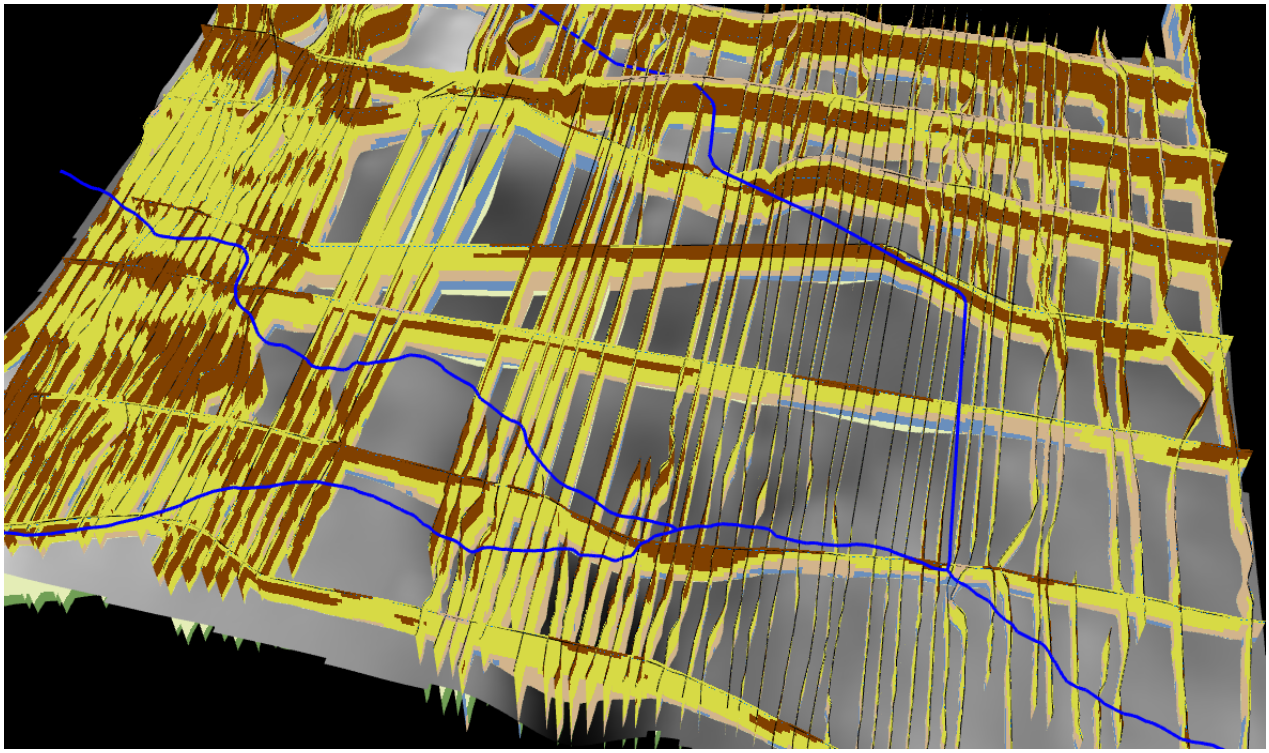
Hydrogeologic Framework of Selected Areas in Lower Loup Natural Resources District, Nebraska



***Prepared for*:**

Lower Loup Natural Resources District

2620 Airport Rd
Ord, Nebraska 68862

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Aqua Geo Frameworks, LLC.

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Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled "*Hydrogeologic Framework of Selected Areas in the Lower Loup 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 Loup Natural Resources District (LLNRD) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the LLNRD project Area 28 as well as the Columbus survey area and to recommend future work to enhance groundwater management activities.

The scope of work for this project was as follows:

1. SCOPE OF WORK

1.1 An AEM survey utilizing the SkyTEM304M system was flown over the LLNRD Area including around Columbus and west in Area 28. These flights have been provided as preliminary AEM inversions on July 16-20, 2016 and the final AEM data and inversions are included as a product attached to this data report.

1.2 AGF began project planning upon signing of the project between the parties. This work included flight plans, database development, and review of hydrogeologic and geologic work for the area. The LLNRD assisted in providing information such as power line maps, a test hole database, and related aquifer characteristic studies to AGF including 2016 water table elevation data.

Upon conclusion of the design process, the LLNRD Area 28 reconnaissance flight lines were approximately 38 miles in length (east-west) and 7 miles (north-south) and were separated by approximately 1 mile in both east-west and north-south directions. The Columbus Block flight lines were approximately 9 miles in length and were separated by about 0.12 miles (634 feet).

1.4 AGF acquired AEM data over the LLNRD, commencing 14 July 2016 and finishing on 18 July 2016, to support development of the hydrogeological framework. Approximately 666 line-miles (1,078 line-kilometers) were acquired over the LLNRD AEM survey area. Status reports of the flying were provided to the Contract Representative of LLNRD on a daily basis, including the areas flown, production rates, and flight plan for the following day.

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

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

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

2. KEY FINDINGS

2.1 **Boreholes** - Information from boreholes was used to analyze the AEM inversion results. These included CSD (Within the LLNRD, 51 CSD holes contained lithology information, 45 holes contained stratigraphic information, and 5 holes contained geophysical information) and NE-DNR (A total of 2,414 registered wells contained usable lithology information) boreholes.

2.2 **Merging 2014 and 2016 AEM Databases** - The LLNRD survey area encompassed an additional 12.2 line-miles of AEM data collected in 2014 by the LENRD and the ENWRA. The 2014 AEM data contains valuable information that can be utilized in the interpretation of the larger LLNRD AEM survey area. The 2014 AEM data was combined with the 2016 AEM data. This combination did not include reinverting the 2014 data, but included merging the 2014 inversions into the current database and reinterpretation.

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

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

2.5 **Hydrogeological Framework of the LLNRD** - The AEM reveals considerable variability in the Quaternary and Tertiary deposits across the LLNRD. The subsurface distribution of materials can be generally characterized into in two parts. These areas include the Quaternary Aquifer Area and the Cretaceous bedrock aquiclude. The ***Q*** aquifer of the LLNRD AEM survey area is predominantly composed of Quaternary unconsolidated aquifer and coarse aquifer materials composed of alluvial sediments. These materials are sitting on varying thickness of ***Kn*** and ***Kc*** which is the bedrock aquiclude for the area.

2.6 **Hydrogeological Framework of the Columbus AEM Block Survey Area** - The Columbus Block AEM flight area is within the Quaternary Aquifer system. The area is composed of mostly aquifer materials lying on the ***Kc*** bedrock surface. The bedrock is eroded and has two channels cut into it. The main channel trends from west to east in the center of the block and the second channel trends from the center of the block to the south. The channels are flanked by three bedrock highs that are in the block area which have an increased relief of up to 80 feet in elevation. The area is dominated by aquifer materials and coarse aquifer materials and a high water table with

good aquifer properties. The thicker sequences of aquifer to coarse aquifer materials lie to the north and center of the block with marginal and non-aquifer materials lying basal in nature.

2.7 Estimation of Aquifer Volume and Water in Storage in the Columbus Block - The non-aquifer material has an estimated volume of 597,836 acre-ft and contains 239,134 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 1,276,259 acre-ft and contains 446,691 acre-ft, aquifer material has an estimated volume of 2,586,263 acre-ft and contains an estimated volume of 517,253 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 1,270,318 acre-ft for a total of 317,580 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 1,520,657 acre-ft. Non-aquifer materials in the Columbus Block AEM survey area will yield approximately 4,783 acre-ft, marginal aquifer materials will yield approximately 22,335 acre-ft, aquifer materials will yield 77,588 acre-ft, and the coarse aquifer material will yield approximately 47,637 acre-ft. A total of 125,225 acre-ft is available from the combined aquifer and coarse aquifer materials.

2.8 Potential Recharge Zones within the Area 28 Reconnaissance Survey Area - Each LLNRD AEM flight line was interpreted for aquifer material in the first model layer (0 – 10 ft). Areas of coarse aquifer material will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material potentially transmitting slightly less precipitation downward as both units are permeable. The marginal aquifer material has the lowest potential to transmit some water downward and the non-aquifer material will transmit minimal to no water to the groundwater aquifer. The use of widely-spaced reconnaissance lines (approximately 1 mile apart) in the Area 28 AEM survey illustrates patterns or areas where the potential for recharge can be high and low. Locations where the flight lines intersect and both lines show either aquifer or coarse aquifer material should be considered as higher likelihood for recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true where two flight lines intersect and both lines show non-aquifer or marginal material, those areas will likely not be optimal recharge locations.

2.9 Potential Recharge Zones within the Columbus Block AEM Survey Area - The closely spaced flight lines (0.11 mile (about 175 m)) within the Columbus Block survey area allowed for nearly continuous mapping of the different aquifer material types in the first model layer, 0 to 10 ft. There is heterogeneity in the aquifer materials but it is quite easy to identify the areas of aquifer materials that will transmit the most, and the least, amounts of water from the surface down to the groundwater system.

3. Recommendations

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

3.1 **Additional AEM Mapping** - The aquifer maps provided in this report represent the detailed framework developed for the Columbus Block Area and at a reconnaissance level for Area 28. The detail provided in the hydrogeological interpretation of the Columbus Block Area allowed for confident development of hydrogeologic framework. The interpretations match well with the CSD and NE-DNR test holes. No additional high resolution AEM information is needed within Columbus Block Area to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or "block flights" be collected to develop detailed frameworks in other areas.

Area 28 and the surrounding area should be mapped in detail by block flights to provide information on the hydrogeologic framework and the recharge areas. This would potentially be done in cooperation with the neighboring NRDs to get details to the continuous aquifer system that is shared in the area. The line spacing for the block flights should be on the order of 0.25 mile (1,320 ft).

For example, the detailed hydrogeologic frameworks presented in this report have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield. It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of eastern LLNRD. This will supply the LLNRD with information on groundwater flow, aquifer sustainability, and depletion to streams, well interference, groundwater withdrawal, and other management considerations.

Reconnaissance flight lines expanding out from Area 28 to the west and north will help the district understand the hydrogeologic framework adjacent to Area 28. This will focus the ongoing water quality work to the adjacent areas to determine if additional management is needed. It will also provide locations for new monitoring wells and water level locations.

3.2 **Update the Water Table map** - The groundwater data used in the analyses presented in this report use the 2016 water table map. Additional water level measurement locations would improve the water table map. This is especially true on the north and west side of Columbus side of the AEM survey area. The transition from the flood plain to areas out of the flood plain would be a good addition to the network.

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

sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in optimal locations.

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

3.4 **Aquifer testing and borehole logging** - Aquifer tests are recommended to improve estimates of aquifer characteristics. Limited aquifer properties from previous reports were available outside the larger cities in the survey area. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. The few test holes with geophysical logs LLNRD survey area were inadequate. None were calibrated and several had apparent hardware malfunctions. The borehole geophysical logs provided for this investigation demonstrate that additional calibrated and verified geophysical logs are required in the LLNRD.

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 LLNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. The block flights of AEM data acquisition provide the most detailed information for understanding recharge throughout the Columbus Block area. It is recommended that additional AEM data be collected and interpreted utilizing closely-spaced flight lines using an AEM system that has near-surface resolution. It is further recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

3.6 **Managed Aquifer Recharge**- The area which lies out of the flood plain on the north side of Columbus may have potential for managed aquifer recharge. Detailed analysis for this purpose would need to be done to determine if this is a viable opportunity for the LLNRD. Additional AEM mapping along the streams in the LLNRD would also locate similar locations. A detailed plan for locating and developing Managed Aquifer Recharge sites would be beneficial to the LLNRD for providing storage and release of water for stream flow and other uses.

4. Deliverables

In summary, the following are included as deliverables:

- Raw EM Mag data 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 Area 28 Reconnaissance survey lines
- 3D voxel models as ASCII *.xyz and *.gdb for the Columbus flight block

KMZs for LLNRD Columbus and Area 28 Reconnaissance flight lines

Profile Analyst sessions for the Profiles and 3D grids for Columbus Block and Area 28 Reconnaissance data analysis.

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List of Abbreviations

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
$A*m^2$	Ampere meter squared
AEM	Airborne Electromagnetic
AGF	Aqua Geo Frameworks, LLC
Bgl/Bgs	Below Ground Level/Below Ground Surface
dB/dt	Change in amplitude of magnetic field with time
CSD	Conservation and Survey Division
DEM	Digital Elevation Model
DOI	Depth of Investigation
DGPS	Differential global positioning system
em, EM	Electromagnetic
ENWRA	Eastern Nebraska Water Resources Assessment
ft	Feet
Fm	Formation
GIS	Geographic Information System
gpm	Gallons per minute
HEM	Helicopter Electromagnetic
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
Km/km	Kilometers
KMZ/kmz	Keyhole Markup language Zipped file
Kc	Cretaceous Carlile Fm
Kd	Cretaceous Dakota Group
Kgg	Cretaceous Greenhorn/Graneros Fm
Kn	Cretaceous Niobrara Fm
Kp	Cretaceous Pierre Fm
LENRD	Lower Elkhorn Natural Resources District
LLNRD	Lower Loup Natural Resources District
MAG	Magnetic (data); Magnetometer (instrument)
MCG	Minimum curvature gridding
m	Meters
mg/L	Milligrams per liter
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NE-DEQ	Nebraska Department of Environmental Quality
NE-DNR	Nebraska Department of Natural Resources
NMR	Nuclear Magnetic Resonance
NOGCC	Nebraska Oil and Gas Conservation Commission
NRD	Natural Resources Districts
OA	Olsson Associates
OM	Geosoft Oasis montaj
PFC	Primary Field Compensation
PLNI	Power Line Noise Intensity
Q	Quaternary

Rx	Receiver
SCI	Spatially-Constrained Inversion
STD	Standard Deviation
To	Tertiary Ogallala Group
TEM	Transient 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
V/m^2	Volts per meter squared
XRI	Exploration Resources International

1 Introduction

1.1 Purpose of Current Project

The Lower Loup Natural Resources District (LLNRD) desired an improved understanding of the hydrogeologic framework in the LLNRD within the Columbus area to support continued development of the Columbus Area Water Resource Assessment (Figure 1-1). It also wished to have detailed information on the subsurface geology to assist in understanding the groundwater quality problems in Area 28, the area to the west of Columbus. An Airborne Electromagnetic (AEM) survey was selected to assist in the development of a 3D hydrogeologic framework of these project areas and recommend future work to enhance groundwater management activities (Figure 1-2).

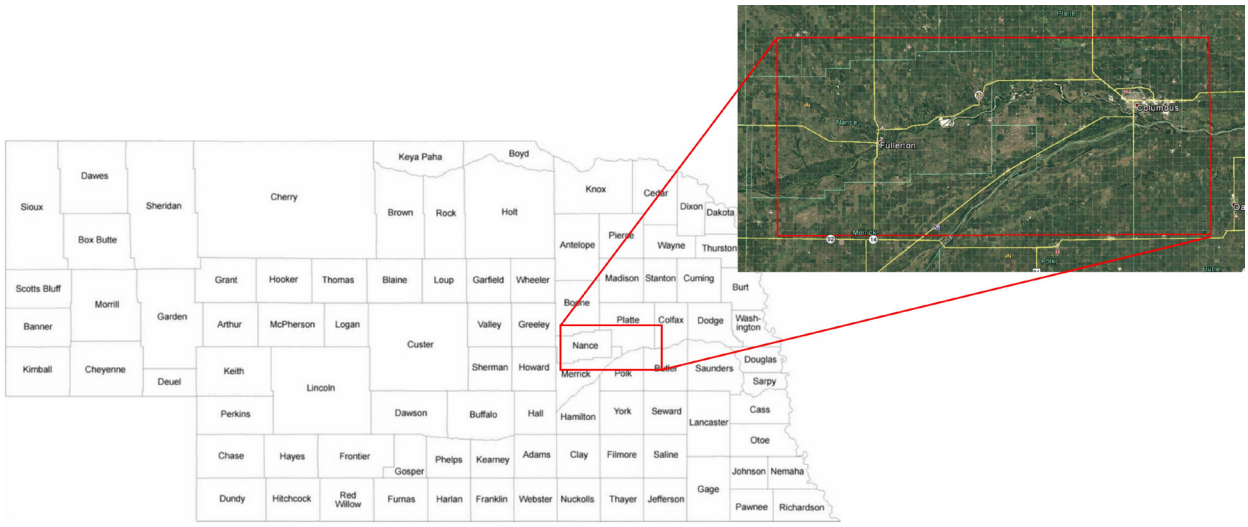


Figure 1-1. Map of Nebraska counties, indicating the location of the Lower Loup Natural Resources District (LLNRD) airborne electromagnetic (AEM) survey with an inset of the project area.

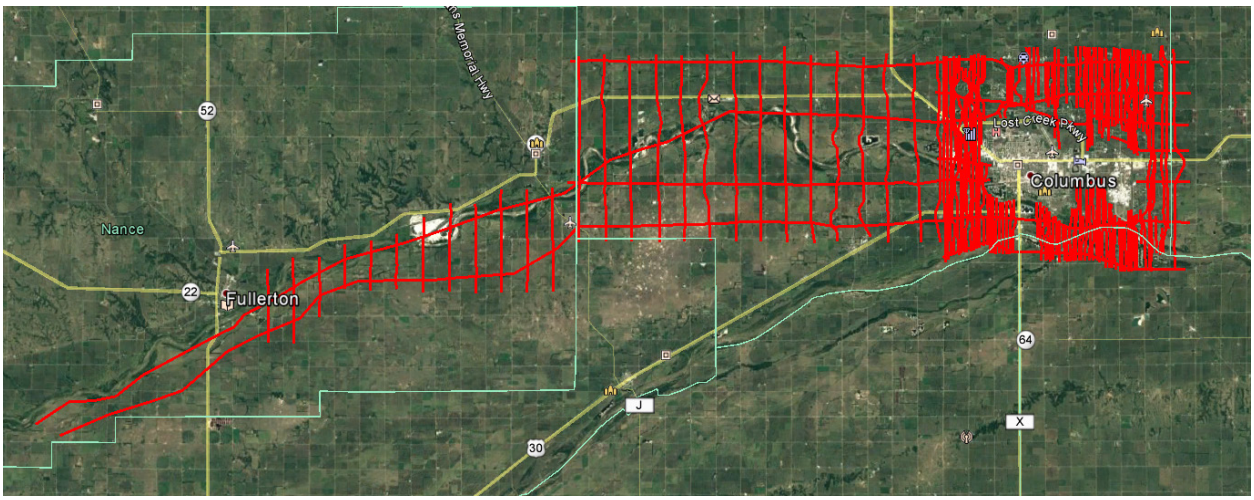


Figure 1-2. The LLNRD AEM survey area including county lines and major roads (NE 30, 22, 64). The LLNRD Reconnaissance survey area is on the left with the widely spaced lines and the Columbus Block flight area is on the right where the flight lines are very close.

1.2 Background

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

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

The ENWRA project was formed in 2006 with sponsors from six NRDs (Lewis and Clark, Lower Elkhorn, Papio-Missouri River, Lower Platte North, Lower Platte South, and Nemaha) and cooperating agencies including the CSD and the USGS. The long-term goal of the project is to develop a geologic framework and water budget for the glaciated portion of eastern Nebraska. In March 2007, ENWRA funded a study where AEM methods were implemented by the USGS to characterize the hydrogeologic conditions in the Platte River valley near Ashland, as well as in areas underlain by glacial till near Firth and Oakland, Nebraska (Abraham et al., 2011; Hanson et al., 2012; Korus et al., 2013). In the following years, individual reports utilizing the AEM data collected in 2007 were released by the USGS and CSD. In 2009, a multi-faceted investigation incorporating the 2007 AEM data and 2009 ground-based geophysical techniques was conducted by the USGS to characterize the hydrogeologic setting near Oakland, Nebraska (Abraham et al., 2011). In 2009, the Lower Platte North NRD funded the USGS for the development of a 3D hydrostratigraphic framework of the subsurface near Swedeburg, Nebraska based on an AEM survey (Smith et al., 2009; Divine and Korus, 2013). Also in 2009, the Lower Platte South NRD funded the USGS and CSD for a similar investigation of the hydrostratigraphy near Sprague, Nebraska (Smith et al., 2009; Divine and Korus, 2012). 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 extensive, buried

paleovalley aquifers beneath thick sequences of 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 (Exploration Resources International, 2015). In 2014-2015 the ENWRA funded XRI for a large-scale reconnaissance AEM survey over the glaciated portion of Nebraska, approximately 2,200 line-km of approximately 32 km spaced lines (Abraham et al., 2015; Carney et al., 2015a; Carney et al., 2015b). In 2016, a study led by the CSD showed that the details gained from the AEM survey in around the Firth and Sprague area provided unique details that assisted in the management of the groundwater resources (Korus et al., 2016). In 2017, A study led by AGF provided information to improve the understanding of the hydrogeologic framework including areas of recharge to the aquifer and details for well head protection areas in the Bazile Creek Groundwater Management area (AGF, 2017a). Additionally, in 2017 another study led by AGF provided detailed 3D hydrogeologic framework for the western portions of Sarpy County characterized by eroded Dakota Sandstone aquifers overlain with glacial deposits (AGF, 2017b). Thus, AEM surveys of the glacial terrain of Nebraska have followed a progressive, long-term plan spanning nearly 10 years. This body of work shows continuing advancements in the science and application of AEM to support groundwater management.

In addition to the AEM and Magnetic Total Field data acquired during this investigation, multiple resources were used to develop the presented hydrogeologic framework and subsequent recommendations for potential recharge areas and well locations. Data and findings from previous studies, along with geologic descriptions and geophysical data were utilized to develop the hydrogeologic framework presented herein. A location map showing the LLNRD survey flight areas and flight lines is presented in Figure 1-4. A Google Earth kmz of the “as-flown” flight lines is included in Appendix 3/KMZ.

1.3 Description of the LLNRD AEM Project Area

The two areas of interest, the Columbus block and Area 28, in the LLNRD AEM survey area, are located in east-central Nebraska and encompass approximately 134 and 291 square miles, respectively (Figure 1-2). These areas lie within parts of six counties: Butler. Colfax, Merrick, Nance, Platte and Polk. Precipitation and irrigation runoff within the Columbus block and Area 28 feed into three major river basins (NEDNR, 2016c): the Loup, the Lower Platte, and the Middle Platte (Figure 1-3 and Figure 1-4) and the area sits in distinct groundwater regions; namely, the East Central Dissected Plains, the Platte River Valley, and the Nebraska Glacial Drift (Pederson et al., 1986). The towns of Columbus, Fullerton, Genoa, and Monroe lie within the LLNRD AEM survey area. The entire LLNRD is under Phase 1 water quality controls for nitrogen management and the Area 28 survey area is under Phase III water quality controls for nitrogen management.

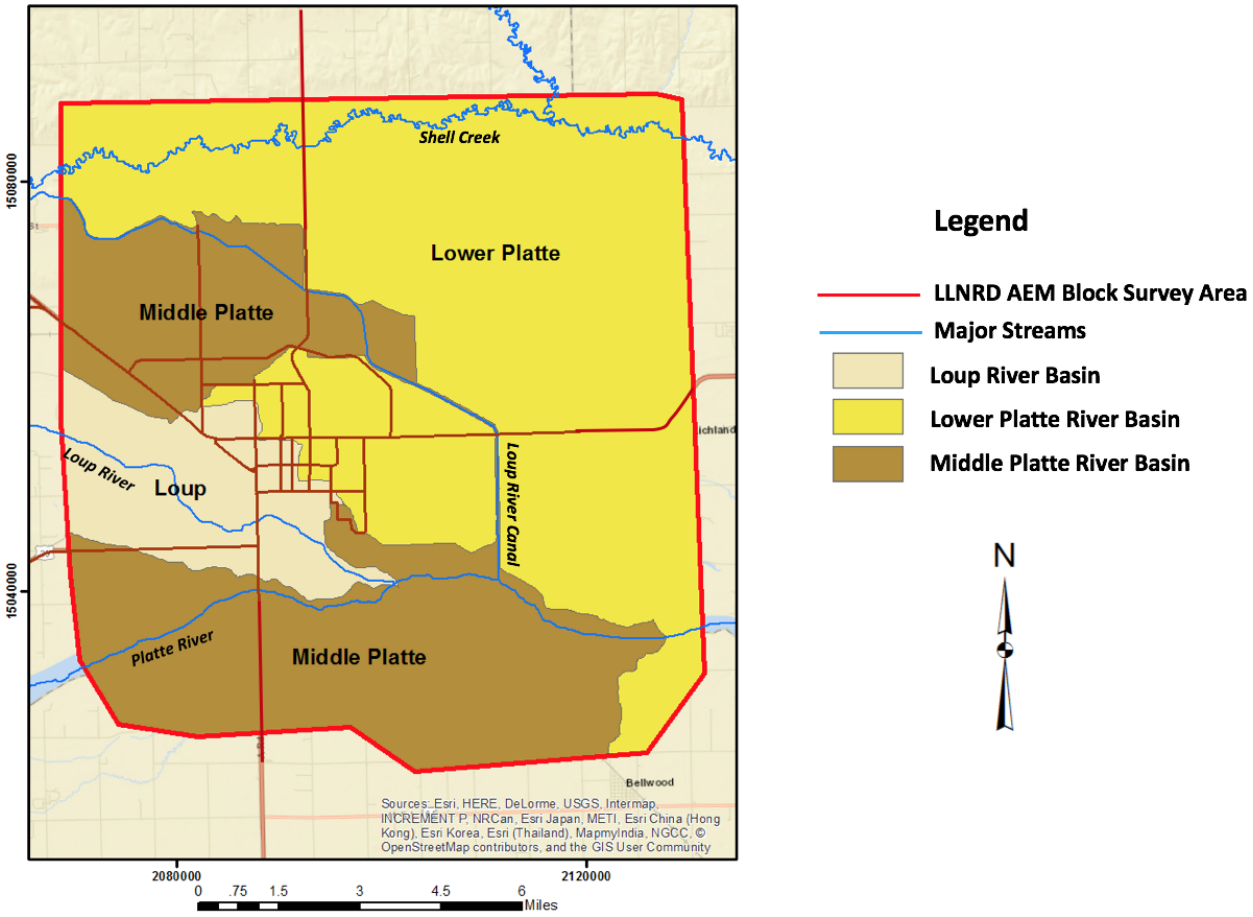


Figure 1-3: Map of major river basins within the Columbus Block AEM survey area (NE-DNR, 2016c).

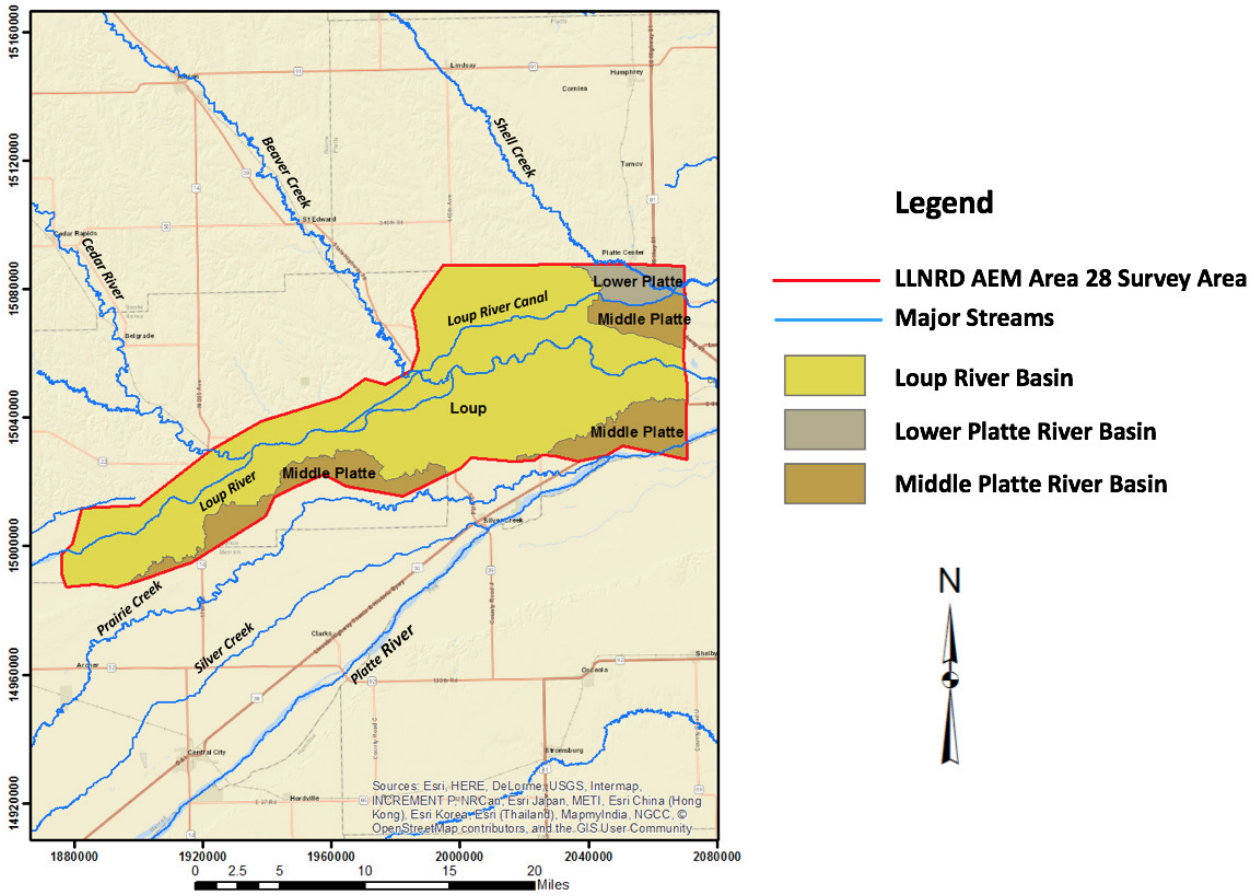


Figure 1-4: Map of major river basins within the LLNRD Area 28 AEM survey area (NE-DNR, 2016c).

2 Project Area Hydrogeology

2.1 Geologic Setting

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

2.1.1 Physiography and Regional Geologic Setting

The project area is in east-central Nebraska near the towns of Fullerton and Columbus within the Valleys, Sand Hills, Dissected Plains, Plains, and Rolling Hills topographic regions of Nebraska (Conservation and Survey Division, University of Nebraska-Lincoln, 1951). Bedrock geology in the project area is comprised of consolidated marine and consolidated to unconsolidated non-marine sedimentary rocks as presented in Figure 2-1 (from Burchett, 1986). These deposits are not deformed by folding and faulting. The Quaternary (***Q***) sediments are made up alluvial materials in the west and glacial deposits, located in the northeast, containing aquifer materials.

2.1.2 Surficial Geology

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

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

Three historic CSD geologic cross sections (from Divine (2012), Divine et al. (2010), and Korus et al. (2012)) are available for the LLNRD AEM survey area and will be used in comparison to the interpreted AEM results. The three geologic cross sections are: Platte 2004WW1604W, Platte 2003W1602W, and Platte 2001W1701W. The comparisons are made in figures 5-22, 5-23, and 5-24 in this report.

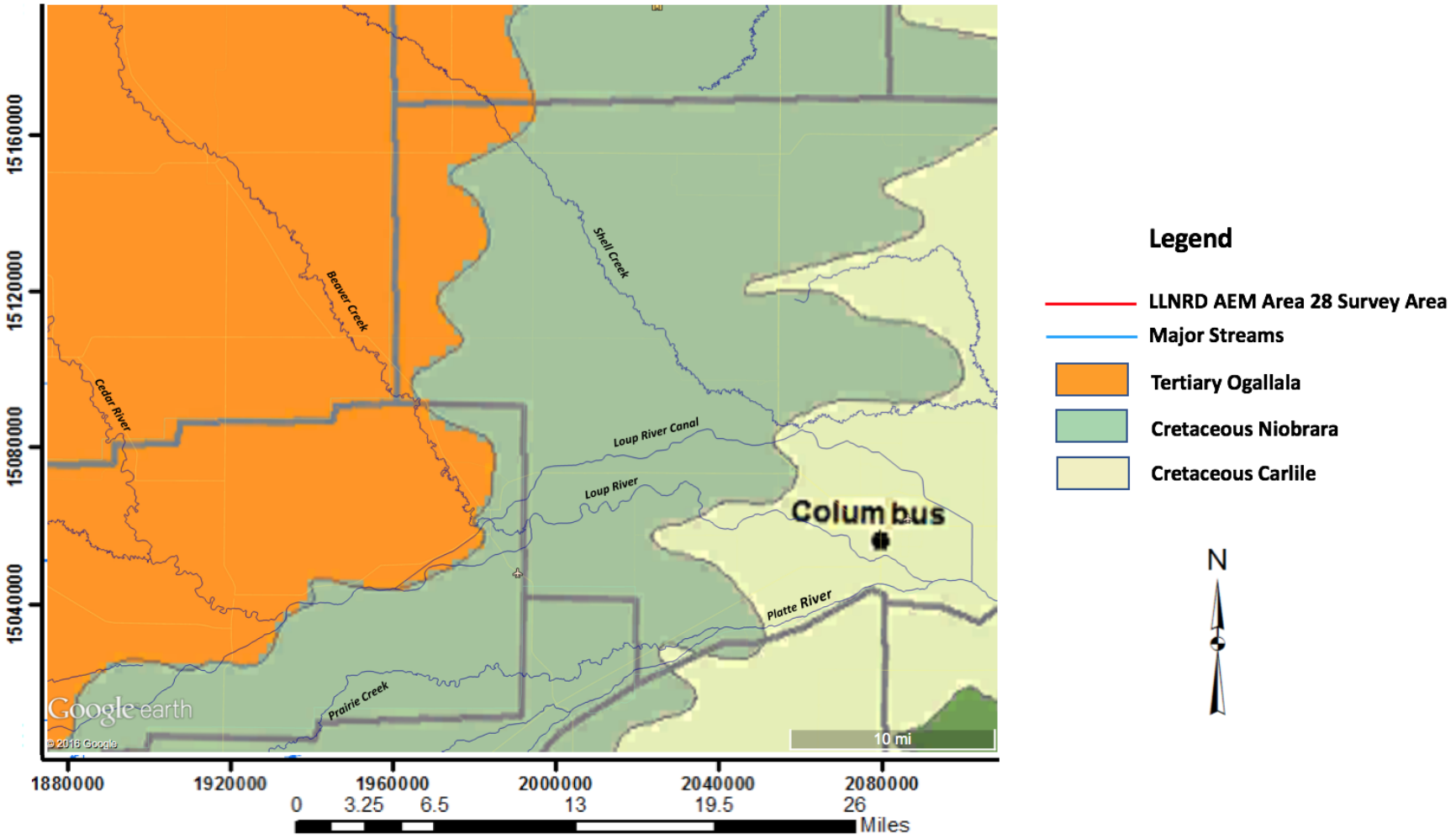


Figure 2-1. Bedrock map of the area west of Columbus, modified from Burchett (1986).

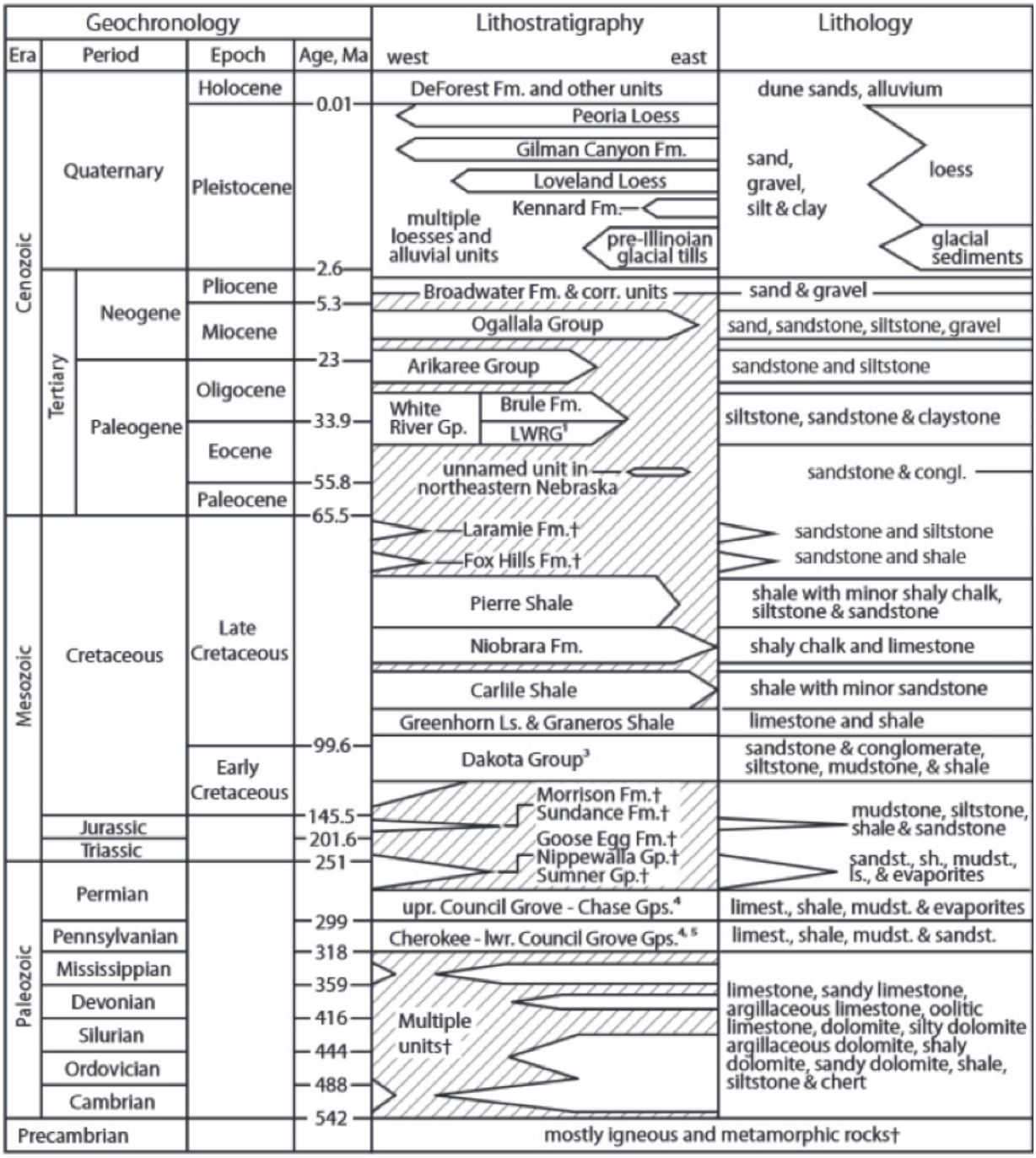


Figure 2-2. Geologic time scale with lithostratigraphic sequence underlying Nebraska, modified from Korus and Joeckel (2011).

2.1.3 Tertiary Geology

The Tertiary deposits near the northwest-west part of project area are Miocene Ogallala Group (***To***). The ***To*** predominantly is fluvial material comprised of unconsolidated to consolidated, irregularly distributed beds of silt, clay, sand, and gravel (Souders, 2000). Some members of the ***To*** contain partially cemented friable sands or sandstone (Condra and Reed, 1959). The ***To*** thins and pinches out near the town of Fullerton and rests unconformably on underlying Cretaceous strata (Burchett, 1986). Where present, the ***To*** is thin and is on the northwest boundary of Area 28 (Figure 2-1). The ***To*** can serve as an aquifer where it is saturated.

2.1.4 Cretaceous Geology

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

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

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

Maps showing the major streams and rivers with the associated basin areas within the LLNRD AEM survey area are shown in Figure 2-3 and Figure 2-4. The Columbus AEM Block Area and associated major streams tributaries and canals along with surface water basins that exist between the Loup, Middle Platte, and Lower Platte rivers are presented in Figure 2-3 (NE-DNR, 2016c). Area 28 and the associated major streams tributaries and canals along with surface water basins that exist between the Loup, Middle Platte, and Lower Platte rivers are presented in Figure -2-4 (NE-DNR, 2016c). The largest surface-water systems in the project area are the Platte and Loup rivers (U.S. Geological Survey, 2015) which flow west to east to their confluence near Columbus, NE.

The overall elevation of the water table within the project area is shown in Figure 2-5 for the Columbus Block and Figure 2-6 for Area 28. The water table maps are from the 2016 LLNRD water table map (personal communication, Tyler Naprstek Lower Loup Natural Resources District. 2017, Water table map of the District 2016) and represent the general shape of the water table as 10 foot contours of elevation; actual water levels will likely be somewhat different.

Regional groundwater-flow direction for the project area is predominately from west to east (Figure 2-5 and Figure 2-6). The direction is similar to the course of the major streams and rivers. Groundwater locally is hydrologically connected to surface water and groundwater levels are located at shallower depths in the alluvial valleys and at deeper depths below the uplands. Water levels change with the seasons and typically reach maximum depths from extensive groundwater pumping and usage during the crop growing months. Groundwater levels typically return to shallower, pre-stress levels in the March to June timeframe. Annual depths of drawdown and recharge of aquifers highly depend on the type of aquifer (e.g. confined or unconfined), proximity of the aquifer to the land surface, and the magnitude of stress exhibited on the system during the pumping season, combined with the amount of recharge available to the aquifer.

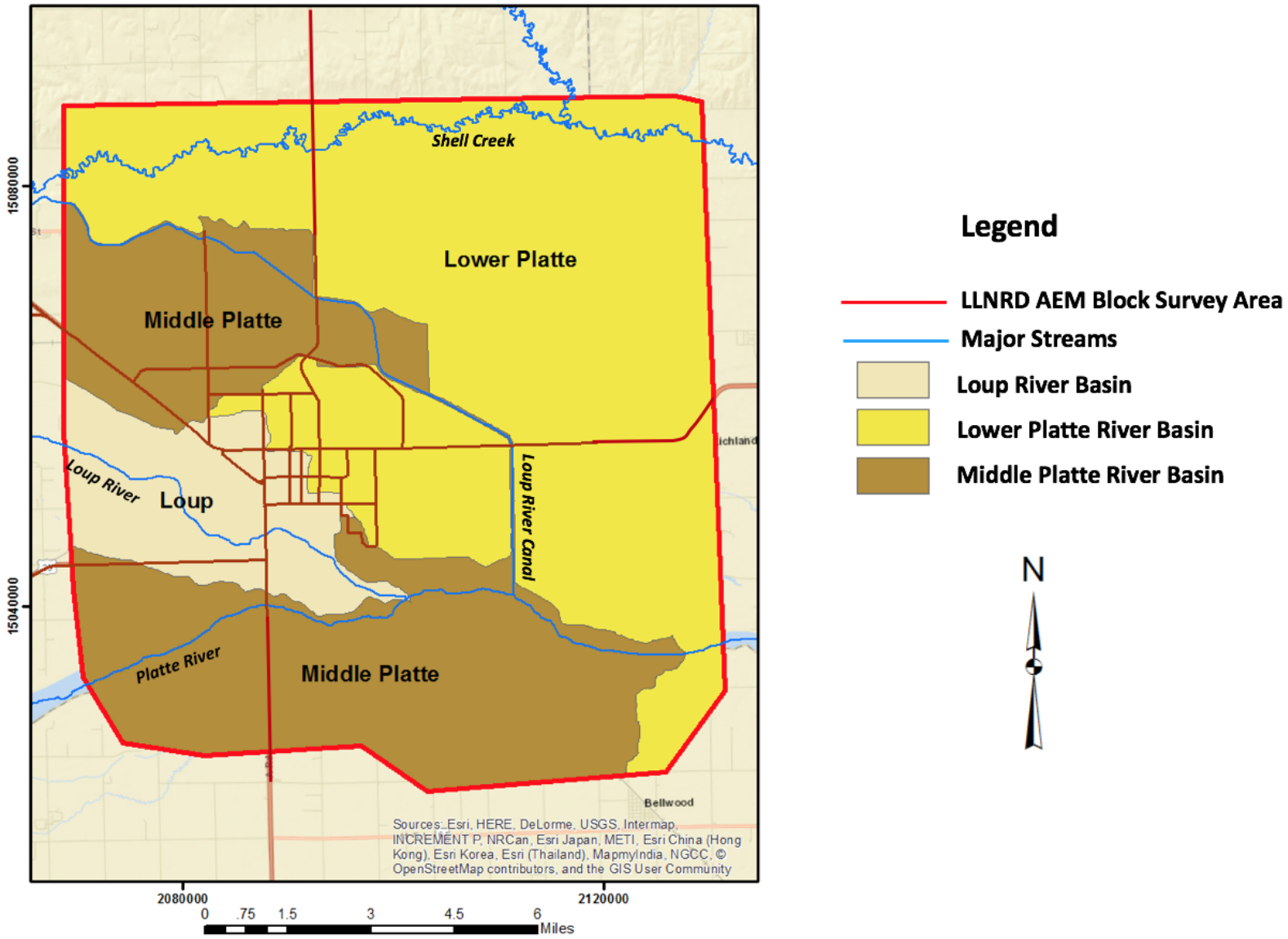


Figure 2-3. Map displaying the major streams and rivers within the LLNRD AEM survey area (NE-DNR, 2016c). The surface water divide is also shown separating drainages flowing to the Missouri and Elkhorn Rivers.

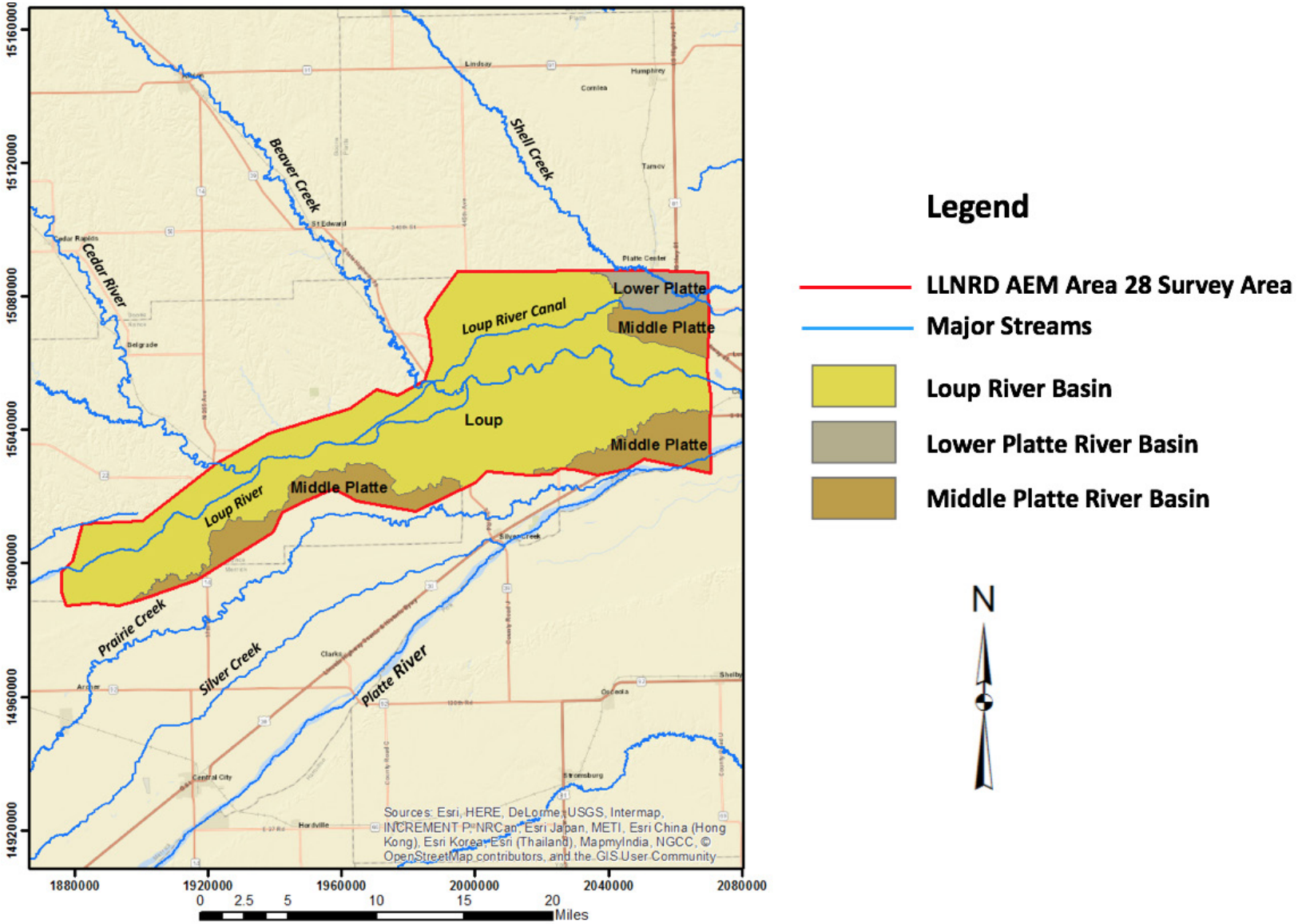


Figure 2-4. Map displaying the major streams and rivers within the LLNRD AEM survey area (NE-DNR, 2016c). The surface water divide is also shown separating drainages flowing to the Missouri and Elkhorn Rivers.

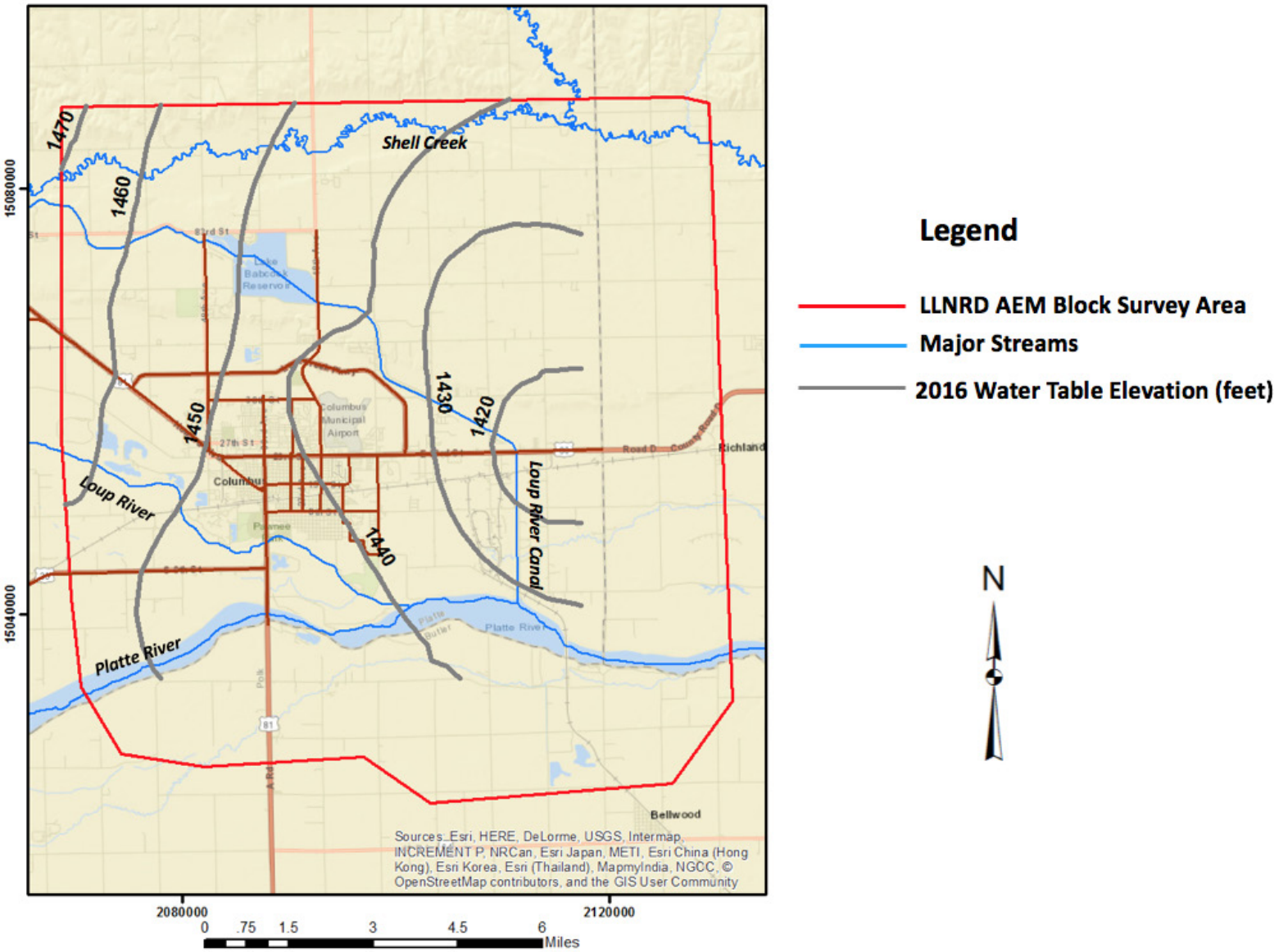


Figure 2-5. Elevation of ground water surface in the Columbus Block AEM survey area (personal communication, Tyler Naprstek Lower Loup Natural Resources District. 2017, Water table map of the District 2016).

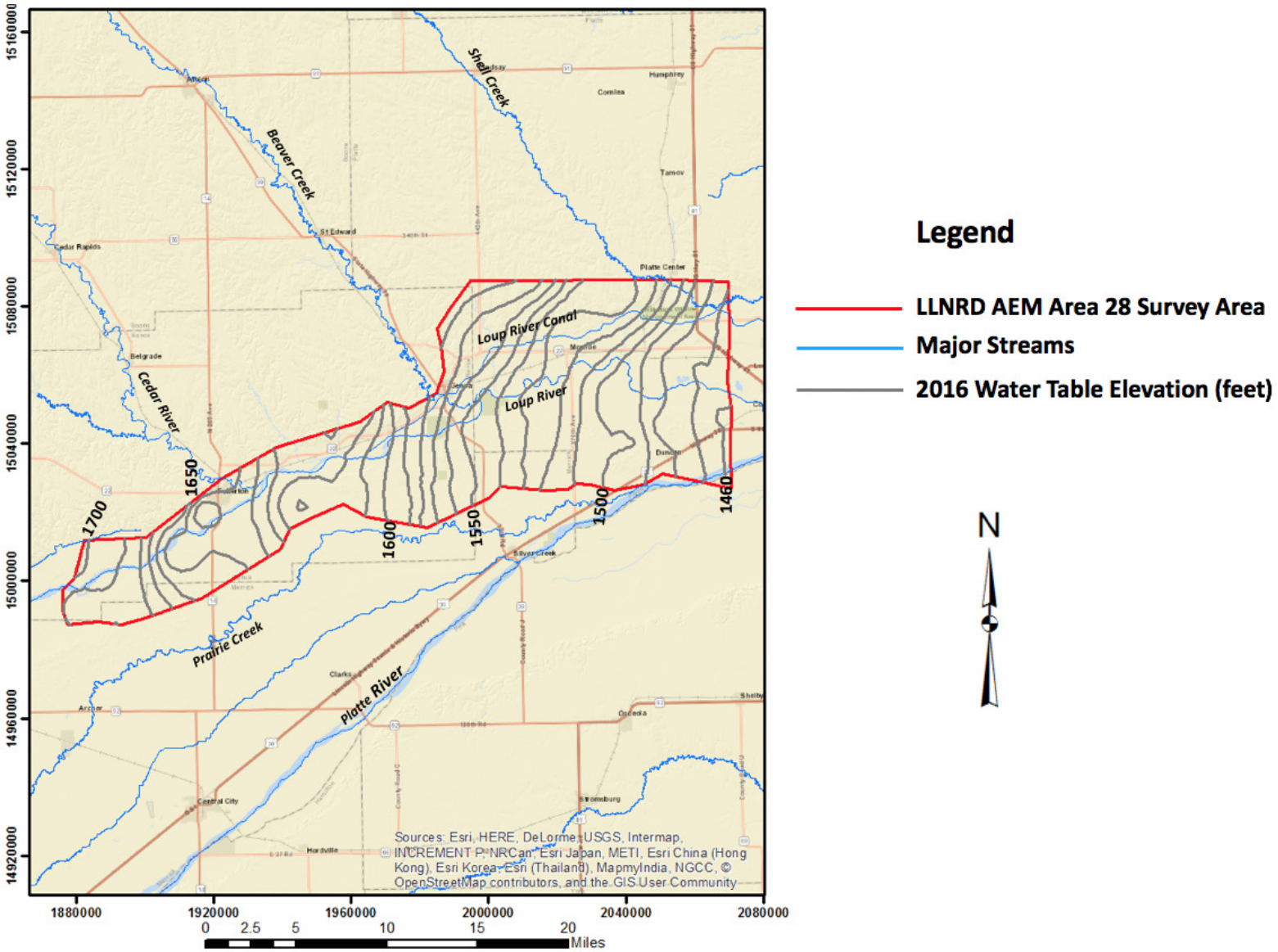


Figure 2-6. Elevation of ground water surface in Area 28 ((personal communication, Tyler Naprstek Lower Loup Natural Resources District. 2017, Water table map of the District 2016)).

Groundwater can be confined in aquifers near or beneath glacial till (Figure 2-7 and Figure 2-8), and typically exhibits more drawdown than groundwater in unconfined systems that are present in alluvial settings. The groundwater system for the LLNRD AEM survey area is generally under unconfined conditions.

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

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

The ***To*** is generally thin to absent in the western regions of the project area.

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

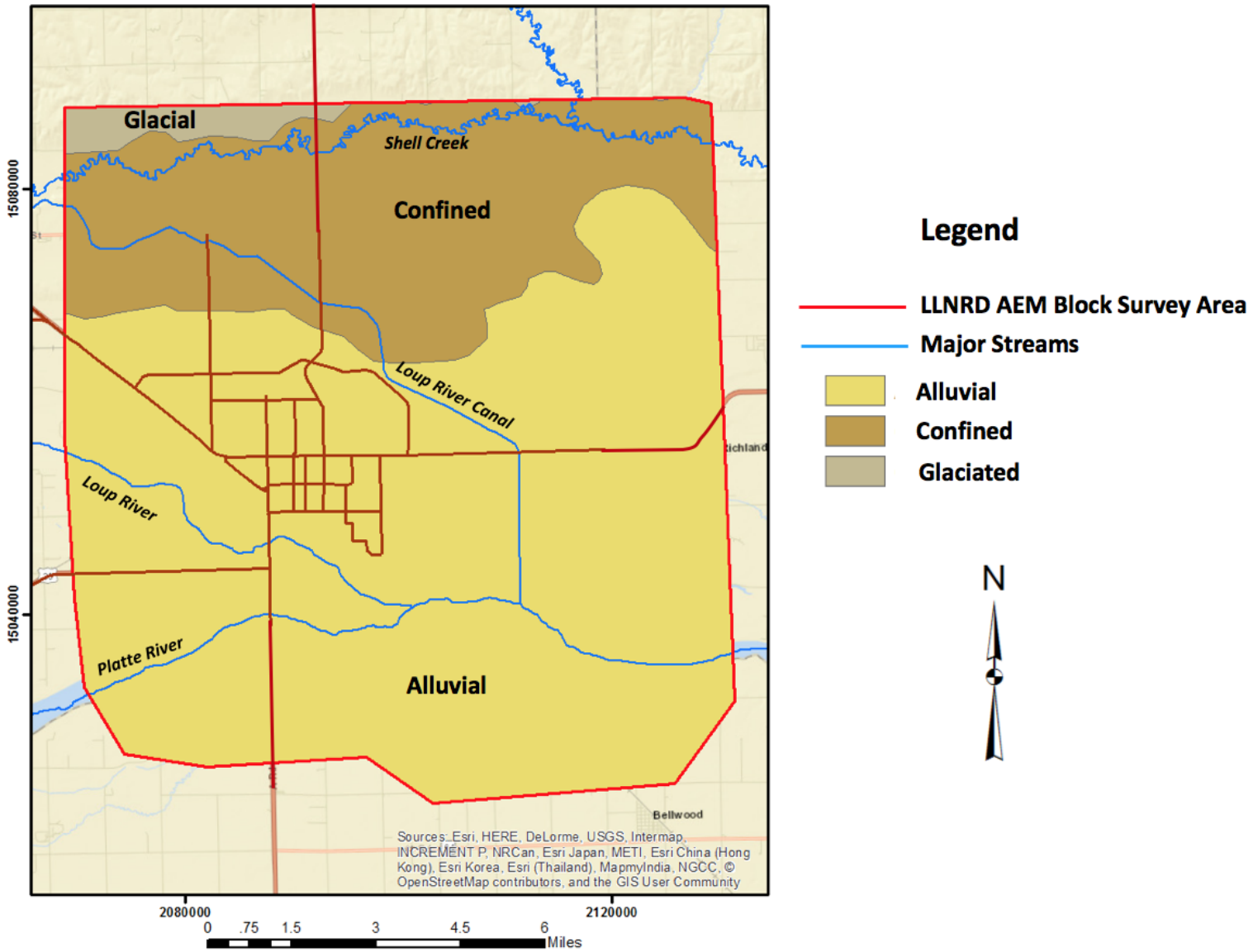


Figure 2-7. Generalized hydrogeologic areas within the Columbus Block Area (Olafsen-Lackey et al., 2005a; Summerside et al., 2005a). These maps show generalized hydrologic connections to the streams and rivers.

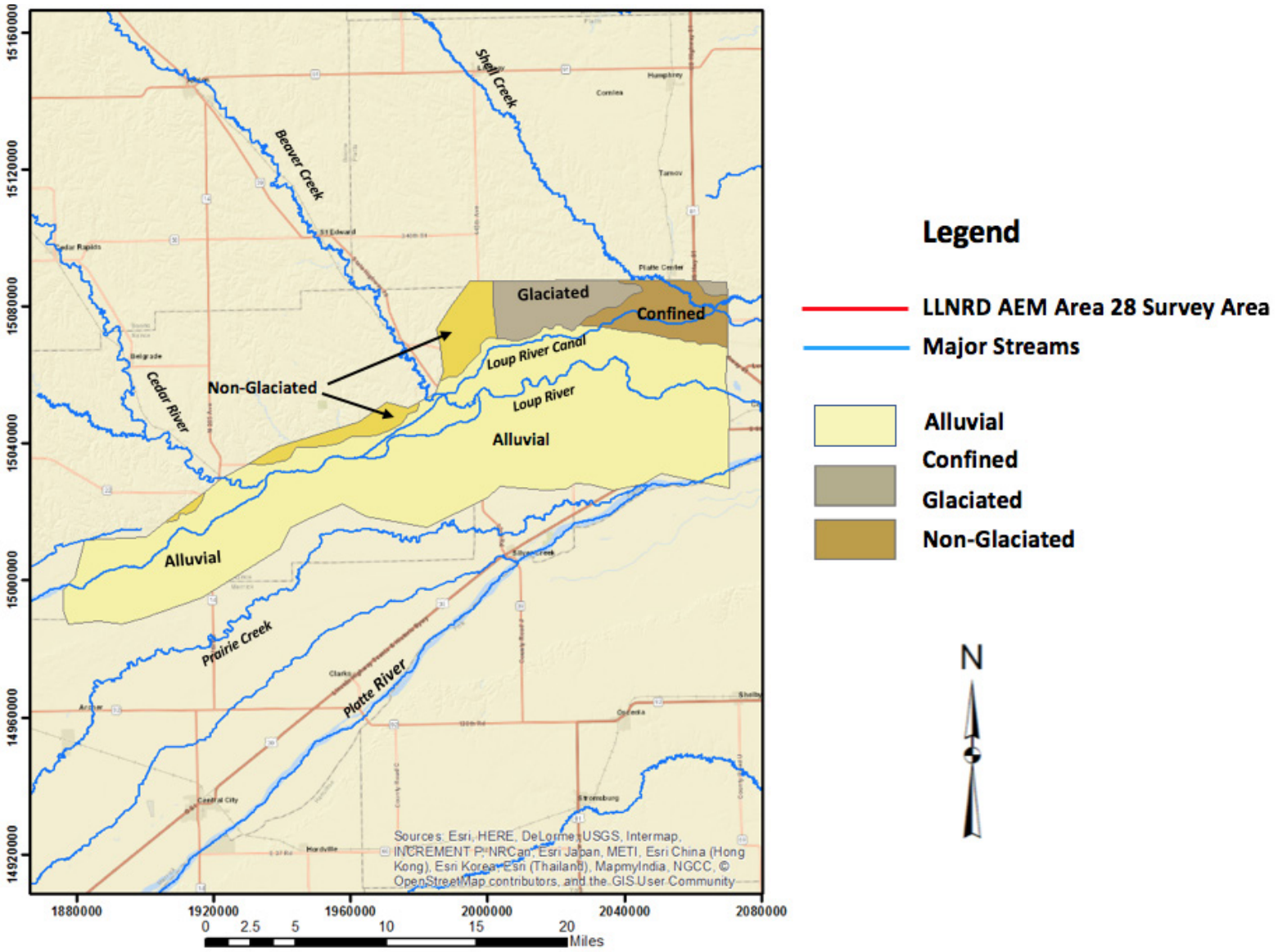


Figure 2-8. Generalized hydrogeologic areas within Area 28 (Olafsen-Lackey et al., 2005a; Summerside et al., 2005a). These maps show generalized hydrologic connections to the streams and rivers.

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

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

2.2.1 Soil Characteristics in the LLNRD AEM Survey Area

The soils within the LLNRD AEM survey area, in particular Nance and Platte Counties, are well described by Loerch et al. (1988) and Willard et al. (1960). The soils consist mostly of well drained soils with some poorly drained soils along the northern edge of the Columbus Block area and Area 28. The terraces in and near the bottom lands of the river valleys tend to have a large variety of soil types and characteristics. The sandy classes of soils have the greatest water infiltration rates while the silty to clay rich classes have lesser amounts of infiltration. These areas have high groundwater levels and can be prone to flooding with their gentle slopes. The uplands bordering the river valleys can have high rates of runoff due to the presence of loess, clay, glacial till, and steep hill slopes that may exist.

2.2.2 Aquifer Characteristics

Historic specific yield values in the project area for the High Plains aquifer materials ranges from 0.5 to 0.20 based on Figure 2-9 and Figure 2-10 from Olafsen-Lackey et al. (2005b) and Summerside et al. (2005b). Specific yields are approximately 0.10 where the aquifer materials are made of mostly silt size particles. Aquifer materials made up of sand and gravel size particles range from approximately 0.10 to 0.25. This work is regional in nature and can change with the addition of aquifer tests to determine aquifer characteristics. Specific Yield is an estimate of the percentage of water in an aquifer that will drain under gravity (Heath, 1983).

Historic transmissivity values in the project area for the High Plains aquifer materials range from 50 to 250 gpd/ft based on Figure 2-11 and Figure 2-12 from Olafsen-Lackey et al., 2005c and Summerside et al., 2005c. This work is regional in nature and can change with the addition of aquifer tests to determine aquifer characteristics. Transmissivity is the capacity of an aquifer to transmit water and is a function of the hydraulic conductivity times the aquifer thickness (Heath, 1983).

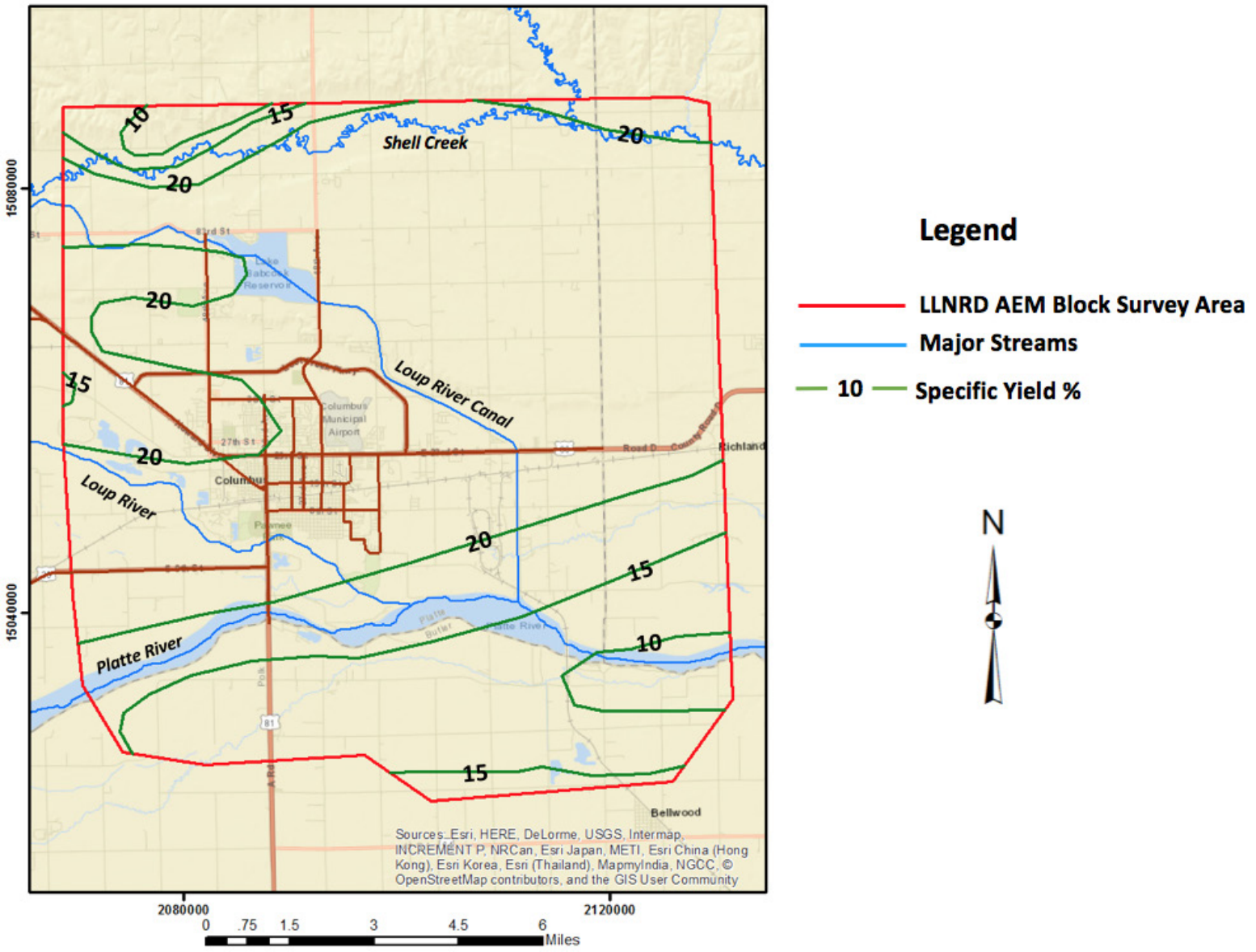


Figure 2-9. Specific yield values within the Columbus Block Area (Olafsen-Lackey et al., 2005b; Summerside et al., 2005b).

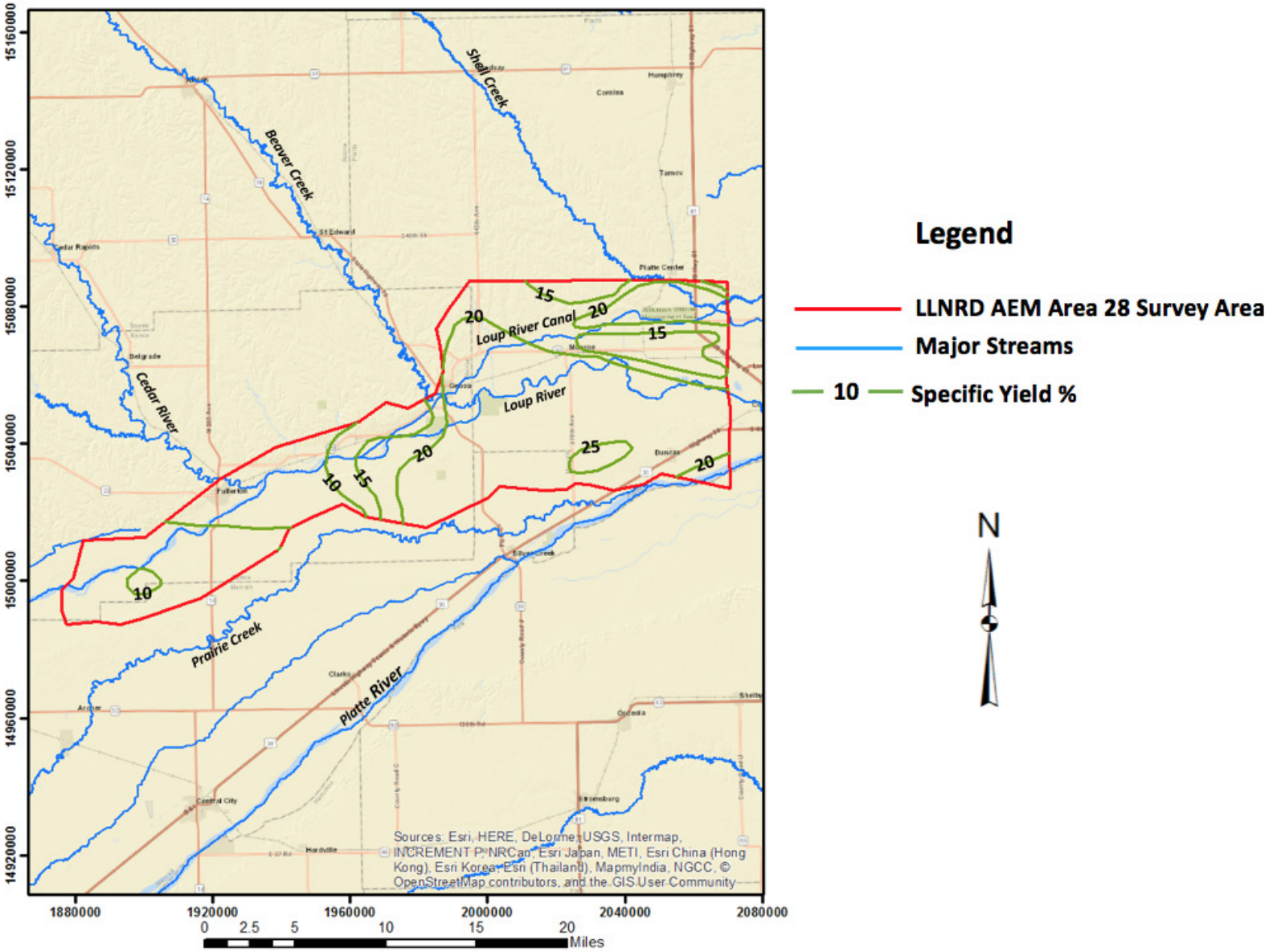


Figure 2-10. Specific yield values within Area 28 (Olafsen-Lackey et al., 2005b; Summerside et al., 2005b)

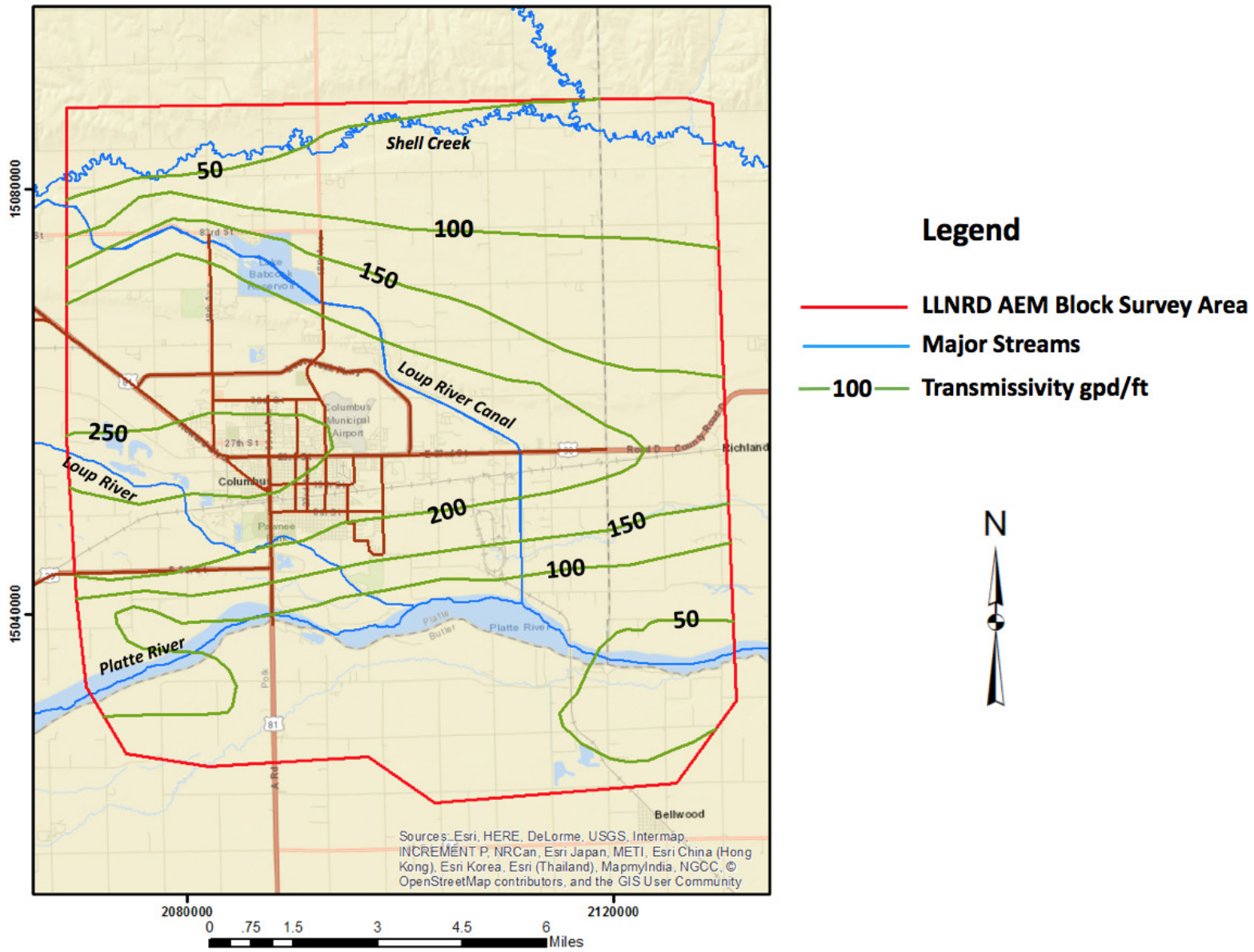


Figure 2-11. Transmissivity values within the Columbus Block AEM survey area (Olafsen-Lackey et al., 2005c; Summerside et al., 2005c).

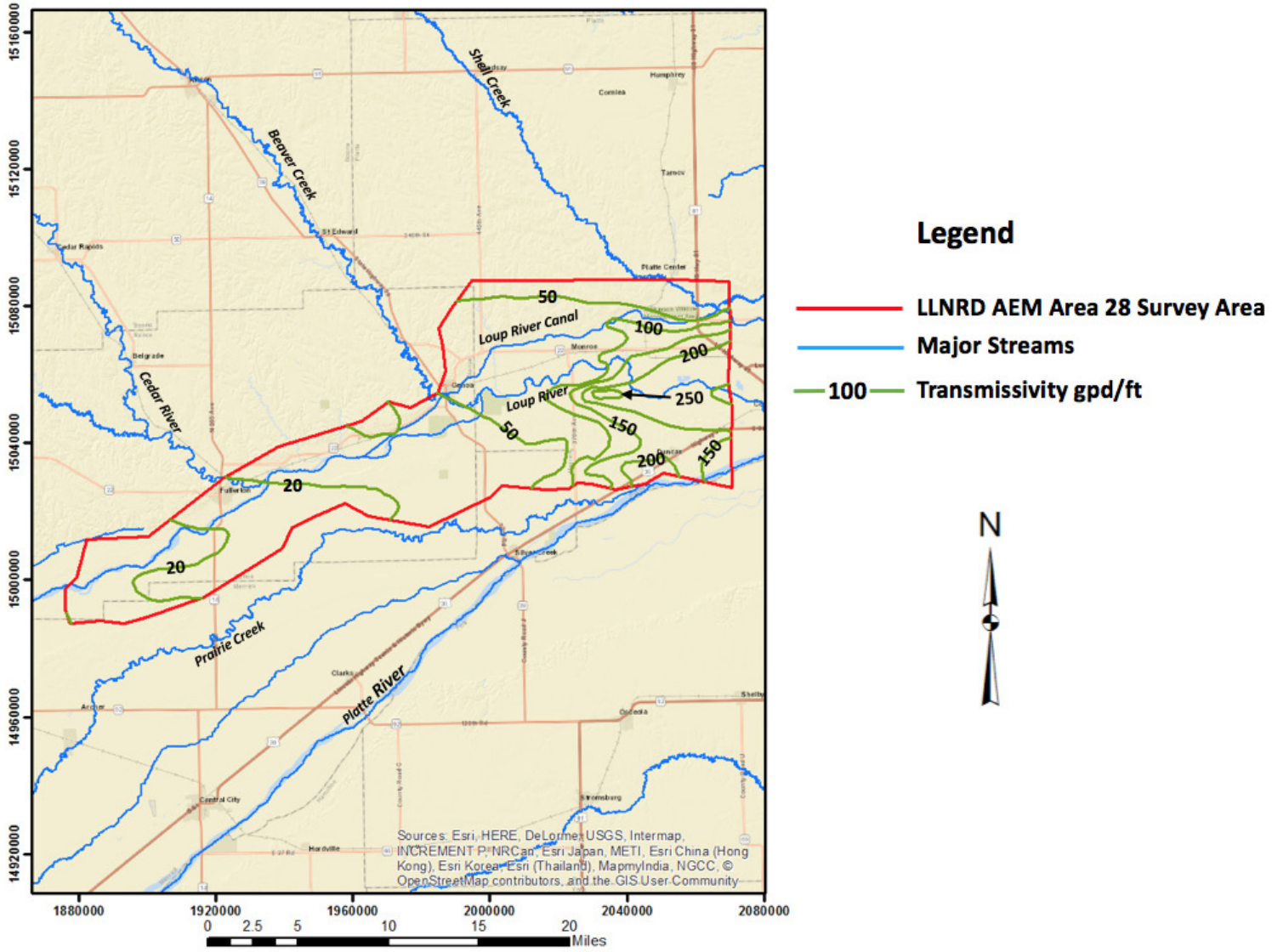


Figure 2-12. Transmissivity values within the Area 28 reconnaissance survey area (Olafsen-Lackey et al., 2005c; Summerside et al., 2005c).

2.2.3 Connectivity to Surface Water and to Other Aquifers

Groundwater flow connectivity to surface water features is largely undocumented. However, Peterson and Strauch (2006) report stream flow measurements at 531 sites conducted in November 2006 in the Elkhorn and Loup River basins and selected streams in the Niobrara and Platte River basins in north-central Nebraska. Most of these sites were located throughout the Elkhorn and Loup River basins, while 14 are in the project area. Results at three sites showed stream flow decreasing in a downstream direction along Loup River indicating surface-water losses to the groundwater system. However, a more detailed review and analysis of the 14 sites near the project area (which was not a part of the scope of work for this project) would provide a more detailed explanation of these results. It is recognized that there is a strong groundwater-surface water connection along the rivers and streams in the project area.

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

2.2.4 Water Quality

U.S. Geological Survey Water Supply Paper 2245 provides an historic overview of water quality in the state of Nebraska (Enberg, 1984). Of interest is the map of Total Dissolved Solids (TDS) for the state which shows that the overall groundwater quality for TDS in the LLNRD AEM survey area ranges from 0 to 750 mg/l. This is important to the AEM survey results because concentrations of TDS above 1500 mg/l can affect the bulk resistivity values impacting the interpretations of the geological materials. Additional detailed information on Water Quality can be found in Carney et al. (2015a).

The Lower Loup NRD has been monitoring groundwater quality across the district with a network of monitoring wells since the late 1970s. One of the primary pollutants of concern is nitrate because of its steady rise in concentration to levels above the U.S. Environmental Protection Area (EPA) Maximum Contaminant Level (MCL) of 10 milligrams per liter (mg/L) in certain areas of the district. Area 28, due west of Columbus between the Loup River and the boundary with Central Platte NRD, has seen a steady increase in nitrate levels from an average of 9.3 mg/L in 1978 to 18.6 mg/L in 2015 (https://www.llnrd.org/assets/site/LLNRDNMgtAreaPhaseSumupdate.pdf).

In 2002, Area 28 was moved into Phase III management in accordance with the Lower Loup Groundwater Management Plan which meant that agricultural producers had to pass a certification class, limit fertilizer applications, monitor water applications, and sample soil, water, and report nitrogen application rates to the NRD each year. Since 2002, groundwater monitoring has continued to show increased nitrate concentration even with the additional Phase III requirements. More information can be found at https://www.llnrd.org/.

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 four sources: 1) CSD Nebraska Statewide Test Hole Database (UNL, 2016) accessed January 28, 2017, which contains information from boreholes drilled between 1930 and 2016 by the CSD and other cooperating agencies.; 2) NE-DNR (Nebraska Department of Natural Resources, 2016b) accessed September 22, 2016; 3) NRD contracted driller records conducted by Olsson Associates provided by the Lower Loup Natural Resources District (LLNRD) (personal comm. Tyler Naprstek, LLNRD March 3, 2017); and 4) Nebraska Oil and Gas Conservation Commission (NOGCC, 2017)

The locations of the CSD boreholes utilized in the LLNRD Survey Area are indicated in Figure 3-1. A total of 51 CSD holes contained lithology information, 45 holes contained stratigraphic information, and 5 holes contained geophysical information were within the LLNRD Survey Area. The locations of the NE-DNR registered wells used in the LLNRD Survey Area are indicated in Figure 3-2. A total of 2,414 registered wells contained usable lithology information. The locations of the NRD contracted driller records conducted by Olsson Associates provided by the LLNRD are indicated in Figure 3-3. A total of 5 wells contained lithology information. The locations of the NOGCC wells used in the LLNRD Survey Area are indicated in Figure 3-4. Three wells contained limited stratigraphy and geophysical information.

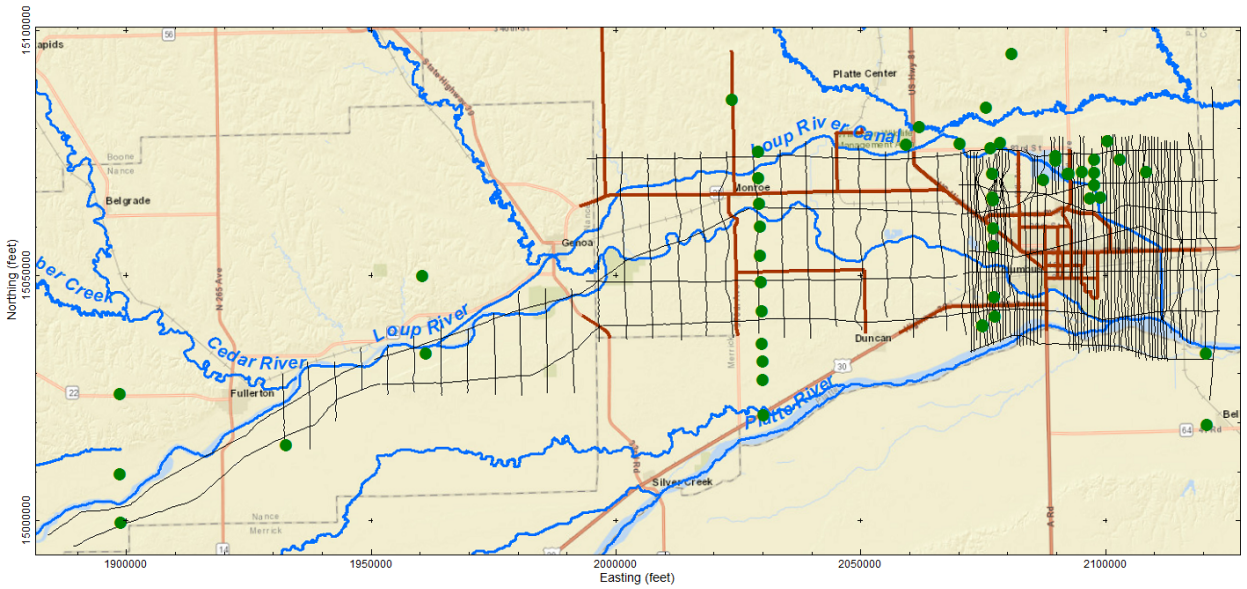


Figure 3-1. Locations of the Conservation Survey Division (CSD) boreholes (green dots) and the airborne electromagnetic flight lines (black lines) in the LLNRD AEM survey area. Projection is NAD83, UTM 14 North (feet).

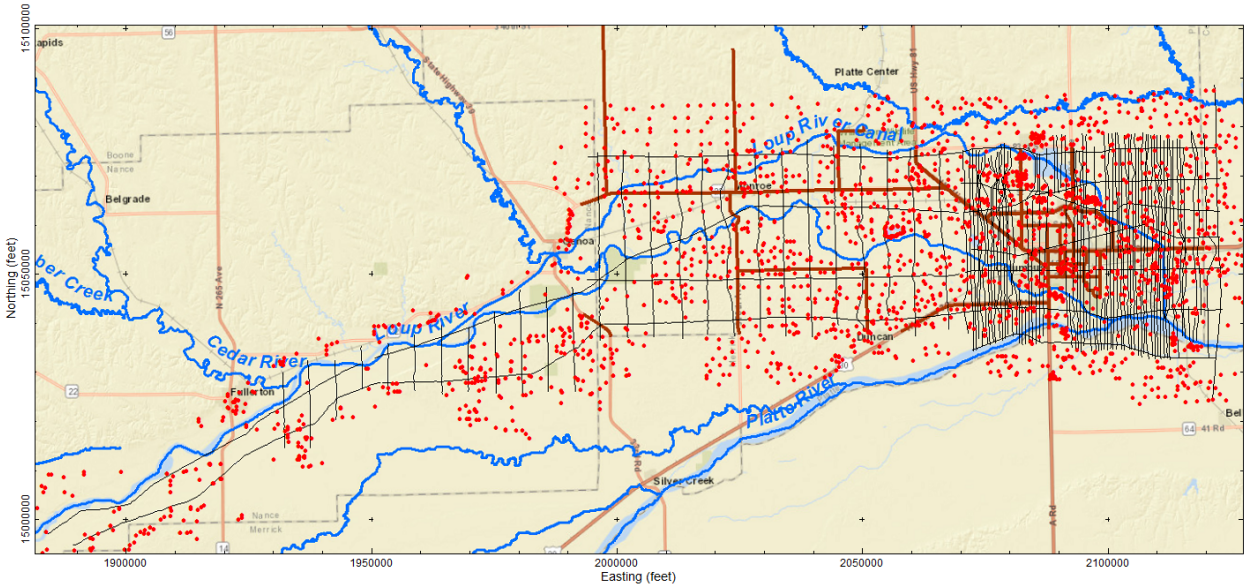


Figure 3-2. Locations of the Nebraska Division of Natural Resources Registered wells (red dots) and the airborne electromagnetic flight lines (black lines) in the LLNRD AEM survey area. Projection is NAD83, UTM 14 North (feet).

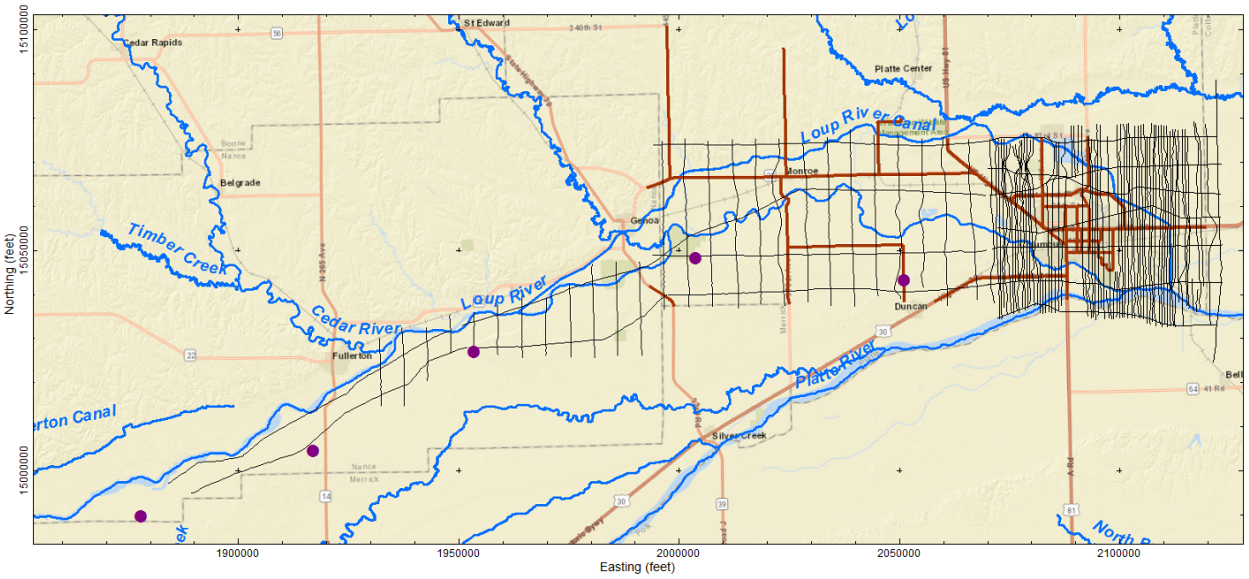


Figure 3-3. Locations of the LLNRD contracted driller records conducted by Olsson Associates. Provided by the LLNRD (purple dots) and the AEM flight lines (black lines) in the LLNRD AEM survey area. Projection is NAD83, UTM 14 North (feet).

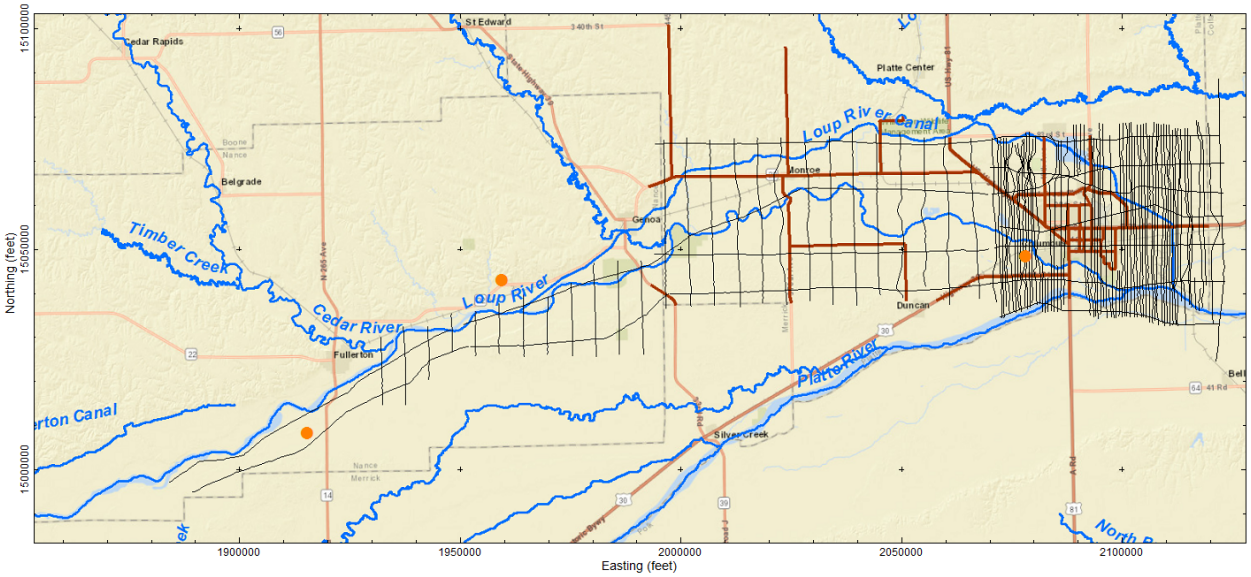


Figure 3-4. Locations of Nebraska Oil and Gas Conservation Commission wells (orange dots) and the AEM flight lines (black lines) in the LLNRD Survey Area. Projection is NAD83, UTM 14 North (feet).

4 Geophysical Methodology, Acquisition and Processing

4.1 Geophysical Methodology

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

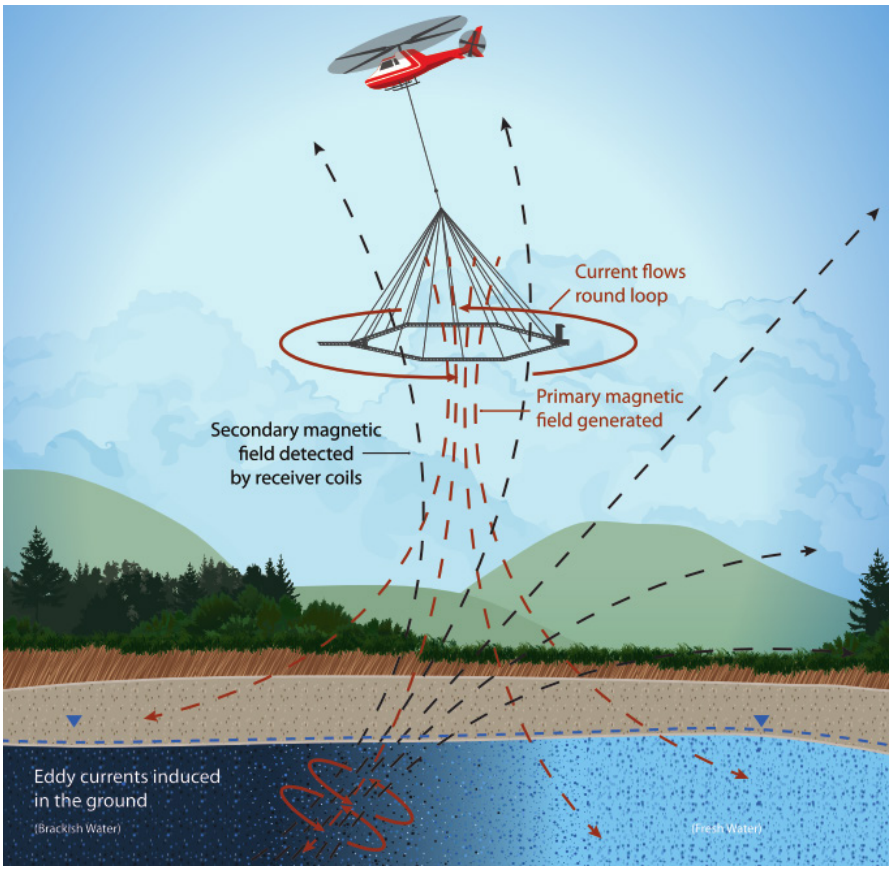
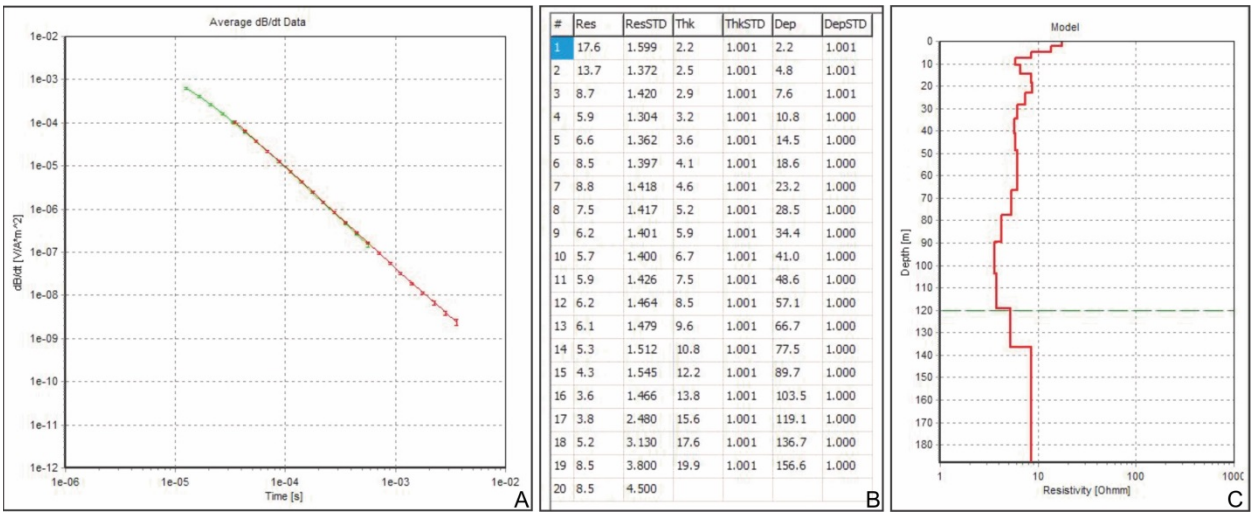


Figure 4-1: Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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

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

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



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

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

4.2 Flight Planning/Utility Mapping

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

A GIS Arc shapefile of railroads in Nebraska was downloaded from the United States Department of Agriculture’s Natural Resource Conservation Service (US Dept Agriculture, 2014) and a shapefile of the pipelines in Nebraska was provided by the ENWRA group. Maps of the three utilities were exported in GeoTIFF and Google Earth kmz formats and were used during data processing and interpretation.

The locations of the flight lines were converted from a regularly spaced grid to one with flight lines optimized 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 the LLNRD reconnaissance flight lines were approximately 38 miles in length (east-west) and 7 miles (north-south) and were separated by approximately 1 mile in both east-west and north-south directions (Figure 1-2 and Figure 4-5). The Columbus block flight lines were approximately 9 miles in length and were separated by about 0.12 miles.

4.3 AEM Survey Instrumentation

AEM data were acquired using the SkyTEM304M (304M) airborne electromagnetic system (SkyTem Airborne Surveys Worldwide, 2016). The 304M is a rigid frame, dual-magnetic moment (Low and High) TEM system. The area of the 304M Tx coil is 337 m^2 and the coil contains four (4) turns of wire. A peak current of nine (9) amps is passed through one turn of wire in the Tx for Low Moment measurements and a peak current of 120 amps is passed through the four turns of wire for High Moment measurements. This results in peak Tx Low and High magnetic moments of ~3,000 Ampere-meter-squared ($A*m^2$) and ~160,000 $A*m^2$, respectively.

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

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

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

North American Datum of 1983 (NAD83 in feet). All elevations are from USGS's National Elevation Dataset, referenced to the North American Vertical Datum of 1988; with feet as the unit of measurement.

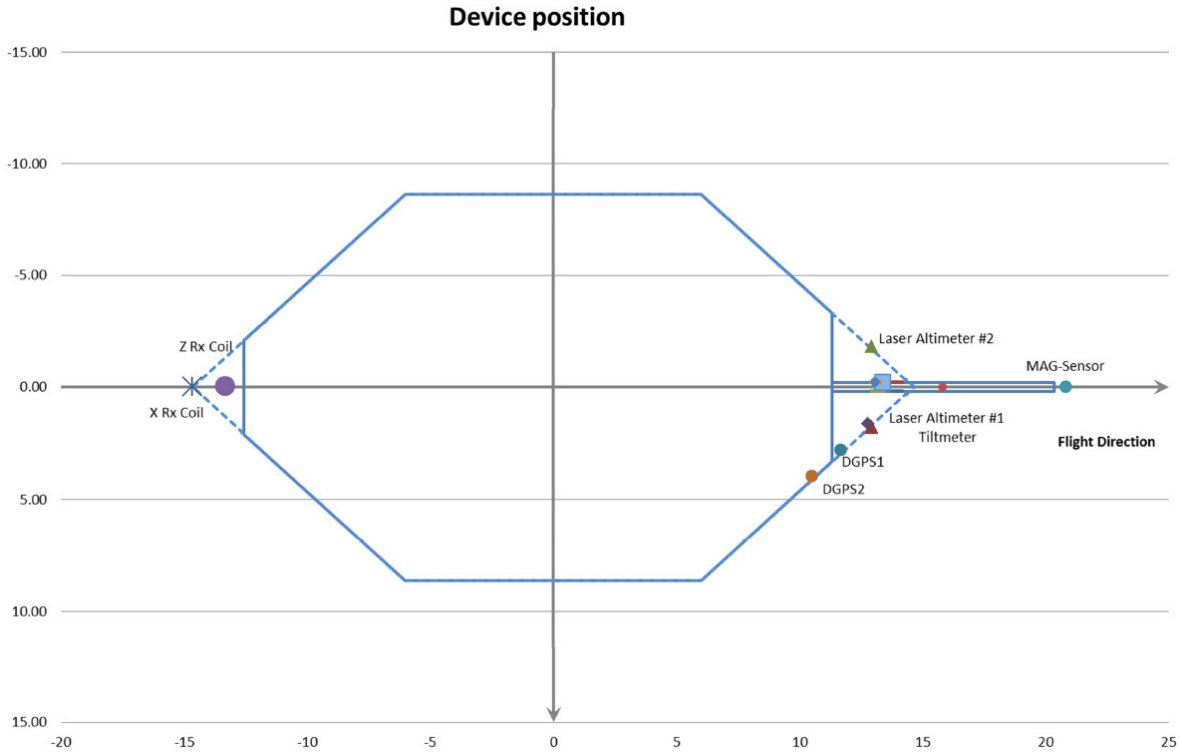


Figure 4-3: SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1.



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

For this project, the 304M was flown at an average speed of 62 mi/hr (100.5 kilometers/hr) at an average flight height of 36.4 m above land surface, using the sling-load cargo system of a Eurocopter AS350BA FX2 helicopter. Figure 4-4 displays a couple of images of the 304M in operation.

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

	DGPS 1	DGPS 2	Inclinometer 1	Inclinometer 2	Altimeter 1	Altimeter 2	Magnetic Sensor	Rx Coil
X	38.31	34.47	41.95	41.95	42.44	42.44	67.24	-43.46
Y	9.15	12.96	5.38	-5.38	5.87	-5.87	0.00	0.00
Z	-0.52	-0.52	-0.39	-0.39	-0.39	-0.39	-1.71	-6.56

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

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

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

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

4.4 Data Acquisition

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

For these surveys, installation of the navigational instruments in the helicopter and assembly of the SkyTEM304M system commenced at the beginning of the project. The helicopter and the SkyTEM304M system were located at the Genoa airport. Calibration test flights were flown to ensure that the equipment was operating within technical specifications. Survey set-up procedures included measurement of the transmitter waveforms, verification that the receiver was properly located in a null position, and verification that all positioning instruments were functioning properly. A high altitude test, used to verify system performance, was flown prior to the beginning of the survey's production flights. In the field, quality control of the operational parameters for the EM and magnetic field sensors including current levels, positioning sensor dropouts, acquisition speed, and system orientation were conducted with proprietary SkyTEM software following each flight.

Approximately 665.6 line-miles (1,078.28 line-kilometers) were acquired over the LLNRD AEM survey area on July 14-18, 2016. The Genoa Municipal airport was used for landing and refueling between production flights. A data acquisition map is presented in Figure 4-5 with the flight lines grouped by acquisition date.

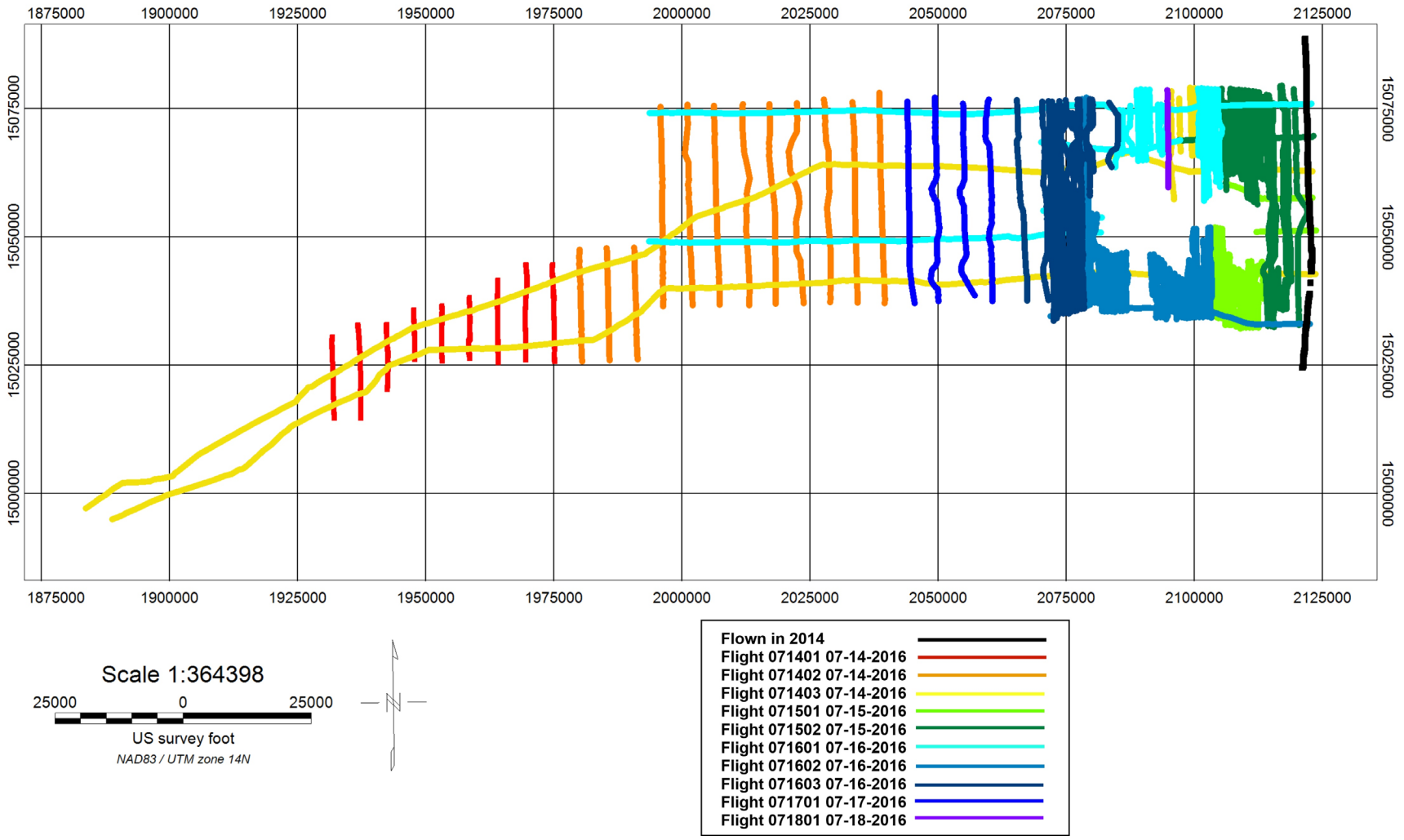


Figure 4-5: LLNRD AEM flight lines grouped by acquisition date.

4.4.1 Primary Field Compensation

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

4.4.2 Automatic Processing

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

Automatic processing algorithms provided within the Workbench program are initially applied to the AEM data. DGPS locations were filtered using a stepwise, second-order polynomial filter of nine seconds with a beat time of 0.5 seconds, based on flight acquisition parameters. The AEM data are corrected for tilt deviations from level and so filters were also applied to both of the tilt meter readings with a median filter of three seconds and an average filter of two seconds. The altitude data were corrected using a series of two polynomial filters. The lengths of both eighth-order polynomial filters were set to 30 seconds with shift lengths of six (6) seconds. The lower and upper thresholds were 1 and 100 meters, respectively.

Trapezoidal spatial averaging filters were next applied to the AEM data. The times used to define the trapezoidal filters for the Low Moment were $1.0x10^{-5}$ sec, $1.0x10^{-4}$ sec, and $1.0x10^{-3}$ sec with widths of 8, 10, and 12 seconds. The times used to define the trapezoid for the High Moment were $1.0x10^{-4}$ sec, $1.0x10^{-3}$ sec, and $1.0x10^{-2}$ sec with widths of 10, 12, and 20 seconds. The trapezoid sounding distance was set to 2.5 seconds and the left/right setting, which requires the trapezoid to be complete on both sides, was turned on. The spike factor and minimum number of gates were both set to 25 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

4.4.3 Manual Processing and Laterally-Constrained Inversions

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

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

After final processing, 543.1 line-miles (879.6 line-km) of data were retained for the final inversions for the LLNRD AEM survey area. This amounts to a data retention of 82%. This high rate is the result of careful flight line planning and design.

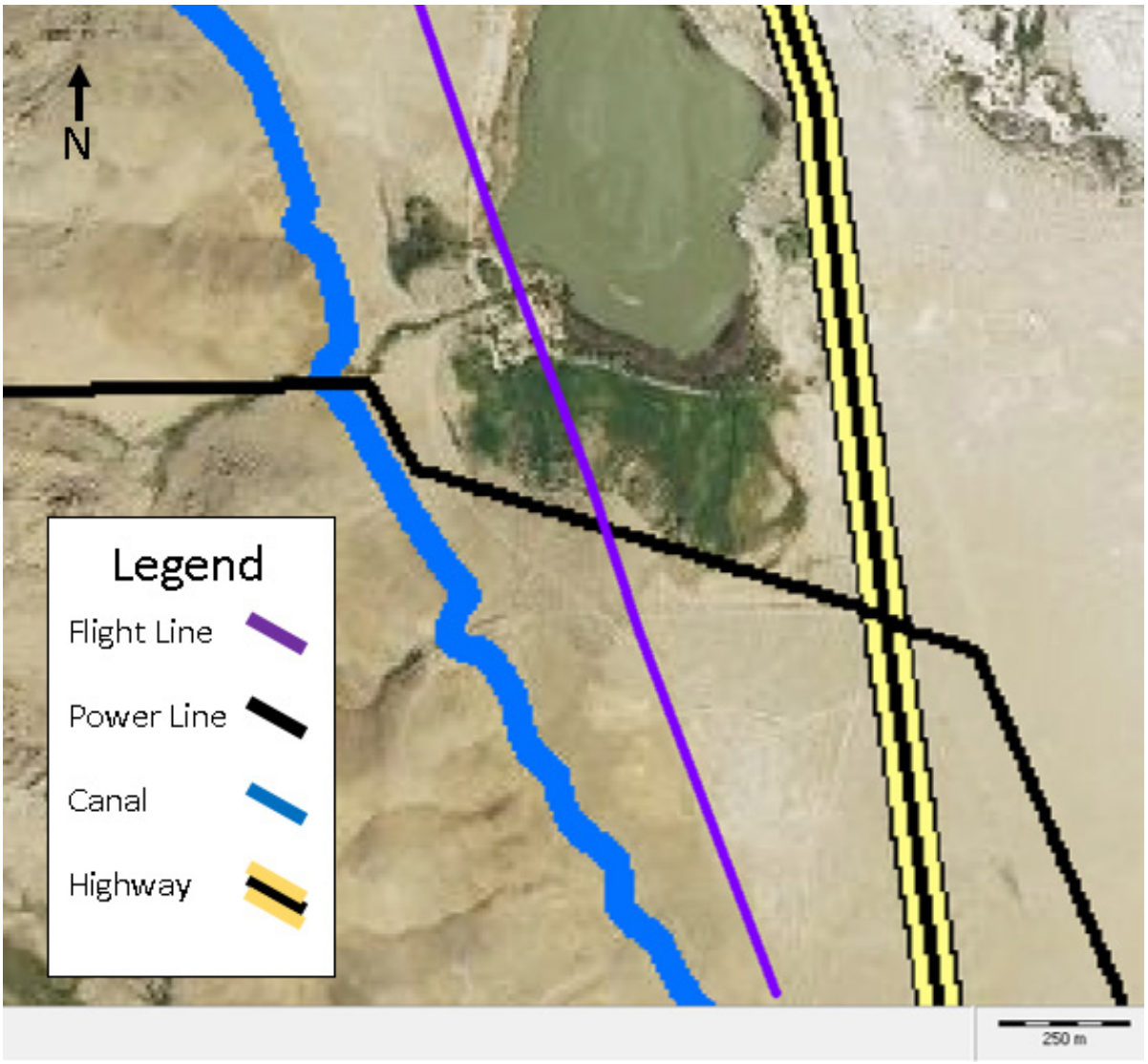


Figure 4-6: Example locations of electromagnetic coupling with pipelines or power lines.

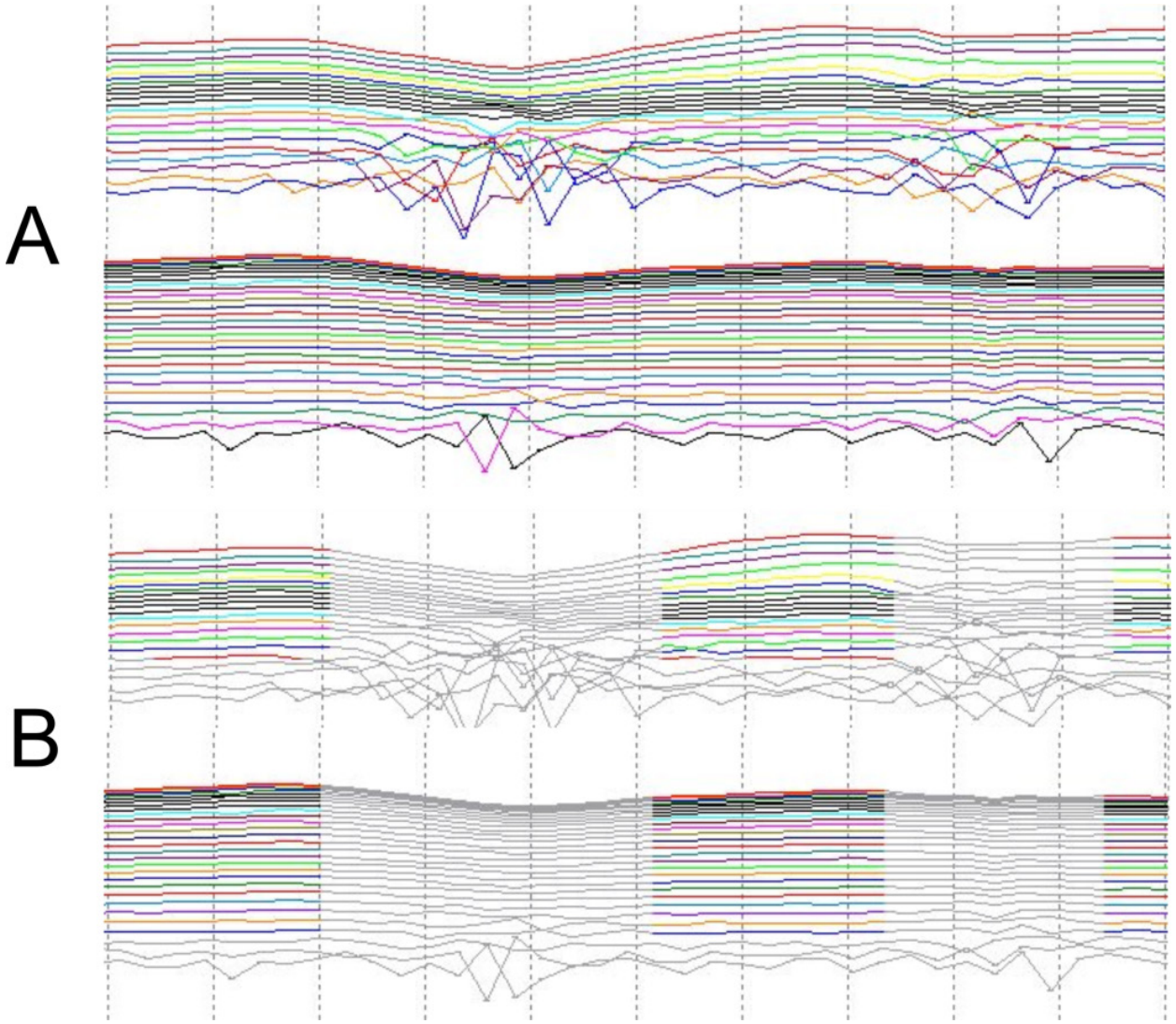


Figure 4-7: A) Example of AEM data from the LLNRD AEM survey affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

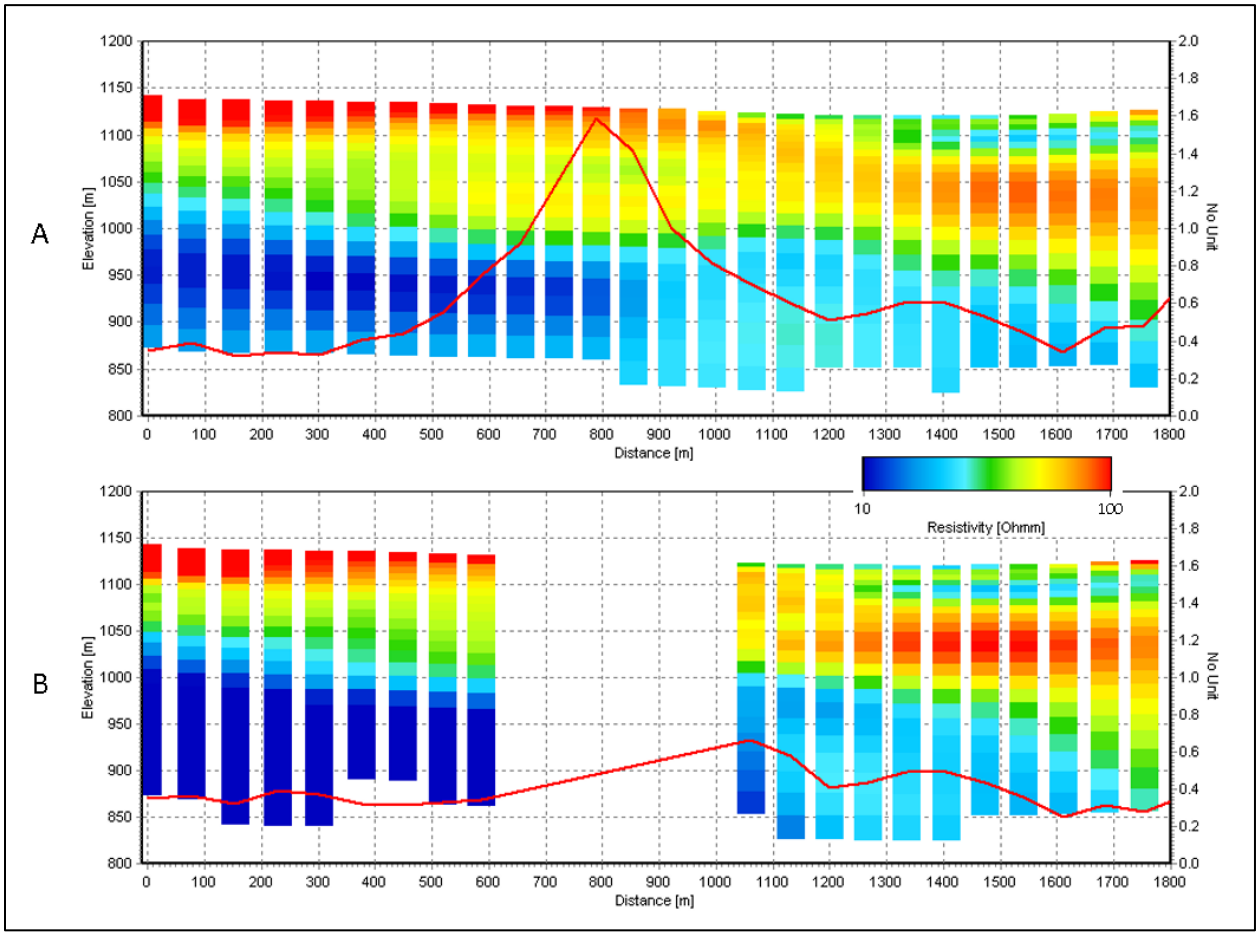


Figure 4-8: A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

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 LLNRD AEM survey are presented in Figure 4-9. The LLNRD-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.

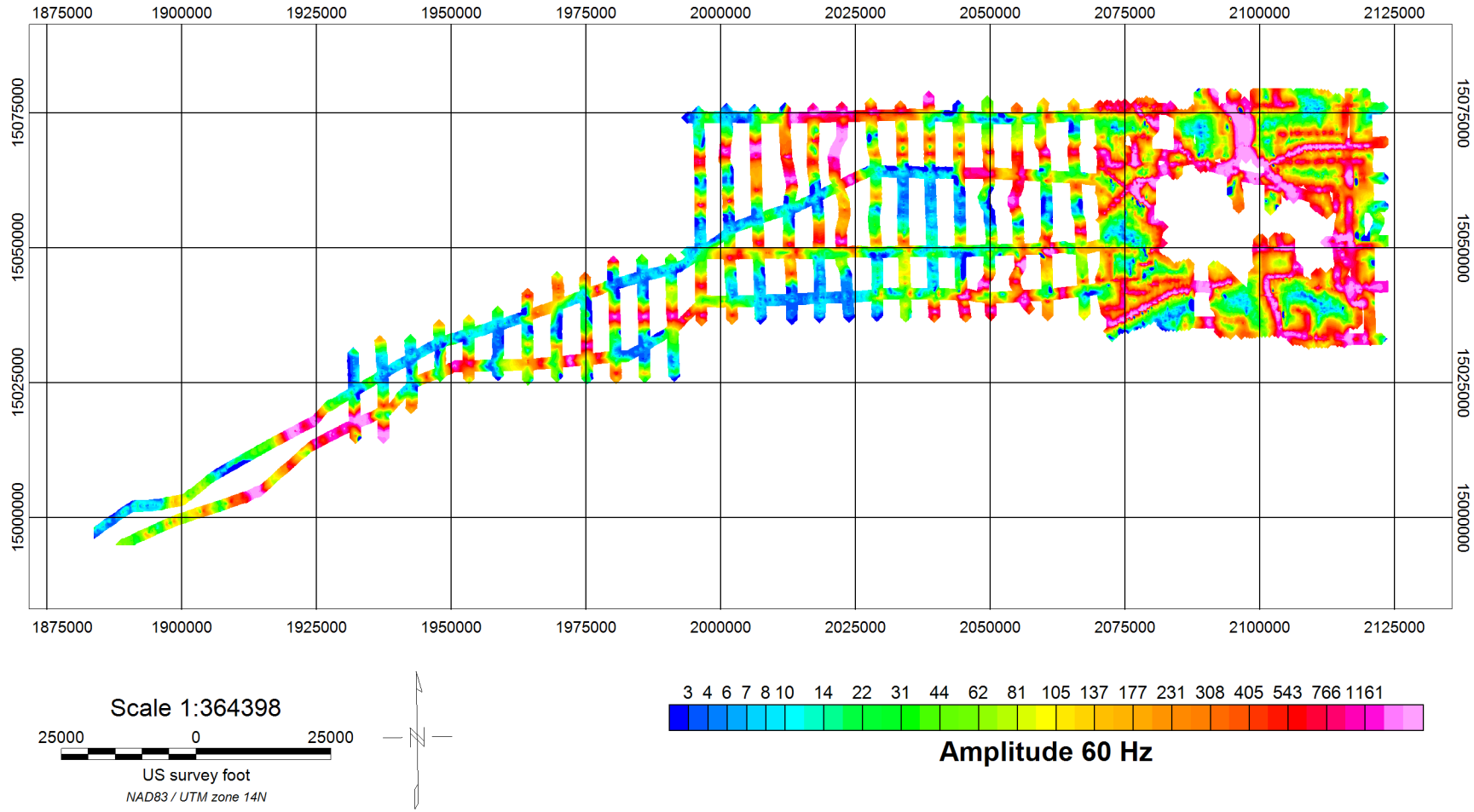


Figure 4-9: Power Line Noise Intensity (PLNI) map of the LLNRD project area.

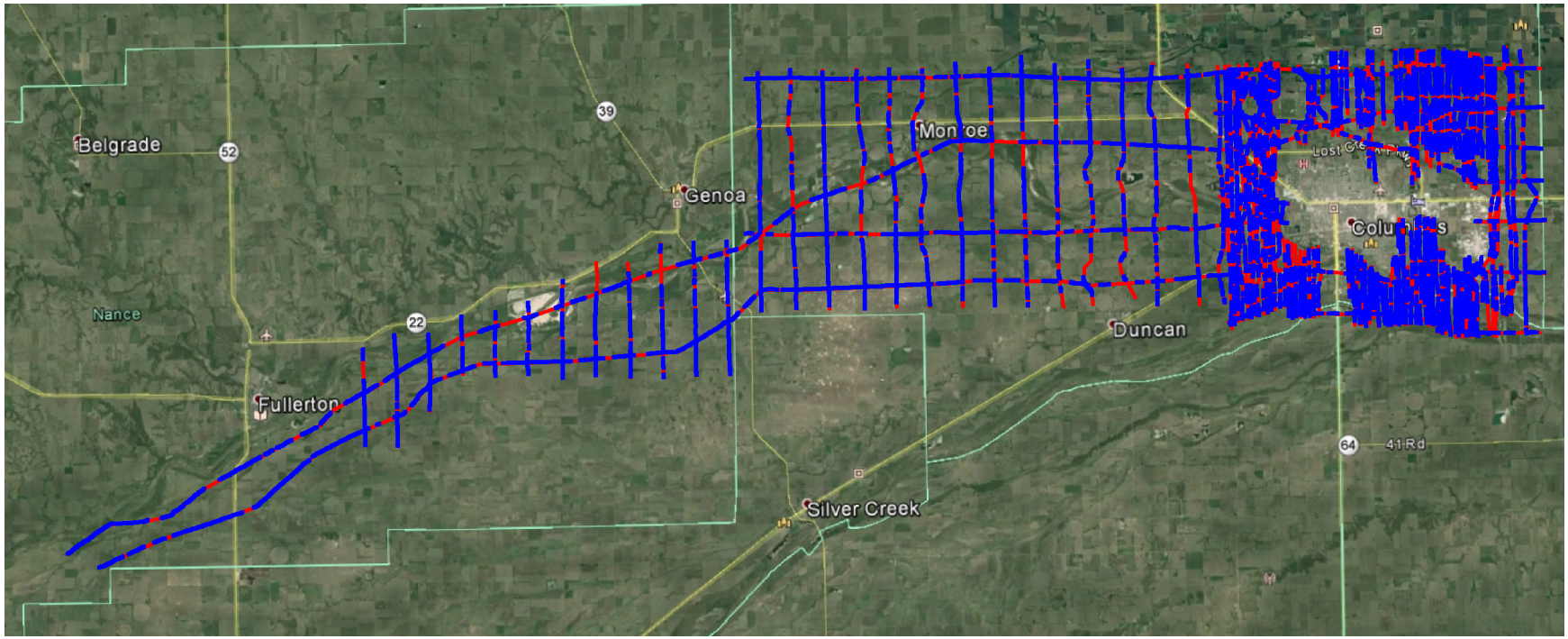


Figure 4-10: Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LLNRD AEM survey area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix 3\KMZ.

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 LLNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). This data is used in decoupling efforts.

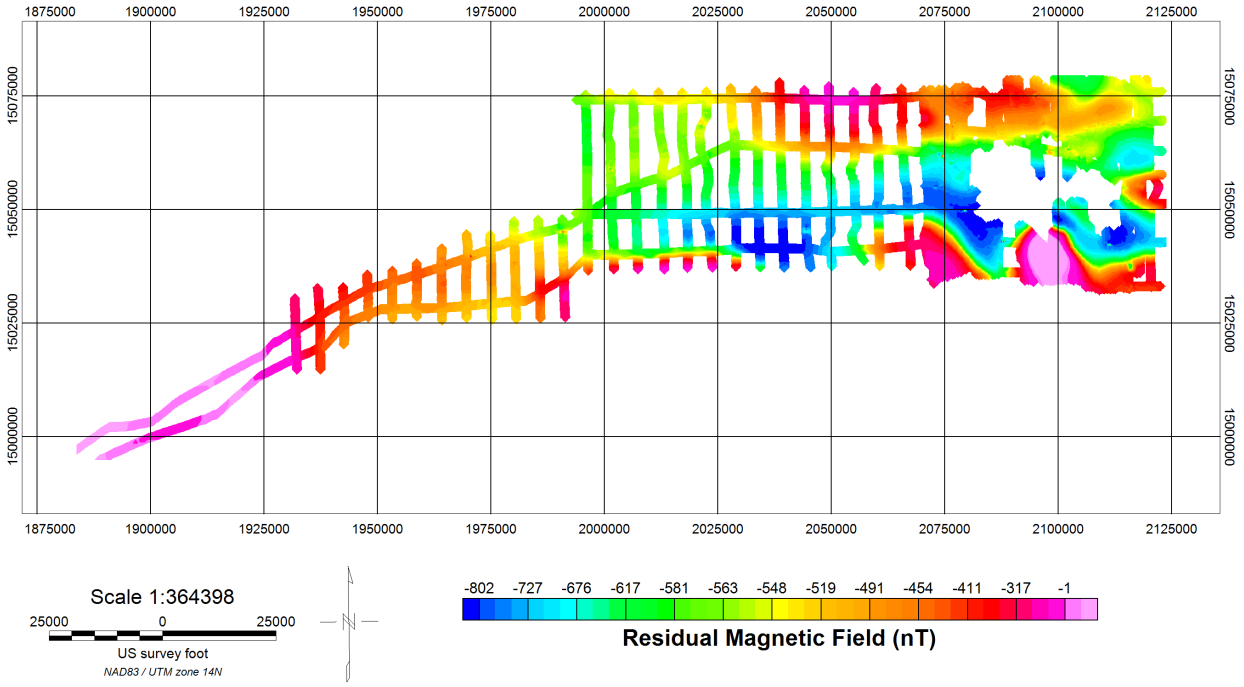


Figure 4-11: Magnetic Total Field intensity data for the LLNRD survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

For comparison purposes, an image of magnetic Total Field data collected by the USGS (Sweeney and Hill, 2005) are presented in Figure 4-12. The USGS data were collected over a much larger reconnaissance grid spacing (5 mile line separation) than was collected in the present survey over the LLNRD and then the USGS data were "upward continued" to a 1000 ft elevation. Even so the comparison between the two data sets is quite good – especially the large high amplitude anomaly in the northeastern region of the survey area and the smaller high amplitude anomaly south of the Columbus area.

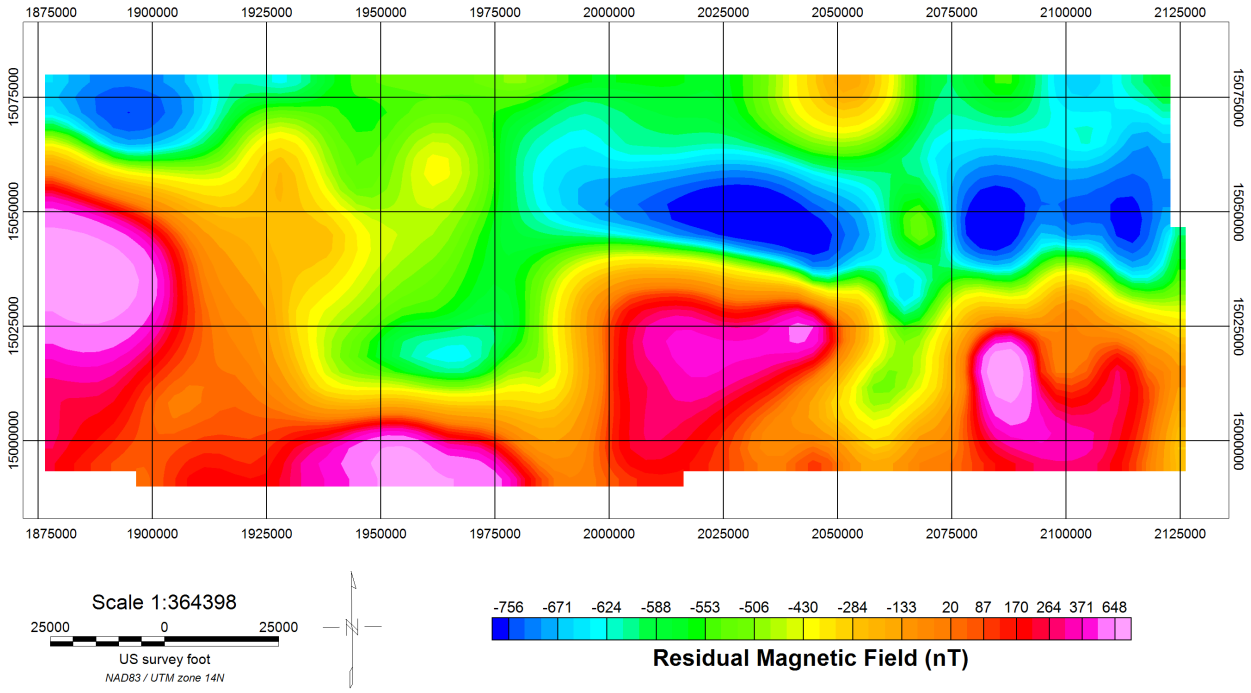


Figure 4-12: USGS magnetic Total Field intensity data for the LLNRD survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5 mile line spacing and upward continued to a reference elevation of 1000 ft.

4.5 Spatially-Constrained Inversion

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

The LLNRD 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			

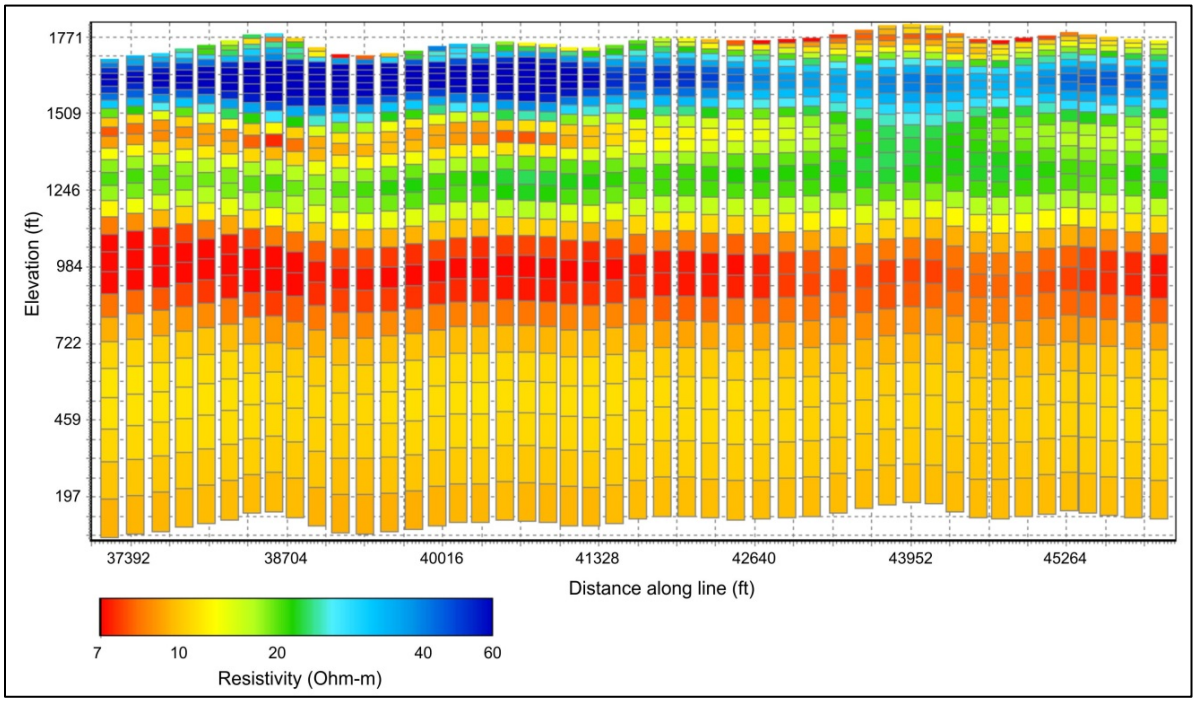


Figure 4-13: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

Figure 4-14 presents a histogram of the LLNRD SCI inversion data/model residuals. A map of data residuals for the study area is presented in Figure 4-15.

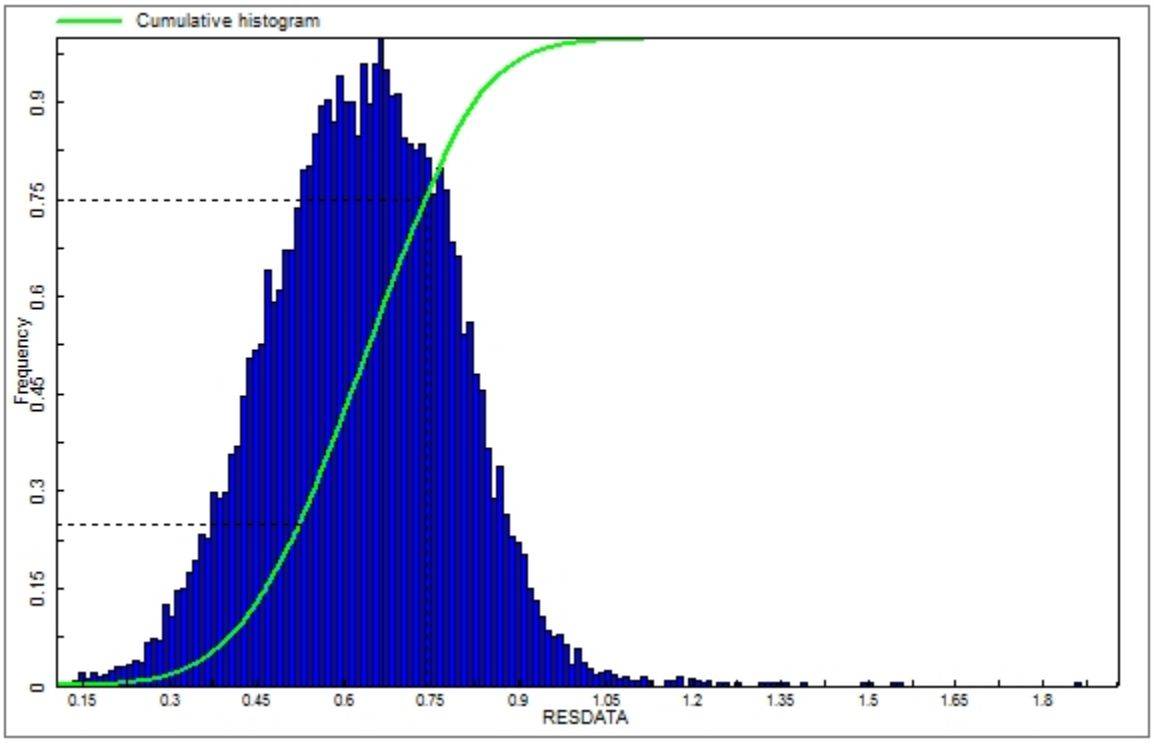


Figure 4-14: Data/model residual histogram for the LLNRD SCI inversion results.

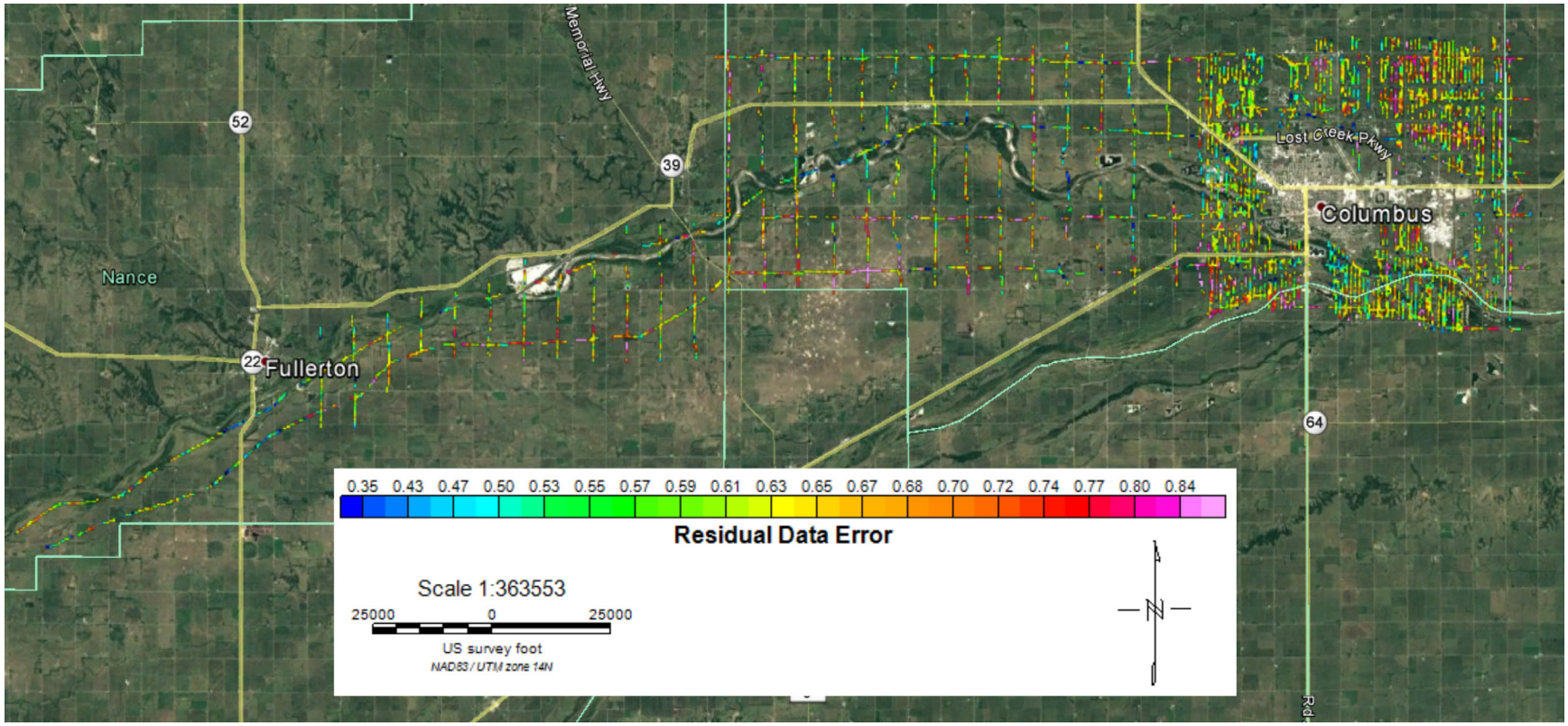


Figure 4-15. Map of data residuals for the LLNRD SCI inversion results.

5 AEM Results and Interpretation

This section provides the details on the process involved in the interpretation of the LLNRD 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 survey area. These included lines that composed the Columbus Block. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. Not all the short lines were combined due to the irregular flight patterns around Columbus due to FAA regulations and infrastructure. Table 5-1 lists the original flown lines and the new combined lines. The two long reconnaissance lines collected in the western portion of the LLNRD Survey Area L107101 and L107301 were broken into three segment each to facilitate interpretation and display. These breaks were made on bearing changes along the flight line. Table 5-2 lists the new naming convention for the two long reconnaissance lines.

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

Original Source Lines	Direction	New Line
L111801 and L120601	North-South	L232402
L112001 and L120801	North-South	L232802
L112201 and L121601	North-South	L233802
L112401 and L121801	North-South	L234202
L112601 and L122201	North-South	L235202
L112601 and L122201	North-South	L236202
L113601 and L122601	North-South	L235202
L113801 and L123001	North-South	L236802
L114001 and L123201	North-South	L237202
L114201 and L123401	North-South	L237602
L114401 and L123601	North-South	L237602
L114201 and L123401	North-South	L238002
L114601 and L124001	North-South	L238602
L114801 and L124401	North-South	L239202
L115001 and L125001	North-South	L240002
L115201 and L125201	North-South	L240402
L115401 and L125401	North-South	L240802
L115601 and L125601	North-South	L241202
L115801 and L125801	North-South	L241602
L116001 and L126001	North-South	L242002

L116201 and L126201	**North-South**	**L242402**
L116401 and L126401	**North-South**	**L242802**
L116601 and L126601	**North-South**	**L243202**
L116801 and L126801	**North-South**	**L243602**
L117201 and L127001	**North-South**	**L244202**
L117401 and L127201	**North-South**	**L244602**
L117201 and L127001	**North-South**	**L244202**
L117601 and L127401	**North-South**	**L245002**
L117801 and L127601	**North-South**	**L245402**
L117801 and L127601	**North-South**	**L245402**
L118001 and L127801	**North-South**	**L245802**
L118201 and L128001	**North-South**	**L246202**
L118401 and L128201	**North-South**	**L246402**
L118601 and L128401	**North-South**	**L247002**
L118801 and L128601	**North-South**	**L247402**
L119001 and L128801	**North-South**	**L247802**
L119201 and L129001	**North-South**	**L248202**
L105501 and L105502	**East-West**	**L211003**
L105701 and L105702	**East-West**	**L211403**
L105901 and L106101	**East-West**	**L211002**
L106301 and L106501	**East-West**	**L212802**

The eastern side of the Columbus Block is adjacent to one of the reconnaissance lines that were flown by ENWRA in 2014. This line was added to the LLNRD Columbus Block to aid in interpretation and to extend the block to just outside the NRD boundary. The 2014 survey line L201001 added an additional 12.2 line-miles of AEM data collected in 2014 by the LENRD and the ENWRA (Carney et al., 2015a) (Figure 4-5 in previous section).

Table 5-2. Splitting of Area 28 reconnaissance flight lines within the LLNRD 2016 survey

Original Line	New Line	Line Length (mile)
L107101	**L107101a**	**13.66**
	L107101b	**9.18**
	L107101c	**13.8**
L107301	**L107301a**	**13.98**
	L107301b	**15.74**
	L107301c	**7.91**

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, AEM 2014, and LLNRD 2016 AEM), a Digital Elevation Model (DEM) was constructed for the LLNRD 2016 AEM 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 5-1 is a map of the DEM showing a vertical relief of 521 ft with a minimum elevation of 1,387 ft and a maximum elevation of 1,908 ft. This DEM was used to reference all elevations within the AEM datasets.

5.1.3 Create Interpretative 2D Profiles

After final combination of the AEM data, characterization of the subsurface was performed in cross-section format using Encom PA (pbEncom, 2016). 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 model related to the area being interpreted. The first step in the interpretation is digitizing the contacts between the geologic units including: Quaternary (***Q***), Cretaceous Niobrara (***Kp***), Cretaceous Carlile (***Kc***), Cretaceous Greenhorn limestone and Graneros shale (***Kgg***), and Cretaceous Dakota (***Kd***). The interpreted geological units included the ***Q***, ***Kn***, ***Kc***, ***Kgg***, and ***Kd*** from the upper surface to the DOI. There was no attempt at interpreting the Tertiary Ogallala (***To***) within the LLNRD AEM survey area. Only a few of the CSD test wells indicated ***To*** within the section and no obvious contact was observed within the AEM results. Most of the ***To*** according to Burchett (1986) occurs out of the river valleys and away from the flight lines. The interpretive process benefited from the use of CSD, NE-DNR, NRD provided Olsson and Associate boreholes, and NOGCC borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (Burchett, 1986).

The interpretation began with picking the ***Kc*** contact, then the ***Kn***, ***Kgg***, and finally the ***Kd*** interfaces. The process was more iterative in the eroded ***Kn*** sitting on the ***Kc*** along the Loup River within the reconnaissance area of the LLNRD AEM survey area.

The interpretation of the ***Kc*** included examining the AEM profile sections for a low electrical resistivity layer that was also indicated in the borehole logs as the base of aquifer. Many of the CSD as well as the NE-DNR borehole logs stop at the ***Kc*** due to that stratigraphic unit not being considered an aquifer being composed predominantly of shale containing clay minerals. Many of the CSD boreholes have stratigraphic calls that assisted in the location of the ***Kc***. For the profiles, the clipping distance from the flight line was set independently for the CSD boreholes and for the NE-DNR boreholes. Typically, the CSD clipping distance was set to ½ mile or 2,640 ft, and for the NE-DNR boreholes it was set to 1,000 ft. The inversion DOI was also inspected during interpretation of the profiles, but it was almost always below the top of the ***Kc*** in the LLNRD AEM survey area.

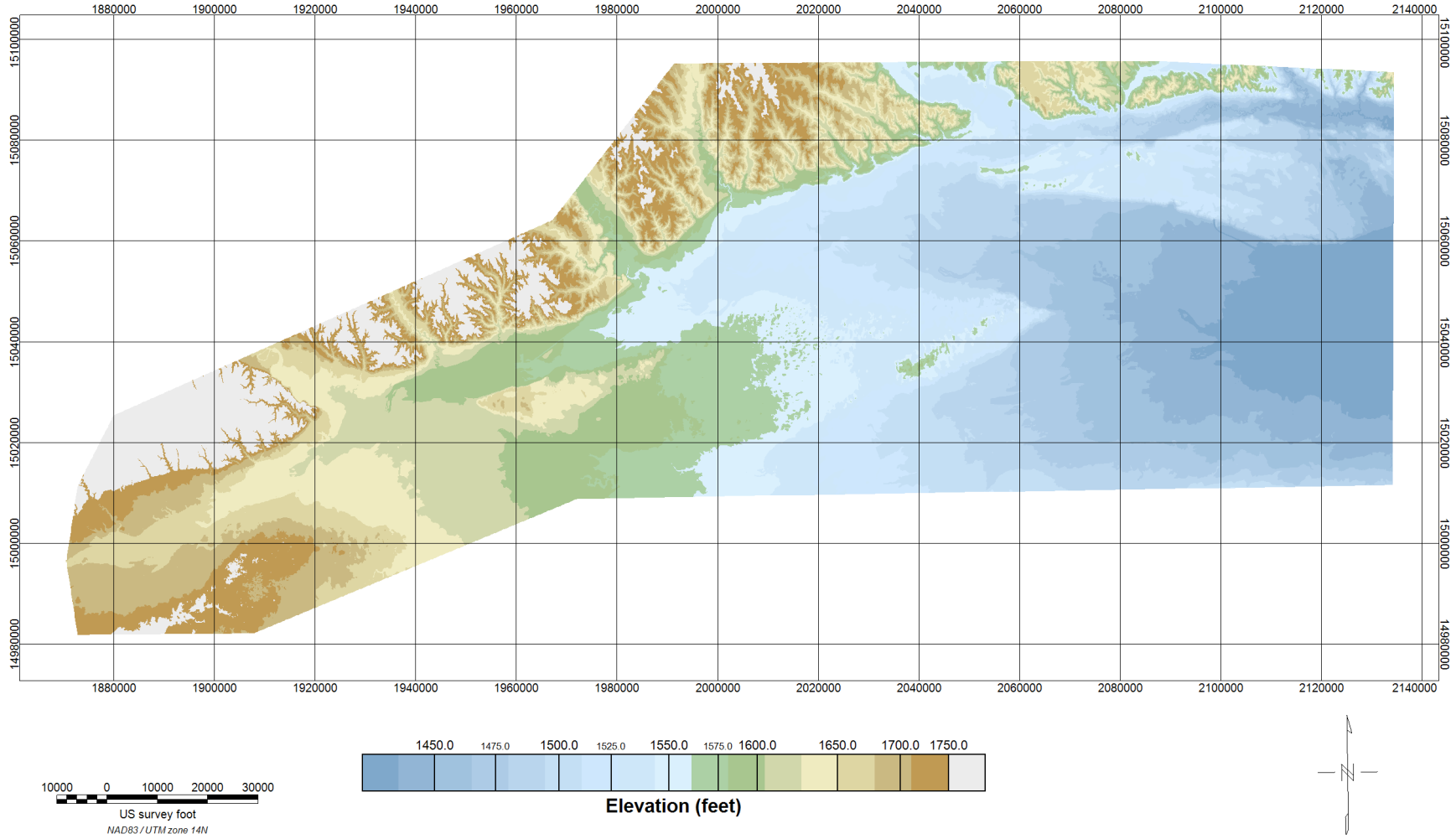


Figure 5-1. Map of the Digital Elevation Model for the LLNRD AEM survey area. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2016). North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD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

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Figure 5-2 is an approximately 15-mile segment of the diagonal reconnaissance line L107301 that was flown along the Loup River within the LLNRD Reconnaissance survey area. Figure 5-2 illustrates the interpretation of the tops of the ***Kn*** and ***Kc***. Both units dip up toward the east. The ***Kc*** is indicated as the blue-colored low resistivity area that is obvious within the section. The ***Kn*** is a much more difficult unit to interpret due to its variable resistivity ranging from high resistivity to low resistivity. This variable resistivity is representing the inherent variability within the ***Kc*** due to limestone and shale deposits. This was also observed in Carney et al. (2015a). To assist in the interpretation of the top of the ***Kn*** boreholes are critical. By using a combination of the CSD and NE-DNR holes an improved interpretation of the top of the ***Kn*** can be made. Another important fact that can be used in the determination of the top of the ***Kn*** is that most irrigation wells stop at the contact of the ***Q*** with the ***Kn*** due to the presence of shale and/or limestone. Figure 5-2 also indicates that the nature of the resistivity of the ***Q*** changes from west to east along the flight line. NE-DNR wells confirm that the sediments around *G-148052* are predominately clay.

Figure 5-3 is an approximately 14-mile segment of the east-west reconnaissance line L107701 flown south of the Loup River within the LLNRD Area 28 reconnaissance survey area. Figure 5-3 illustrates the interpretation of the top of the ***Kn*** and ***Kc***. Both units dip up towards the east and the ***Kn*** pinches out where it is eroded. The ***Kc*** is indicated as the blue-colored low resistivity area that is obvious within the section. The ***Kn*** is a much more difficult unit to interpret due to its variable resistivity from high resistivity to low resistivity. This variable resistivity is indicative of the variability in the limestone and shale deposits within the ***Kn***. By using a combination of the CSD and NE-DNR holes a confident interpretation of the top of the ***Kn*** can be made. Another important fact that can be used in the determination of the top of the ***Kn*** is that most irrigation wells stop at the contact of the ***Q*** with the ***Kn*** due to the presence of shale and/or limestone. This is indicated by the wells west of CSD test hole *22-A-42*. Figure 5-2 also indicates that the nature of the resistivity of the ***Q*** changes from west to east along the flight line. Half way along flight line L107701 and approximately east of CSD test hole *22-A-42* the ***Q*** material is overlying the ***Kc***. The ***Kc*** displays erosion to the east of the ***Kn*** contact.

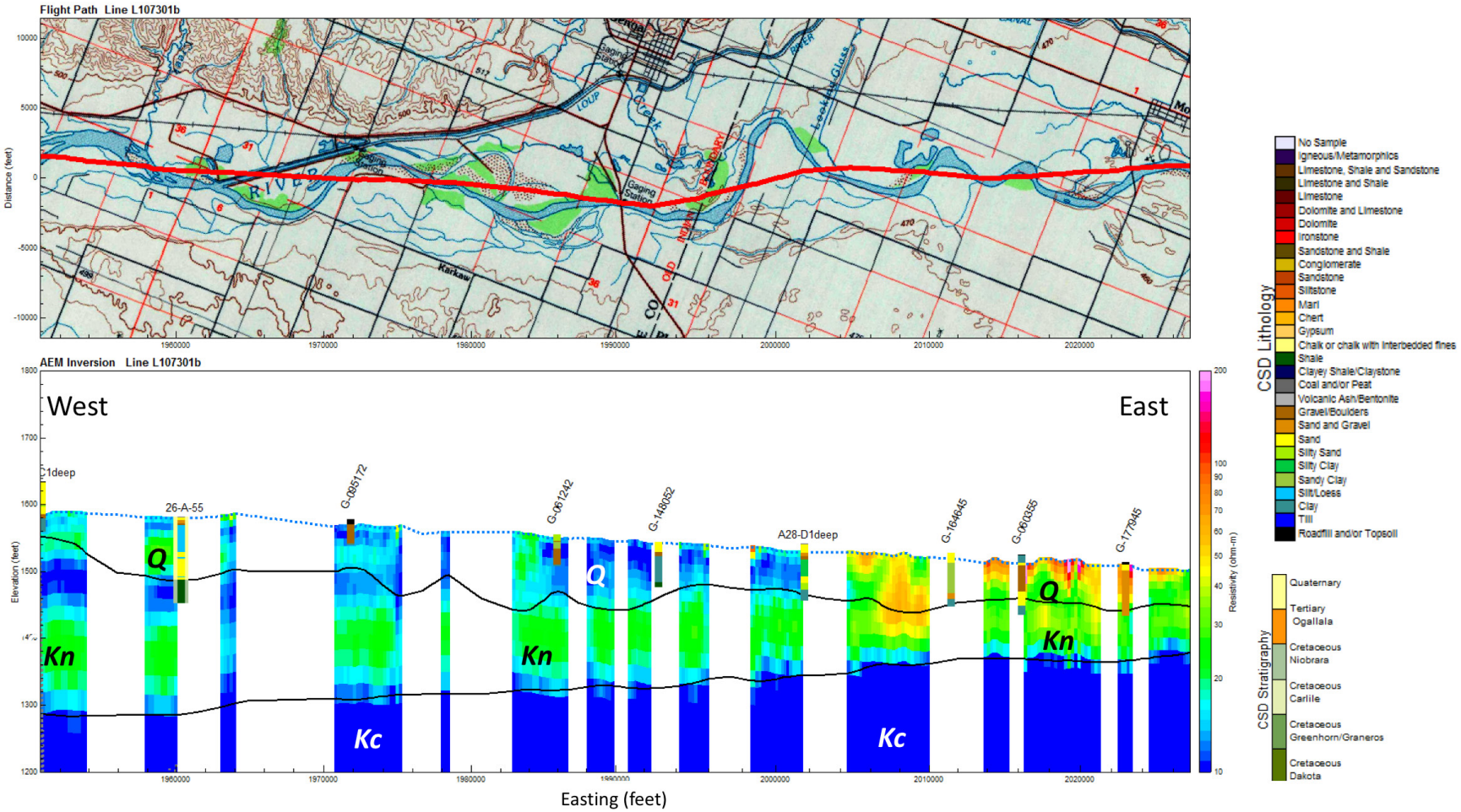


Figure 5-2. Line L107301b displaying the flight path (red line) on the USGS 100K topo map (top map) and the resistivity section along the flight line (bottom profile). CSD (within ½ mile), LLNRD-OA Within ½ mile), and NE-DNR (within 1200 feet) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names (*Q*-Quaternary, *Kn*-Cretaceous Niobrara, *Kc*-Cretaceous Carlile). White gaps in the profile indicate areas clipped out due to coupling or not flown due to infrastructure.

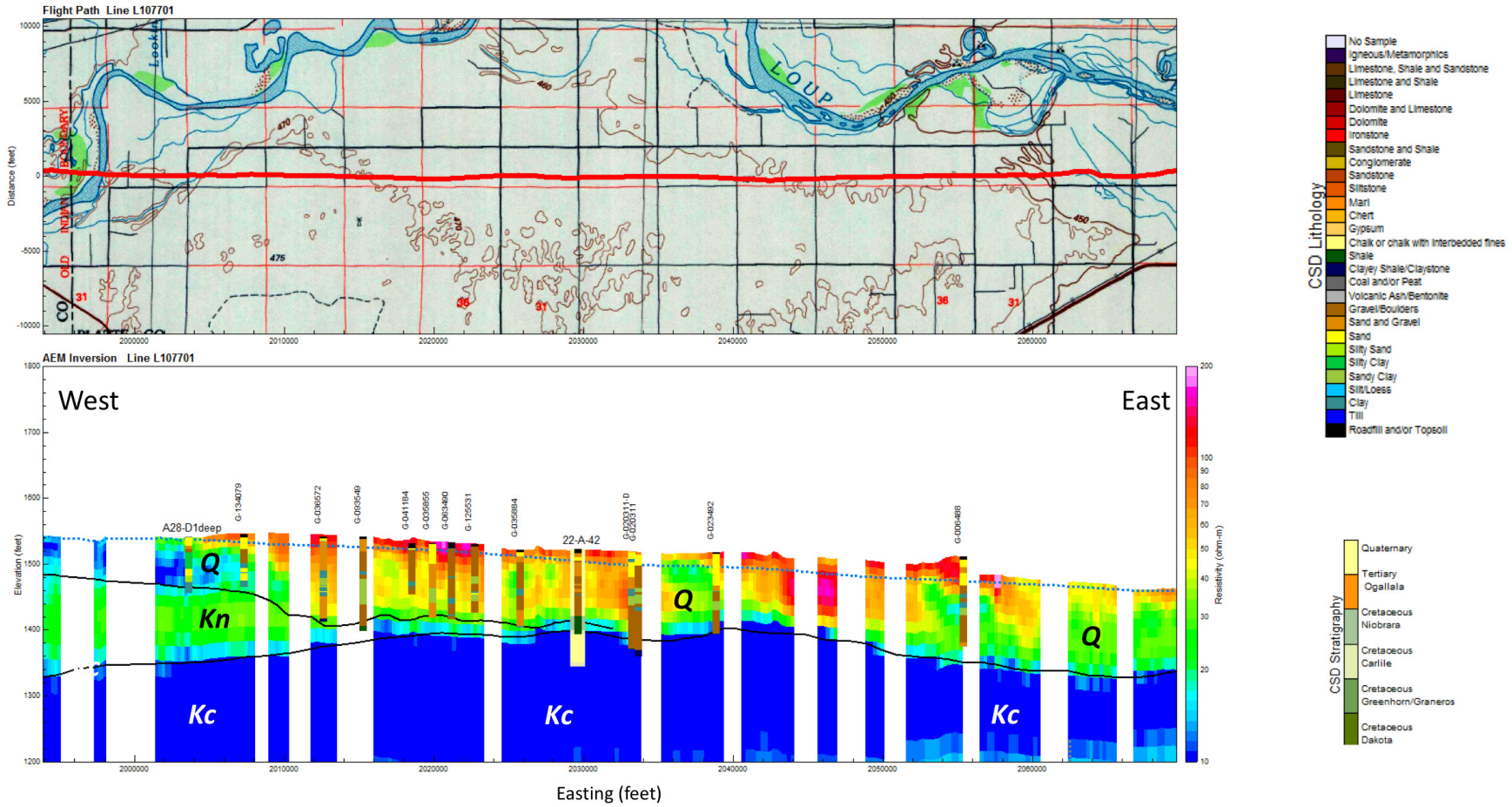


Figure 5-3. Line L107701 displaying the flight path (red line) on the USGS 100K topo map (top map) and the resistivity section along the flight line (bottom profile). CSD (within ½ mile), LLNRD-OA Within ½ mile), and NE-DNR (within 1200 feet) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names (*Q*-Quaternary, *Kn*-Cretaceous Niobrara, *Kc*-Cretaceous Carlile). White gaps in the profile indicate areas clipped out due to coupling or not flown due to infrastructure.

Figure 5-4 is an approximately seven mile long north-south reconnaissance line L131001 flown just east of the town of Monroe, NE that is crossing the Loup River. This flight line is also close to a series of CSD test holes. Figure 5-4 illustrates the interpretation of the top of the ***Kn*** and ***Kc***. Also indicated is an erosional gap in the ***Kn***. As discussed above, the ***Kn*** can be a challenge to interpret directly from the resistivity values. However, the interpretation of the top of the ***Kn*** is facilitated by the presence of the CSD and NE-DNR holes in the area. Figure 5-4 also indicates that the nature of the resistivity of the ***Q*** changes from north to south along the flight line.

L110801, presented in Figure 5-5, is also an approximately seven mile long north-south survey line flown on the western side of the Columbus Block crossing the Loup and Platte rivers. Figure 5-5 illustrates the interpretation of the top of the ***Kc*** and ***Kgg***. This flight line is also close to series of CSD test holes. As discussed above, the ***Kc*** is obvious in the AEM inversion results serving as the base of the Quaternary aquifer system in the area. Several of the NE-DNR wells indicated a coarse sediment package in the area above the ***Kc***. To the north of the profile indications of the topography outside of the flood plain can be observed around CSD test hole *4-A-42*.

L120201, presented in Figure 5-6, is also an approximately seven mile long north-south survey line flown on the eastern side of the Columbus Block, north of the Platte River, and also illustrates the interpretation of the top of the ***Kc*** and ***Kgg***. The ***Kc*** in this region has become thin due to erosion and the ***Kgg*** and ***Kd*** are visible in the profile. The ***Kc*** is less obvious in this area of the Columbus AEM survey block than indicated above to the west. This is a consequence of the eroded nature of the ***Kc*** and that the ***Kgg*** can be composed of shale material that will not necessarily contrast with the ***Kc*** at depth. However, a confident interpretation of the base of the Quaternary aquifer system can be made in this area. Several of the NE-DNR wells indicated a coarse sediment package in the area above the ***Kc***. The exception is around *G-166244* which indicates a clay layer that is also indicated by the resistivities. To the north of the profile, the topography outside the flood plain indicates a loess cover on the ***Q*** sediments.

AEM survey line L211403, presented in Figure 5-7, is approximately 10-miles long and runs east-west south of Lake Babcock and north of Columbus, on the north side of the Columbus Block crossing the Loup River Canal. Figure 5-7 illustrates the interpretation of the top of the ***Kc*** and ***Kgg***. The ***Kc*** in this region becomes thin to the east due to erosion, making the ***Kgg*** more visible in the profile. However, as discussed above the base of the Quaternary aquifer system is confidently interpreted. Many NE-DNR wells in the area indicate the presence of coarse sediments. Outside the flood plain, the ***Q*** materials are covered with a layer of loess.

AEM survey line L211403, presented in Figure 5-8, is also approximately a 10-miles in length and runs approximately east-west along the Loup and Platte rivers confluence and crosses the Loup River Canal on the southern end of the Columbus Block. Figure 5-8 illustrates the interpretation of the top of the *Kc*, *Kgg,* and a portion of the *Kd*. The *Kc* in this region is eroded and indicates a deeper erosional channel below *G-120040E*. Many NE-DNR wells in the area indicate coarse sediments. The up dipping ***Kgg*** and ***Kd*** can also be seen on the eastern end of the profile.

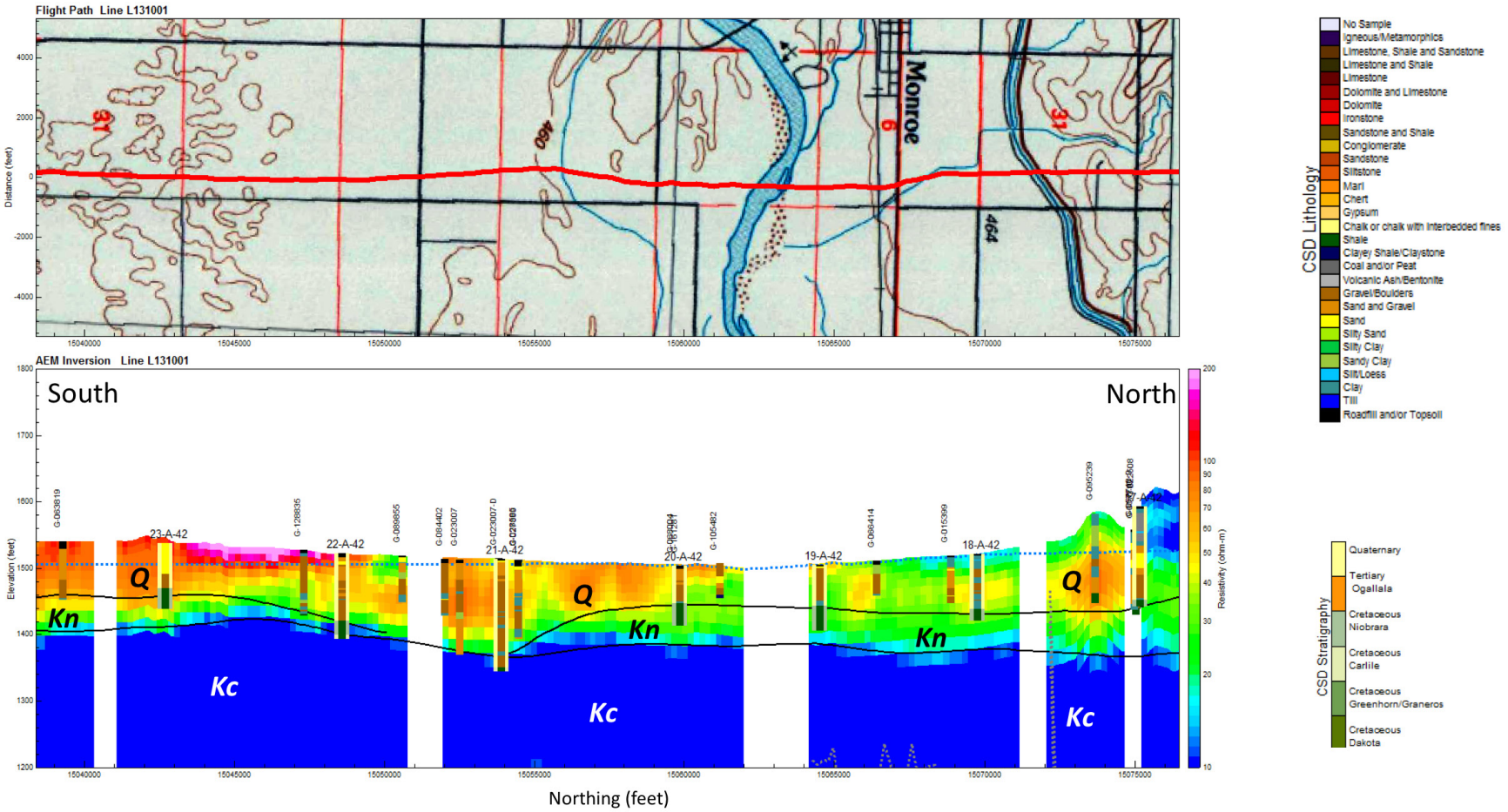


Figure 5-4. Line L131001 displaying the flight path (red line) on the USGS 100K topo map (top map) and the resistivity section along the flight line (bottom profile). CSD (within ½ mile) and NE-DNR (within 1200 feet) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names (*Q*-Quaternary, *Kn*-Cretaceous Niobrara, *Kc*-Cretaceous Carlile). White gaps in the profile indicate areas clipped out due to coupling or not flown due to infrastructure.

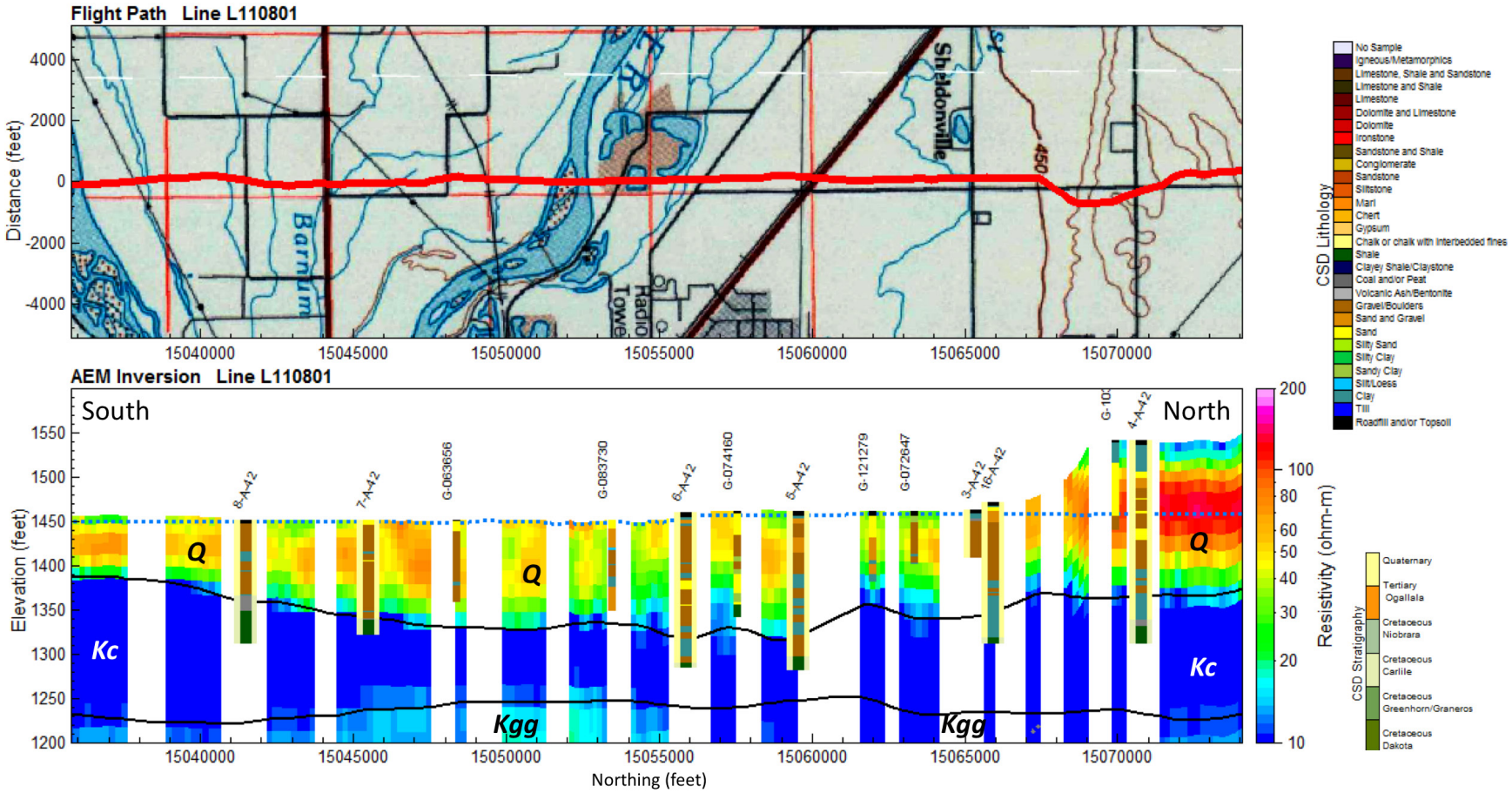


Figure 5-5. Line L110801 displaying the flight path (red line) on the USGS 100K topo map (top map) and the resistivity section along the flight line (bottom profile). CSD (within ½ mile) and NE-DNR (within 1000 feet) borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names (*Q*-Quaternary, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn limestone and Graneros shale). White gaps in the profile indicate areas clipped out due to coupling or not flown due to infrastructure.

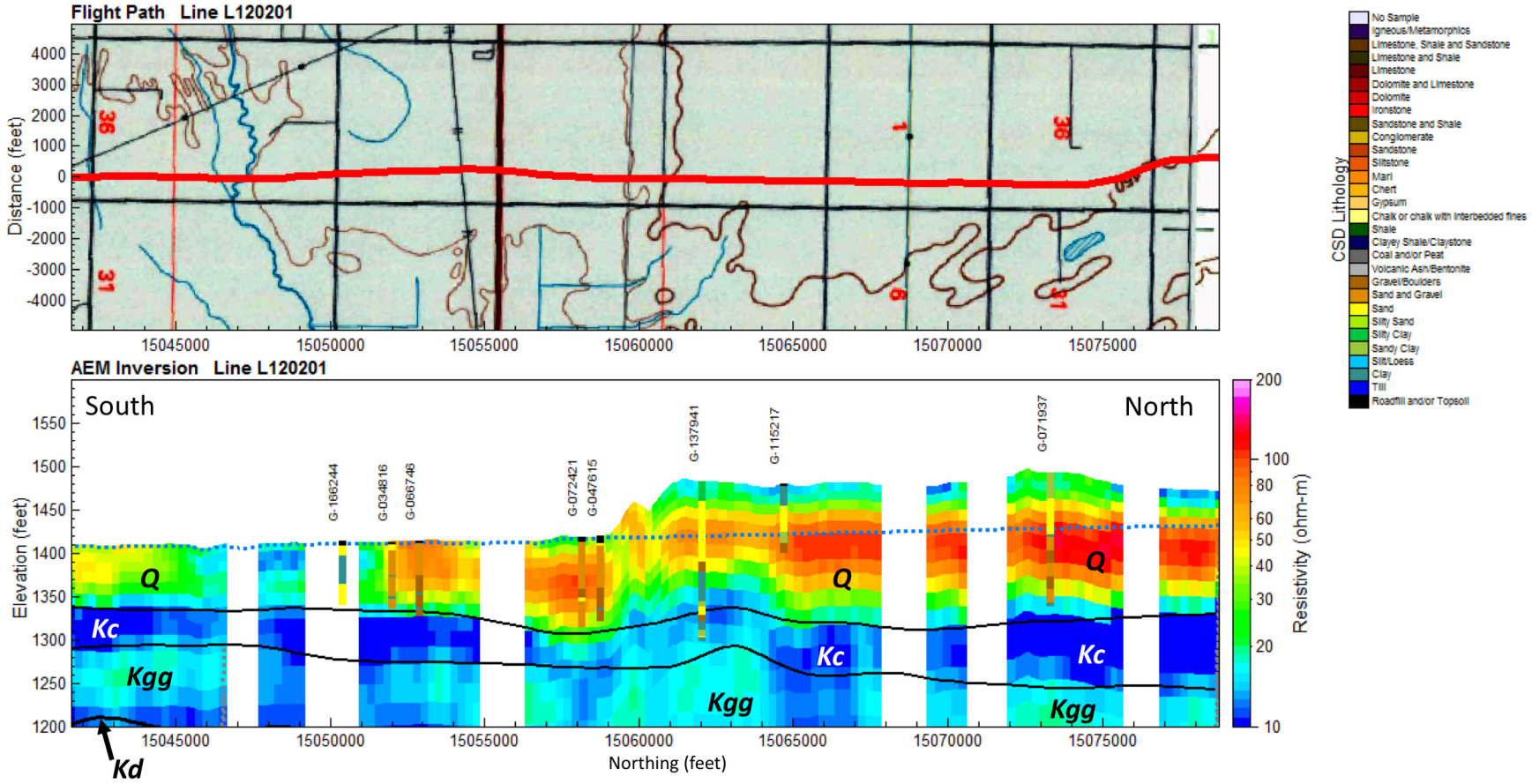


Figure 5-6. Line L120201 displaying the flight path (red line) on the USGS 100K topo map (top map) and the resistivity section along the flight line (bottom profile). NE-DNR (within 1000 feet) borehole lithology are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names (*Q*-Quaternary, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn/Graneros, *Kd*-Cretaceous Dakota). White gaps in the profile indicate areas clipped out due to coupling or not flown due to infrastructure.

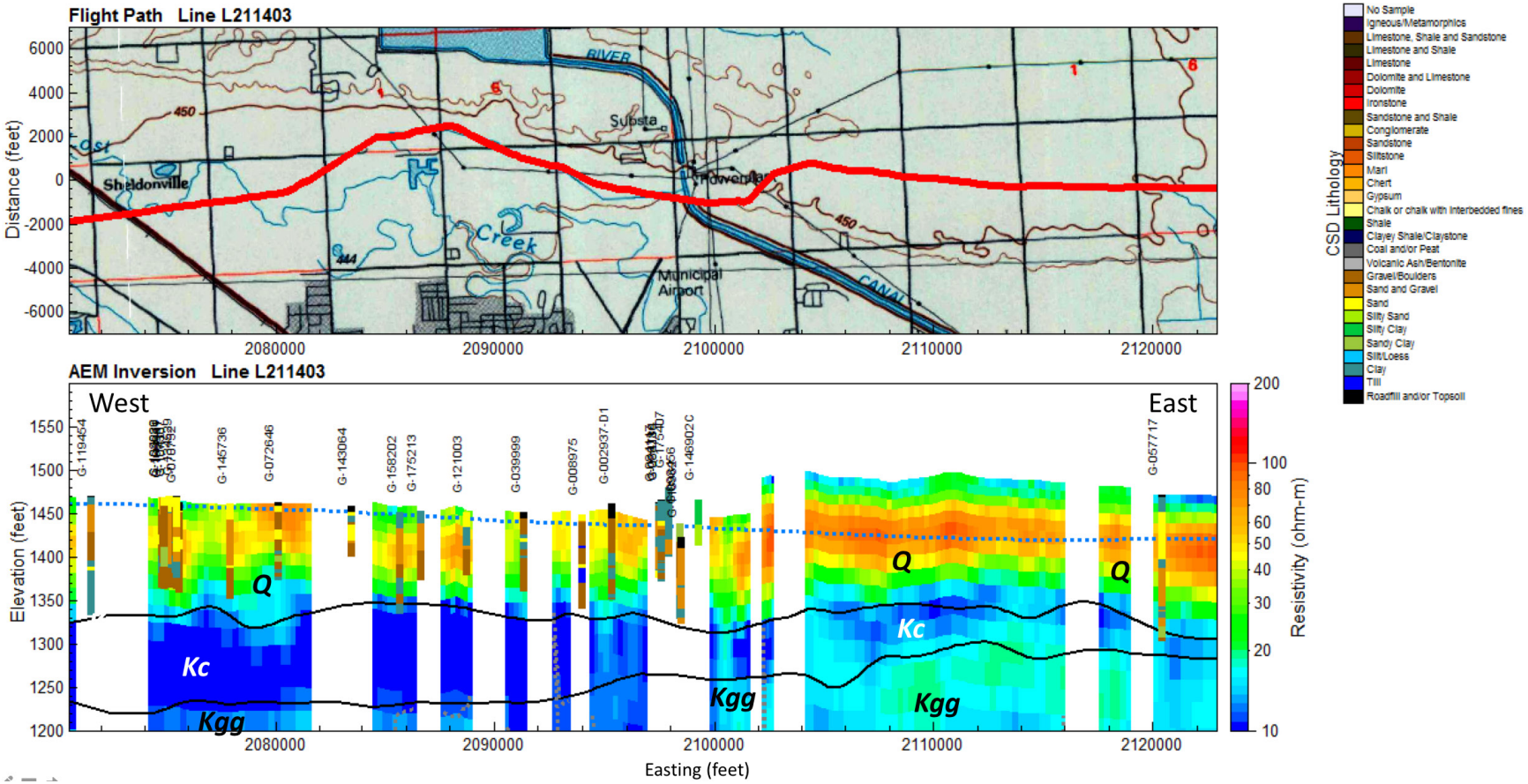


Figure 5-7. Line L211403 displaying the flight path (red line) on the USGS 100K topo map (top map) and the resistivity section along the flight line (bottom profile). NE-DNR (within 1000 feet) borehole lithologies are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names (*Q*-Quaternary, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn limestone and Graneros shale). White gaps in the profile indicate areas clipped out due to coupling or not flown due to infrastructure.

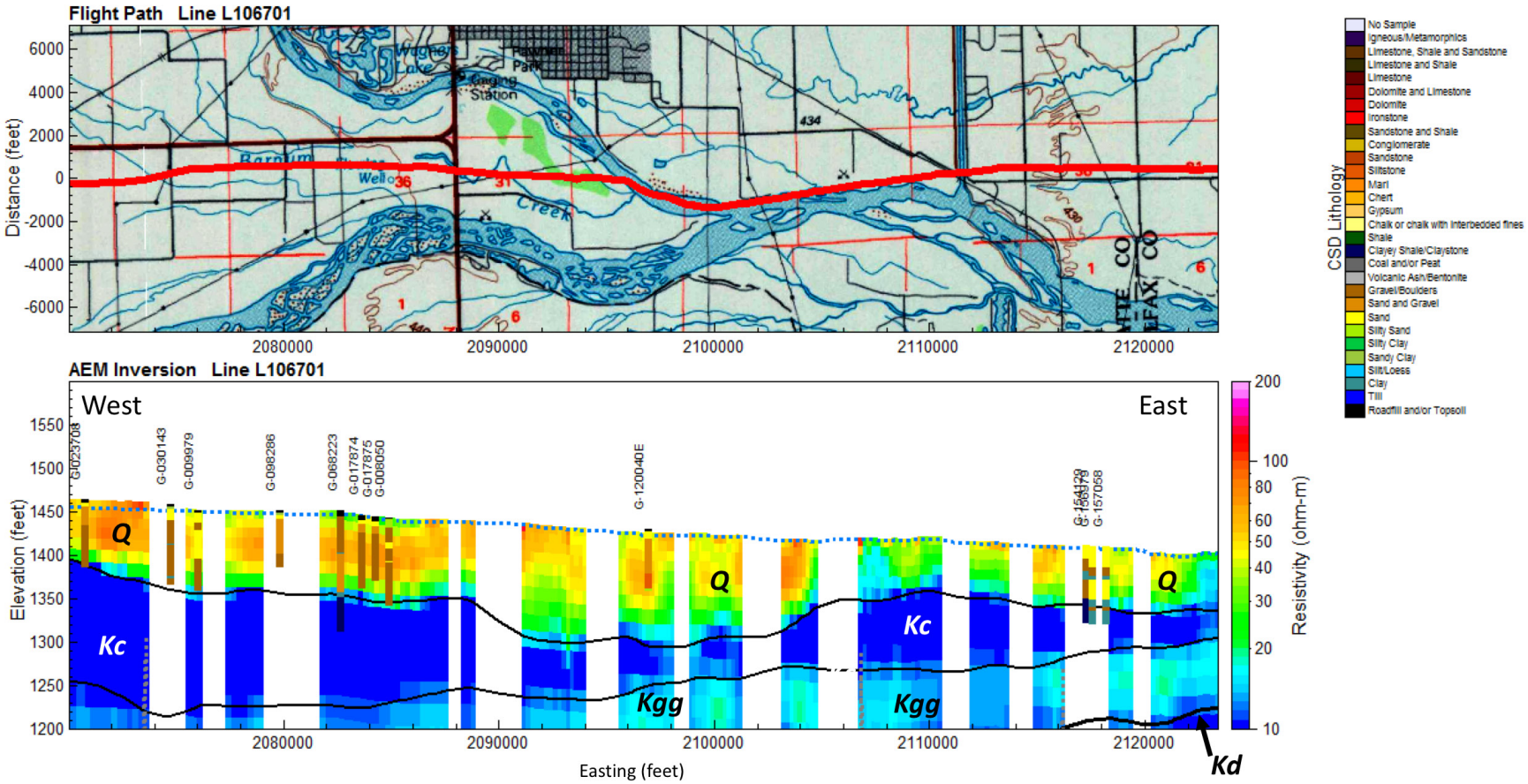


Figure 5-8. Line L106701 displaying the flight path (red line) on the USGS 100K topo map (top map) and the resistivity section along the flight line (bottom profile). NE-DNR (within 1000 feet) borehole lithologies are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names (*Q*-Quaternary, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn limestone and Graneros shale, *Kd*-Cretaceous Dakota). White gaps in the profile indicate areas clipped out due to coupling or not flown due to infrastructure.

5.1.4 Create Interpretative Surface Grids

LLNRD AEM survey area surface grids of geologic formations were also produced. To create these grids, the elevations of the AEM-interpreted top of the formation as well as data from CSD and NE-DNR holes were integrated into 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 with a 250 ft cell size, a blanking distance of 2,500 ft, and the 'cells to extend beyond' set to 50. The grids were then clipped to the area of the survey lines to remove any gridding artifacts from the edges of the areas with no AEM data.

For the ***Kn*** top surface 13 CSD boreholes, two NOGCC holes, and 51 NE-DNR holes were used in addition to the 740 AEM picks. Using the above gridding specifications all other parameters were either left as the default or blank. The large blanking distance was required to fill in between the broadly spaced reconnaissance lines where three miles or more separated adjacent flight lines. A 5x5 cell averaging filter was used to smooth out any gridding artifacts. CSD, NOGCC, and NE-DNR holes were used to provide additional formation elevation data throughout the project area. The 250 ft cell size preserved most of the spatial resolution obtained from the AEM data but minimized artifacts from the MCG routine. While the MCG routine performs reasonably well with honoring the data, in areas where the spatial density of data points is low, the MCG routine may trend towards an overall average data value. Figure 5-9 is a map of the elevation of the top of the ***Kn*** within the LLNRD AEM survey area.

To define the ***Kc*** top surface 10 CSD boreholes, two NOGCC wells, and 140 NE-DNR holes were used in addition to the 2,821 AEM picks. Using the above specifications in the previous paragraph all other parameters were either left as the default or blank. As with the ***Kn*** process, the large blanking distance was required to fill in between the broadly spaced reconnaissance lines where three miles or more separated adjacent flight lines. A 7x7 cell averaging filter was used in this case to removing any gridding artifacts. CSD and NE-DNR holes were used to provide additional formation elevation data throughout the project area. The 250 ft cell size preserved most of the spatial resolution obtained from the AEM data but minimized artifacts from the MCG routine. While the MCG routine performs reasonably well with honoring the data, in areas where the spatial density of data points is low, the MCG routine may trend towards an overall average data value. Figure 5-10 is a map of the elevation of the top of the ***Kc*** within the LLNRD AEM survey area. Figure 5-11 is a map of the top of the ***Kc*** within the Columbus AEM survey block.

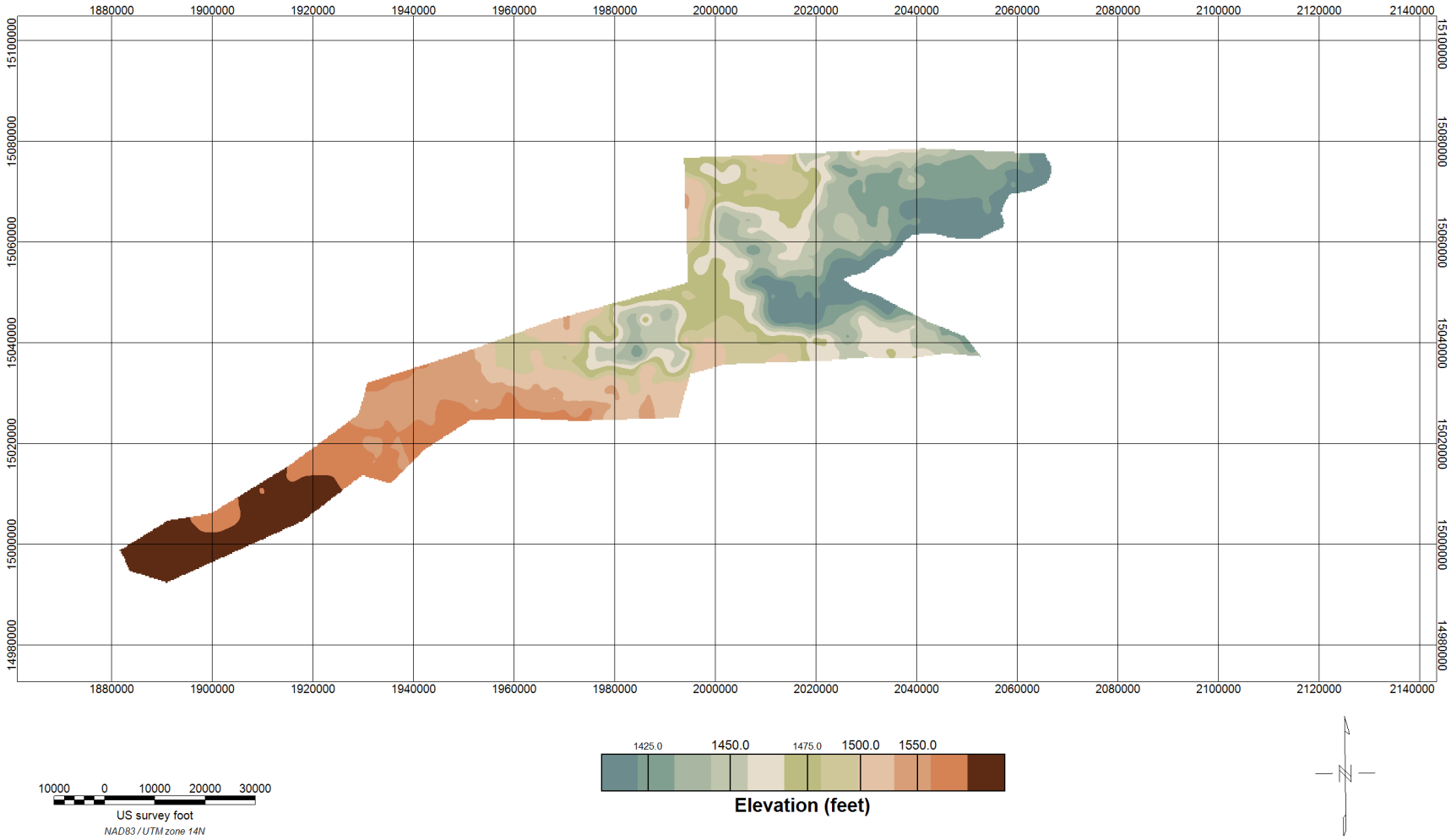


Figure 5-9. Map of the elevation of the top of the Cretaceous Niobrara (*Kn*) Fm within the LLNRD AEM survey area. The projection is NAD83 and the elevation values are referenced to NAVD 88.

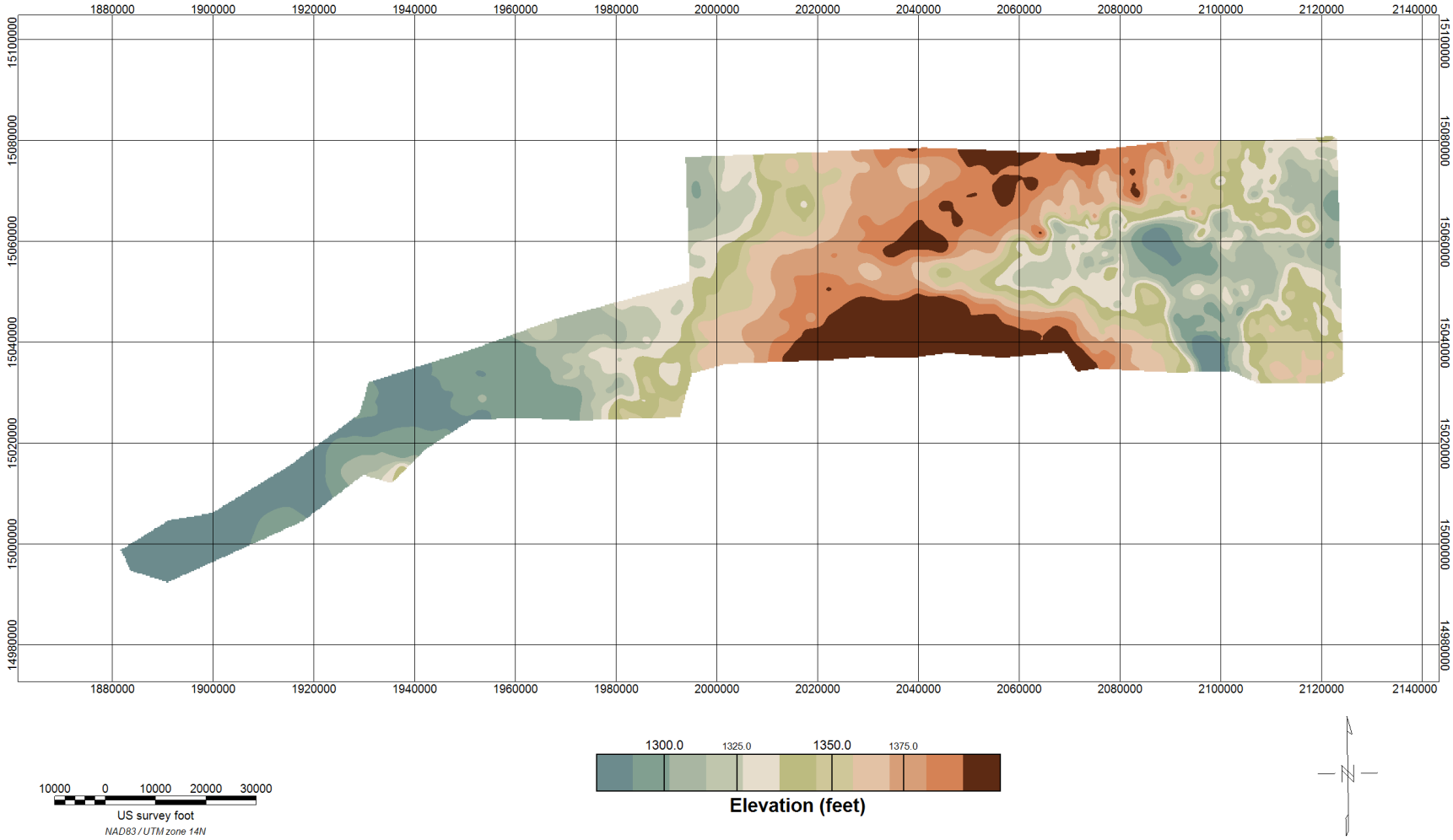


Figure 5-10. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) Fm within the LLNRD AEM survey area. The projection is NAD83 and the elevation values are referenced to NAVD 88.

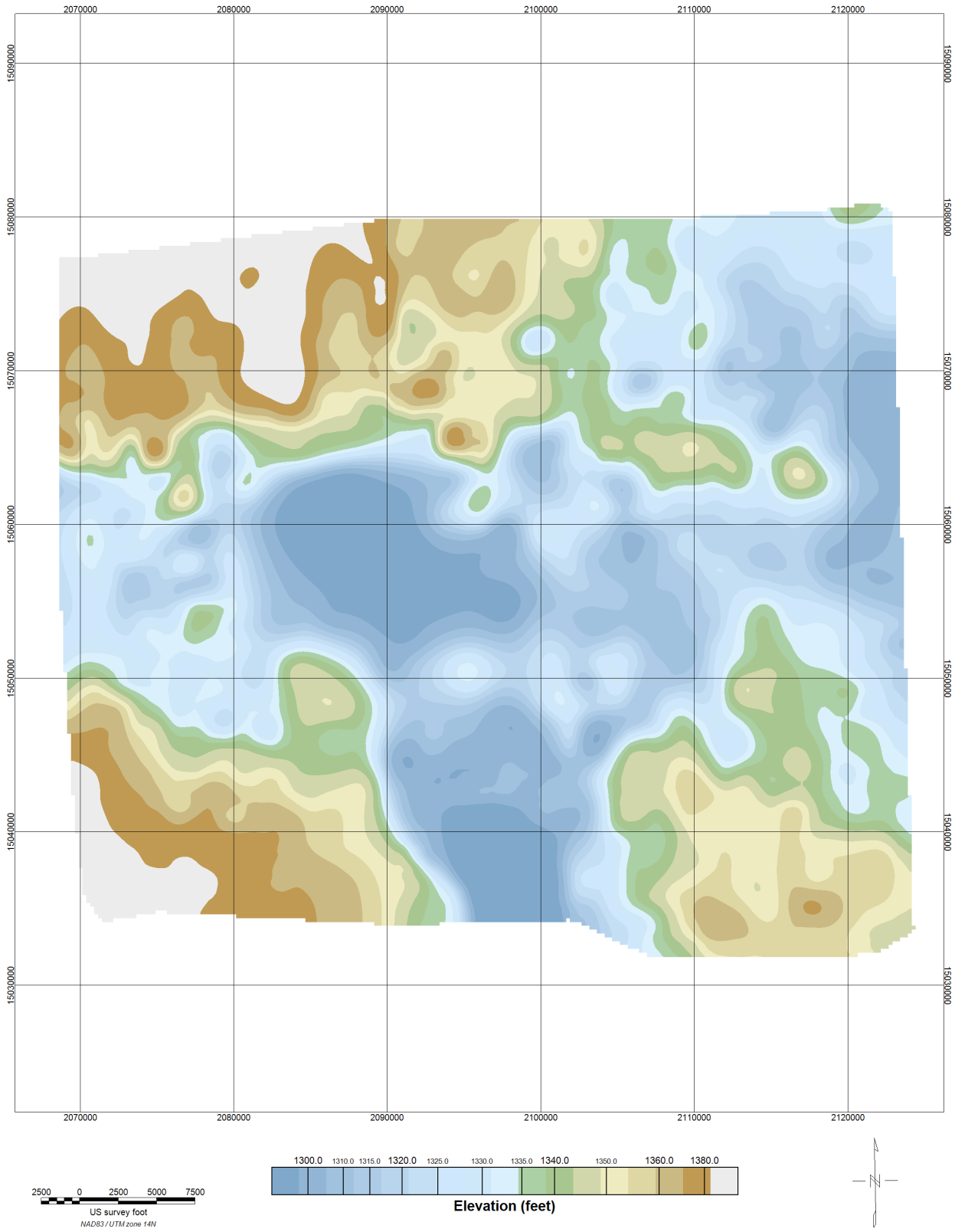


Figure 5-11. Map of the elevation of the top of the Cretaceous Carlile (*Kc*) Fm within the Columbus Block. The projection is NAD83 and the elevation values are referenced to NAVD 88.

The bedrock or the base of the Quaternary (***Q***) aquifer throughout the LLNRD is a combination of the ***Kn*** and ***Kc*** surfaces. The ***Kn*** is eroded away on the eastern end of the reconnaissance area and under all the Columbus AEM survey block area. As indicated in Carney et al. (2015a), the ***Kn*** can be a local aquifer when fractured and the fractures have connection to surface water sources. However, in this region it is assumed that the ***Kn*** is a non-aquifer and thus the base of the aquifer system in the area. To construct the top of bedrock or the base of the aquifer system, the two surfaces were combined into one at a 250 ft grid cell size (Figure 5-12). The grid was then clipped to the LLNRD flight lines area.

For the ***Kgg*** top surface, three NOGCC holes were used in addition to the 1,778 AEM picks. Using the above gridding specifications all other parameters were either left as the default or blank. The large blanking distance was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. A 5x5 cell averaging filter was used to smooth out any gridding artifacts. NOGCC holes were used to provide additional formation elevation data throughout the project area. The 250 ft cell size preserved most of the spatial resolution obtained from the AEM data but minimized artifacts from the MCG routine. While the MCG routine performs reasonably well with honoring the data, in areas where the spatial density of data points is low, the MCG routine may trend towards an overall average data value. The ***Kgg*** is not considered an aquifer in the LLNRD AEM survey area and is included for geological control. Figure 5-13 is a map of the elevation of the top of the ***Kgg*** within the LLNRD AEM survey area. Figure 5-14 is a map of the elevation of the top of the ***Kgg*** within the Columbus Block.

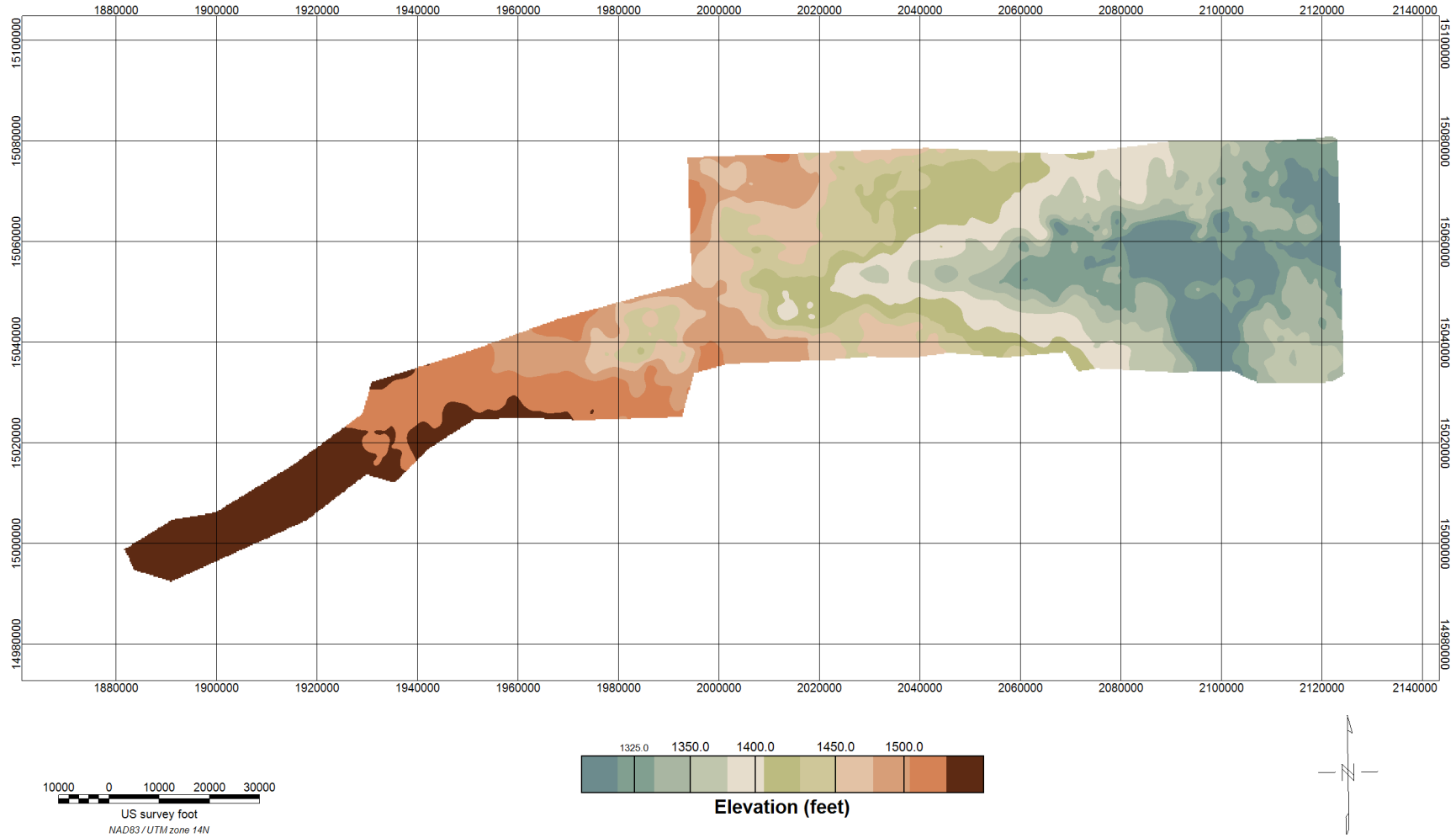


Figure 5-12. Map of the elevation of the top of the bedrock or the base of the Quaternary (*Q*) aquifer composed of the Cretaceous Niobrara (*Kn*) and the Cretaceous Carlile (*Kc*) within the LLNRD AEM survey area. The projection is NAD83 and the elevation values are referenced to NAVD 88.

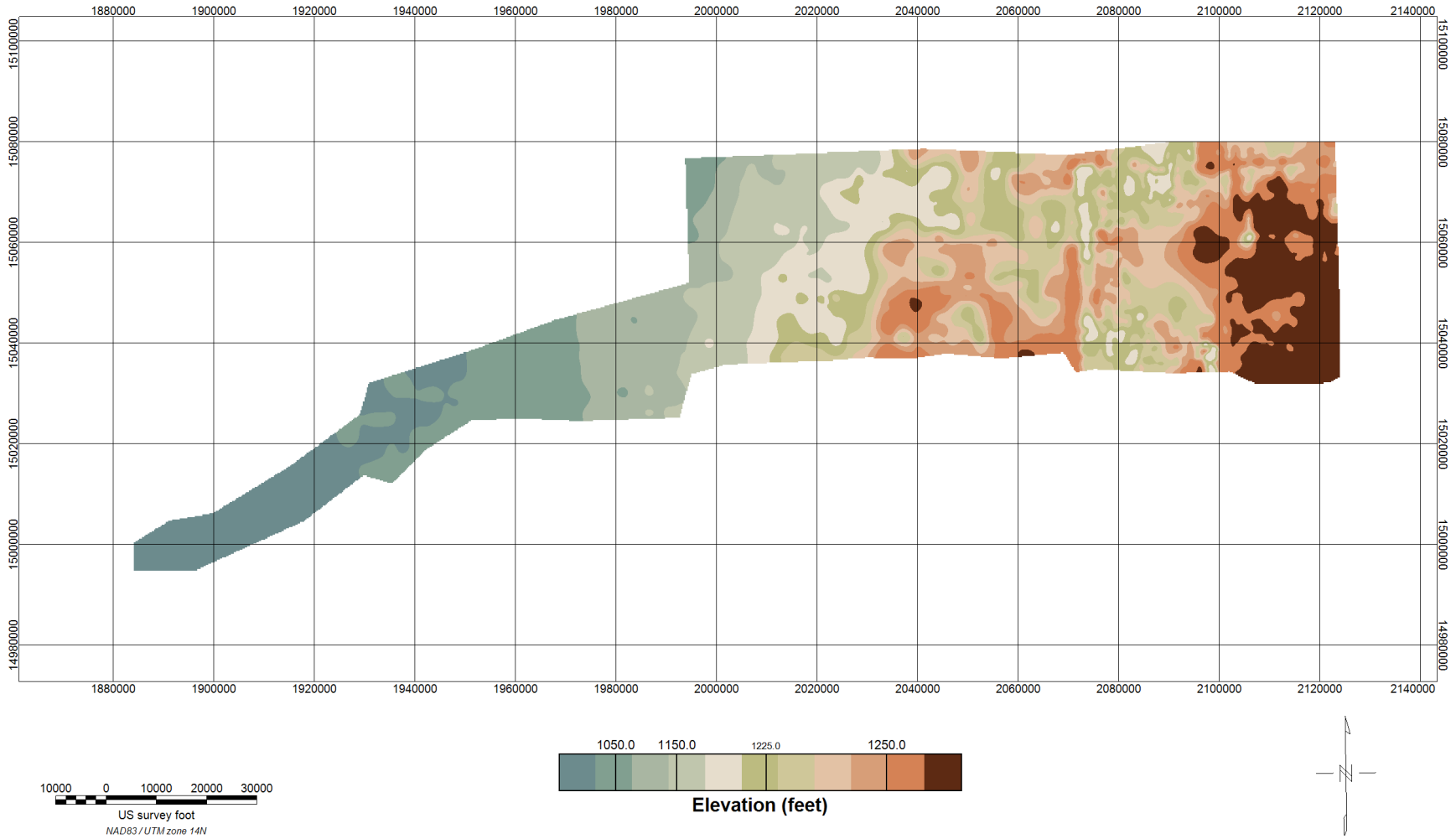


Figure 5-13. Map of the elevation of the top of the Cretaceous Greenhorn limestone and Graneros shale (*Kgg*) within the LLNRD AEM survey area. The projection is NAD83 and the elevation values are referenced to NAVD 88.

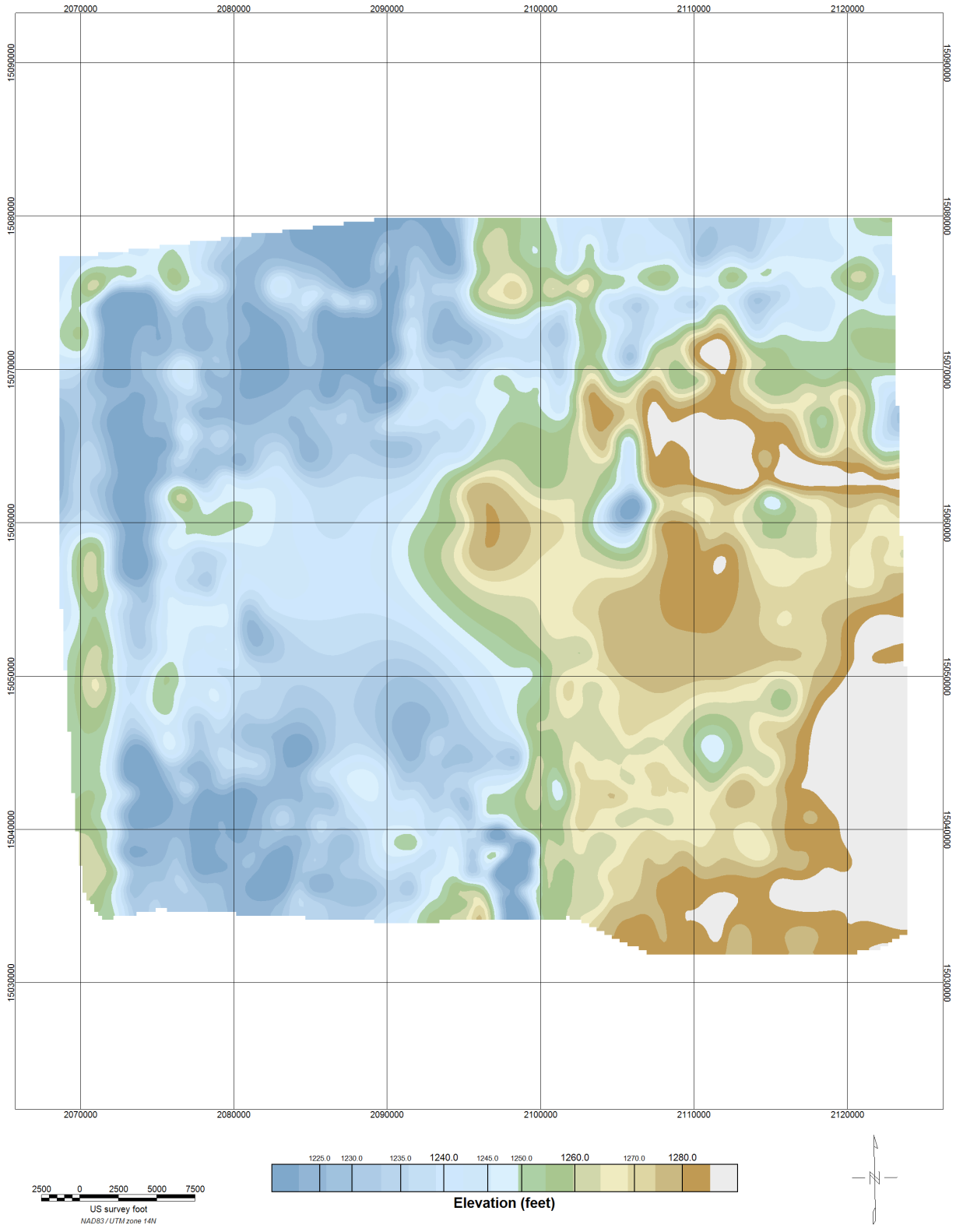


Figure 5-14. Map of the elevation of the top of the Cretaceous Greenhorn limestone and Graneros shale (*Kgg*) within the Columbus Block. The projection is NAD83 and the elevation values are referenced to NAVD 88.

For the ***Kd*** top surface three NOGCC holes were used in addition to the 285 AEM picks. The ***Kd*** was gridded at a 500-foot cell size due to the limited control within the area and the fact that the ***Kd*** is below the DOI at the western end of the reconnaissance area and was not interpreted. The large blanking distance was required to fill in between the broadly spaced reconnaissance lines, where three miles or more separated adjacent flight lines. A 5x5 cell averaging filter was used to smooth out any gridding artifacts. NOGCC holes were used to provide additional formation elevation data throughout the project area. The 500 ft cell size preserved most of the spatial resolution obtained from the AEM data but minimized artifacts from the MCG routine. While the MCG routine performs reasonably well with honoring the data, in areas where the spatial density of data points is low, the MCG routine may trend towards an overall average data value. The ***Kd*** is not considered an aquifer in the LLNRD AEM survey area and is included for geological control. Figure 5-15 is a map of the elevation of the top of the ***Kd*** within the LLNRD AEM survey area. Figure 5-16 is a map of the elevation of the top of the ***Kd*** within the Columbus Block.

Following construction of the bedrock surface, the consolidated and unconsolidated deposits were isolated within the AEM data. The aquifer and non-aquifer materials in the Quaternary system were separated by four major resistivity thresholds (selected in Encom PA (pbEncom, 2016)). These ranges include 1) less than 12 ohm-m, representing non-aquifer materials ("aquitard"- primarily glacial till, loess); 2) 12-20 ohm-m, representing marginal aquifer deposits with potential for interlayered silt and clay, 3) 20-50 ohm-m, indicating the Quaternary system's principal aquifer, and 4) an interval of 50 ohm-m or greater, indicating the coarsest, sand-rich intervals within the principal aquifer (further discussion regarding the selection of these threshold ranges is provided in the following section and in Carney et al. (2015a)). Results of these interpretations can be found in appendices 1 (2D profiles) and 2 (3D images) for the LLNRD AEM survey area reconnaissance lines the Columbus Block flight lines.

To assist in the approximation of the saturated materials along the surveyed AEM flight lines, the LLNRD provided water tables from their 2016 measurements (section 2.2) for both the Area 28 Reconnaissance Area and the Columbus Block (LLNRD, 2017). The water table in much of the LLNRD AEM survey area is close to the surface. To this end a topographic correction was required to ensure that the water table elevation be below the surface topography. Thus, for both the LLNRD Reconnaissance Area and the Columbus Block 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 regridded at a 100 ft cell size and compared with the DEM of the LLNRD AEM survey area. In areas where the water table elevation was greater than the topography, the water table was set to the elevation of the topography minus two feet. The grid was then clipped to the LLNRD Area 28 Reconnaissance Area and the Columbus Block area. The results are presented in Figure 5-17 for the Reconnaissance Area and Figure 5-18 for the Columbus Block.

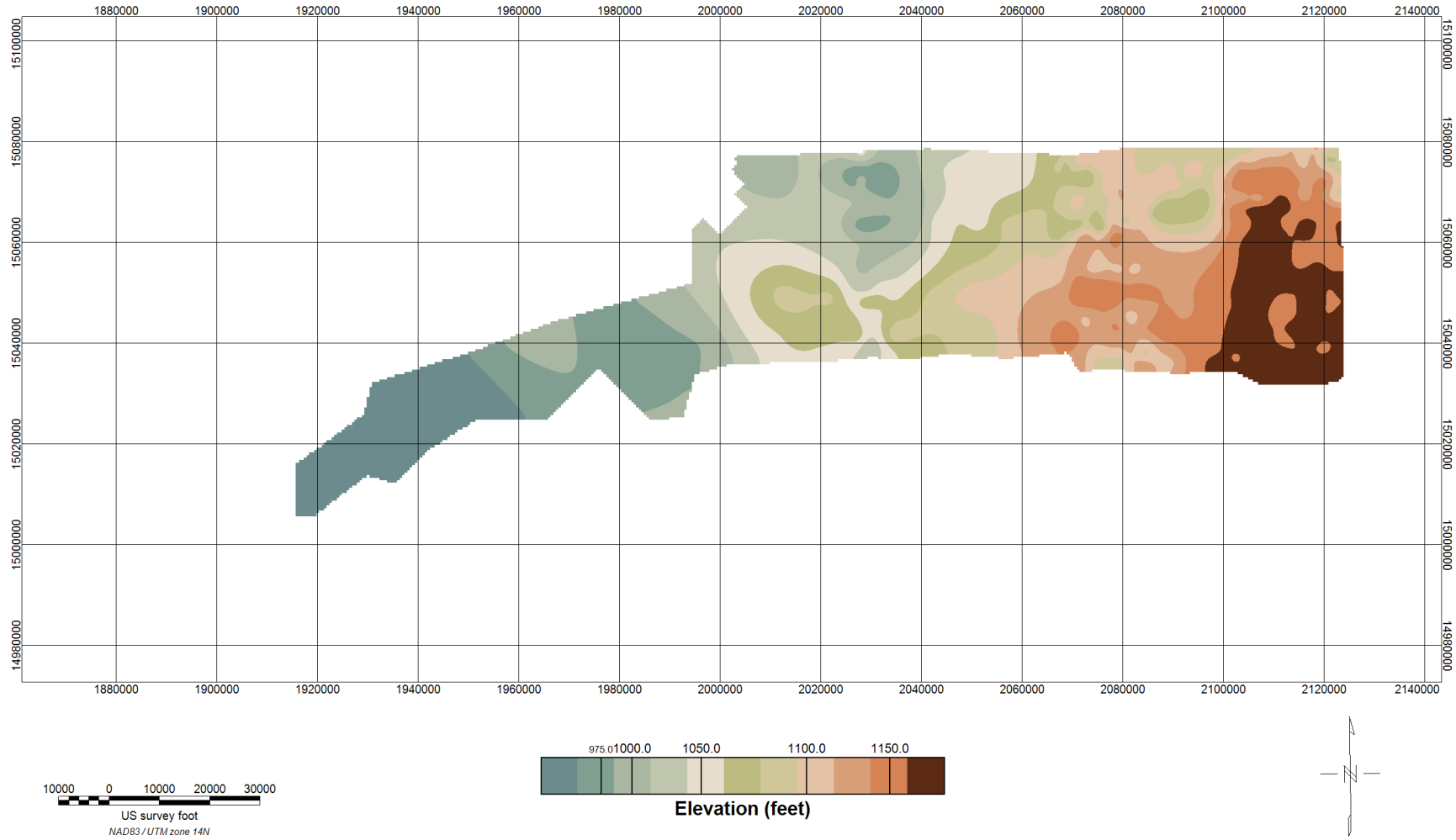


Figure 5-15. Map of the elevation of the top of the Cretaceous Dakota (*Kd*) Group within the LLNRD AEM survey area. The projection is NAD83 and the elevation values are referenced to NAVD 88.

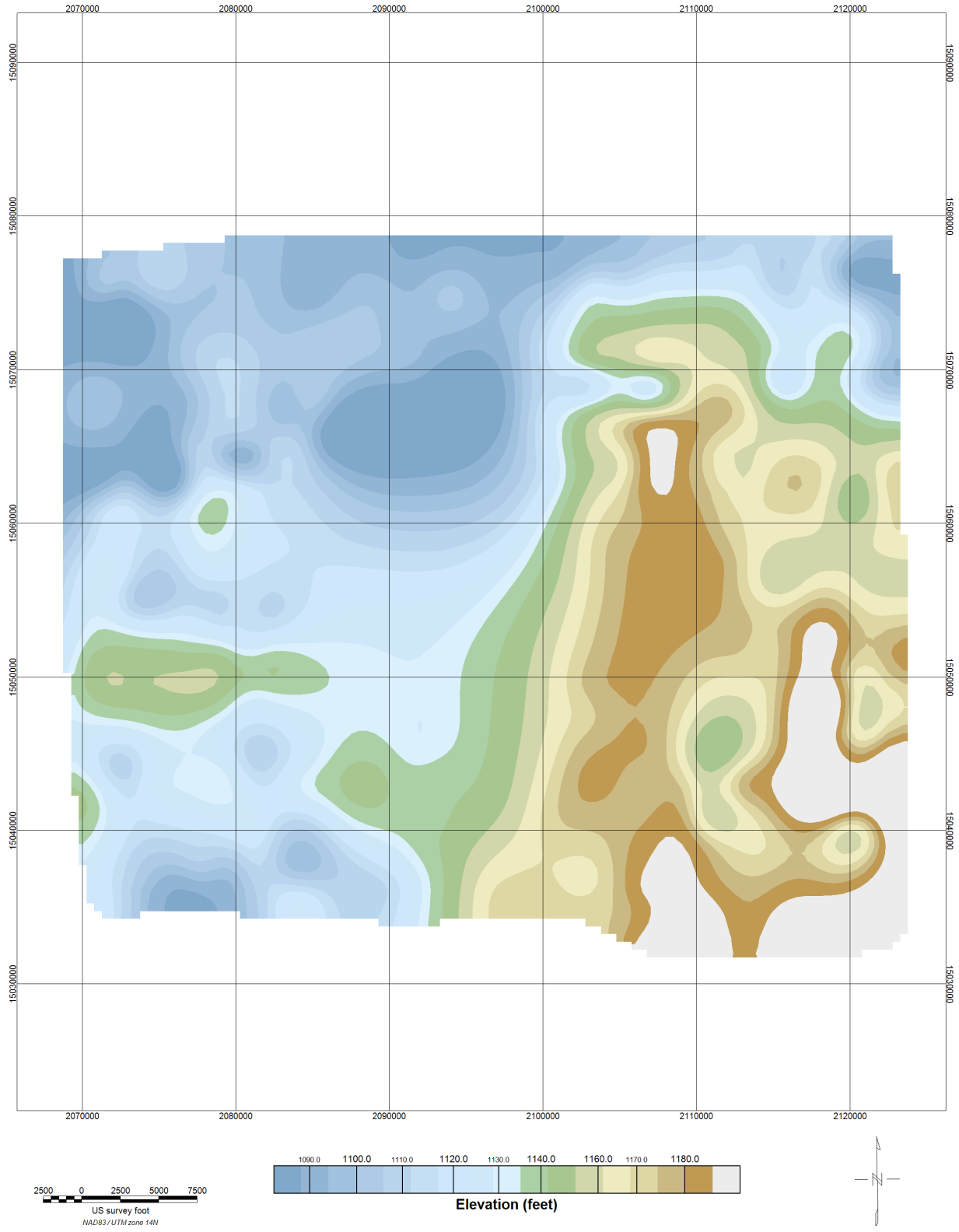


Figure 5-16. Map of the elevation of the top of the Cretaceous Dakota (*Kd*) Group within the Columbus Block. The projection is NAD83 and the elevation values are referenced to NAVD 88.

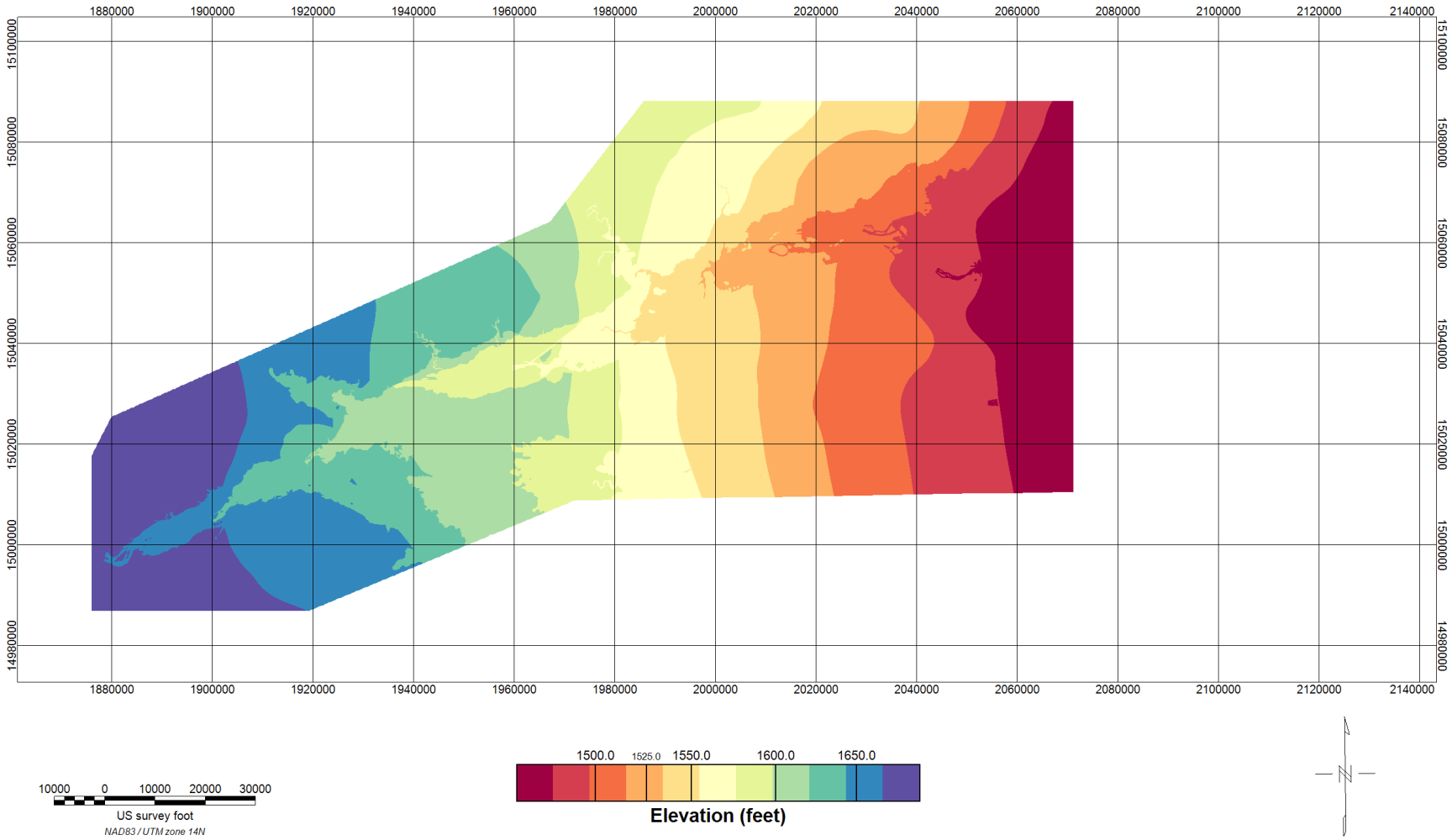


Figure 5-17. Map of the elevation of the 2016 water table for the Area 28 Reconnaissance Area. The projection is NAD83 and the elevation values are referenced to NAVD 88.

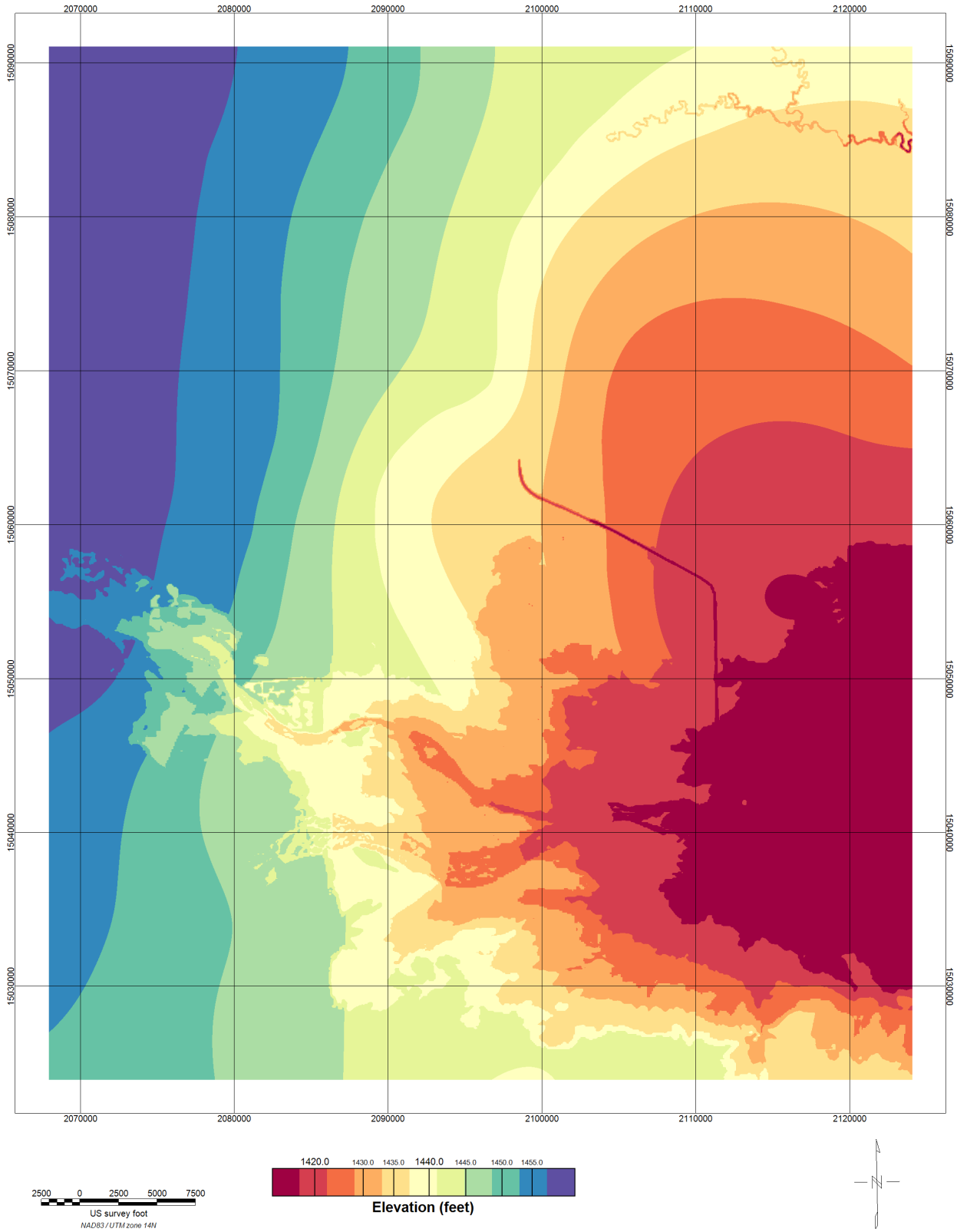


Figure 5-18. Map of the elevation of the 2016 water table within the Columbus Block. The projection is NAD83 and the elevation values are referenced to NAVD 88.

A voxel grid was completed for the Columbus Block area within the LLNRD AEM survey area. A voxel grid was not completed for the reconnaissance flight lines due to the large distance (approximately three miles) between lines and the variable aquifer material within that spacing. The voxel grids were made using a 250 ft grid cell size and the model layer thickness (Table 4-4 in the previous section). A minimum curvature method was used within Encom PA (pbEncom, 2016). All layers were referenced to their depth from the surface. After the grid was calculated, the bedrock/base of aquifer system was then truncated/clipped from the voxel grid using the bedrock/base of aquifer grid explained above (This is also the ***Kc*** surface in the Columbus Block). It is important to note that within the survey area, the portion of the Columbus block that were not flown with the AEM system required interpolation. Figure 1-2 shows the flight lines and how there is an AEM data gap within the area of Columbus. To assist the interpolation, selected wells were used as control points in the voxel grid. This was accomplished by assigning resistivities to the lithology based on the work from Carney et al. (2015a). Those points were then included in the voxel grid to assist in the interpolation between lines.

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

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

5.2 Resistivity-Lithology Relationship

5.2.1 Quaternary/Tertiary Ogallala Aquifer System

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

Data for this analysis was utilized from locations across the ENWRA reconnaissance line area (Carney et al., 2015a). The relationship between resistivity and lithology type was assessed by performing an association function that linked nine lithologic descriptor codes for ***Q/To*** sediments used in the CSD test hole lithologic characterization with the resistivity values across that depth interval as indicated in 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. (2015a). A summary of the resistivities and the color scale is shown in Figure 5-19.

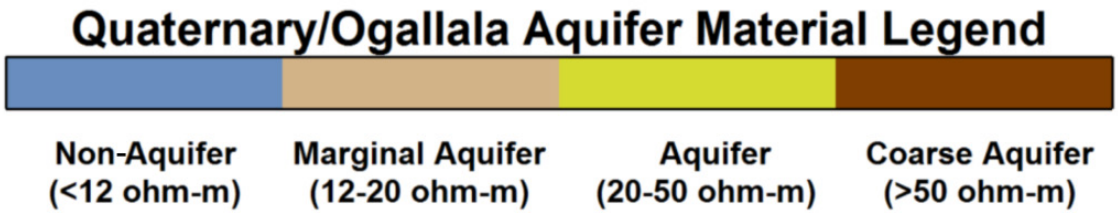


Figure 5-19. Plot displaying the resistivities by major aquifer material color categories (blue- non-aquifer material, tan- marginal aquifer, yellow- aquifer, brown- sand-rich, coarse intervals of the aquifer material).

5.2.2 Bedrock Resistivity Thresholds

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

5.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs

One CSD borehole geophysical resistivity log *26-A-55* and one NOGCC borehole (*API-1234567819999999*) (also with NE-DNR registration *G-87761*) were selected from the LLNRD for comparison with the AEM inversions: Since the resistivity logs within the database are of various vintages and conducted by various staff with differing equipment, a critical examination of the absolute values of the resistivity needs to include an awareness of errors in calibration and in the proper operation of the equipment. There is a long-standing issue with using geophysical logs as ground truths when comparing to AEM inversions that are well calibrated using modern techniques. Throughout much of the world of 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 being included within the CSD database. Note that these logs still have scientific merit in their ability to relatively indicate an increase or a decrease in the formation resistivity. The logs used herein are for qualitative comparison to the AEM because detailed calibration and corrections would need to be carried out for the resistivity values in the logs to be directly used as numerical constraints in the inversion of the AEM data (Ley-Cooper and Davis, 2010).

Figure 5-20 is a plot of the *26-A-55* 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L107301. Borehole *26-A-55* is located about 2,253 feet from line L107301 and the AEM sounding was selected as the closest point to the borehole geophysical log. The agreement in the resistivity is not great with the AEM indicating a much lower resistivity. While the shape of the curves are somewhat similar, there is a shift in the general location of the relatively resistive body. The AEM is indicating the aquifer material higher in the section then the geophysical log and the lithology log. This would indicate that the lithology has changed over the distance of the borehole to the AEM sounding. The AEM and *26-A-55* both indicate the lower resistivity of the ***Kn*** at the same location. Overall, the borehole log and the AEM show that there is a change in the position of the Quaternary Aquifer material within the distance of 2,253 feet but the depth of the ***Kn*** is consistent at 98 feet.

Figure 5-21 is a log of NOGCC borehole *API-1234567819999999* (NE-DNR registration *G-87761*) 16-inch short normal resistivity log plotted with the inverted AEM resistivity for line L111202. *G-87761* is located 30 ft feet from line L111202 and the AEM sounding presented was the closest point to the borehole geophysical log. The well does not contain any lithology information and the geophysical starts at the top of the bedrock units. Overall there is not a good match in the resistivity values. This may indicate a shift in the geophysical log. However, there is good agreement in a portion of the log within the ***Kd***, but the magnitude of the resistive anomaly in the ***Kgg*** is higher than that seen in other locations Carney et al. (2015a). The increased resistivity in the ***Kd*** is not indicated in the AEM and that may be due to the resistive anomaly is below the DOI. Also important to note is that the character of the logs indicates some potential that the stratigraphy may be composed of Pennsylvanian units (Carney et al., 2015b). Overall this log provides very little to the understanding of the bedrock unit resistivity due to the poor agreement and the potential that the log is shifted and that there is not 500 ft of ***Kd*** at this location.

5.2.4 Comparison of AEM Inversion Resistivity to Historic CSD Cross Sections

A comparison has also been conducted between available historic CSD cross sections and the AEM inverted earth models in Area 28 and the Columbus Block survey areas. The historic cross sections are derived from Divine (2012), Divine et al. (2010), and Korus et al. (2012). The color scheme is modified after Carney et al. (2015a).

A comparison of CSD cross section Platte2004W1604W and a north-south reconnaissance flight line on the western side of Area 28 is presented in Figure 5-22. CSD cross section Platte2003W1602W and another north-south reconnaissance flight line on the eastern side of Area 28 are presented in Figure 5-23. A north-south AEM flight line on the west side of the Columbus block is compared with CSD cross section Platte2001W1701W in Figure 5-24.

Close examination of the sections indicates good correlation between the historic cross sections and the AEM inverted earth models. In particular, where aquifer materials and coarse aquifer materials are indicated in the interpreted AEM cross sections, sand and gravel units are indicated in the historic CSD cross sections. Similarly, non-aquifer materials and marginal aquifer materials in the AEM sections correlate with silts and other fine-grained material in the CSD cross sections.

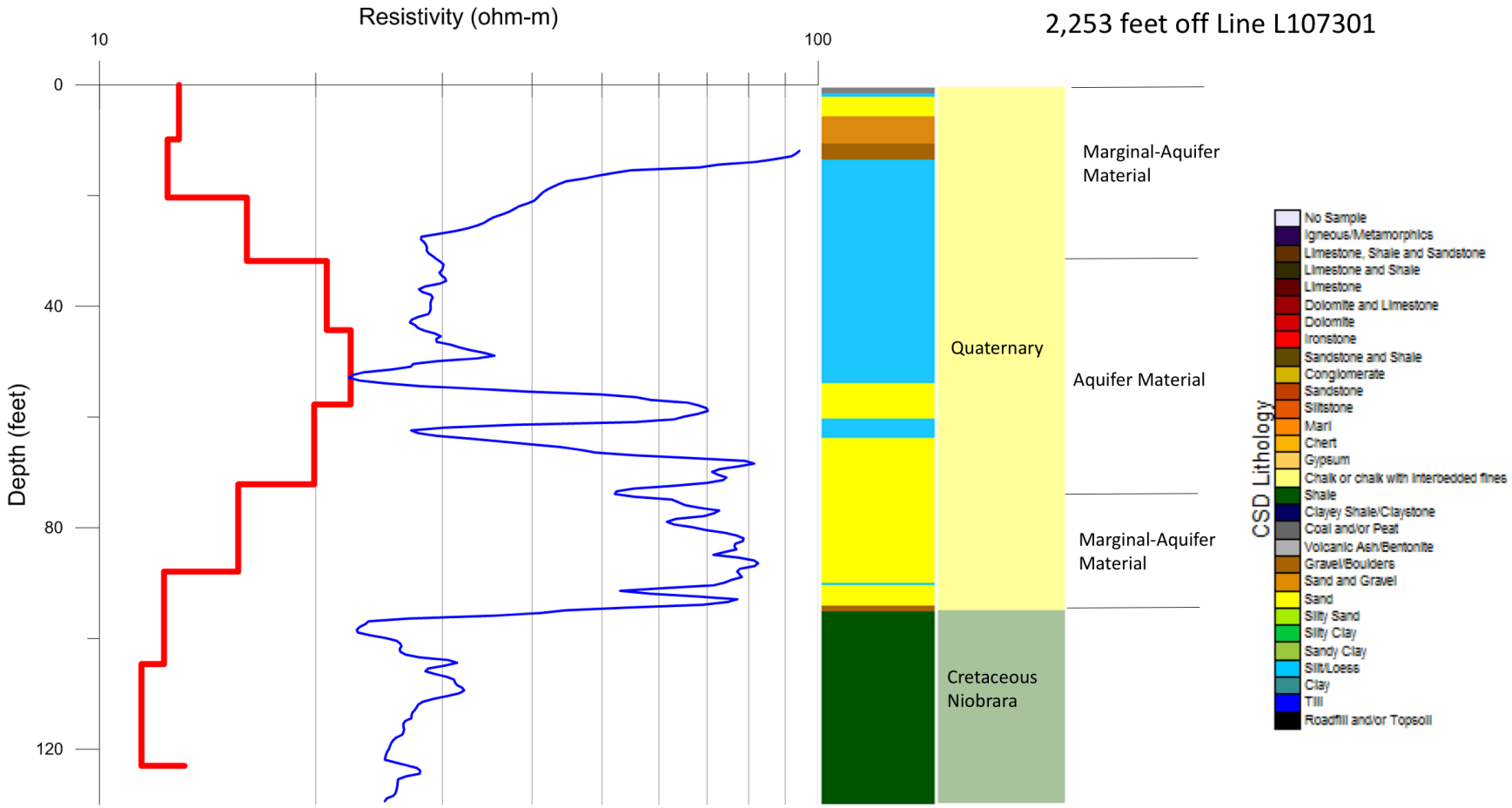


Figure 5-20. Graph of the *26-A-55* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology and stratigraphy log from *26-A-55* as well as the aquifer material categories from the AEM inversion.

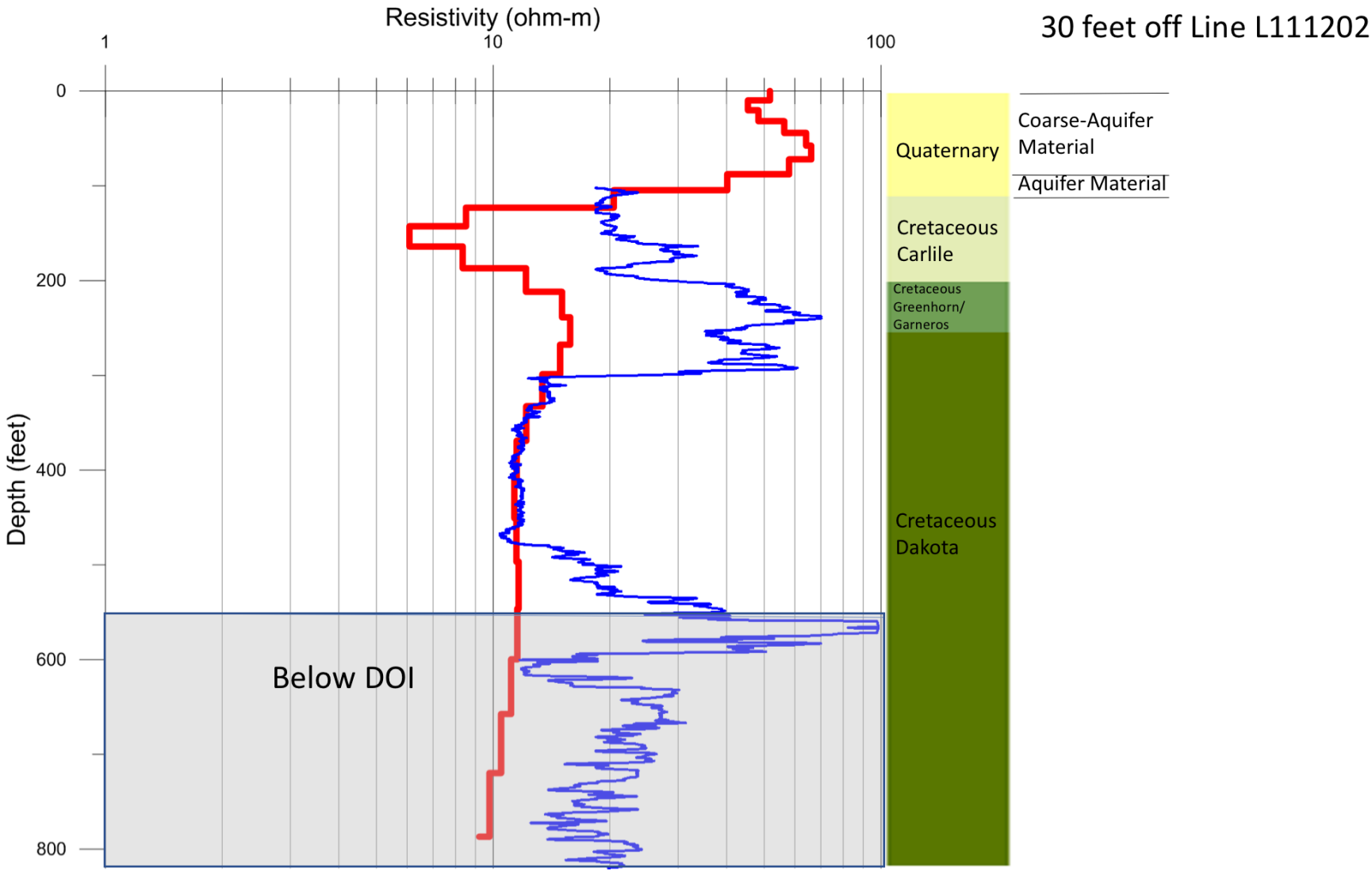


Figure 5-21. Graph of the NOGCC borehole *API-1234567819999999* (NE-DNR registration *G-87761*) 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the stratigraphy log from *G-87761* as well as the aquifer material categories from the AEM inversion of the Quaternary.

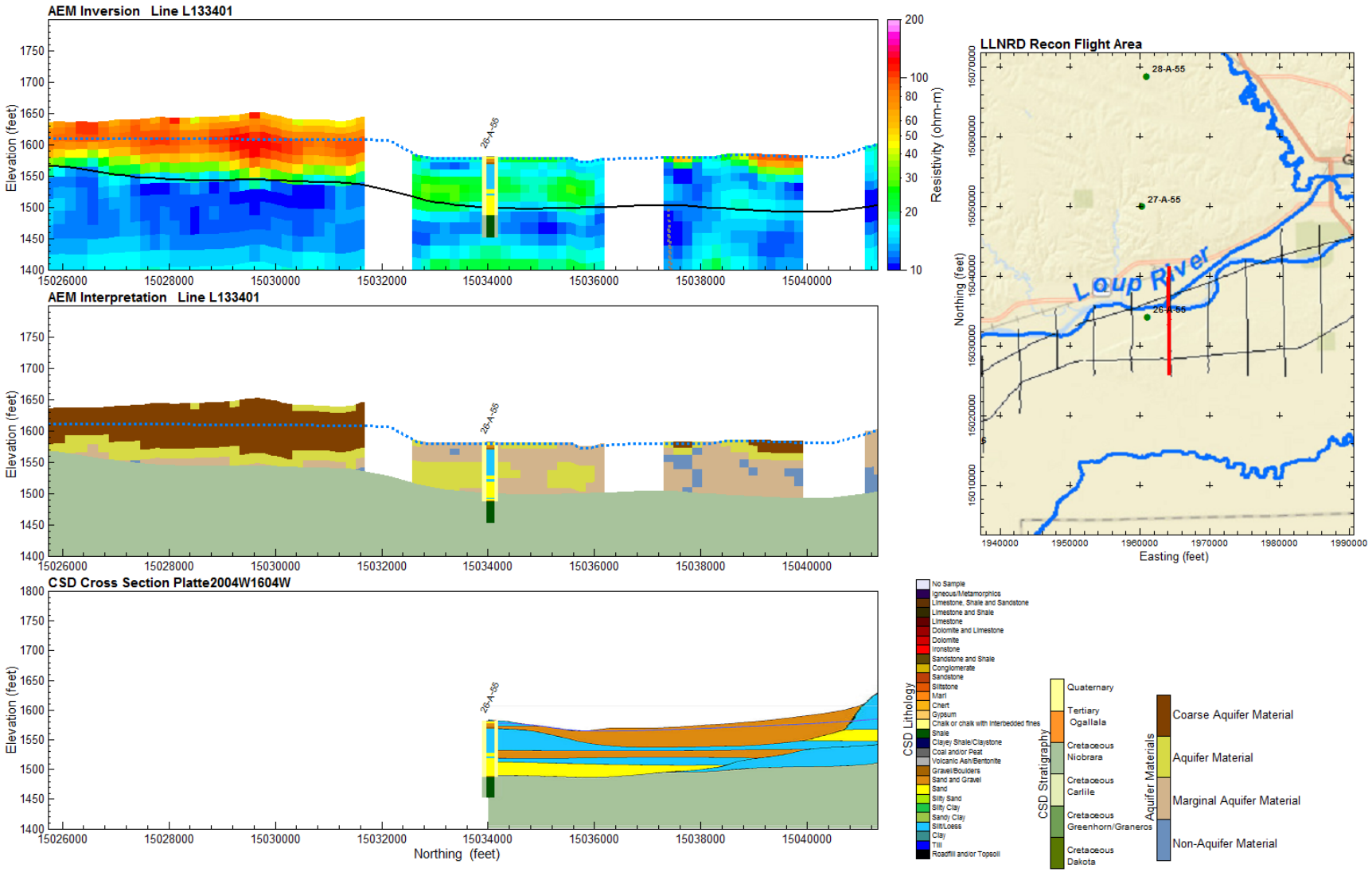


Figure 5-22. Comparison of AEM inverted earth models and CSD cross section Platte2004W1604W. The historic cross sections are derived from Divine (2012), Divine et al. (2010), and Korus et al. (2012). The color scheme is modified after Carney et al. (2015a).

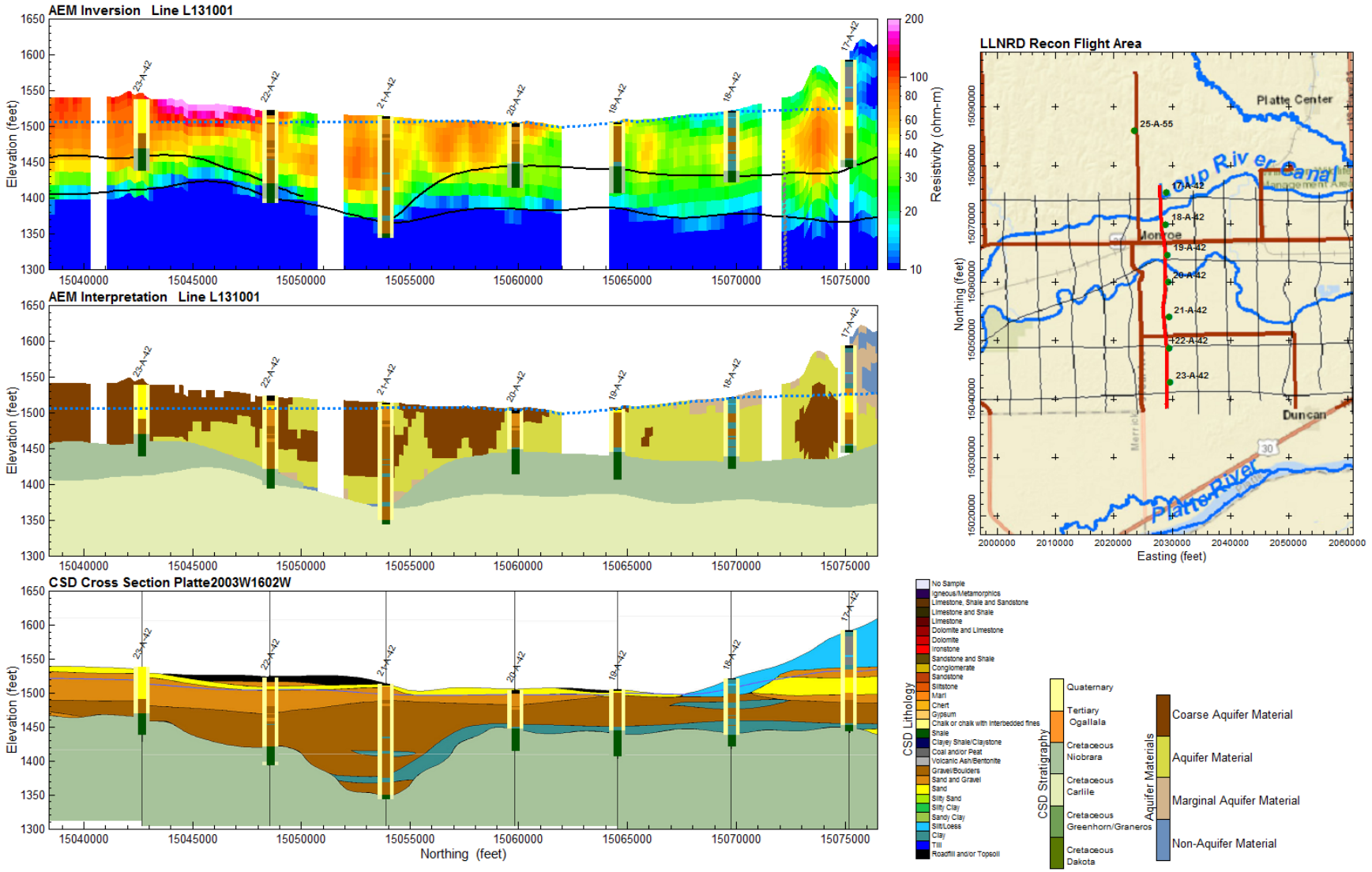


Figure 5-23. Comparison of AEM inverted earth models and CSD cross section Platte2003W1602W. The historic cross sections are derived from Divine (2012), Divine et al. (2010), and Korus et al. (2012). The color scheme is modified after Carney et al. (2015a).

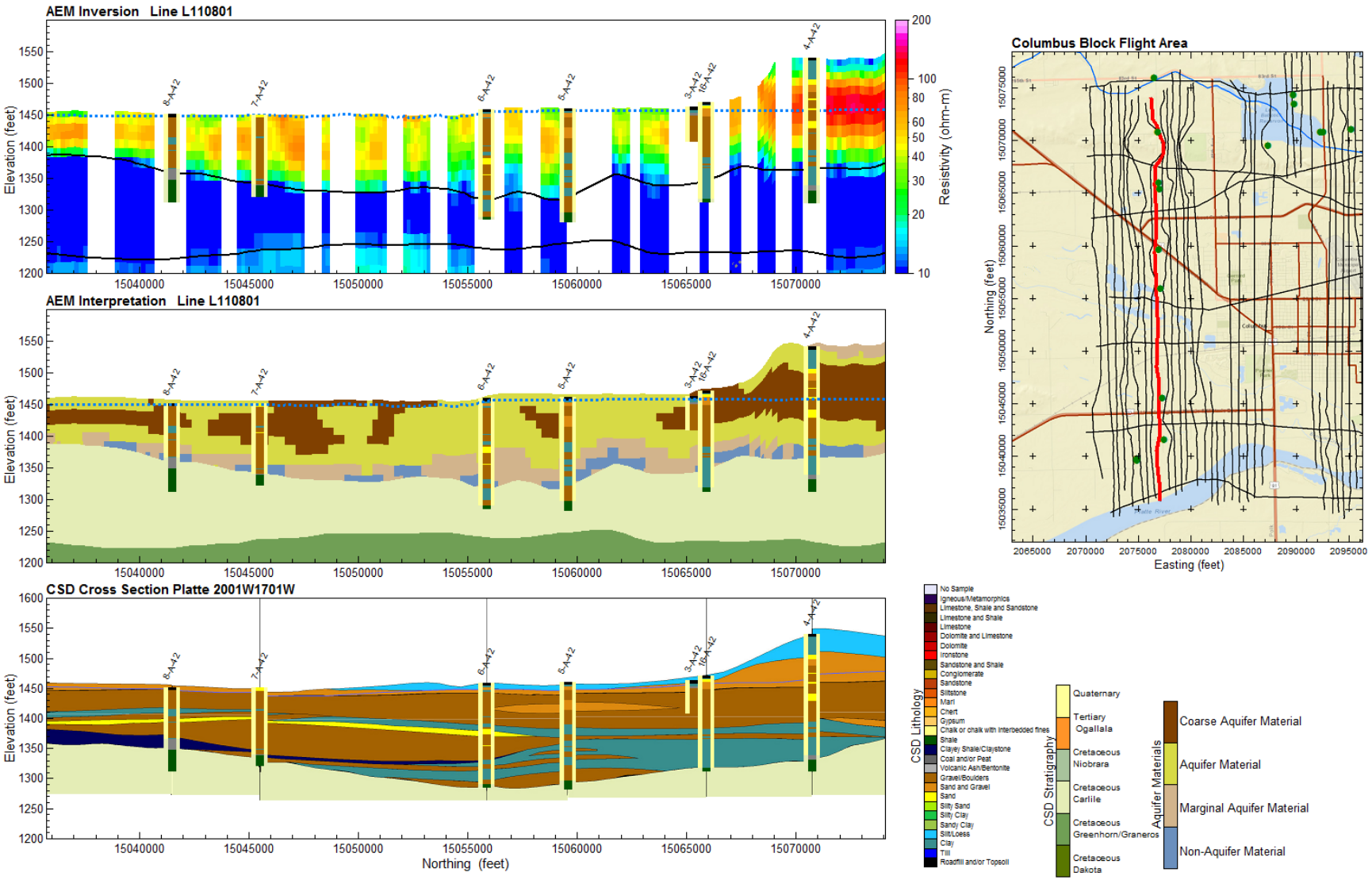


Figure 5-24. Comparison of AEM inverted earth models and CSD cross section Platte2001W1701W. The historic cross sections are derived from Divine (2012), Divine et al. (2010), and Korus et al. (2012). The color scheme is modified after Carney et al. (2015a).

5.3 Hydrogeological Framework of the LLNRD AEM Survey Area

The AEM reveals variability in the Quaternary (***Q***) deposits across the LLNRD AEM survey area. There was no identifiable ***To*** along the flight lines. The ***Q*** makes up the aquifer materials overlying the Cretaceous bedrock units. Figure 5-25 and Figure 5-26 display in 3D the overall distribution of ***Q***, ***Kn*****,** and ***Kc*** materials (as described in the previous section) across the LLNRD Survey Area. The subsurface distribution of ***Q*** materials can be generally characterized into two somewhat overlapping, but distinct, areas distributed at various locations within the survey area. These areas are fine grained basal material identified as marginal aquifer and non-aquifer deposits near the base of the ***Q*** beneath prevalent alluvial deposits. The approximate locations are given in Figure 5-27 and Figure 5-28.

5.3.1 The Quaternary Aquifer

The ***Q*** aquifer of the LLNRD Survey Area is predominantly composed of Quaternary unconsolidated aquifer (yellow color in figures) and coarse aquifer (brown color in figures) materials composed of alluvial sediments. These materials are sitting on the ***Kn*** and ***Kc*** which is the bedrock aquiclude for the area. The maps showing the elevations of the tops of the ***Kn*** and ***Kc*** can be found in Figure 5-9 and Figure 5-10, respectively, in Section 5.1.4. The thickness of the Q materials within the LLNRD Survey Area range from 25 to 271 feet thick (Figure 5-29). The thickness of the ***Q*** materials increase toward the east. The ***Q*** alluvial system can be very heterogeneous in places with a changing mix of all aquifer materials. Most of the LLNRD AEM survey area contains aquifer and coarse aquifer materials that act as the groundwater supply route which is hydrologically connected to the surface water system. Accompanying the aquifer and coarse aquifer materials are areas of non-aquifer and marginal aquifer materials. The marginal and non-aquifer materials are typically located proximally to near-surface loess deposits, basal silts and clays, and some continuous layers of fine grained material. These layers can locally act as aquicludes and prevent hydrologic connection to a stream, recharge areas, or serve as locally confining units. Figure 5-30 presents an example of this displaying a 3D image of several of these layers of marginal (tan color) and non-aquifer (blue color) materials found in the central Area 28. Figure 5-31 presents a profile view of line L132201, a north-south flight line in Area 28. All aquifer type materials are indicated along this profile with the center of the profile indicating the positions of marginal and non-aquifer materials which impact the area hydrologically by blocking or slowing down water movement to and from the surface. The Columbus Block area (which is discussed in greater detail in Section 4.2) has higher resolution of the subsurface due to the denser flight lines flown together providing near-continuous data for a high resolution interpretation of the area. On the other hand, Area 28 was flown with a reconnaissance line approach where the data density used for interpretation is much less. A disadvantage of the reconnaissance lines is that they have only identified these deposits along AEM acquisition flight lines thus the complete extent of these deposits cannot be determining expediently without further AEM acquisition or exhaustive interpretation from added boreholes. Appendix 1 contains interpreted profiles that illustrate the details of the Quaternary in the LLNRD AEM survey area. Appendix 2 contains 3D images of the LLNRD AEM survey area that have been rotated around various angles to allow viewing of the overall distribution of materials. The Quaternary units of the LLNRD AEM survey area contain zones of saturated thickness up to 150 ft and, in some places, more.

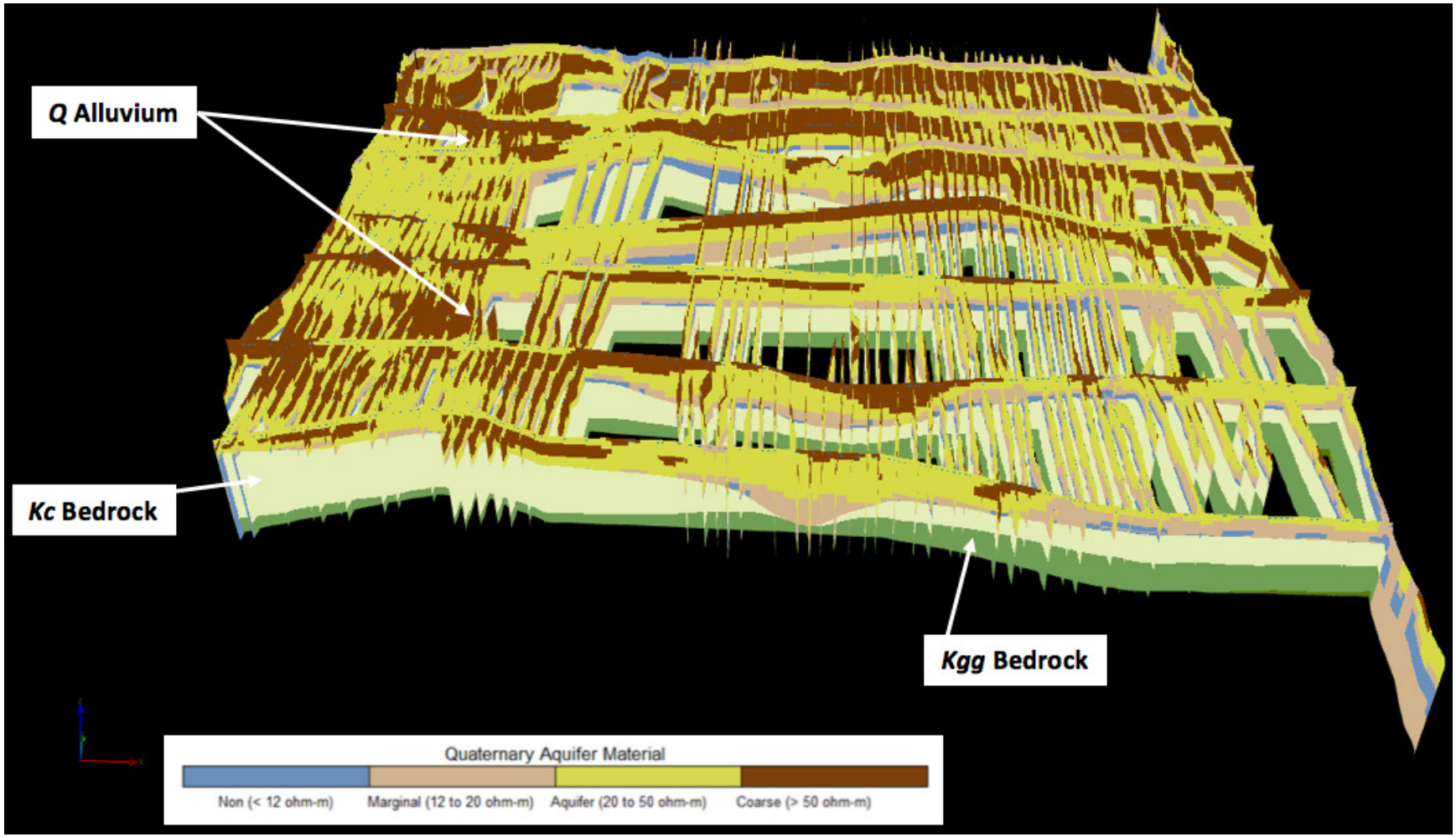


Figure 5-25. 3D map looking to the north of the interpreted distributions of aquifer materials within the Columbus Block AEM flight area. Vertical exaggeration is 20x. (*Q*-Quaternary, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale). The image projection is NAD 83, UTM Zone 14 North.

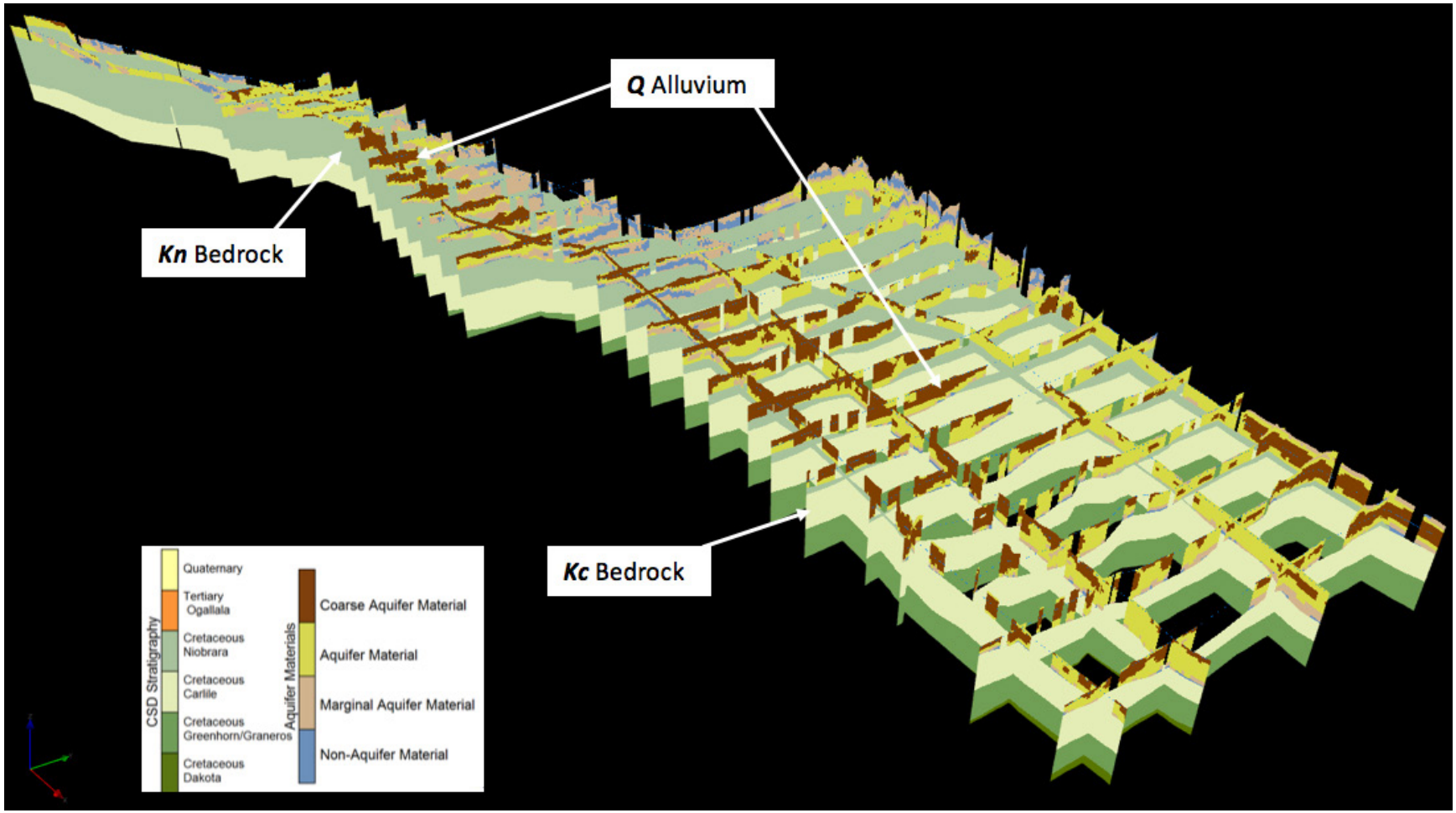


Figure 5-26. 3D map looking to the north of the interpreted distributions of aquifer material within the Area 28 reconnaissance AEM survey area. Vertical exaggeration is 20x. (*Q*-Quaternary, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale). The image projection is NAD 83, UTM Zone 14 North.

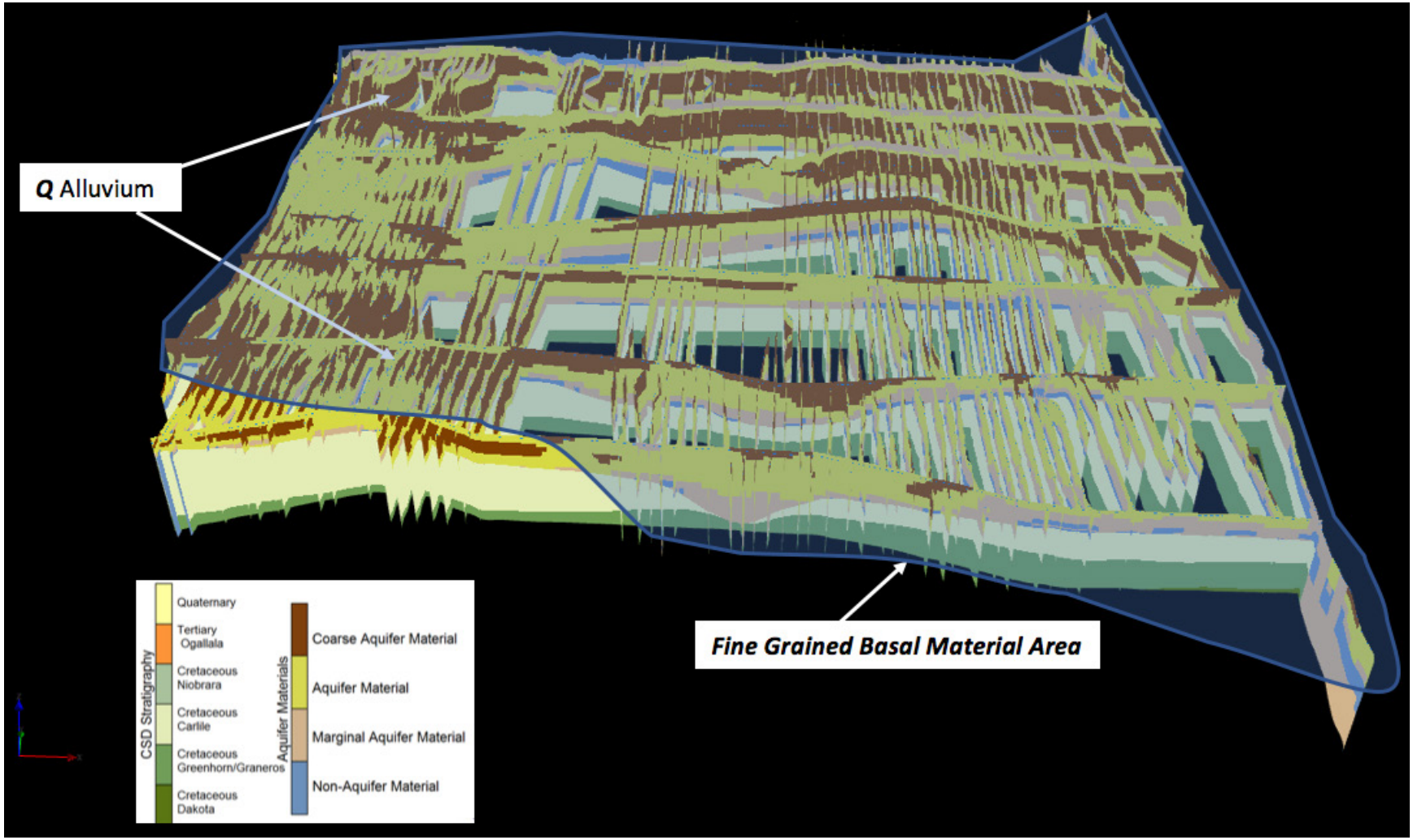


Figure 5-27. 3D map looking to the north of the interpreted distributions of fine grained marginal and non-aquifer material basal deposits within the Columbus Block Area. Vertical exaggeration is 20x. Geological units include *Q*-Quaternary. The image projection is NAD 83, UTM Zone 14 North.

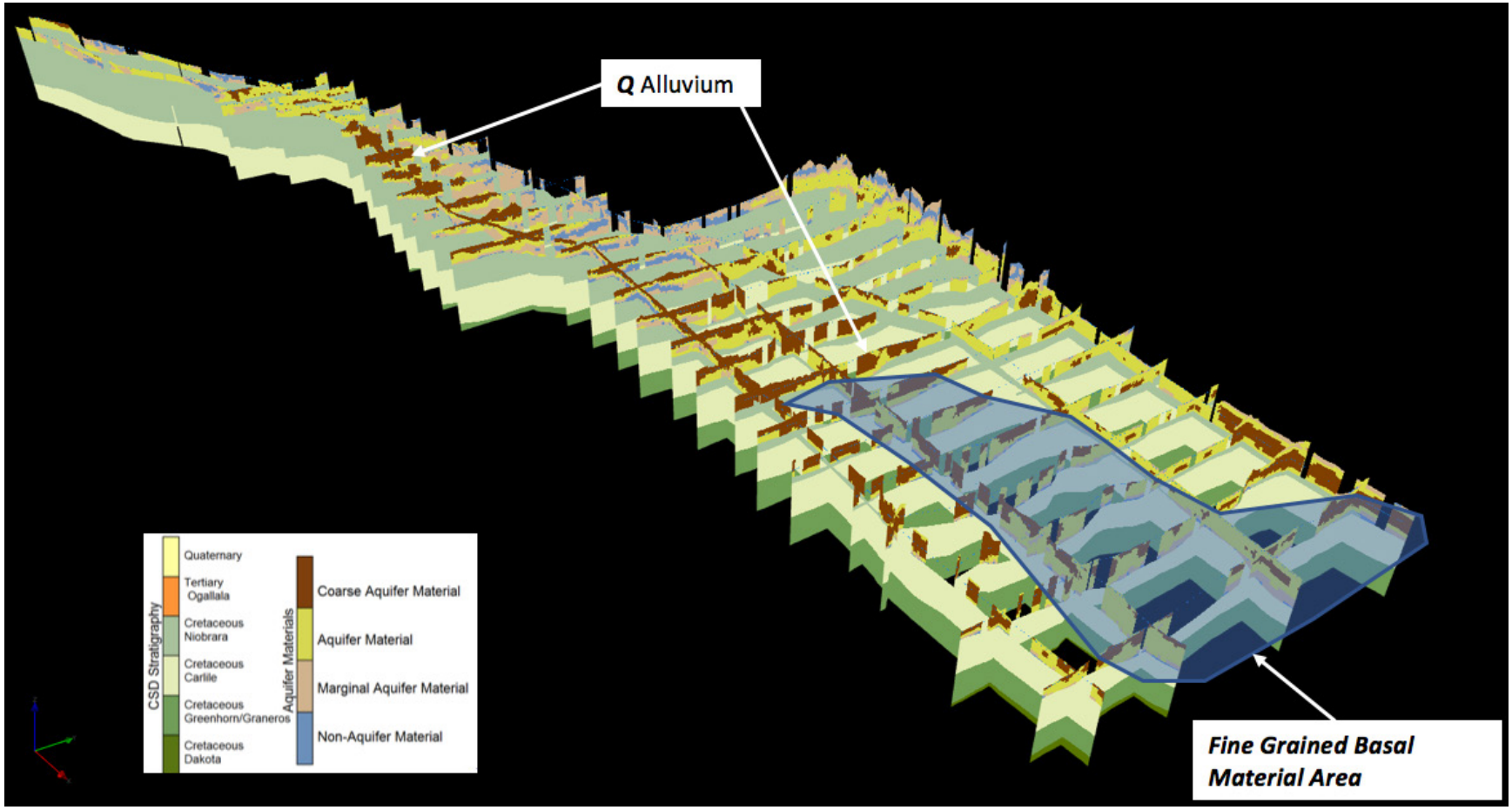


Figure 5-28. 3D map looking to the north of the interpreted distributions of fine grained marginal and non-aquifer material basal deposits within Area 28. Vertical exaggeration is 20x. Geological units include *Q*-Quaternary. The image projection is NAD 83, UTM Zone 14 North.

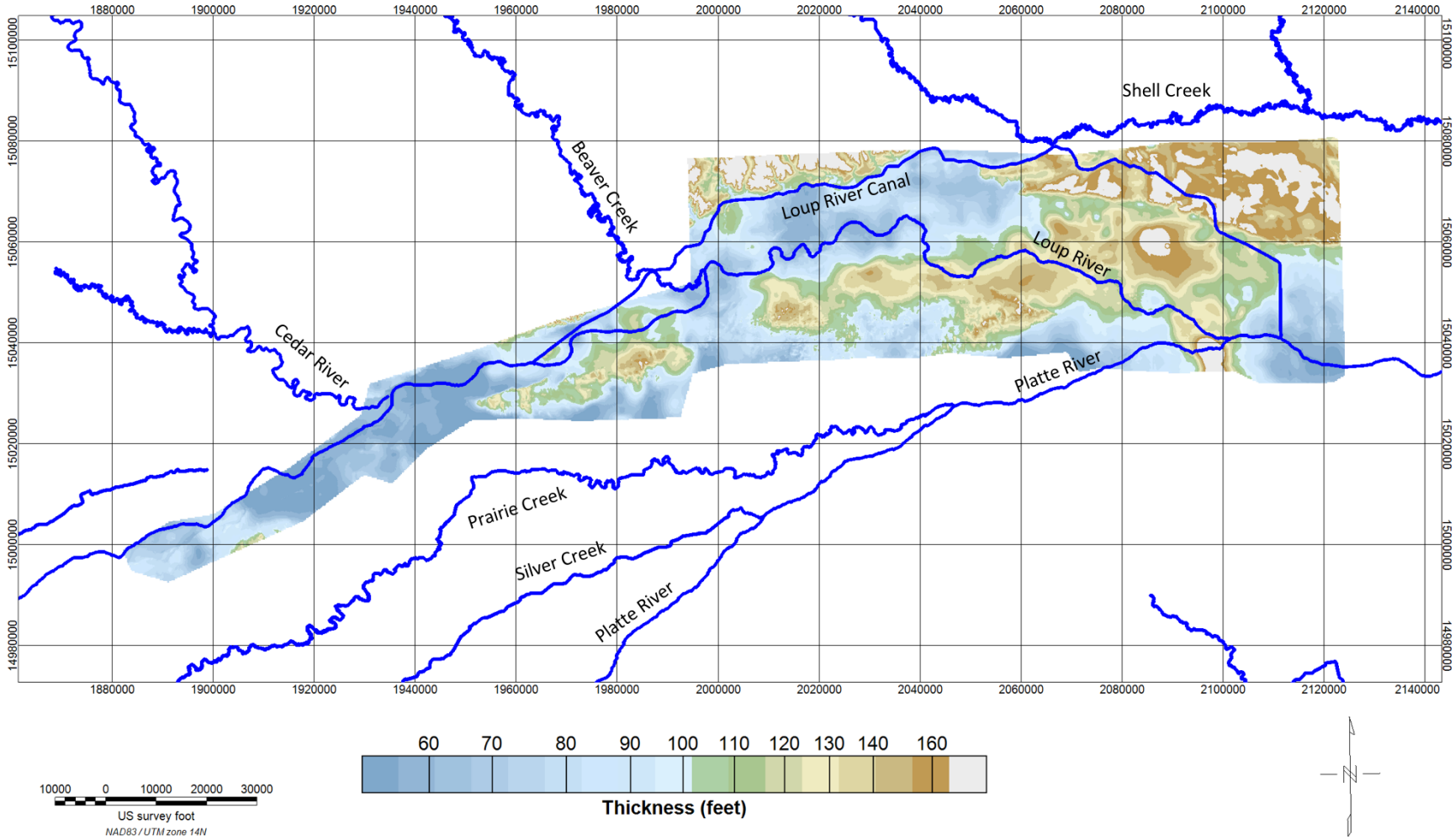


Figure 5-29. Map of the thickness of Quaternary (Q) materials in the LLNRD AEM survey area. The projection is NAD83 and the elevation values are referenced to NAVD 88 feet.

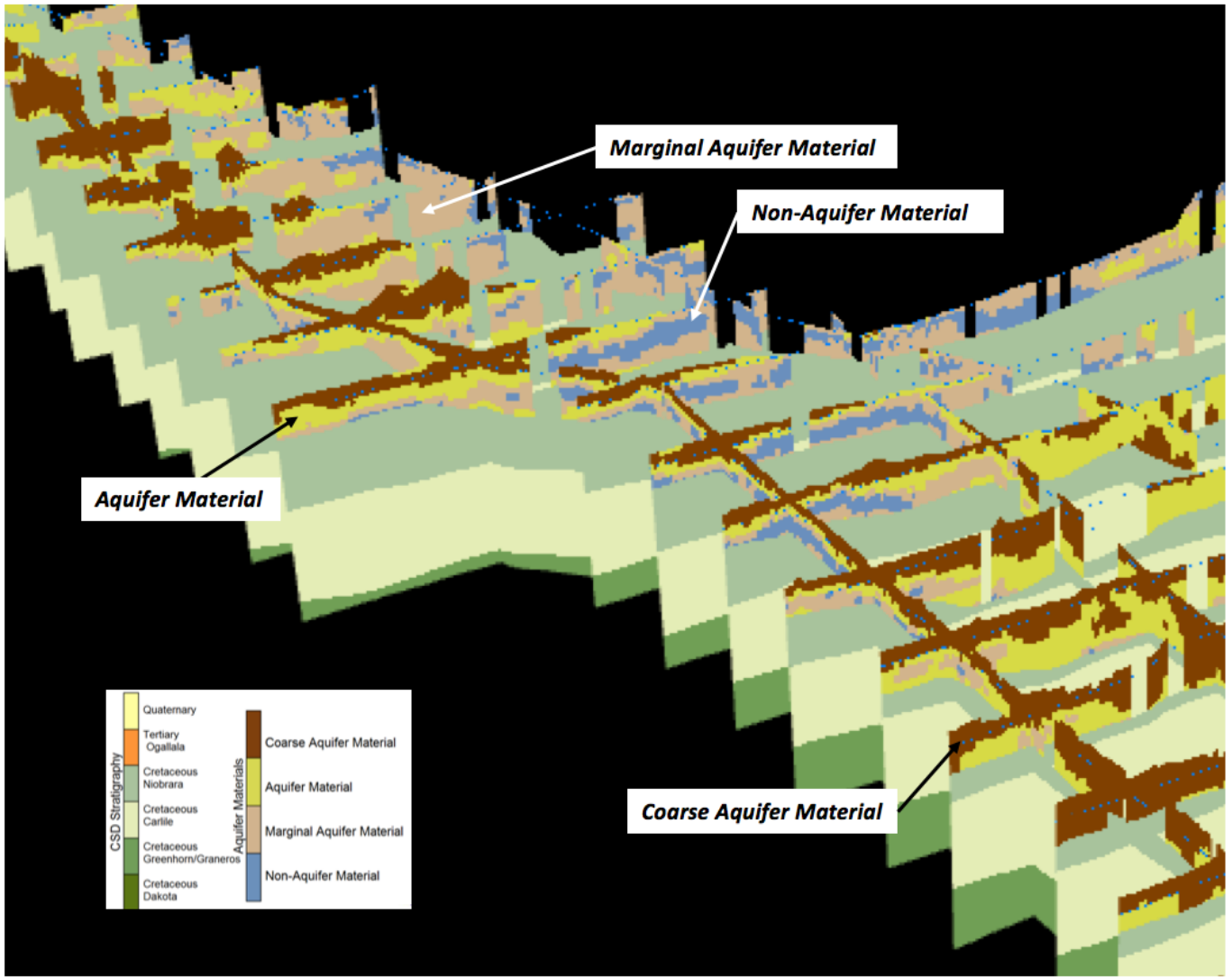


Figure 5-30. 3D map looking to the northwest of the interpreted distributions of marginal and non-aquifer materials that accompany the aquifer and coarse aquifer materials found in the central regions of Area 28. Vertical exaggeration is 20x. Geological units include Q, Kn, and Kc. The image projection is NAD 83, UTM Zone 14 North.

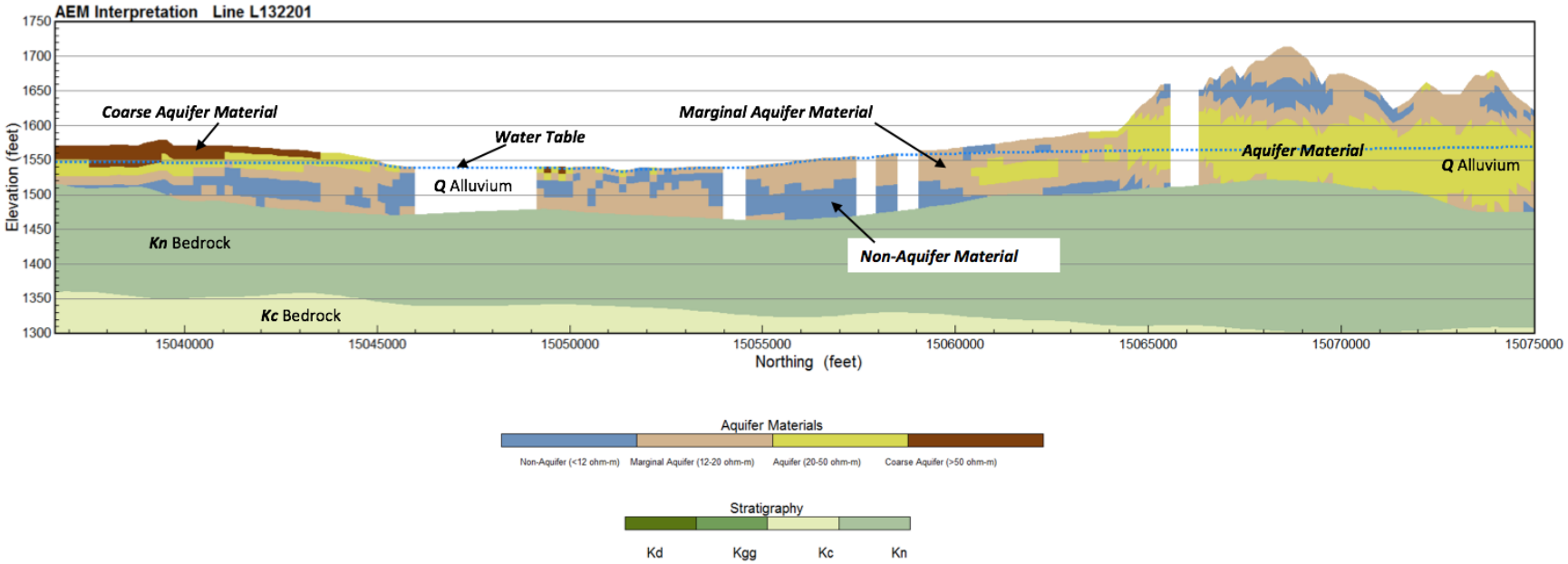


Figure 5-31. Profile view of line L132201 showing a north-south profile in Area 28 (north is on the right). There is aquifer and coarse aquifer material on the south separated by marginal and non-aquifer material in the center and aquifer material to the north. The surface water is hydrologically disconnected from the north and south aquifers. The water table is represented by the dashed blue line. (*Q*-Quaternary, Kn-Cretaceous Niobrara, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale, Kd-Cretaceous Dakota). The image projection is NAD 83, UTM Zone 14 North, feet.

5.3.2 The Cretaceous Bedrock Aquiclude

The Cretaceous bedrock is made up of the ***Kc*** on eastern side of the LLNRD AEM survey area and the ***Kn*** on the west. These units make up a continuous surface beneath the Quaternary alluvial sediments that combine to act as an aquiclude restricting groundwater flow across the boundaries. Figure 5-12 in Section 5.1.4 present an image of the surface of the bedrock. On the eastern end of the LLNRD AEM survey area the ***Kc*** thins considerably and the ***Kgg*** is in close proximity to the ***Q*** material.

5.4 Hydrogeological Framework of the Columbus Block AEM Survey Area

The Columbus Block AEM flight area is within the Quaternary Aquifer system defined above (Section 5.3.1). Figure 5-32 is a map showing the AEM survey lines included within the Columbus Block AEM survey area, the locations of the NE-DNR registered wells, the CSD test holes, the oil and gas wells, and the locations of the Platte and Loup rivers along with the Loup River Canal. The area is composed of mostly aquifer materials lying on the ***Kc*** bedrock surface.

The bedrock is eroded and has two channels cut into it. The main channel trends from west to east in the center of the block and the second channel trends from the center of the block to the south (Figure 5-33). The channels are flanked by three bedrock highs that are in the block area which have an increased relief of up to 80 feet in elevation. The thickness of the Quaternary material within the Columbus Block ranges from 29 to 224 feet thick (Figure 5-34). The area is dominated by aquifer materials and coarse aquifer materials and a high water table with good aquifer properties. Figure 5-35 shows a 3D fence diagram with the bedrock surface in grey showing the large amount of aquifer (yellow) and coarse aquifer (brown) material in the block. The thicker sequences of aquifer to coarse aquifer materials lie to the north and center of the block with marginal and non-aquifer materials lying basal in nature.

A voxel model showing continuous volumes of the four different types of aquifer materials above the water table is presented in Figure 5-36. This shows the thin nature of the unsaturated sediments in the flood plain and the thicker sequence of sediments to the north out of the flood plain. The marginal aquifer material (tan) and the non-aquifer material (blue) mantle the north area out of the flood plain which is made up of mostly silts and clays. Figure 5-37 is a voxel model showing continuous volumes of the four different types of aquifer materials below the water table and above the bedrock. This is a representation of the saturated materials in the Columbus Block AEM survey area. The aquifer and coarse aquifer materials tend to lie on top of the basal marginal and non-aquifer materials.

There are no marginal and non-aquifer materials that are saturated out of the flood plain in the near-surface mantle of these materials. The aquifer and coarse aquifer materials, where saturated, are the water bearing materials for the large capacity wells (greater than 50 gpm) in the area. Figure 5-38 is a voxel model of the volumes of the aquifer and coarse aquifer materials below the water table. These materials are the most productive for water wells and have the most transmissivity allowing for the most groundwater flow. This map also shows the areas with hydrologic connection to the streams of the area as these materials are continuous from the flood plain to the areas out of the flood plain to the

north. In the southeast corner, there are areas of no aquifer or coarse aquifer materials which have locally reduced the groundwater flow.

A voxel model of the volumes of the aquifer and coarse aquifer materials below the water table is presented in Figure 5-39. These sediments are the most productive of the ***Q*** aquifer materials and have the greatest amount of groundwater flow. Figure 5-40 presents the earth model for north-south flight profile L242002 showing the cross section of the Columbus Block area east of Columbus including the features discussed above.

Of note is the thick sequence of aquifer materials in the area out of the flood plain to the north. The materials between the water table and land surface are unsaturated as shown from the LLNRD water table (LLNRD, 2017), this has the potential for aquifer storage that can be used in a managed aquifer recharge (MAR) plan. Care should be taken to do a detailed assessment as to the effects such a management plan may have on the local water table conditions and estimates of time of travel for the groundwater to return to the surface water system.

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

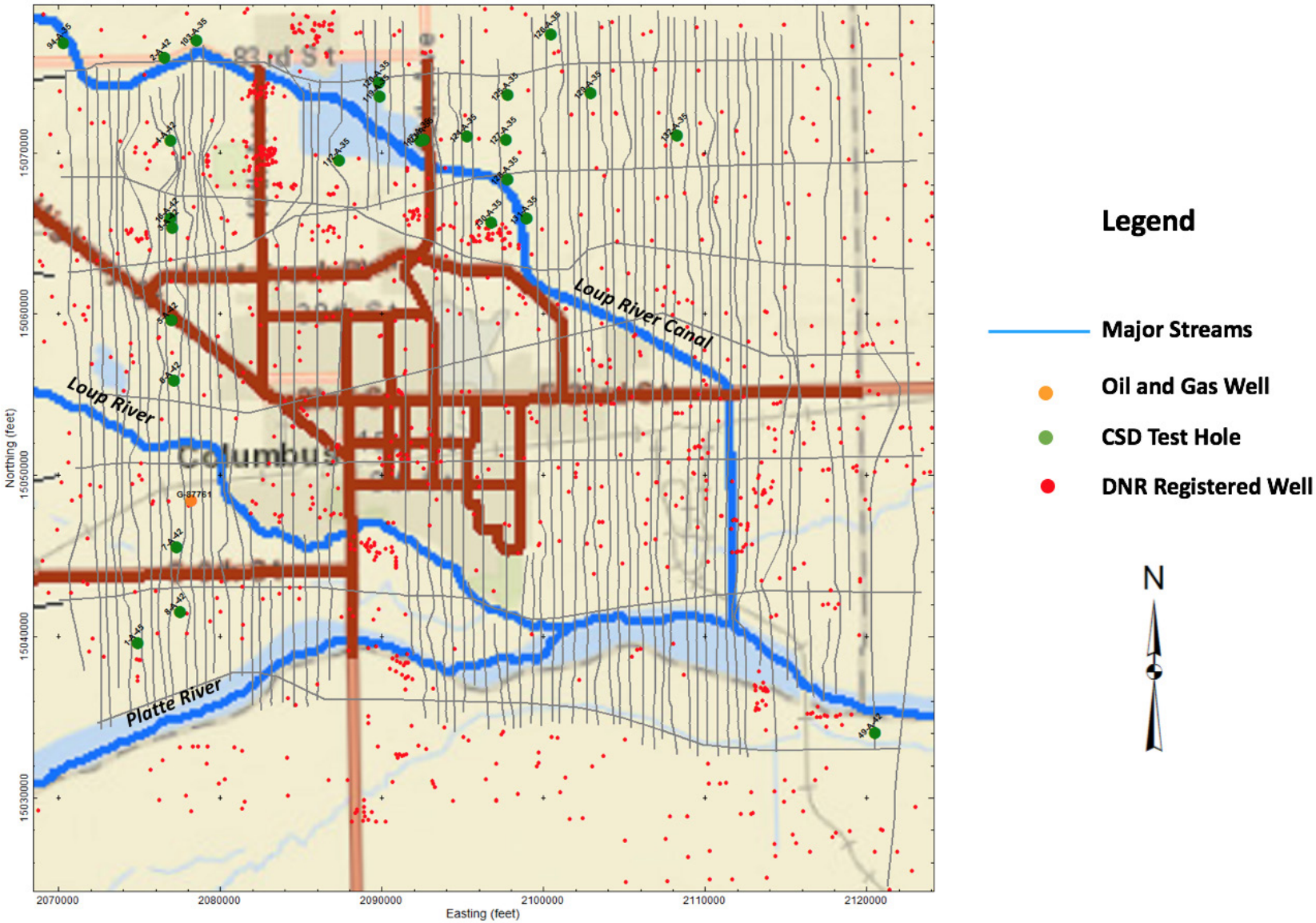


Figure 5-32. Map of the AEM flight lines within the Columbus Block AEM survey area. The orange dots indicate the locations of the Nebraska DNR registered wells. The image projection is NAD 83, UTM Zone 14 North feet.

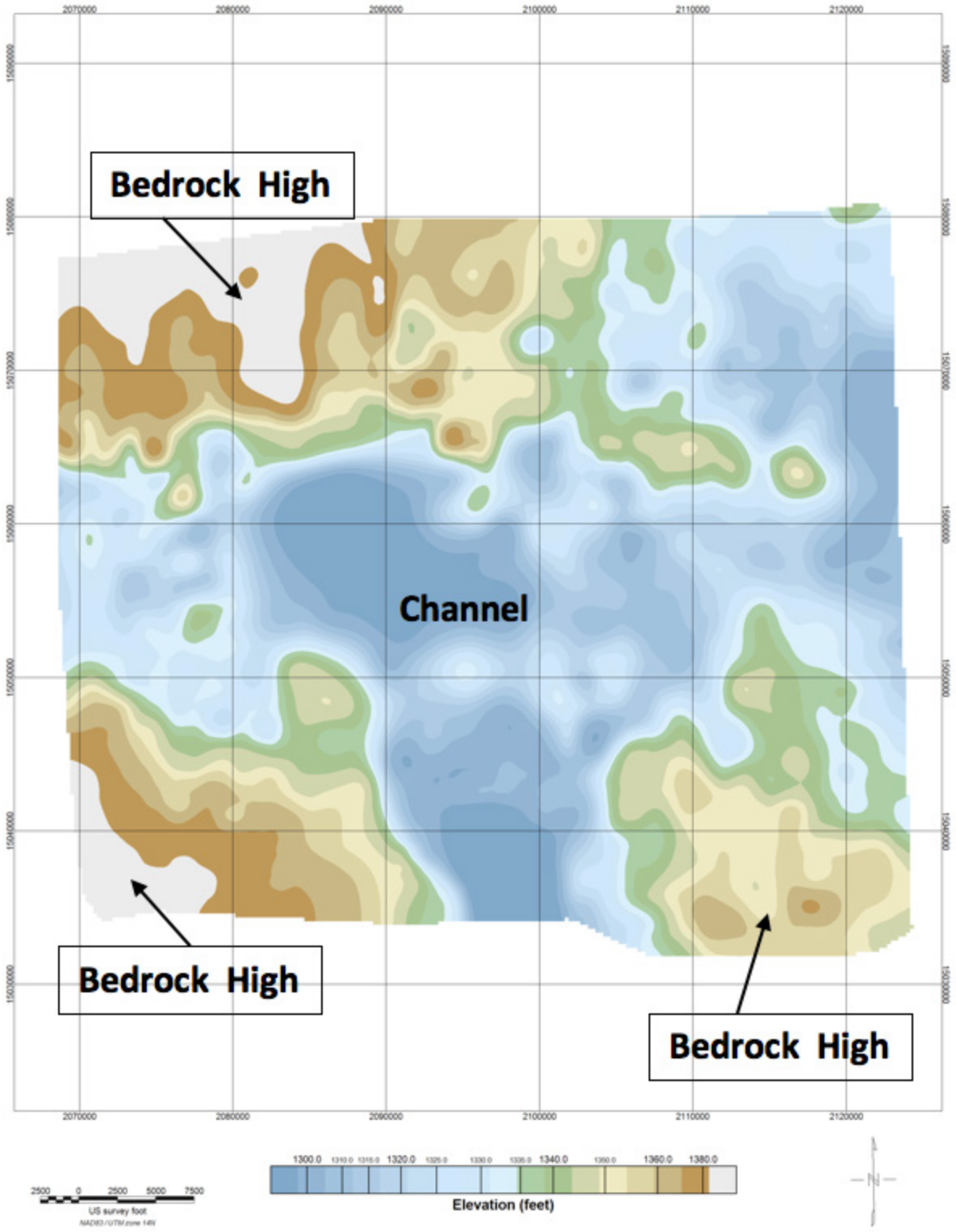


Figure 5-33. Base of the *Q* aquifer which is the top of the *Kc* bedrock. Two channels eroded into the bedrock can be seen lying between three bedrock highs. The image projection is NAD 83, UTM Zone 14 North feet.

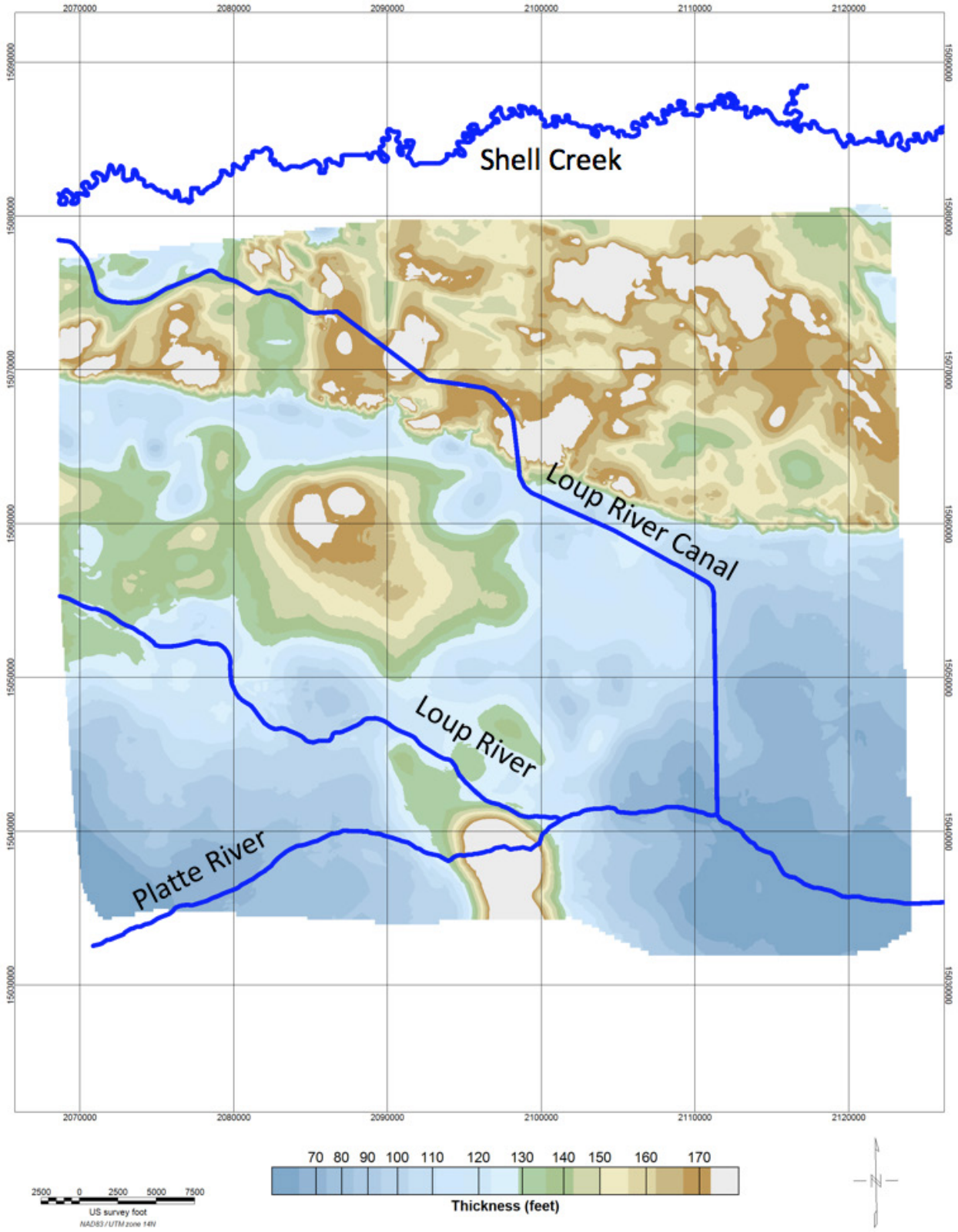


Figure 5-34. Thickness of the Quaternary (*Q*) materials within the LLNRD Columbus Block AEM survey area. The projection is NAD83 and the elevation values are referenced to NAVD 88 feet

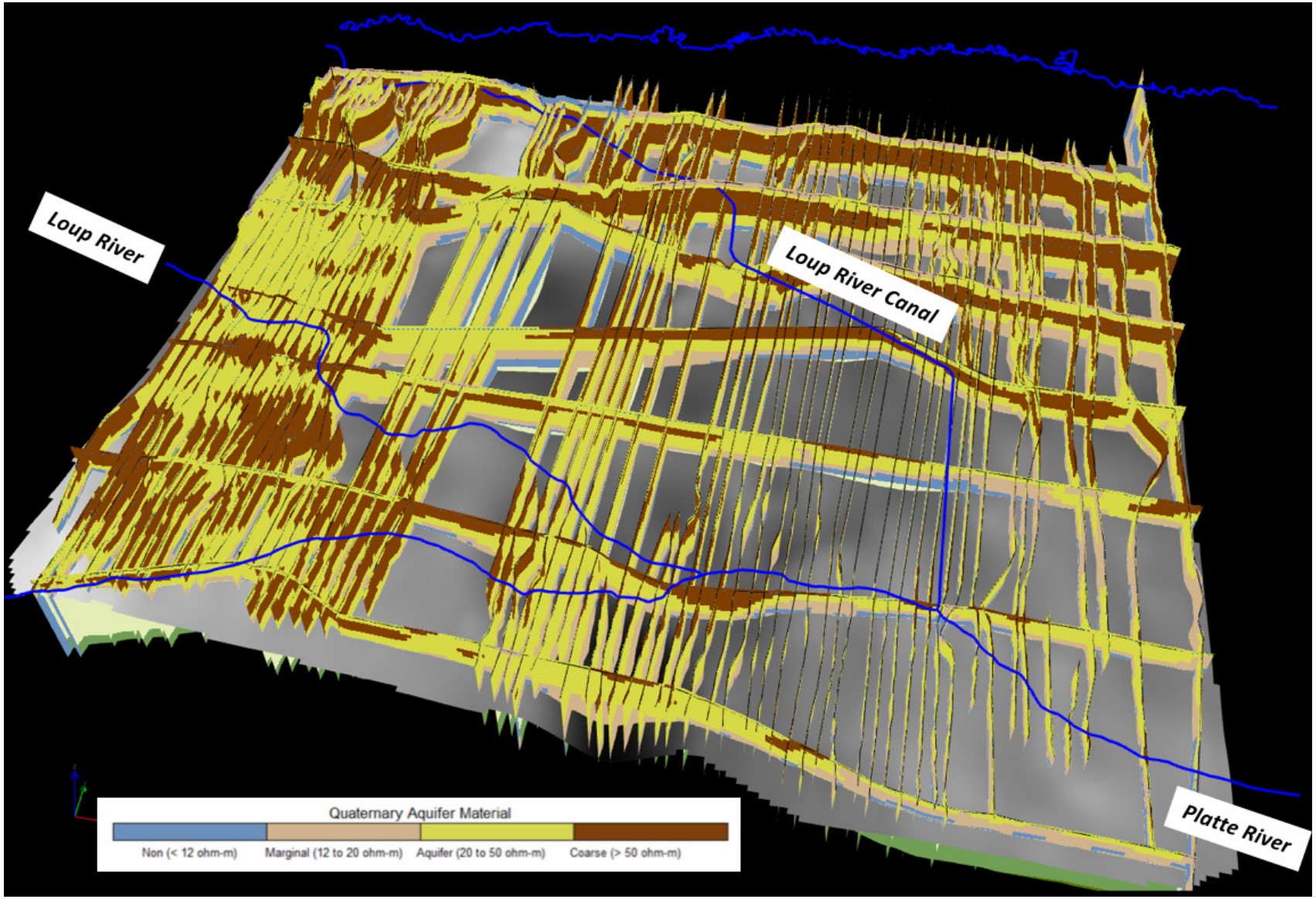


Figure 5-35. 3D fence diagram with a bedrock surface in gray showing the large amount of aquifer (yellow) and coarse aquifer (brown) material in the block. The map projection is NAD 83, UTM Zone 14 North, feet.

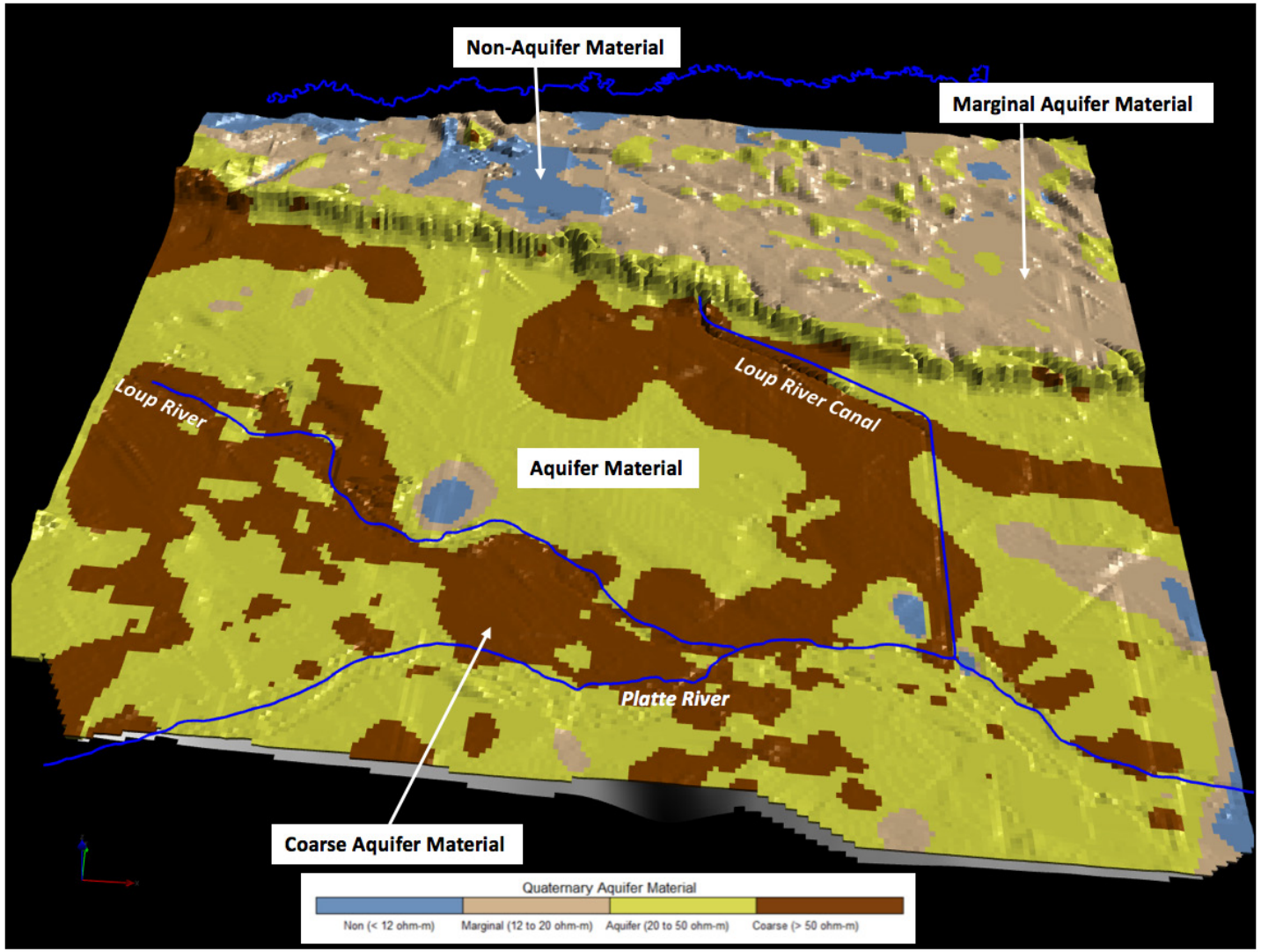


Figure 5-36. Voxel model with a view to the north, showing continuous volumes of the four different types of aquifer materials above the water table: Non-aquifer materials (blue), marginal aquifer (tan), aquifer (yellow), and coarse aquifer materials (brown). Note the mantle of fine grained marginal and non-aquifer materials to the north out of the flood plain. Streams are located in their approximate locations.

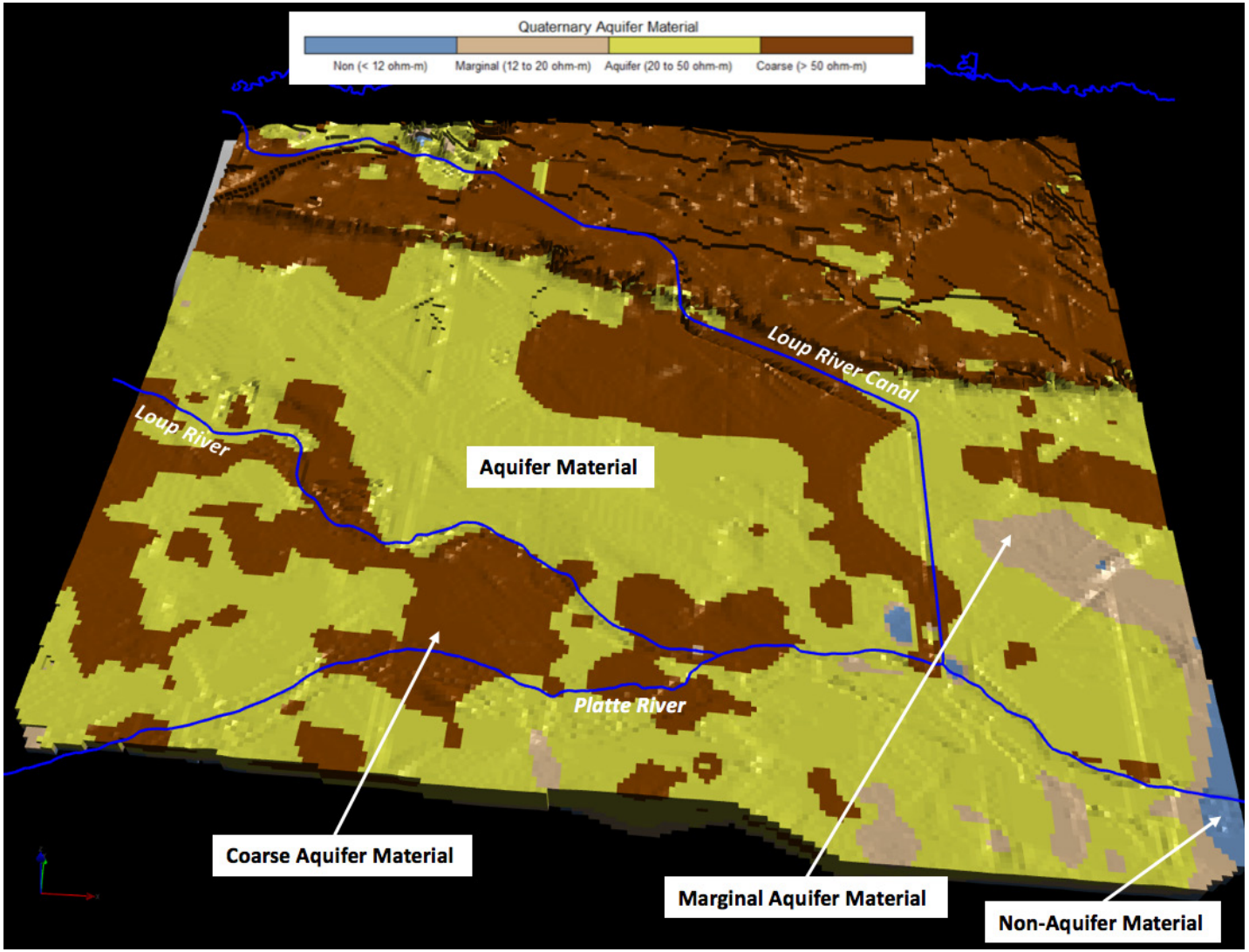


Figure 5-37. Voxel model with a view to the north, showing continuous volumes of the four different types of aquifer materials below the water table: Non-aquifer materials (blue), marginal aquifer (tan), aquifer (yellow), and coarse aquifer materials (brown). Notice the amount of aquifer and coarse aquifer materials that dominate the area. Also note the fine grained marginal and non-aquifer materials to the southeast in the flood plain. Streams are represented in their approximate locations.

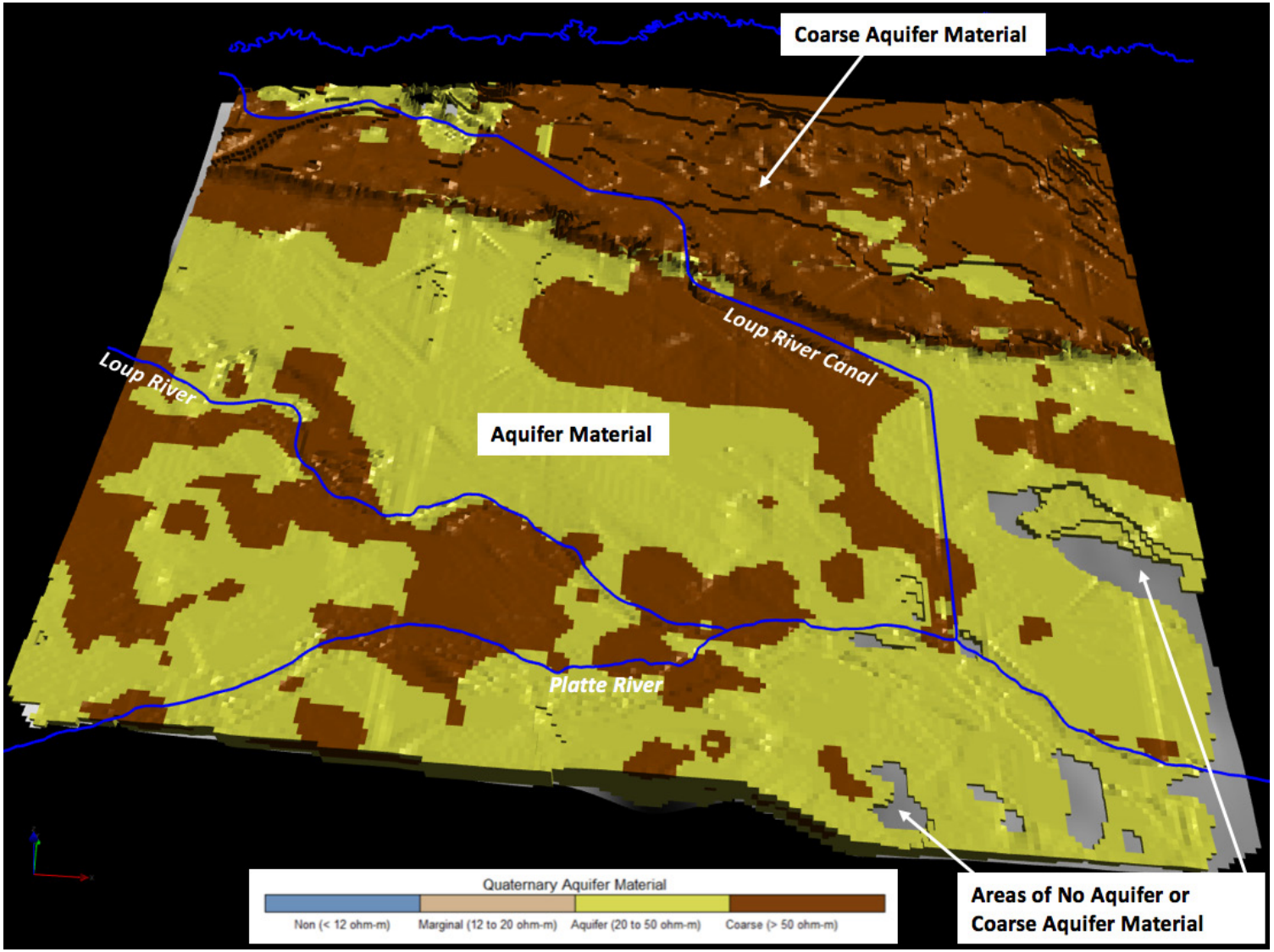


Figure 5-38. Voxel model with view to the north, showing continuous volumes of two dominant types of aquifer materials below the water table: Aquifer (yellow) and coarse aquifer materials (brown). Note the aquifer and coarse aquifer materials missing in parts of the southeast in the area of the flood plain. Streams are represented in their approximate locations.

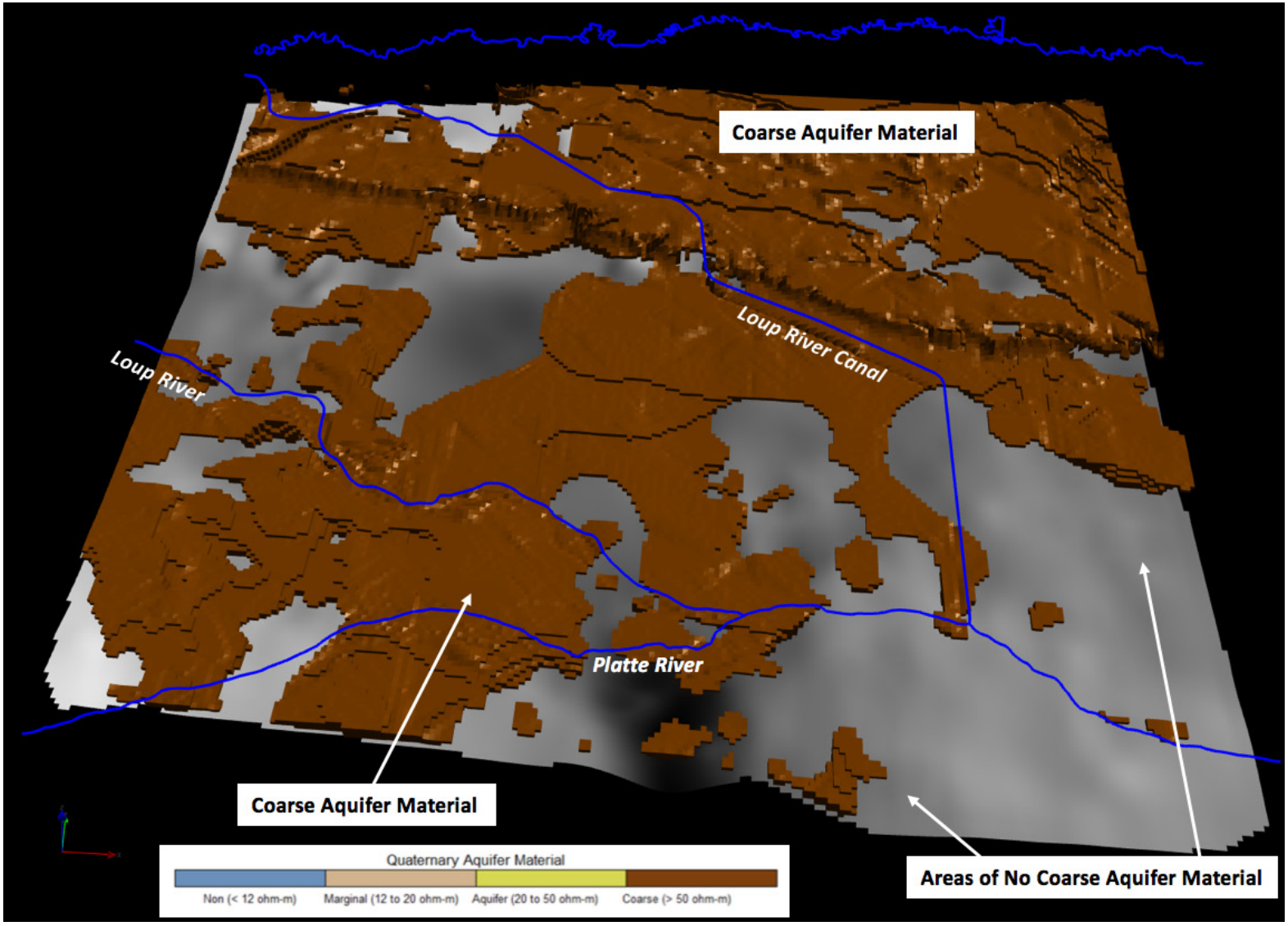


Figure 5-39. Voxel model with view to the north, showing continuous volumes of coarse aquifer materials below the water table. Notice the amount of aquifer and coarse aquifer materials that dominate the area. Also, note the aquifer and coarse aquifer materials missing in parts of the flood plain in the southeast. Streams are represented in their approximate locations.

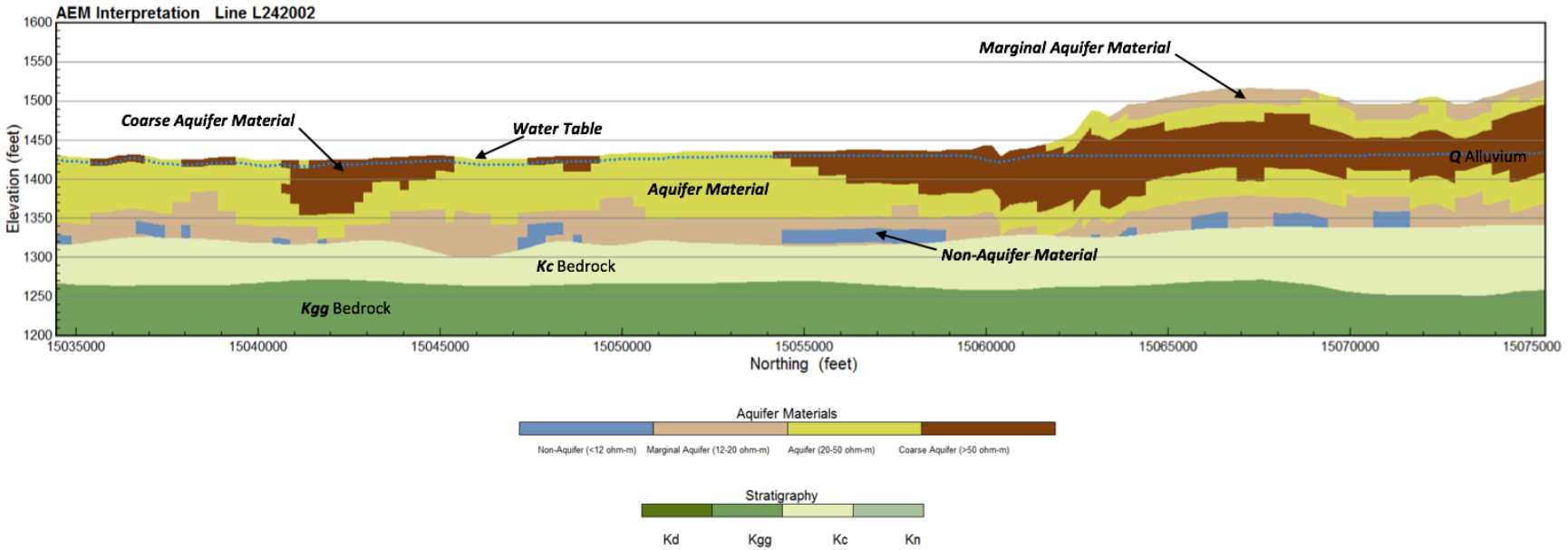


Figure 5-40. Profile L 242002 showing the cross section of the Columbus Block Area east of Columbus. Notice thick sequence of aquifer materials in the area out of the flood plain to the north showing the unsaturated aquifer materials between the water table and land surface. There is continuous hydrologic connection between the surface water system and the aquifer. (Kn-Cretaceous Niobrara, *Kc*-Cretaceous Carlile, *Kgg*-Cretaceous Greenhorn Limestone and Graneros Shale, Kd-Cretaceous Dakota).

5.5 Estimation of Aquifer Volume and Water in Storage for the Columbus Block AEM Survey Area

The 3D digital representation of the subsurface resulting from the AEM method provides users the ability to more accurately estimate total unsaturated and saturated aquifer volume and the amount of extractable water present. The Columbus Block AEM survey area was mapped at high resolution for this purpose. Approximately 134 square miles (approximately 85,937 acres) of AEM data were collected were collected in the Columbus area and interpreted (Figure 1-2).

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 5.2. Figure 5-19 shows resistivity ranges for interpreted non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. This report provides information on unsaturated and saturated volumes of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials.

Figure 5-37 shows the distribution of the volumes of all saturated Quaternary aquifer materials, including non-aquifer, marginal aquifer, aquifer and coarse aquifer material from the water table down to bedrock showing the complex nature of the area. Understanding this complexity in the area and within the sedimentary deposits shows that estimated average values for porosity and specific yield are the best values to use in making the following calculations. The area beneath the Columbus Block Area is included in these calculations and are represented in Figure 5-37, Figure 5-38, and Figure 5-39. Note that the images in these figures were created in pbEncom Discover PA, version 2015, Release Build 15.0.13 (pbEncom, 2016). They can be examined in greater detail by opening the PA sessions provided in *Appendix_3_Deliverables\PA_Session*.

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

Specific yield values were selected by estimating values (Figure 5-41) from Olafsen-Lackey (2005) and personal communication (Susan Olafsen Lackey, UNL-CSD, Northeast Research and Extension Center, January 5, 2017). No aquifer test information was available for this report for the Columbus Block AEM survey area. Estimates of specific yield were made for all aquifer materials. Specific yield for non-aquifer (<12 ohm-m) materials was chosen at 0.02, for marginal aquifer materials (12-20 ohm-m) a value of 0.05 was selected (Heath, 1983). The aquifer material (20-50 ohm-m) ranges from 0.1 to 0.2 with an average of 0.15 (Olafsen-Lackey, 2005). Coarse aquifer materials exist as continuous deposits across 50 percent of the area. Estimates of specific yield for the coarse aquifer material (>50 ohm-m) ranges from 0.10 to 0.20 with an average of 0.15 (Olafsen-Lackey, 2005).

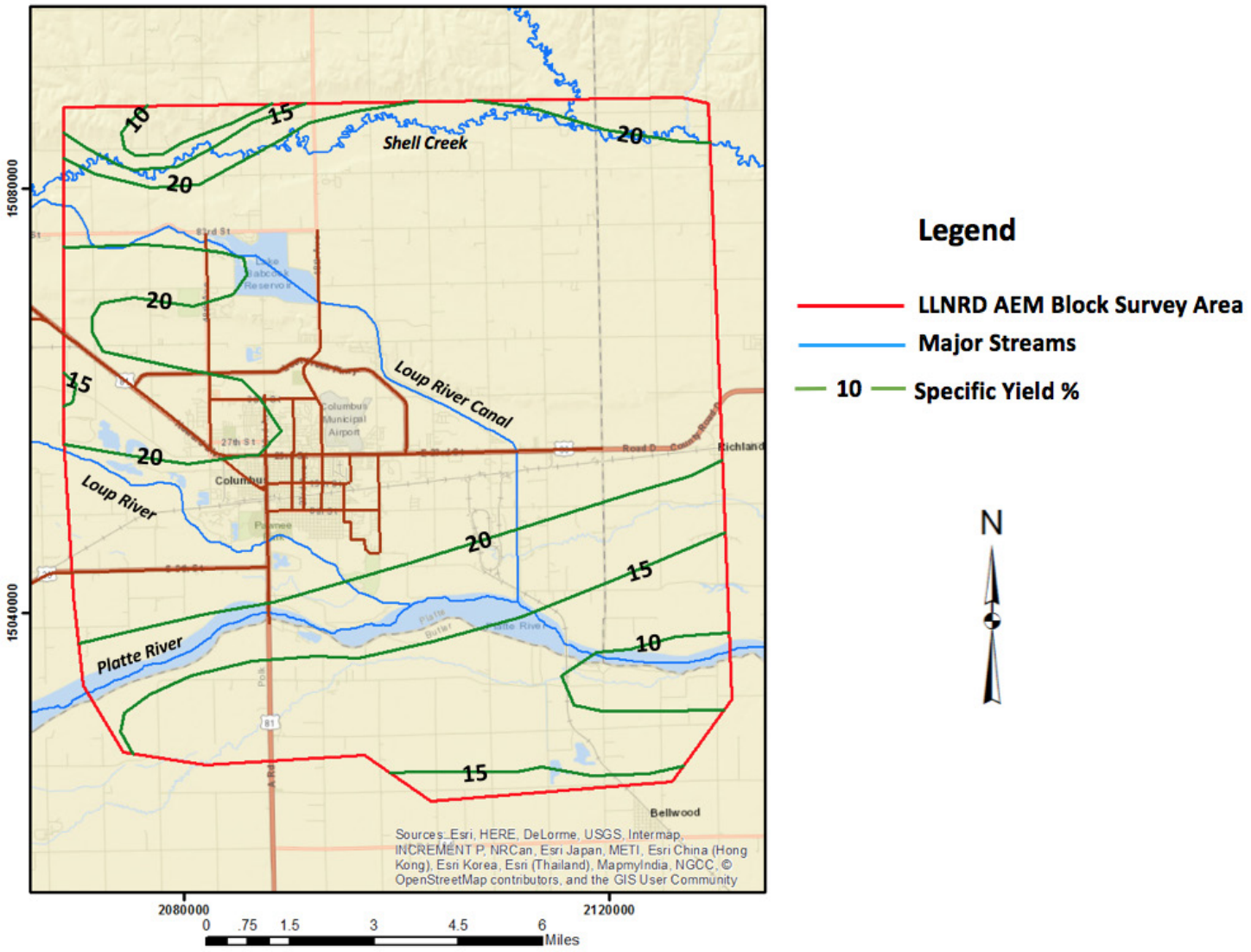


Figure 5-41. Specific yield map of the Columbus Block survey area adapted from Olafsen-Lackey (2005). Lines of equal specific yield percent value are drawn as contours within and near the Survey area which is bounded by the red box. The map projection is NAD 83, UTM Zone 14 North, feet.

Table 5-3 shows the results of calculations for the amount of groundwater in storage calculated by volume of all aquifer materials below the water table then multiplied by the estimated porosity. The following calculation from values in the table shows the non-aquifer material has an estimated volume of 597,836 acre-ft and contains 239,134 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 1,276,259 acre-ft and contains 446,691 acre-ft, aquifer material has an estimated volume of 2,586,263 acre-ft and contains an estimated volume of 517,253 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 1,270,318 acre-ft for a total of 317,580 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 1,520,657 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 Columbus Block AEM survey area will yield approximately 4,783 acre-ft, marginal aquifer materials will yield approximately 22,335 acre-ft, aquifer materials will yield 77,588 acre-ft, and the coarse aquifer material will yield approximately 47,637 acre-ft. A total of 125,225 acre-ft is available from the combined aquifer and coarse aquifer materials.

These estimates are based on the CSD 1995 water table map. These values are conservative, as portions of the AEM data were removed during the inversion process due to interference from infrastructure at the land surface. Also, these volumetric estimates consider only the volume of water assumed in the pore spaces of the aquifer material defined by the resistivity threshold levels and do not account for the amount of the possible “confined or semi-confined” water under pressure (head above the aquifer). This volume of water would add to the values reported in Table 5-3. 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.

Table 5-3. Estimates of groundwater in storage and extractable water content in all aquifer materials underlying the Columbus Block 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	26,041,730,737	597,836	0.40	239,134	0.02	4,783
Marginal	55,593,791,131	1,276,259	0.35	446,691	0.05	22,335
Aquifer	112,657,476,450	2,586,263	0.20	517,253	0.15	77,588
Coarse	55,334,987,231	1,270,318	0.25	317,580	0.15	47,637
TOTAL	249,627,985,550	5,730,678		1,520,657		152,343

5.6 Recharge Areas within the LLNRD AEM Survey Area

3D representations of the subsurface resulting from the AEM method illustrate areas of aquifer materials from the bedrock up to the land surface. The interpreted aquifer materials maps for the LLNRD AEM survey area including the Columbus Block AEM survey area. From these maps a new series of near-surface maps, which includes the interval from 0 to10 feet, were constructed. The interval of 0-10 feet is noteworthy because this is the first layer of the inverted AEM earth model. Remember from the discussion around Table 4-4 that each model layer represents an average of the earth's resistivities within the bounds of each layer, based on the physics behind the electromagnetic exploration technique. These first layer maps show all aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material. These maps indicate the areas at the land surface that can potentially transmit water to the groundwater aquifers in the area. The coarse aquifer material transmits the largest volume of water and the non-aquifer material being the least able to transmit water. The information from the interpreted aquifer materials maps and the information from Section 2.2.2 provides the basis of the information utilized in this section which is divided into the Area 28 AEM Reconnaissance area and the Columbus Block AEM survey area.

5.6.1 Area 28 Reconnaissance Area

The results of the interpretation of the aquifer materials of the LLNRD Survey Area survey area are explained in detail in Section 5.3. A total of 666 line-miles (1,078 line-kilometers) of AEM data were acquired for the entire project area including Area 28 and the Columbus Block survey areas. Each LLNRD AEM flight line in Figure 5-32 was interpreted for aquifer material in the first model layer (0 – 10 ft) using the colors in the Quaternary/Ogallala Aquifer Material legend in Figure 5-19. Areas of coarse aquifer material (brown) will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material (yellow color)potentially transmitting slightly less precipitation downward as both units are permeable. The marginal aquifer material (tan) has the lowest potential to transmit some water downward and the non-aquifer material (blue) will transmit minimal to no water to the groundwater aquifer.

The use of widely-spaced reconnaissance lines (approximately 1 mile apart) illustrates patterns or areas where the potential for recharge can be high and low. Locations where the flight lines intersect and both lines show either aquifer or coarse aquifer material should be considered as higher likelihood for recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true where two flight lines intersect and both lines show non-aquifer or marginal material, those areas will likely not be optimal recharge locations. The area marked "*Low Recharge Area*" in Figure 5-42 shows the area where recharge is potentially less than the rest of Area 28 being composed of non-aquifer and marginal aquifer material. There are other discontinuous zones of potentially lower recharge scattered throughout Area 28; to map their extent, additional flight lines are required. Figure 5-43 presents a Google Earth image showing areas of potential recharge based on the aquifer materials and the coarse aquifer materials noted along the flight lines in Area 28. This data is included as a kmz file in *Appendix_3_Deliverables\KMZ\Recharge*.

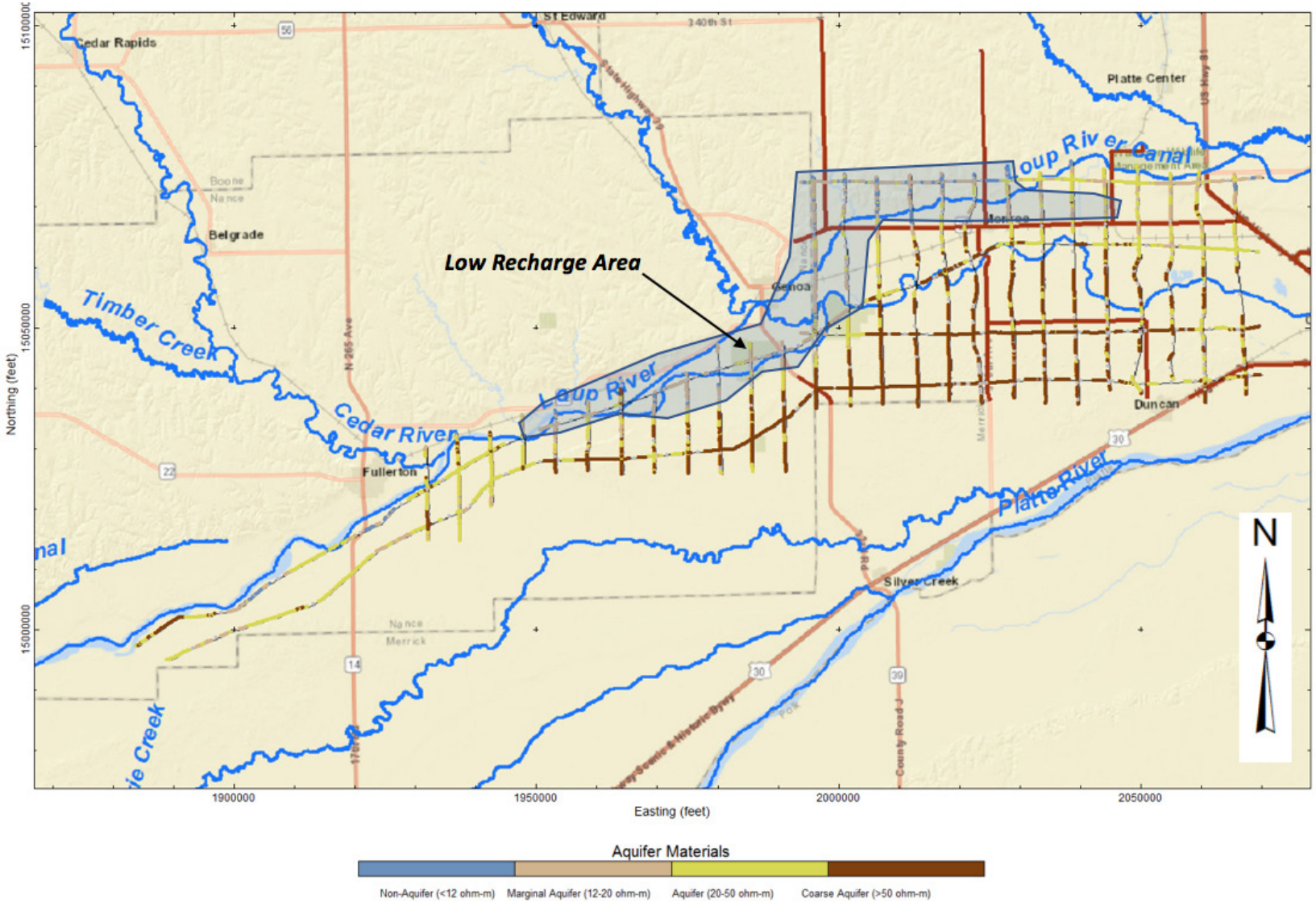


Figure 5-42. Map of aquifer materials for the first 0 to 10 feet, by flight line, displayed over Area 28. Area highlighted by blue polygon shows area of least potential recharge. The rest of Area 28 has a moderate to high potential for recharge. This is an example of how to use the map by selecting an area where the dominant color is continuous along the flight line (s). Map projection is NAD 83, UTM Zone 14 North, feet.

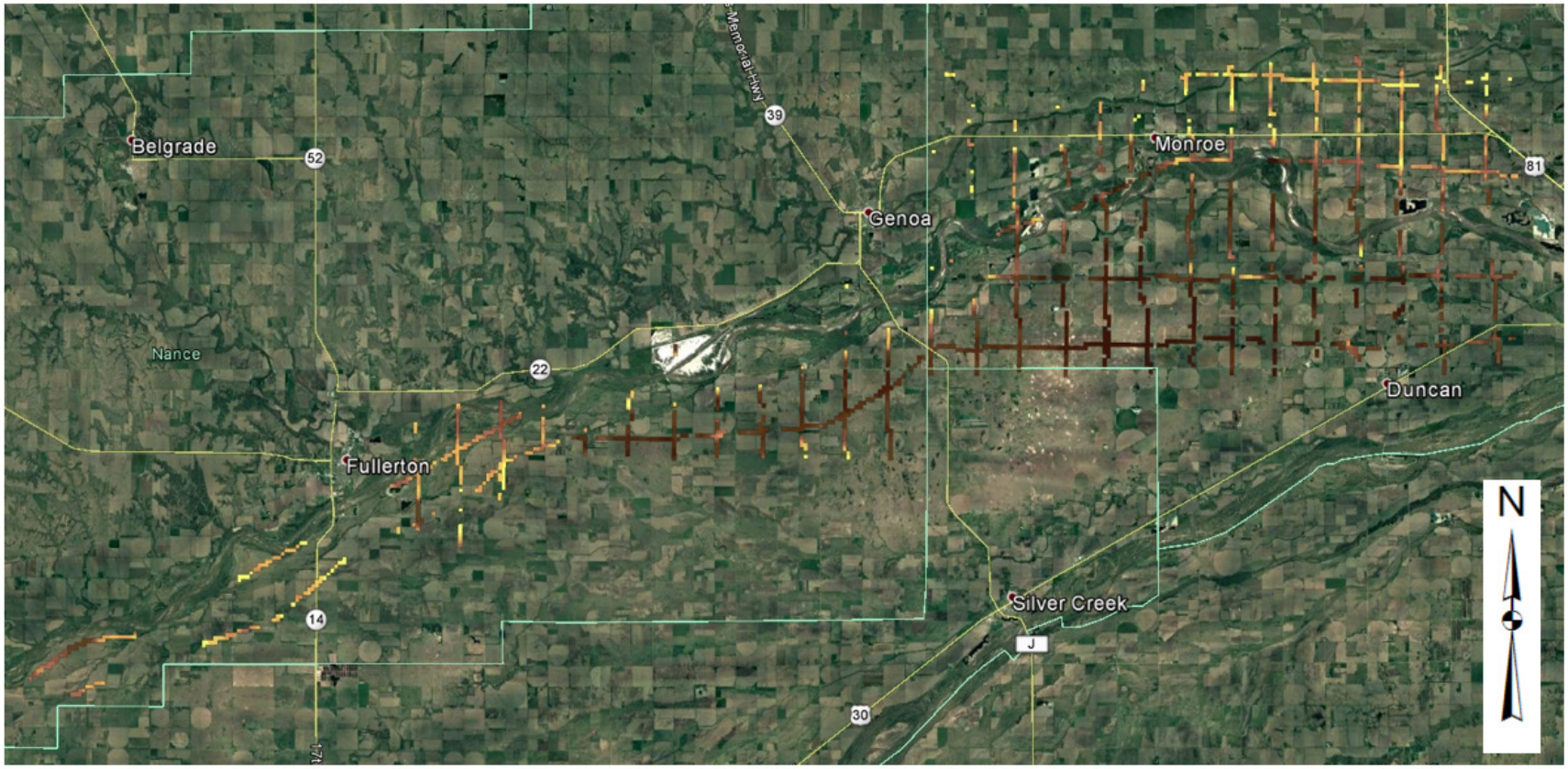


Figure 5-43. Potential aquifer and coarse material recharge zones within the LLNRD AEM survey area displayed as a kmz in Google Earth. This kmz is included as a deliverable in Appendix_3_Deliverables\KMZ\Recharge.

5.6.2 Columbus Block AEM Survey Area

The Columbus Block survey area was mapped at a high resolution (Section 4.2) with the goal of constructing a detailed 3D hydrogeologic framework. Part of that framework was the delineation of potential recharge zones in that area. During the Columbus Block survey, approximately 134 square miles (approximately 85,937 acres) of AEM data were collected and interpreted. The closely spaced flight lines (0.11 mile (about 175 m)) within the Columbus Block survey area allowed for nearly continuous mapping of the different aquifer material types. Figure 5-44 is a map displaying all the AEM-inferred aquifer materials in the first model layer, 0 to 10 ft. There is heterogeneity in the aquifer materials but it is quite easy to identify the areas of aquifer materials that will transmit the most, and the least, amounts of water from the surface down to the groundwater system. It should be noted that the development associated with Columbus, NE will have an impact on the recharge rates. Parking lots, built up areas, storm water collections, and baseball fields can all modify the recharge. Figure 5-45 is a Google Earth image which displays of the potential recharge based only on the aquifer materials and coarse aquifer materials detected in the near surface in the Columbus Block survey area. Lighter colors are aquifer materials and darker colors represent coarse aquifer materials. This kmz is included in *Appendix_3_Deliverables\KMZ\Recharge*.

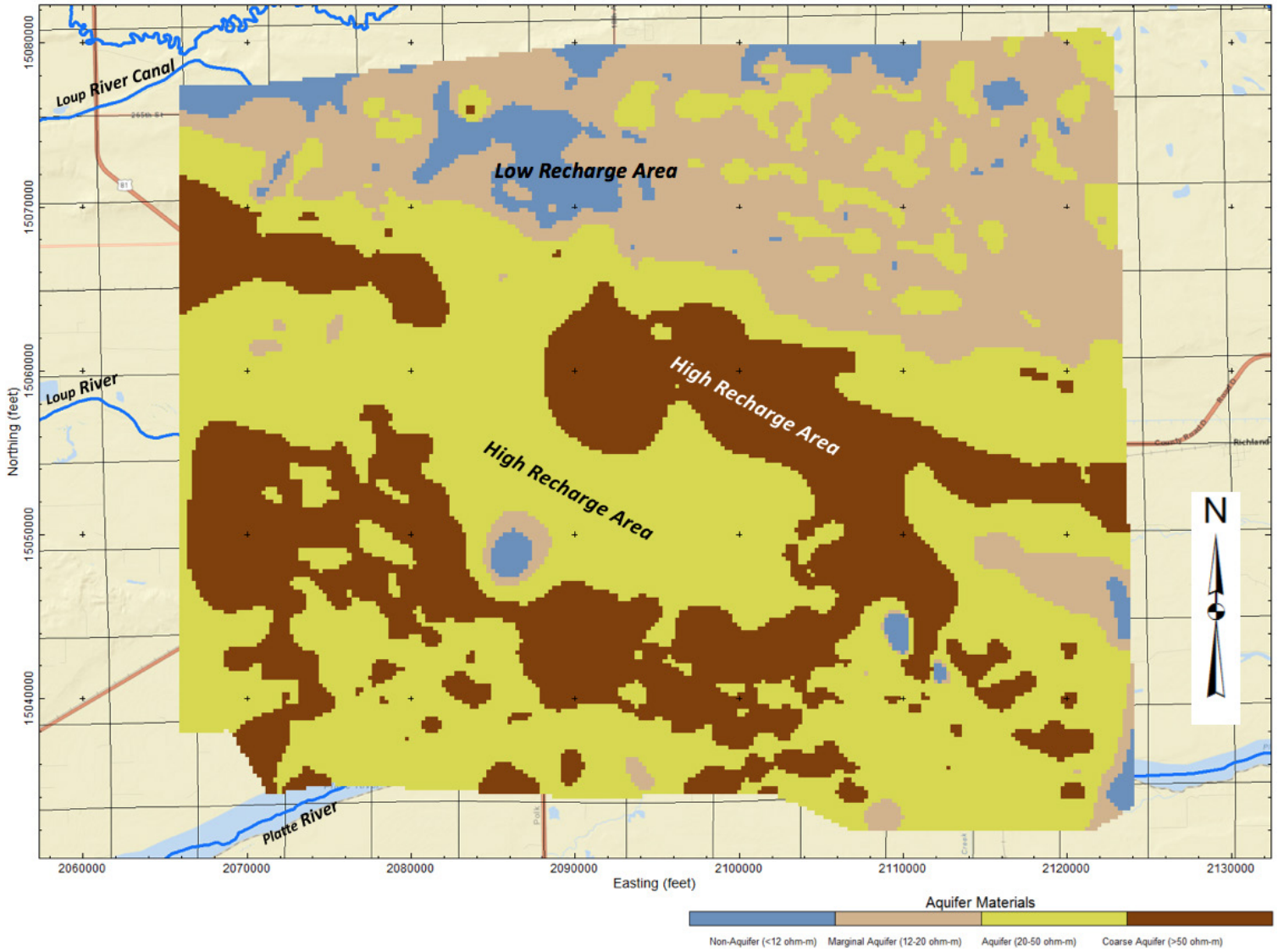


Figure 5-44. Map of aquifer materials for the first 0 to 10 feet displayed over Columbus Block Area. Areas of aquifer (yellow) and coarse aquifer (brown) materials have the highest rates of potential recharge. Non-aquifer (blue) and marginal aquifer (tan) have the lowest rates of potential recharge. Map projection is NAD 83, UTM Zone 14 North feet.

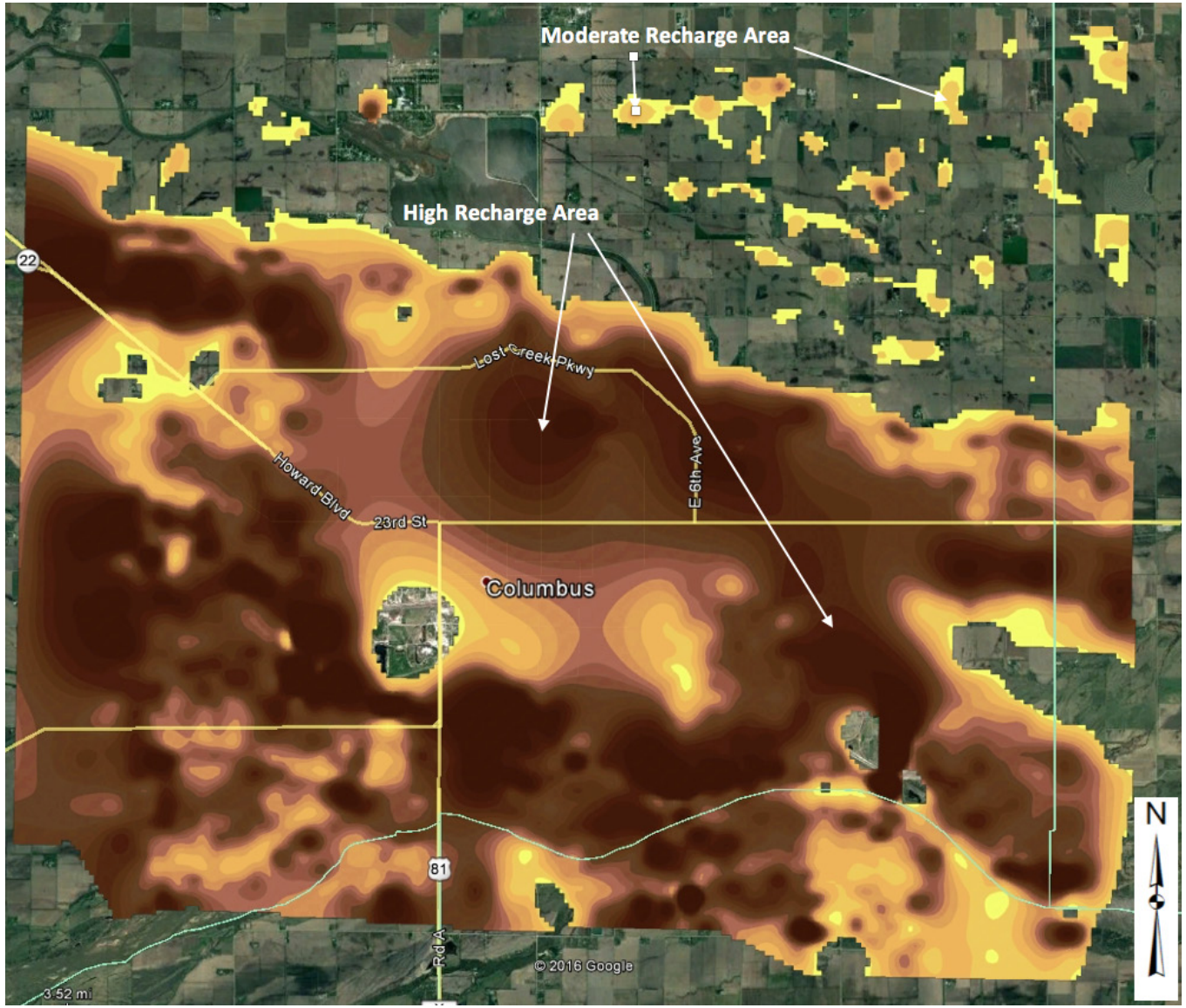


Figure 5-45. Potential recharge zones based on aquifer and coarse aquifer materials within the Columbus Block Area AEM survey area displayed as a kmz in Google Earth. This kmz is included as a deliverable in Appendix_3_Deliverables\KMZ\Recharge.

5.7 Key AEM Findings

5.7.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results. These included CSD (Within the LLNRD, 51 CSD holes contained lithology information, 45 holes contained stratigraphic information, and 5 holes contained geophysical information) and NE-DNR (A total of 2,414 registered wells contained usable lithology information) boreholes.

5.7.2 Merging 2014 and 2016 AEM Databases

The LLNRD survey area encompassed an additional 12.2 line-miles of AEM data collected in 2014 by the LENRD and the ENWRA. The 2014 AEM data contains valuable information that can be utilized in the interpretation of the larger LLNRD AEM survey area. The 2014 AEM data was combined with the 2016 AEM data. This combination did not include reinverting the 2014 data, but included merging the 2014 inversions into the current database and reinterpretation.

5.7.3 Digitizing Interpreted Geological Contacts

Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q***) and Cretaceous Niobrara (***Kn***), Carlile (***Kc***), Greenhorn limestone and Graneros shale (***Kgg***), and Dakota (***Kd***). The interpretive process benefited from the use of CSD and NE-DNR borehole logs. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the Quaternary/Tertiary aquifer material mapping are included in the appendices as well as interpretative surface grids.

5.7.4 Resistivity/Lithology Relationship

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

5.7.5 Hydrogeological Framework of the LLNRD

The AEM reveals considerable variability in the Quaternary and Tertiary deposits across the LLNRD. The subsurface distribution of materials can be generally characterized in two blocks. These areas include the Quaternary Aquifer Area and the Cretaceous bedrock aquiclude. The ***Q*** aquifer of the LLNRD AEM survey area is predominantly composed of Quaternary unconsolidated aquifer and coarse aquifer materials composed of alluvial sediments. These materials are sitting on varying thickness of ***Kn*** and ***Kc*** which is the bedrock aquiclude for the area.

5.7.6 Hydrogeological Framework of the Columbus AEM Block Survey Area

The Columbus Block AEM flight area is within the Quaternary Aquifer system. The area is composed of mostly aquifer materials lying on the ***Kc*** bedrock surface. The bedrock is eroded and has two channels cut into it. The main channel trends from west to east in the center of the block and the second channel trends from the center of the block to the south. The channels are flanked by three bedrock highs that are in the block area which have an increased relief of up to 80 feet in elevation. The area is dominated by aquifer materials and coarse aquifer materials and a high water table with good aquifer properties. The thicker sequences of aquifer to coarse aquifer materials lie to the north and center of the block with marginal and non-aquifer materials lying basal in nature.

5.7.7 Estimation of Aquifer Volume and Water in Storage in the Columbus Block

The non-aquifer material has an estimated volume of 597,836 acre-ft and contains 239,134 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 1,276,259 acre-ft and contains 446,691 acre-ft, aquifer material has an estimated volume of 2,586,263 acre-ft and contains an estimated volume of 517,253 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 1,270,318 acre-ft for a total of 317,580 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 1,520,657 acre-ft. Non-aquifer materials in the Columbus Block AEM survey area will yield approximately 4,783 acre-ft, marginal aquifer materials will yield approximately 22,335 acre-ft, aquifer materials will yield 77,588 acre-ft, and the coarse aquifer material will yield approximately 47,637 acre-ft. A total of 125,225 acre-ft is available from the combined aquifer and coarse aquifer materials.

5.7.8 Potential Recharge Zones within the Area 28 Reconnaissance Survey Area

Each LLNRD AEM flight line was interpreted for aquifer material in the first model layer (0 – 10 ft). Areas of coarse aquifer material will have the highest potential to transmit the largest amount of water to the grou12ndwater system with the aquifer material potentially transmitting slightly less precipitation downward as both units are permeable. The marginal aquifer material has the lowest potential to transmit some water downward and the non-aquifer material will transmit minimal to no water to the groundwater aquifer. The use of widely-spaced reconnaissance lines (approximately 1 mile apart) in the Area 28 AEM survey illustrates patterns or areas where the potential for recharge can be high and low. Locations where the flight lines intersect and both lines show either aquifer or coarse aquifer material should be considered as higher likelihood for recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true where two flight lines intersect and both lines show non-aquifer or marginal material, those areas will likely not be optimal recharge locations.

5.7.9 Potential Recharge Zones within the Columbus Block AEM Survey Area

The closely spaced flight lines (0.11 mile (about 175 m)) within the Columbus Block survey area allowed for nearly continuous mapping of the different aquifer material types in the first model layer, 0 to 10 ft. There is heterogeneity in the aquifer materials but it is quite easy to identify the areas of aquifer materials that will transmit the most, and the least, amounts of water from the surface down to the groundwater system.

5.8 Recommendations

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

5.8.1 Additional AEM Mapping

The aquifer maps provided in this report represent the detailed framework developed for the Columbus Block Area and reconnaissance level of Area 28. The detail provided in the hydrogeological interpretation of the Columbus Block Area allowed for confident development of a hydrogeologic framework. The interpretations match well with the CSD and NE-DNR test holes. While no additional high resolution AEM information is needed within Columbus Block Area to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or "block flights" be collected to develop detailed frameworks in other areas.

Area 28 and the surrounding area should be mapped in detail by block flights to provide information on the hydrogeologic framework and the recharge areas. This would potentially be done in cooperation with the neighboring NRDs to get details to the continuous aquifer system that is shared in the area. The line spacing for the block flights should be on the order of 0.25 mile (1,320 ft). For example, the detailed hydrogeologic frameworks presented in this report have provided estimates of groundwater storage capacity. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield. It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of eastern LLNRD. This will supply the LLNRD with information on groundwater flow, aquifer sustainability, depletion to streams, well interference, groundwater withdrawal, and other management considerations.

Reconnaissance flight lines expanding out from Area 28 to the west and north will help the district understand the hydrogeologic framework adjacent to Area 28. This will focus the ongoing water quality work to the adjacent areas to determine if additional management is needed. It will also provide locations for new monitoring wells and water level locations.

5.8.2 Update the Water Table map

The groundwater data used in the analyses presented in this report use the 2016 water table map (personal communication, Tyler Naprstek Lower Loup Natural Resources District. 2017, Water table map of the District 2016). Additional water level measurement locations would improve the water table map. This is especially true on the north and west side of Columbus side of the AEM survey area. The transition from the flood plain to areas out of the flood plain would be a good addition to the network.

5.8.3 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 LLNRD area was used in building the framework maps and profiles. It is

recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in optimal locations. The location of new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution.

5.8.4 Aquifer testing and borehole logging

Aquifer tests are recommended to improve estimates of aquifer characteristics. Limited aquifer properties from previous reports were available outside the larger cities in the survey area. A robust aquifer characterization program is highly recommended at the state, regional (NRD's), and smaller municipal levels. Aquifer tests can be designed based on the results of AEM surveys and existing production wells could be used in conjunction with three or more installed water level observation wells. Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. The few test holes with geophysical logs LLNRD survey area were inadequate. None were calibrated and several had apparent hardware malfunctions. The borehole geophysical logs provided for this investigation demonstrate that additional calibrated and verified geophysical logs are required in the LLNRD. 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.

5.8.5 Recharge Zones

The LLNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. The block flights of AEM data acquisition provide the most detailed information for understanding recharge throughout the Columbus Block area. It is recommended that additional AEM data be collected and interpreted utilizing closely-spaced flight lines using an AEM system that has near-surface resolution. It is further recommended that future work integrate new soils maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

5.8.6 Managed Aquifer Recharge

The area which lies out of the flood plain on the north side of Columbus may have potential for managed aquifer recharge. Detailed analysis for this purpose would need to be done to determine if this is a viable opportunity for the LLNRD. Additional AEM mapping along the streams in the LLNRD would also locate similar locations. A detailed plan for locating and developing Managed Aquifer Recharge sites would be beneficial to the LLNRD for providing storage and release of water for stream flow and other uses.

6 Description of Data Delivered

6.1 Tables Describing Included Data Files

Table 6-1 describes the data columns in the ASCII *.xyz file LLNRD_EM_MAG_UTM14n_feet.xyz as well as the Geosoft database file LLNRD_EM_MAG_UTM14n_feet.gdb. This file contains the electromagnetic data, plus the magnetic and navigational data, as supplied directly from SkyTEM.

The result of the SCI is included in LLNRD_AEM_SCI_INV_v1.gdb files and LLNRD_AEM_SCI_INV_v1.xyz and the data columns of these databases are described in Table 6-2.

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

The various interpretation results are included in data files LLNRD_Block_InterpSurfaces_v1 and LLNRD_Recon_InterpSurfaces_v1 in gdb and ASCII xyz formats. Table 6-6 describes the data columns of those files.

Table 6-7 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, ten (10) flights were required to acquire the LLNRD AEM data (Figure 4-5). Grouped by flight date, there are four (4) data flies included in Appendix 3\Raw_Data for each flight. These files have extensions of “*.sps” and “*.skb”. The “*.sps” files include navigation and DGPS location data and the “*.skb” files include the raw AEM data that have been PFC-corrections (discussed in section 4.4.1). Two additional files are used for all the flights. These are the system description and specifications file (with the extension “*.gex”) in the GEO subdirectory and the ‘mask’ file (with the extension “*.lin”), in the MASK subdirectory, which correlates the flight dates, flight numbers, and assigned line numbers.

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

A voxel grid was completed for the Columbus dense flight block within the LLNRD survey area. The voxel grid was made using a 250 ft grid cell size and the model layer thickness (Table 4-4). The voxel grid was clipped below the bedrock surface interpreted from the AEM and the boreholes as detailed in section 5.2.3. The bedrock surface grid “*LLNRD_Kc_top_Columbus_Block_elevation*” was used to clip the voxel, and can be found in (Table 6-8). Table 6-9 is a list of the channel names in both ASCII *.xyz and Geosoft *.gdb format for the *LLNRD_ColumbusBlock* voxel.

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 Area 28 Reconnaissance survey lines
- 3D voxel models as ASCII *.xyz and *.gdb for the Columbus flight block

KMZs for LLNRD Columbus and Area 28 Reconnaissance flight lines (Discussed in Section 6.2)

Profile Analyst sessions for the Profiles and 3D grids for Columbus Block and Area 28 Reconnaissance data analysis. (Discussed in Section 6.3)

Table 6-1: Channel name, description, and units for LLNRD_EM_MAG_UTM14n_feet.gdb and LLNRD_EM_MAG_UTM14n_feet.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	Easting, NAD83 UTM Zone 14N	Meters [m]
N	Northing, NAD83 UTM Zone 14N	Meters [m]
DEM	Digital Elevation	Meters [m]
Alt	DGPS Altitude above sea level	Meters [m]
GDSpeed	Ground Speed	Kilometers/hour [km/h]
Curr_2	Current, Low Moment	Amps [A]
Curr_1	Current, High Moment	Amps [A]
LMZ_G01	Normalized (PFC-Corrected) Low Moment Z-RxCoil value	$pV/(m^4*A)$
HMZ_G01	Normalized (PFC-Corrected) High Moment Z-RxCoil value	$pV/(m^4*A)$
LMX_G01	Normalized (PFC-Corrected) Low Moment X-RxCoil value	$pV/(m^4*A)$
HMX_G01	Normalized (PFC-Corrected) High Moment X-RxCoil value	$pV/(m^4*A)$
_60Hz_IntenSity	Power Line Noise Intensity monitor	
Bmag_f	Raw Base Station Mag Data filtered	nanoTesla [nT]
Diurnal	Diurnal Mag Data	nanoTesla [nT]
MA1_orig	Raw Mag Data	nanoTesla [nT]
Mag_fil	Mag filtered	nanoTesla [nT]
Mag_CD	Mag Data Corrected for Diurnal Drift	nanoTesla [nT]
RMF	Residual Magnetic Field	nanoTesla [nT]
IGRF	International Geomagnetic Reference Field	nanoTesla [nT]
X_ft	Easting, NAD83 UTM Zone 14N	Feet [ft]
Y_ft	Northing, NAD83 UTM Zone 14N	Feet [ft]
Z_ft	Elevation, 100 ft grid of NED DEM NAVD88	Feet [ft]

Table 6-2: Channel name, description, and units for LLNRD_AEM_SCI_Inv_v1.gdb and LLNRD_AEM_SCI_Inv_v1.xyz with EM inversion results.

Parameter	Description	Unit
X_FT	Easting NAD83, UTM Zone 14	Feet [ft]
Y_FT	Northing NAD83, UTM Zone 14	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]
DEM_FT	DEM from 100 ft grid NED NAVD88	Feet [ft]
FID	Unique Fiducial Number	
LINE	Line 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_LOWER_M	Less conservative estimate of DOI	Meters [m]
DOI_UPPER_M	More conservative estimate of DOI	Meters [m]
DOI_LOWER_FT	Less conservative estimate of DOI	Feet [ft]
DOI_UPPER_FT	More conservative estimate of DOI	Feet [ft]
RHO_I_0 THROUGH RHO_I_28	Inverted resistivity of each later	Ohm-m
SIGMA_I_0 THROUGH SIGMA_I_28	Conductivity	S/m
DEP_BOT_0_M THROUGH DEP_BOT_28_M	Depth to the bottom of individual layers	Meters [m]
DEP_TOP_0_M THROUGH DEP_TOP_28_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_FT THROUGH DEP_BOT_28_FT	Depth to the bottom of individual layers	Feet [ft]
DEP_TOP_0_FT THROUGH DEP_TOP_28_FT	Depth to the top of individual layers	Feet [ft]
THK_0_M THROUGH THK_28_M	Thickness of individual layers	Meters [m]
THK_0_FT THROUGH THK_28_FT	Thickness of individual layers	Feet [ft]

Table 6-3: Files containing borehole information.

Database (*.xyz, *.gdb)	Description
LLNRDDNRBlockLith_Collar_project.	Lithology logs from NE-DNR registered wells within the Columbus Block of the LLNRD Survey Area
LLNRDDNRBlockLith_Data_project.	
LLNRDCSDLith_Collar_project.	Lithology logs from CSD boreholes in the LLNRD Survey Area
LLNRDCSDLith_Data_project.	
LLNRDCSDStrat_Collar_project.	Stratigraphy logs from CSD boreholes in the LLNRD Survey Area
LLNRDCSDStrat_Strat_project.	
LLNRDDNRReconLith_Collar_project.	Lithology logs from NE-DNR registered wells within the Reconnaissance area of the LLNRD Survey Area
LLNRDDNRReconLith_Data_project.	
LLNRDCSDElogs_Collar_project.	Geophysical Logs from CSD within the LLNRD Project Area
LLNRDCSDElogs_Data_project.	
LLNRDOALith_Collar.	Lithology logs from LLNRD contracted wells conducted by Olsson and Associates within the LLNRD Survey Area
LLNRDOALith_Lith.	
LLNRDO&GStrat_Collar_project.	Stratigraphy Data from wells from the Nebraska Oil and Gas Conservation Commission within the LLNRD Survey Area
LLNRDO&GStrat_Strat_project.	

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

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

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

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

Table 6-6: Channel name description and units for the interpretation results file LLNRD_Block_InterpSurfaces_v1 and LLNRD_Recon_InterpSurfaces_v1 "gdb" and "xyz" files.

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

Table 6-7: Raw SkyTEM data files

Folder	File Name	Description
Data	..NavSys.sps, …PaPc.sps, ...RawData_PFC.skb, …DPGS.sps	Raw data files included for each flight used in importing to Aarhus Workbench
Geo	20160815_337m2_Cal_DualWaveform_60Hz.gex	304M System Description
Mask	LLNRD_Linefile.lin	Production file listing dates, flights, and assigned line numbers

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

Grid File Name	Description	Grid Cell Size (feet)
LLNRD_bedrock_top_elevation.	Grid of the Bedrock composed of Kn and Kc which is also the Base of the Aquifer elevation NAVD88 (feet) LLNRD Survey Area	250
LLNRD_DEM.	Grid of the Digital Elevation Model (DEM) downloaded from the National Elevation Dataset (NED) August 2016 NAVD88 (feet)	100
LLNRD_Kn_top_elevation.	Grid of the top of the Kn elevation NAVD88 (feet) LLNRD Survey Area	250
LLNRD_Kc_top_elevation.	Grid of the top of the Kc elevation NAVD88 (feet) LLNRD Survey Area	250
LLNRD_Kgg_top_elevation.	Grid of the top of the Kgg elevation NAVD88 (feet) LLNRD Survey Area	250
LLNRD_Kd_top_elevation.	Grid of the top of the Kd elevation NAVD88 (feet) LLNRD Survey Area	500
LLNRD_WT_Recon_area_elevation.	Grid of the water table as provided by the LLNRD for the Reconnaissance Area NAVD88 (feet)	100
LLNRD_Quaternary_thickness	Grid of the thickness of the Quaternary material within the LLNRD Survey Area (feet)	100
LLNRD_DEM_Columbus_Block_elevation.	Grid of the Digital Elevation Model (DEM) downloaded from the National Elevation Dataset (NED) August 2016 NAVD88 (feet) for the Columbus Block	100
LLNRD_WT_Columbus_Block_elevation.	Grid of the water table as provided by the LLNRD for the Columbus Block NAVD88 (feet)	100
LLNRD_Kc_top_Columbus_Block_elevation.	Grid of the top of the Kc elevation for the Columbus Block NAVD88 (feet) This is also the top of bedrock and the base of aquifer in the Columbus Block	250
LLNRD_Kgg_top_Columbus_Block_elevation.	Grid of the top of the Kgg elevation for the Columbus Block NAVD88 (feet)	250
LLNRD_Kd_top_Columbus_Block_elevation.	Grid of the top of the Kd elevation for the Columbus Block NAVD88 (feet)	500
LLNRD_surface_layer_Columbus_Block	Grid of the top layer of the AEM model 0-10 feet in depth resistivity (ohm-m)	250
LLNRD_Quaternary_Columbus_Block_thickness	Grid of the thickness of the Quaternary material within the LLNRD Columbus Block (feet)	100

Table 6-9. Channel name, description, and units for LLNRD_ColumbusBlock*.csv and *.gdb.

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

6.2 Description of Included Google Earth KMZ Data and Profiles

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

KMZ files of the potential recharge zones in the Columbus Block and the Area 28 Reconnaissance area are included in the folder "*Appendix_3_Deliverables\KMZ\LLNRD_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 (2016), and the elevations of the tops of the Cretaceous Niobrara (if present), Carlile, Greenhorn and Graneros, and Dakota formations. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\LLNRD_Interp\LLNRD_Prof*" folder. Also in this folder is a "*GoogleE_Readme_LLNRD.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 Columbus Block KMZ is presented in Figure 6-1 and for the Area 28 Reconnaissance area in Figure 6-2.

6.2.1 Included README for the LLNRD Interpretation KMZ's

README for:

LLNRD_Columbus_Block_Interpretation_v1.kmz

LLNRD_Area28_Reconnaissance_Interpretation_v2.kmz

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

Google Earth Instructions:

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

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

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

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

STEP 5: The *LLNRD_Columbus_Block_Interpretation_v1.kmz* file (Figure 6-1) and/or the *LLNRD_Area28_Reconnaissance_Interpretation_v2.kmz* file (Figure 6-2) within the folder named *LLNRD_Prof* can now be opened and viewed in Google Earth.

Data:

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

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

East (ft) – Easting coordinate in NAD83, UTM 14N, in feet

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

Elev (ft) – DEM elevation in feet

WaterTable2016 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

Elev Kn (ft) – Elevation of Cretaceous Niobrara Fm (included in the Reconnaissance set)

Elev Kc (ft) – Elevation of Cretaceous Carlile Fm

Elev Kgg (ft) – Elevation of Greenhorn and-Graneros Fm

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

Profile – Link to Interpreted AEM profile images

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

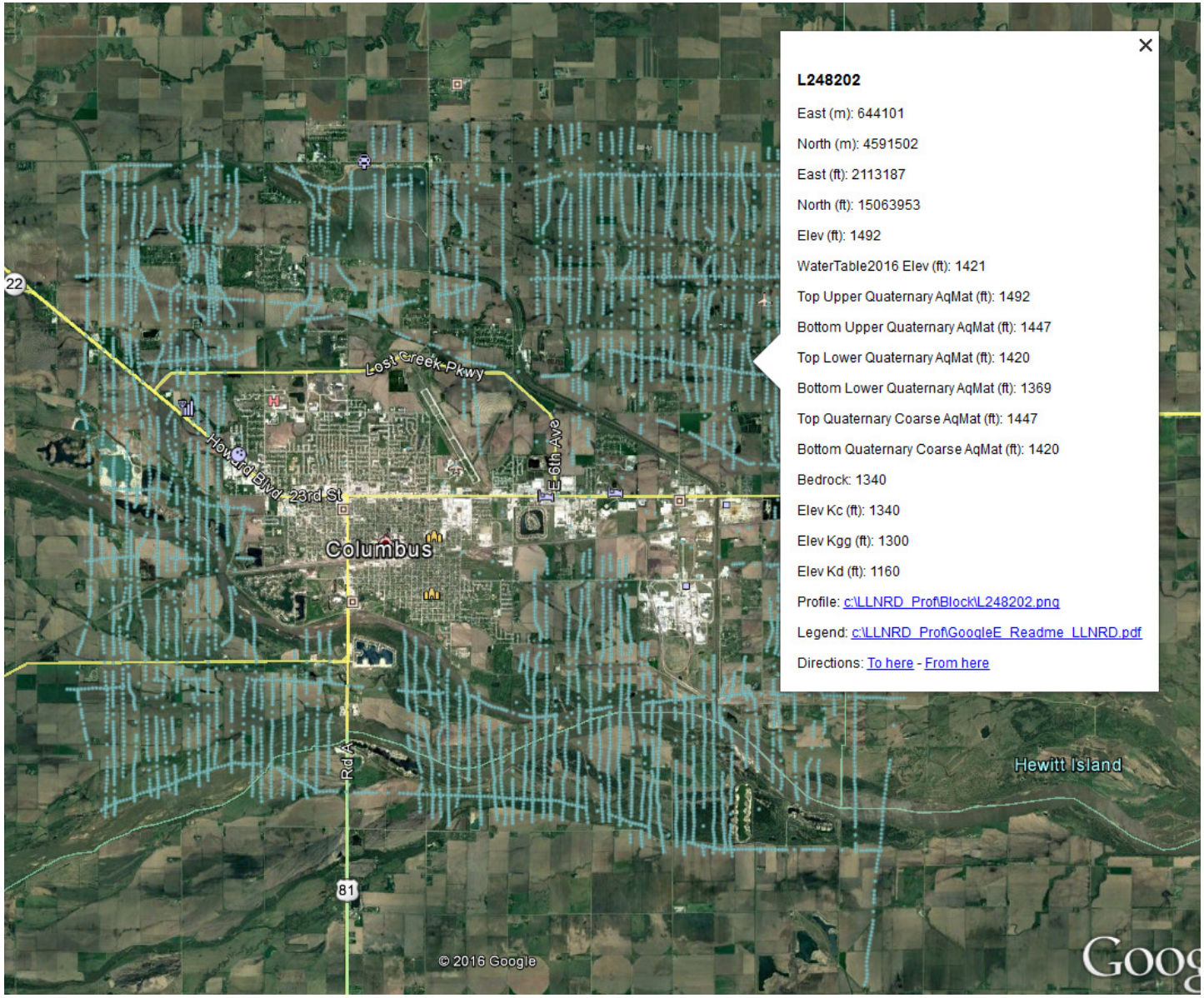


Figure 6-1. Example Google Earth image for the LLNRD Columbus Block Interpretation kmz.

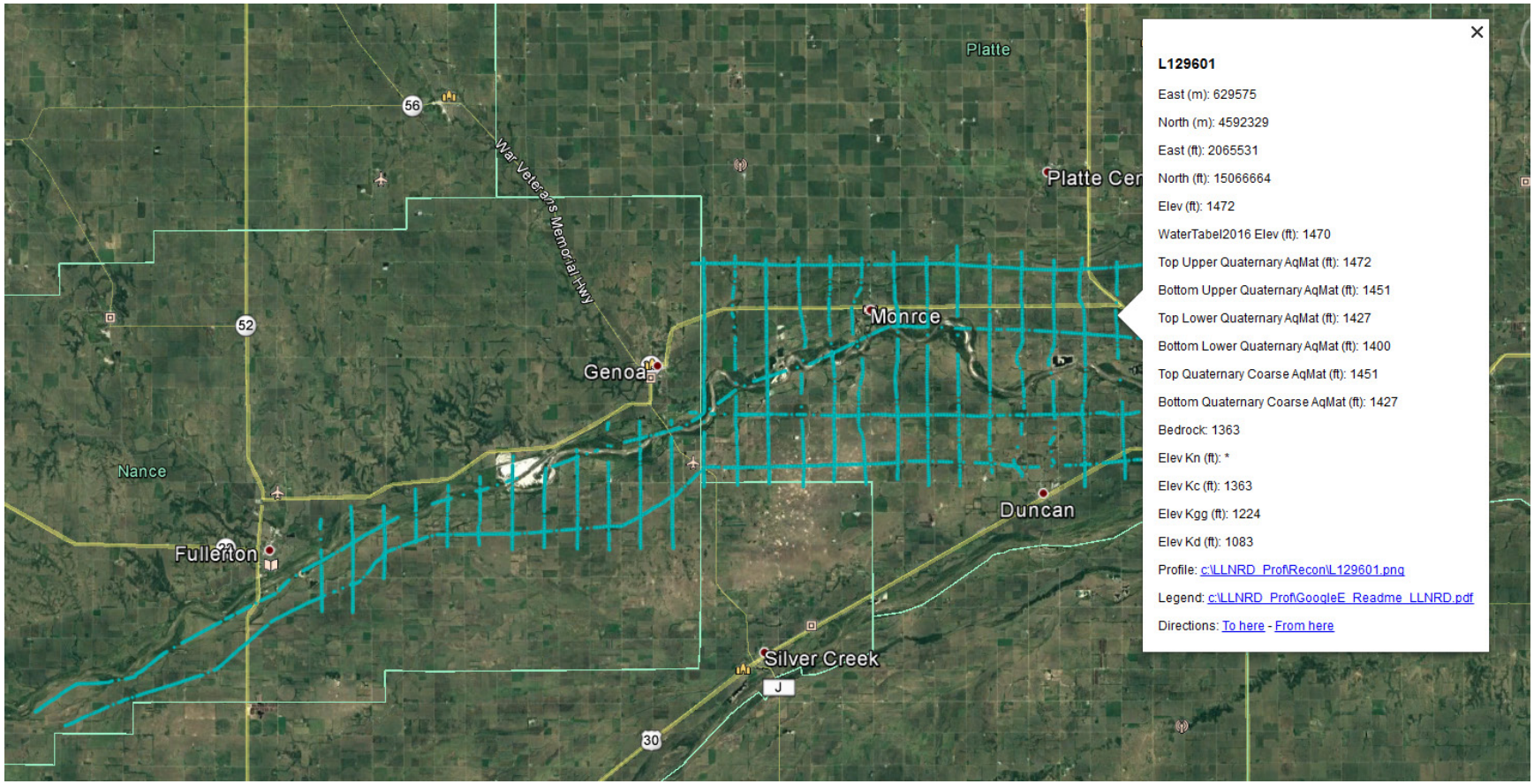


Figure 6-2. Example Google Earth image for the LLNRD Area 28 Reconnaissance Interpretation kmz.

6.3 Description of Included Profile Analyst (PA) Session Material

As discussed above PitneyBowes pbEncom Discover PA Version 2015 Release Build 15.0.13 (pbEncom, 2016) 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 pbEncom Discover PA website: http://web2.encom.com.au/downloads/discover_3D/Discover_Viewer_2015.exe

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. pbEncom Discover PA Session Files

Area Covered	View Format	File name
LLNRD Columbus Block and Recon	**3D**	**LLNRD_FenceDiagrams.egs**
LLNRD Columbus Block	**2D**	**LLNRD_Profiles_Block.egs**
LLNRD Recon	**2D**	**LLNRD_Recon_Profiles.egs**

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