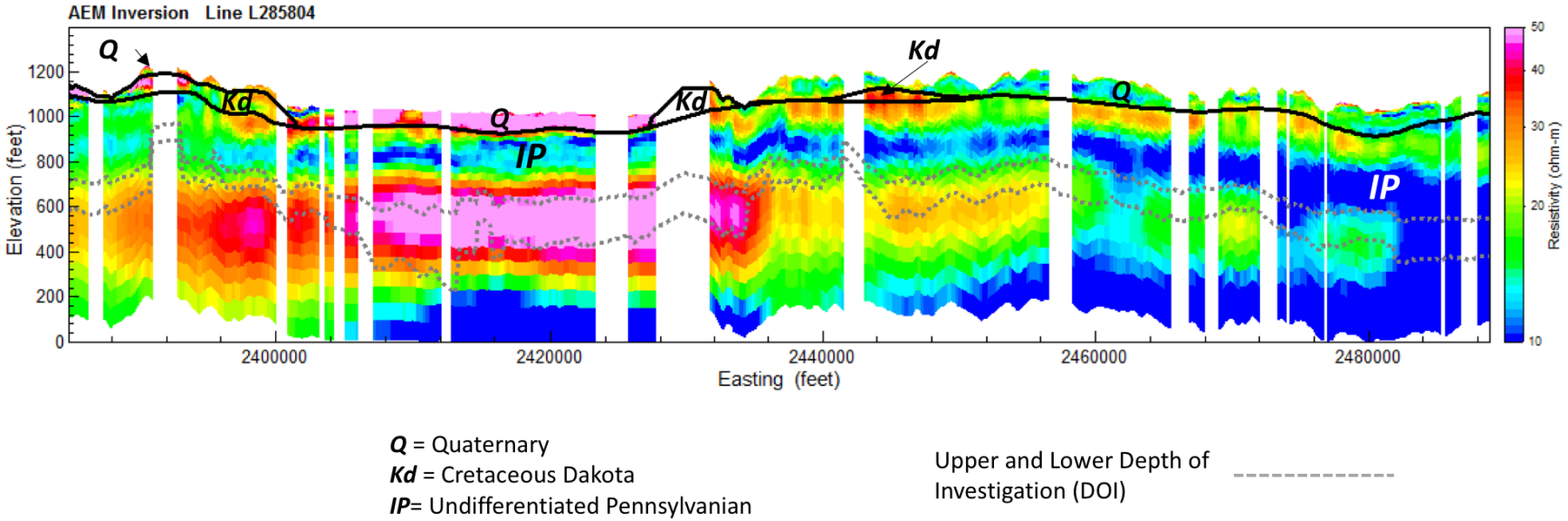


Figure 5-4. Selected profile from the LPSNRD AEM dataset showing the full depth of the AEM inversions and the changes in the resistivity structure below the undifferentiated Pennsylvanian contact. Black lines indicate stratigraphic contacts. Gray dashed lines indicated upper and lower depth of investigation (DOI).

Figure 5-5 presents an approximately 19.7-mile-long east-west line, L100702, that extends eastward from the Waverly Block through the Eagle to east of the Elmwood block. The upper map on Figure 5-5 is the bedrock geology (Burchett, 1986) overlain with the location of the flight line. This line illustrates the eroded ***Kd*** overlying the ***IP***. Many NE-DNR registered well lithology logs lie within one quarter of a mile of the flight line. Six CSD test holes are within one mile of the flight line. In the west, the NE-DNR registered wells clearly indicate the presence of sandstone within the ***Kd*** and then transition to a more sand and shale dominated ***Kd*** in the east. While the ***IP*** exhibits a range of resistivities along this line, it is readily identified in the CSD test holes and as relative depths in the NE-DNR registered wells. The ***Q*** is composed of low resistivity units that correlate with till, clay, and silt in the CSD test holes and the NE-DNR registered wells.

Figure 5-6 presents an approximately 6.6-mile-long southeast to northwest line, L341803, that is perpendicular to Lower Salt Creek. The upper map on Figure 5-6 is the bedrock geology (Burchett, 1986) and the location of the flight line. This line displays the eroded ***Kd*** within the center of the Salt Creek area. Three CSD test holes are within one mile of the flight line. There is a resistive section of ***Q*** within the center of the line, with the ***Q*** directly overlying the ***IP***. The NE-DNR registered wells indicate a section of sandstone on the northwestern end of the line. There is also a segment of sandstone on the southeastern end of the line. The ***IP*** exhibits a range of resistivities along this line, but is identified by the CSD test holes and the relative depths of the NE-DNR registered wells. The contact is also identified by the decrease in resistivity within the ***IP*** as compared to the ***Q*** and the ***Kd***.

Figure 5-7 is an approximately 4.4-mile-long north-south line, L180401, in the Eagle Block. The upper map on Figure 5-7 is the bedrock geology indicating ***Kd*** (Burchett, 1986) and the location of the flight line. This profile illustrates the ***Kd*** overlying the ***IP*** with a low resistivity ***Q*** cover. Many NE-DNR registered well lithology logs lying within one half of a mile of the flight line clearly indicate the presence of sandstone within the ***Kd.*** The ***Kd*** in the center of the flight line shows an increase in the resistivity. While the ***IP*** exhibits a range of resistivities along this line, it is still identified by the NE-DNR registered wells. The contact is also identified by the decrease in resistivity within the ***IP*** as compared to the ***Kd***. The ***Q*** is composed of low resistivity units that correlate with clay in the NE-DNR registered wells.

Figure 5-8 is an approximately 5.7-mile-long east-west line, L147501, in the Union Block. The upper map on Figure 5-8 is the bedrock geology indicating only Pennsylvanian Units (Burchett, 1986) and the location of the flight line. This line illustrates the ***Q*** overlying the ***IP.*** A few NE-DNR registered well lithology logs lie within one half of a mile of the flight line on the eastern end of the line where a sizable deposit of ***Q*** material is on the bluff above the Missouri river. The NE-DNR registered wells clearly indicate the presence of sands along the eastern end of the line***.*** The CSD test holes that are within one mile of the survey line indicate thin ***Q*** above the ***IP*** on the western end of the line. While the ***IP*** exhibits a range of resistivities along this line, it is identifiable in the NE-DNR registered wells and the CSD test holes and is generally resistive compared to the low resistivity of the ***Q*** deposits. This is inverted on the eastern end of the line with the ***Q*** deposits more resistive than the underlying ***IP***.

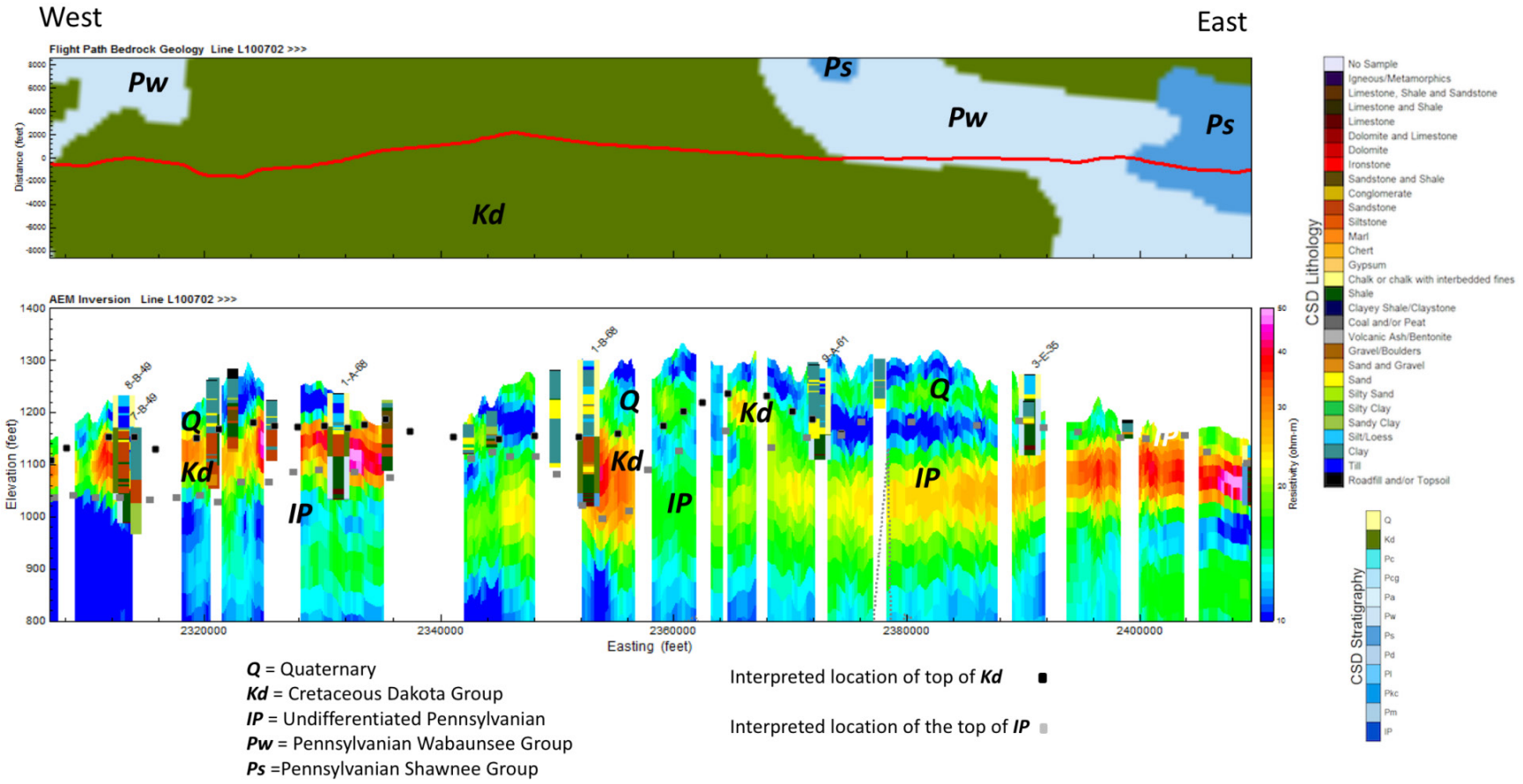


Figure 5-5. 19.7-mile long east-west line L100702. The upper map is the location of the flight line as a red line on the Bedrock Geology Map (Burchett, 1986). The profile shows CSD (within one mile) and Nebraska DNR borehole (within ¼ mile) lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by points and are labeled with stratigraphic names.

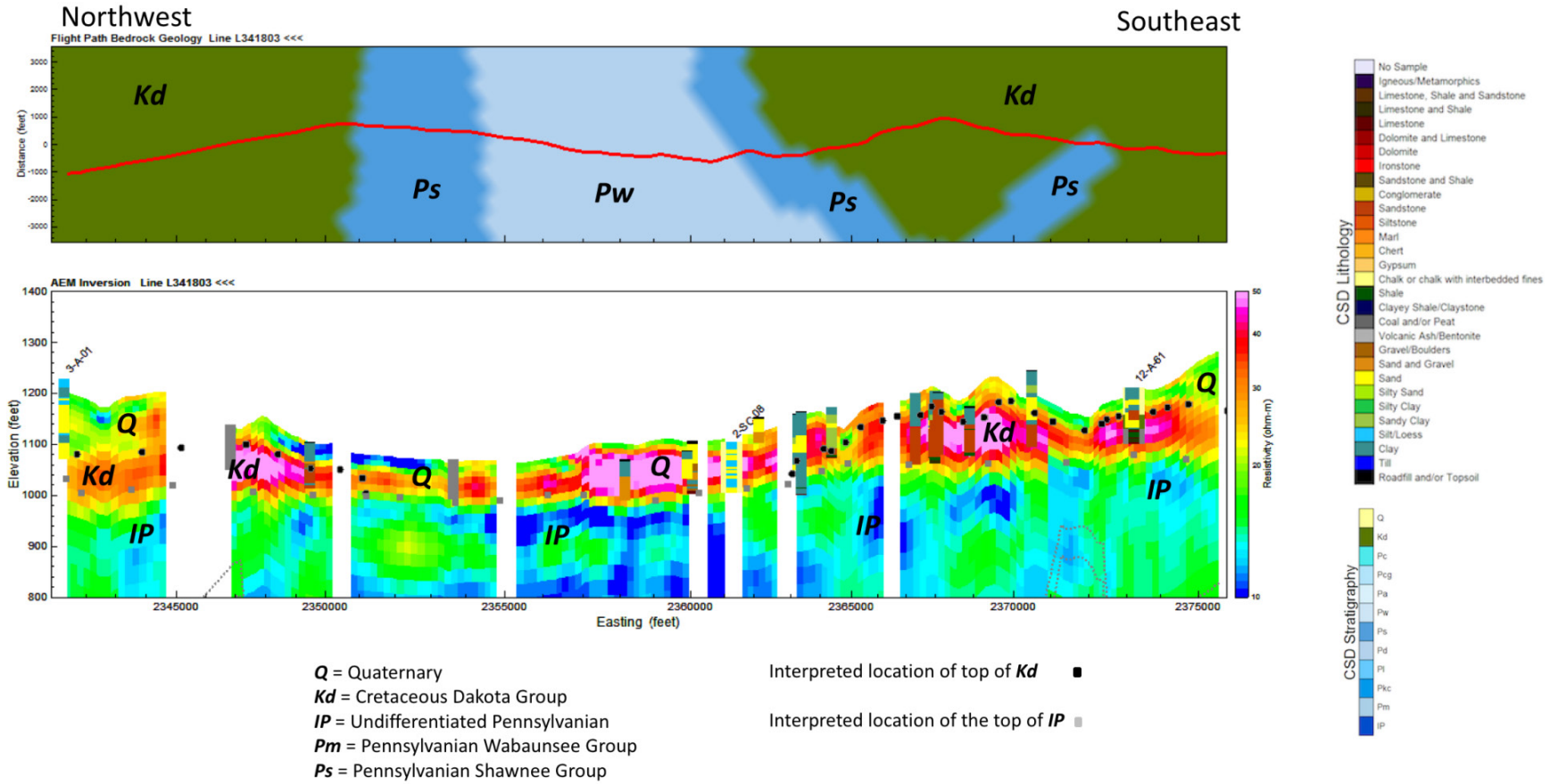


Figure 5-6. 6.6-mile long east-west line L341803. The upper map is the location of the flight line as a red line on the Bedrock Geology Map (Burchett, 1986). The profile shows CSD (within one mile) and Nebraska DNR borehole (within ½ mile) lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by points and are labeled with stratigraphic names. Detailed stratigraphic descriptions of the Paleozoic units can be found Section 2.1.2).

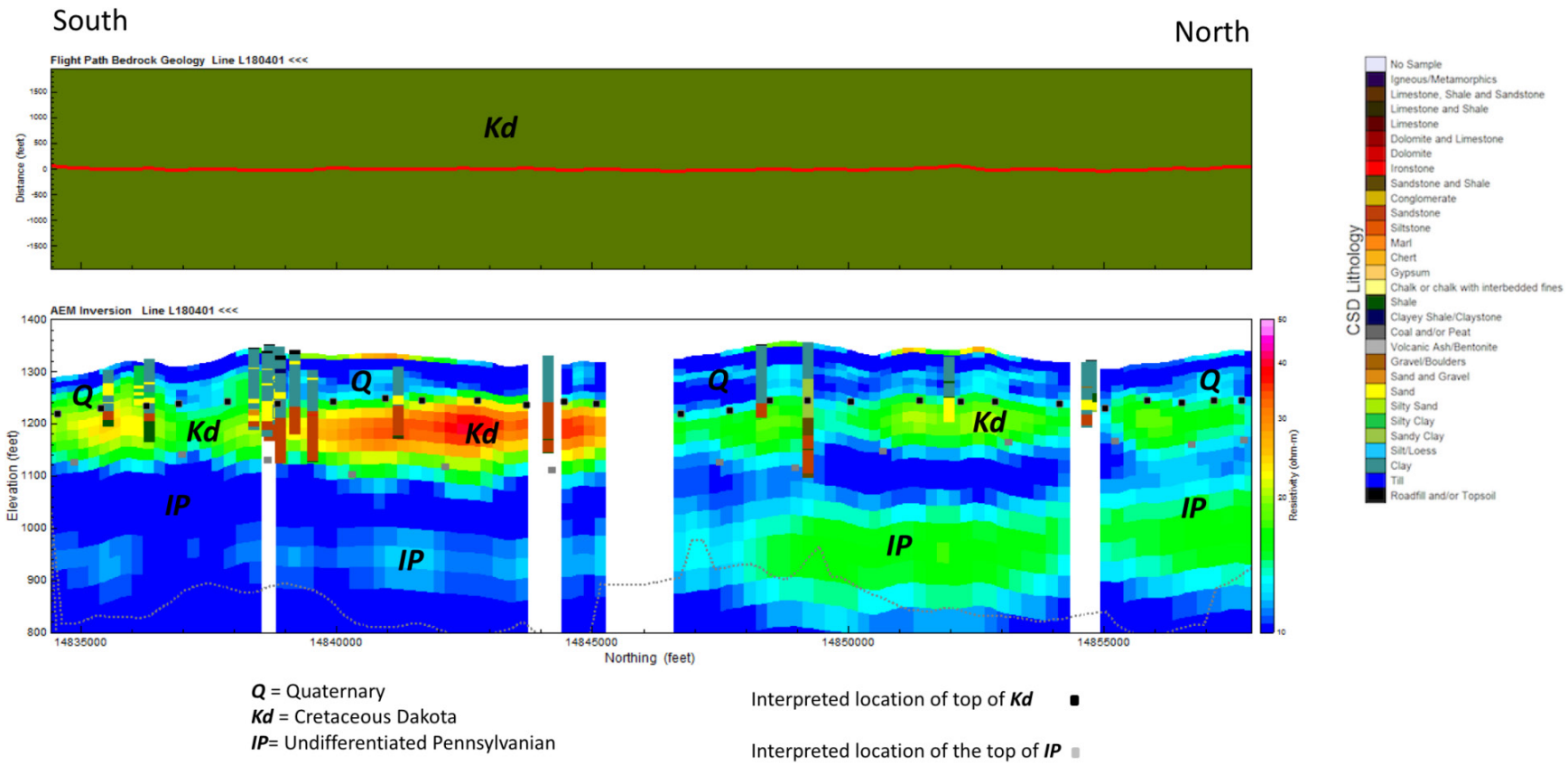


Figure 5-7. 4.4-mile long north-south line L180401. The upper map is the location of the flight line as a red line on the Bedrock Geology Map (Burchett, 1986). The profile shows Nebraska DNR borehole (within ½ mile) lithology logs are indicated on the AEM inverted earth models. Interpretations are indicated by points and are labeled with stratigraphic names. Detailed stratigraphic descriptions of the Paleozoic units can be found Section 2.1.2).

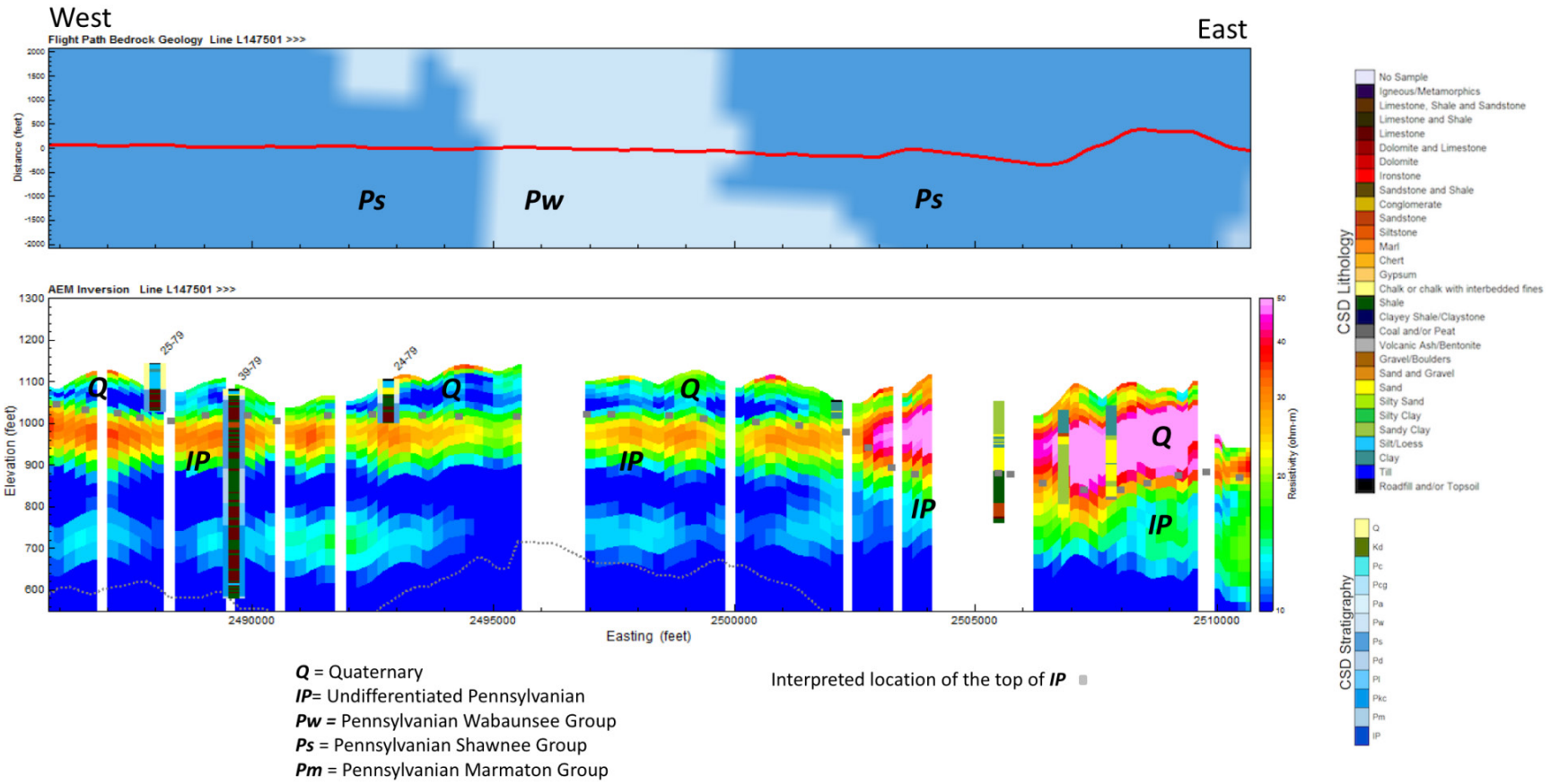


Figure 5-8. 5.7-mile-long east-west line L147501. The upper map is the location of the flight line as a red line on the Bedrock Geology Map (Burchett, 1986). The profile shows Nebraska DNR borehole (within ½ mile) lithology logs are indicated on the AEM inverted earth models. Interpretations are indicated by points and are labeled with stratigraphic names. Detailed stratigraphic descriptions of the Paleozoic units can be found Section 2.1.2).

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 and the splitting out the sand/sandstone versus the clay/shale dominant ***Kd*** (Section 5.2.1) are included in *Appendix 1-Profiles*, which are broken down by the survey block and reconnaissance lines.

5.1.4 Create Interpretative Surface Grids

Within the LPSNRD AEM survey area surface grids of geologic formations were produced for the five survey blocks including the Salt Creek Block. 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. CSD test hole and selected NE-DNR test hole picks were used to augment the AEM data.

For the ***Kd*** top surface 3,024 AEM picks and 11 CSD test hole picks were used in the grid with a cell size of 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 individual AEM survey blocks. Figure 5-9 is a map of the elevation of the top of the ***Kd*** within the Waverly Block. The ***Kd*** surface grids for the Eagle, Elmwood, Lower Salt Creek, and Weeping Water Blocks can be found in *Appendix 2-Interpretive Surfaces*. No ***Kd*** surface grid was made for the Union Block since the ***Kd*** is eroded off that area.

For the top of the ***IP*** surface, 3,182 AEM picks, 305 NE-DNR, and 69 CSD test hole picks were used in the grid with a cell size of 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 individual AEM survey blocks. Figure 5-10 is a map of the elevation of the top of the ***IP*** within the Union Block. The ***IP*** surface grids for the Eagle, Elmwood, Salt Creek, Waverly, and Weeping Water Blocks can be found in *Appendix 2-Interpretive Surfaces*.

The bedrock or the base of the Quaternary (***Q***) aquifer within the Lower Salt Creek and Waverly Blocks are a combination of the ***Kd*** and the ***IP*** surfaces. Figure 5-11 is a map of the bedrock elevation in the Lower Salt Creek Block. The bedrock within the Eagle, Elmwood, and Weeping Water Blocks is the top of the ***Kd.*** For the Union Block the undifferentiated Pennsylvanian **(*IP*)** is the bedrock unit.

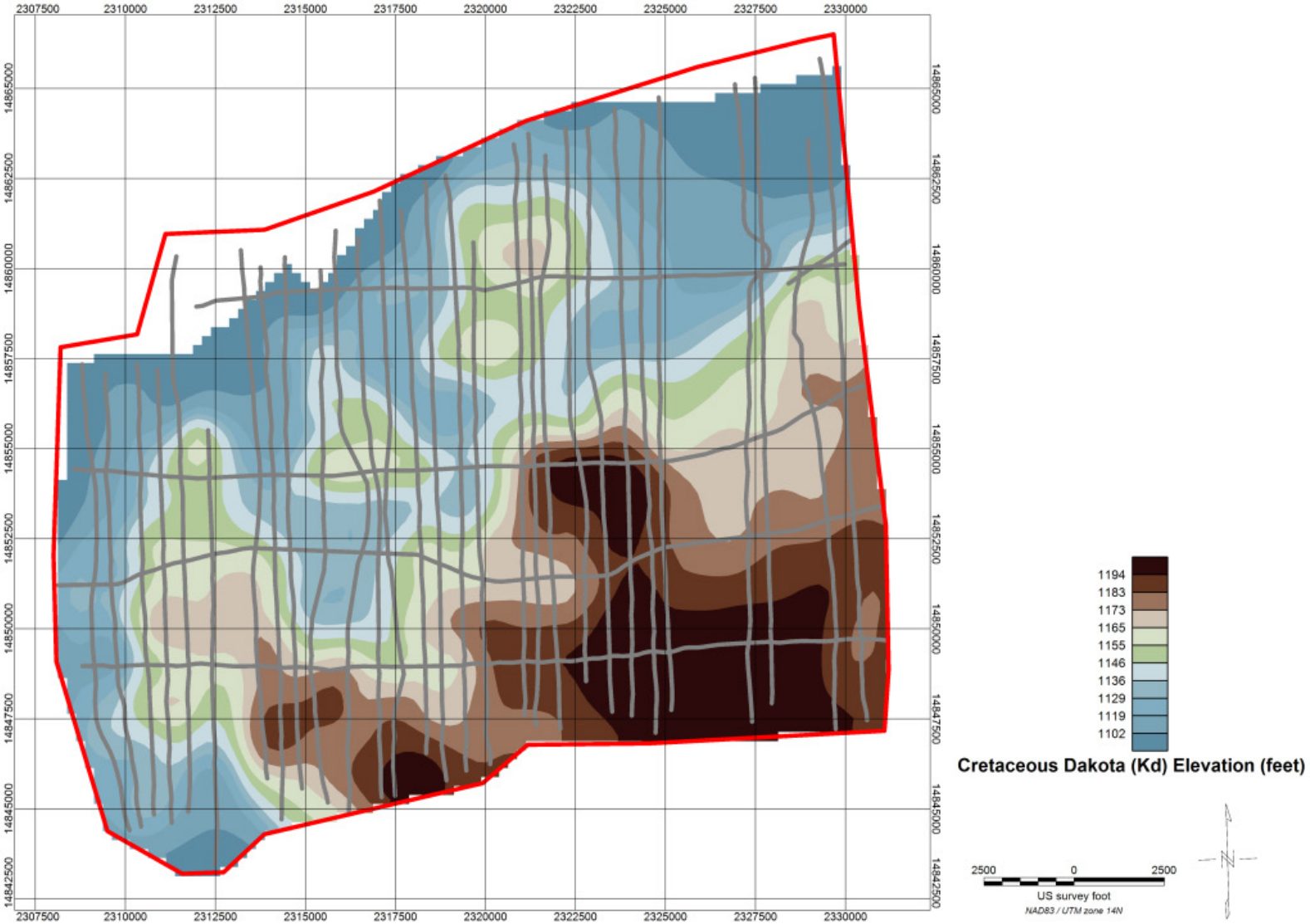


Figure 5-9. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Waverly Block. The red line is the boundary of the block and the gray lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

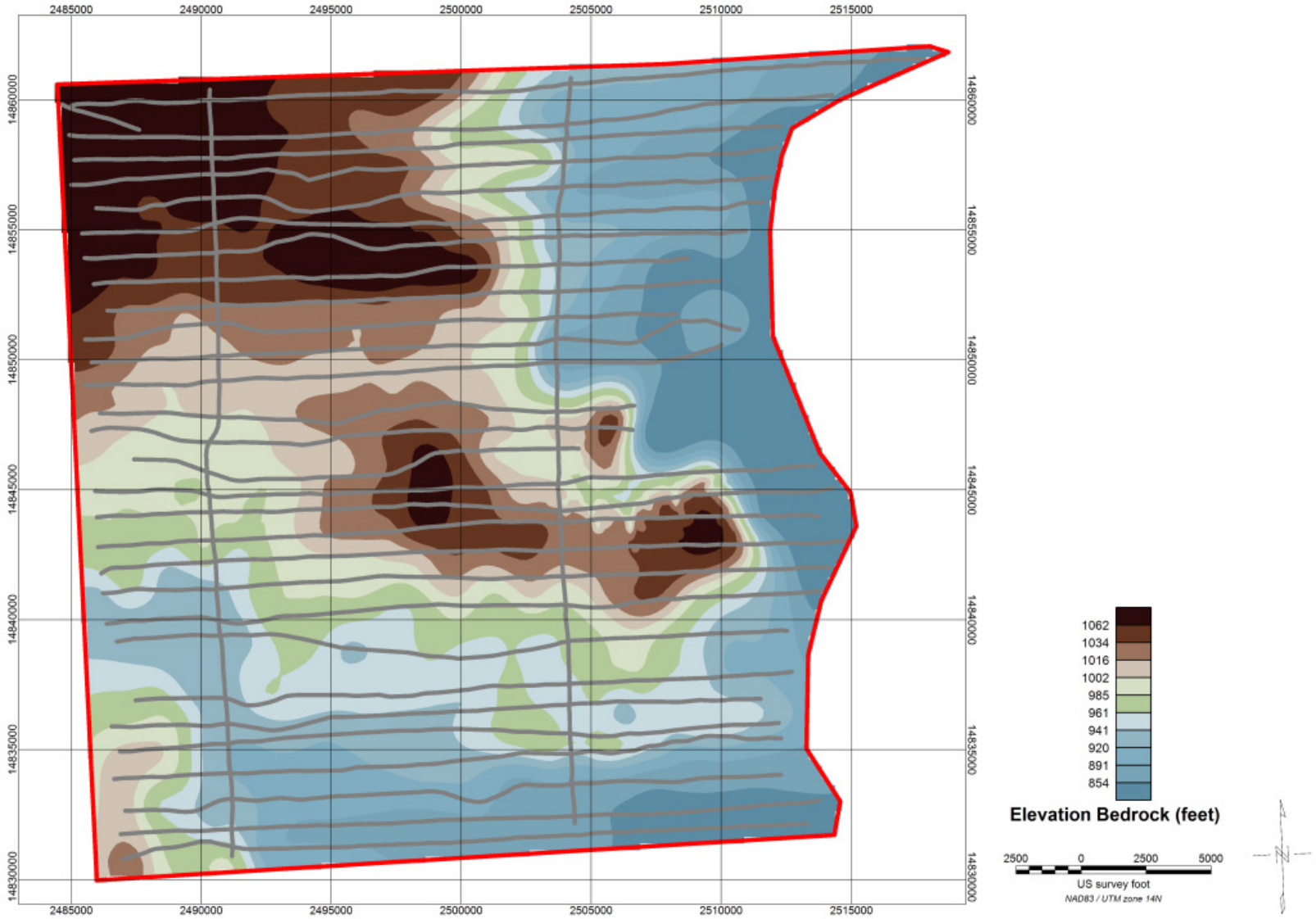


Figure 5-10. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) within the Union Block. The red line is the boundary of the block and the gray lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

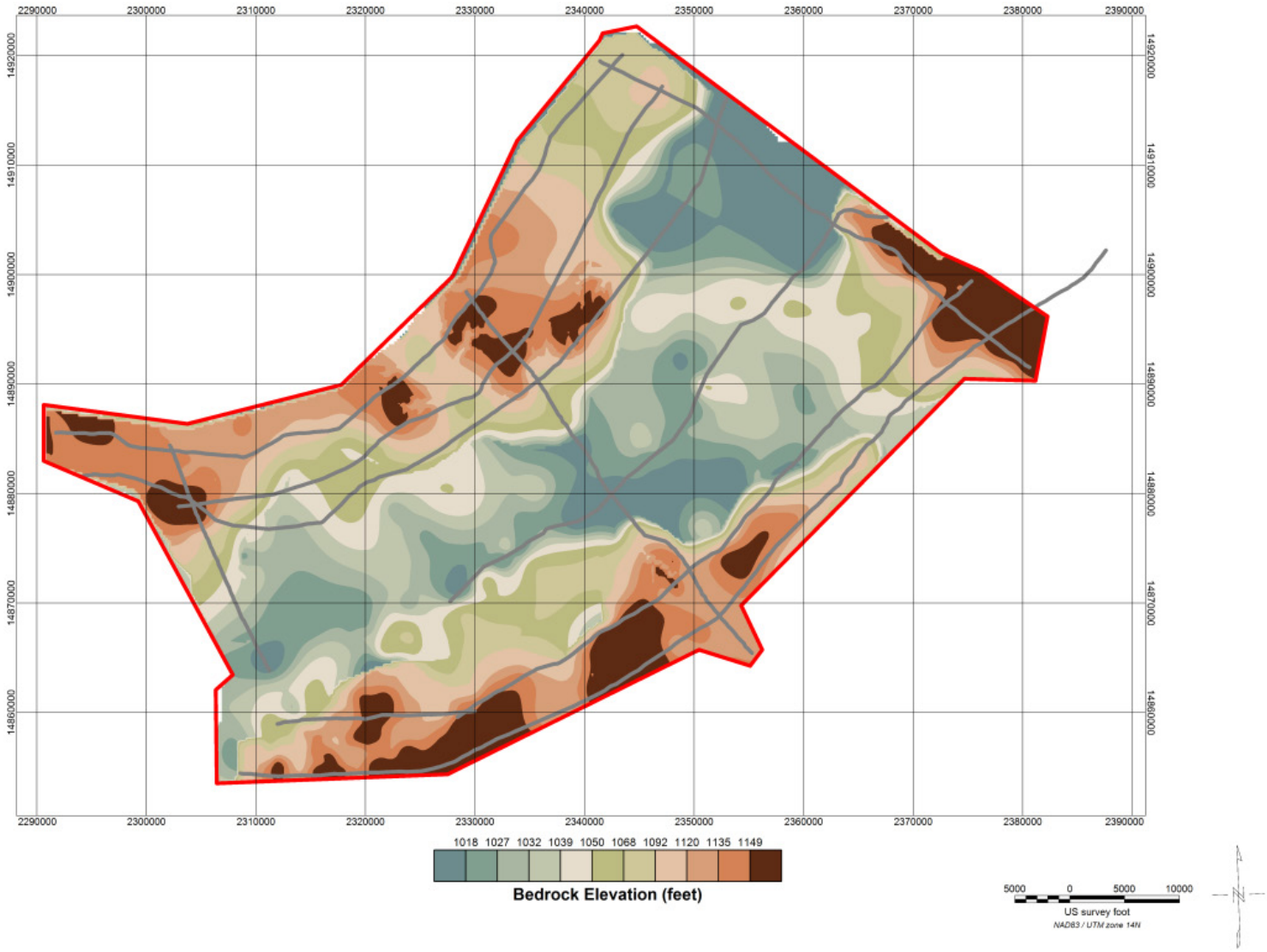


Figure 5-11. Map of the elevation of the top of the bedrock in the Lower Salt Creek Block composed of the Cretaceous Dakota Group (*Kd*) and the undifferentiated Pennsylvanian (*IP*). The red line is the boundary of the block and the gray lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

Following construction of the bedrock surfaces, the ***Q*** deposits were isolated within the AEM data. Figure 5-12 is an example Quaternary thickness map from the Eagle Block.

The 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 Section 5.2 and in Carney et al. (2015c). Using the top of the ***Kd*** and the top of the ***IP*** surface, the ***Kd*** deposits were also isolated and separated into a less than 27 ohm-m range representing clay/shale dominant deposits, and 27 ohm-m or greater range representing sand/sandstone dominant deposits (Section 5.2). Figure 5-13 is an example of the thickness of the ***Kd*** within the Waverly Block. Results of these interpretations can be found in *Appendix_1-Profiles* and in *Appendix 2-Interpretive Surfaces*.

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 LPSNRD AEM survey, and local conditions have likely deviated in areas with variable topography. The water table in the LPSNRD 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 250 ft cell size and compared with the DEM of the LPSNRD AEM survey area. In areas where the water table was greater than the topography, the water table was set to an elevation of the topography minus three feet. The grid was then clipped to the six AEM block flight areas within the LPSNRD survey area (Figure 5-14).

Using the water table and estimates of the saturated thicknesses of the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***), the saturated thickness of the ***IP*** can also be calculated using the ***IP*** surface. For the Union Block the saturated thickness is only composed of the ***Q***. Figure 5-15 is an example of the saturated thickness for the Elmwood Block.

All the interpretive surface plots of the surfaces can be found in *Appendix 2-Interpretive Surfaces*. Arc and Geosoft format grids of the interpretive surfaces can be found in *Appendix 3 Deliverables/Grids*.

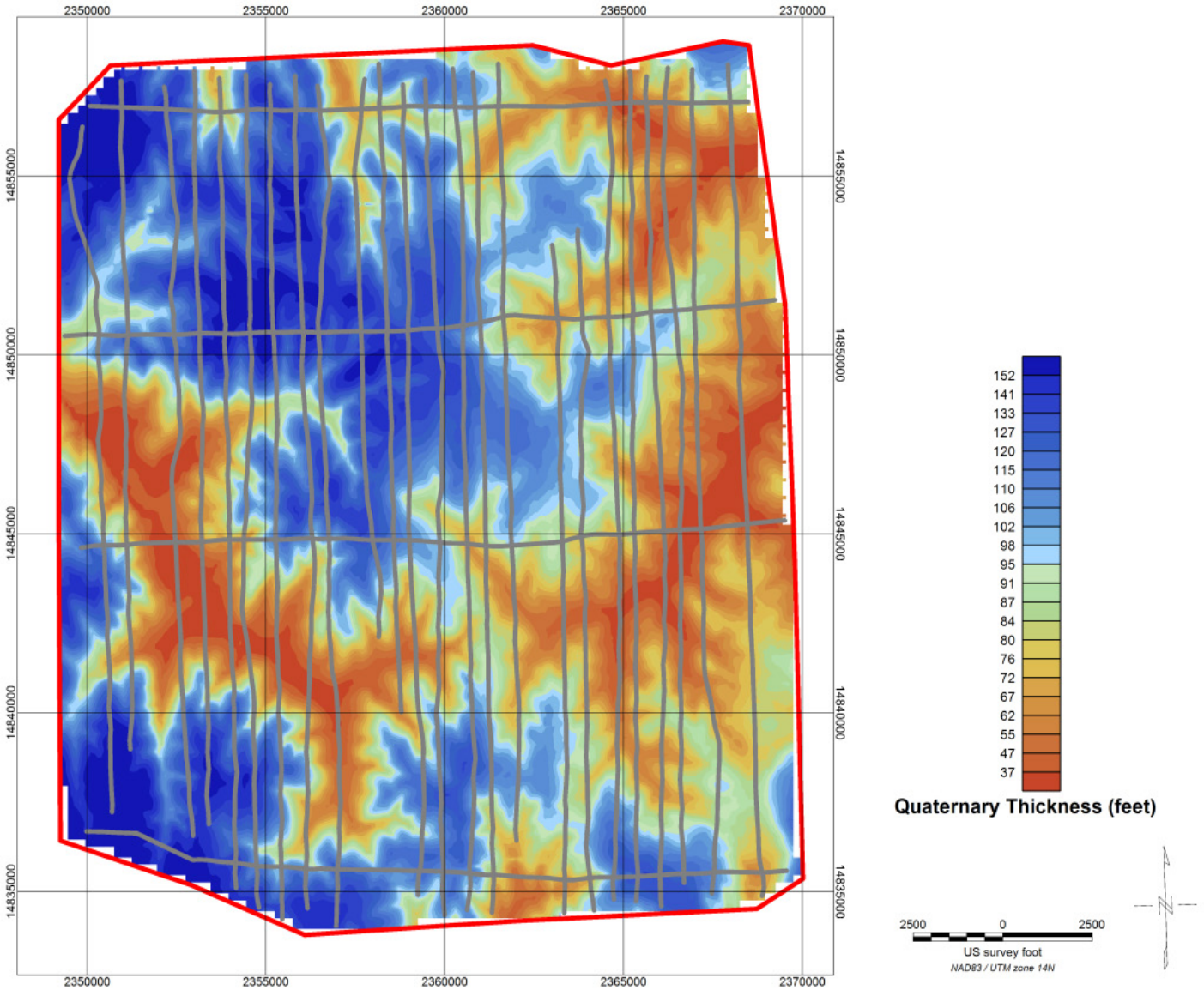


Figure 5-12. Map of the Quaternary thickness in the Eagle Block. The red line is the boundary of the block and the gray lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North.

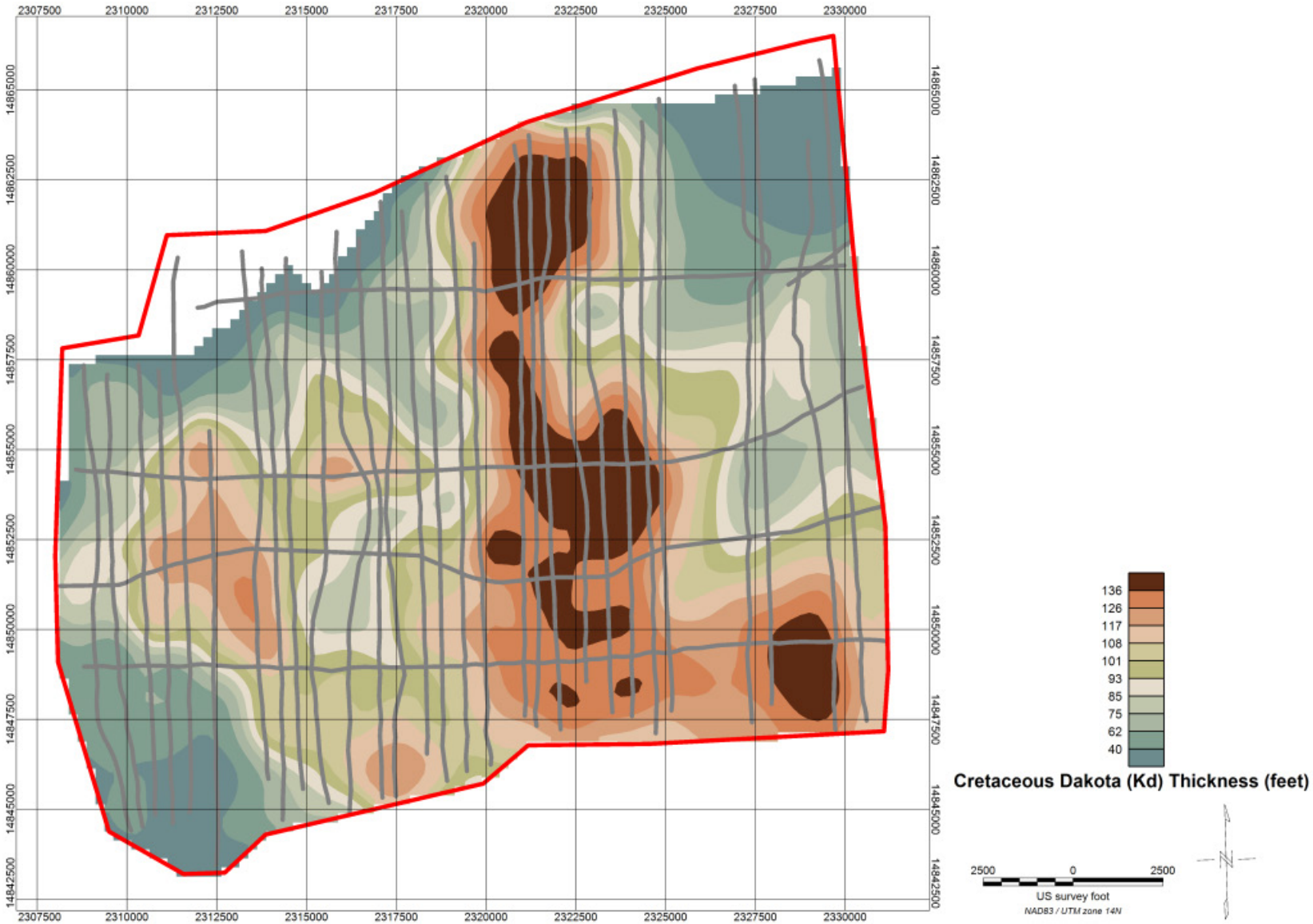


Figure 5-13. Map of the Cretaceous Dakota Group (*Kd*) thickness in the Waverly Block. The red line is the boundary of the block and the gray lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North.

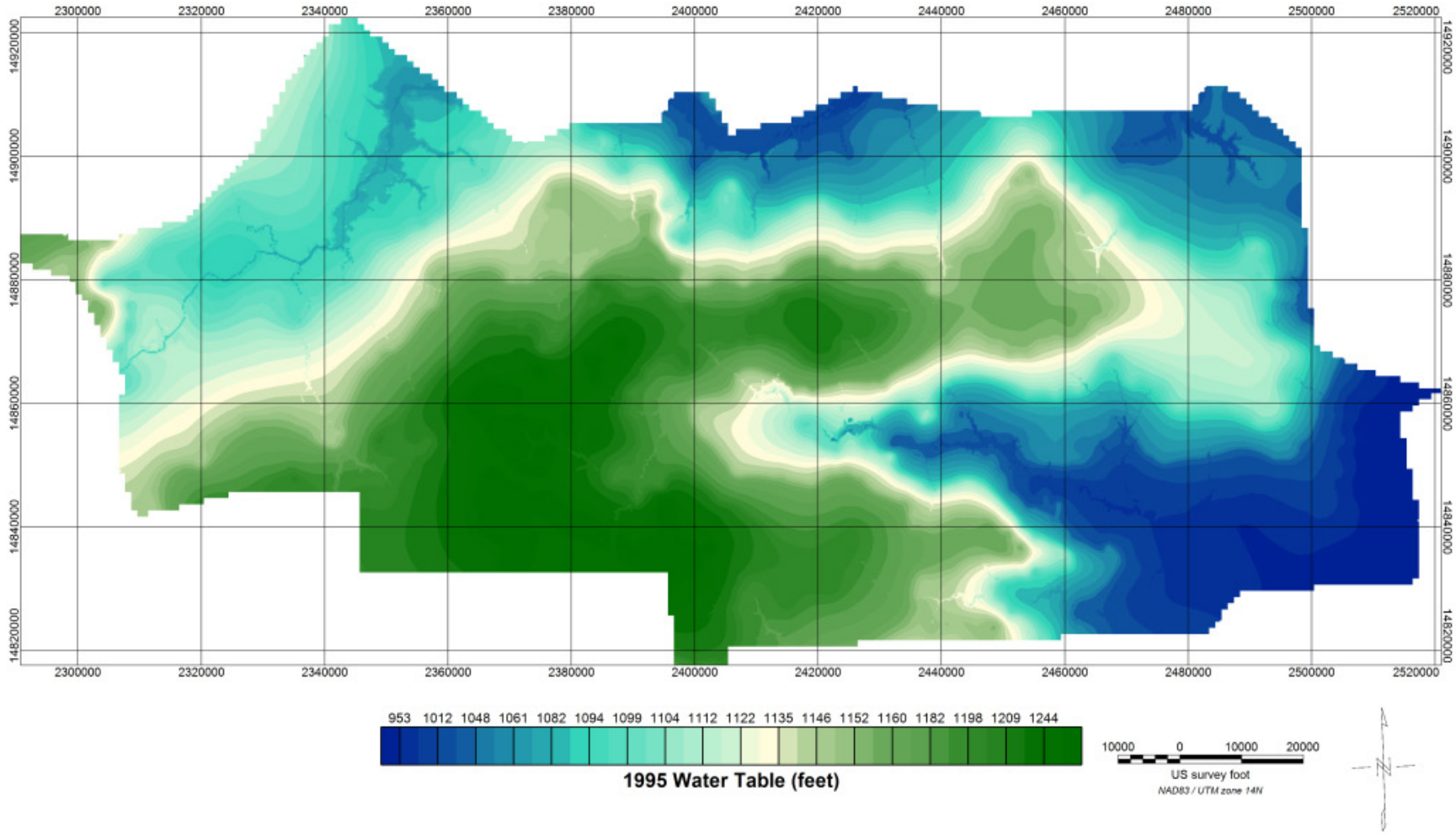


Figure 5-14. Map of the elevation of the 1995 CSD water table (NE CSD, 1995) within the LPSNRD AEM survey area. The projection is NAD83 UTM Zone 14 North and the elevation values are referenced to NAVD 88.

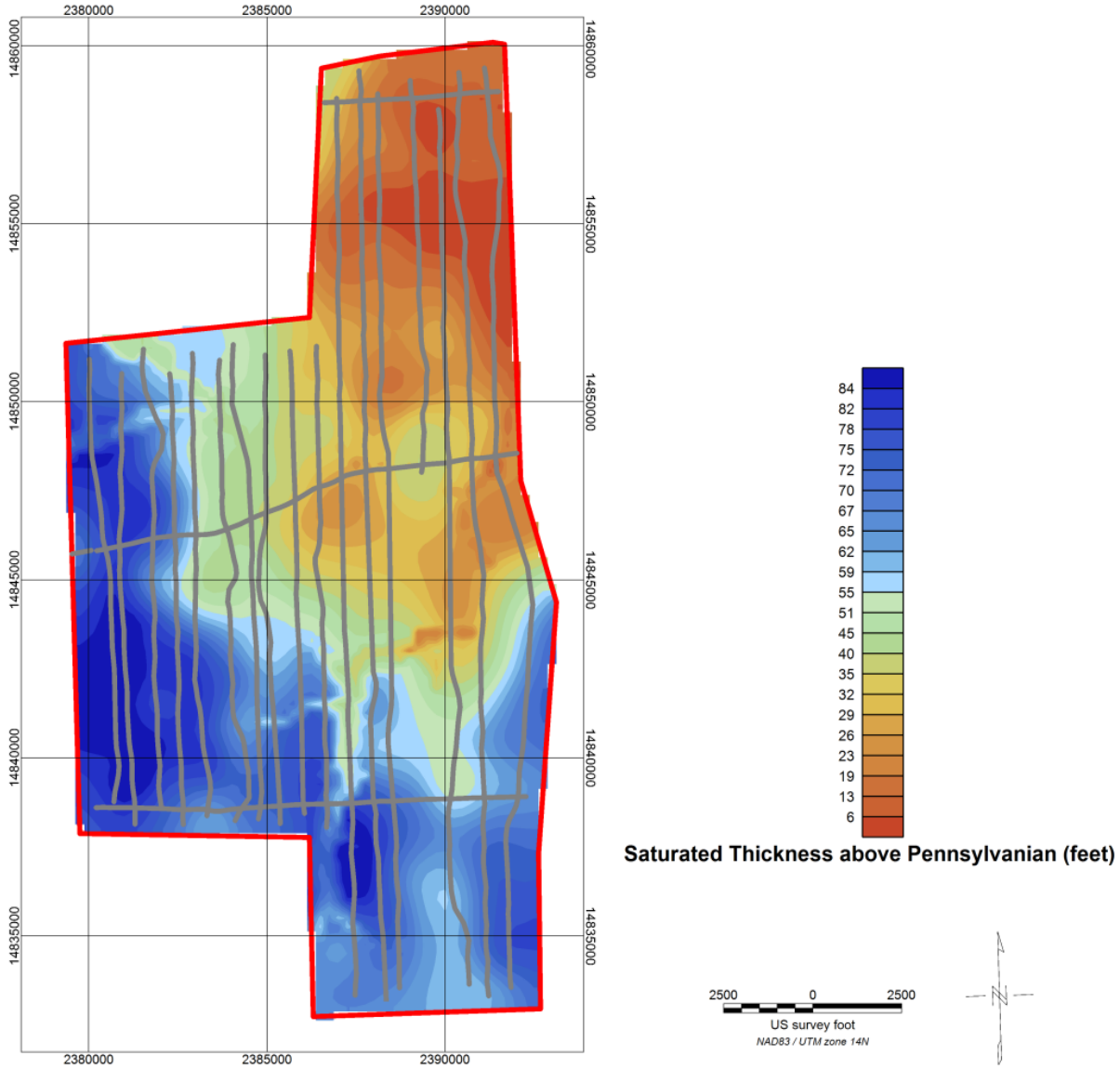


Figure 5-15. Map of the saturated thickness of the Quaternary (*Q*) and Cretaceous Dakota Group (*Kd*) within the Elmwood Block. The red line is the boundary of the block and the gray lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North.

5.1.5 Create 3D Interpretative Voxel Grids

A voxel grid was completed for the Eagle, Elmwood, Union, and Waverley Blocks within the LPSNRD AEM survey area. A voxel grid was not created for the Lower Salt Creek block due to the large distance between lines and the reconnaissance nature of the survey line layout. 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 Datamine Discover PA (DatamineDiscover, 2017). All layers were referenced to their depth from the surface. After the grid was calculated, the ***IP*** surface or base of aquifer system was then truncated/clipped from the voxel grid using the ***IP*** elevation grids discussed above in Section 5.1.4. For the Eagle, Elmwood, and Waverley Blocks the voxel was further sliced at the ***Kd*** elevation.

The resulting ***Q*** grids are from the surface down to the top of the ***Kd*** for the Eagle, Elmwood, Weeping Water, and Waverly Blocks, and from the surface down to the ***IP*** for the Union Block. Additionally, there are voxel grids from the top of the ***Kd*** down to the top of the ***IP*** for the ***Kd*** aquifer system for the Eagle, Elmwood, and Waverley Blocks. 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 sliced from the voxel grids. Using the 1995 CSD water table surface (NE CSD, 1995), the voxel grids were clipped again from the water table to the top of the ***Kd*** surface and from the water table to the top of the ***IP*** surface. These subset voxel grids represent the saturated area from the base of ***Q*** and ***Kd*** aquifer system up to the water table.

Thickness grids are calculated for the thickness of the saturated aquifer materials (>20 ohm-m) in the ***Q*** section and the saturated sand/sandstone dominant materials in the ***Kd*** section. These grids can be used to explore the distribution of the aquifer materials within the areas in 3D. When these grids are displayed the materials that are below the thresholds are transparent, only showing the thickness of the materials above the specified thresholds for the ***Q*** and ***Kd***. 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*. An example of the saturated ***Q*** aquifer materials (>20 ohm-m) from the Union block is shown in Figure 5-16. An example of the saturated ***Kd*** sand/sandstone dominant materials (>27 ohm-m) from the Waverly Block is shown in Figure 5-17. *Appendix 2-Interpretive Surfaces* contains the thickness grids for the ***Q*** and ***Kd*** aquifers.

Estimates of the recharge of an area can be made by looking at the surface layer of the voxel grids. This layer is 9.8 ft thick (Table 4-4) and represents the average resistivity of that zone. Grids of the surface layer were constructed for the Eagle, Elmwood, Union, and Waverly Blocks. *Appendix 2-Interpretive Surfaces* contains the surface layer grids for the survey blocks. Figure 5-18 is an example of the surface layer from the Waverly Block.

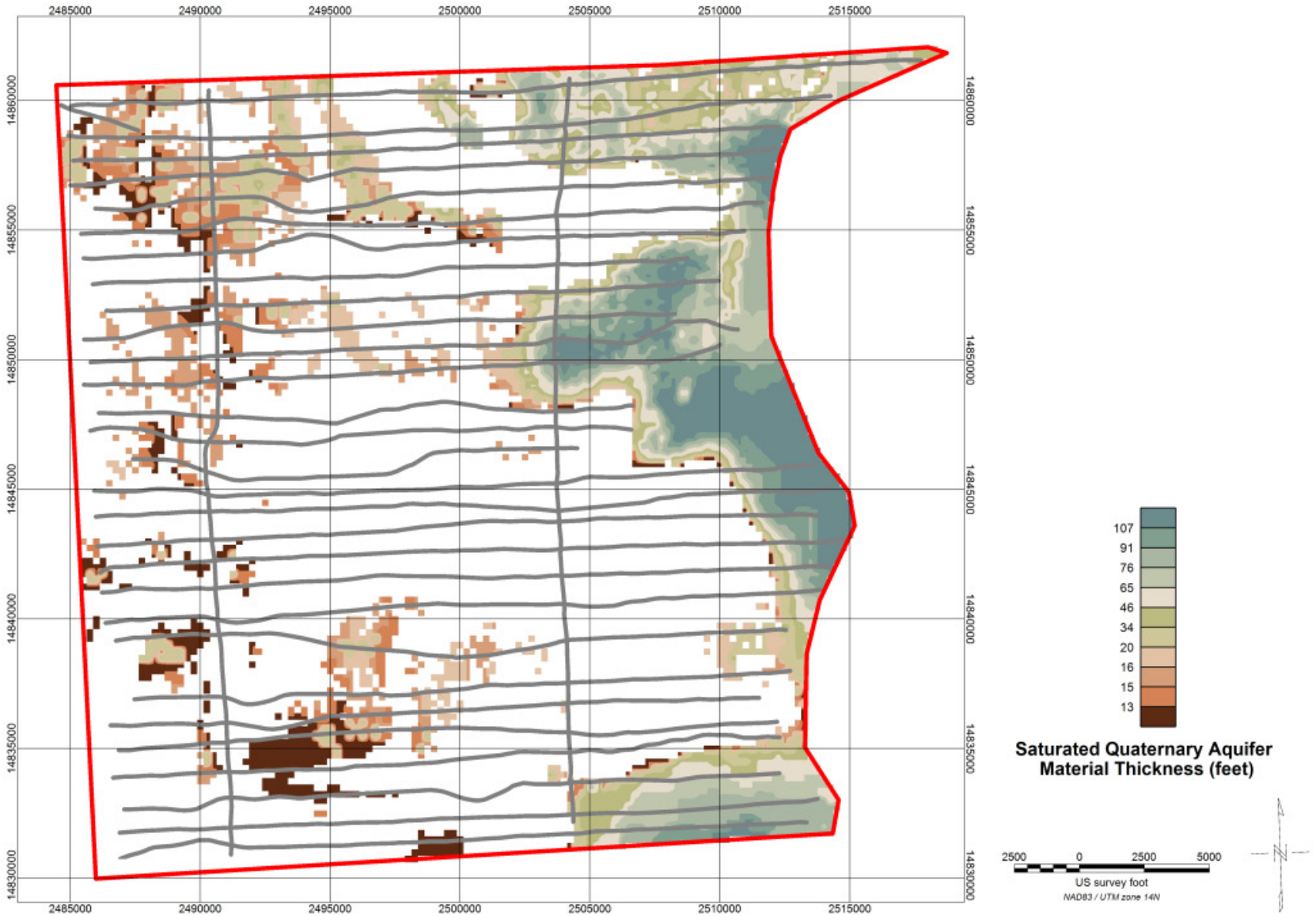


Figure 5-16. Map of the saturated Quaternary (*Q*) aquifer material thickness of the Union Block. The red line is the boundary of the block and the gray lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North.

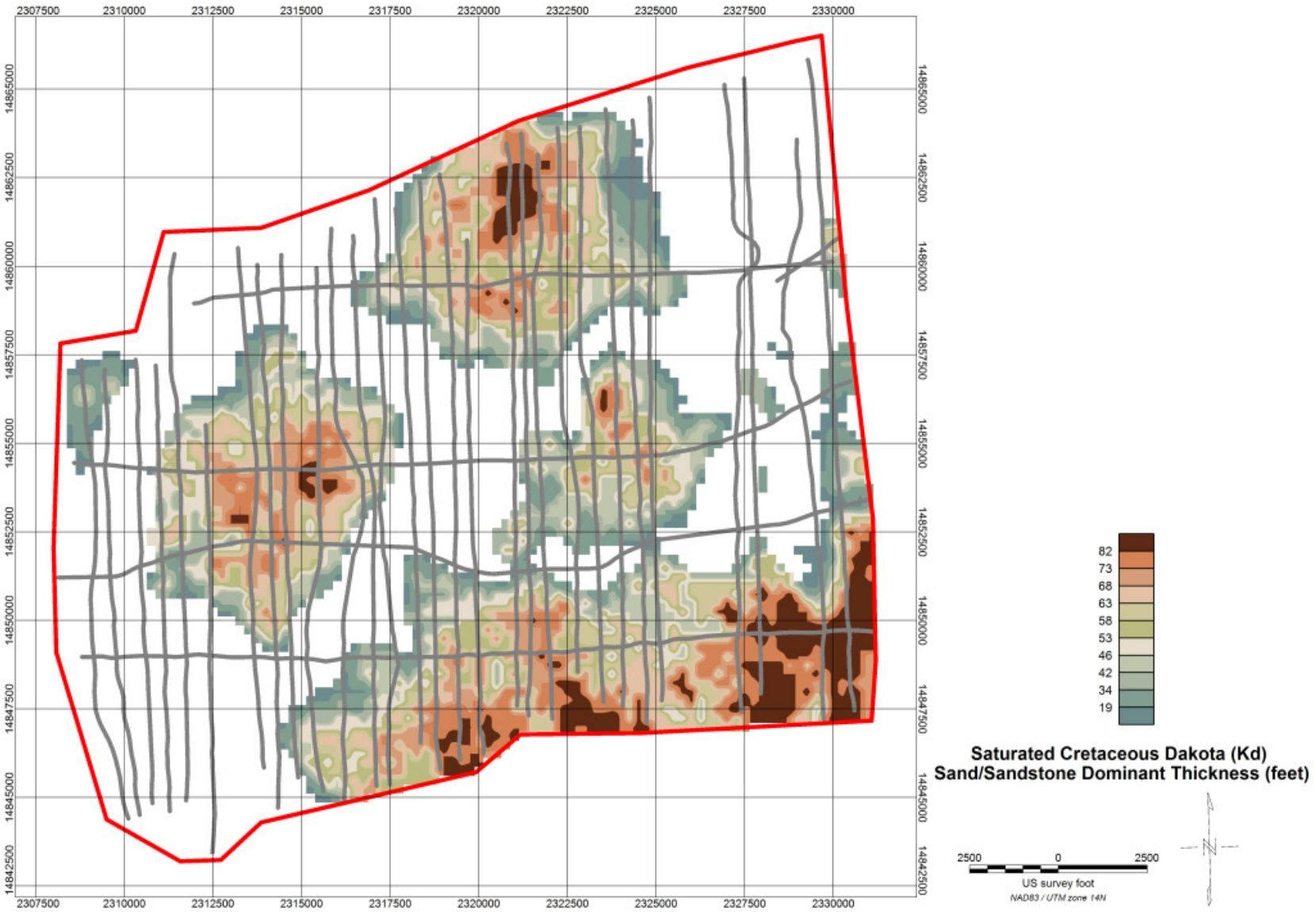


Figure 5-17. Map of the saturated Cretaceous Dakota Group (*Kd*) sand/sandstone dominant thickness of the Waverly Block. The red line is the boundary of the block and the gray lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North.

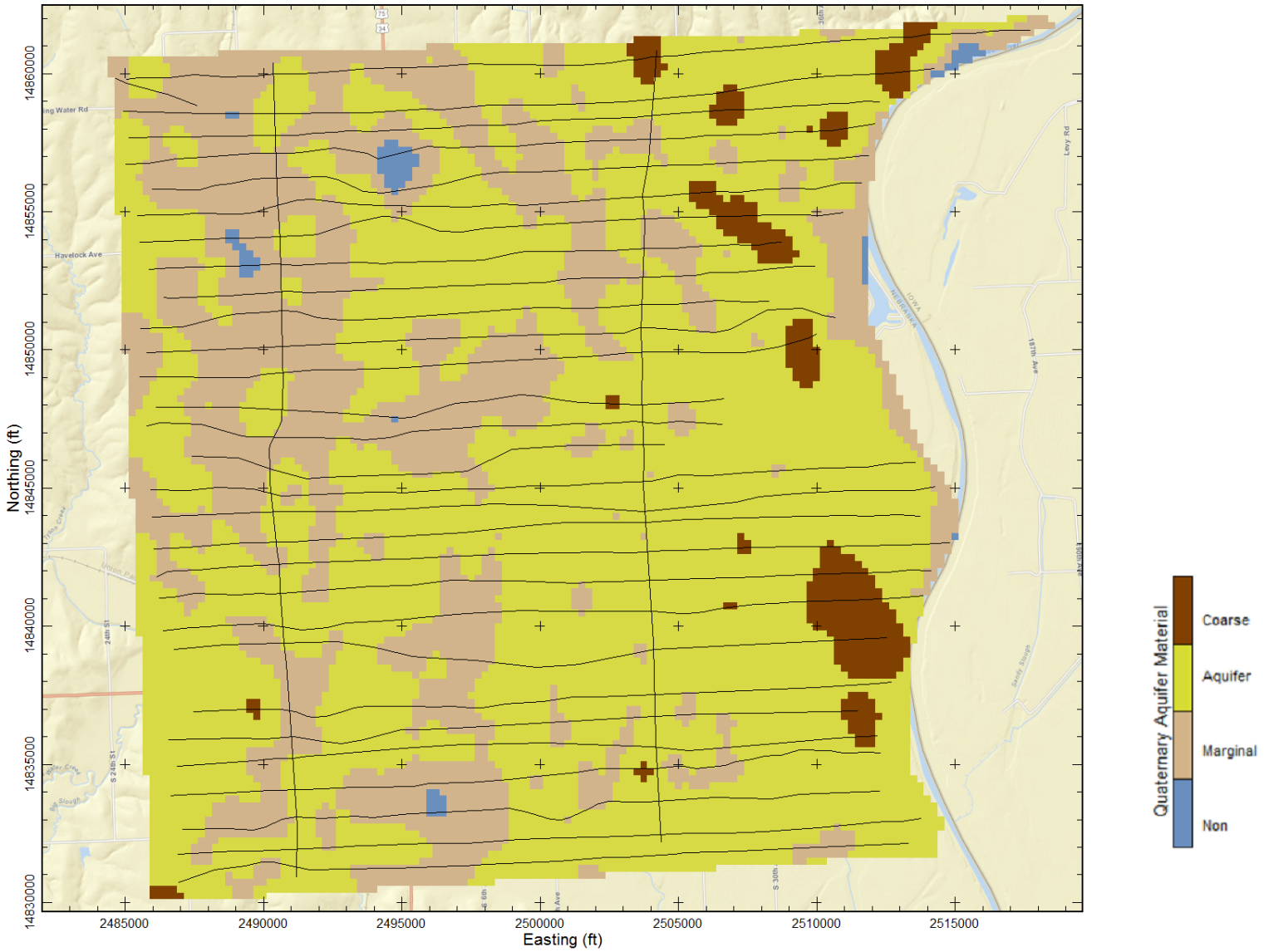


Figure 5-18. Map of the surface layer interpreted Quaternary aquifer materials for the Waverly Block. The black lines are the AEM flight lines. The projection is NAD83 UTM Zone 14 North.

5.2 Resistivity-Lithology Relationship

5.2.1 Quaternary Aquifer System

A critical aspect of a geophysical survey is assessing the nature of the material detected by the geophysical method applied in the investigation. Regarding the LPSNRD AEM survey area, assessment of the sediment character in the Quaternary (***Q***) aquifer system 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 ***Q*** units described in this report. It should be noted that this analysis encompasses all Quaternary/Tertiary Ogallala (***Q***/***To***) aquifer systems from the ENWRA project area (Carney et al., 2015b). The original analysis that was completed as part of Carney et al. (2015c) included the area within the LPSNRD AEM survey area. 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 flight line area (Carney et al., 2015b and Carney et al., 2015c). The relationship between resistivity and lithology type was assessed by performing an association function that linked nine lithologic descriptor codes for ***Q*** 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 5-19.

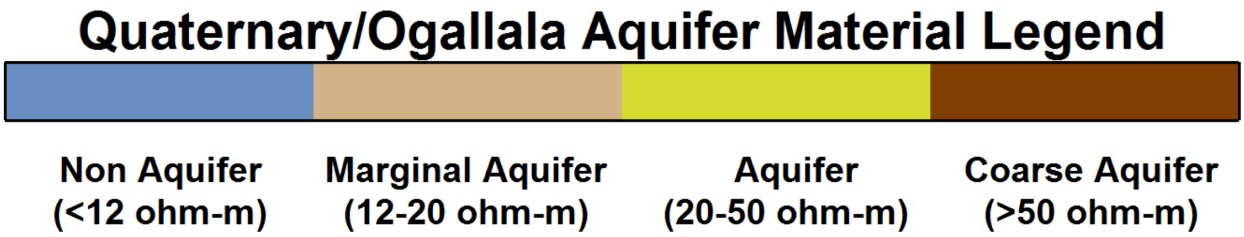


Figure 5-19. Plot displaying the resistivities by major aquifer material color categories (blue- non-aquifer material, tan- marginal aquifer, yellow- aquifer, brown- sand-rich, coarse intervals of the aquifer material).

5.2.2 Bedrock Resistivity Thresholds

The bedrock in the LPSNRD AEM survey area analyzed in this study includes the Cretaceous Dakota (***Kd***) and undifferentiated Pennsylvanian (***IP***). Carney et al. (2015b) provided a distribution of the ***Kd*** and the undifferentiated Paleozoic units, of which the undifferentiated Pennsylvanian (***IP***) is a part, from an examination of the bedrock resistivity values from the CSD test holes. The ***Kd*** has a median resistivity of approximately 20 ohm-m as the ***Kd*** is predominately a sandstone, but can contain shale and electrically conductive clay minerals. The undifferentiated Paleozoic strata also have resistivity characteristics, with a median value around 16 ohm-m. The undifferentiated Paleozoic units show a wide range in detected resistivities, which should not be unexpected as this sequence contains resistive limestone and conductive shale units. Additionally, the Paleozoic and the ***Kd*** can be saturated with saline waters, which will lower the bulk resistivity. Figure 5-20 is a figure out of Carney et al. (2015b) showing the distribution of the bedrock units within the ENWRA area.

Carney et al. (2015b) also looked at the ***Kd*** throughout the ENWRA to characterize the variability in the ***Kd***'s resistivity distribution. The relationship of lithology and resistivity was evaluated using the same method applied in associating unconsolidated ***Q*** lithologies to resistivity. Borehole geophysical log resistivities were associated with each lithologic description in the CSD test holes that contained information on the ***Kd.*** As described above in Section 2.1.2, the ***Kd*** is typically known as a sandstone and shale, but contains intervals of unconsolidated lithologies as noted in the CSD test hole descriptions. Figure 5-21 (from Carney et al., 2015b) shows a breakdown of textural size and nature of consolidation (unconsolidated (clay/silt) and consolidated fines (shale)), unconsolidated (sand and gravel) and consolidated coarse (sandstone). The distributions of the coarse categories are similar, with the 25th quartile for each greater than 50 ohm-m and median values over 70 ohm-m. Distributions for the fine textured materials are also similar, with the median values ranging from 25 to 30 ohm-m. Carney et al. (2015b) illustrated that shale has a wider range of values detected in comparison to unconsolidated fines and grouped unconsolidated and consolidated fines as one group and coarse-textured unconsolidated and consolidated materials as another group. The objective of this analysis in Carney et al. (2015b) was to determine if any natural breaks in the resistivity distribution were evident on which to base selection of categorical ranges for showing the variation in resistivity within the ***Kd***.

Carney et al. (2015b) examined the distribution of resistivity for coarse materials (sandstone/sand) and fine materials (shale/silt/clay). From this distribution Carney et al. (2015b) concluded that the bulk of fine textured materials are generally below 40 ohm-m, and that the bulk of the coarse textured distribution is above 30 ohm-m, with overlap of the two groups in the 30 to 40 ohm-m range. The fine textured materials indicated bimodal distribution. The distribution below 10 ohm-m was attributed to brackish/saline water in the ***Kd***, and the distribution greater than 10 ohm-m is related to lithologic character. Carney et al. (2015a) grouped the ***Kd*** into three general categories: 1) 0-20 ohm-m, representing zones of the ***Kd*** predominately consisting of fines or high TDS pore water; 20-40 ohm-m, representing intervals of interbedded fine and coarse materials, and zones of 40 ohm-m or greater, which are intervals of the ***Kd*** where coarse textured deposits comprise the bulk of the material in that interval.

An additional analysis was done for the ***Kd*** for the Sarpy County AEM survey area (AGF, 2017b). In Sarpy County the availability of reliable borehole resistivity logs was a problem. The seven resistivity logs in the study area showed severe issues with calibration and scale offsets typical of CSD logs within ENWRA. Still, these logs have value in that they clearly show the changes in the resistivity at geological and lithologic contacts, but cannot be used in a quantified manner. One important issue with the ***Kd*** in the Sarpy County AEM survey area was that there was no evidence of saline waters associated with ***Kd*** wells (Section 2.2.2), Hydrogeologic Character-Water Quality). This would reduce the range of the ***Kd*** resistivities in the Sarpy County AEM survey area by increasing the minimum resistivities over the ranges that were reported in Carney et al. (2015b) and Carney et al. (2015c). The LPSNRD area suffered from the same lack of reliable electrical logs within the ***Kd*** to develop a statistical break off for the aquifer materials or the sand/sandstone dominant section. Without the availability of calibrated geophysical logs, an empirical inspection was used to characterize the ***Kd*** aquifer materials within the Sarpy County AEM survey area. To accomplish this characterization, the NE-DNR lithology logs as well as the limited CSD lithology logs were plotted on the AEM profile sections. Then the ***Kd*** resistivity range was adjusted to maximize the correlation of the sandstones/sand sections with the lithology logs. A value of 27 ohm-m was determined to be the best empirical cut-off for the shale/clay versus the sandstone/sand dominant ***Kd*** aquifer materials. Due to the proximity of the Sarpy survey area to the LPSNRD survey area, the same division of the ***Kd*** was used. Figure 5-22 is a plot of the color scale used in the interpretation of the ***Kd*** materials.

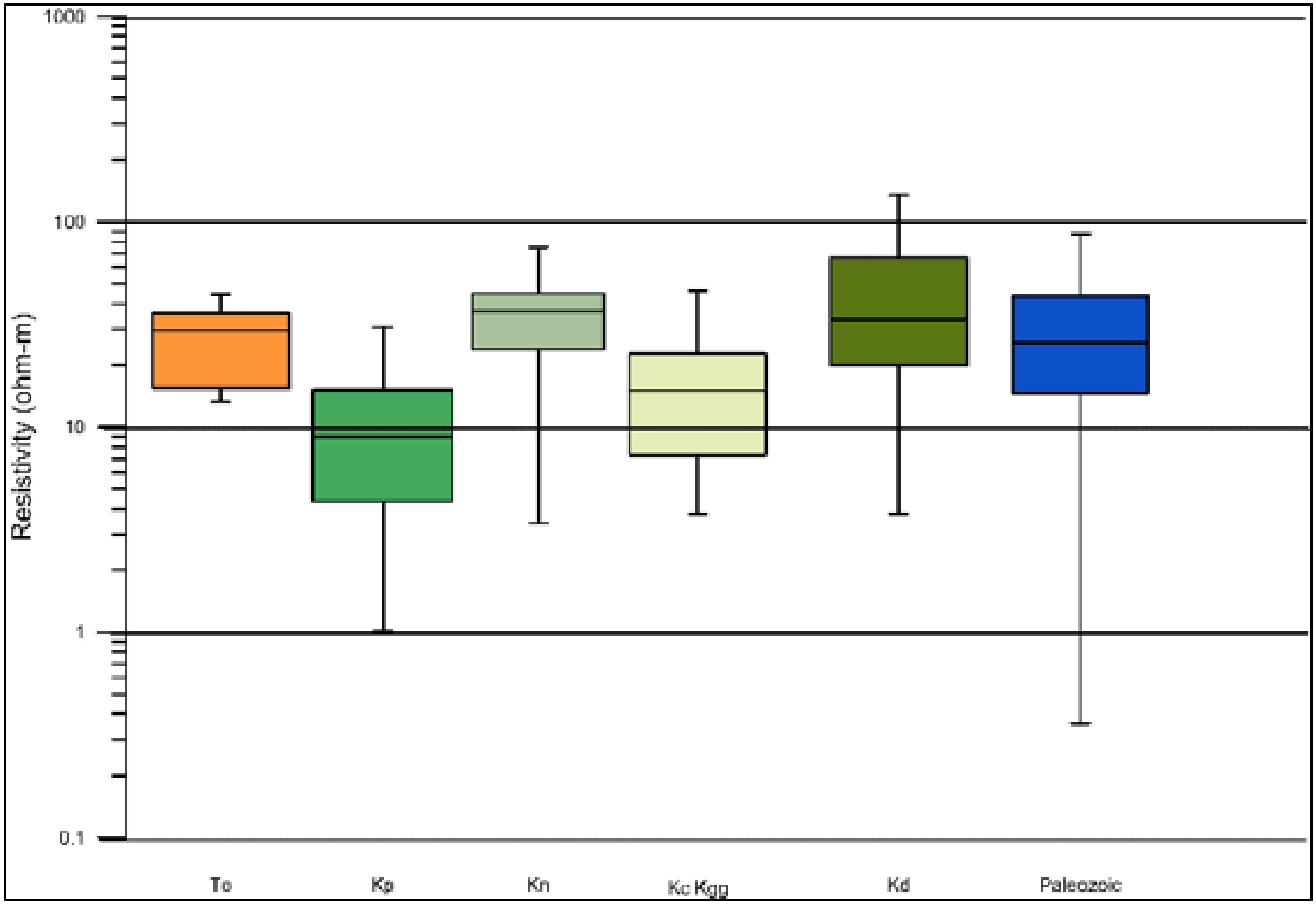


Figure 5-20. Box and whiskers plot of the resistivity distribution of the Tertiary, Cretaceous, and Paleozoic bedrock units discussed in the interpretation of the AEM data (Carney et al., 2015b).

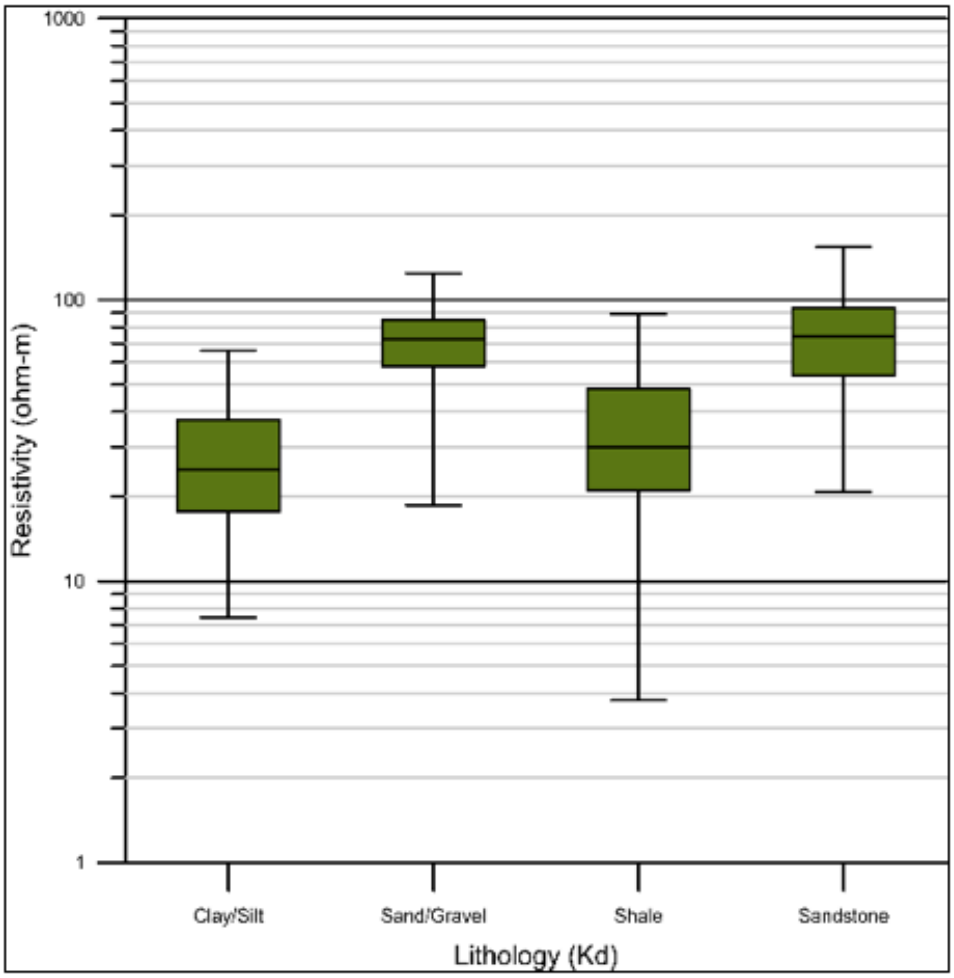


Figure 5-21. Box and whisker plot for the major lithologic texture categories within the *Kd* from CSD E-logs located across the entire ENWRA project area (Carney et al., 2015c).



Clay/Shale Dominant (< 27 ohm-m)

Sand/Sandstone Dominant (> 27 ohm-m)

Figure 5-22. Plot displaying the relation between resistivities and Cretaceous Dakota Group (*Kd*) clay/shale dominant (<27 ohm-m) and the sand/sandstone dominant (>27 ohm-m) used in the following figures

5.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs

Of the 56 geophysical logs in the LPSNRD AEM survey area only five logs showed some degree calibration and were close enough to the flight lines to be useful. These included *3-SC-08*, *11-A-61*, *11-79*, *12-79*, and *31-79*. The remaining logs showed either log malfunctions, calibrations errors, or were too far from the flight lines. Since the resistivity logs within the CSD database are of various vintages and were 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-Copper and Davis, 2010).

Figure 5-23 is a plot of *3-SC-08* 16-inch short normal, 64-inch long normal, and lateral resistivity log plotted with the inverted AEM resistivity for line L142301. *3-SC-08* is located 938 feet from line L142301 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is reasonable with the AEM indicating a lower overall resistivity in the sand/sandstone section of the ***Kd*** from approximately 42-118 feet as compared to the geophysical log. The shape of the curves shows good agreement. The key is that the AEM clearly indicates the Sand/Sandstone dominant material area of ***Kd***. The upper section of the log in the ***Q*** is impacted by the air-filled borehole. It is also important to note that the ***Kd*** is highly spatially variable. The 938 feet difference in the AEM sounding and the log may explain the difference in the resistivity values from the geophysical log and the AEM. The hydrogeologically important observation is that the ***Kd*** aquifer can be detected.

Figure 5-24 is a plot of *11-A-61* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L286402. *11-A-61* is located 5,847 feet from line L286402 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is reasonable with the AEM indicating a lower overall resistivity in the sand section of the ***Q*** from approximately 55-62 feet compared to the geophysical log. The shape of the curves shows a general agreement. The key is that the AEM clearly indicates the marginal to non-aquifer material within the ***Q***. This log is far away from the reconnaissance line L286402, but the AEM indicates that the area is not good aquifer.

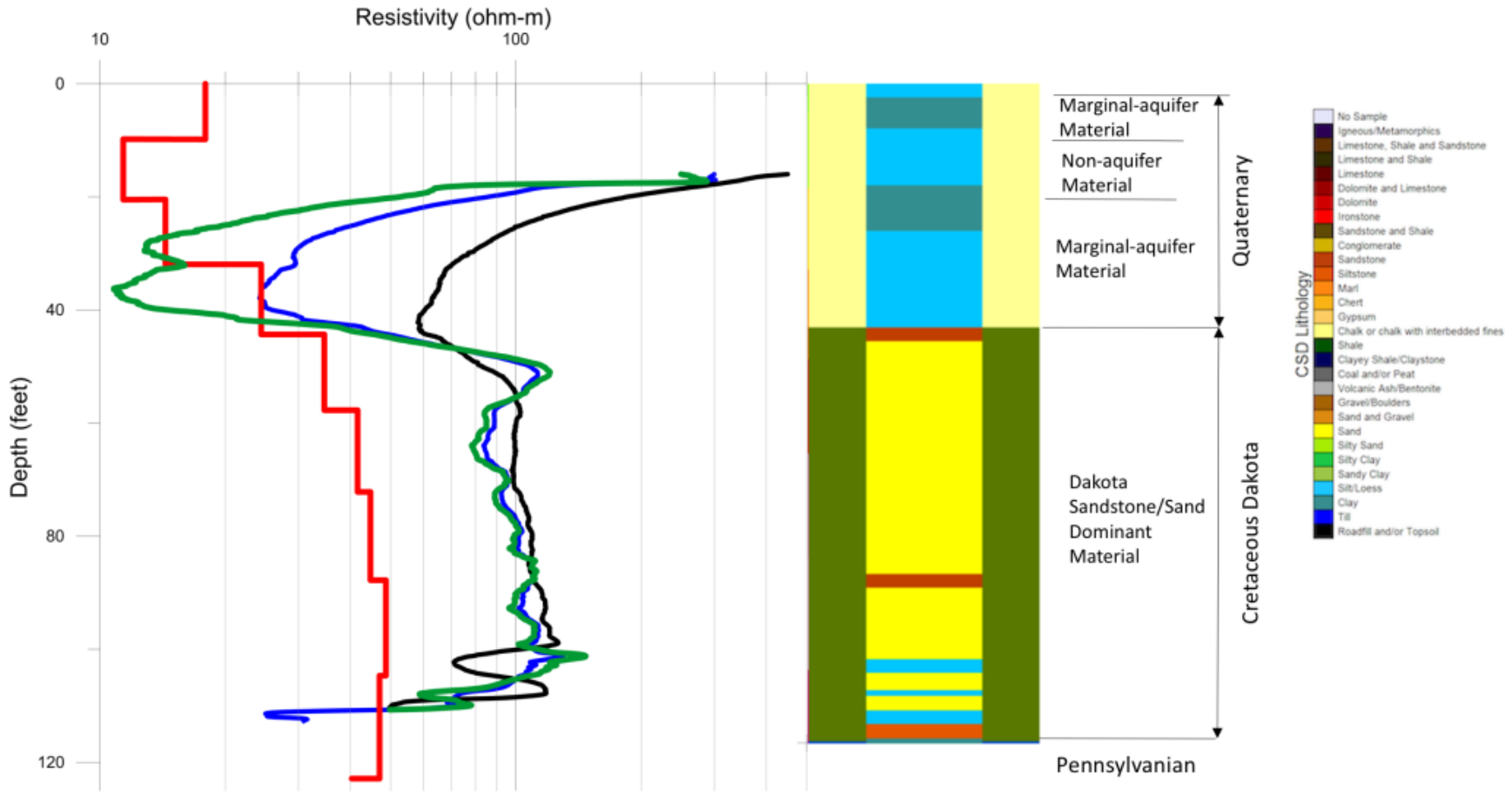


Figure 5-23. Graph of the *3-SC-08* 16-inch normal resistivity log values (blue line), 64-inch normal (black line), lateral resistivity log (green line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *3-SC-08* as well as the Quaternary aquifer material categories and the Cretaceous Dakota material properties from the AEM inversion.

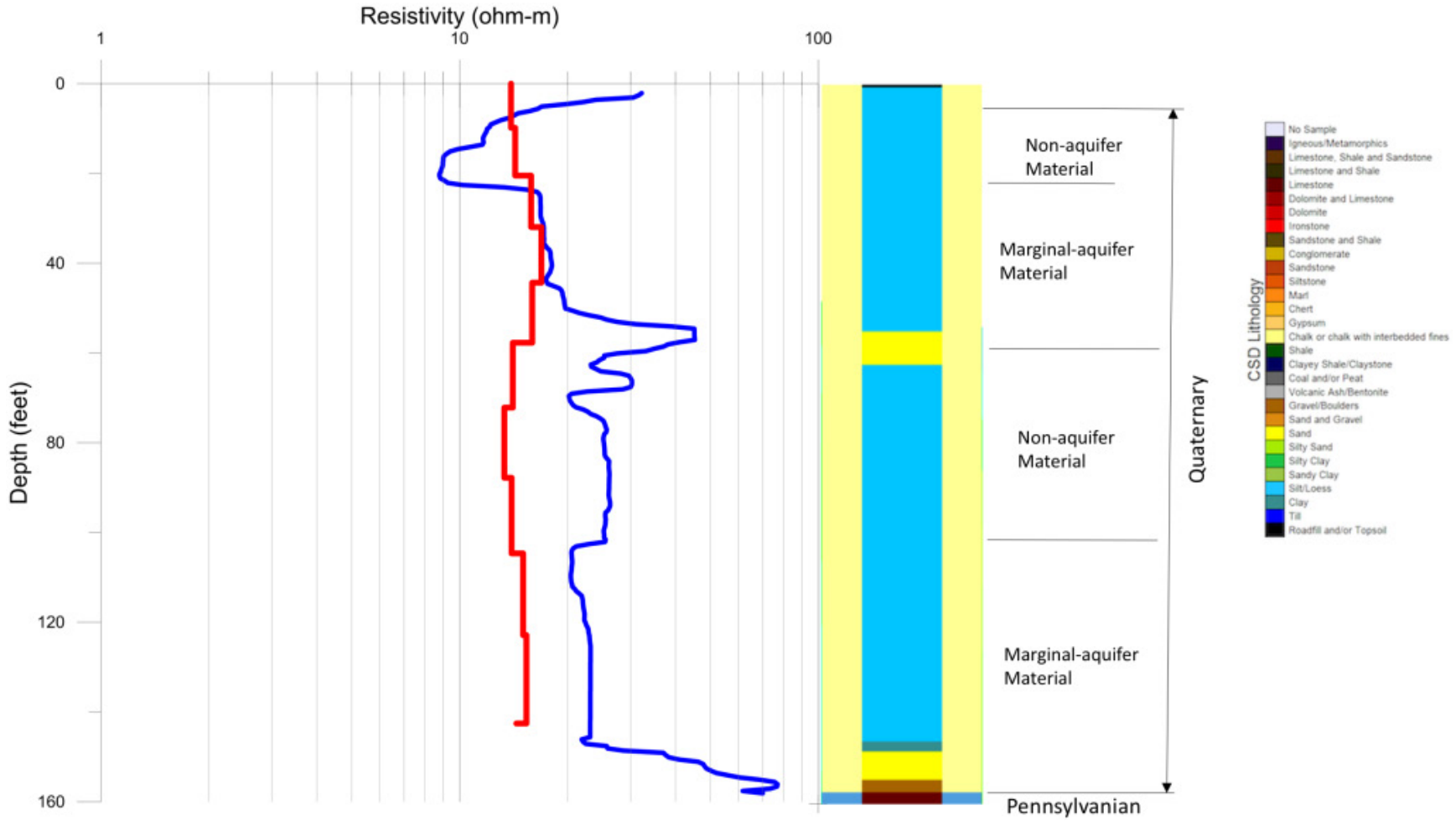


Figure 5-24. Graph of the *11-A-61* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *11-A-61* as well as the Quaternary aquifer material from the AEM inversion.

Figure 5-25 is a plot of *11-79* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L171401. *11-79* is located 484 feet from line L171401 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is reasonable with the AEM indicating a lower overall resistivity in the sand section of the ***Q*** from approximately 50-110 feet compared to the geophysical log. The shape of the curves shows a general agreement. The key is that the AEM clearly indicates the aquifer material within the ***Q***. The hydrogeologically important observation is that the ***Q*** aquifer can be detected.

Figure 5-26 is a plot of *12-79* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L171401. *12-79* is located 907 feet from line L171401 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is reasonable with the AEM indicating a lower overall resistivity in the sand section of the ***Q*** from approximately 61-118 feet compared to the geophysical log. The shape of the curves shows a general agreement. The key is that the AEM clearly indicates the aquifer material within the ***Q***. The hydrogeologically important observation is that the ***Q*** aquifer can be detected.

Figure 5-27 is a plot of *31-79* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L171401. *31-79* is located 1,497 feet from line L171401 and the AEM sounding is selected from the closest point to the borehole geophysical log. The agreement in the shape of the resistivity is reasonable with the AEM indicating a lower overall resistivity in the silt section of the ***Q*** from approximately the surface down to 40 feet compared to the geophysical log. The shape of the curves shows a general agreement with the exception of the thin bed of limestone in the log that is noted as an “erratic”. The key is that the AEM clearly indicates that there is non-aquifer material within the ***Q*** at this location.

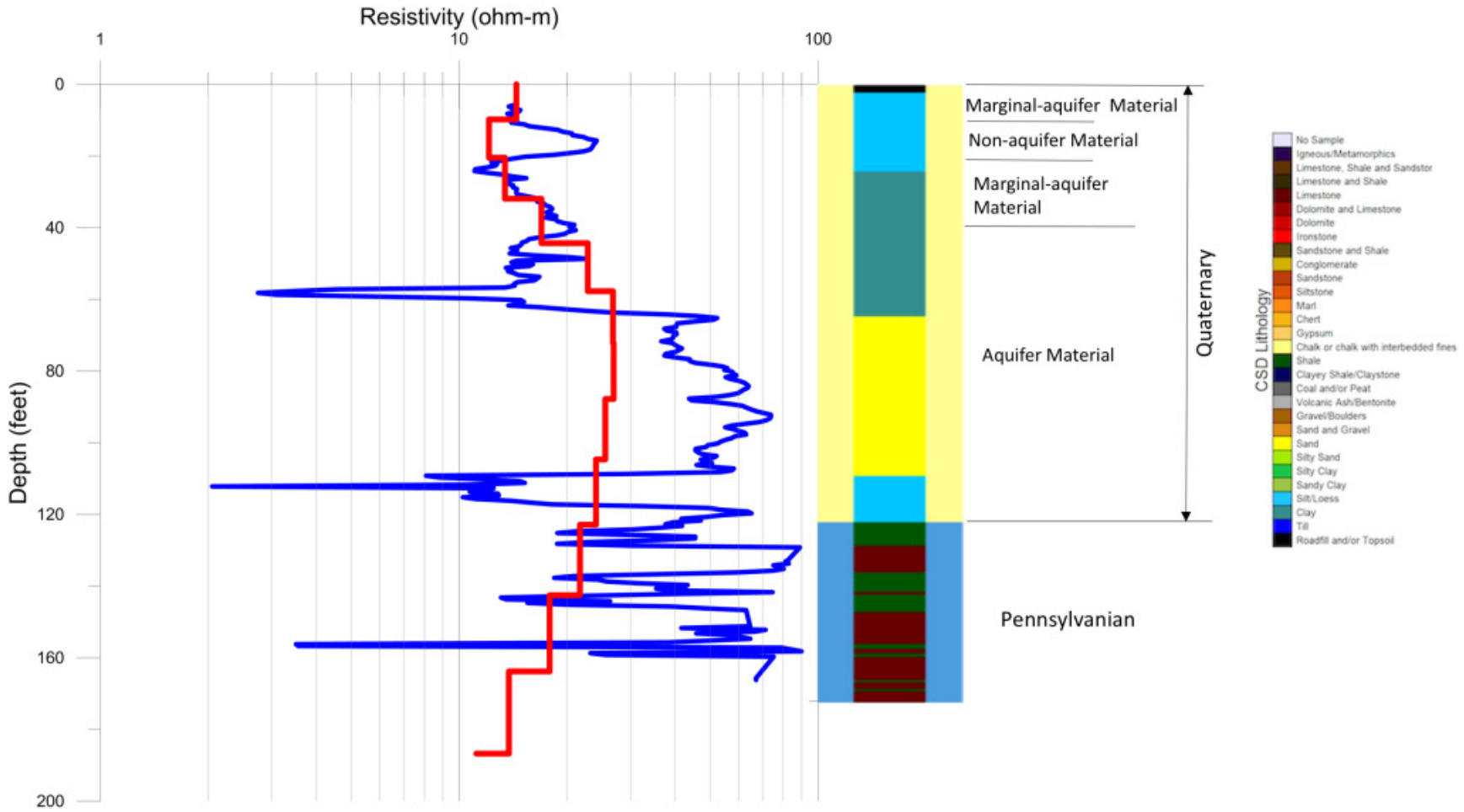


Figure 5-25. Graph of the 11-79 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from 11-79 as well as the Quaternary aquifer material from the AEM inversion.

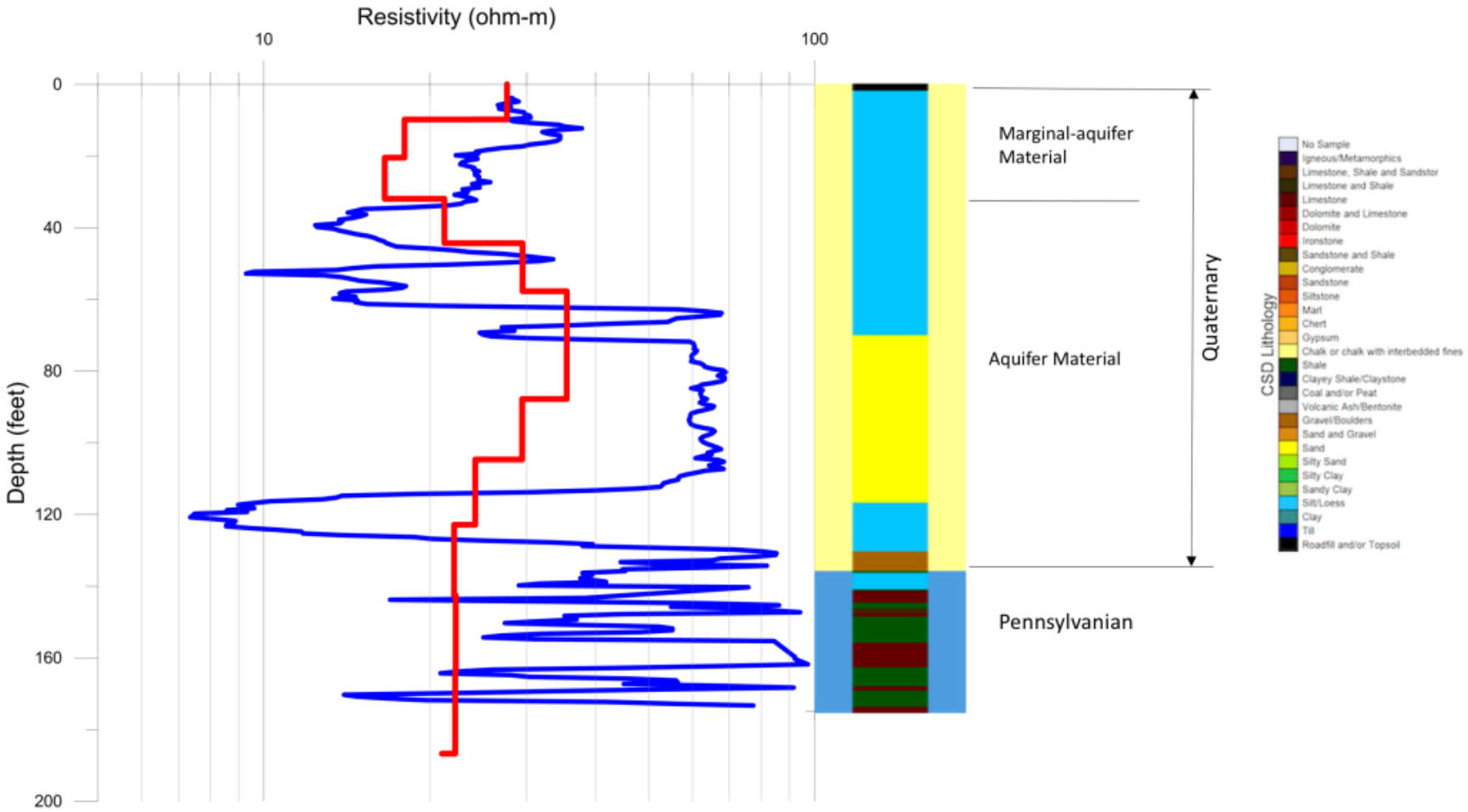


Figure 5-26. Graph of the 12-79 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from 12-79 as well as the Quaternary aquifer material from the AEM inversion.

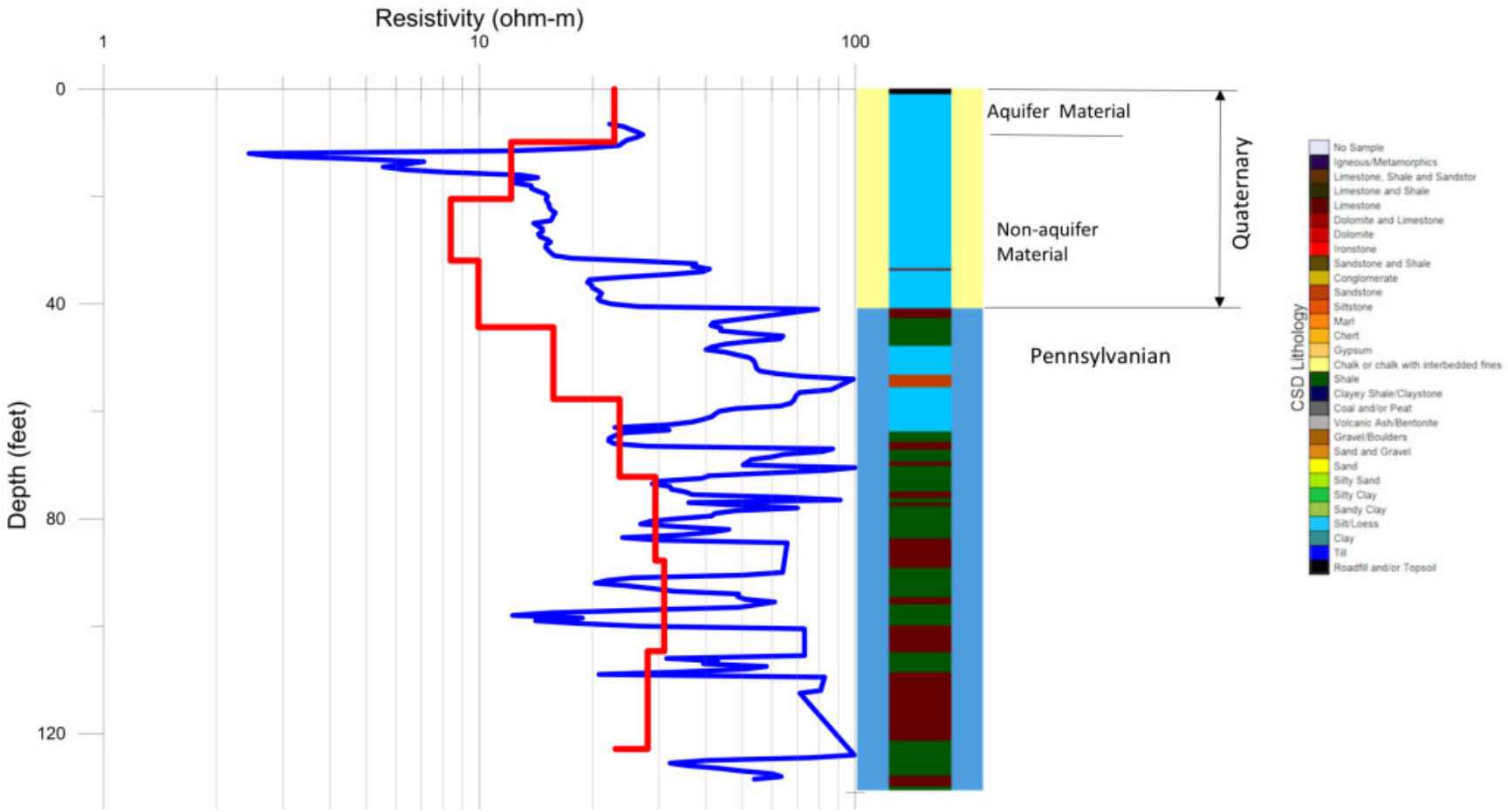


Figure 5-27. Graph of the 31-79 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from 31-79 as well as the Quaternary aquifer material from the AEM inversion.

5.3 Hydrogeological Framework of the LPSNRD AEM Survey Area

The AEM reveals the variability in the Quaternary and Cretaceous deposits which make up the aquifers across the AEM survey area. "***Q***" and "***Kd***" are terms used in the interpretative section of this report to describe all unconsolidated, semi-consolidated and consolidated materials overlying the undifferentiated ***IP***, thus including aquifer and non-aquifer materials alike. The 3D fence diagram displayed in Figure 5-28 presents interpreted profiles showing the overall distribution of ***Q***, ***Kd*** and ***IP*** materials along the reconnaissance lines within the LPSNRD survey area (interpreted as described in Section 5.2). Due to the small geographic area of the individual block flights and the large distance between each block, it is difficult to display them all as one figure. Additional fence diagrams and interpretation for the individual block flights of Eagle, Elmwood, Union, Waverly, and Weeping Water will be described separately later in this section. Along the reconnaissance lines the subsurface distribution of materials can generally be characterized into four somewhat overlapping, but distinct, areas with smaller localized depositional features described within the block flight areas. These include the Quaternary alluvium in a limited area, Quaternary glacial deposits that covers most of the project area, the ***Kd*** bedrock area which occurs mostly in the west and is eroded away in the east, and the ***IP*** bedrock area where the ***Kd*** is eroded off. Figure 5-29 presents a 3D fence diagram of these areas interpreted along the reconnaissance lines of the LPSNRD AEM survey area.

5.3.1 The Quaternary Alluvium and Glacial Aquifer Areas

The ***Q*** alluvium aquifer area of the LPSNRD AEM survey area is predominantly composed of unconsolidated aquifer and coarse aquifer materials composed of alluvial sediments. The alluvial sediments also contain marginal aquifer and non-aquifer materials but they are isolated and limited in geographic area. Most alluvial materials lie in the Platte River plain, the Missouri River plain, the North Fork of the Nemaha River, Salt Creek and Weeping Water Creek and are saturated from the near surface down to the base of the deposits. The ***Q*** alluvium overlies the ***IP*** in many areas along some of the listed streams. The approximate locations of these areas are given in Figure 5-30.

The ***Q*** alluvium is eroded into the surface of the ***IP*** and is observed frequently along the Platte River, the Missouri River, Salt Creek, and Weeping Water Creek. There can be strong groundwater-surface water communication between ***Q*** and the streams. The ***IP*** bedrock is an aquiclude along the streams. The maps of the elevation of the top of the ***IP*** is considered the base of ***Q*** and ***Kd*** materials and can be found in *Appendix 2, Surfaces*. Within the alluvial aquifer system there are areas of non-aquifer and marginal aquifer materials. These areas are typically confined to near surface deposits and basal silts and clays. These layers are localized and can act as an aquiclude and prevent recharge or serve as local confining units. Figure 5-31 is a 3D image of several of these layers of marginal and non-aquifer materials found along Salt Creek lying on the ***IP*** bedrock. Due to the nature of the reconnaissance flight lines being widely spaced, greater detail of the aquifer materials distribution can be achieved in this area with block flight-type surveys. Figure 5-32 is a profile view of line L170201 showing the north-south flight line near the west end of the Salt Creek area. There is an area within the profile that shows coarse aquifer material that is deposited within aquifer material, marginal aquifer, and non-aquifer materials lying on the ***IP*** contact. This highlights the often seen heterogeneity of these sediments.

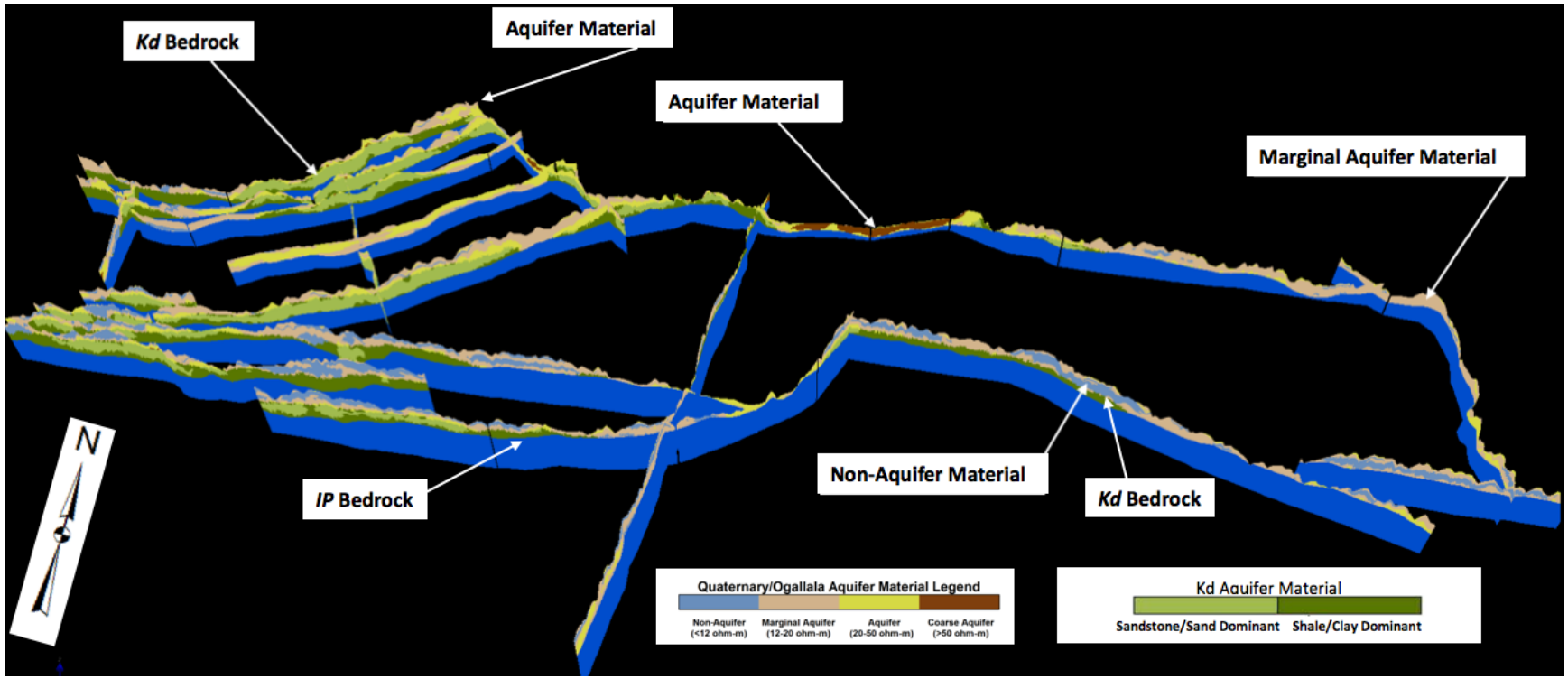


Figure 5-28. 3D fence diagram showing the reconnaissance flight lines, looking to the north of the interpreted distributions of aquifer material within the LPSNRD AEM survey area. Geologic units include Quaternary deposits (*Q*) and Cretaceous Dakota (*Kd*) described in the legend at the bottom right and the dark blue base is undifferentiated Pennsylvanian (*IP*) and is the aquiclude for the area. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

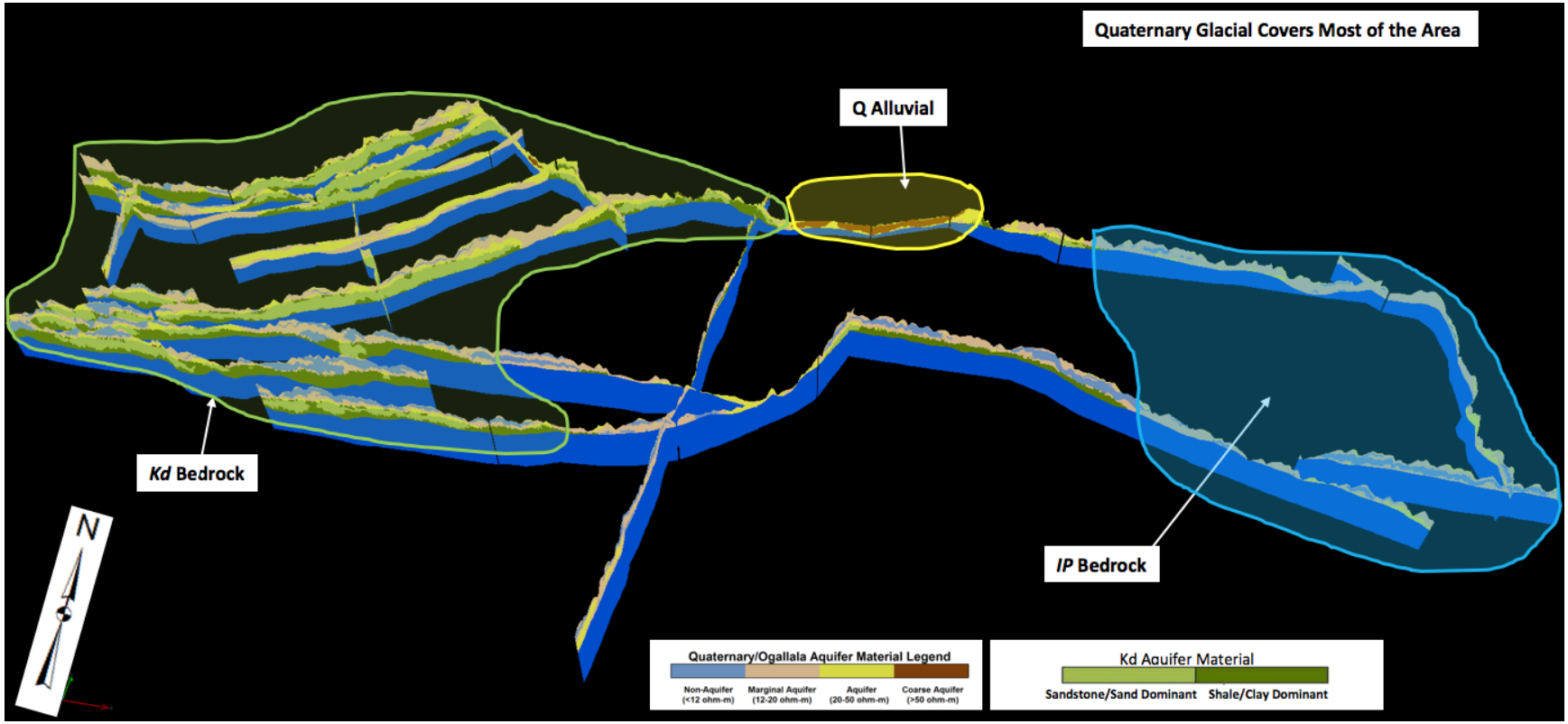


Figure 5-29. 3D fence diagram of the reconnaissance flight lines, looking to the north of the four distinct areas, Quaternary alluvium (*Q*) (yellow), Quaternary (*Q*) glacial (most of the figure and not outlined), Cretaceous Dakota (*Kd*) (green) bedrock and undifferentiated Pennsylvanian bedrock (*IP*)(blue) within the LPSNRD AEM survey area. Not all areas of localized depositional features are shaded in the figure. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

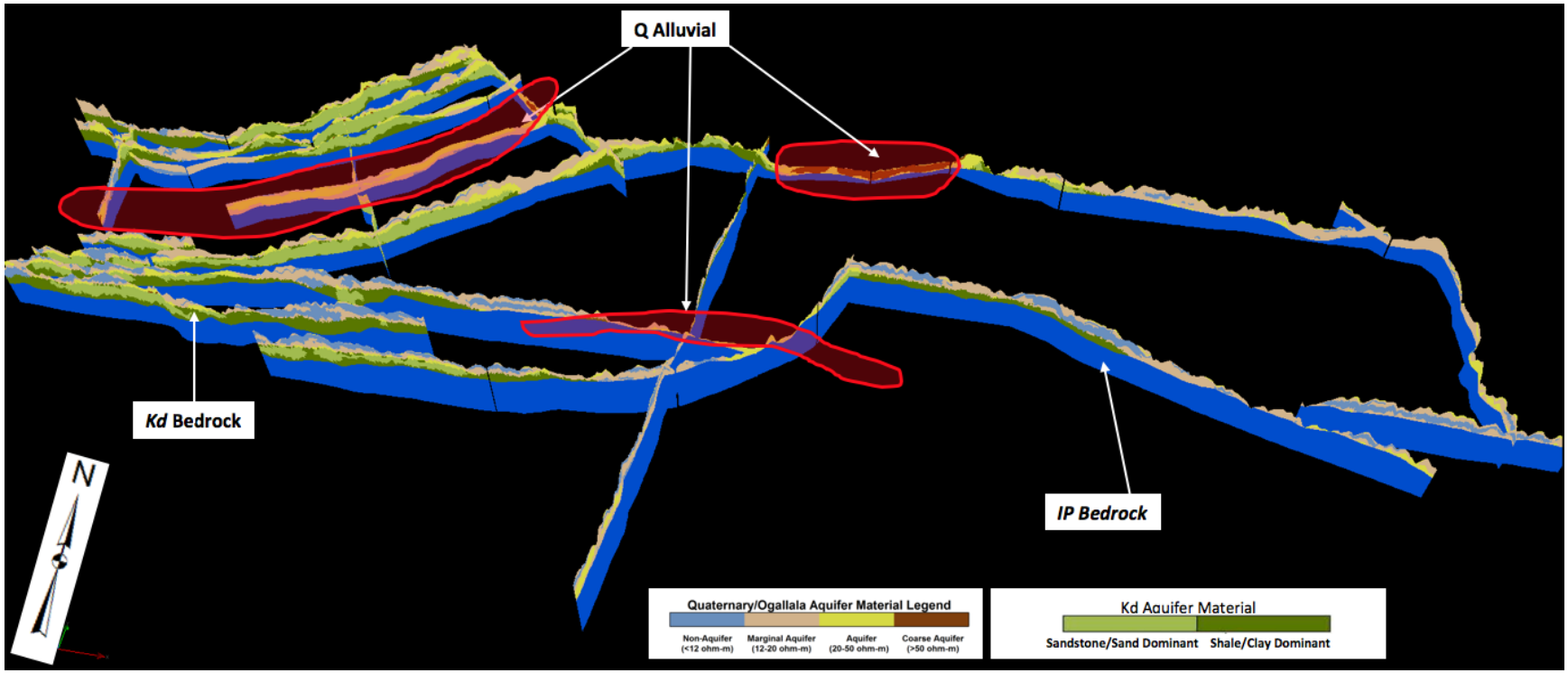


Figure 5-30. 3D fence diagram of the reconnaissance flight lines, looking to the north showing the approximate locations of the Quaternary (*Q*) alluvium (red) lying on the Cretaceous Dakota bedrock (*Kd*) (green) and undifferentiated Pennsylvanian bedrock (*IP*) (blue) within the LPSNRD AEM survey area. Not all areas of Quaternary (*Q*) alluvium features are shaded in the figure. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

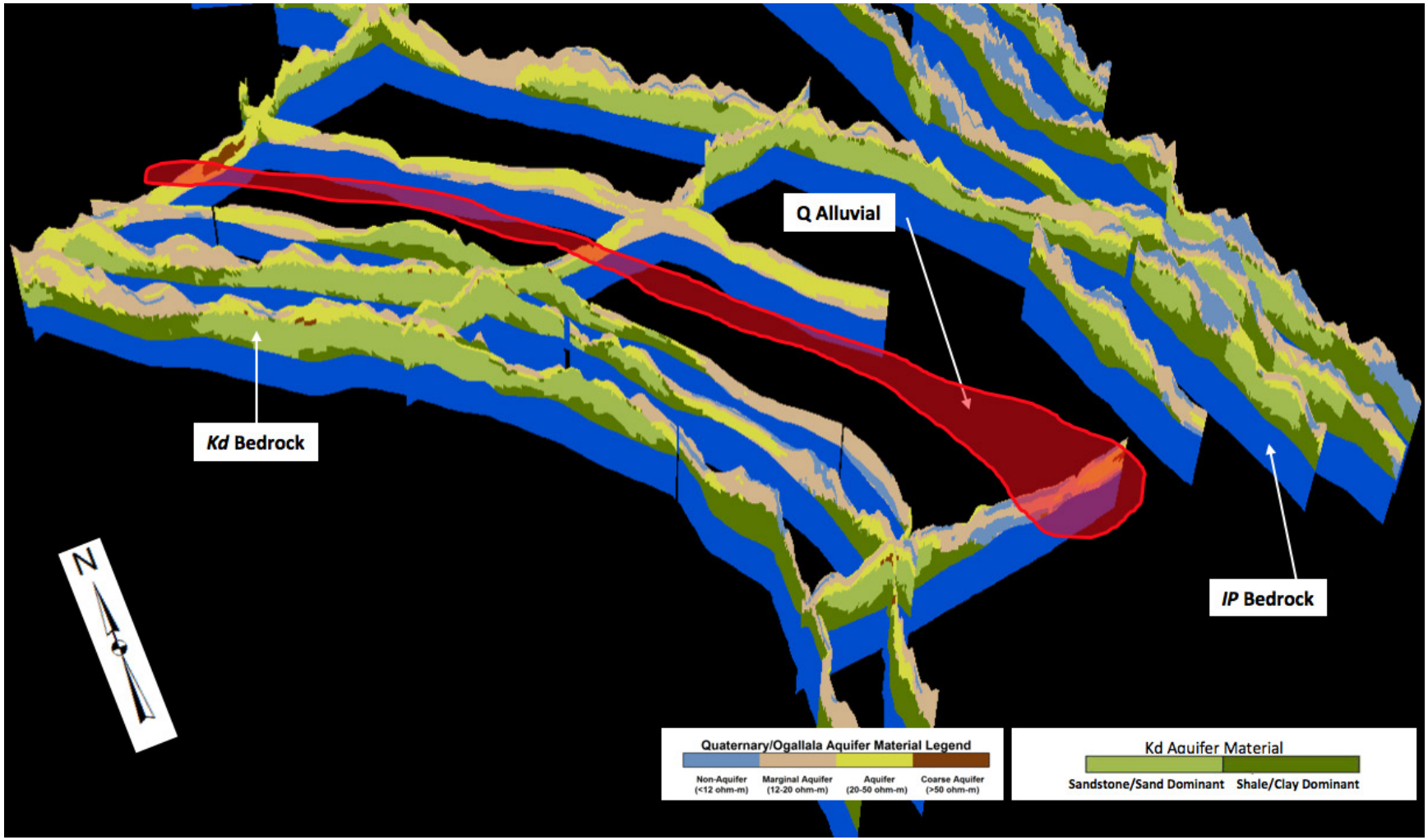


Figure 5-31. 3D fence diagram of the reconnaissance flight lines, looking to the northwest showing the approximate locations of the Quaternary (*Q*) alluvium (red) lying on the undifferentiated Pennsylvanian bedrock (*IP*)(blue) along Salt Creek. Note the change in aquifer materials including basal marginal and non-aquifer with overlying aquifer and coarse aquifer materials. Not all areas of Quaternary (*Q*) alluvium features are shaded in the figure. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

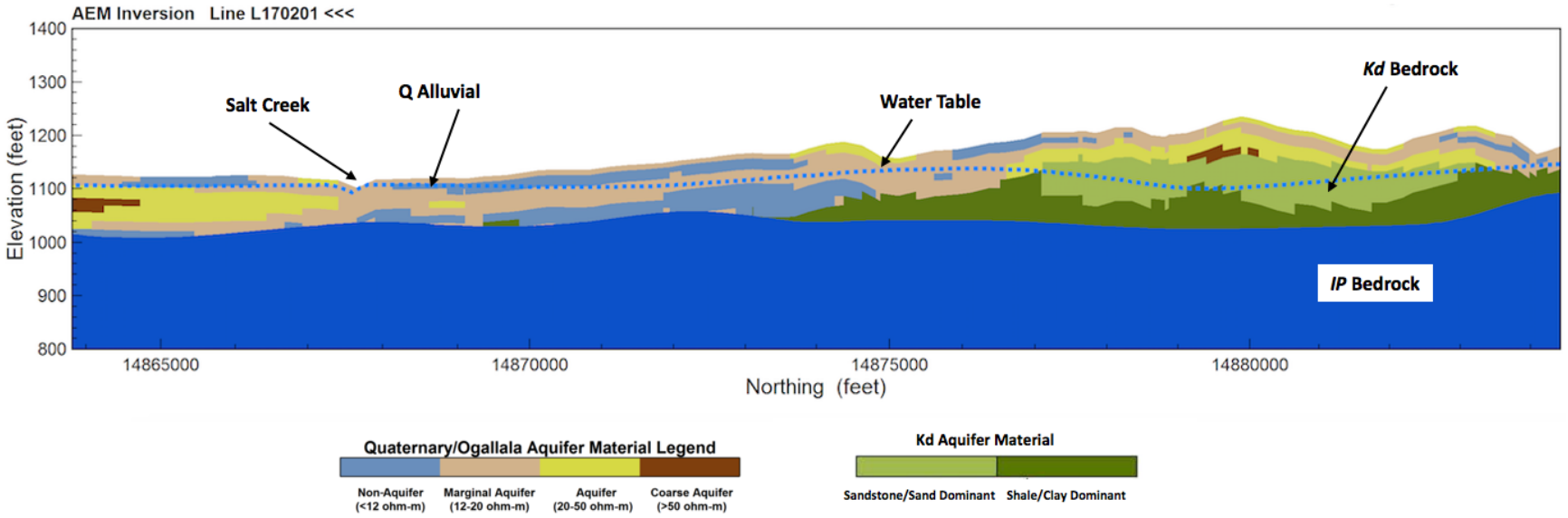


Figure 5-32. Profile L170201 showing the north-south flight line near the west end of the Salt Creek AEM survey area that aligns with the 3D image in Figure 5-31. This shows coarse aquifer, aquifer, marginal aquifer, and non-aquifer materials that are deposited above the undifferentiated Pennsylvanian (*IP*) contact to the south and the Cretaceous Dakota (*Kd*) materials to the north. Projection is NAD83, UTM14N, feet.

It also shows marginal to non-aquifer material lying directly on the ***IP*** and ***Kd*** that limits the hydrologic connection from the uplands to the stream.

Figure 5-33 is a profile of flight line L171201 which lies along a north south line that moves from the uplands to the south to the Platte River valley and illustrates the complexity of the aquifer materials and bedrock units. The south uplands area contains ***Q*** glacial material containing aquifer, marginal aquifer and non-aquifer materials lying on undifferentiated ***IP***. As you approach the north part of the upland area erosional remnants of the ***Kd*** bedrock that includes sandstone/sand and shale/clay dominant fractions above the ***IP*** bedrock are covered in ***Q*** glacial deposits. The combination of ***Q*** glacial deposits and the ***Kd*** shale/clay deposits does not allow a hydrologic connection from the uplands to the Platte River in this area. This continues down into the Platte River valley where there are coarse aquifer, aquifer and marginal aquifer materials that are in hydrologic connection with the Platte River.

A disadvantage of the reconnaissance lines and widely spaced block flight lines is that they have only identified deposits along the AEM flight line and the complete extent of these deposits cannot be determined expediently without further AEM acquisition or exhaustive interpretation from added boreholes or ground EM surveys.

Q glacial deposits cover much of the LPSNRD AEM survey area and vary in thickness across the area but, in general, reach a maximum thickness of greater than 150 feet (Figure 2-5, Section 2). These materials are a combination of tills and outwash deposits. They lie unconformably upon the ***Kd*** and ***IP***. The bedrock surfaces of the ***Kd*** and ***IP*** generally have little relief beneath the uplands with some shallow channels eroded into them along the larger streams. Near the Platte River and the Missouri River there can be up to 200 feet of relief in the bedrock surface of the uplands to the river flood plain areas, Figure 5-33 is an example of this near the Platte River along profile L171201. The mantle of glacial materials in the area is extensive and details of the glacial deposition can be found in McGuire et al. (2012). Within the glacial sequence there are probable multiple advances of moraines as well as multiple occurrences of tunnel valleys or outwash deposits (Carney et al., 2015c). Hydrogeologically, the key to the area is the presence of separated zones of aquifer materials and how those zones are connected to surface water and subsequently compartmentalized by zones of marginal or non-aquifer materials. These zones of marginal aquifer material still can yield water to a water well but are typically composed of interlayered fine sands or thin sand layers and have abundant fine grained material composed of silt, clay, and till. Figure 5-28 is a 3D map view looking to the north displaying the distribution of aquifer materials within the glacial deposits along the reconnaissance lines. Within the survey area there is little coarse aquifer material in the glacial deposits. The bulk of the glacial deposits is made up of aquifer, marginal aquifer and non-aquifer materials. Figure 5-34 provides a view from the southeast looking northwest across the project area showing the distribution and thickness of ***Q*** aquifer materials which are predominately glacial in origin. The eastern end of the survey area is where the thickest sequence of marginal to non-aquifer material can be seen. Figure 5-35 is a profile L145101 which is oriented southeast-northwest on the eastern end of the survey area showing a thin section of mostly unsaturated glacial material. Note the water table that is near or below the ***IP*** bedrock leaving the Q materials mostly unsaturated. The southwest-northeast line L144701 in Figure 5-36 shows all ***Q*** deposits above the ***IP*** and ***Kd*** including those that are of glacial origin which are mostly unsaturated.

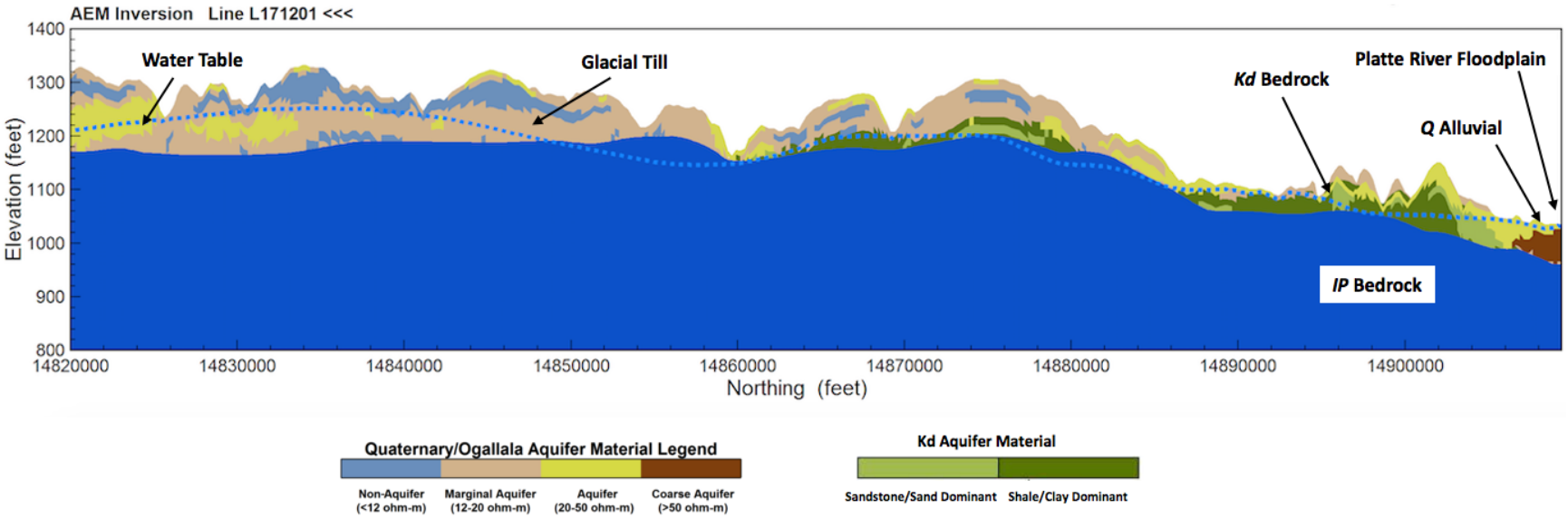


Figure 5-33. Profile L171201 showing the north-south flight line from the uplands to the south to the Platte River valley. This shows the complex geology of the Quaternary (*Q*) deposits and the remnant Cretaceous Dakota *(Kd)* materials deposited above the undifferentiated Pennsylvanian (*IP*) contact. There is no hydrologic connection from the uplands to the Platte River along this flight line. Projection is NAD83, UTM14N, feet.

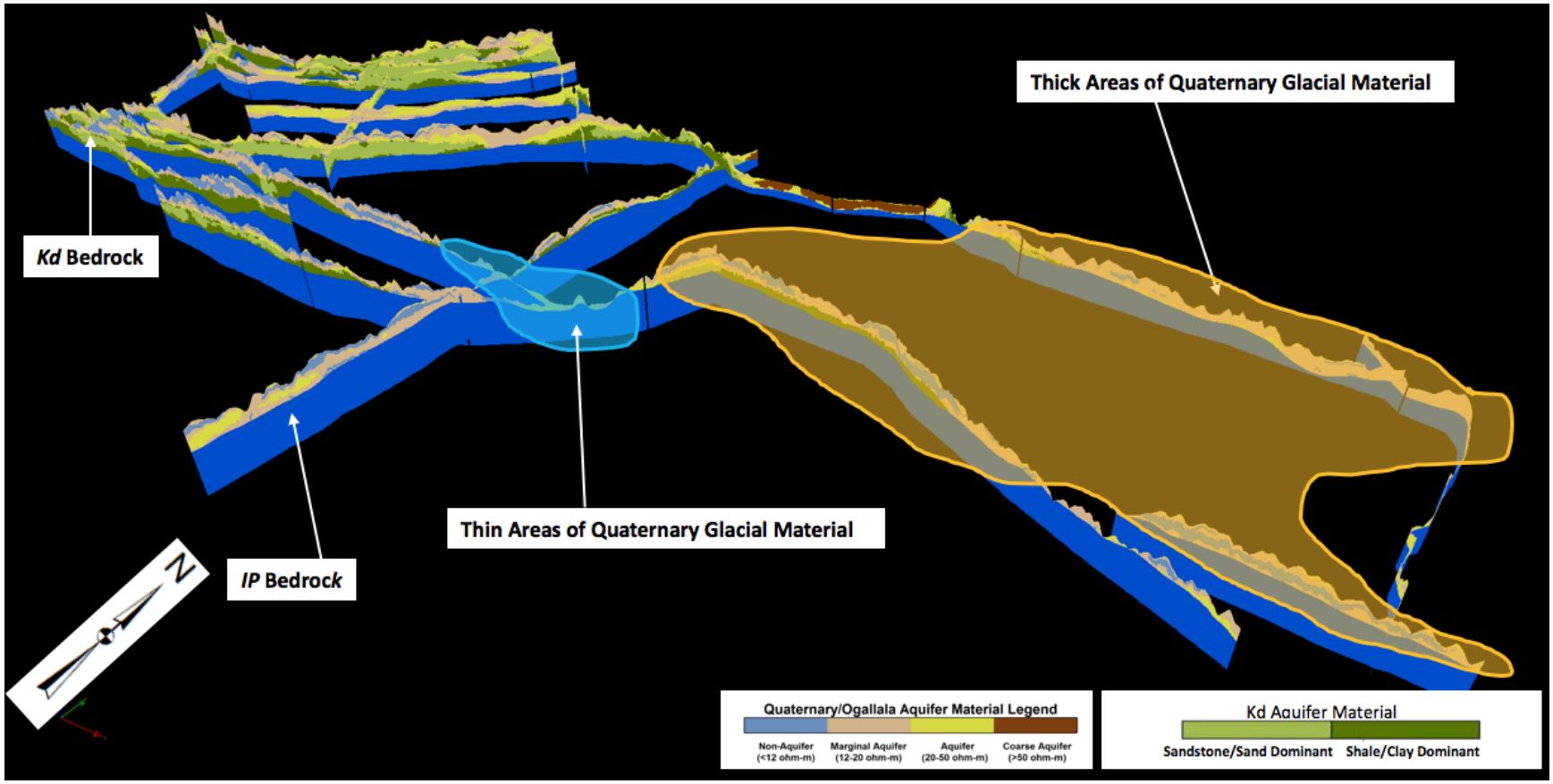


Figure 5-34. 3D fence diagram (showing the reconnaissance flight lines) looking to the northeast showing distribution and thickness of Quaternary (*Q*) glacial material. The area shaded in orange on the east side of the survey area has thick glacial material (> that 150 feet) and the area in blue is thin. Not all areas of thick and thin Quaternary (*Q*) glacial material are shaded on figure. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

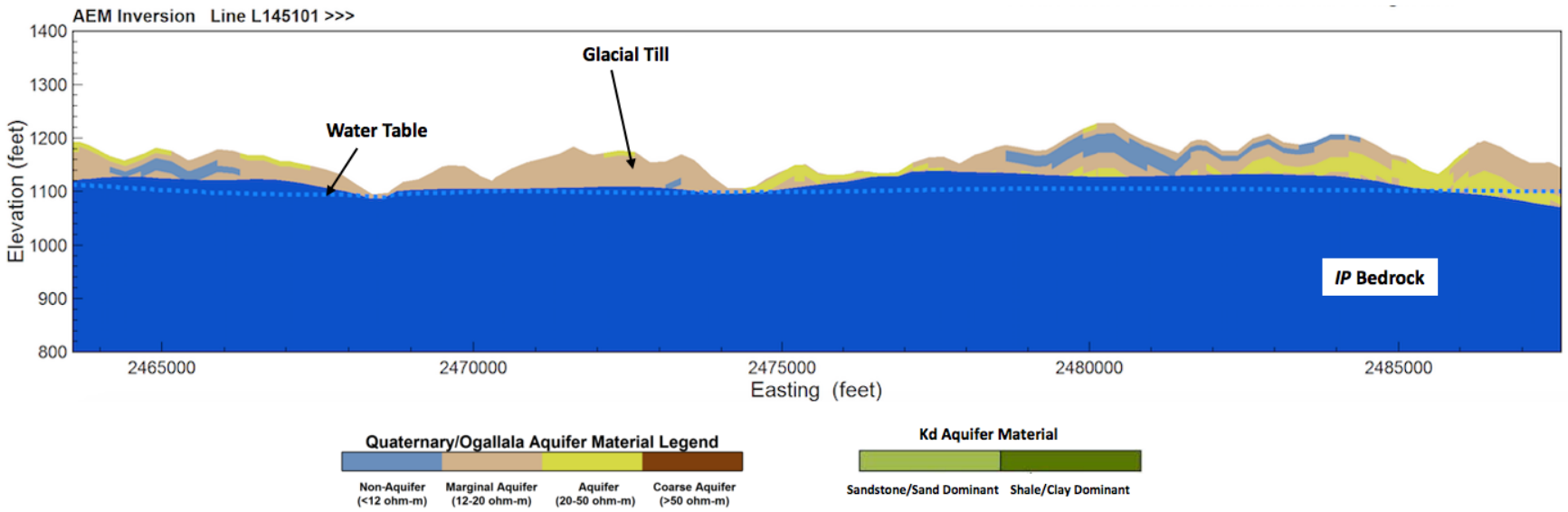


Figure 5-35. Profile L145101 oriented southeast-northwest from the uplands to the Platte River valley. This shows the complex geology of the Quaternary (*Q*) deposits which are variable in thickness deposited above the undifferentiated Pennsylvanian (*IP*) contact. The Quaternary is mostly unsaturated along this profile and the water table is below the undifferentiated Pennsylvanian (*IP*) surface. Projection is NAD83, UTM14N, feet.

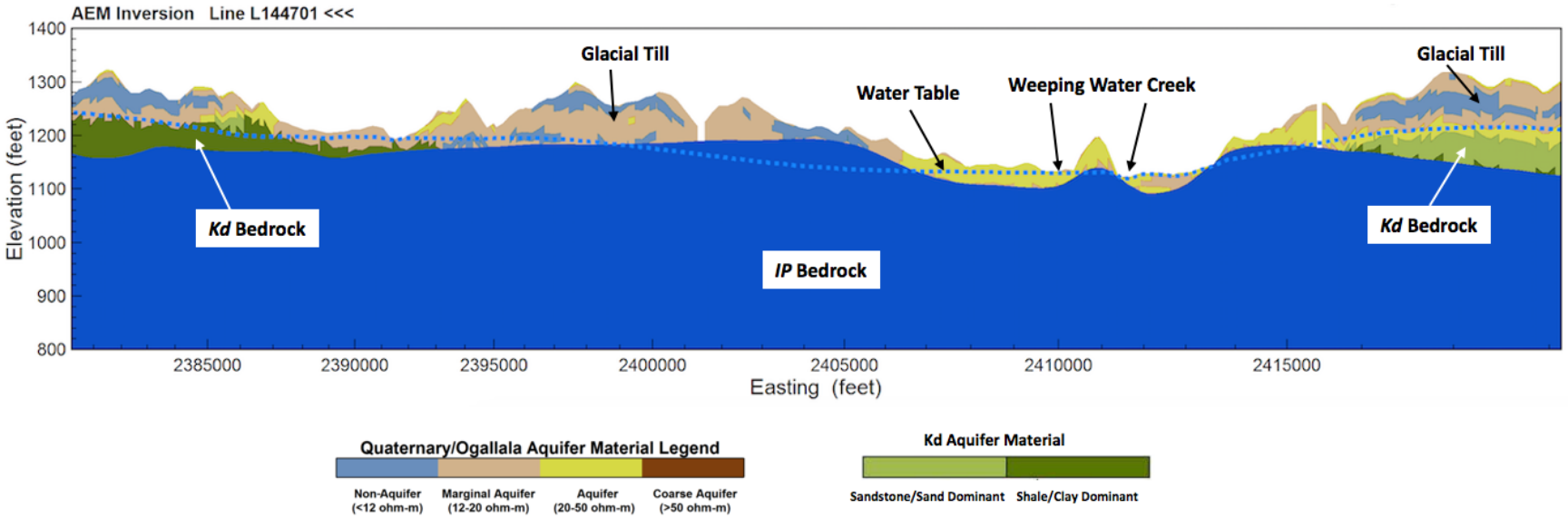


Figure 5-36. Profile L144701 oriented southwest-northeast in the uplands near Elmwood. This shows the complex geology of the Quaternary (*Q*) deposits which are variable in thickness deposited above the undifferentiated Pennsylvanian (*IP*) and Cretaceous Dakota (*Kd*) bedrock. The Quaternary is mostly unsaturated along this profile. There is Quaternary Alluvial material within the Weeping Water Creek channel. Projection is NAD83, UTM14N, feet.

There is an erosional channel that is part of a meander of Weeping Water Creek near Elmwood that has ***Q*** alluvial materials present. This feature would have been difficult to detect and map by the CSD drilling alone unless they had been lucky enough to site many boreholes across the area in the right locations.

Appendix 1, 2D Profiles contains interpreted profiles that illustrate the details of the ***Q*** and ***Kd*** aquifer areas of the LPSNRD AEM survey. Appendix 2 contains 3D images of the LPSNRD AEM survey area that have been rotated to allow viewing of the overall distribution of materials.

5.3.2 The Cretaceous Dakota Group

The ***Kd*** is a bedrock unit located mostly in the western end of the survey area although there are additional erosional remnants in the central-east. The ***Kd*** is characterized by a combination of sandstone/sand dominant and shale/clay dominant units. The sandstone/sand dominant part of the ***Kd*** is an important aquifer where saturated. It can also be hydrologically connected to the Quaternary aquifer materials and streams. The ***Kd*** shale/clay dominant materials are considered an aquiclude which acts as a boundary condition to groundwater flow. The ***Kd*** is sometimes covered by a small amount of ***Q*** alluvium and typically covered by ***Q*** glacial materials. There are some ***Kd*** outcrops along the streams of the survey area. The ***Kd*** varies in thickness from absent to over approximately 150 feet which is shown in Figure 5-37 on a southeast-northwest oriented profile L341002. This profile shows two erosional remnants of the ***Kd*** separated by Salt Creek. The remnants are mostly sandstone/sand dominant materials which are mostly saturated on the south side and less saturated on the north. Along the profile the ***Kd*** is in hydrologic connection to the stream. Within the survey area the ***Kd*** is a combination of a discontinuous erosional surface with small remnants of the original surface scattered through the area lying unconformably on the ***IP***. The patterns that define the shape of present day ***Kd*** are related to erosion over many episodes of glaciation and fluvial processes in addition to recent erosion by the Platte River, North Fork of the Nemaha River, the Missouri River, Salt Creek, and Weeping Water Creek. The sandstone/sand dominant portion of the ***Kd*** is the aquifer material and the shale/clay dominant portion is the aquitard. Many areas of ***Kd*** have sufficient saturated thickness to be an effective water supply to wells. The block flight areas of the survey will be described in the following subsections which will include the location and thickness of the saturated sandstone/sand dominant portion of the ***Kd.*** Selection of drilling sites based on the greatest ***Kd*** thickness improves the chances of a successful water supply. Thickness of the aquifer does not include the effect of cementation of the pore space of the sandstone/sand unit, which would lead to lower yield and transmissivity. Caution needs to be used in application of the aquifer thickness maps. Where the ***Q*** and ***Kd*** are in contact is an area of good hydrologic connection. Due to the nature of the reconnaissance flight lines greater detail of the ***Kd*** sandstone/sand dominant and shale/clay dominant materials distribution can be achieved in this area with increased numbers of flight lines similar to the block flight areas elsewhere in this project

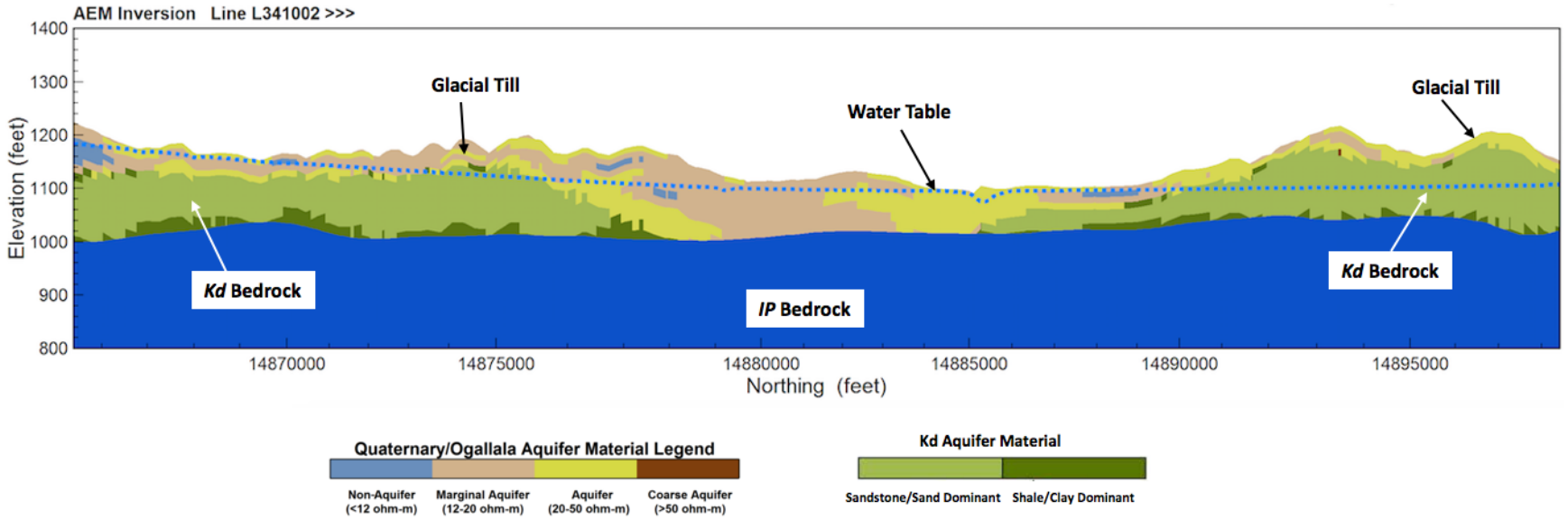


Figure 5-37. Profile L341002 oriented southeast-northwest between Waverly and Greenwood. This shows the complex geology of the Quaternary (*Q*) deposits which are variable in thickness deposited between two erosional remnants of the Cretaceous Dakota Group (*Kd*) above the undifferentiated Pennsylvanian (*IP*) and bedrock. The Quaternary and Cretaceous Dakota (*Kd*) are mostly saturated along this profile. There are Quaternary (*Q*) deposits and Cretaceous Dakota (*Kd*) material in hydrologic connection with the stream. Projection is NAD83, UTM14N, feet.

5.3.3 The IP Bedrock Area

The undifferentiated Pennsylvanian (***IP***) age bedrock surface is considered the base of aquifer for ***Q*** and the ***Kd***. The heavily eroded upper surface of the ***IP*** is present throughout the survey area. There is approximately 150 feet of relief in the bedrock surface from the upland areas to the Platte and Missouri river basins. There is less relief along the creeks and smaller streams. The ***IP*** outcrops along the incised stream valleys in the survey area. Some of the local quarries have exposures of ***IP*** and mine the limestone. There are channels cut into the ***IP*** surface the most notable is along Weeping Water Creek drainage that has a low relief of approximately 50 feet (Figure 5-36). Overall the ***IP*** is relatively flat lying throughout most of the survey area, but is interrupted by structural deformations in some areas (Carney et al., 2015c). Detailed descriptions of the ***IP*** surface follow in the descriptions of the block flight areas and detailed surfaces along the reconnaissance flight lines in the Salt Creek area are available in *Appendix 2, Surfaces*. The Salt Creek area is a complicated heterogeneous combination of ***Q*** deposits that can be better understood if there was additional collection of AEM flight lines similar to the block flights.

5.3.4 Hydrogeology of the AEM Block Flight Areas

5.3.4.1 Eagle Block Flight Area

The hydrogeology of the Eagle block flight area is dominated by thick glacial deposits in some areas greater than 100 feet thick. This material is almost exclusively made up of marginal and non-aquifer material. Figure 5-38 shows a fence diagram showing the ***Q*** glacial deposits resting on the ***Kd*** saturated sandstone/sand material (the ***Kd*** shale/clay dominant material are not shown). This figure provides insight into the aquifer of this area which is made up of thin Q aquifer material directly in contact with the ***Kd*** saturated sandstone/sand material. Figure 5-39 shows profile L181001 which shows the complex nature of the hydrogeology and the limited extent of the aquifer made up of the ***Kd*** and ***Q*** materials which are capped by marginal and non-aquifer materials. ***Kd*** bedrock, composed of shale/clay dominant material, makes up most of ***Kd*** materials in this area and acts as an aquiclude. The aquifer material is generally bound on all sides and hydrologic connection with other aquifers or streams is not present within the block except where the ***Q*** aquifer and ***Kd*** sandstone/sand is present and in contact with those features. When these deposits reach the edges of the survey block it is unknown how far it extends to the surrounding area except along the reconnaissance lines such as L00702 which can be continuous from one block flight area to the next.. The ***Kd*** materials rest upon the ***IP*** which has some relief with approximately 116 feet of elevation change from the high in the east moving to the west. The ***IP*** surface map is shown in Figure 5-40. The volume of all saturated ***Q*** aquifer material and ***Kd*** aquifer material has been calculated and is presented in Section 5.4. Figure 5-41 shows the specific yield values estimated for the block flight area which is used in the groundwater volume calculations in Section 5.4. The average SY is 5% or less for ***Q*** aquifer materials, the stippled areas on the map are areas that the ***Q*** aquifer is very thin or absent (Summerside and Meyers, 2005b). Figure 5-42 shows the reported DNR well discharge value for individual wells is shown on the map of the saturated ***Q*** aquifer materials thickness (grey tones) which can be up to 60 feet thick and ***Kd*** sandstone/sand dominant thickness (color tones) which can be up to >120 feet thick.

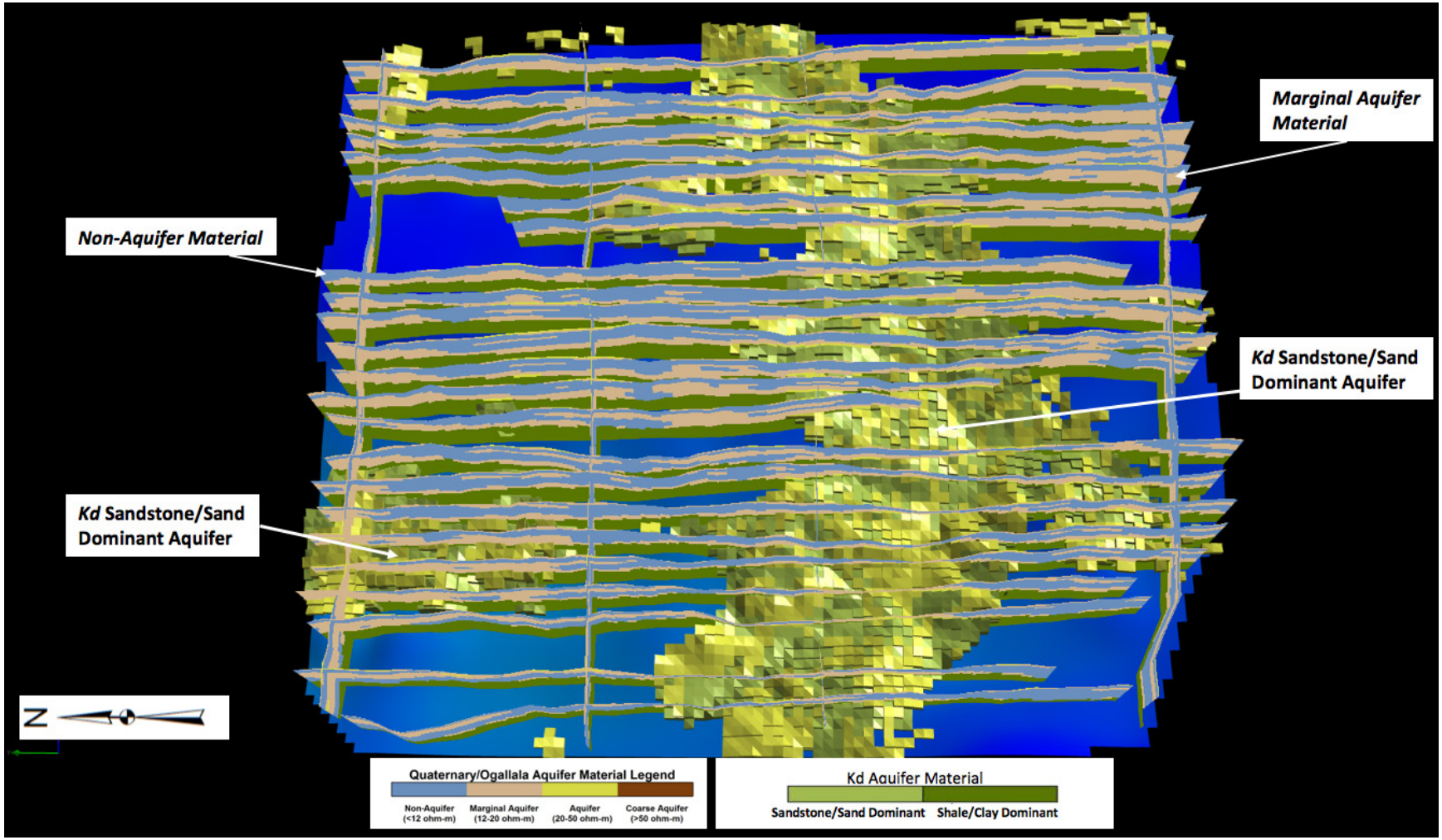


Figure 5-38. 3D fence diagram showing the Eagle block flight lines looking to the east showing distribution and thickness of Quaternary (*Q*) glacial material and Cretaceous Dakota (*Kd*) materials. The area has thick glacial material (> that 100 feet is some areas). The saturated *Q* aquifer material and *Kd* sandstone/sand dominant material is limited in volume. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

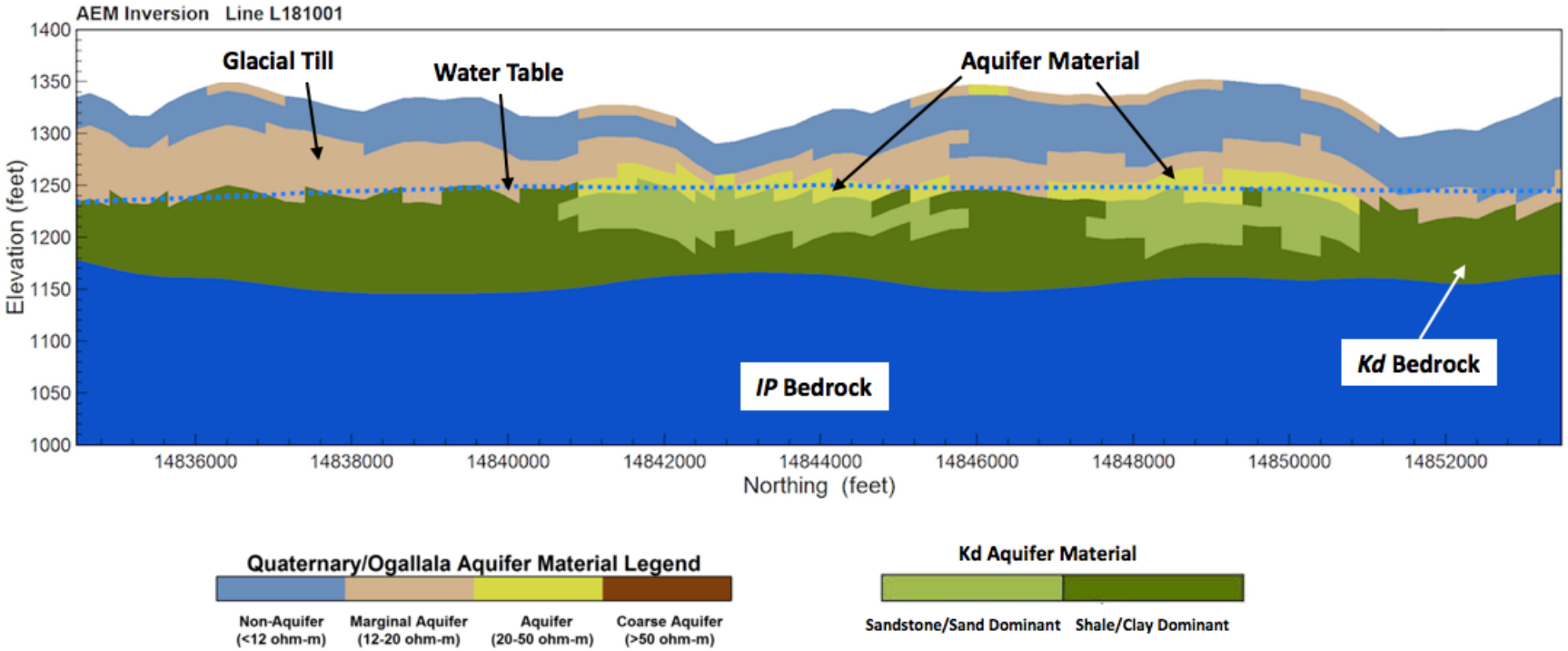


Figure 5-39. Profile L184201, oriented north, is south of Eagle. This profile shows the complex geology of the Quaternary (*Q*) deposits which are variable in thickness deposited above the Cretaceous Dakota (*Kd*). The Q aquifer material and the Kd sandstone/sand dominant materials have limited volume and saturation along this profile. Projection is NAD83, UTM14N, feet.

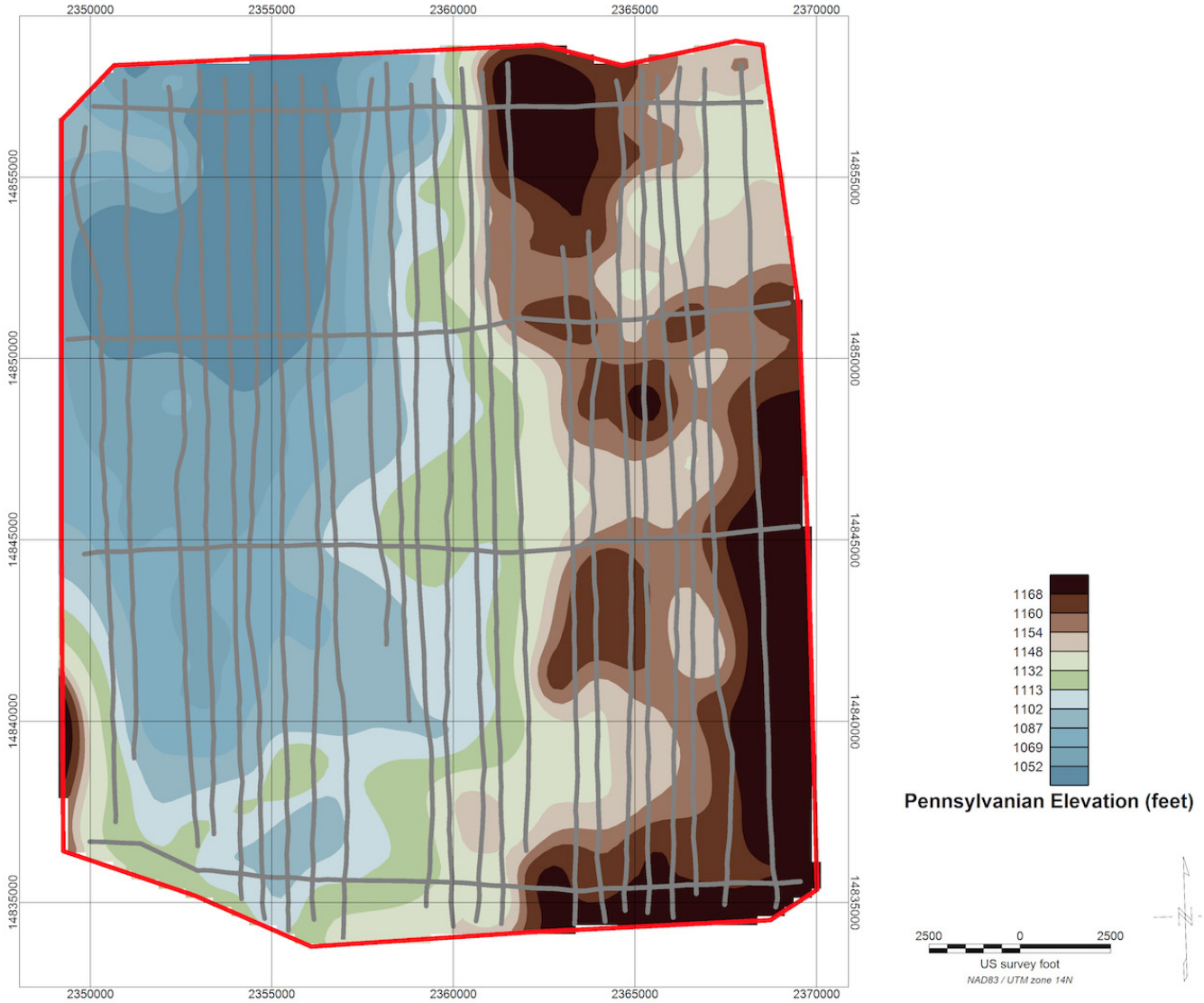


Figure 5-40. Elevation map of the undifferentiated Pennsylvanian (*IP*) bedrock surface which is considered the base of aquifer. Highest elevations are to the east and slope to the west with 16 feet of relief. Gray lines are the flight lines and the red box is the block out line. Projection is NAD83, UTM14N, feet.

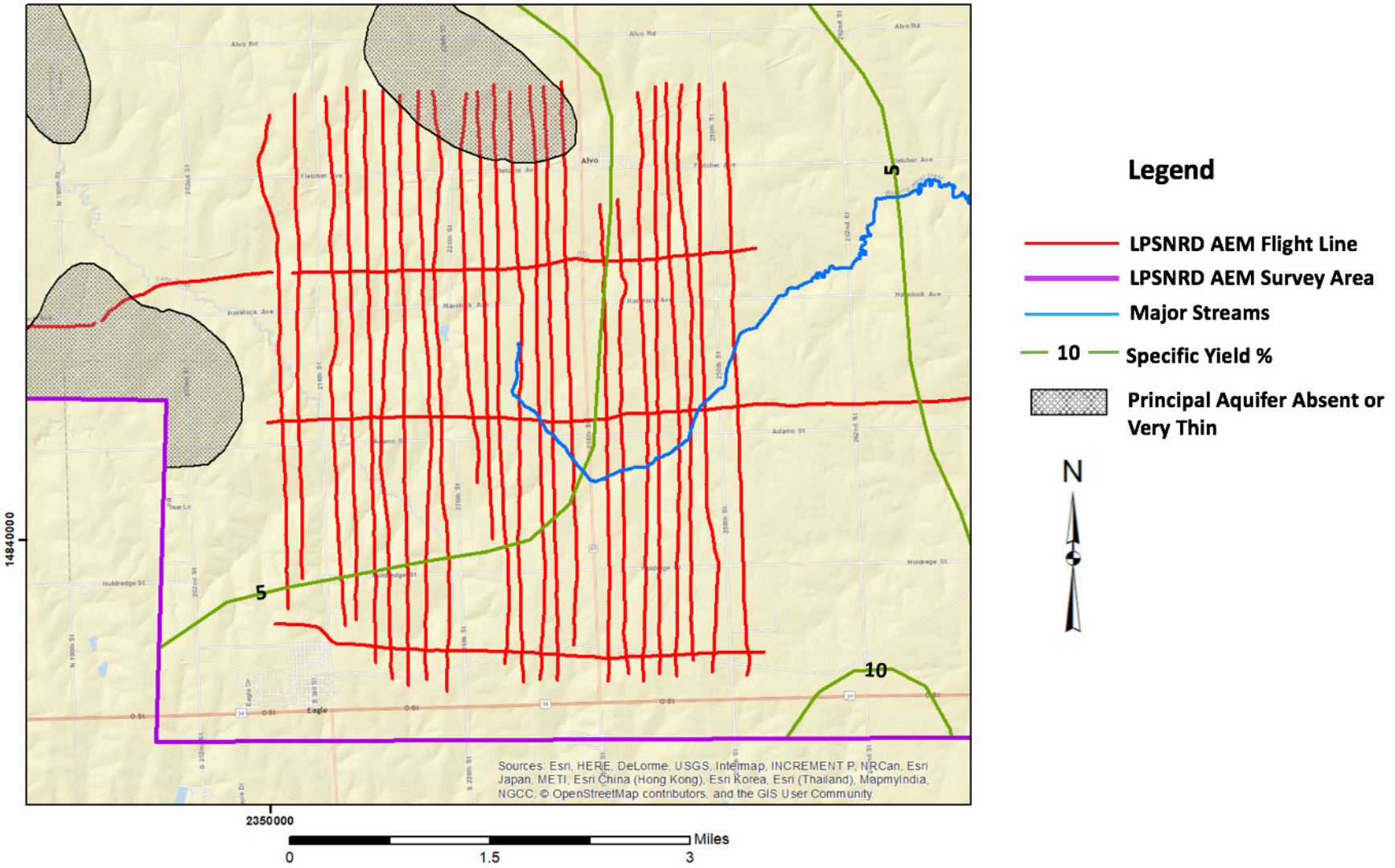


Figure 5-41. Specific yield values within the Eagle AEM block survey area (Summerside and Meyers, 2005b). Note the large areas of the uplands that have Quaternary aquifer materials that are absent or very thin. Accurate specific yield values are not able to be determined due to the constraint of using the 1995 water table (NE-CSD, 1995). Projection is NAD83, UTM14N, feet.

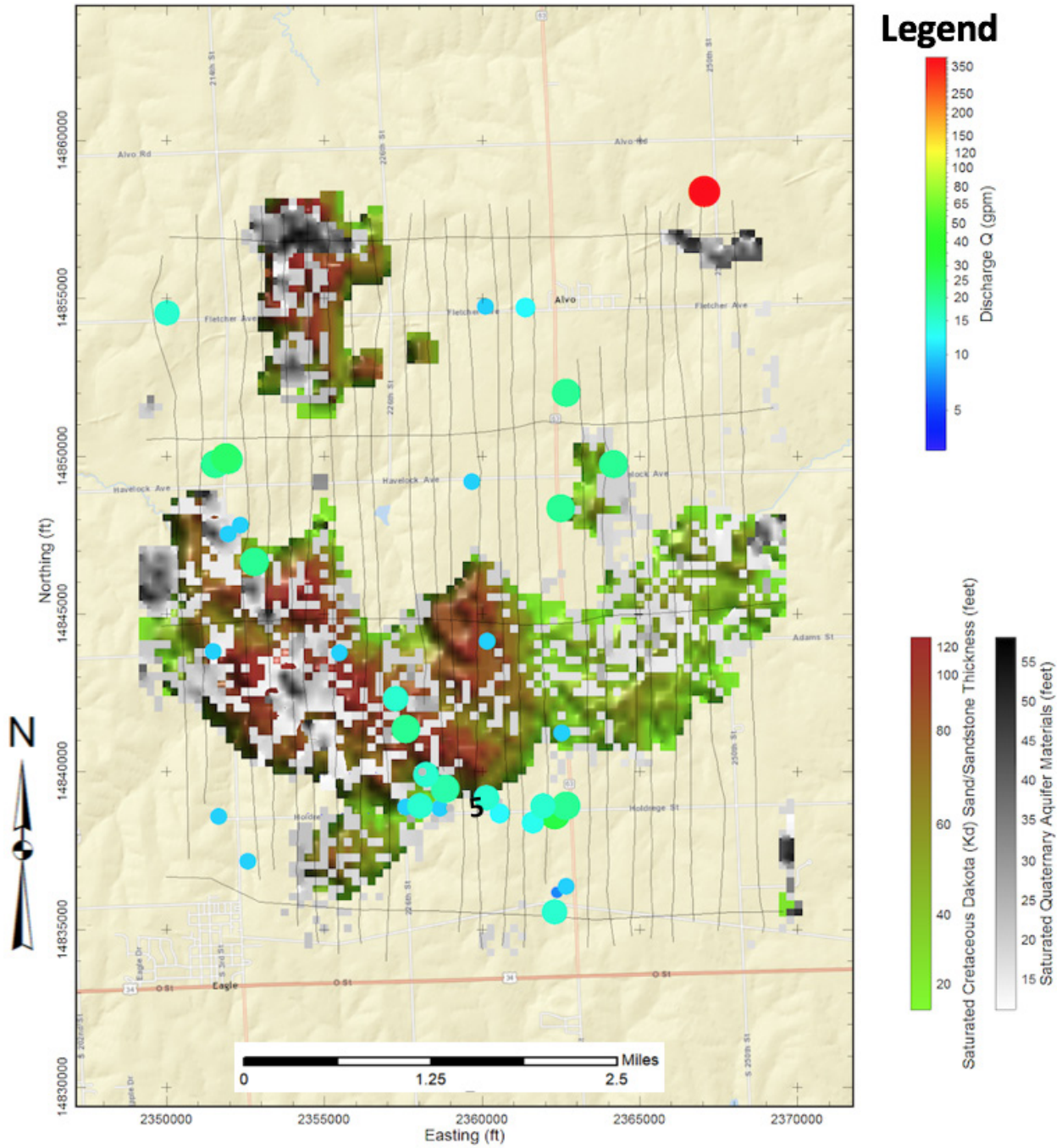


Figure 5-42. Comparison of discharge values (color and size) from individual well locations (NEDNR, 2016b) compared to saturated thickness of the Quaternary aquifer (*Q*) shown in grey tones and the Cretaceous Dakota sandstone/sand dominant material (*Kd*) shown in colored tones. Gray lines are flight line locations. Projection is NAD83, UTM14N, feet.

There is a correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge. The discharge values range from <5 to >350 gallons per minute (NEDNR, 2016b). There is a correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge.

5.3.4.2 Elmwood Block Flight Area

The hydrogeology of the Elmwood block flight area is dominated by thick glacial deposits in some areas greater than 100 feet thick. This material is almost exclusively made up of marginal aquifer material and non-aquifer material. Figure 5-43 shows a fence diagram showing the ***Q*** glacial deposits resting on the ***Kd*** saturated sandstone/sand material (the ***Kd*** shale/clay dominant material are not shown). This image provides insight into the aquifer of this area which is made up of thin Q aquifer material directly in contact with limited amounts of ***Kd*** saturated sandstone/sand material. Figure 5-44 shows profile L184201 which shows the complex nature of the hydrogeology and the limited extent of the aquifer made up of the ***Kd*** and ***Q*** materials which are capped by marginal and non-aquifer materials. ***Kd*** bedrock made up of mostly the shale/clay dominant material makes up most of ***Kd*** materials in this area and acts as a aquiclude. The aquifer material is generally bound on all sides and hydrologic connection with other aquifers or streams is not present except where the ***Q*** aquifer and ***Kd*** sandstone/sand is present. When these deposits reach the edges of the survey block it is unknown how far it extends to the surrounding area except along the reconnaissance lines such as L00702 which can be continuous from one block flight area to the next. The ***Kd*** materials rest upon the ***IP*** which has small relief of approximately 28 feet of elevation change from the two shallow ridges in the middle south of the flight area with a shallow channel in between them and bedrock high to the north. The ***IP*** surface map is shown in Figure 5-45. The volume of all saturated ***Q*** aquifer material and ***Kd*** aquifer material has been calculated and is presented in Section 5.4. Accurate specific yield values are not able to be determined due to the constraint of using the 1995 water table (NE-CSD, 1995). Figure 5-46 shows the specific yield values estimated for the block flight area which is used in the groundwater volume calculations in Section 5.4. The average SY is 5% or less for ***Q*** aquifer materials, the stippled areas on the map are areas that the aquifer is very thin or absent (Summerside and Meyers, 2005b). Figure 5-47 shows the reported DNR well discharge value for individual wells (NEDNR, 2016b) is shown on the map of the saturated ***Q*** aquifer materials thickness (grey tones) which can be up to >50 feet thick and ***Kd*** sandstone/sand dominant thickness (color tones) which can be up to >30 feet thick. There is a correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge. The discharge values range from 6 to 15 gallons per minute. There is a weak correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge. However, the rates of discharge are small and the marginal aquifer material can provide such a rate of discharge especially in areas where the ***Q*** aquifer and ***Kd*** sandstone/sand are so limited.

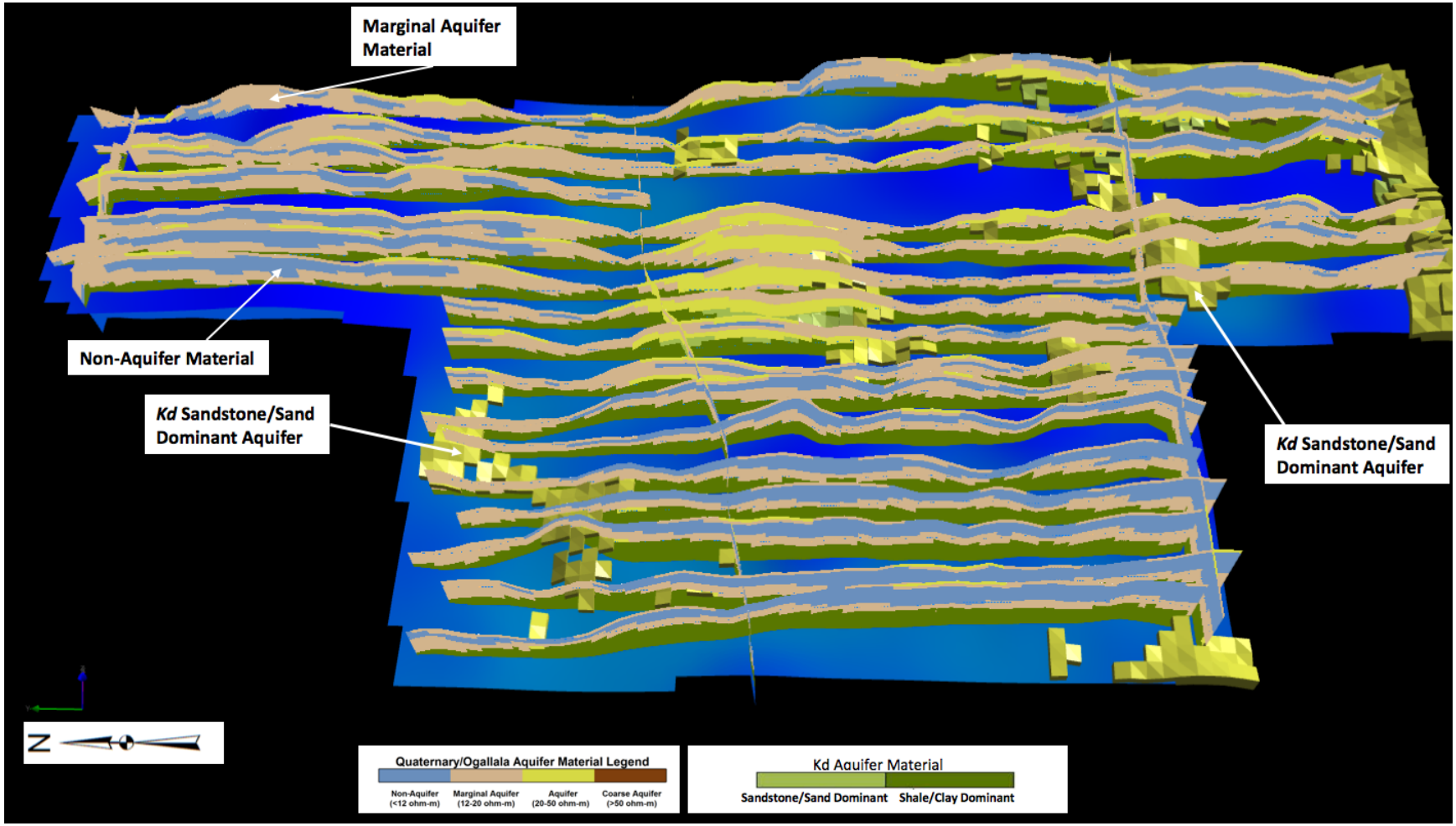


Figure 5-43. 3D fence diagram showing the Elmwood block flight lines looking to the east showing distribution and thickness of Quaternary (*Q*) glacial material and Cretaceous Dakota (*Kd*) materials. The area has thick glacial material (> that 100 feet is some areas). The saturated *Q* aquifer material and *Kd* sandstone/sand dominant material is very limited in volume. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

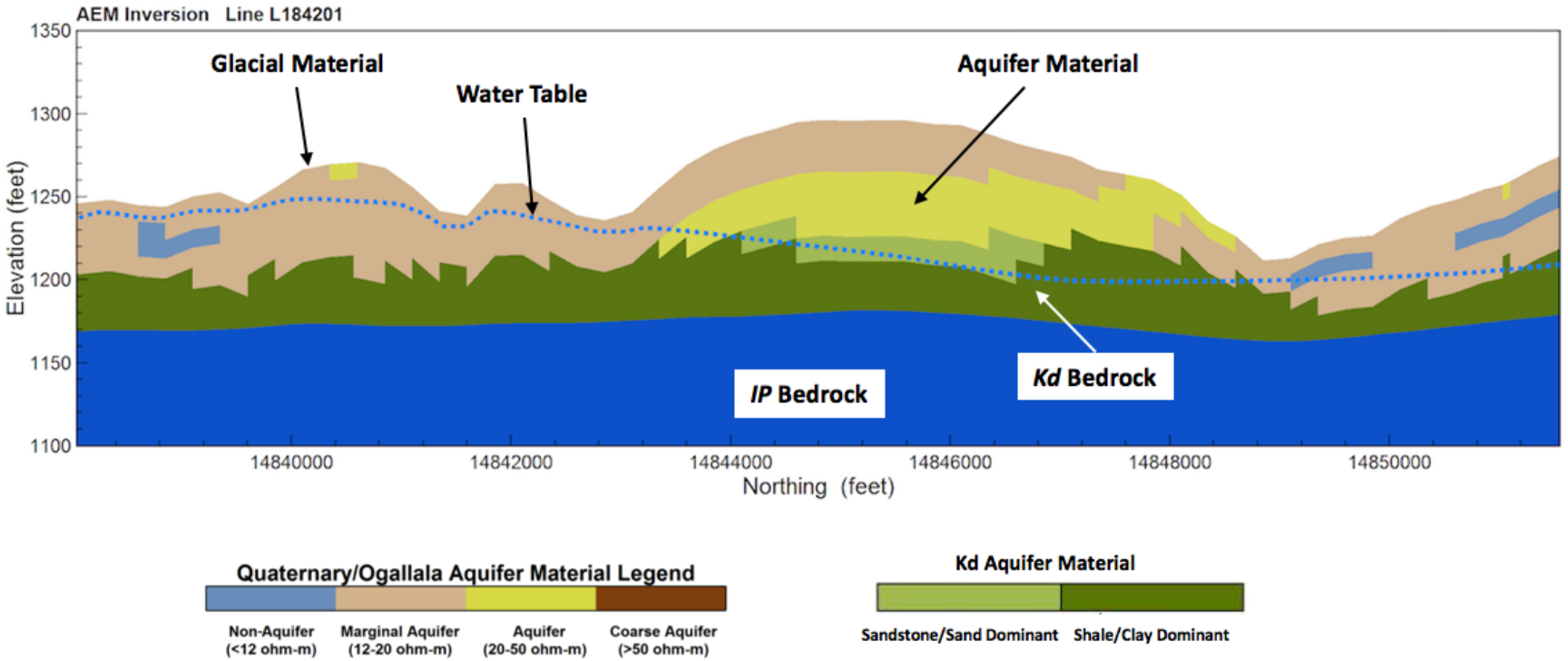


Figure 5-44. Profile L184201, oriented north-south, is west of Elmwood. This profile shows the complex geology of the Quaternary (*Q*) deposits which are variable in thickness deposited above the Cretaceous Dakota (*Kd*). The Q aquifer material and the Kd sandstone/sand dominant materials have very limited volume and saturation along this profile. Projection is NAD83, UTM14N, feet

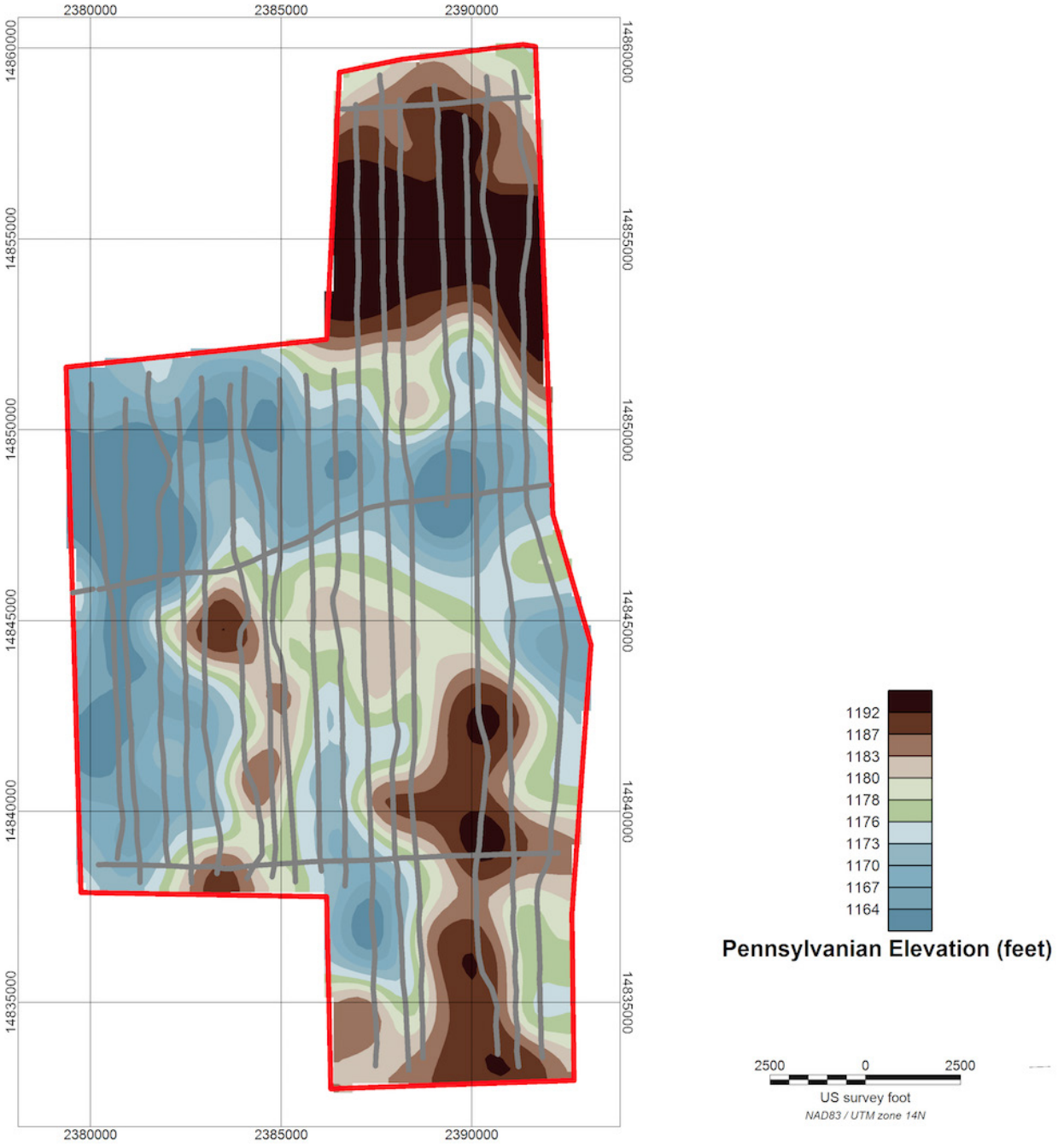


Figure 5-45. Elevation map of the undifferentiated Pennsylvanian bed (*IP*) rock surface which is considered the base of aquifer. Highest elevations are to the east and slope to the west with 16 feet of relief. Gray lines are the flight lines and the red box is the block out line. Projection is NAD83, UTM14N, feet.

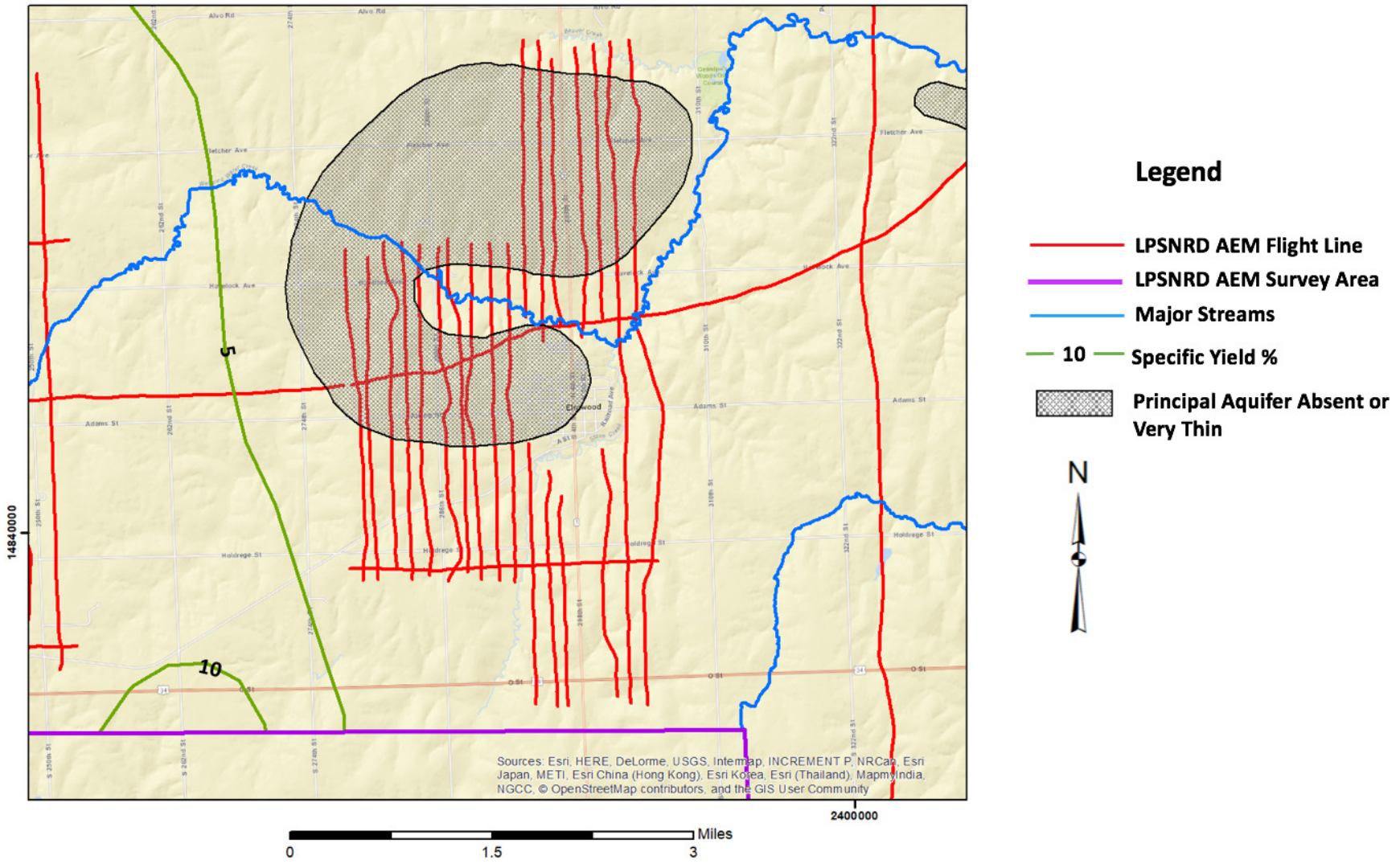


Figure 5-46. Specific yield values within the Elmwood AEM block survey area (Summerside and Meyers, 2005b). Note the large areas of the uplands that have Quaternary aquifer materials that are absent or very thin. Projection is NAD83, UTM14N, feet.

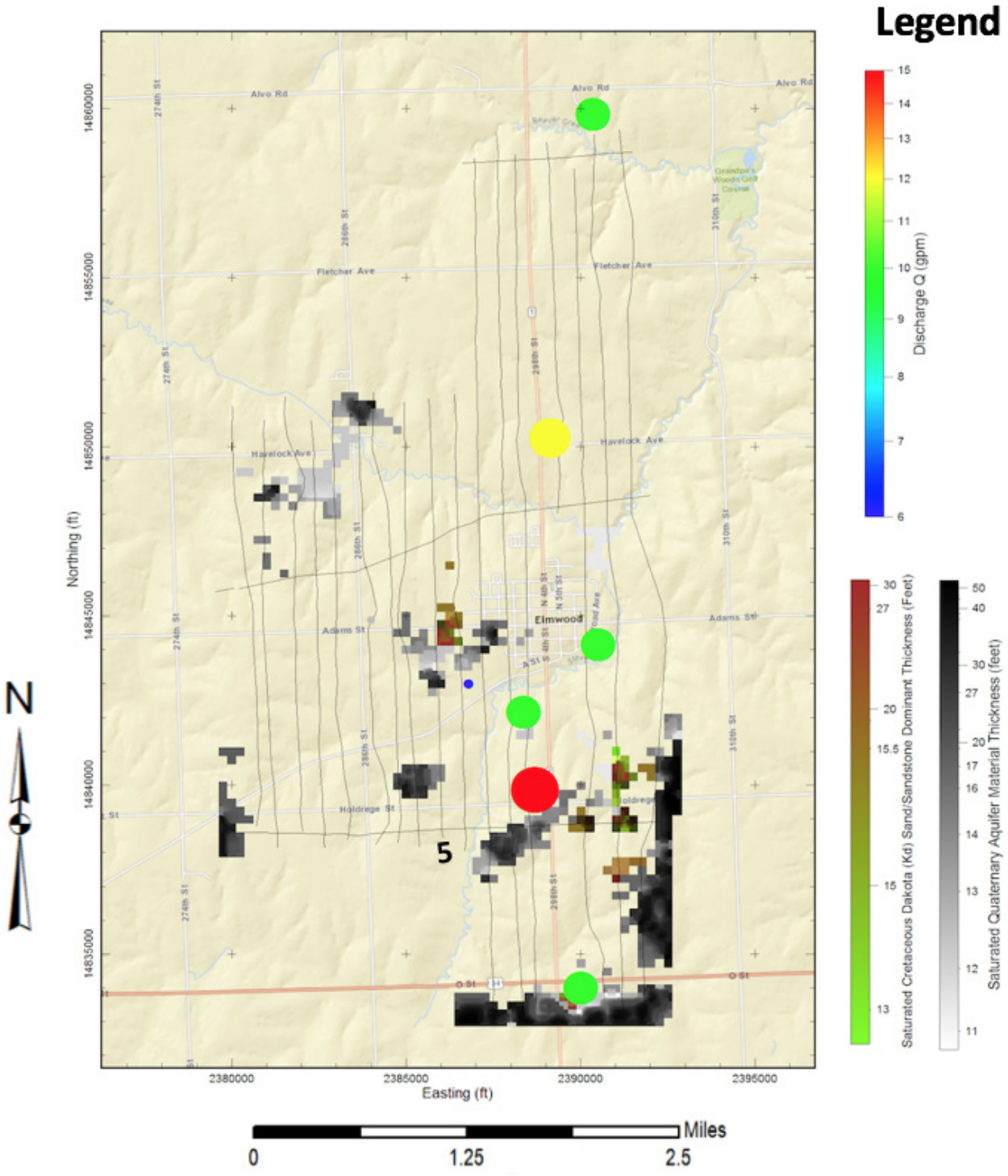


Figure 5-47. Comparison of discharge values (color and size) from individual well locations (NEDNR, 2016b) compared to saturated thickness of the Quaternary aquifer (*Q*) shown in grey tones and the Cretaceous Dakota sandstone/sand dominant material (*Kd*) shown in colored tones. Gray lines are flight lines. Projection is NAD83, UTM14N, feet.

5.3.4.3 Union Block Flight Area

The hydrogeology of the Union block flight area is dominated by variable thickness of glacial deposits in some areas greater than 100 feet thick. This material is made up of a mix of coarse aquifer, aquifer, marginal aquifer and non- aquifer materials. These material packages become finer grained the further west from the Missouri River. Figure 5-48 shows a fence diagram showing the ***Q*** glacial deposits resting on the ***IP*** bedrock surface. The ***Kd*** is eroded out of this area with no deposits present. This figure provides insight into the aquifer of this area which is made up of various thickness of ***Q*** coarse aquifer and aquifer material. The thick sections of the ***Q*** materials are in the north-northeast areas of the flight block. Figure 5-49 shows profile L147701 which shows the complex nature of the hydrogeology and the limited extent of the aquifer made up of the ***Q*** materials. Note the thin saturated thickness to the west that thickens as it nears the Missouri River. The aquifer material can be bounded by marginal and non-aquifer material in local areas. There is a hydrologic connection with other aquifers or streams including the Missouri River where it is mapped. When these deposits reach the edges of the survey block it is unknown how far it extends to the surrounding area except along the reconnaissance lines such as L00702 which can be continuous from one block flight area to the next. The ***Q*** materials rest upon the ***IP*** which has up to >200 feet of relief from the uplands to the Missouri River basin. Figure 5-50 shows the ***IP*** surface elevation map for the flight block, there is approximately 200 feet of relief from the uplands to the Missouri River basin. The volume of all saturated ***Q*** aquifer material and ***Kd*** aquifer material has been calculated and is presented in Section 5.4. Accurate specific yield values are not able to be determined due to the constraint of using the 1995 water table (NE-CSD, 1995). Figure 5-51 shows the specific yield values estimated for the block flight area which is used in the groundwater volume calculations in Section 5.4. The average SY is 5% or less for ***Q*** aquifer materials, the stippled areas on the map are areas that the aquifer is very thin or absent (Summerside and Meyers, 2005b). The area around the Missouri River has much higher specific yield values. Figure 5-52 shows the transmissivity values for the area near the Missouri River (Summerside and Meyers, 2005c). Figure 5-53 shows the reported DNR well discharge value for individual wells (NEDNR, 2016b) is shown on the map of the saturated ***Q*** aquifer materials thickness (grey tones) which can be up to >130 feet thick. There is a correlation between the thickness of the ***Q*** materials and the discharge. The discharge values range from <20 to >1600 gallons per minute. There is a correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge.

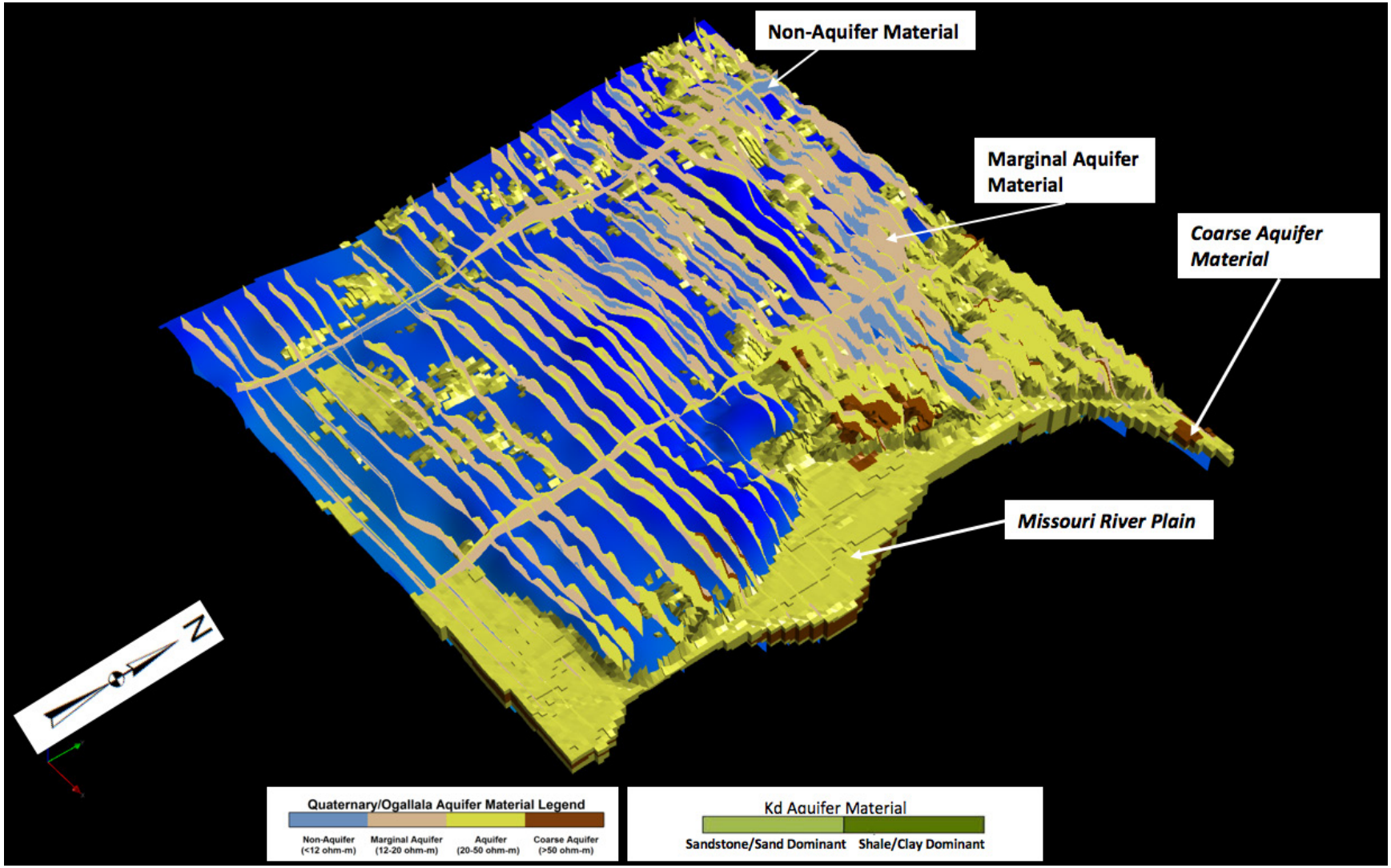


Figure 5-48. 3D fence diagram showing the Union block flight lines looking to the northwest showing distribution and thickness of Quaternary (*Q*) glacial material. The area has thick glacial material (>100 feet is some areas). The saturated *Q* aquifer material is very limited in volume in much of the area. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

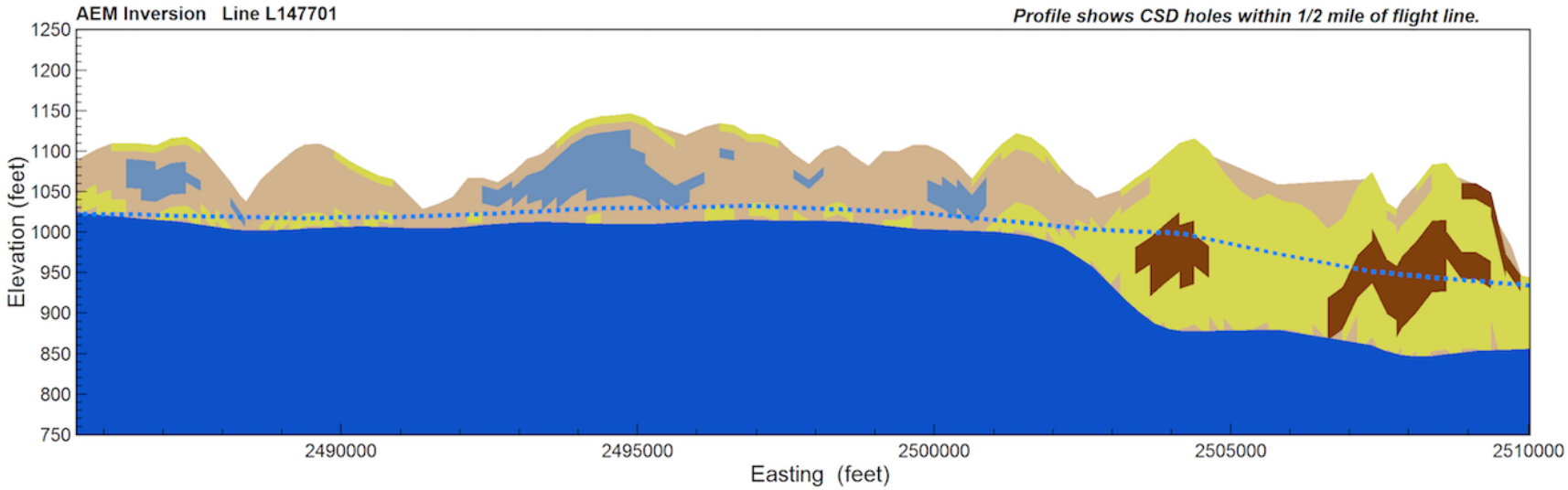


Figure 5-49. Profile L147701, oriented east-west, is north of Union. This profile shows the complex geology of the Quaternary (*Q*) deposits which are variable in thickness deposited on Pennsylvanian undifferentiated bedrock (*IP*). The *Q* aquifer material is thickest on the east and northeast portions of the area. The saturated thickness is thin in the west and thick in the east. Projection is NAD83, UTM14N, feet.

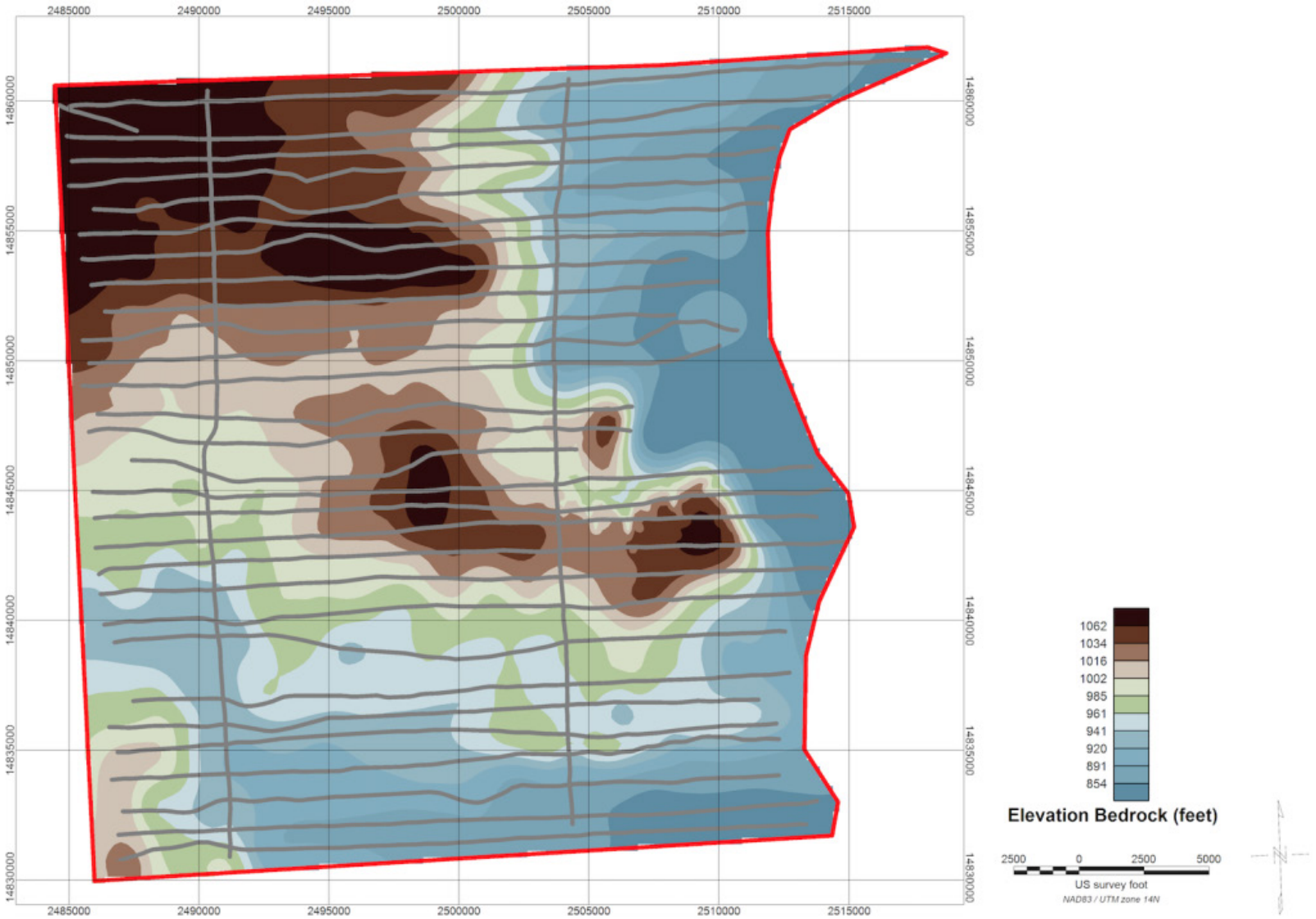


Figure 5-50. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) bedrock within the Union block flight area. Gray lines are the flight lines and the red box is the block out line. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

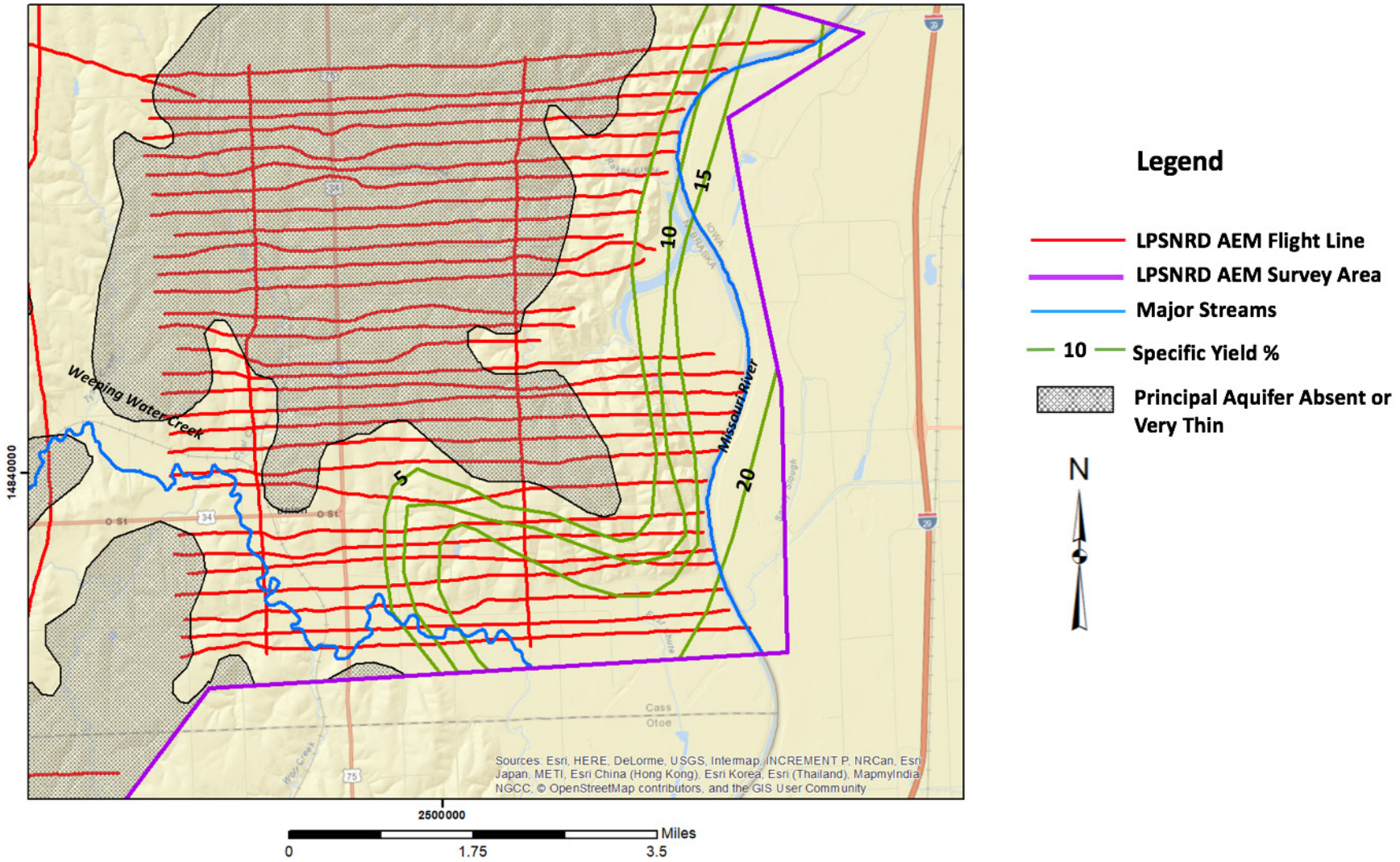


Figure 5-51. Specific yield values within the Union block flight area (Summerside and Meyers, 2005b). Note the large areas of the uplands that have Quaternary aquifer materials that are absent or very thin. Projection is NAD83, UTM14N, feet.

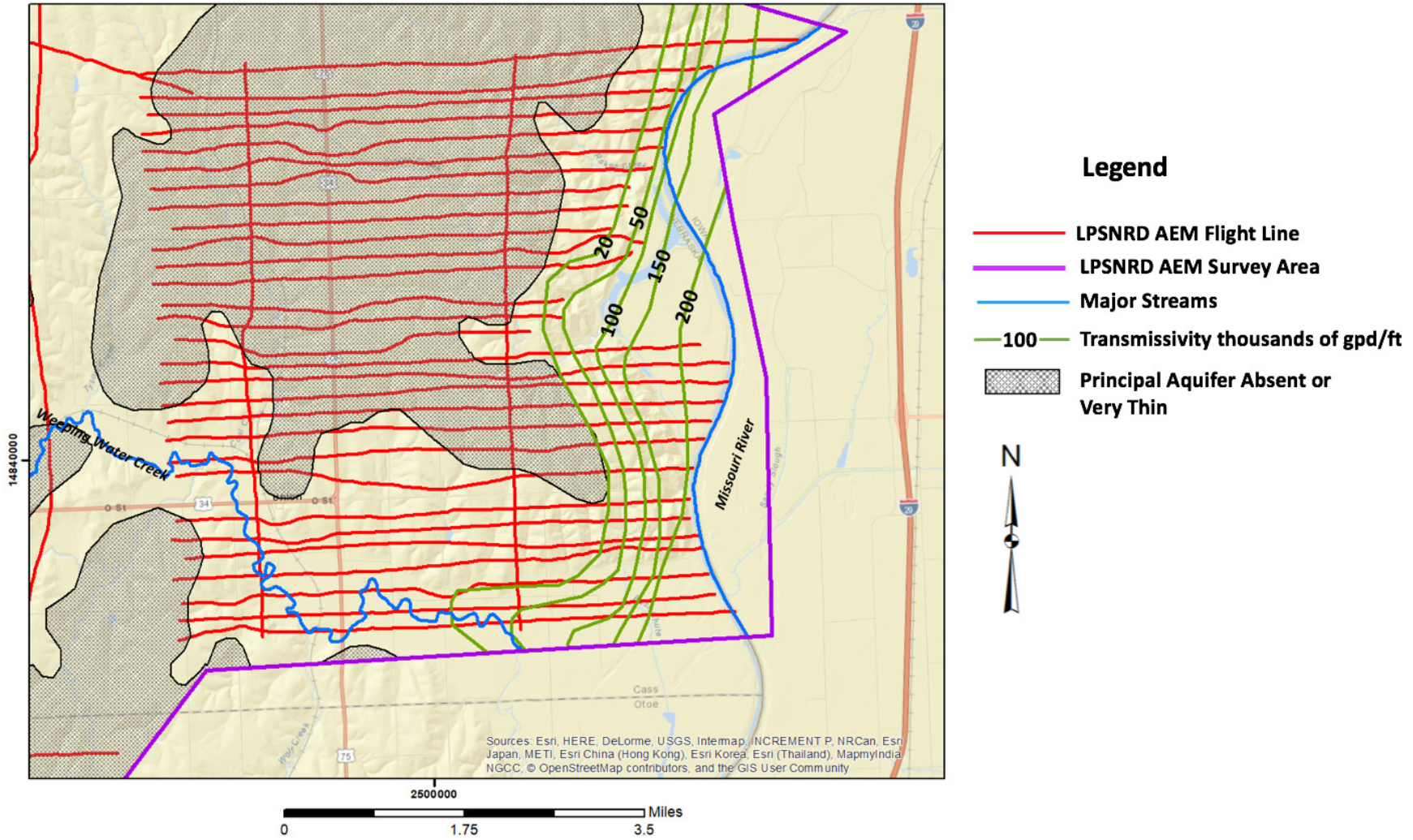


Figure 5-52. Transmissivity values within the Union block flight area (Summerside and Meyers, 2005c). Note the large areas of the uplands that have aquifer materials that are absent or very thin. Projection is NAD83, UTM14N, feet.

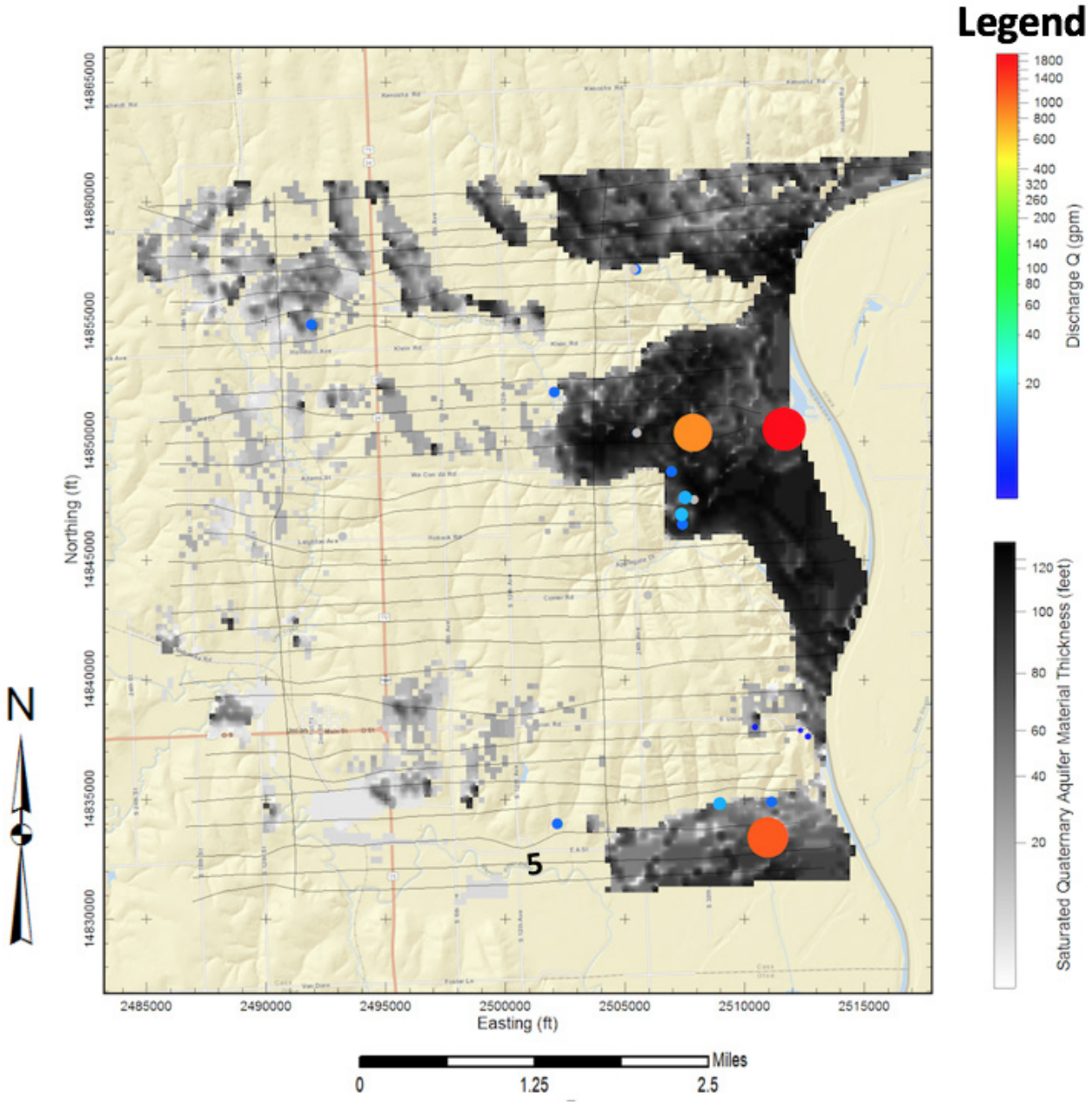


Figure 5-53. Comparison of discharge values (color and size) from individual well locations (NEDNR, 2016b) compared to saturated thickness of the Quaternary aquifer (*Q*) shown in grey tones. Projection is NAD83, UTM14N, feet.

5.3.4.4 *Waverly Block Flight Area*

The hydrogeology of the Waverly block flight area is dominated by varying thickness of glacial deposits, in some areas greater than 100 feet thick. This material is made up of aquifer, marginal aquifer and non-aquifer material. Figure 5-54 shows a fence diagram showing the ***Q*** glacial deposits resting on the ***Kd*** saturated sandstone/sand material (the ***Kd*** shale/clay dominant material are not shown). In a limited area on the eastern side of the flight block along the north end of the flight lines the ***Q*** aquifer materials rest upon the ***IP*** bedrock. This image provides insight into the aquifer of this area which is made up of thin ***Q*** aquifer material directly in contact with ***Kd*** saturated sandstone/sand material. Figure 5-55 shows profile L174201 which shows the complex nature of the hydrogeology and the extent of the aquifer made up of the ***Kd*** and ***Q*** materials which are capped by marginal and non-aquifer materials. The ***Q*** aquifer material along this profile has little saturation. ***Kd*** bedrock is a mix of both material types of mostly the shale/clay dominant material makes up most of ***Kd*** materials in this area and acts as a aquiclude. The ***Q*** aquifer material is generally bound on all sides and hydrologic connection with other aquifers or streams is not present except where the ***Q*** aquifer and ***Kd*** sandstone/sand is present. When these deposits reach the edges of the survey block it is unknown how far it extends to the surrounding area except along the reconnaissance lines such as L00702 which can be continuous from one block flight area to the next.. The ***Q*** and ***Kd*** materials rest upon the ***IP*** which has approximately 100 feet of relief from the uplands down into the Salt Creek area to the north. Figure 5-56 shows the ***IP*** surface elevation map for the flight block. The volume of all saturated ***Q*** aquifer material and ***Kd*** aquifer material has been calculated and is presented in Section 5.4. Figure 5-57 shows the specific yield values estimated for the block flight area which is used in the groundwater volume calculations in Section 5.4. The average SY is 15% or less for the ***Q*** aquifer materials, the stippled areas on the map are areas that the aquifer is very thin or absent (Summerside and Meyers, 2005b). Figure 5-58 shows the reported DNR well discharge value for individual wells (NEDNR, 2016b) is shown on the map of the saturated ***Q*** aquifer materials thickness (grey tones) which can be up to >60 feet thick and ***Kd*** sandstone/sand dominant thickness (color tones) which can be up to >100 feet thick. There is a correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge. The discharge values range from 10 to >700 gallons per minute. There is a correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge. However, the rates of discharge are small and the marginal aquifer material can provide such rates of discharge especially in areas where the ***Q*** aquifer and ***Kd*** sandstone/sand are so limited. Accurate specific yield values are not able to be determined due to the constraint of using the 1995 water table (NE-CSD, 1995).

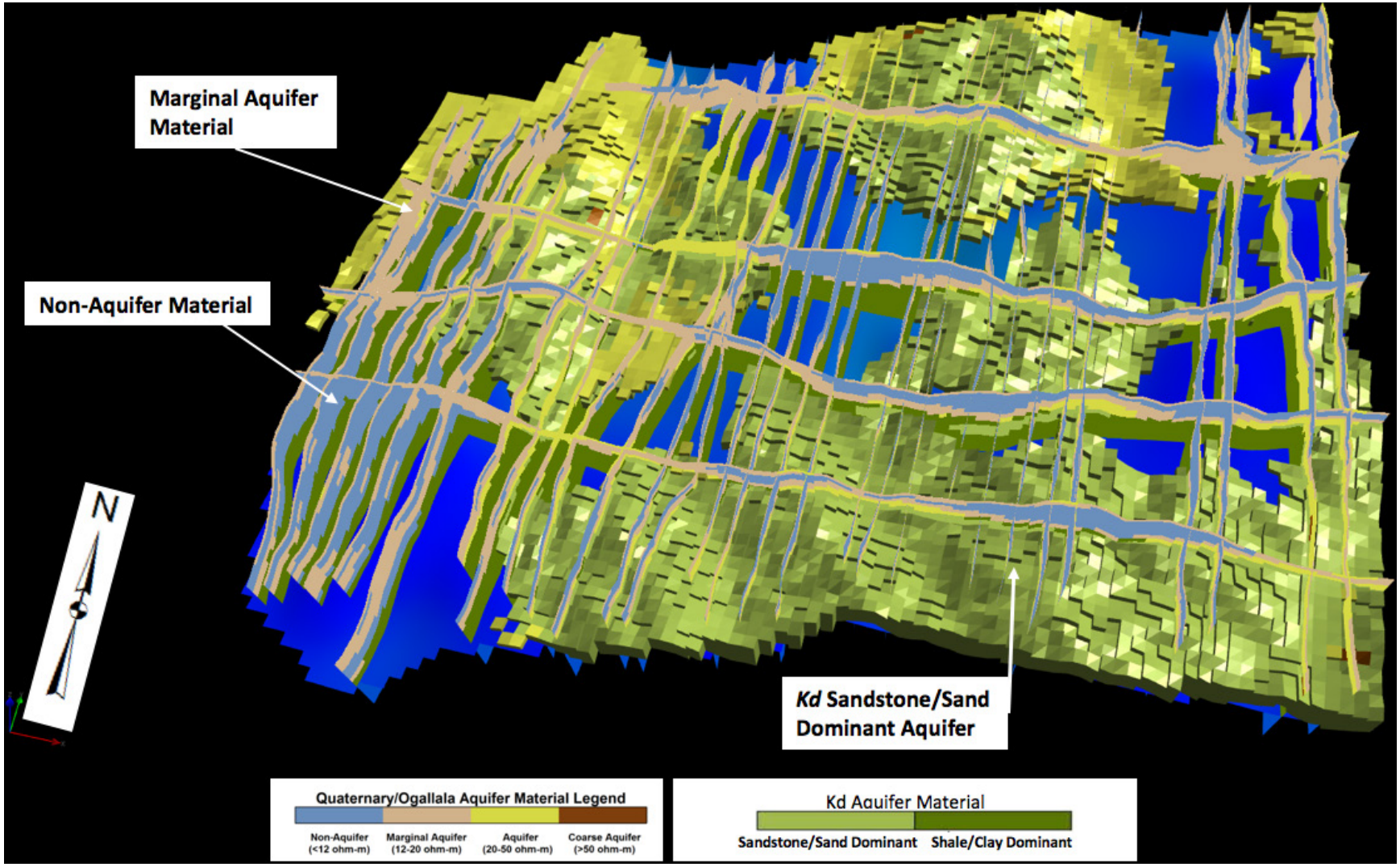


Figure 5-54. 3D fence diagram showing the Waverly block flight lines looking to the east showing distribution and thickness of Quaternary (*Q*) glacial material and Cretaceous Dakota (*Kd*) materials. The area has thick glacial material (>100 feet is some areas). The saturated *Q* aquifer material and *Kd* sandstone/sand dominant material is very limited in volume. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

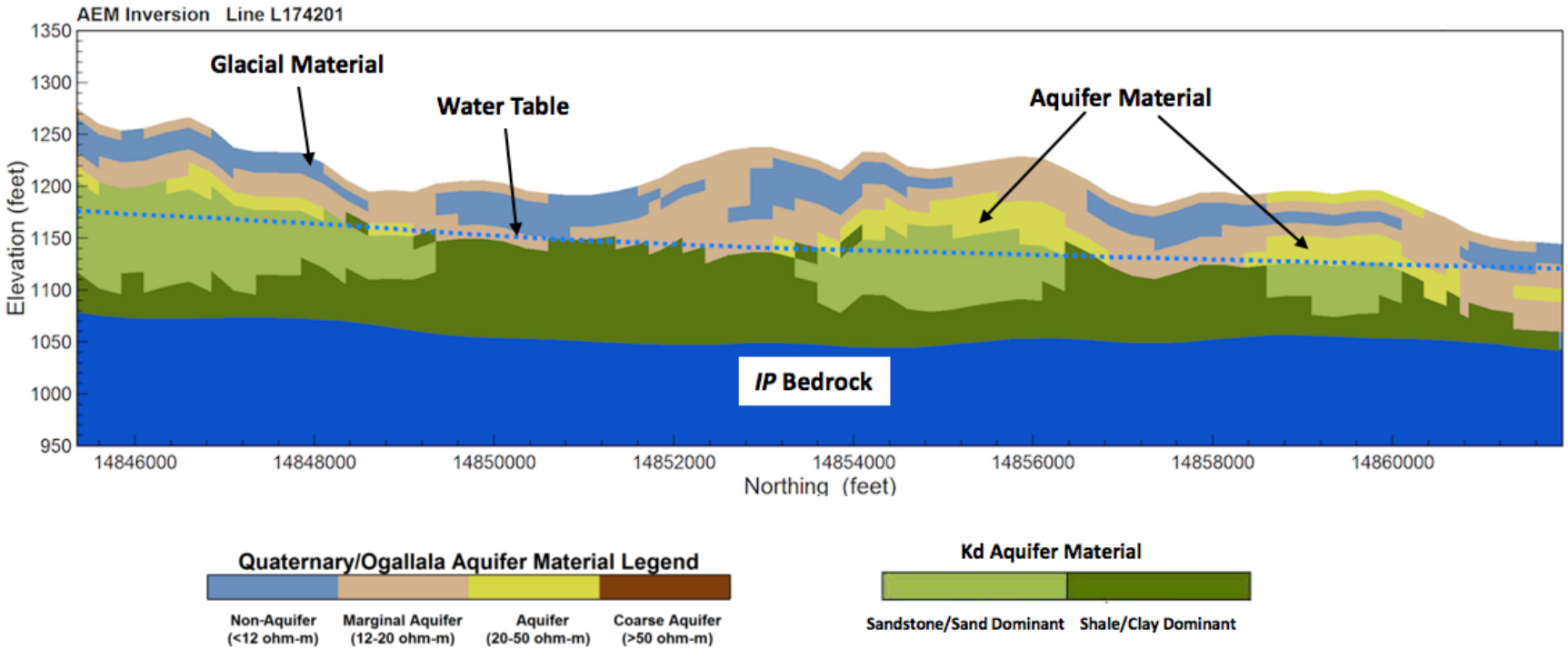


Figure 5-55. Profile L174201, oriented north-south, near the center of the Waverly block. This profile shows the complex geology of the Quaternary (*Q*) aquifer materials are variable in thickness deposited above the Cretaceous Dakota (*Kd*). The saturated *Q* aquifer material have very limited volume and saturation along this profile. The Kd sandstone/sand dominant materials make up the bulk of the aquifer. Projection is NAD83, UTM14N, feet.

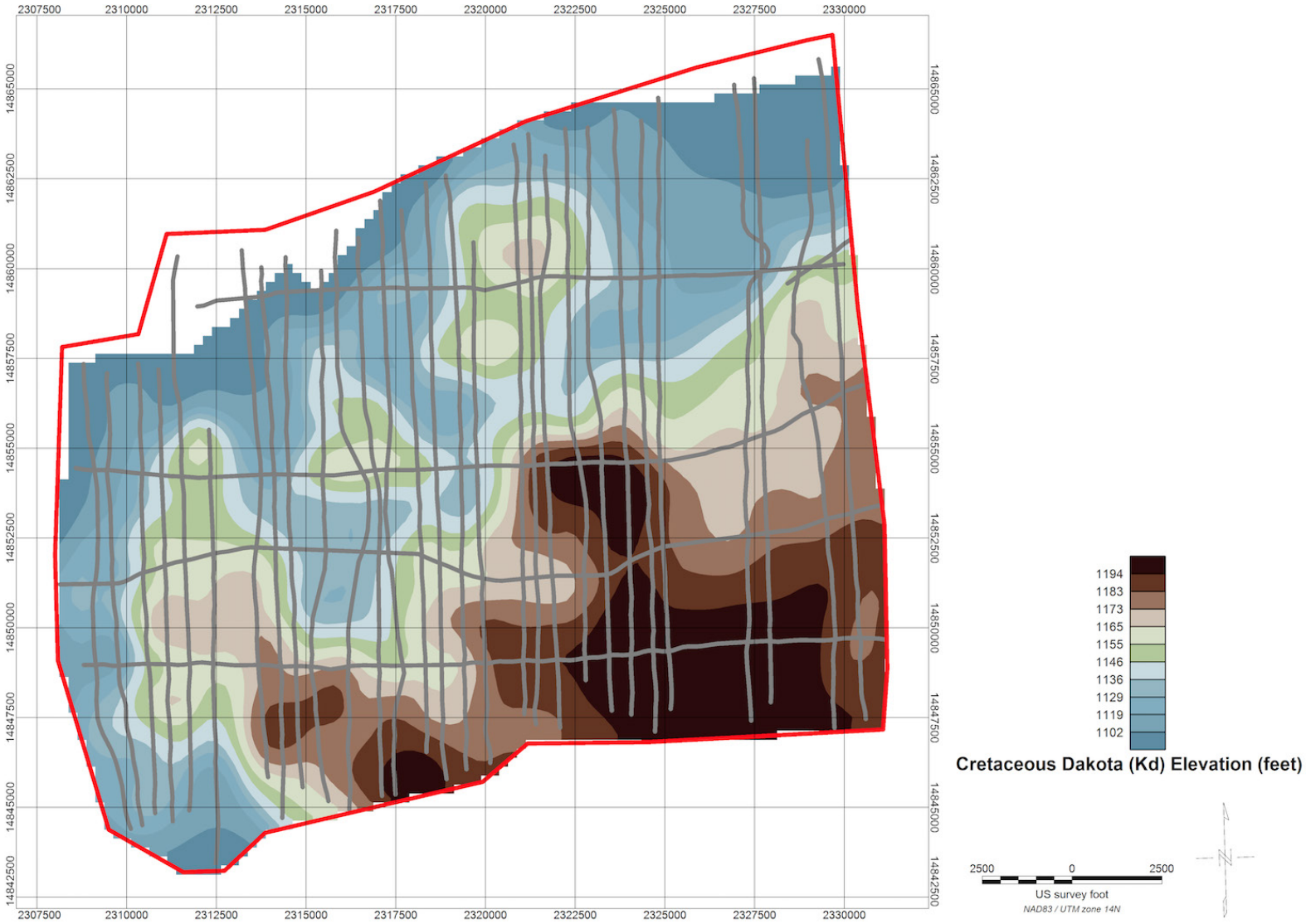


Figure 5-56. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) bedrock within the Waverly AEM block flight area. There is approximately 100 feet of relief from the upland to the salt Creek area. Gray lines are the flight lines and the red box is the block out line. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

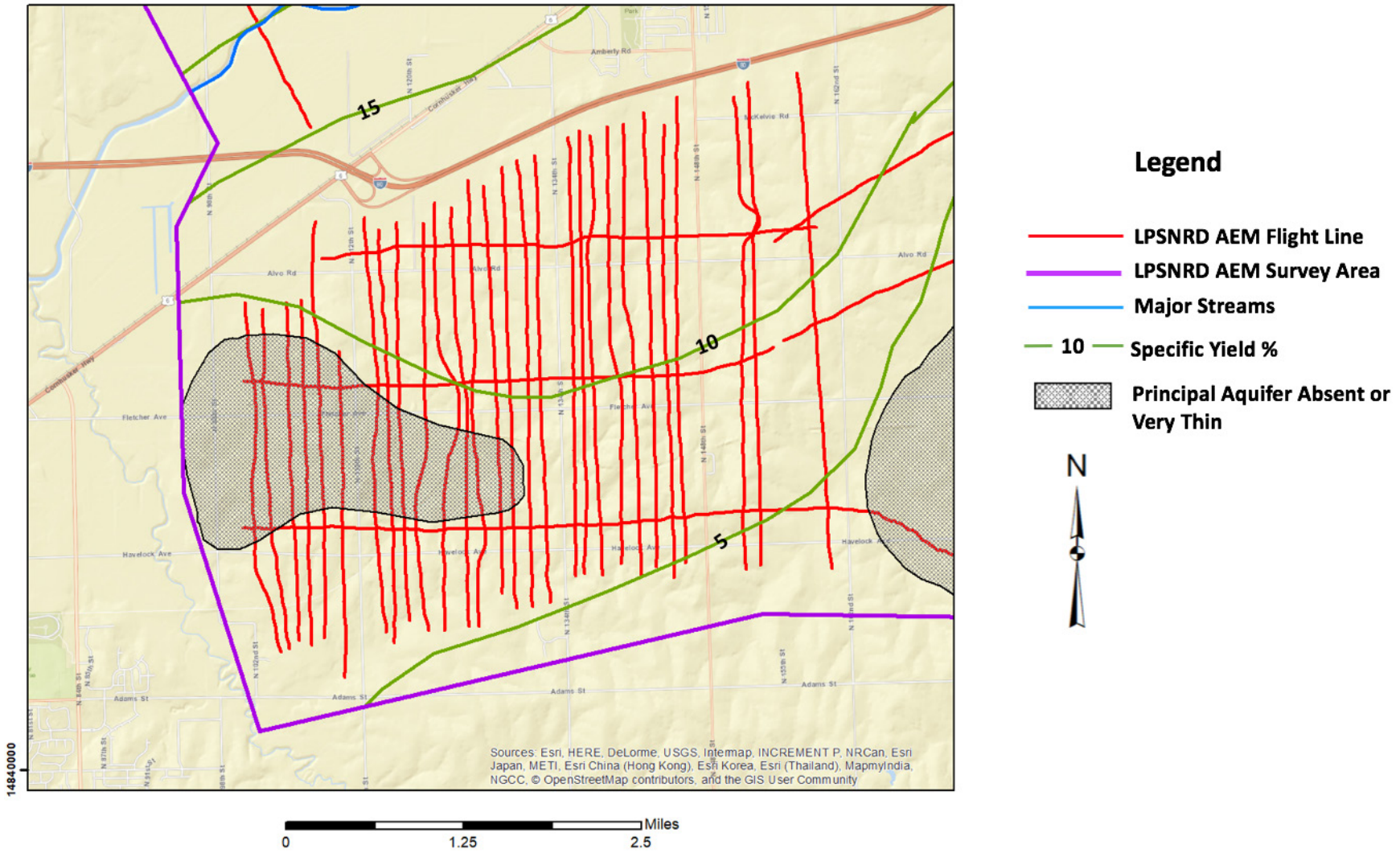


Figure 5-57. Specific yield values within the Waverly AEM block flight area which average approximately 15% (Summerside and Meyers, 2005b). Note the large areas of the uplands that have Quaternary aquifer materials that are absent or very thin. Projection is NAD83, UTM14N, feet.

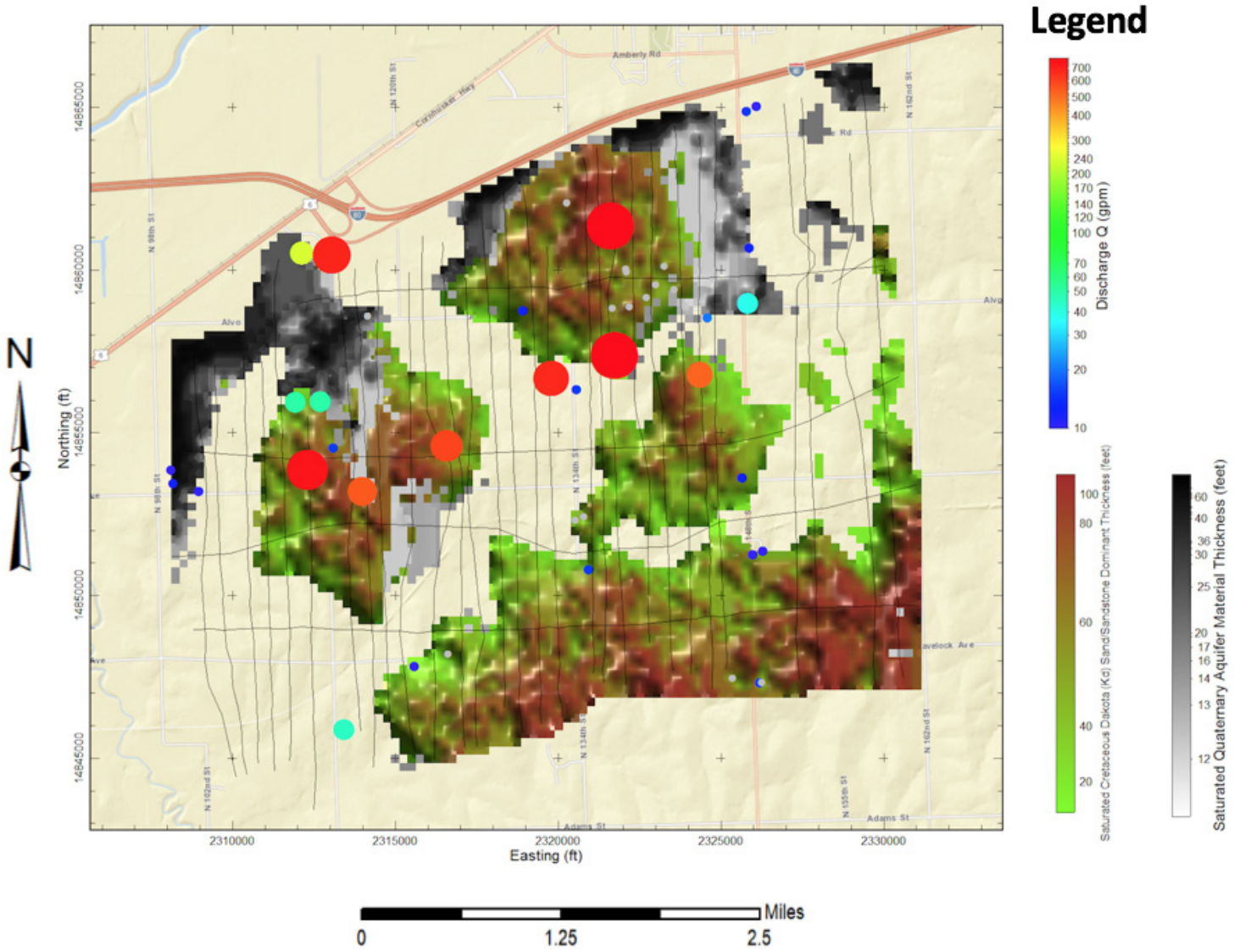


Figure 5-58. Comparison of discharge values (color and size) from individual well locations (NEDNR, 2016b) compared to saturated thickness of the Quaternary aquifer (*Q*) shown in grey tones and the Cretaceous Dakota sandstone/sand dominant material (*Kd*) shown in color tones. Gray lines indicate flight lines. Projection is NAD83, UTM14N, feet.

5.3.4.5 *Weeping Water Flight Block*

The hydrogeology of the Weeping Water block flight area is dominated by varying thickness of glacial deposits in some areas greater than 100 feet thick. This material is made up of aquifer, marginal aquifer and non-aquifer material. Figure 5-59 shows a fence diagram showing the ***Q*** glacial materials resting on the ***Kd*** saturated sandstone/sand material (the ***Kd*** shale/clay dominant material are not shown). In a limited area on the eastern side of the flight block along the north end of the flight lines ***Kd*** sandstone/sand is saturated and is the aquifer for that area. This figure provides insight into the limited size of the aquifer of this block. Figure 5-60 shows profile L188801 which shows the complex nature of the hydrogeology and the extent of the aquifer made up of the ***Kd*** and ***Q*** materials which are capped by marginal and non-aquifer materials, except where the aquifer material that extends from the surface down to contact with the ***Kd*** sandstone/sand dominant materials. The ***Q*** aquifer material along this profile has no saturation. Accurate specific yield values are not able to be determined due to the constraint of using the 1995 water table (NE-CSD, 1995). ***Kd*** bedrock is a mix of both material types of mostly the shale/clay dominant material makes up most of ***Kd*** materials in this area and acts as a aquiclude. The ***Kd*** sandstone/sand dominant materials are not completely saturated along this profile. The ***Q*** aquifer material is generally bound on all sides and hydrologic connection with other aquifers or streams is not present except where the ***Q*** aquifer and ***Kd*** sandstone/sand is present. When these deposits reach the edges of the survey block it is unknown how far it extends to the surrounding area except along the reconnaissance lines such as L00702 which can be continuous from one block flight area to the next. The ***Q*** and ***Kd*** materials rest upon the ***IP*** which has small relief of approximately 60 feet of elevation change from the bedrock high in the southwest corner of the flight area moving to a bedrock low in the north-northeast. The ***IP*** surface map is shown in Figure 5-61. The volume of all saturated ***Q*** aquifer material and ***Kd*** aquifer material has been calculated and is presented in Section 5.4. Figure 5-62 shows the specific yield values estimated for the block flight area which is used in the groundwater volume calculations in Section 5.4. The average SY is 5% or less for the ***Q*** aquifer materials, the stippled areas on the map are areas that the aquifer is very thin or absent (Summerside and Meyers, 2005b). Figure 5-63 shows the reported DNR well discharge values for individual wells (NEDNR, 2016b). on the map of the saturated ***Q*** aquifer materials thickness (grey tones) which can be greater than 20 feet thick and ***Kd*** sandstone/sand dominant thickness (color tones) which can be greater than 90 feet thick. There is a correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge. The discharge values range from 4 to greater than 144 gallons per minute. There is a correlation between the thickness of the ***Q*** and ***Kd*** materials and the discharge.

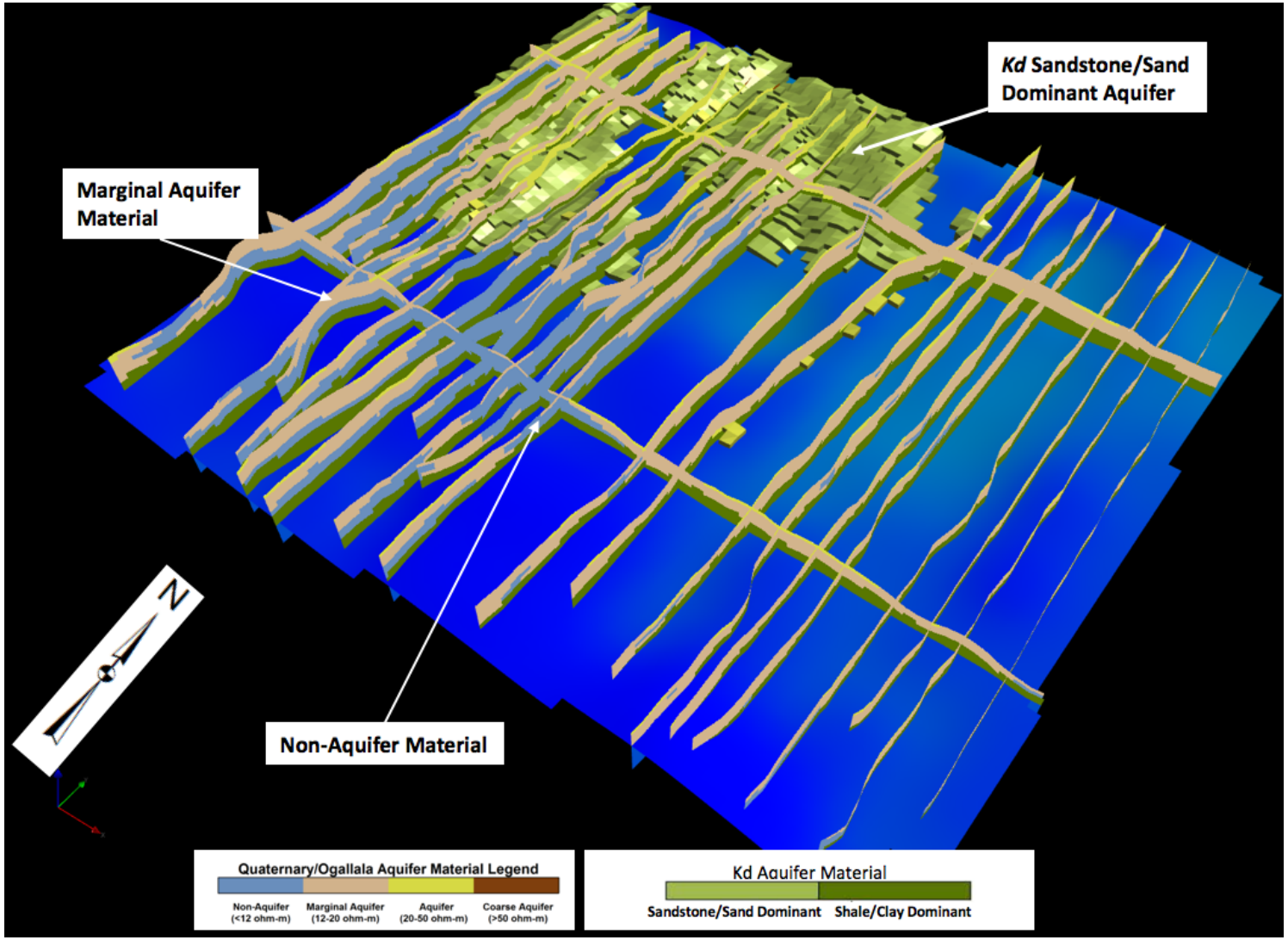


Figure 5-59. 3D fence diagram showing the Weeping Water block flight lines looking to the east showing distribution and thickness of Quaternary (*Q*) glacial material and Cretaceous Dakota (*Kd*) materials. The area has thick glacial material (> that 100 feet is some areas). The saturated *Q* aquifer material and *Kd* sandstone/sand dominant material is very limited in volume. Vertical exaggeration is 20x. Projection is NAD83, UTM14N, feet.

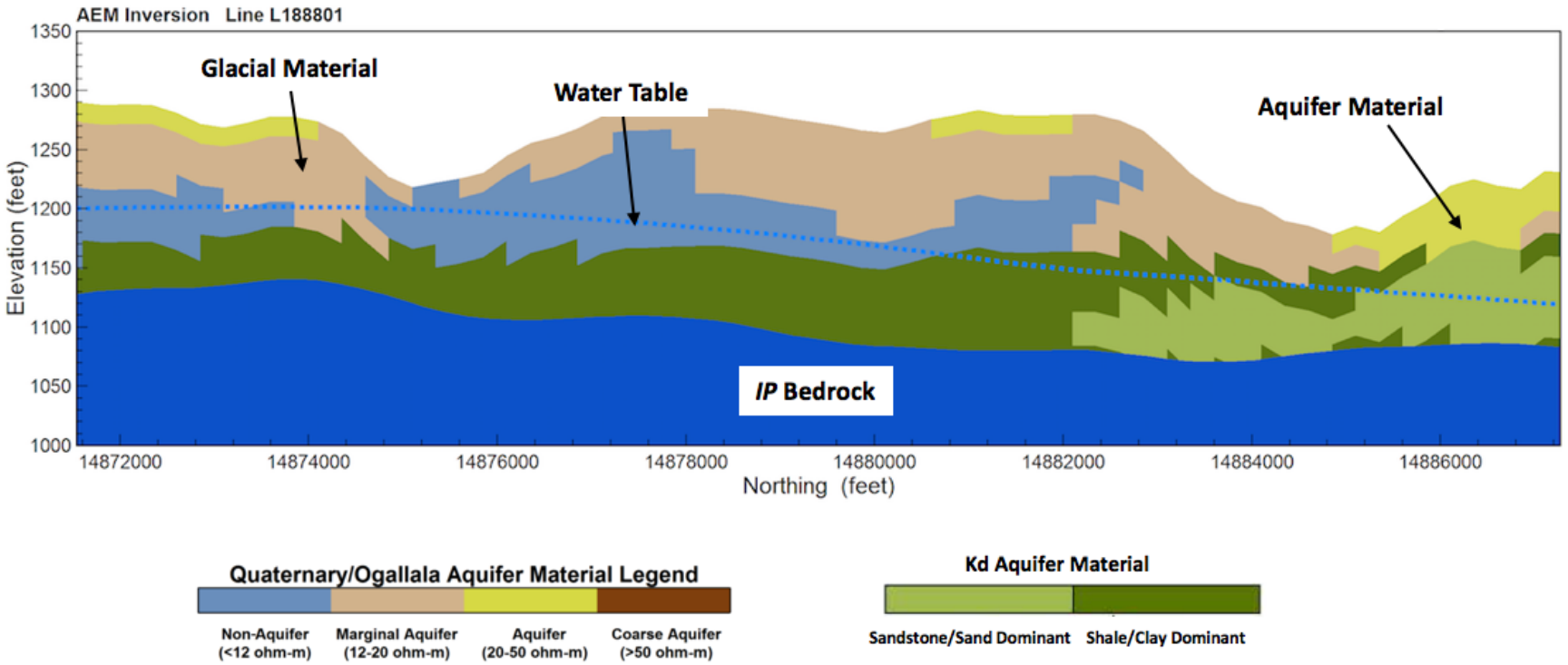


Figure 5-60. Profile L188801, oriented north-south and located north of Manley, shows the complex geology of the Quaternary (*Q*) materials which are variable in thickness deposited on Cretaceous Dakota (*Kd*) sandstone/sand dominant and shale/clay dominant materials. The *Kd* sandstone/sand is limited in size and not fully saturated along the profile. The *Q* aquifer material is thickest on the north end of the profile and is continuous from land surface to the *Kd*. Projection is NAD83, UTM14N, feet.

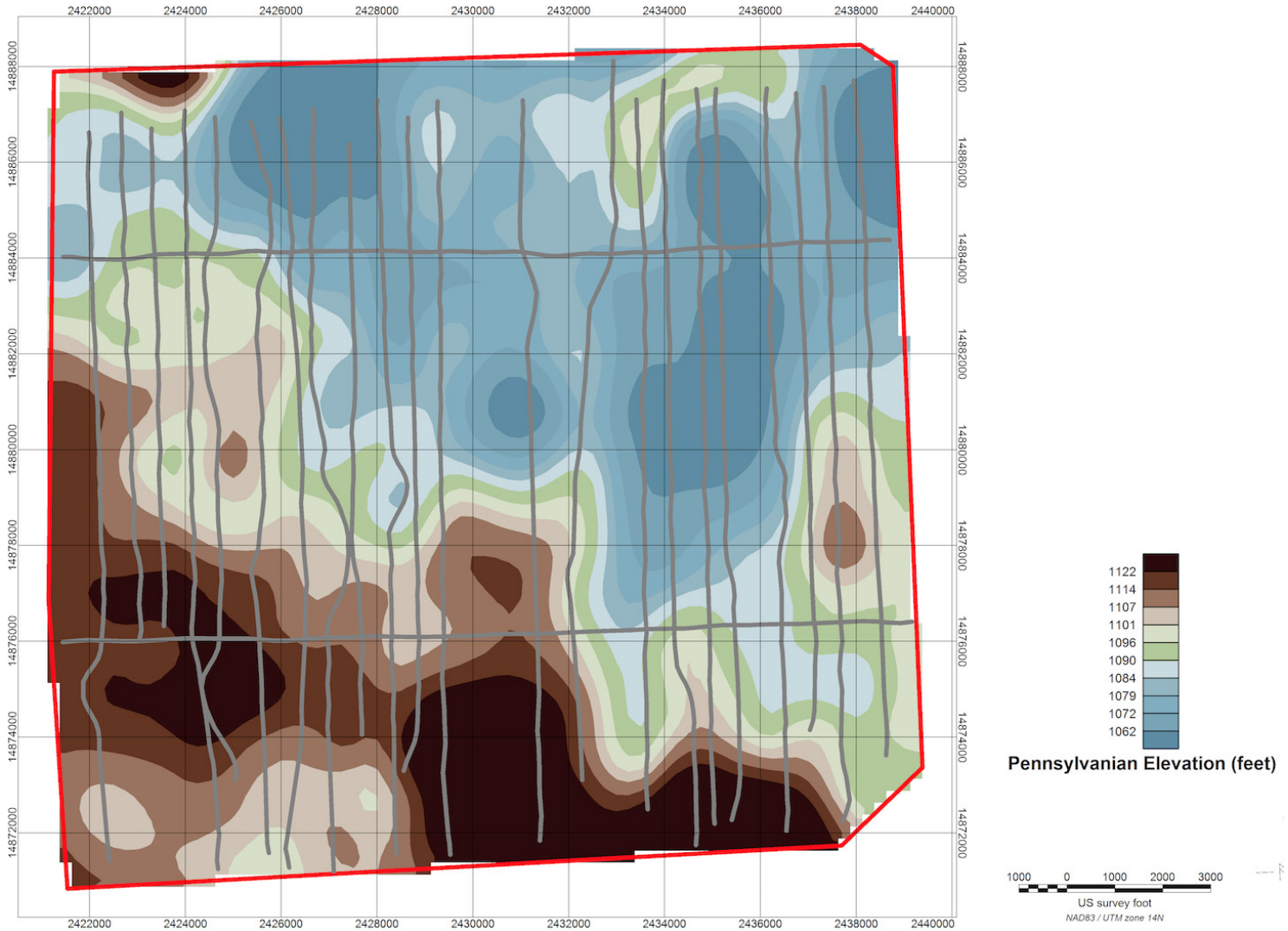


Figure 5-61. Map of the elevation of the top of the undifferentiated Pennsylvanian (*IP*) bedrock within the Weeping Water AEM block flight area. There is approximately 60 feet of relief from the southwest corner to the northeast. The gray lines are the flight lines and the red line is the boundary of the block. The projection is NAD83 UTM Zone 14 North, in feet, and the elevation values are referenced to NAVD 88.

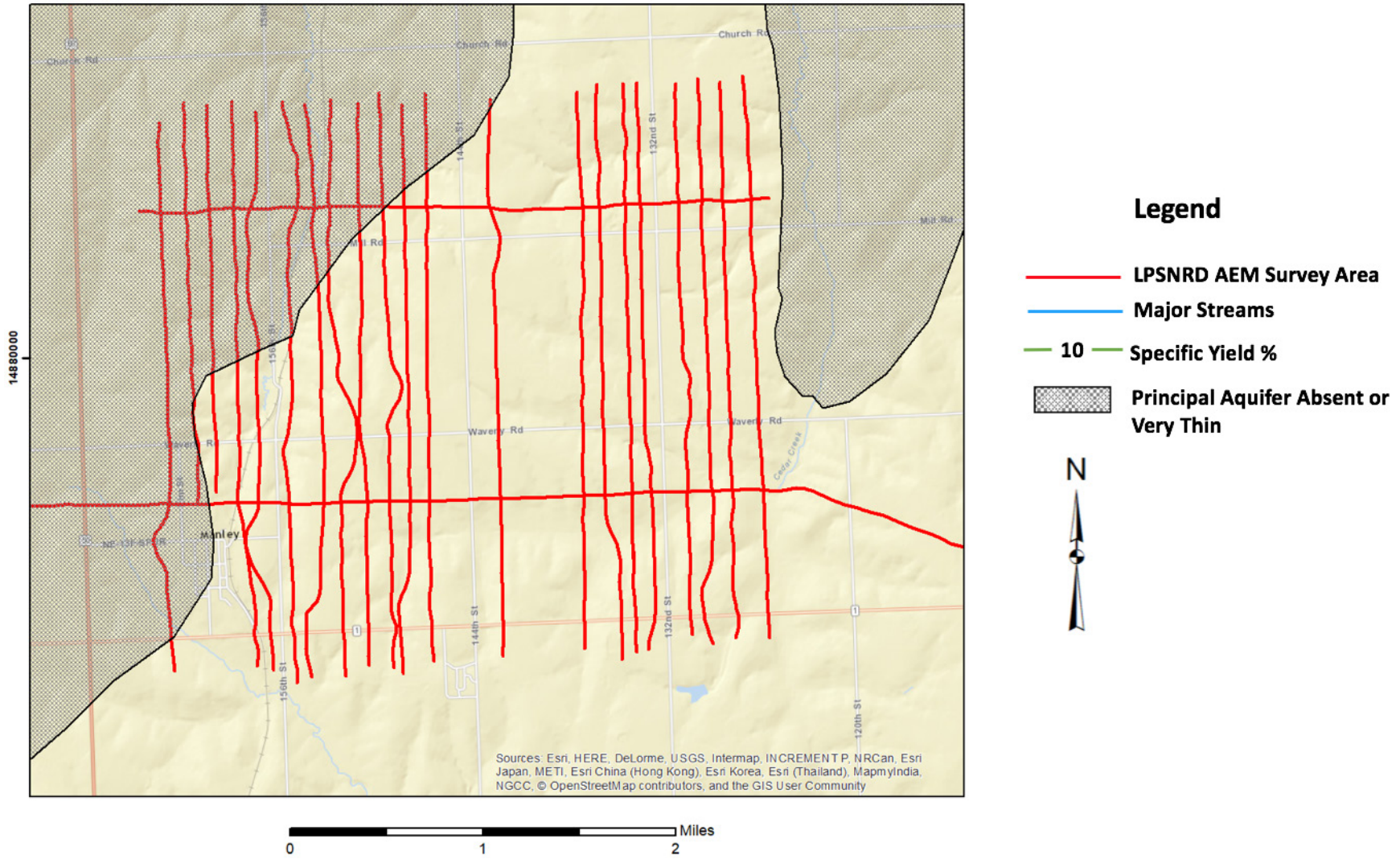


Figure 5-62. Specific yield values within the Weeping Water AEM block flight area (Summerside and Meyers, 2005b). Note the large areas of the uplands that have Quaternary aquifer materials that are absent or very thin. Projection is NAD83, UTM14N, feet.

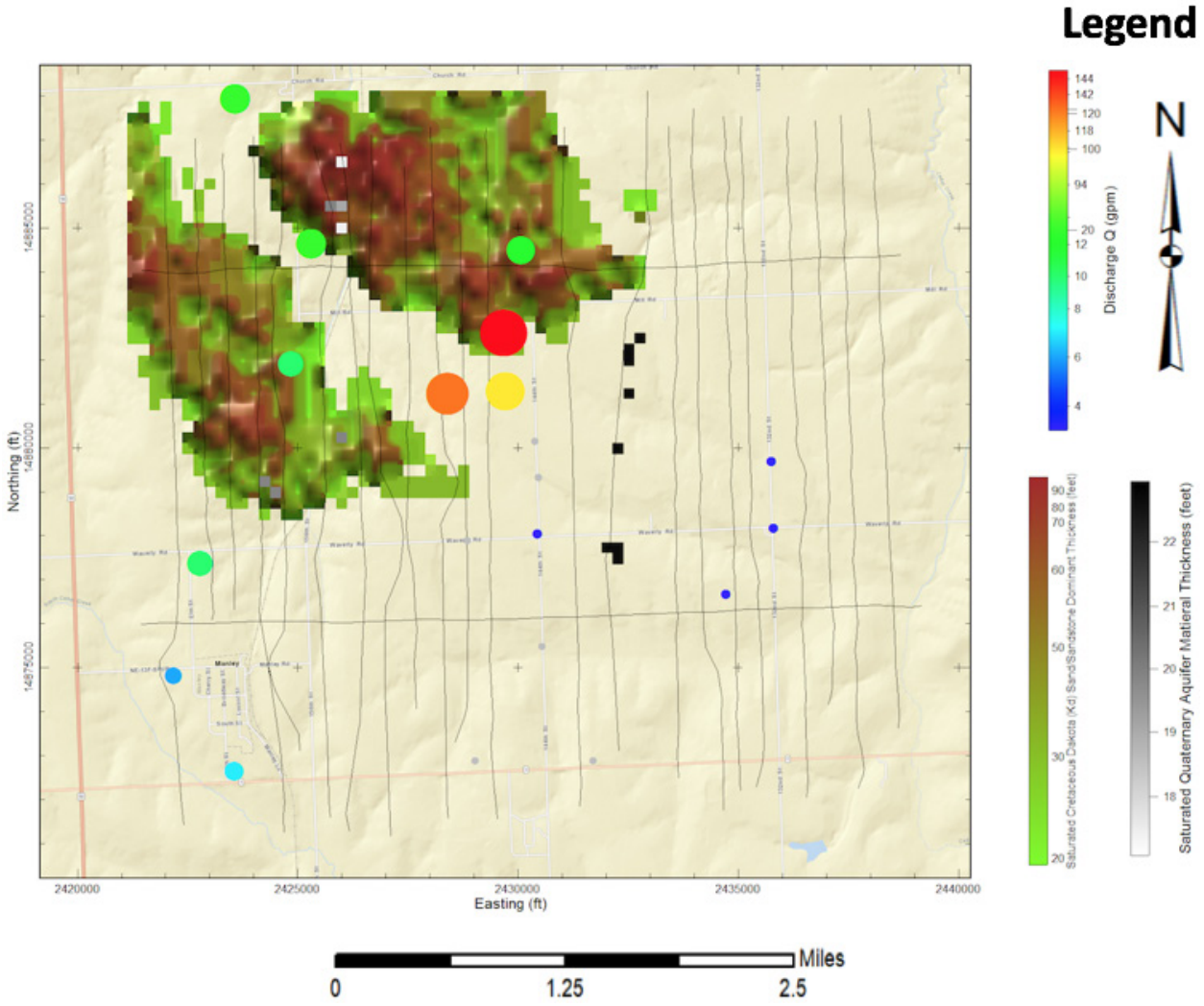


Figure 5-63. Comparison of discharge values (color and size) from individual well locations (NEDNR, 2016b) compared to saturated thickness of the Quaternary aquifer (*Q*) shown in grey tones and the Cretaceous Dakota sandstone/sand dominant material (*Kd*) shown in color tones. Gray lines indicate flight lines. Projection is NAD83, UTM14N, feet.

5.4 Estimation of Aquifer Volume and Water in Storage for the LPSNRD AEM Block Flight Survey Areas

A 3D representation of the subsurface derived from the AEM imaging provides users the ability to more accurately identify the total unsaturated and saturated aquifer volumes for the ***Q*** and the ***Kd***. The saturated zones of the ***Q*** and ***Kd*** materials can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present. Block flights were flown near five towns within the LPSNRD for understanding the hydrogeology near the Community Water System Protection Areas (CWSPAs). The CWSPAs mapped were near the towns of Eagle, Elmwood, Union, Waverly and Weeping Water where AEM data was collected 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. The resistivity ranges for interpreted ***Q*** non-aquifer (<12 ohm-m), marginal aquifer (12-20 ohm-m), aquifer (20-50 ohm-m), and coarse aquifer materials (>50 ohm-m) are presented in Figure 5-19. The resistivity threshold between ***Kd*** sandstone/sand dominant and shale/clay dominant units, discussed in Section 5.2.2, has been determined to be 27 ohm-m.

Individual fence diagrams that show the saturated ***Q*** aquifer and coarse aquifer materials and ***Kd*** sandstone /sand dominant units which make up the aquifers within the individual flight blocks are shown for each CWSPA in Section 5.3. This includes Eagle-Figure 5-38, Elmwood-Figure 5-43, Union-Figure 5-48, Waverly-Figure 5-54, and Weeping Water-Figure 5-59. These figures illustrate the complex nature and interconnections between the saturated ***Q*** and ***Kd*** materials of the area. They show how these aquifers can be limited in extent, both vertically and horizontally. 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 volume and groundwater storage calculations. Note that the images in figures were created in Datamine Discover PA, version 2015, Release Build 15.0.13 (DatamineDiscover, 2017). They can be examined in greater detail by opening the PA sessions provided in Appendix 3\PA Sessions.

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

No aquifer test information was available for this investigation from the survey area. Specific yield values for all ***Q*** aquifer materials were selected by estimating values (Figure 2-7) from Summerside and Meyers (2005b). Specific yield for non-aquifer materials was chosen at 0.02 (Heath, 1983) and for marginal aquifer materials a value of 0.05 was selected (Heath, 1983). The specific yield for the aquifer material ranges from 0.05 to 0.2 with an average of 0.10. While coarse aquifer materials exist as localized deposits in the survey area, estimates of specific yield for the coarse aquifer material ranges from 0.13 to 0.17 with an average of 0.15 (Summerside and Meyers, 2005b). Figure 2-7 provides a map from CSD that has identified areas having none to very thin amounts of aquifer materials present. When compared to the figures of saturated ***Q*** aquifer materials and ***Kd*** Sandstone/sand dominant materials for these CWSPAs: Eagle-Figure 5-38, Elmwood-Figure 5-43, Union-Figure 5-48, Waverly-Figure 5-54, and Weeping Water-Figure 5-59., the complexity of the ***Q*** saturated aquifer thickness is apparent - there are variable amounts of saturated ***Q*** and ***Kd*** materials at each site. Specific yield maps of the area would be improved if new maps were produced using this new information plus the addition of aquifer tests or other methods of gaining new data on aquifer characteristics.

Tables have been developed for the each CWSPA for saturated ***Q*** aquifer materials and saturated ***Kd*** aquifer materials which show the results of calculations for groundwater in storage for each CWSPA calculated by volume of all aquifer materials below the water table then multiplied by the estimated porosity. The following are those calculations per CWSPA.

5.4.1 Eagle

The following calculation from values in the Table 5-3 shows the non-aquifer material has an estimated aquifer volume of **65,902** acre-ft and contains **26,360** acre-ft of groundwater in storage, marginal aquifer material has an estimated aquifer volume of **94,403** acre-ft and contains **33,041** acre-ft groundwater in storage, aquifer material has an estimated aquifer volume of **30,480** acre-ft and contains an estimated volume of **6,096** acre-ft of groundwater in storage. There is no coarse aquifer material in the Eagle AEM block flight area. The amount of groundwater in storage for all material groups is **65,497**acre-ft.

The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the Eagle block flight area will yield approximately **527** acre-ft, marginal aquifer materials will yield approximately **3,304** acre-ft and aquifer materials will yield **914** acre-ft. A total of **4,745** acre-ft is available from the combined aquifer materials.

These estimates are based on the NE-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 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. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-3 are conservative estimates and the amounts released from the decline in pressure are not considered.

Porosity and Specific Yield values for the ***Kd*** sandstone/sand dominant and the shale/clay dominant materials were taken from published values by Heath (1983). O'Connor (1987) made some estimates on specific capacity, hydraulic conductivity, and transmissivity for three high capacity wells in Sarpy County and these values were not used for the volume calculations because there were only three values available and their effect on determining specific yield would be negligible. The values for sandstone/sand dominant materials are modified from Heath (1983) to account for the cemented nature of the ***Kd*** are a porosity of 0.35 of volume and specific yield of 0.05 percent. The ***Kd*** shale/clay dominant materials have values for porosity of 0.40, and specific yield of 0.02. These values will be used for calculating groundwater storage/yield for the ***Kd*** sandstone/sand dominant and shale/clay dominant materials. The results are contained in Table 5-4. The following calculations from values in the table show the ***Kd*** sandstone/sand dominant material has an estimated aquifer volume of **222,835** acre-ft and contains **77,992** acre-ft of groundwater in storage, the ***Kd*** shale/clay dominant material has an estimated aquifer volume of **806,757** acre-ft and contains **322,703** acre-ft of groundwater in storage. The ***Kd*** sandstone/sand dominant material has extractable volume of groundwater of **3,899** acre-ft and the shale/clay dominant material has extractable volume of groundwater of **6,454** for a total of **10,353** acre-ft.

It should be noted that all values are very conservative in nature and are estimates based on published values for porosity and specific yield. The actual amount of extractable water will vary due to many things such as sediment grain size, sorting, cementation and other considerations. Actual values from the various sediment packages in the ***Q*** and ***Kd*** would greatly help the estimates of groundwater in storage and extractable water volume.

Table 5-3. Saturated *Q* aquifer materials underlying the Eagle AEM block flight 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	2,870,733,269	65,902	0.40	26,360	0.02	527
Marginal	4,112,224,156	94,403	0.35	33,041	0.10	3,304
Aquifer	1,327,750,519	30,480	0.20	6,096	0.15	914
TOTAL	8,310,707,944	190,787		65,497		4,745

Table 5-4. Saturated *Kd* aquifer materials underlying the Eagle AEM block flight 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)
Shale/clay	35,142,368,550	806,757	0.40	322,703	0.02	6,454
Sandstone/sand	9,706,699,413	222,835	0.35	77,992	0.05	3,899
TOTAL	44,849,067,963	1,029,592		400,695		10,353

5.4.2 Elmwood

The following calculation from values in the Table 5-5 shows the non-aquifer material has an estimated aquifer volume of **8,754** acre-ft and contains **3,501** acre-ft of groundwater in storage, marginal aquifer material has an estimated aquifer volume of **75,093** acre-ft and contains **26,282** acre-ft groundwater in storage, aquifer material has an estimated aquifer volume of **12,593** acre-ft and contains an estimated volume of **2,518** acre-ft of groundwater in storage. There is no coarse aquifer material in the Elmwood AEM block flight area. The amount of groundwater in storage for all material groups is **32,201** acre-ft.

The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the Elmwood block flight area will yield approximately **70** acre-ft, marginal aquifer materials will yield approximately **1,314**acre-ft and aquifer materials will yield **251** acre-ft. A total of **1,635** acre-ft is available from the combined aquifer materials.

These estimates are based on the NE-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 possible "confined or semi-confined" water under pressure (head above the aquifer). This volume of water would add to the values reported in Table 5-5. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-5 are conservative estimates and the amounts released from the decline in pressure are not considered.

Porosity and Specific Yield values for the ***Kd*** sandstone/sand dominant and the shale/clay dominant materials were taken from published values by Heath (1983). O'Connor (1987) made some estimates on specific capacity, hydraulic conductivity, and transmissivity for three high capacity wells in Sarpy County and these values were not used for the volume calculations because there were only three values available and their effect on determining specific yield would be negligible. The values for sandstone/sand dominant materials are modified from Heath (1983) to account for the cemented nature of the ***Kd*** are a porosity of 0.35 of volume and specific yield of 0.05 percent. The ***Kd*** shale/clay dominant materials have values for porosity of 0.40, and specific yield of 0.02. These values will be used for calculating groundwater storage/yield for the ***Kd*** sandstone/sand dominant and shale/clay dominant materials. The results are contained in Table 5-6. The following calculations from values in the table show the ***Kd*** sandstone/sand dominant material has an estimated aquifer volume of **2,068** acre-ft and contains **723** acre-ft of groundwater in storage, the ***Kd*** shale/clay dominant material has an estimated aquifer volume of **191,807** acre-ft and contains **76,722** acre-ft of groundwater in storage. The ***Kd*** sandstone/sand dominant material has extractable volume of groundwater of **36** acre-ft and the shale/clay dominant material has extractable volume of groundwater of **1,534** for a total of **1,570** acre-ft. It should be noted that all values are very conservative in nature and are estimates based on published values for porosity and specific yield. The actual amount of extractable water will vary due to many things such as sediment grain size, sorting, cementation and other considerations. Actual values from the various sediment packages in the ***Q*** and ***Kd*** would greatly help the estimates of groundwater in storage and extractable water volume.

Table 5-5. Saturated *Q* aquifer materials underlying the Elmwood block flight 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	381,334,263	8,754	0.40	3,501	0.02	70
Marginal	3,271,088,706	75,093	0.35	26,282	0.05	1,314
Aquifer	548,553,431	12,593	0.20	2,518	0.10	251
TOTAL	4,200,976,400	96,441		32,201		1,635

Table 5-6. Saturated *Kd* aquifer materials underlying the Elmwood block flight 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)
Shale/clay	8,355,124,656	191,807	0.40	76,722	0.02	1,534
Sandstone/sand	90,084,150	2,068	0.35	723	0.05	36
TOTAL	8,445,208,806	193,875		77,445		1,570

5.4.3 Union

The following calculation from values in the Table 5-7 shows the non-aquifer material has an estimated aquifer volume of **41,969** acre-ft and contains **16,787** acre-ft of groundwater in storage, marginal aquifer material has an estimated aquifer volume of **201,441** acre-ft and contains **70,504** acre-ft groundwater in storage, aquifer material has an estimated aquifer volume of **297,818** acre-ft and contains an estimated volume of **59,563** acre-ft of groundwater in storage, coarse aquifer volume of **49,051** acre-ft and contains an estimated volume of **12,262** acre-ft of groundwater in storage . The amount of groundwater in storage for all material groups is **159,116** acre-ft.

The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the Union AEM block flight area will yield approximately **335** acre-ft, marginal aquifer materials will yield approximately **3,525** acre-ft, aquifer materials will yield **5,956** acre-ft and coarse aquifer materials will yield **1,839** acre-ft. A total of **11,655** acre-ft is available from the combined aquifer materials.

These estimates are based on the NE-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 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. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-7 are conservative estimates and the amounts released from the decline in pressure are not considered.

There were no ***Kd*** aquifer materials in Union AEM block flight area.

It should be noted that all values are very conservative in nature and are estimates based on published values for porosity and specific yield. The actual amount of extractable water will vary due to many things such as sediment grain size, sorting, cementation and other considerations. Actual values from the various sediment packages in the ***Q*** would greatly help the estimates of groundwater in storage and extractable water volume.

5.4.4 Waverly

The following calculation from values in the Table 5-8 shows the non-aquifer material has an estimated aquifer volume of **14,469** acre-ft and contains **5,787** acre-ft of groundwater in storage, marginal aquifer material has an estimated aquifer volume of **52,370** acre-ft and contains **18,329** acre-ft groundwater in storage, aquifer material has an estimated aquifer volume of **29,675** acre-ft and contains an estimated volume of **5,935** acre-ft of groundwater in storage and coarse aquifer volume of **717** acre-ft and contains an estimated volume of **179** acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is **30,230** acre-ft.

Table 5-7. Saturated *Q* aquifer materials underlying the Union block flight 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	1,828,172,044	41,969	0.40	16,787	0.02	335
Marginal	8,774,785,844	201,441	0.35	70,504	0.05	3,525
Aquifer	12,972,981,338	297,818	0.20	59,563	0.10	5,956
Coarse	2,136,662,256	49,051	0.25	12,262	0.15	1,839
TOTAL	25,712,601,481	590,280		159,116		11,655

The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the Waverly AEM block flight area will yield approximately **115** acre-ft, marginal aquifer materials will yield approximately **916** acre-ft, aquifer materials will yield **593** acre-ft and coarse aquifer materials will yield **26** acre-ft. A total of **1650** acre-ft is available from the combined aquifer materials.

These estimates are based on the NE-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 possible "confined or semi-confined" water under pressure (head above the aquifer). This volume of water would add to the values reported in Table 5-8. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-8 are conservative estimates and the amounts released from the decline in pressure are not considered.

Porosity and Specific Yield values for the ***Kd*** sandstone/sand dominant and the shale/clay dominant materials were taken from published values by Heath (1983). O'Connor (1987) made some estimates on specific capacity, hydraulic conductivity, and transmissivity for three high capacity wells in Sarpy County and these values were not used for the volume calculations because there were only three values available and their effect on determining specific yield would be negligible. The values for sandstone/sand dominant materials are modified from Heath (1983) to account for the cemented nature of the ***Kd*** are a porosity of 0.35 of volume and specific yield of 0.05 percent. The ***Kd*** shale/clay dominant materials have values for porosity of 0.40, and specific yield of 0.02. These values will be used for calculating groundwater storage/yield for the ***Kd*** sandstone/sand dominant and shale/clay dominant materials. The results are contained in Table 5-9. The following calculations from values in the table show the ***Kd*** sandstone/sand dominant material has an estimated aquifer volume of **248,188** acre-ft and contains **86,865** acre-ft of groundwater in storage, the ***Kd*** shale/clay dominant material has an estimated aquifer volume of **450,413** acre-ft and contains **180,165** acre-ft of groundwater in storage. The ***Kd*** sandstone/sand dominant material has extractable volume of groundwater of **4,343** acre-ft and the shale/clay dominant material has extractable volume of groundwater of **3,603** for a total of **7,946** acre-ft.It should be noted that all values are very conservative in nature and are estimates based on published values for porosity and specific yield. The actual amount of extractable water will vary due to many things such as sediment grain size, sorting, cementation and other considerations. Actual values from the various sediment packages in the ***Q*** and ***Kd*** would greatly help the estimates of groundwater in storage and extractable water volume.

5.4.5 Weeping Water

The following calculation from values in the Table 5-10 shows the non-aquifer material has an estimated aquifer volume of **50,959** acre-ft and contains **20,383** acre-ft of groundwater in storage, marginal aquifer material has an estimated aquifer volume of **75,372** acre-ft and contains **26,380** acre-ft groundwater in storage, aquifer material has an estimated aquifer volume of **448** acre-ft and contains an estimated volume of **89** acre-ft of groundwater in storage.

Table 5-8. Saturated *Q* aquifer materials underlying the Waverly AEM block flight 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	630,311,081	14,469	0.40	5,787	0.02	115
Marginal	2,281,271,950	52,370	0.35	18,329	0.05	916
Aquifer	1,292,655,806	29,675	0.20	5,935	0.10	593
Coarse	31,261,894	717	0.25	179	0.15	26
TOTAL	4,235,500,731	97,233		30,230		1650

Table 5-9. Saturated *Kd* aquifer materials underlying the Waverly block flight 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)
Shale/clay	19,620,028,119	450,413	0.40	180,165	0.02	3,603
Sandstone/sand	10,811,075,556	248,188	0.35	86,865	0.05	4,343
TOTAL	30,431,103,675	698,601		267,030		7,946

There is no coarse aquifer material in the Weeping Water AEM block flight area. The amount of groundwater in storage for all material groups is **46,852** acre-ft. The estimate of extractable volume of water is calculated by taking the amount of groundwater in storage times the specific yield. Non-aquifer materials in the Weeping Water AEM block flight area will yield approximately **407** acre-ft, marginal aquifer materials will yield approximately **1,319** acre-ft and aquifer materials will yield **9** acre-ft. A total of **1,735** acre-ft is available from the combined aquifer materials.

These estimates are based on the NE-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 possible "confined or semi-confined" water under pressure (head above the aquifer). This volume of water would add to the values reported in Table 5-10. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 8 are conservative estimates and the amounts released from the decline in pressure are not considered.

Porosity and Specific Yield values for the ***Kd*** sandstone/sand dominant and the shale/clay dominant materials were taken from published values by Heath (1983). O'Connor (1987) made some estimates on specific capacity, hydraulic conductivity, and transmissivity for three high capacity wells in Sarpy County and these values were not used for the volume calculations because there were only three values available and their effect on determining specific yield would be negligible. The values for sandstone/sand dominant materials are modified from Heath (1983) to account for the cemented nature of the ***Kd*** are a porosity of 0.35 of volume and specific yield of 0.05 percent. The ***Kd*** shale/clay dominant materials have values for porosity of 0.40, and specific yield of 0.02. These values will be used for calculating groundwater storage/yield for the ***Kd*** sandstone/sand dominant and shale/clay dominant materials. The results are contained in Table 5-11. The following calculations from values in the table show the ***Kd*** sandstone/sand dominant material has an estimated aquifer volume of **71,027** acre-ft and contains **24,859** acre-ft of groundwater in storage, the ***Kd*** shale/clay dominant material has an estimated aquifer volume of **346,758** acre-ft and contains **138,703** acre-ft of groundwater in storage. The ***Kd*** sandstone/sand dominant material has extractable volume of groundwater of **1,242** acre-ft and the shale/clay dominant material has extractable volume of groundwater of **2,774** for a total of **4,016** acre-ft.

It should be noted that all values are very conservative in nature and are estimates based on published values for porosity and specific yield. The actual amount of extractable water will vary due to many things such as sediment grain size, sorting, cementation and other considerations. Actual values from the various sediment packages in the ***Q*** and ***Kd*** would greatly help the estimates of groundwater in storage and extractable water volume.

Table 5-10. Saturated *Q* aquifer materials underlying the Weeping Water AEM block flight 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	2,219,781,769	50,959	0.40	20,383	0.02	407
Marginal	3,283,216,550	75,372	0.35	26,380	0.05	1,319
Aquifer	19,552,719	448	0.20	89	0.10	9
TOTAL	5,522,551,038	126,779		46,852		1,735

Table 5-11. Saturated *Kd* aquifer materials underlying the Weeping Water AEM block flight 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)
Shale/clay	15,104,807,756	346,758	0.40	138,703	0.02	2,774
Sandstone/sand	3,093,941,081	71,027	0.35	24,859	0.05	1,242
TOTAL	18,198,748,838	417,785		163,562		4,016

5.5 Recharge Areas within the LPSNRD AEM Survey Area

3D representations of the subsurface resulting from AEM investigations illustrate areas of aquifer materials from the bedrock up to the land surface. From these interpretations a new series of near-surface maps were constructed that include the interval from 0 to10 feet (about 3 m). 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 those depths, based on the physics of the electromagnetic exploration technique. These first layer maps show all aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material and indicate the areas at the land surface that can potentially transmit water to the groundwater aquifers in the area. The coarse aquifer material can transmit the largest volume of water and the non-aquifer material being the least able to transmit water.

The results of the interpretation of the aquifer materials of the LPSNRD AEM survey area are explained in detail in Section 5.2 and Section 5.3. The interpreted aquifer materials for the first model layer (0 – 10 ft) are presented in a series of figures for each CWSPA as a color from the ***Q*** material legend (Figure 5-19). Areas of coarse aquifer material (brown colored material) will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material (yellow colored material) potentially transmitting slightly less precipitation downward as both units are permeable and transmissive. The marginal aquifer material (tan colored material) has a very low potential to transmit some water downward and the non-aquifer material (blue colored material) will transmit minimal to no water to the groundwater aquifer.

However, since the amount of slope of the land surface plays a large role in the amount of residence time that water will spend in an area, the greater the length of time spent at a location, the greater the amount of infiltration potential. The greatest possibility for recharge in the LPSNRD AEM survey area is the Platte River and Missouri River alluvial valley floor and the creek beds that have aquifer and coarse aquifer materials are near the land surface. On the table lands, the best possible location for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands with little relief in elevation with a pathway of similar materials down to the saturated aquifer at depth. Figure 5-47 in Section 5-3 provides an example of this on the east end of the profile L147701. Figure 5-37 in Section 5-3 provides a second example of this in the center of the profile L341002 where ***Q*** materials are in contact with ***Kd*** sandstone dominant material at depth.

Google Earth kmz's of the LPSNRD recharge materials and locations are presented as separate figures for each CWSPA as ***Q*** aquifer material and coarse aquifer material. These kmz's are included in Appendix 3\KMZ\LPSNRD_Recharge.

The figures showing the recharge maps for LPSNRD block flight areas are shown in the following order; Eagle AEM block flight near-surface materials - Figure 5-64, Eagle Google Earth image recharge materials - Figure 5-65, Elmwood AEM block flight near-surface materials - Figure 5-66, Elmwood Google Earth image recharge materials - Figure 5-67, Union AEM block flight near-surface materials - Figure 5-68, Union Google Earth image recharge materials - Figure 5-69, Waverly AEM block flight near-surface

materials - Figure 5-70, Waverly Google Earth image recharge materials - Figure 5-71, Weeping Water AEM block flight near-surface materials - Figure 5-72, Weeping Water Google Earth image recharge materials - Figure 5-73.

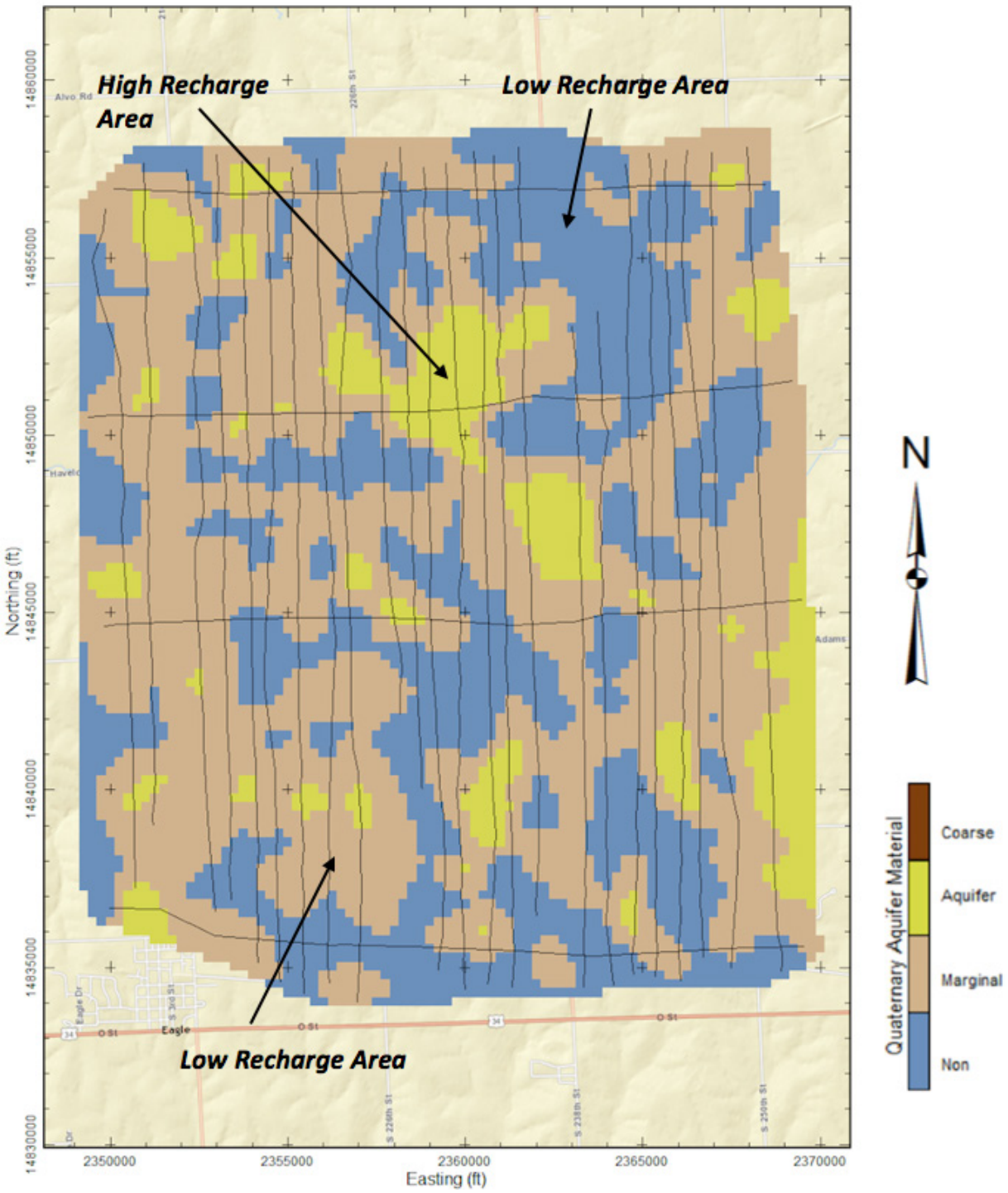


Figure 5-64. Map of all aquifer materials for the first 0 to 10 feet displayed over the Eagle block flight AEM survey area. The material color legend indicates that different colors relate to different aquifer material types. Black lines are the flight lines. Map projection is NAD 83, UTM Zone 14 North, feet.

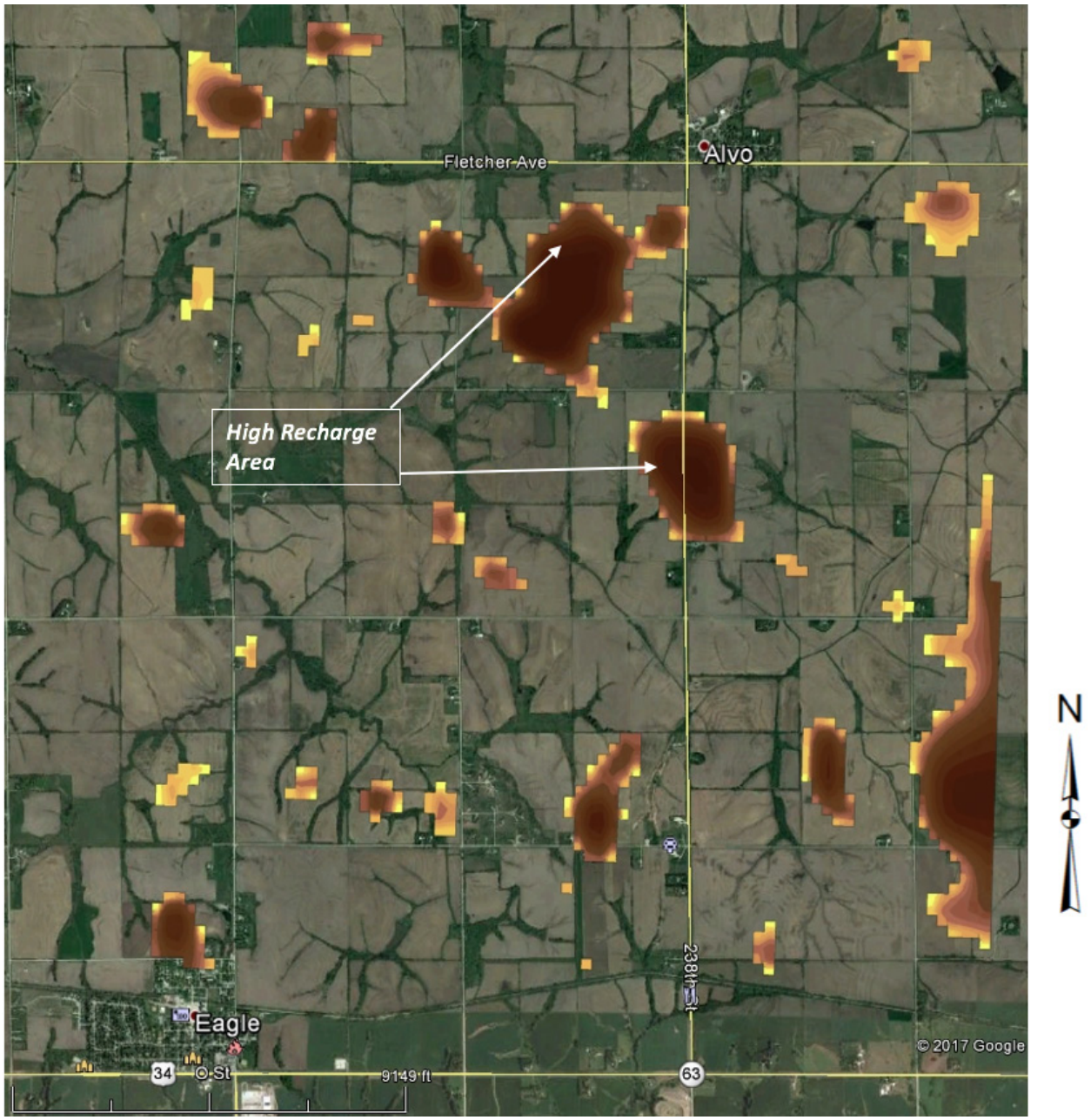


Figure 5-65. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Eagle AEM block flight survey area.

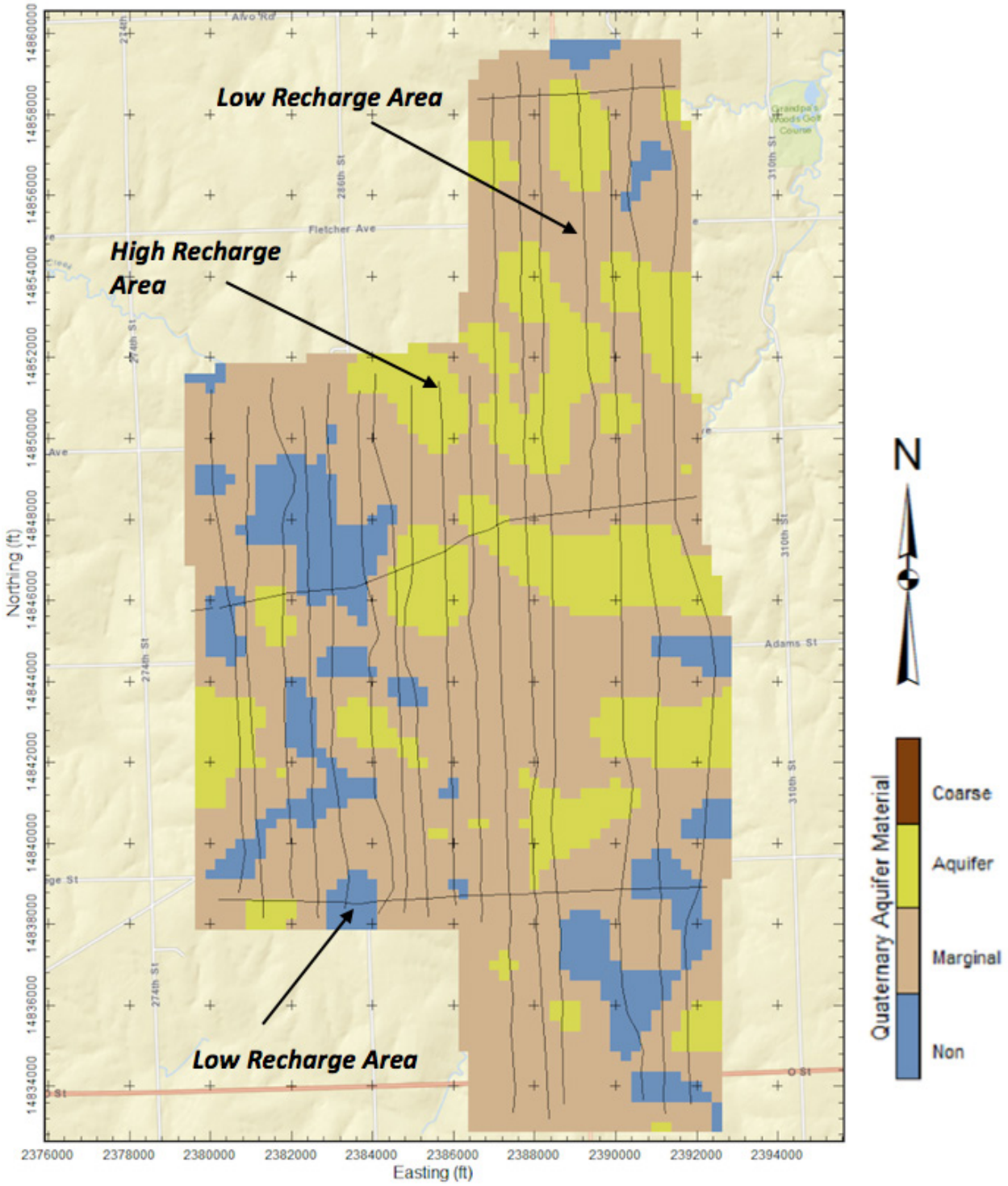


Figure 5-66. Map of <u>all</u> aquifer materials for the first 0 to 10 feet displayed over the Elmwood AEM block flight survey area. The material color legend indicates that different colors relate to different aquifer material types. Black lines are the flight lines. Map projection is NAD 83, UTM Zone 14 North, feet.

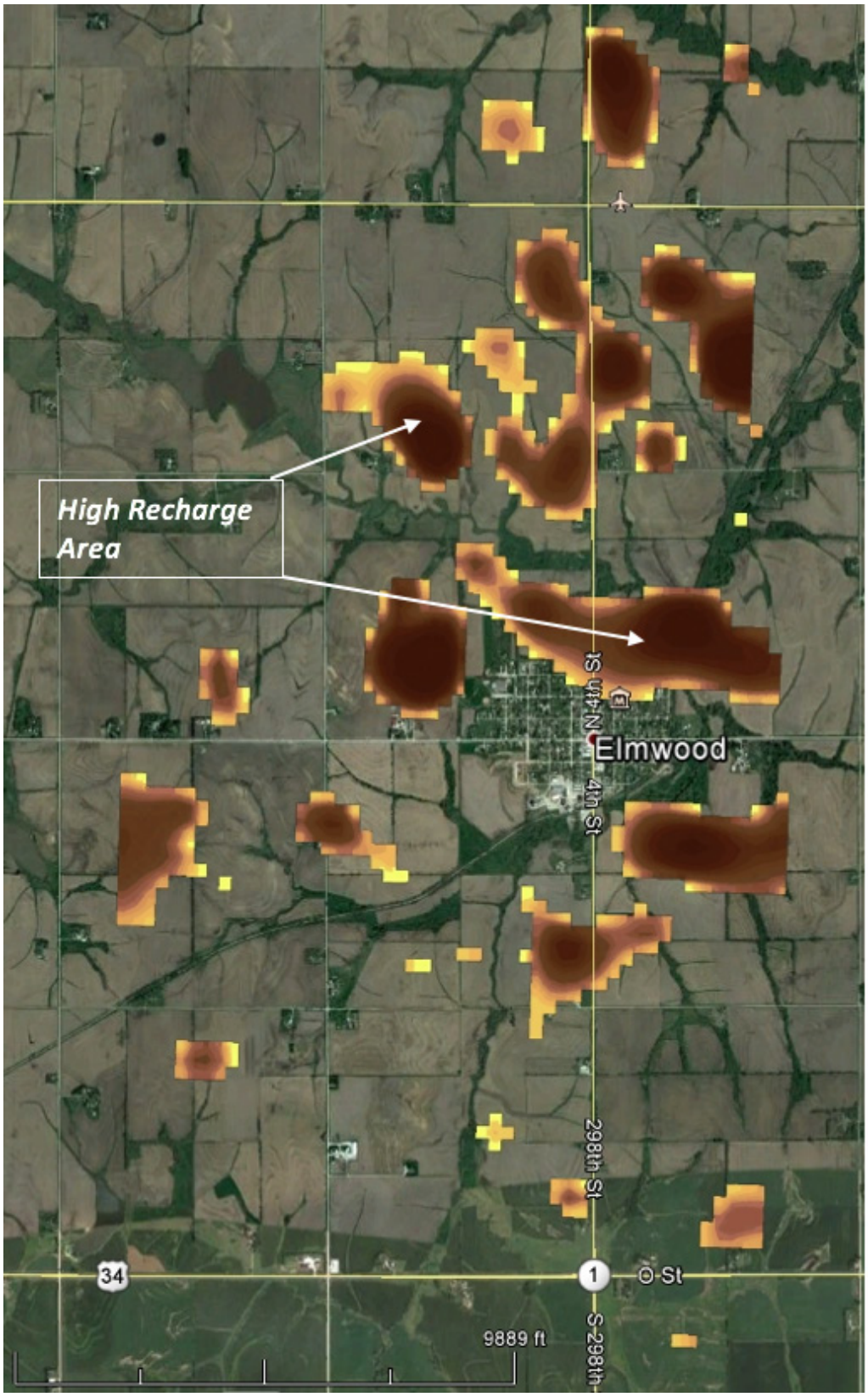


Figure 5-67. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Elmwood AEM block flight survey area.

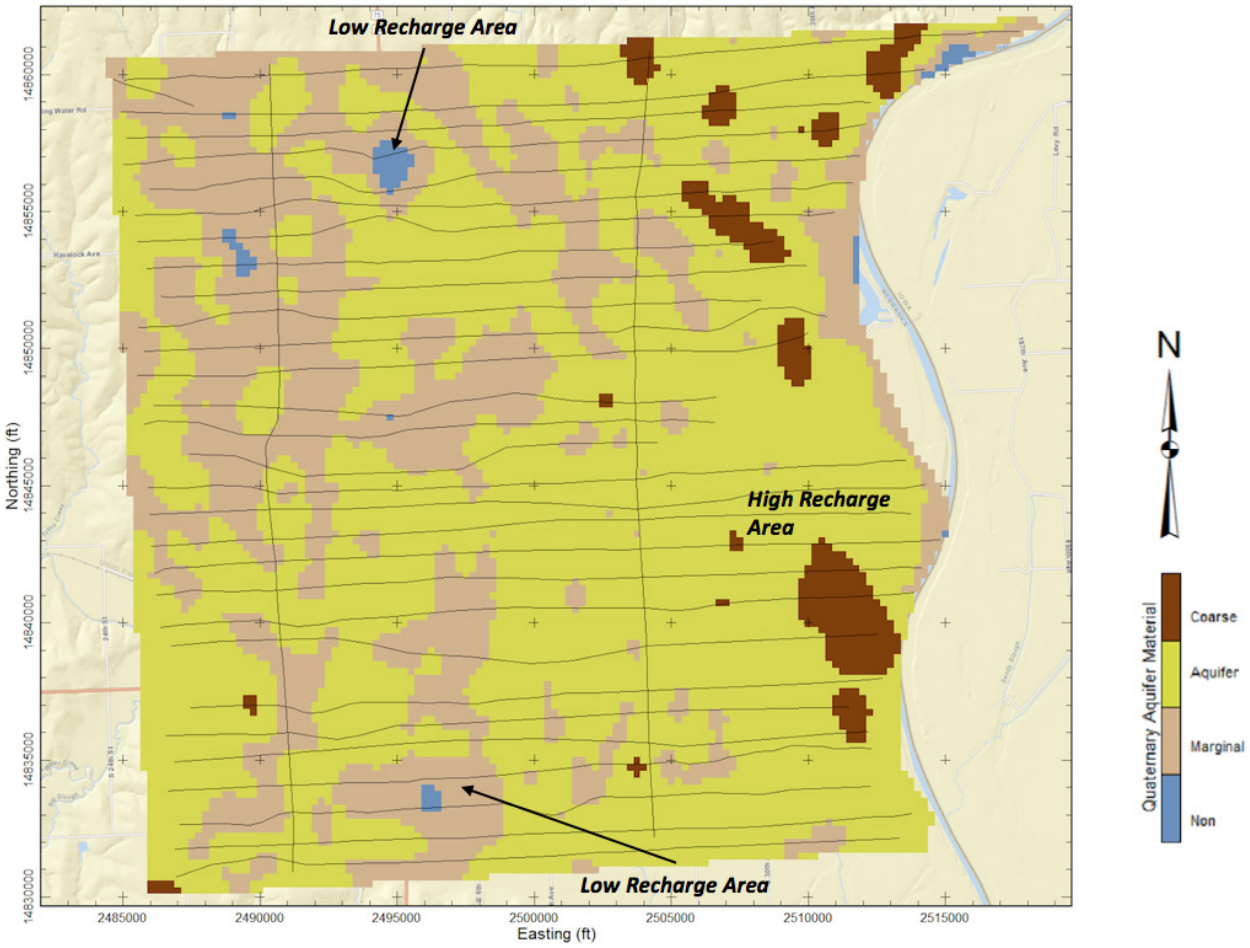


Figure 5-68. Map of <u>all</u> aquifer materials for the first 0 to 10 feet displayed over the Union AEM block flight survey area. The material color legend indicates that different colors relate to different aquifer material types. Black lines are the flight lines. Map projection is NAD 83, UTM Zone 14 North, feet.

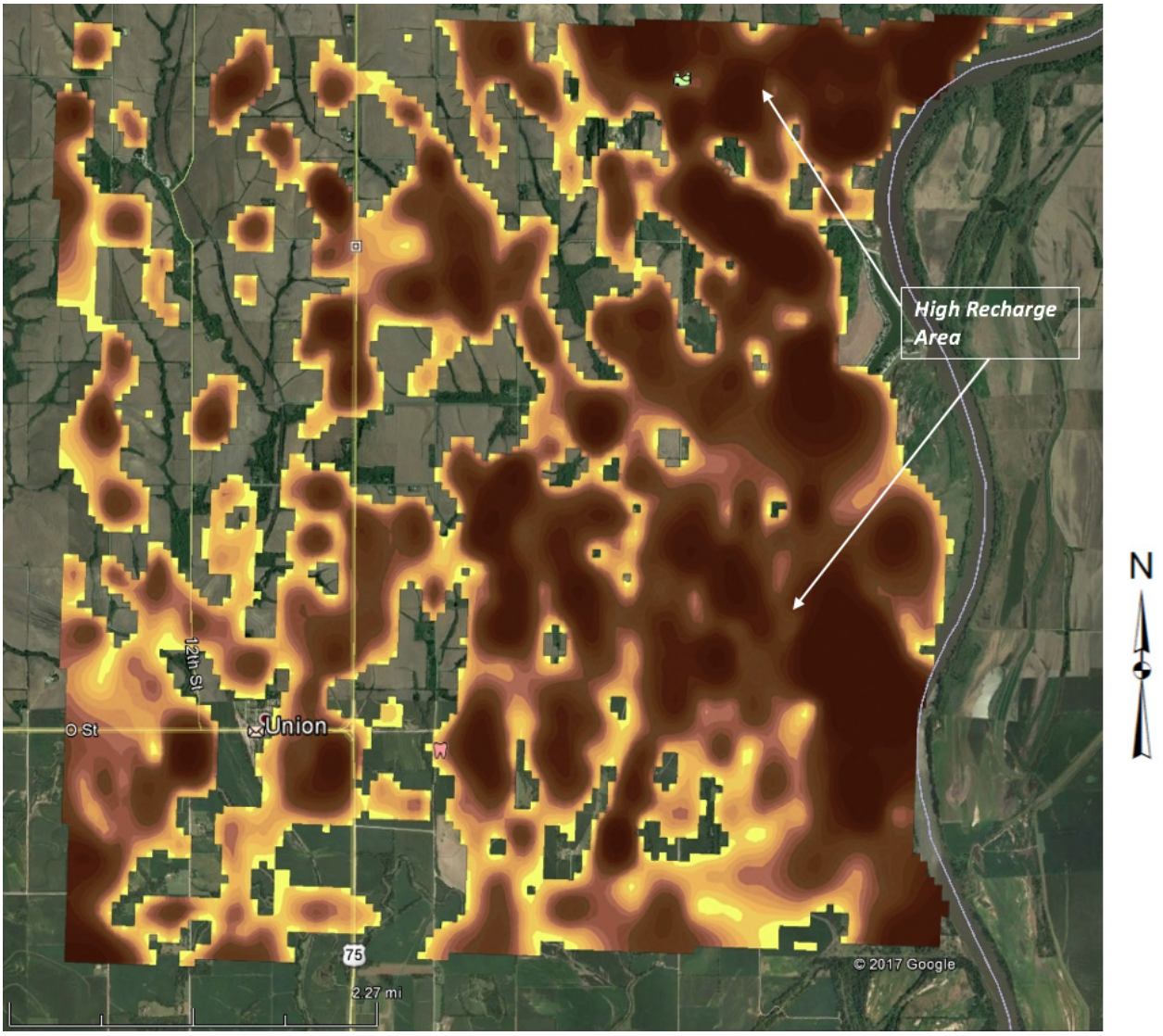


Figure 5-69. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Union AEM block flight survey area.

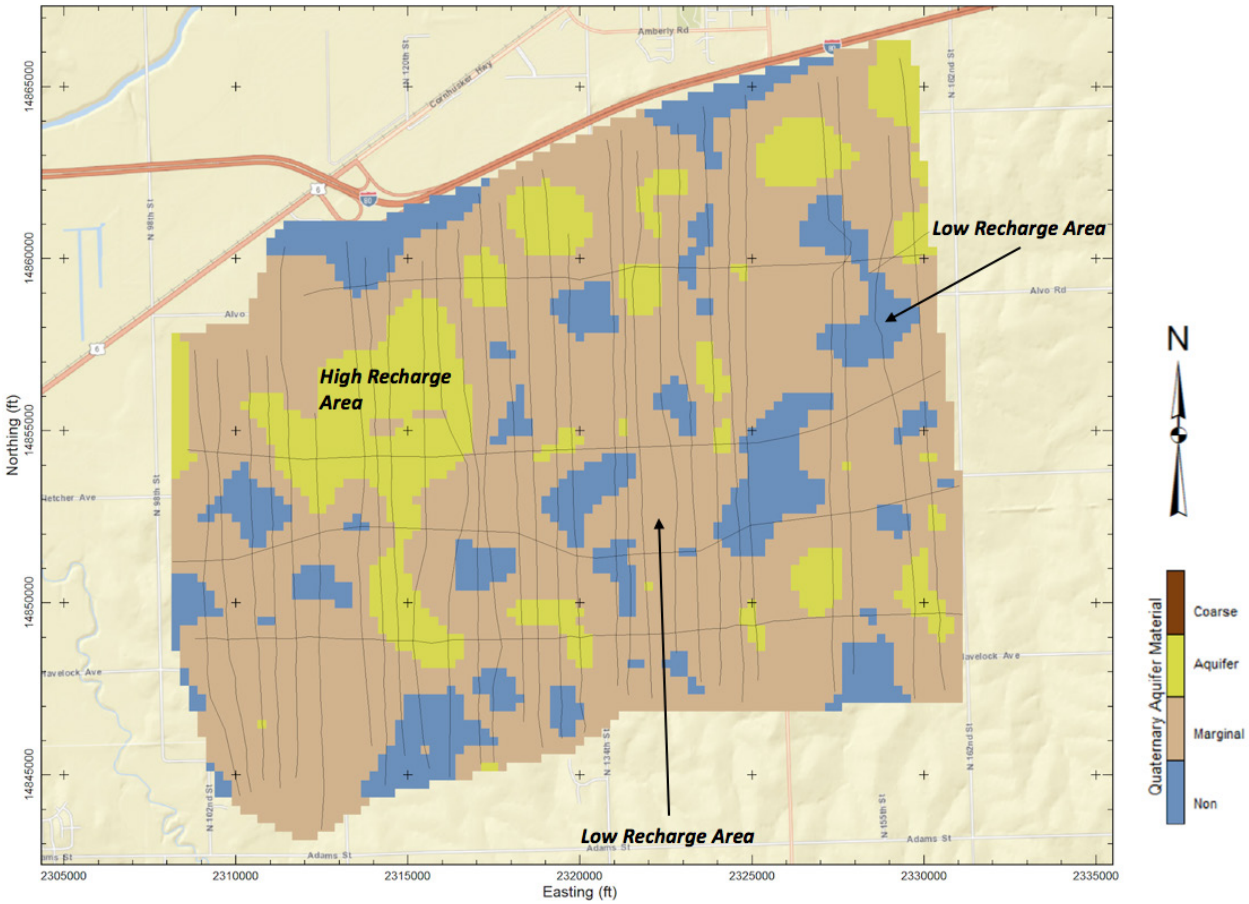


Figure 5-70. Map of <u>all</u> aquifer materials for the first 0 to 10 feet displayed over the Waverly AEM block flight survey area. The material color legend indicates that different colors relate to different aquifer material types. Black lines are the flight lines. Map projection is NAD 83, UTM Zone 14 North, feet.

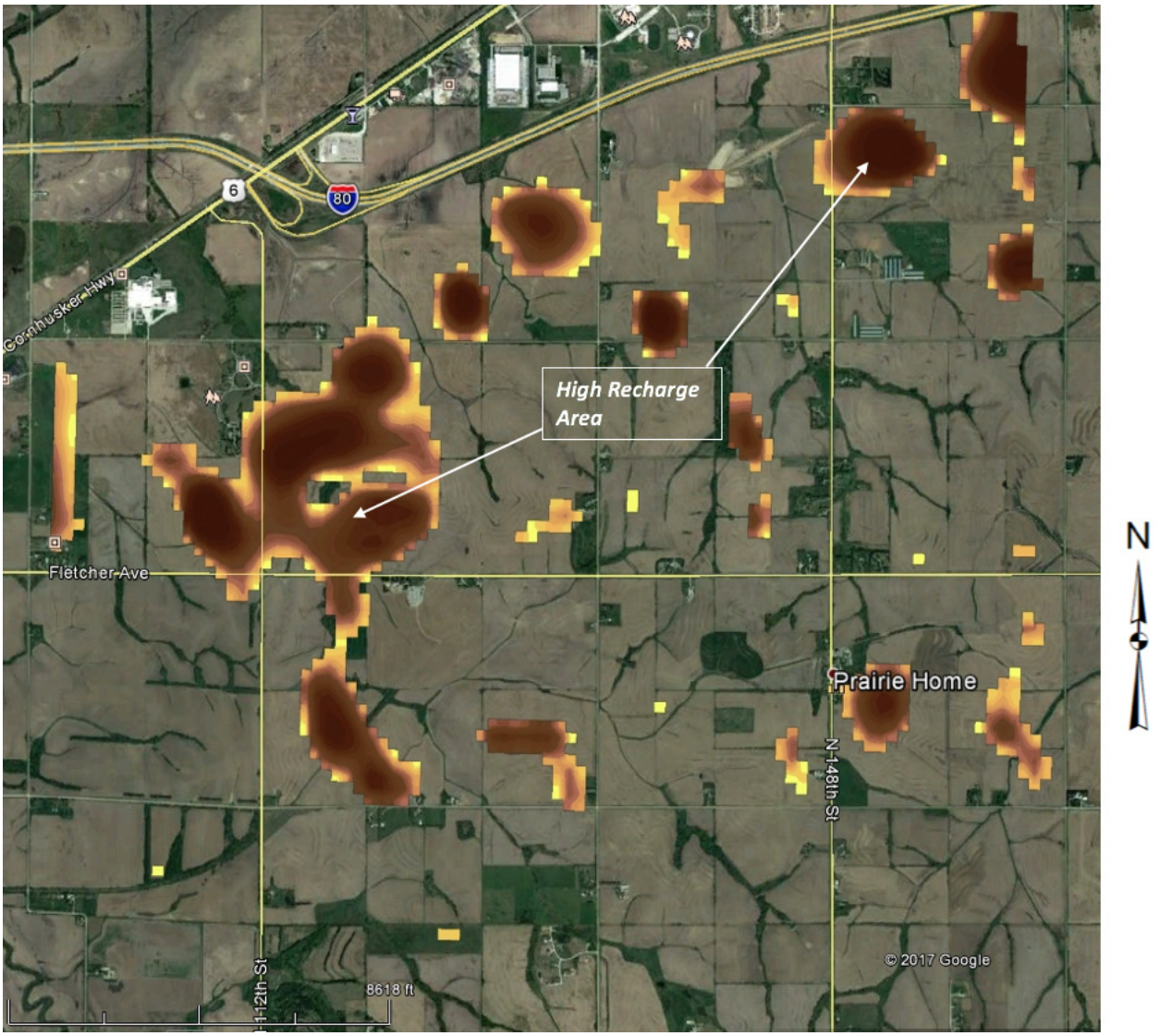


Figure 5-71. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Waverly AEM block flight survey area.

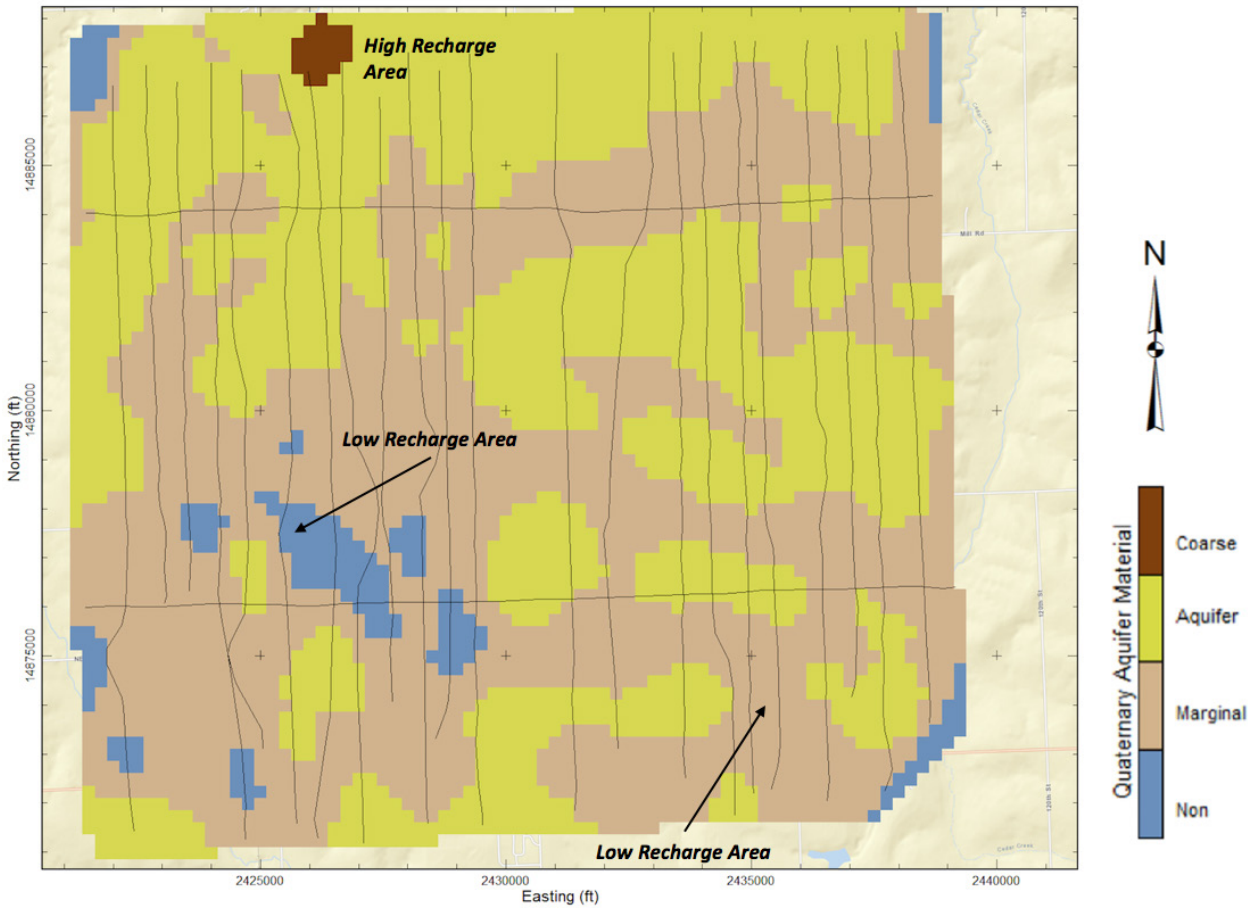


Figure 5-72. Map of <u>all</u> aquifer materials for the first 0 to 10 feet displayed over the Weeping Water AEM block flight survey area. The material color legend indicates that different colors relate to different aquifer material types. Black lines are the flight lines. Map projection is NAD 83, UTM Zone 14 North, feet.

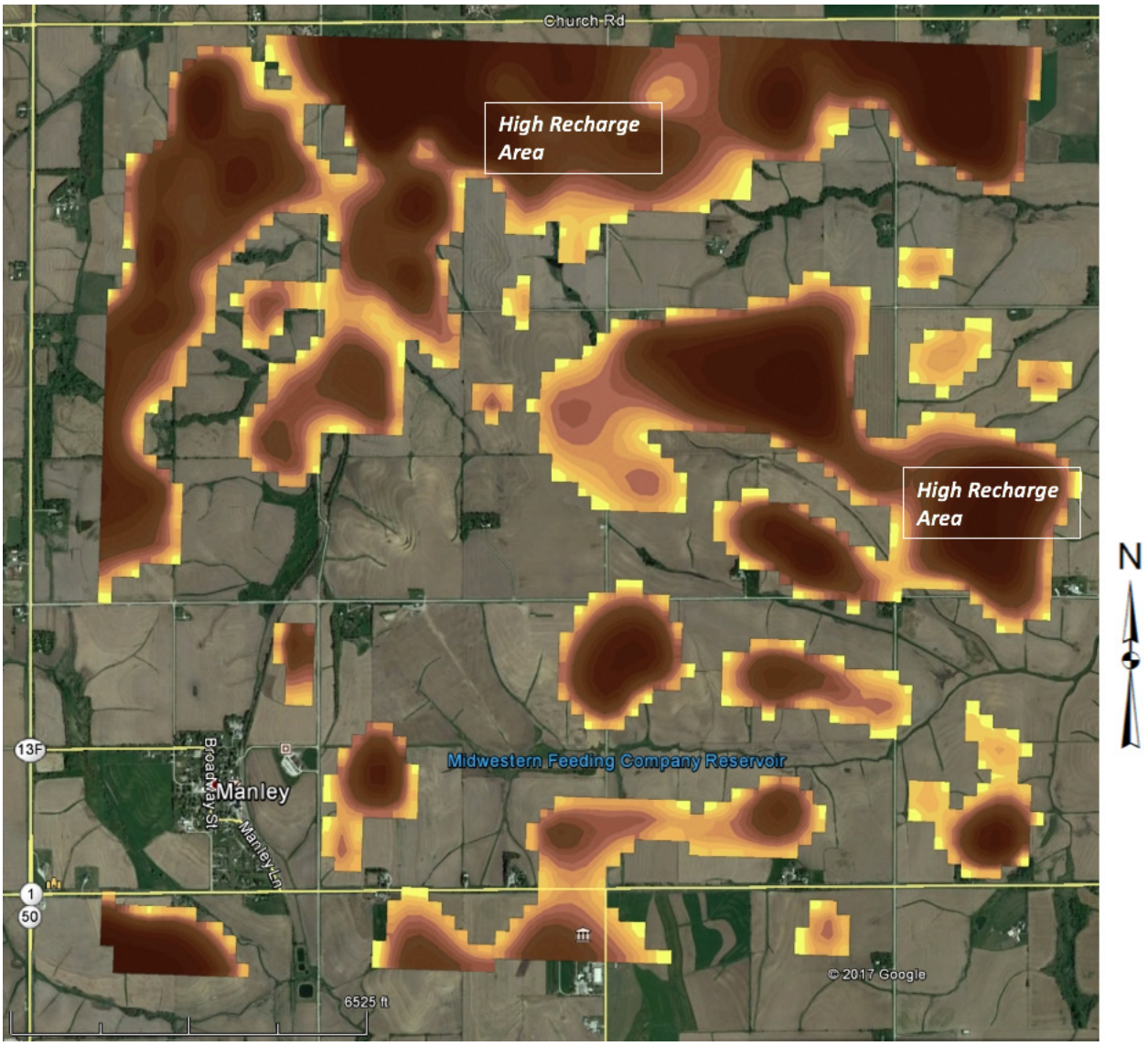


Figure 5-73. Google Earth recharge kmz of aquifer material and coarse aquifer material displayed over the Weeping Water AEM block flight survey area.

5.6 Key AEM Findings

5.6.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results. A total of 78 CSD holes contained lithology information, 72 holes contained stratigraphic information, 49 holes contained geophysical log information from the "ELog" database, and 8 contained geophysical log information from the "GeoLog" database in the LPSNRD AEM survey area. There were also 352 DNR lithology logs that were part of the data delivery from the ENWRA Volume II report (Carney et al., 2015c) as well as 752 more recent DNR lithology logs. The well data correlated well with the AEM and provided control to allow hydrogeological interpretations.

5.6.2 Merging 2015 and 2016 AEM Databases

The LPSNRD AEM survey area analysis encompassed an additional 51.7 line-miles (83.8 line-km) of AEM data collected in 2015 in the LPSNRD area. The 2015 AEM data contains valuable information that can be utilized in the interpretation of the larger LPSNRD AEM survey data. The 2015 AEM results were combined with the 2016 AEM data. Note that this combination did not include reinverting the 2015 data, but rather included merging the 2015 inversion results into the 2016 database and interpretation. The 2015 data correlated and merged well with the 2016 AEM. The systems were both stable and the inversions were well executed.

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***), Cretaceous Dakota (***Kd***), and undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD and NE-DNR. Surface grids of the interpreted geologic formations were then produced and it was found that the AEM allowed interpretation of the geological contacts. Each flight line profile with interpretation including Quaternary aquifer material mapping and Cretaceous Dakota sandstone/sand dominant zones are included as appendices as well as the interpretative surface grids.

5.6.4 Resistivity/Lithology Relationship

Assessment of the sediment character in both the ***Q*** and the ***Kd*** aquifer systems was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. For the ***Q*** aquifer systems, 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). A similar process was applied to the ***Kd*** and a resistivity threshold of 27 ohm-m was determined to separate sandstone/sand dominant zones from shale/clay dominant zones. 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 LPSNRD AEM Survey Area

The AEM reveals considerable variability in the ***Q***, ***Kd***, and undifferentiated ***IP*** deposits across LPSNRD AEM survey area. The subsurface distribution of materials can generally be

characterized into four somewhat overlapping, but distinct, areas with smaller localized depositional features distributed at various locations within the survey area. These include the Quaternary alluvium in a limited area, Quaternary glacial deposits that cover most of the project area, the ***IP*** bedrock area where the ***Kd*** is eroded off, and the ***Kd*** bedrock area which occurs mostly in the west and is eroded away in the east. The ***Q*** alluvium aquifer area of the LPSNRD AEM survey area is predominantly composed of unconsolidated aquifer and coarse aquifer materials composed of alluvial sediments. The alluvial sediments also contain marginal aquifer and non-aquifer materials but they are isolated and limited in geographic area. Most alluvial materials lie in the Platte River plain, the Missouri River plain, the North Fork of the Nemaha River, Salt Creek and Weeping Water Creek and are saturated from the near surface down. The ***Q*** alluvium overlies the ***IP*** in many areas along the listed streams. The ***Kd*** can act both as an aquifer and an aquiclude. Water from the alluvium or ***Kd*** can move between the units. The coarse aquifer and aquifer materials are most likely to have this connection and interaction.

The ***Q*** glacial deposits covering much of the LPSNRD AEM survey area vary in thickness but in general reach a maximum thickness of greater than 150 feet (Figure 2-5, Section 2). These materials are a combination of tills and outwash deposits. They lie unconformably upon the ***Kd*** and ***IP***.

The ***Kd*** bedrock unit is located mostly in the western end of the survey area although there are additional erosional remnants in the central-eastern regions. The ***Kd*** is characterized by a combination of sandstone/sand dominant and shale/clay dominant units. The sandstone/sand dominant part of the ***Kd*** is an important aquifer where saturated. It can also be hydrologically connected to the Quaternary aquifer materials and Streams. The ***Kd*** shale/clay dominant materials are considered an aquiclude which acts as a boundary condition to groundwater flow. The ***Kd*** is mostly covered by a small amount of ***Q*** alluvium and mostly covered by ***Q*** glacial materials. There are areas of some ***Kd*** outcrops along the streams of the survey area.

5.6.6 Estimation of Aquifer Volume and Water in Storage in the LPSNRD AEM Survey Areas

Estimations were calculated for both ***Q*** and ***Kd*** aquifer materials for 5 CWSPA locations. A 3D representation of the subsurface derived from the AEM imaging provides users the ability to more accurately identify the total unsaturated and saturated aquifer volumes for the ***Q*** and the ***Kd***. The saturated zones of the ***Q*** and ***Kd*** materials can be analyzed to estimate the amount of groundwater in storage and the amount of extractable water present. Block flights were flown near five towns within the LPSNRD for understanding the hydrogeology near the Community Water System Protection Areas (CWSPAs). The CWSPA mapped were near the towns of Eagle, Elmwood, Union, Waverly and Weeping Water where AEM data was collected and interpreted (Figure 1-2). The amount of groundwater in storage for each location is: Eagle, ***Q*** material is 65,497 acre-ft and ***Kd*** is 400,695 acre-ft, Elmwood, ***Q*** material is 32,201 acre-ft and ***Kd*** is 77,992 acre-ft, Union, ***Q*** material is 77,445 acre-ft, Waverly, ***Q*** material is 30,320 acre-ft and ***Kd*** is 267,030 acre-ft and Weeping Water, ***Q*** material is 46,852 acre-ft and ***Kd*** is 163,562 acre-ft.

5.6.7 Potential Recharge Zones within the LPSNRD AEM Survey Area

3D representations of the subsurface resulting from the LPSNRD AEM investigation illustrate areas of aquifer materials from the bedrock up to the land surface. From these interpretations a series of near-surface maps were constructed to display the ***Q*** aquifer materials in the first 10 ft. These indicate that while there is some heterogeneity in the aquifer materials, it is easy to identify the areas of aquifer materials that will transmit the most (aquifer and coarse aquifer materials), and the least (non-aquifer and marginal aquifer materials), amounts of water from the surface down to the groundwater system. The greatest possibility for recharge in the LPSNRD AEM survey area is the Platte River and Missouri River alluvial valley floor and the creek beds that have aquifer and coarse aquifer materials are near the land surface. On the table lands, the best possible location for recharge would be where there is a combination of aquifer and coarse aquifer materials at the land surface on the uplands with little relief in elevation with a pathway of similar materials down to the saturated aquifer at depth. Since most of the LPSNRD is covered in glacial sediments the pathways for recharge from the land surface to the saturated aquifers tend to be limited in most areas, the best locations are Waverly, Union flight blocks.

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 the LPSNRD. The discharge rates match the aquifer configuration and aquifer materials description well.

5.6.9 Value of AEM Data Analysis and Images

One of the most important key findings from the LPSNRD 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 LPSNRD 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 LPSNRD about their management challenges.

5.7.1 Additional AEM Mapping

The aquifer maps provided in this report represent the detailed framework developed for the LPSNRD AEM survey area. The detail provided in the hydrogeological interpretation of the LPSNRD AEM survey area allowed for confident development of hydrogeologic framework. The interpretations match well the CSD and NE-DNR test holes. If additional high resolution information is needed within LPSNRD to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or "block flights" be collected to develop detailed frameworks.

It should be noted that the ability to effectively map erosional remnants of the ***Kd*** can only happen with block flights. Thus, if ***Kd*** remnants are suspected and are targets of interest within an area designated for investigation, then block flights are required for effective characterization.

For example, the detailed hydrogeologic frameworks presented in this report have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield for 5 CWSPAs. It was noted that the edges of the CWSPA flight blocks often terminated with geological features important to understanding the amount of groundwater in storage and hydrologic connection to the surrounding area extend beyond the flight area boundary. It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of LPSNRD. This will supply the LPSNRD with information on aquifer sustainability, depletion to streams, well interference, groundwater withdrawal, and other management considerations.

5.7.2 Update the Water Table map

The groundwater data used in the analyses presented in this report use the 1995 CSD water table data (Nebraska CSD, 1995). 22 years is a long time in the evolution of a groundwater system and, in many areas, the water table used for this report was found not to be inconsistent with other recent borehole data.

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 LPSNRD AEM survey area was used in building the framework maps and profiles. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in optimal locations.

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

5.7.4 Aquifer testing and borehole logging

Additional aquifer tests are recommended to improve estimates of aquifer characteristics. No aquifer properties were available outside the larger cities in the survey area. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. The few test holes with geophysical logs in the LPSNRD AEM survey 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 LPSNRD.

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 LPSNRD AEM survey hydrogeologic framework provides areas of recharge from the ground surface to the groundwater aquifer. The block flights of AEM data acquisition provide the most detailed information for understanding recharge throughout the LPSNRD AEM survey area. It is recommended that additional AEM data be collected and interpreted along the reconnaissance lines in promising locations 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 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 file LPSNRD_EM_MAG_v1.xyz as well as the Geosoft database file LPSNRD_EM_MAG_v1.gdb. These files contain the electromagnetic raw data, plus the magnetic and navigational data, as supplied directly from SkyTEM.

The results of the SCI are included in LPSNRD_AEM_SCI_INV_v1.gdb and .xyz and the data columns of these files 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 the LPSNRD survey 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.

Table 6-6 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, ten (10) flights were required to acquire the LPSNRD AEM data (Figure 4-5). 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.

The various interpretation results are included in data files LPSNRD_InterpSurfaces_v1 in gdb and ASCII xyz formats. Table 6-7 describes the data columns of those files.

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 LPSNRD AEM block survey areas. The voxel grids were 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 voxel 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 LPSNRD AEM survey lines.
- 3D voxel models as ASCII *.xyz and *.gdb for the LPSNRD AEM survey areas

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

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

Table 6-1: Channel name, description, and units for LPSNRD_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_UTM14N_m	Easting, NAD83 UTM Zone 14N	Meters [m]
N_UTM14N_m	Northing, NAD83 UTM Zone 14N	Meters [m]
DEM_m	Digital Elevation	Meters [m]
Alt	DGPS Altitude above sea level	Meters [m]
GDSpeed	Ground Speed	Kilometers/hour [km/h]
Curr_LM	Current, Low Moment	Amps [A]
Curr_HM	Current, High Moment	Amps [A]
LMZ_G01 [Gates 0-27]	Normalized (PFC-Corrected) Low Moment Z-RxCoil value	pV/(m^4*A)
HMZ_G01 [Gates 0-36]	Normalized (PFC-Corrected) High Moment Z-RxCoil value	pV/(m^4*A)
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]
East_ft	Easting, NAD83 UTM Zone 14N	Feet [ft]
North_ft	Northing, NAD83 UTM Zone 14N	Feet [ft]
Elevation_ft	Elevation, 100 ft grid of NED DEM NAVD88	Feet [ft]

Table 6-2: Channel name, description, and units for LPSNRD_AEM_SCI_Inv_v1 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 the LPSNRD AEM survey.

Database (*.xyz, *.gdb)	Description
LPSNRDElogs_Collar	Geophysical ELogs from CSD registered wells within the LPSNRD AEM survey area
LPSNRDElogs_Data	
LPSNRDGeolog_Collar	Recent geophysical logs from CSD registered wells within the LPSNRD AEM survey area
LPSNRDGeolog_Data	
LPSNRDCSDlith_Collar	Lithology logs from CSD registered wells within the LPSNRD AEM survey area
LPSNRDCSDlith_Data	
LPSNRDCSDstrat_Collar	Stratigraphic logs from CSD registered wells within the LPSNRD AEM survey area
LPSNRDCSDstrat_Data	
LPSNRDDNR15lith_Collar	Lithology logs from NE-DNR registered wells within the LPSNRD AEM survey area used in the 2015 AEM survey
LPSNRDDNR15lith_Data	
LPSNRDDNRLith_Collar	Lithology logs from NE-DNR registered wells within the LPSNRD AEM survey area
LPSNRDDNRLith_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: 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	LPSNRD_Linefile.lin	Production file listing dates, flights, and assigned line numbers

Table 6-7: Channel name description and units for the interpretation results file LPSNRD_InterpSurfaces_v1 "gdb" and "xyz" files.

Parameter	Description	Unit
Line	Flight Line Number	
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
RHO_STD[0] through RHO_STD[28]	Array of standard deviations of inverted model resistivities of each layer	
RESDATA	Inversion model residuals of each individual sounding	
RESTOTAL	Average of all model inversion residuals	
DEP_TOP_ft[0] through DEP_TOP_ft[28]	Depth to the top of individual layers	Feet [ft]
DEP_BOT_ft[0] through DEP_BOT_ft[28]	Depth to the bottom of individual layers	Feet [ft]
DOI_UPPER	More conservative estimate of DOI from Workbench	Feet [ft]
DOI_LOWER	Less conservative estimate of DOI from Workbench	Feet [ft]
DEP_TOP_ELEV	Elevation of top of each inversion model layer	Feet (ft)
WaterTable_1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
AquiferMaterialType[0] through AquiferMaterialType[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
Q_Top_Upper_AqMat	Elevation of top of Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Q_Bot_ Upper_AqMat	Elevation of bottom of Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Q_Top_Lower_AqMat	Elevation of top of Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Q_Bot_ Lower_AqMat	Elevation of bottom of Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Q_Top_CoarseAqMat	Elevation of top of Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Q_Bot_CoarseAqMat	Elevation of bottom of Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bedrock	Elevation of interpreted bedrock surface	Feet [ft]
Kd	Elevation of the top of the Cretaceous Dakota Formation.	Feet [ft]
Kd_SandDomTop	Top of Sand-dominant zone in the ***Kd***	Feet [ft]
Kd_SandDomBot	Bottom of Sand-dominant zone in the ***Kd***	Feet [ft]
Penn	Elevation of the top of the Pennsylvanian units.	Feet [ft]
*	No data or unit not detected	

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)
EagleBlock_1995WT_elevation ElmwoodBlock_1995WT_elevation SaltCreekBlock_1995WT_elevation UnionBlock_1995WT_elevation WaverlyBlock_1995WT_elevation WeepingWaterBlock_1995WT_elevation LPSNRD2016Area_1995WT_elevation	Grids of the 1995 water table elevation; NAVD88 (feet)	250
EagleBlock_Kd_elevation ElmwoodBlock_Kd_elevation SaltCreekBlock_Bedrock_elevation UnionBlock_IP_elevation WaverlyBlock_Bedrock_elevation WeepingWaterBlock_Kd_elevation	Grids of the top of the Bedrock composed of either Cretaceous Dakota Group (***Kd***) and/or undifferentiated Pennsylvanian (***IP***); NAVD88 (feet)	250
EagleBlock_DEM ElmwoodBlock_ DEM SaltCreekBlock_ DEM UnionBlock_IP_ DEM WaverlyBlock_ DEM WeepingWaterBlock_ DEM LPSNRD2016Area_DEM	Grids of the Digital Elevation Models (DEM) downloaded from the National Elevation Dataset (NED) August 2016; NAVD88 (feet)	250
EagleBlock_Kd_elevation ElmwoodBlock_Kd_elevation SaltCreekBlock_Kd_elevation WaverlyBlock_Kd_elevation WeepingWaterBlock_Kd_elevation LPSNRD2016Area_Kd_elevation	Grid of the top of the Cretaceous Dakota Group (***Kd***) elevation; NAVD88 (feet)	250
EagleBlock_IP_elevation ElmwoodBlock_ IP_elevation SaltCreekBlock_ IP_elevation WaverlyBlock_ IP_elevation WeepingWaterBlock_ IP_elevation LPSNRD2016Area_IP_elevation	Grid of the top of the undifferentiated Pennsylvanian (***IP***) elevation; NAVD88 (feet)	250
EagleBlock_QuaternaryThickness ElmwoodBlock_QuaternaryThickness SaltCreekBlock_QuaternaryThickness UnionBlock_QuaternaryThickness WaverlyBlock_QuaternaryThickness WeepingWaterBlock_QuaternaryThickness	Grids of the thickness of the Quaternary (***Q***) material (feet)	250
EagleBlock_ Kd_Thickness ElmwoodBlock_ Kd_Thickness SaltCreekBlock_ Kd_Thickness WaverlyBlock_ Kd_Thickness WeepingWaterBlock_ Kd_Thickness	Grids of the thickness of Cretaceous Dakota Group (***Kd***) material (feet)	250
EagleBlock_SaturatedThickness ElmwoodBlock_SaturatedThickness	Grids of the thickness of the saturated Quaternary (***Q***) or Quaternary (***Q***) and	250

SaltCreek_ SaturatedThickness UnionBlock_ SaturatedThickness WaverlyBlock_ SaturatedThickness WeepingWaterBlock_ SaturatedThickness	Cretaceous Dakota Group (***Kd***) material; (feet)	
EagleBlock_SatQ_AquifMat_Thickness ElmwoodBlock_SatQ_AquifMat_Thickness UnionBlock_SatQ_AquifMat_Thickness WaverlyBlock_SatQ_AquifMat_Thickness WeepingWaterBlock_SatQ_AquifMat_Thickness	Grids of the thickness of the saturated Quaternary (***Q***) Aquifer Material (feet)	250
EagleBlock_SatKd_Sand_Thickness ElmwoodBlock_SatKd_Sand_Thickness WaverlyBlock_SatKd_Sand_Thickness Weepingwater_SatKd_Sand_Thickness	Grids of the thickness of the saturated Cretaceous Dakota Group (***Kd***) sand/sandstone Material (feet)	250
EagleBlock_surface_material_layer_1 ElmwoodBlock_surface_material_layer_1 UnionBlock_surface_material_layer_1 WaverlyBlock_surface_material_layer_1 WeepingWaterBlock_surface_material_layer_1	Grids of the top layer of the AEM model 0-10 feet in depth resistivity (ohm-m)	250

Table 6-9. Channel name, description, and units for EagleVoxel, ElmwoodVoxel, UnionVoxel, WaverlyVoxel, and WeepingWaterVoxel Blocks as*.xyz 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\LPSNRD_FlightLines*".

KMZ files of the potential recharge zones in the LPSNRD AEM block survey areas are included in the folder "*Appendix_3_Deliverables\KMZ\LPSNRD_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 Dakota Group (***Kd***) and undifferentiated Pennsylvanian units. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\LPSNRD_Interpretation_Profiles* folder. Also in this folder is a "*GoogleE_Readme.pdf*" file that provides instructions in regards to the "*Settings*" changes that need to be made in Google Earth, and how to use the KMZ files in Google Earth including a legend of what attributes are displayed when an AEM sounding location is clicked. This file is repeated below as a convenience. An example of the KMZ is presented in Figure 6-1.

6.2.1 Included README for the LPSNRD Interpretation KMZ's

README for:

LPSNRD_Interpretation_v1.kmz

Data Files – Within the folder "*LPSNRD_Interpretation_Profiles*" is the folder "*LPSNRD_Profiles*". Please copy the folder *LPSNRD_Profiles* 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 *LPSNRD_Interpretation_v1.kmz* file within the folder named *LPSNRD_Interpretation_Profiles* can now be opened and viewed in Google Earth.

Data:

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

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

East (ft) – Easting coordinate in NAD83, 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

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

Kd Sand Dominant Top Elevation (ft) – Elevation of Top of sand-dominant zone within the ***Kd***, in feet

Kd Sand Dominant Bottom Elevation (ft) – Elevation of Bottom of sand-dominant zone within the ***Kd***, in feet

Elevation Penn (ft) – Elevation of Top of Pennsylvanian formations, in feet

Profile – Link to Interpreted AEM profile images

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

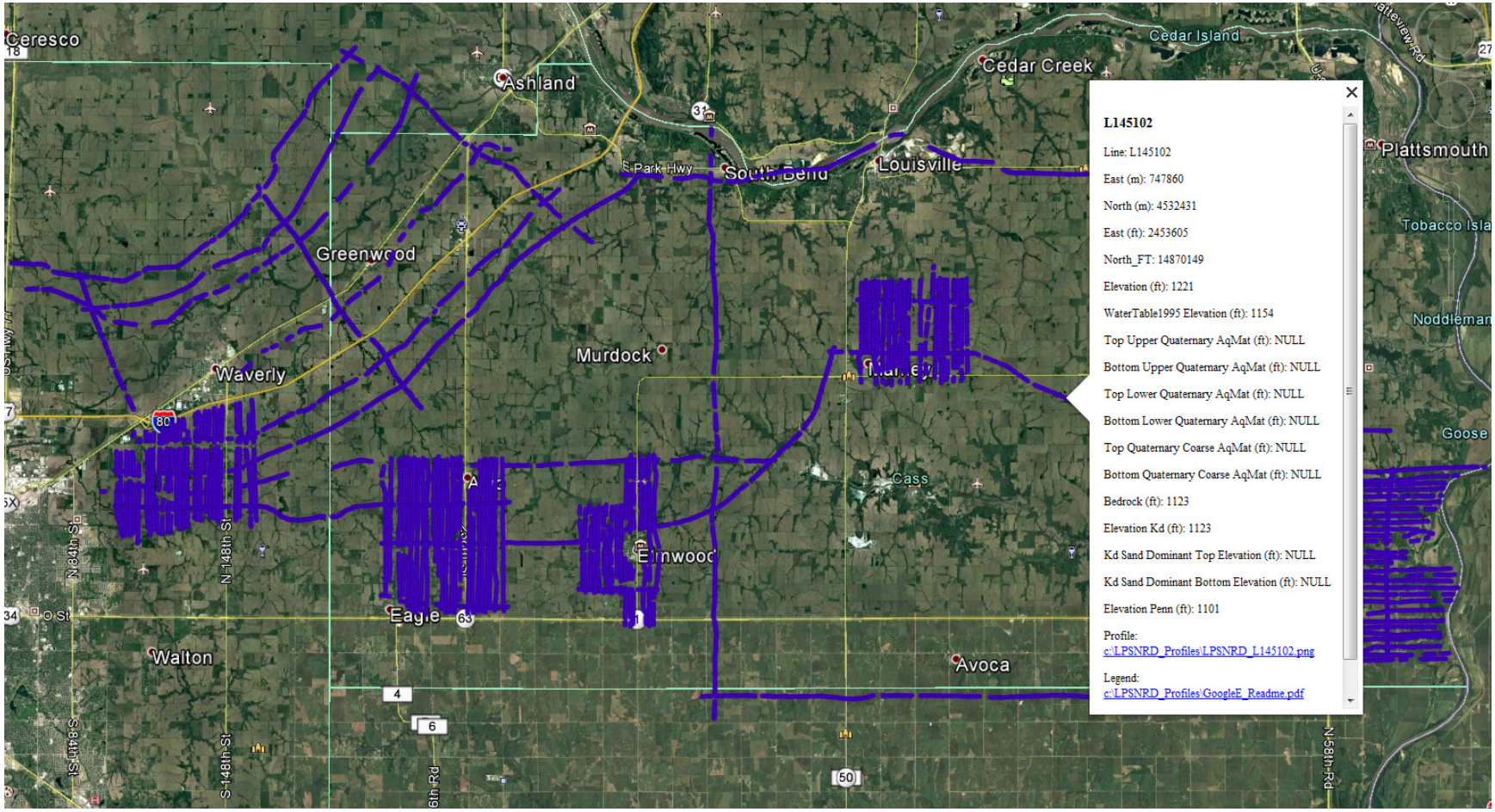


Figure 6-1. Example Google Earth image for the LPSNRD Interpretation kmz.

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 (*.zip)
Reconnaissance (including Salt Creek) 2D Profiles	2D	PA_package_LPSNRDRecon_profiles
Reconnaissance (including Salt Creek) 3D Fence Diagrams	3D	PA_package_LPSNRDRecon_fence
Salt Creek Block 3D Fence Diagrams	3D	PA_package_SaltCreek_fence
Eagle Block 2D Profiles	2D	PA_package_EagleBlock_profiles
Elmwood Block 2D Profiles	2D	PA_package_ ElmwoodBlock_profiles
Union Block 2D Profiles	2D	PA_package_ UnionBlock_profiles
Waverly Block 2D Profiles	2D	PA_package_ WaverlyBlock_profiles
Weeping Water Block 2D Profiles	2D	PA_package_ WeepingWaterBlock_profiles
LPSNRD Eagle, Elmwood, Union, Waverly and Weeping Water Blocks Block 3D Voxel Images, Fence Diagrams	3D	PA_package_ LPSNRDBlocks_voxel_fence

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 November 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 November 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. http://enwra.org/coop.html (accessed on November 9, 2017

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. http://enwra.org/aem2016.html (accessed on November 9, 2017)

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. http://enwra.org/coop.html (accessed on November 9, 2017)

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. (accessed on November 9, 2017)

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. (accessed on November 9, 2017)

AGF, 2017f, Hydrogeologic Framework of Selected Areas in Lower Platte North Natural Resources District, Prepared for the Lower Platte North Natural Resources District: by Aqua Geo Frameworks, LLC, Mitchell, Nebraska. (accessed on November 9, 2017)

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., Reed, E.C., Dreeszen, V.H. Prichard, G.E., 1975, Bedrock geologic map showing thickness of overlying Quaternary deposits, Fremont quadrangle and part of Omaha quadrangle,

Nebraska, U.S. Geological Survey, Miscellaneous Investigations Series, Map I-905. (accessed January 19, 2017). https://ngmdb.usgs.gov/Prodesc/proddesc_9797.htm (accessed on November 9, 2017)

Burchett, R.R., 1981, Regional Tectonics and Seismicity of Eastern Nebraska, Nebraska Geological Survey, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Nuclear Regulatory Commission CR-2132.

Burchett, R. R. 1982. Thickness and structure maps of the Pennsylvanian and Permian rocks across southern Nebraska. Nebraska Geological Survey Report of Investigations No. 7. Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. 15 p.

Burchett, R. R. 1983. Surface and subsurface correlation of Pennsylvanian and Lower Permian rocks across southern Nebraska. Nebraska Geological Survey Report of Investigations No. 8. Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. 24 p.

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). (accessed on November 9, 2017)

Carney, C.P., Abraham, J.D., Cannia, J.C., and Steele, G.V., 2015a, Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for Selected Sites in the Lower Elkhorn Natural Resources District: prepared for the Lower Elkhorn Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. (accessed on January 9, 2017). http://www.enwra.org/LENRD2014AEMDataDownload.html (accessed on November 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 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 November 9, 2017).

Carney, C.P., Abraham, J.D., Cannia, J.C., and Steele, G.V. 2015c. 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 November 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. (accessed on November 9, 2017)

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/2013SwedeburgFINAL.pdf (accessed November 9, 2017).

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), http://www.enwra.org/media/2013SwedeburgFINAL.pdf (accessed November 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.

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. http://www.enwra.org/media/Ashland_ENWRA_Bull_2_2012_small.pdf (accessed November 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 November 9, 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., 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). http://www.enwra.org/media/Firth_ENWRA_Bull_3_2013_small%20red.pdf (accessed November 9, 2017)

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.

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

LPSNRD, 1995. Ground Water Management Plan. Lower Platte South NRD, 68 p. plus appendices.

McGuire, V.L., Ryter, D.W., and Flynn, A.S., 2012, Altitude. Age, and Quality of Groundwater, Papio-Missouri River Natural Resources District, Eastern Nebraska, 1992-2009, U.S. Geological Survey, Scientific Investigations Report 2012-5036. https://pubs.er.usgs.gov/publication/sir20125036 (accessed on November 9, 2017).

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 November 9, 2017). .

Nebraska Conservation and Survey Division, 1995. Configuration of the water table in 1995. Institute of Agriculture & Natural Resources, University of Nebraska-Lincoln. https://cohyst.nebraska.gov/cohyst_preliminarydata.html.

Nebraska Conservation and Survey Division, 2009. Till Map of Nebraska. Institute of Agriculture & Natural Resources, University of Nebraska-Lincoln. (accessed November 9,2017) http://snr.unl.edu/data/geographygis/geology.aspx

Nebraska Department of Natural Resources (NEDNR), 2016a, National Hydrographic Dataset, http://www.dnr.ne.gov/surface-water-data (accessed November 9,2017).

Nebraska Department of Natural Resources. 2016b. Registered Groundwater Wells Data Retrieval. http://dnr.ne.gov/gwr/groundwaterwelldata (accessed November 9,2017)

Nebraska Department of Natural Resources, 2016c, National Hydrographic Dataset http://www.dnr.ne.gov/surface-water-data (accessed November 9, 2017)

O'Connor, T.M. 1987. A Preliminary Study of the Hydrogeology of the Dakota Formation in Douglas, Sarpy and Washington Counties, Eastern Nebraska. M.S. Thesis, Department of Geology, University of Nebraska.

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.).

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/tem-systems/ (accessed November 9, 2017)

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. https://pubs.usgs.gov/of/2010/1288/ (accessed November 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 November 9, 2017)

United States Department of Agriculture, 2014. USDA Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/oh/technical/dma/gis/?cid=nrcs144p2_029530 (accessed November 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.aspx (accessed November 9, 2017).

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

U.S. Geological Survey, 2015, USGS surface-water data for Nebraska. http://waterdata.usgs.gov/ne/nwis/sw/ (accessed November 9, 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 November 9, 2017)

U.S. Geological Survey, National Water Information System, 2017a. Accessed November 9, 2017 https://waterdata.usgs.gov/nwis

U.S. Geological Survey, 2017b, USGS groundwater quality data for Lancaster and Cass counties, Nebraska.

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