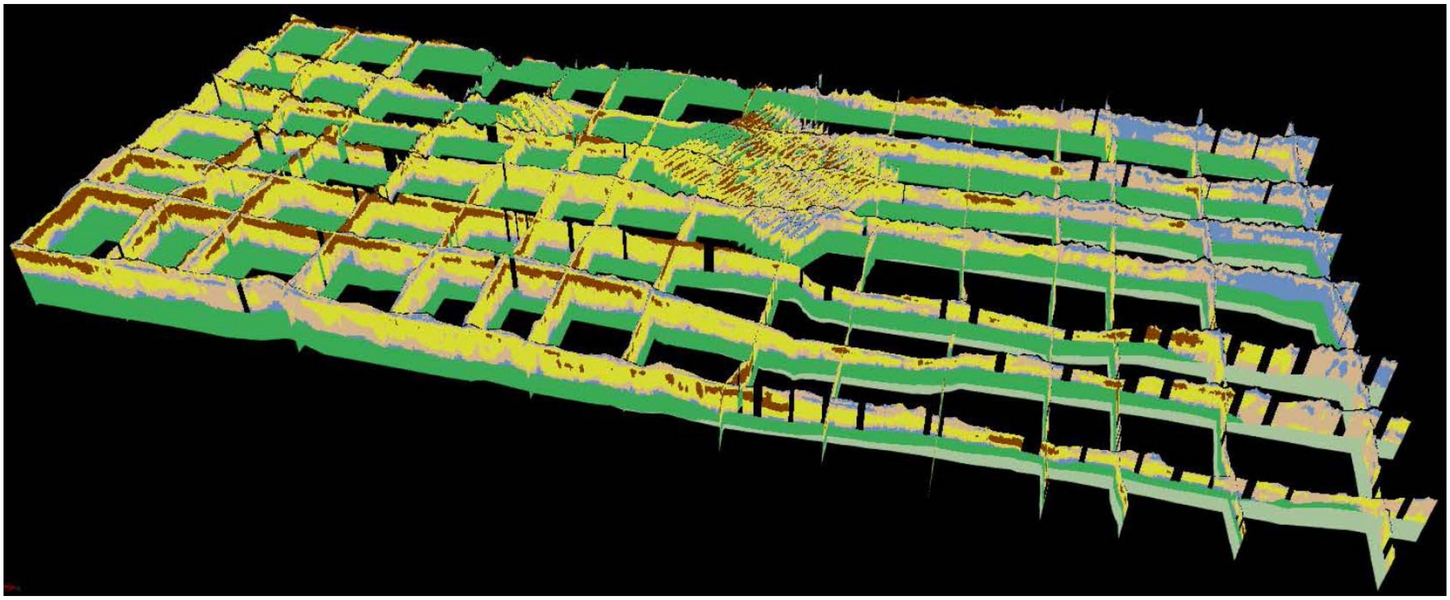
Mapping the Hydrogeology of the Bazile Groundwater Management Area with Airborne Electromagnetics Surveys



***Prepared for*:**

Lewis and Clark Natural Resources District
Lower Elkhorn Natural Resources District
Lower Niobrara Natural Resources District
Upper Elkhorn Natural Resources District

301 North Harrison Street
O'Neill, Nebraska 68763

January 10, 2017

AGF

Aqua Geo Frameworks, LLC.

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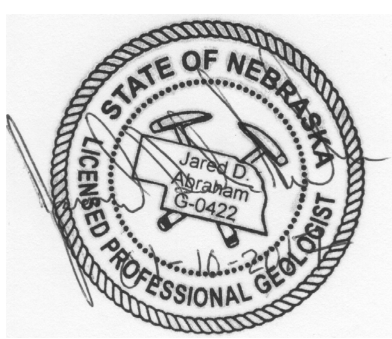

Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled "*Mapping the Hydrogeology of the Bazile Groundwater Management Area with Airborne Electromagnetics Surveys*". 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 Bazile Groundwater Management Area (BGMA) sponsors to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the BGMA project area as well as the Creighton Water System and West Knox Rural Water System survey areas and to recommend future work to enhance groundwater management activities.

The scope of work for this project was as follows:

1. SCOPE OF WORK

1.1 An AEM survey utilizing the SkyTEM304M system was flown over the BGMA Area. These flights have been provided as preliminary AEM data on July 26, 2016 and the final AEM data are included as a product attached to this data report. In addition to the BGMA AEM reconnaissance survey, denser flight blocks were flown over the Creighton Water System and the West Knox Rural Water System areas.

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 BGMA assisted in providing information such as power line maps, a test hole database, and related aquifer characteristic studies to AGF.

At the conclusion of the design process the BGMA reconnaissance flight lines were approximately 43 miles in length (east-west) and 18 miles (north-south) and were separated by approximately 3 miles in both east-west and north-south directions. The Creighton Water System flight lines were approximately 6 miles in length and were separated by about 0.25 miles. The West Knox Rural Water System flight lines were approximately 2.5 miles in length and were separated by about 0.33 miles. Approximately 644 line-miles of AEM survey were flown, in total, over the area.

1.4 AGF acquired AEM data over the BGMA, commencing 22 July 2016 and finishing on 25 July 2016, to support development of the hydrogeological framework. Status reports of the flying were provided to the Contract Representative of UENRD 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 26, 2016.

1.6 AGF inverted the AEM data. These final inverted georeferenced data are delivered to the UENRD 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 - As discussed above, borehole information was used to analyze the AEM inversion results. These included State of Nebraska Conservation and Survey Division (CSD) (Within the BGMA, a total of 58 holes contained lithology information, 50 holes contained stratigraphy information, and 30 holes contained geophysical information) and NE Department of Natural Resources boreholes (NE-DNR) (A total of 2,934 registered wells contained usable lithology information), and West Knox Rural Water System boreholes (A total of 13 wells contained lithology information, and 11 wells contained geophysical information) were utilized in the analysis of the AEM inversion results.

2.2 Merging 2014 and 2016 AEM Databases - The BGMA survey area encompassed an additional 107.62 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 BGMA and the Creighton Water System. 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***), Tertiary Ogallala (***To***), Cretaceous Pierre (***Kp***), and Cretaceous Niobrara (***Kn***). The interpretive process benefited from the use of CSD, NE-DNR, and West Knox Rural Water System borehole logs. Surface grids of the interpreted geologic formations ***Kp*** and ***Kn*** were then produced. Each flight line profile with interpretation including the Quaternary/Tertiary Aquifer material mapping are included as Appendices by flight area as well as the 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 Quaternary/Tertiary Ogallala aquifer system described in this report.

2.5 Hydrogeological Framework of the BGMA - The AEM reveals considerable variability in the Quaternary and Tertiary deposits across the northern BGMA. The subsurface distribution of materials can be generally characterized into four somewhat overlapping, but distinct, areas with smaller localized depositional features distributed at various locations within the survey area. These areas include the Quaternary and Ogallala Aquifer Area, the shallow ***Kp*** area, the glacial area, and the ***Kn*** bedrock area. The Quaternary and Ogallala Aquifer Area of the BGMA contains areas of saturated alluvium thickness up to 300 ft. The shallow ***Kp*** area is located in northwestern extent of the BGMA and is characterized by the bedrock/base of aquifer unit ***Kp*** being close to the surface. The glacial area is located in the northeastern and eastern areas of the BGMA and is characterized by ***Q*** glacial deposits overlaying pre-Pleistocene ***Q*** alluvial deposits or thin ***To*** deposits overlying bedrock of ***Kp*** or ***Kn***. The importance of the ***Kn*** bedrock area is that the character of the ***Kp*** is as an aquiclude and the ***Kn*** may contain fractures that will hold water

2.6 Hydrogeological Framework of the Creighton Water System Area - The Creighton Water System Area is within the Quaternary and Tertiary Ogallala Aquifer system region. The area is composed of mostly aquifer materials. The area on the east side of Bazile Creek shows little to no ***To*** present. The area is dominated by aquifer materials and coarse aquifer materials that thin considerably around Bazile Creek with the ***Kp*** close to the surface. Some of the coarse aquifer material is above the water table and may not be saturated. However, it also shows that much of this coarse material is close to the surface and may serve as a conduit for recharge.

2.7 Hydrogeological Framework of the West Knox Rural Water System Area - The West Knox Rural Water System survey area is also within the Quaternary and Tertiary Ogallala Aquifer system region. The area is characterized by being composed of mostly aquifer materials composed of predominately of ***To*** with ***Q*** deposits overlaying the ***To***. Much of the area is aquifer material with minor coarse aquifer material types. There are non-aquifer and marginal aquifer materials present on the top of some of the AEM profiles and at the bottom of the sections above the ***Kp*** bedrock.

2.8 Creighton Water System Estimation of Aquifer Volume and Water in Storage - The non-aquifer material has an estimated volume of 158,333 acre-ft and contains 63,333 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 482,282 acre-ft and contains 168,798 acre-ft, aquifer material has an estimated volume of 1,782,523 acre-ft and contains an estimated volume of 356,504 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 357,775 acre-ft for a total of 89,443 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 678,078 acre-ft. Non aquifer materials in the Creighton survey area will yield approximately 1,266 acre-ft, marginal aquifer materials will yield approximately 8,440 acre-ft, aquifer materials will yield 35,650 acre-ft, and the coarse aquifer material will yield approximately 13,416 acre-ft. A total of 57,506 acre-ft is available from the combined aquifer and coarse aquifer materials.

2.9 West Knox Rural Water System Estimation of Aquifer Volume and Water in Storage - The non-aquifer material has an estimated volume of 110,490 acre-ft and contains 44,196 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 118,818 acre-ft and contains 41,586 acre-ft, and aquifer material has an estimated volume of 403,659 acre-ft and contains an estimated volume of 90,731 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 24,085 acre-ft for a total of 6,021 acre-ft of groundwater in storage. The amount of groundwater in storage for both material groups is 182,534 acre-ft. Non aquifer materials in the West Knox survey area will yield approximately 884 acre-ft. marginal aquifer materials will yield 2,079 acre-ft, aquifer materials will yield 8,073 acre-ft and the coarse aquifer material will yield approximately 903 acre-ft. A total of 11,939 acre-ft is available from the combined aquifer and coarse aquifer materials.

2.10 Potential Recharge Zones within the BGMA – There are locations where the AEM flight lines intersect and both lines show either aquifer or coarse aquifer material. These locations should be considered as higher likelihood for better recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true – there are locations within the BGMA where two flight lines intersect and both lines show non-aquifer or marginal material; those areas will likely not be optimal recharge locations. An overlay of the AEM-inferred aquifer materials on soil maps of the area from Gosselin (1991) suggest areas where the interpreted aquifer materials and the soil types are very similar and some other areas where they are not similar. This may be due to the shallow nature of soil sampling and/or the averaging of the first 10 feet due to the nature of the AEM technique.

2.11 Potential Recharge Zones within the Creighton Water System AEM Survey Area – A display of the AEM-inferred aquifer materials in the first 10 ft indicates that while there is some heterogeneity in the aquifer materials, it is easy to identify the areas of aquifer materials that will transmit the most (aquifer and coarse aquifer materials), and the least (non-aquifer and marginal aquifer materials), amounts of water from the surface down to the groundwater system. An overlay of the AEM-interpreted aquifer materials on the Gosselin (1991) soil maps show strong correlation between the interpreted aquifer materials and the boundaries of the 5-89 and 5-122 soil groups.

2.12 Potential Recharge Zones within the West Knox Rural Water System AEM Survey Area – An examination of the AEM-interpreted aquifer materials within the West Knox AEM survey block indicates that about half of the mapped area (the southwestern half) displays aquifer material suitable for recharge and the other half is identified as non-aquifer and marginal aquifer material types. There is apparently no coarse aquifer material at the land surface in this area. When these materials are overlain on the soil maps (Gosselin, 1991), there are coincident locations of the interpreted aquifer materials and the 11-5 soils group boundary. It should be noted that coarse aquifer material can be identified just east of the West Knox AEM survey block along several BGMA reconnaissance flight lines.

3. Recommendations

Recommendations provided to the client in this section are based on the interpretation and understanding gained from adding the AEM data to existing information and from discussions with the clients about their needs. AGF is providing a hydrogeologic framework report that includes maps of aquifer materials and their relationships to current test holes and production groundwater wells, estimates of water storage capacity and water availability, and maps of estimated potential recharge areas.

3.1. **Additional AEM Mapping.** The aquifer maps provided in this report represent general frameworks based on the BGMA AEM reconnaissance lines flown and the detailed frameworks developed for the Creighton Water System AEM survey area and the West Knox Rural Water System AEM survey area.

a. The detail provided in the hydrogeological interpretation of the Creighton Water System and the West Knox Rural Water System AEM survey areas allowed for confident development of hydrogeologic frameworks for each of these areas. The interpretations match particularly well with the CSD and NE-DNR test holes. If additional high resolution information is needed within the BGMA to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or “block flights” be collected in order to develop detailed frameworks similar to those developed for the Creighton Water System and West Knox Rural Water System survey area.

For example, the detailed hydrogeologic frameworks presented in this report have provided estimates of water storage capacity only in the areas of closely spaced flight lines where volumes of aquifer materials can be calculated. This is done by using existing aquifer characteristic information and calculating groundwater in storage and effective yield. It is recommended that additional closely spaced flight lines for collection of AEM data and interpretation be considered in critical areas of the BGMA and surrounding areas. This will supply the project sponsors with information impacting aquifer sustainability, depletion to streams, well interference, groundwater withdrawal and other management considerations.

b. Since groundwater flowing into and out of the BGMA generally flows from west to east, understanding the hydrogeology of the areas up gradient from the BGMA would give useful information on the hydraulic connection between the aquifers. It is therefore recommended that additional reconnaissance lines be collected west, south, and possibly east of the current BGMA project area. In addition, the AEM data could be used for identification of additional sites for water supply and monitoring wells for water level and water quality data collection.

The additional AEM data collection and interpretation could also be used to show the hydrological connections between aquifers and streams. Data collection along streams can provide information directly within the streambed. The additional studies on groundwater-surface water relationships could possibly be quantified as to impacts on stream flow and groundwater increases or losses. A good example of future work would be mapping in and around Verdigre Creek, a priority watershed.

3.2. **Siting new test holes and production wells**. The framework maps and profiles provided in this report provide insight in 3D on the relationship between current test holes and production groundwater wells. All of the available well data for the BGMA were 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 can be sited in optimal locations for the purpose intended. This is efficient and saves money by planning the new locations with details not previously available.

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. Care should be taken to locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution. It is possible that new wells will need to be sited outside the current BGMA project area using future AEM data interpretation derived from the reconnaissance or detailed block surveys recommended above.

3.3. **Aquifer testing and borehole logging.** Additional aquifer tests are recommended to improve estimates of aquifer characteristics. Aquifer Tests can be designed based on the AEM survey.

Existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed well calibrated geophysical logging for aquifer characteristics is recommended. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, and induction logs. Plus, there are new technologies for collecting detailed aquifer characteristics from a borehole such as 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.

3.4. **Recharge Zones**. The new hydrogeologic framework provides approximate areas of recharge from the ground surface to the groundwater aquifer. The discussions in Section 5.8, it is clear that most detailed information for this purpose was obtained from the closely-spaced block flights in the Creighton Water System and West Knox Rural Water System areas where nearly continuous data was collected. It is recommended that if detailed information is required for understanding recharge throughout the BGMA, then additional AEM data be collected and interpreted for closely-spaced flight lines utilizing an AEM system that has near-surface resolution.
It is recommended that future work integrate modern soils maps with the results of this study to provide details on soil permeability, slope, water retention, etc. to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

4. Deliverables

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and xyz
- SCI inversion Geosoft database and xyz
- Borehole Geosoft databases and xyz
- Interpretations Geosoft database and xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView files – surface, topo, etc
- 3D voxel models as ASCII xyz for the Creighton and Knox flight blocks

KMZs for BGMA Reconnaissance, Creighton Water System, and West Knox Rural Water System flight lines

Profile Analyst sessions for the Profiles and 3D voxels for Creighton Water System and West Knox Rural Water System.

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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
BGMA	Bazile Groundwater Management Area
BGMAP	Bazile Groundwater Management Area Project
Bgl/Bgs	Below Ground Level/Below Ground Surface
dB/dt	Change in amplitude of magnetic field with time
cm	centimeters
cm/yr	centimeters per year
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
GIS	Geographic Information System
GWA	Groundwater Associates, Inc.
HEM	Helicopter Electromagnetic
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
Km/km	Kilometers
Kc	Cretaceous Carlile Fm
Kd	Cretaceous Dakota Group
Kgg	Cretaceous Greenhorn-Grenaros Fm
Kn	Cretaceous Niobrara Fm
Kp	Cretaceous Pierre Fm
M	Mississippian Period
LCNRD	Lewis and Clark Natural Resources District
LENRD	Lower Elkhorn Natural Resources District
LNNRD	Lower Niobrara 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
NRD	Natural Resources Districts
OM	Geosoft Oasis montaj
P	Pennsylvanian Period
PFC	Primary Field Compensation

PLNI	Power Line Noise Intensity
Q	Quaternary
Rx	Receiver
SCI	Spatially-Constrained Inversion
STD	Standard Deviation
Ta	Tertiary White River Group Arikaree Group
Tb	Tertiary White River Group Brule Formation
Tbw	Tertiary Broadwater Formation
Tc	Tertiary White River Group Chadron Formation
To	Tertiary Ogallala Group
TEM	Transient Electromagnetic
TDEM	Time-Domain Electromagnetic
TDS	Total dissolved solids
Tx	Transmitter
UENRD	Upper Elkhorn Natural Resources District
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 Bazile Groundwater Management Area (BGMA) is located in northeast Nebraska and encompasses 21 townships or 756 square miles (Figure 1-1). The BGMA lies within three counties: Antelope, Knox, and Pierce and parts of four Natural Resource Districts (NRD): Lewis and Clark (LCNRD), Lower Elkhorn (LENRD), Lower Niobrara (LNNRD), and Upper Elkhorn (UENRD). Precipitation and irrigation runoff feed into three major river basins: Elkhorn, Missouri, and Niobrara. The area sits in distinct groundwater regions: the Sandhills, the North-Central Tableland, and the Northeast Nebraska Glacial Drift (BGMAP, 2016). The BGMA was originally identified as an area of concern in the late 1980s as a result of nitrate contamination affecting municipal wells in the vicinity of the Villages of Brunswick, Creighton, Orchard, Osmond, Plainview, Royal, and Wausa Nebraska. The BGMA currently supplies water resources to ten communities and approximately seven thousand area residents (BGMAP, 2016).

The BGMAP desired an improved understanding of the hydrogeological framework in the BGMA, in the area of the Creighton Water System, and the West Knox Rural Water System in order to assist in resource management. An Airborne Electromagnetic (AEM) survey was selected to assist in the development of a 3D hydrogeologic framework of the project area and recommend future work to enhance groundwater management activities (BGMAP, 2016).

Figure 1-1: Map of Nebraska counties, indicating the location of the Bazile Groundwater Management Area (BGMA) airborne electromagnetic (AEM) survey with an inset of the project area. Red – Reconnaissance survey area, Blue – Creighton Water System survey area, Yellow – West Knox Rural Water System survey area.

1.2 Background

In 1990 the Conservation and Survey Division of the University of Nebraska (CSD) published results from a nitrate study in the BGMA. The conclusions of the report indicated the aquifers appeared to be contaminated to varying degrees and the cause was likely related to fertilizer application and irrigation practices. The report also concluded that the data was insufficient at that time to implement a specific groundwater management strategy (UNL, 1990). A study completed in 2000 for the Lewis and Clark NRD by the CSD also concluded the aquifer's nitrate contamination is related to fertilizer application and irrigation practices (UNL, 2000). Monitoring by the NRDs and communities in the BGMA show that nitrates concentrations continue to increase in groundwater (BGMAP, 2016). The water quality concerns in the BGMA are the result of nonpoint source pollution and the geology of the area. Permeable soils, shallow depth to groundwater in much of the BGMA, and widespread use of fertilizers and some irrigation practices have contributed to nitrate pollution of groundwater, which is the source of public drinking water in the area. Nitrate pollution poses a human health risk to sensitive populations within the BGMA. There is also an impact to the streams of the BGMA due to the gaining part of their flow from surrounding aquifers (BGMAP, 2016). In 2014 the Bazile Groundwater Management Area Project (BGMAP) was created by the UENRD, LENRD, LNNRD, LCNRD, Nebraska Department of Environmental Quality (NE-DEQ), with funding contributions from the Nebraska Environmental Trust to cooperatively manage the BGMA.

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.

The ENWRA project was formed in 2006 with sponsors from six Natural Resources Districts (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 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 airborne electromagnetic survey over the glaciated portion of Nebraska. The AEM survey, composed of 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 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). 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 BGMA survey flight areas and flight lines is presented in Figure 1-2. A Google Earth kmz of the flight lines is included in Appendix 14/KMZ.

1.3 Description of the BGMA Project Area

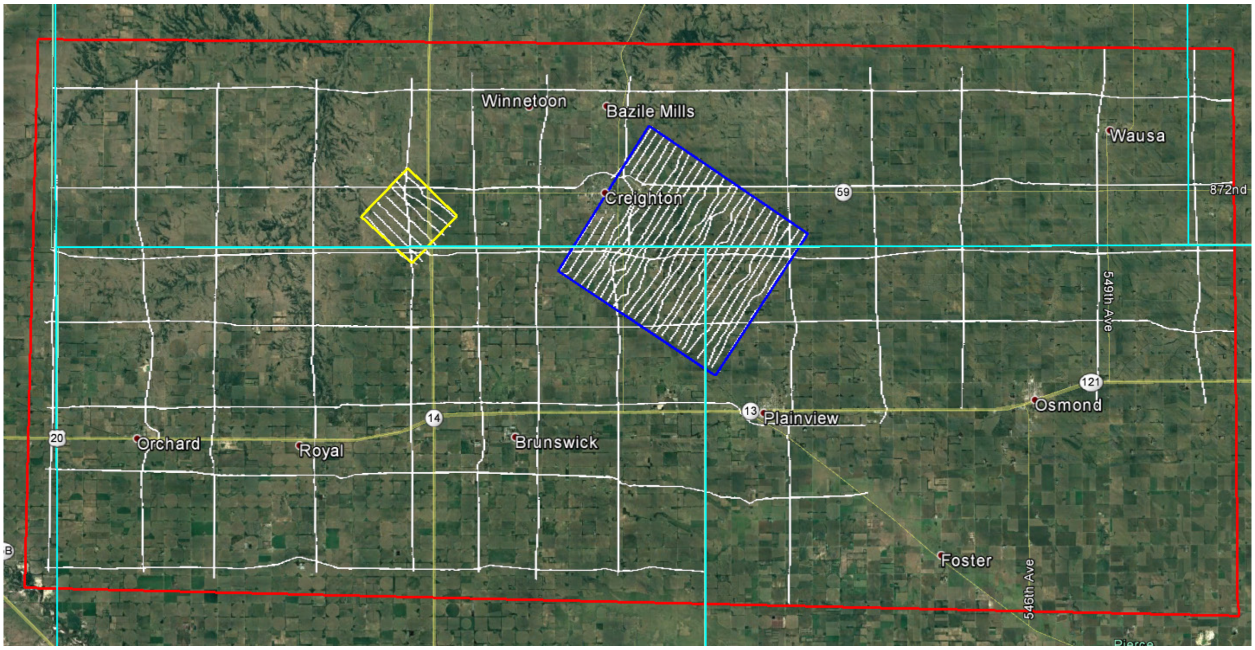


Figure 1-2. Outline of the BGMA project area including county lines and major roads (NE 13, 14, 121). The BGMA Reconnaissance survey area is outlined in red, the Creighton Water System survey area in blue, and the West Knox Rural Water System survey area in yellow. As-flown flight lines are in white.

The area investigated by the AEM reconnaissance surveys near Antelope, Pierce, and Knox counties in eastern Nebraska spans approximately 908.7 square miles (mi^2) (Figure 1-2). More detailed, block-like surveys were performed over the Creighton Water System and West Knox Rural Water System areas. The surveyed area total for Creighton Water System is approximately 47.5 square miles and about 7.8 square miles for the West Knox Rural Water System survey area.

2 Project Area Hydrogeology

2.1 Geologic Setting

The geology and hydrogeology of the BGMA 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 the 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. 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 located in northeastern Nebraska near the town of Creighton and lies within the Valleys, Bluffs and Escarpments, 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 shown in Figure 2-1 (Burchett, 1986). These deposits are not deformed by folding and faulting. Outcrops of these rocks are present in the project area within the valleys along the north and west areas of the project area. The Quaternary (***Q***) sediments made up alluvial materials in the west and glacial deposits located in the east also contain aquifer materials.

2.1.2 Surficial Geology

The complex Pleistocene and Holocene Quaternary geology in northeast 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 & 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., Elkhorn River Valley).

CSD test holes and drillers logs obtained from NE-DNR indicate glacial till units are prevalent across the north eastern portion of the project area. Beneath much of the BGMA the surficial deposits consist of Quaternary alluvium composed of inter-bedded gravel, sand, and silt.

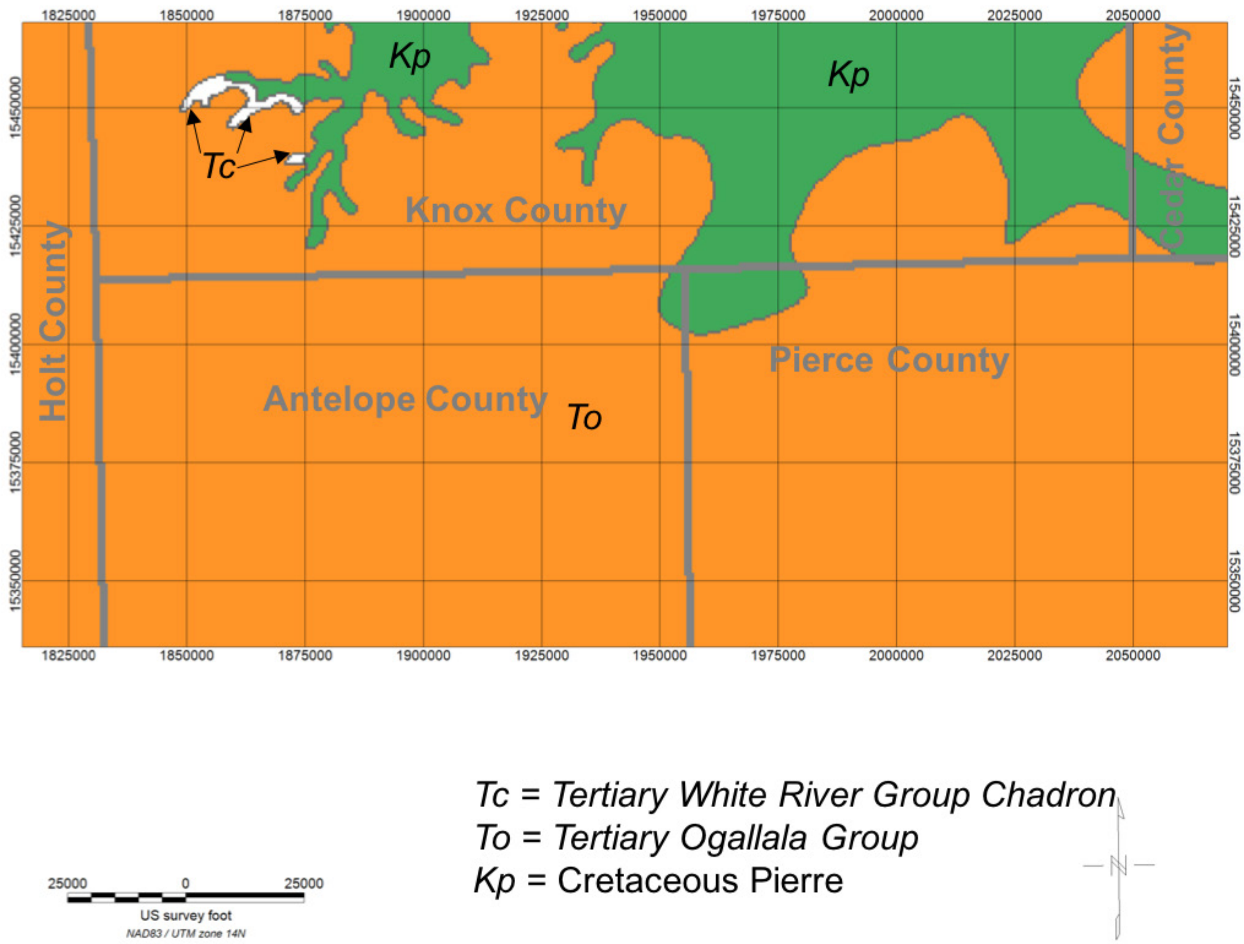


Figure 2-1. Bedrock map of Bazile Groundwater Management Area modified from Burchett (1986)

2.1.3 Tertiary Geology

The Tertiary deposits in the project area include the Oligocene Chadron Formation (***Tc***) of the White River Group and the Miocene Ogallala Group (***To***). The ***Tc*** is comprised of mostly silt with some sand and is of limited extent in the area. There are only a few CSD boreholes that indicate ***Tc*** within the BGMA. 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 to the east and rests unconformably on underlying Cretaceous strata (Divine, 2012). Where present, the ***To*** acts as a primary aquifer and generally is saturated and yields sufficient quantities of groundwater for irrigation purposes. Areas of the ***To*** with the greatest abundance of groundwater occur where the Platte River or its ancestral drainages (Diffendal, 1995).

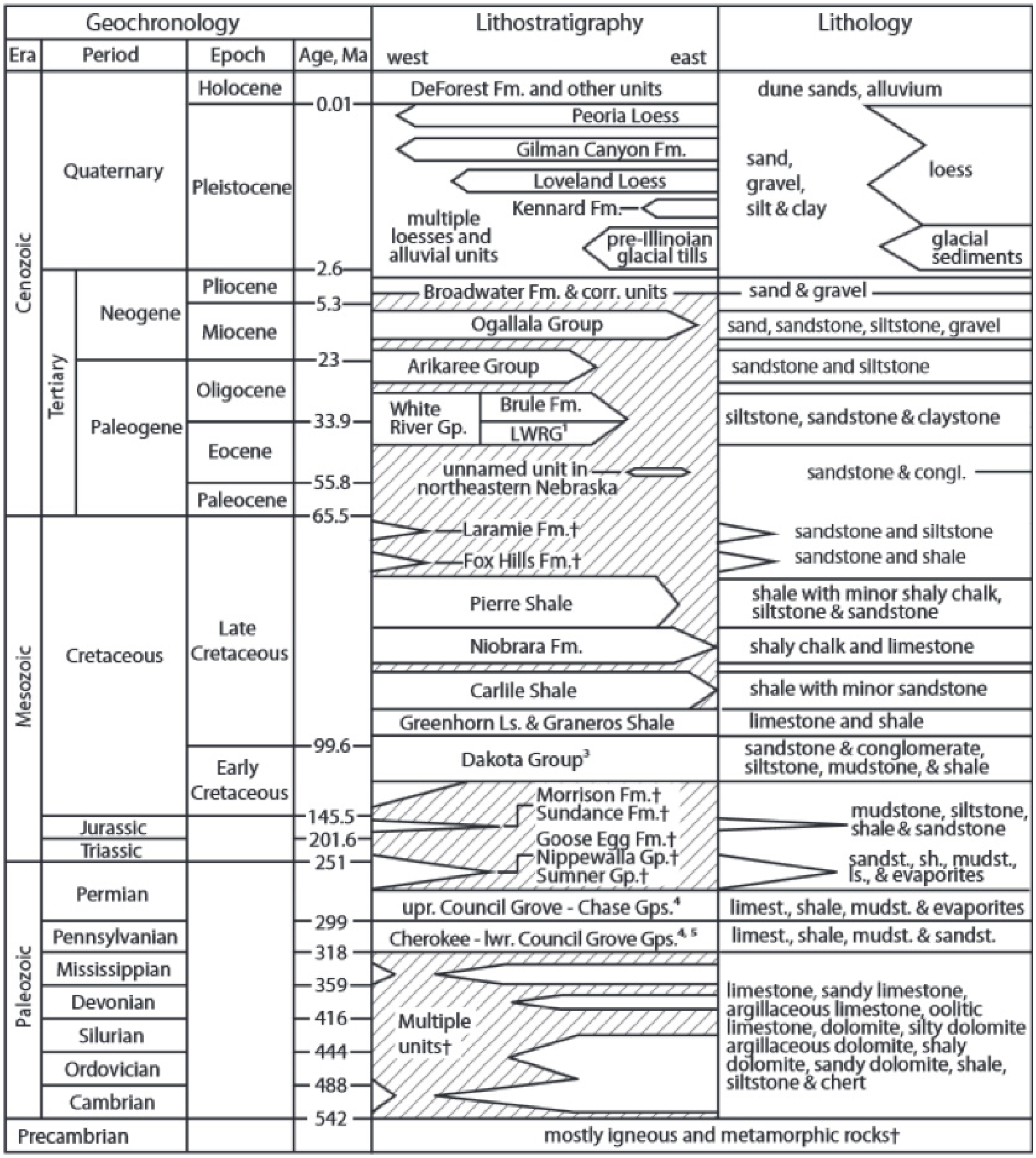


Figure 2-2. Geologic time scale with lithostratigraphic sequence underlying Nebraska, modified from Korus and Joeckel (2011).

2.1.4 Cretaceous Geology

There are deposits within the area from both the Upper and Lower Cretaceous. The Upper Cretaceous bedrock formations are the Pierre Shale (***Kp***), Niobrara Formation (***Kn***), Carlile Shale (***Kc***), Greenhorn Limestone and Graneros Shale (***Kgg***) which lie unconformably over the Dakota Sandstone (***Kd***). Together these formations are comprised of interbedded to sandy shales, indurated to shaly chalks, thin layers of bentonite, limestones, and massive sandstones (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, 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 unconsolidated units overlying it. A hydraulic connection can exist in locations where the Dakota is in contact with overlying saturated ***Q*** deposits (Gutentag et al., 1984), but no ***Kd*** is in contact with any ***Q*** in the BGMA. While all of these Cretaceous units above occur under the BGMA, this report will focus on the ***Kp*** and ***Kn*** as they directly underlie the Quaternary and Tertiary aquifers.

2.2 BGMA Hydrogeologic Characteristics in the Quaternary and Tertiary Ogallala System

A map showing the major streams and rivers within the project area is shown in Figure 2-3. A surface water divide exists between the Bazile Creek and the drainages of Dry Creek and Elkhorn River tributaries (Figure 2-3). The largest surface-water systems in the project area are the tributaries of the Elkhorn River (U.S. Geological Survey, 2015) which flows south to southeast from the center of the project area to its confluence with the Platte River west of Omaha, NE. The second most important drainages are Verdigre and Bazile Creek which drain north out of the project area and to the Missouri River.

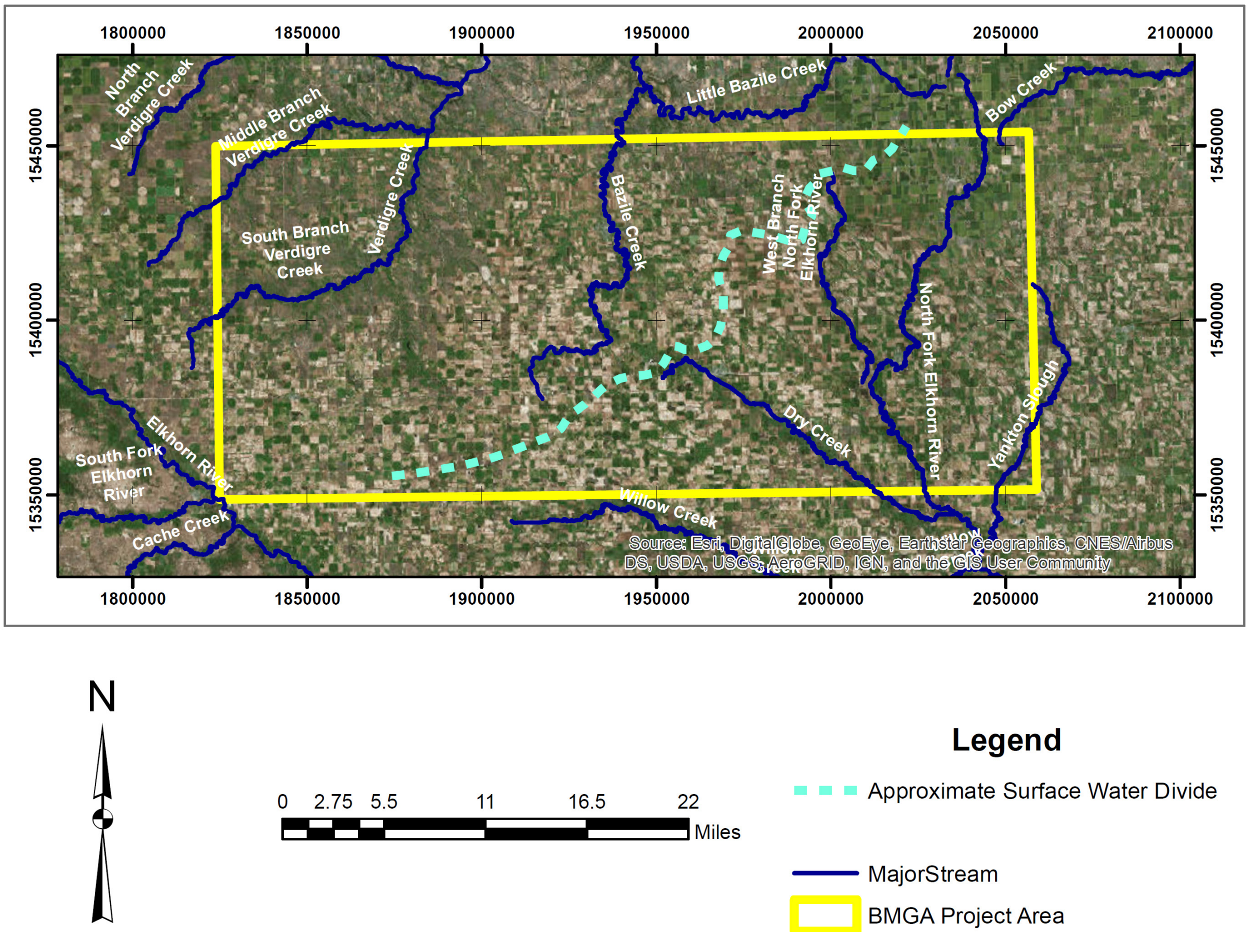


Figure 2-3. Map displaying the major streams and rivers within the BGMA project area. The approximate surface water divide is also shown separating drainages flowing to the Missouri and Elkhorn Rivers.

The overall elevation of the water table within the project area is shown in Figure 2-4. It was derived from the 1995 CSD statewide map (Nebraska CSD, 1995) and represents the general shape of the water table; actual water levels will be different.

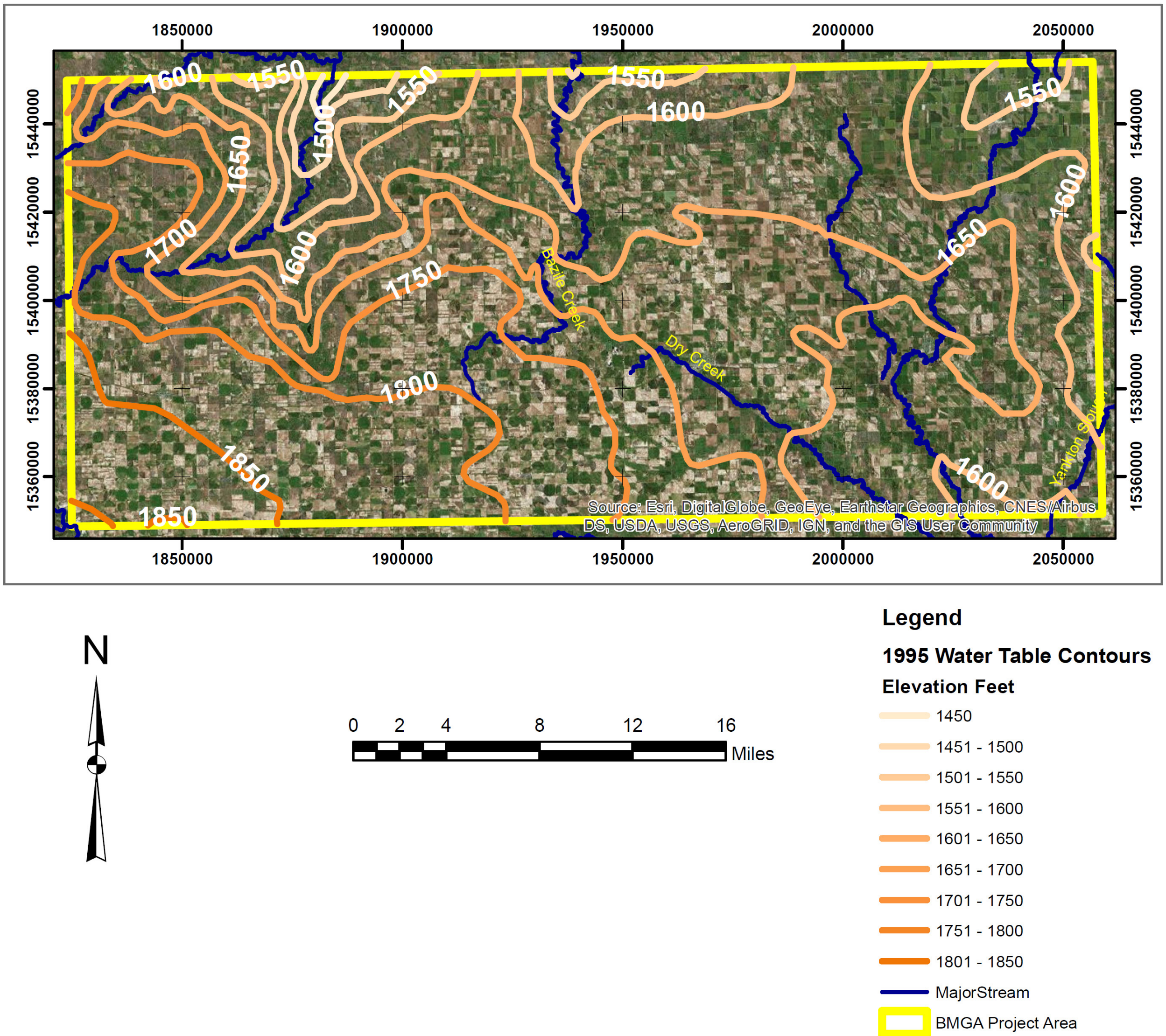


Figure 2-4. Elevation of ground water surface in the BGMA project area.

Regional groundwater-flow direction for the project area is complicated by a regional groundwater divide and local groundwater divides related to incised drainages (Figure 2-5). The regional groundwater flows primarily from west to east. Similar to the surface water systems, the groundwater flows into the Missouri and the Elkhorn Rivers with the divide location dependent on the water table elevation. The water table for this project is from CSD 1995 (Nebraska CSD, 1995). Groundwater locally can be hydraulically connected to surface water. Groundwater levels are located at shallower depths in the alluvial valleys and at deeper depths to the southwest and under glaciated areas, 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. Groundwater under confined systems, such as in aquifers beneath glacial till, typically exhibits more drawdown than groundwater in unconfined systems that are present in alluvial settings.

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.

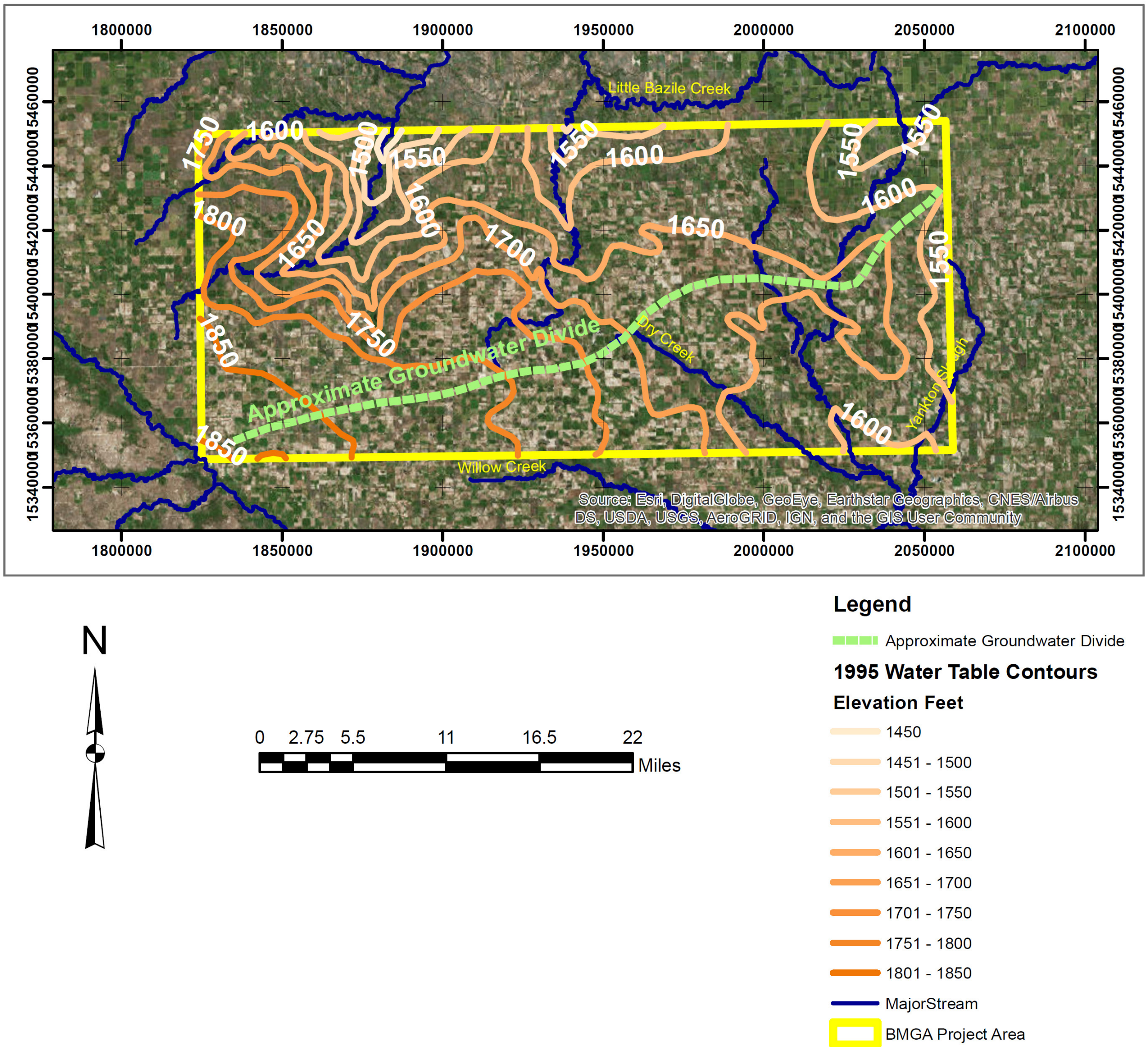


Figure 2-5. Map displaying the regional groundwater divide and rivers within the BGMA project area. Local groundwater divides are not indicated on map.

There are two principal ***Q*** hydrogeologic units within the BGMA boundary. The first are saturated alluvial and ***To*** deposits that make up the stream-valley (valley fill) and table land aquifers. These aquifers are considered one unit for this report. The second are 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 northeast 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 (Bentall, 1971; Miller and Appel, 1997; Flowerday et al, 1998; Stanton et al., 2007). Stream-valley and glacial-drift systems locally can be hydraulically connected with other, similar systems.

Table 2-1 contains summary information for each known aquifer (***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.

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

<table>
<tr><th>System</th><th>Series</th><th>Hydrologic unit</th><th>Maximum thickness, ft.</th></tr>
<tr><td>Quaternary</td><td>Holocene, Pleistocene</td><td>Aquifer in undifferentiated alluvial deposits</td><td>Generally less than 100 ft</td></tr>
<tr><td colspan="4">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 rapid if the source area is primarily sand and gravel. Wells are capable of yielding up to several thousand gallons per minute.</td></tr>
<tr><td>Quaternary</td><td>Holocene, Pleistocene</td><td>Aquifer in undifferentiated glacial-drift deposits</td><td>Up to 300 ft</td></tr>
<tr><td colspan="4">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.</td></tr>
<tr><td>Tertiary</td><td>Miocene</td><td>Aquifer in Ogallala Group</td><td>Up to 300 ft, typically 100 ft or less, thins west to east</td></tr>
<tr><td colspan="4">Generally unconsolidated to semi-consolidated sand, gravel, silt, and clay, underlying saturated Quaternary deposits. Serves as principal hydrogeologic unit of the eastern 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. Irrigation wells capable of producing yielding several thousand gallons per minute.</td></tr>
</table>

2.2.1 Soil Characteristics in the BGMA

The soils within the BGMA project area are well described by Gosselin (1991) and consist mostly of well drained to excessively well drained soils. The exception to this is lies in the northwest part of the BGMA and is found in the Brunswick-Paka-Simeon association zone 11 on Figure 2-6. Soils within the BGMA transmit very little (zone11) to greater than 25% (zone 122) of the precipitation that falls to the water table.

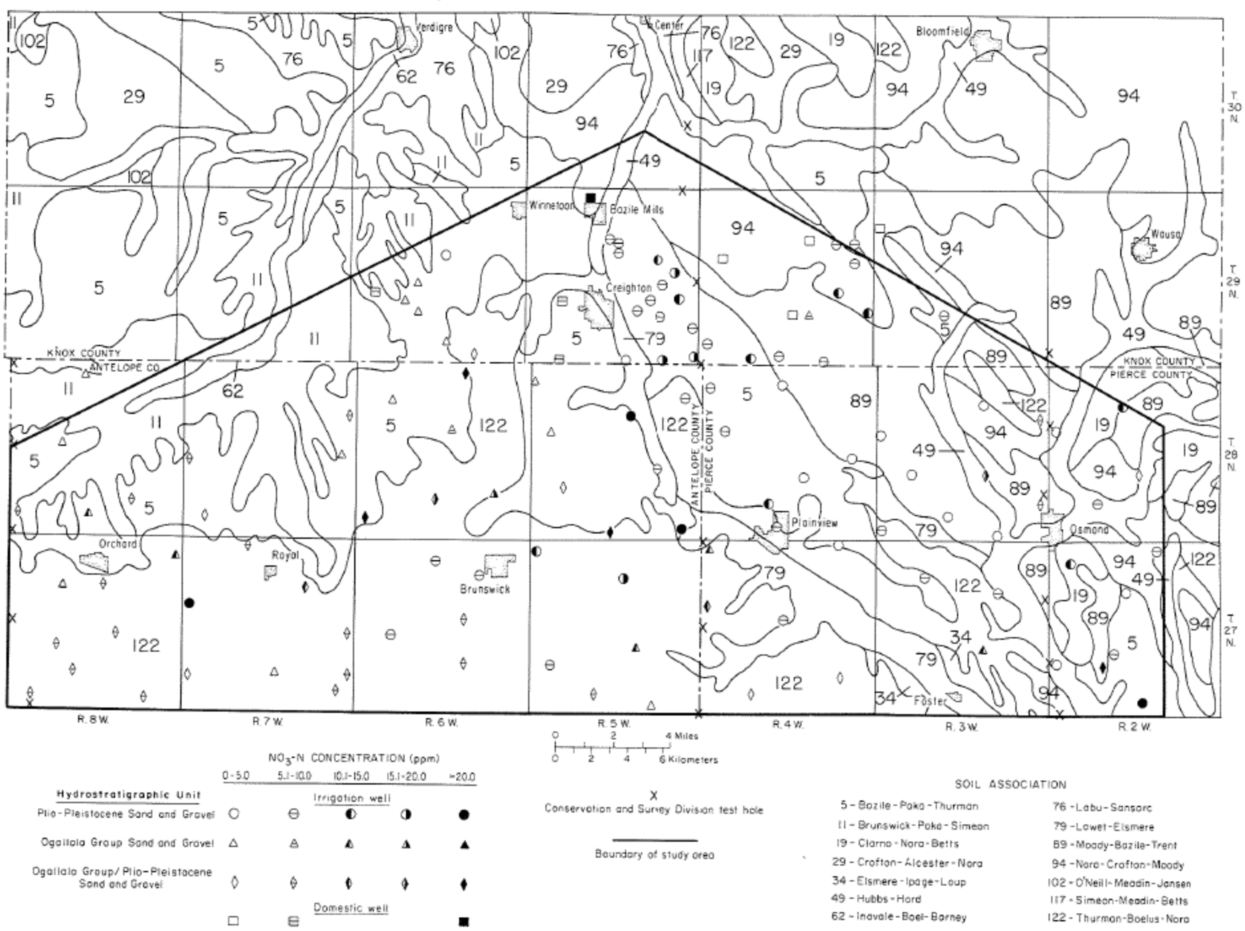


Figure 2-6. Soil associations in the BGMA adapted from Gosselin (1991).

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 2-7 from Pettijohn and Chen (1982). 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 .10 to .20 percent. This work is regional in nature and the work done by Olafsen-Lackey (2005) is used in calculations for this report in later sections.

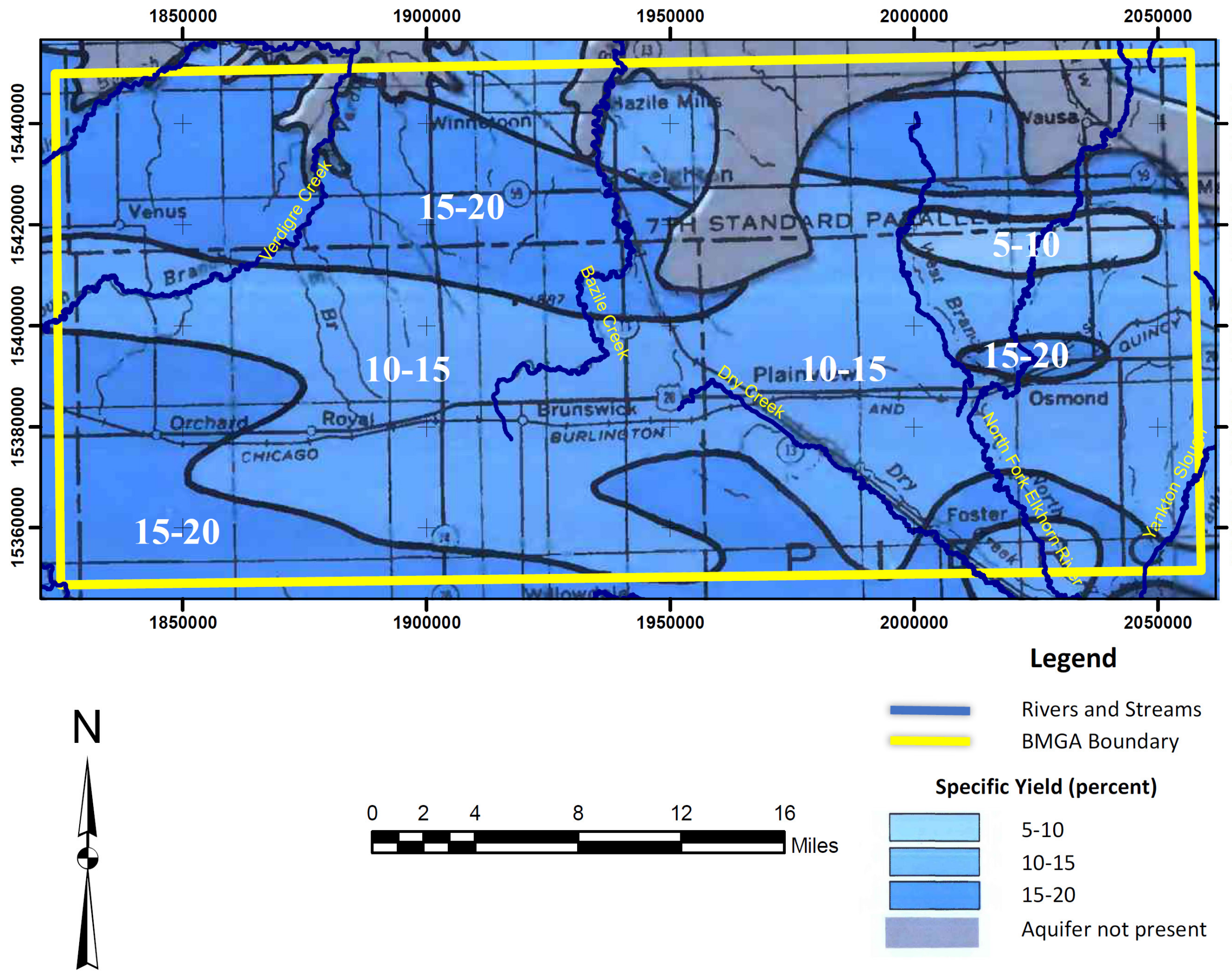


Figure 2-7. Specific yield values within the BGMA project area (Pettijohn and Chen, 1982).

Lower and upper ranges of horizontal hydraulic conductivity in Madison and Pierce Counties were reported between 25 to 100 ft/d (Pettijohn and Chen, 1982). Overall, most hydraulic conductivity values within the BGMA project area likely range from 10 ft/day in wells open to the ***To*** up to 100 ft/day in wells screened in ***Q*** alluvium and glacial-drift sand and gravel (Figure 2-8).

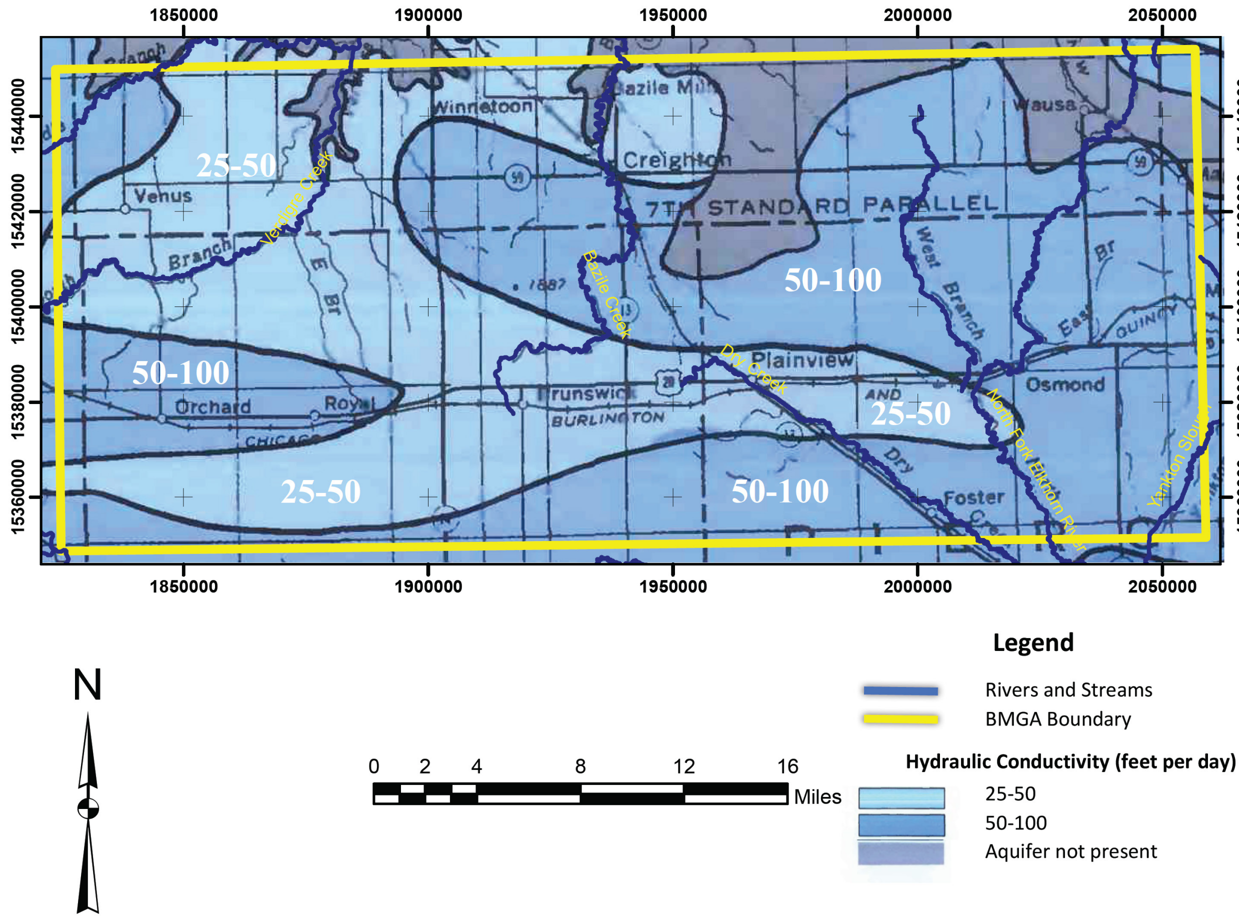


Figure 2-8. Hydraulic conductivity values within the BGMA project area (Pettijohn and Chen, 1982).

The only values for transmissivity in the project area come from aquifer tests performed in the West Knox Rural Water System well field during 2012. The data were found in an LNNRD contractor letter from Ground Water Associates, Inc.(GWA) on wells drilled within the West Knox Rural Water System Area (personal comm. Terry Julesgard, LNNRD May 12, 2016). Two tests were done for wells *TW-10-12* and *TW 11-12*. Results for the 230 minute test for *TW 10-12* was a calculated transmissivity of 11,950 g/ft/d. Results for the 240 minute test for *TW 11-12* was a calculated transmissivity of 20,050 g/ft/d.

2.2.3 Connectivity to Surface Water

Groundwater flow connectivity to surface water features is largely undocumented in the glaciated BGMA project area. 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 eleven (11) were located in the project area. Results at five (5) sites showed stream flow both increasing and decreasing in a downstream direction along Verdigre Creek and its tributaries, indicating surface-water gains and losses from and to the groundwater system.

Six (6) sites where measurements were made along Dry Creek and the Elkhorn River and its tributaries show a loss to the groundwater system (Peterson and Strauch, 2006).

Measurements were not collected in the glaciated areas of the BGMA project area.

2.2.4 Connectivity to other Aquifers

Locally, ***Q*** and ***To*** deposits are hydraulically connected to shallower aquifers and streams (Gosselin, 1991). 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. Aerial communication is variable as it is possible that a glacial-drift aquifer (such as a paleovalley aquifer) could be in communication with an aquifer or stream at one location and not another. There is limited connection from the glacial aquifers to the streams.

2.2.5 Water Quality

Gosselin (1991) provides results from 125 historic water quality samples in the BGMA. These samples were divided into four classes of wells:

1. 10 domestic and unregistered wells with no geologic classification
2. 61 Plio-Pleistocene age sand and gravel wells
3. 34 combined Plio-Pleistocene-Ogallala wells
4. 20 Tertiary Ogallala wells

The samples from these wells were analyzed for major ions including Total Dissolved Solids (TDS). TDS is an indicator of saline water. The maximum TDS value recorded was 828 mg/l in a domestic and unregistered well which is well below the brackish water limit of 1500 mg/l and saline water limit of 10,000 mg/l. Table 2-2 shows the highest recorded value and average value of all wells combined for TDS in mg/l. Based on this information there is no evidence of saline water present in the BGMA project area that could impact the resistivities determined by the AEM. This report will not address any of the nitrate contamination in the BGMA.

Table 2-2. The highest recorded value and average value of all wells combined for Total Dissolved Solids (TDS)

Well Class	Highest TDS value (mg/l)	Average TDS value (mg/l)
Domestic and unregistered	828	335
Plio-Pleistocene geologic unit	428	282
Plio-Pleistocene-Ogallala unit	482	235
Tertiary Ogallala unit	327	212

3 Additional Background Information

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

3.1 Borehole Data

Borehole data for this project consisted of a combination of lithologic, stratigraphic, and downhole geophysical logs. The borehole information was gathered from three sources: 1) CSD Nebraska Statewide Test Hole Database (UNL, 2016) accessed April 22, 2016, which contains information from boreholes drilled between 1930 and 2007 by the CSD and other cooperating agencies. CSD test holes drilled subsequent to 2007 were provided as a dataset directly from ENWRA (personal comm. Kathleen Cameron, ENWRA October 2016); NE-DNR (Nebraska Department of Natural Resources, 2016) accessed September 22, 2016; and the LNNRD contractor letter from GWA on wells drilled within the West Knox Rural Water System Area (personal comm. Terry Julesgard, LNNRD May 12, 2016). Appendix 14\Boreholes contains the borehole data utilized within the study.

The locations of the CSD boreholes utilized in the BGMA survey are indicated in Figure 3-1. A total of 58 CSD holes contained lithology information, 50 holes contained stratigraphic information, and 30 holes contained geophysical information were within the BGMA. Of the CSD holes used within the study problems were encountered with the following holes: *5-A-57*, *6-A-57*, *7-A-57*, and *8-A-57*. These problems included obvious incorrect locations, erroneous stratigraphy, and lithology that did not correlate with the surrounding information. These holes were not used in the interpretation of the AEM data within this study.

The locations of the NE-DNR registered wells used in the BGMA survey are indicated in Figure 3-2. A total of 2,934 registered wells contained usable lithology information.

The locations of the GWA West Knox Rural Water System Area wells used in the BGMA survey are indicated in Figure 3-3. A total of 13 wells contained lithology information, and 11 wells contained geophysical information.

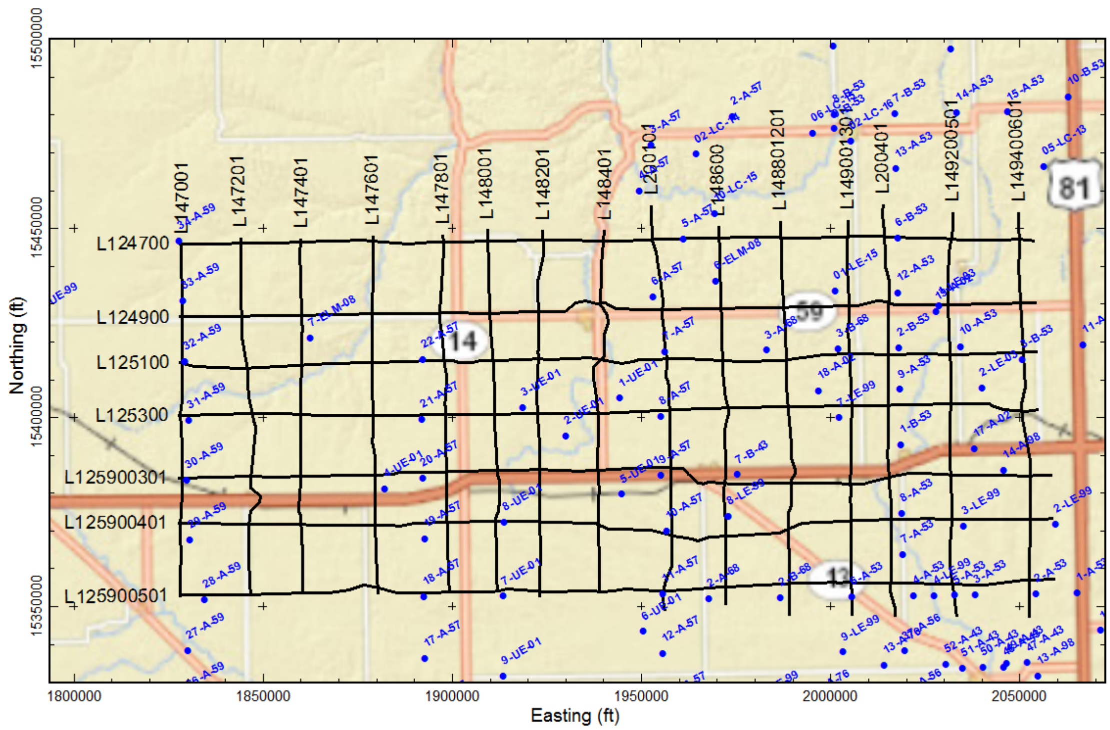


Figure 3-1: Locations of the Conservation Survey Division boreholes (blue dots) and the airborne electromagnetic flight lines in the Bazile Groundwater Management Area. Projection is NAD83, UTM 14 North.

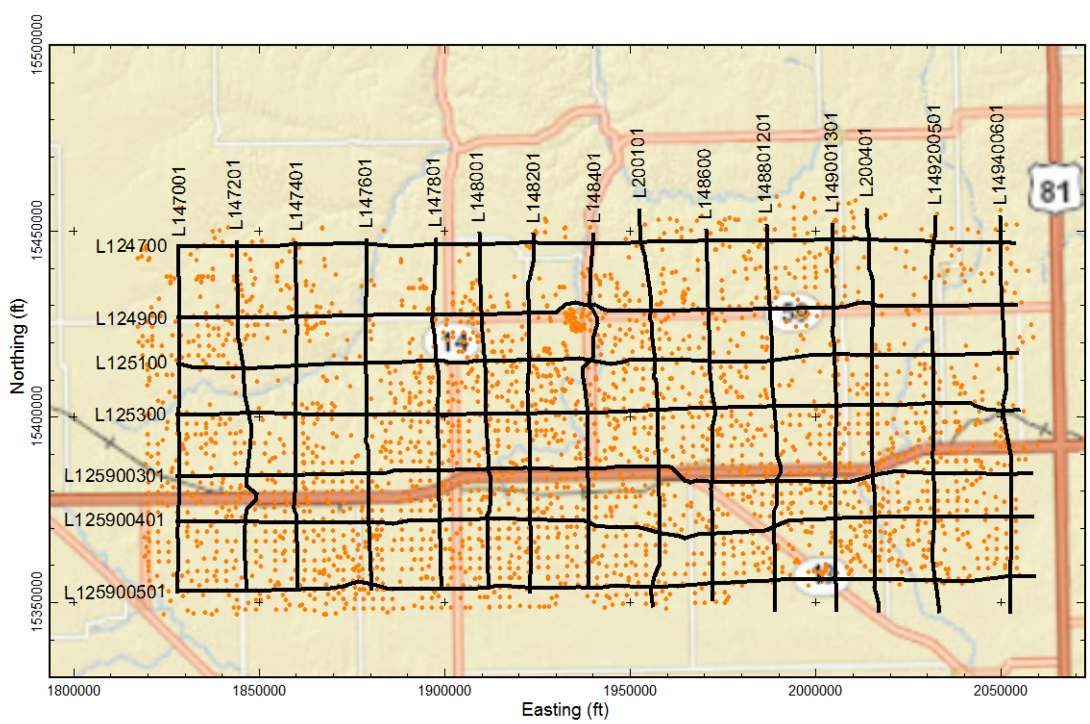


Figure 3-2: Locations of the Nebraska Division of Natural Resources Registered wells (orange dots) and the airborne electromagnetic flight lines in the Bazile Groundwater Management Area. Projection is NAD83, UTM 14 North.

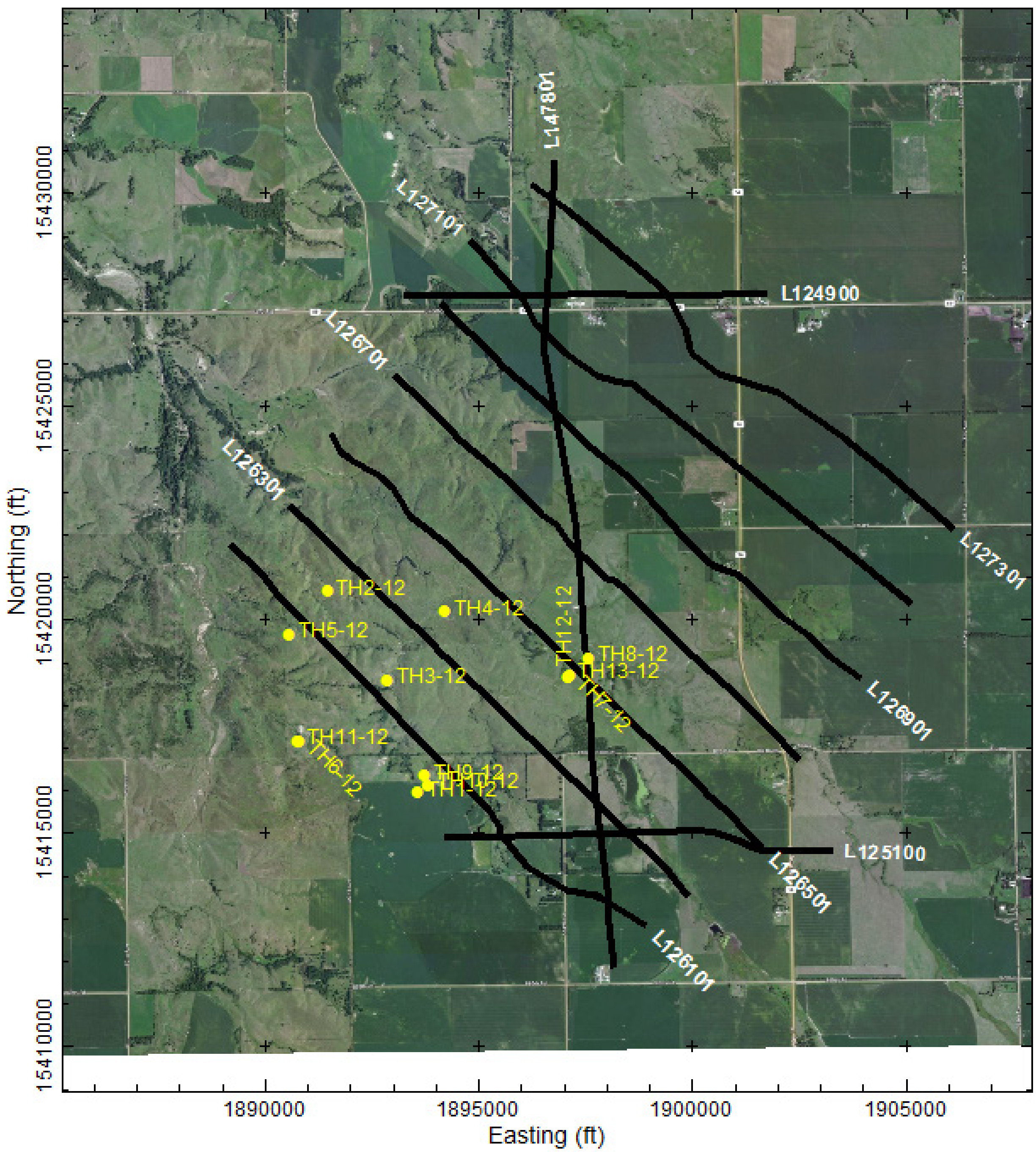


Figure 3-3: Locations of the GWA West Knox Rural Water System Area wells (yellow dots) and the AEM flight lines in the Bazile Groundwater Management Area. Projection is NAD83, UTM 14 North.

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.

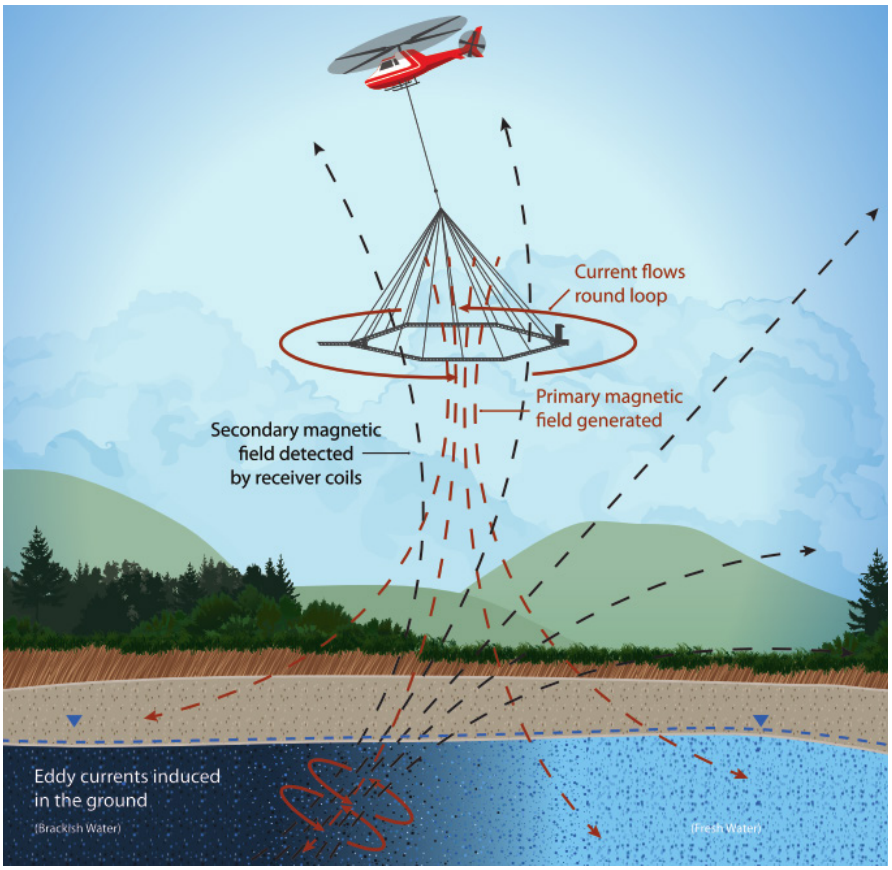
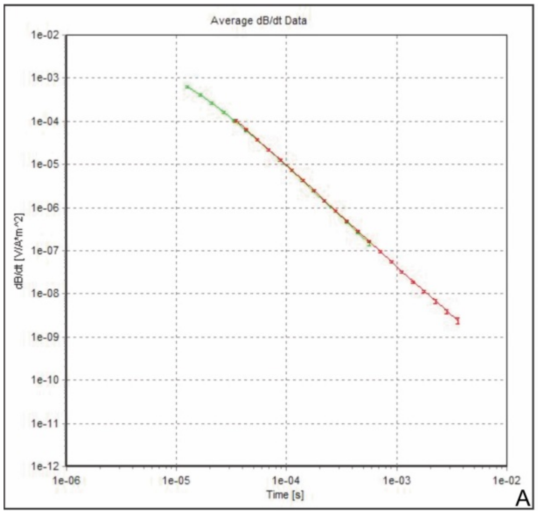


Figure 4-1: Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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				

B

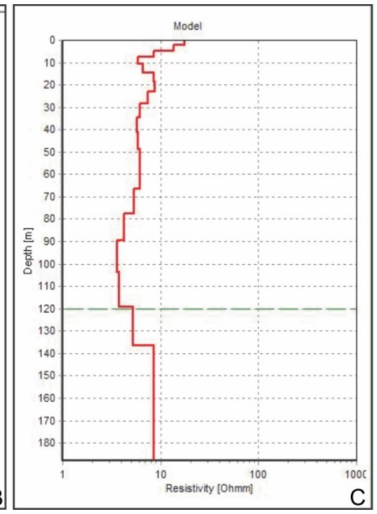


Figure 4-2: A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model.

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 BGMA, 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: Cedar-Knox Power District, Elkhorn Rural Public Power District, Nebraska Public Power District, North Central Public Power District, Northeast Nebraska Public Power District, and Stanton County Public Power District.

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

The locations of the flight lines were converted from a regularly spaced grid to one with flight lines optimized 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 BGMA reconnaissance flight lines were approximately 43 miles in length (east-west) and 18 miles (north-south) and were separated by approximately 2.5 mile to 3.5 miles in both east-west and north-south directions (Figure 1-2 and Figure 4-5). The Creighton Water System flight lines were approximately 6 miles in length and were separated by about 0.25 miles. The West Knox Rural Water System flight lines were approximately 2.5 miles in length and were separated by about 0.33 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.

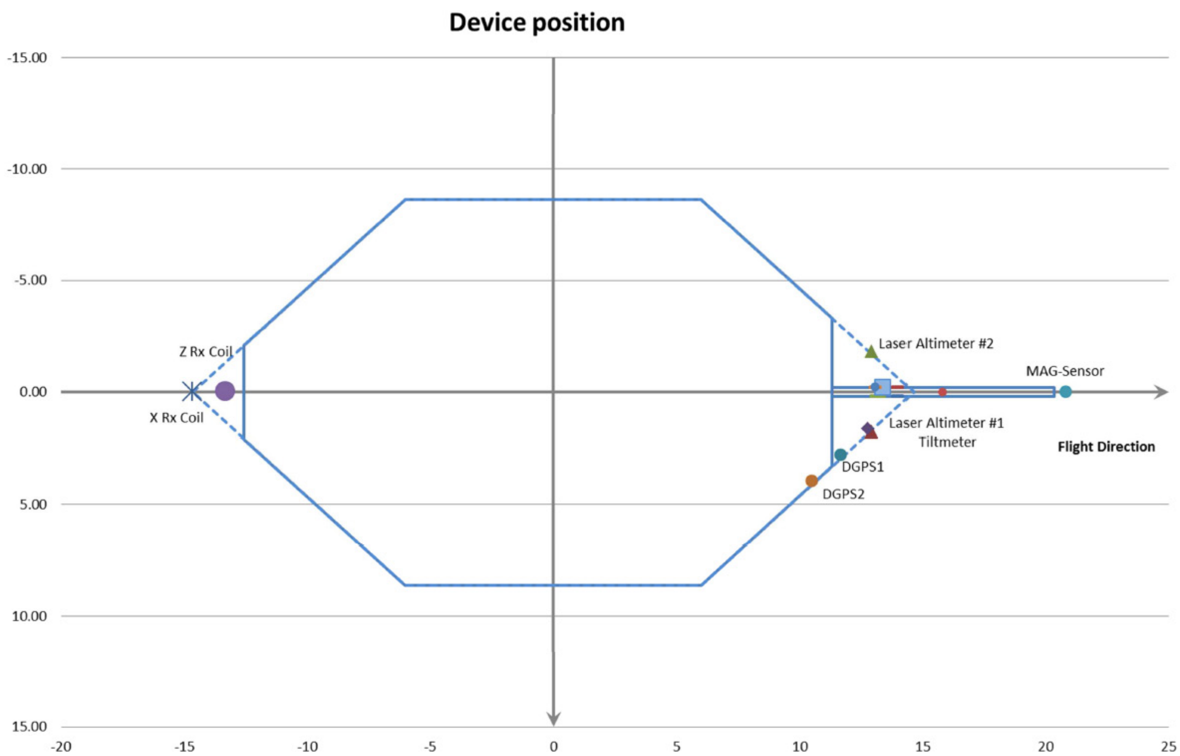


Figure 4-3: SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 4-1.

Figure 4-4: Photo 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 an image 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.

Instrument	Easting (ft)	Northing (ft)	UTM Zone
Magnetometer Base Station and DGPS Base Station	2063601	15252463	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 Creighton Municipal and Norfolk airports. 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 643.9 line-miles (1,036.5 line-kilometers) were acquired over the BGMA project area on July 22-25, 2016. The Creighton Municipal and Norfolk airports were 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.

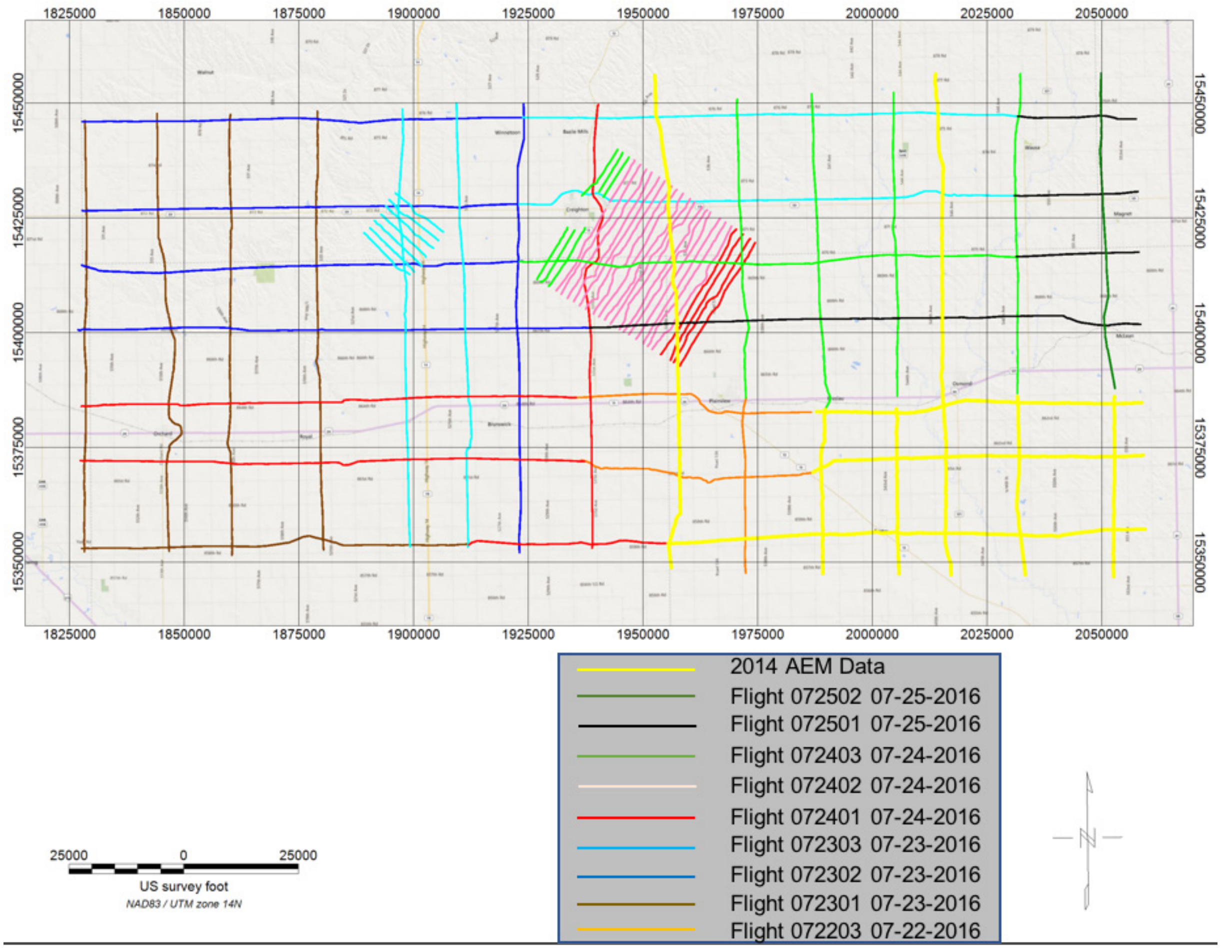


Figure 4-5: BGMA AEM flight lines grouped by acquisition date.

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 1.0×10^{-5} sec, 1.0×10^{-4} sec, and 1.0×10^{-3} sec with widths of 8, 10, and 12 seconds. The times used to define the trapezoid for the High Moment were 1.0×10^{-4} sec, 1.0×10^{-3} sec, and 1.0×10^{-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.

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, 531 line-miles (860.2 line-km) of data were retained for the final inversions for the BGMA area. This amounts to a data retention of 83% for the BGMA area. This high rate is the result of careful flight line planning and design.

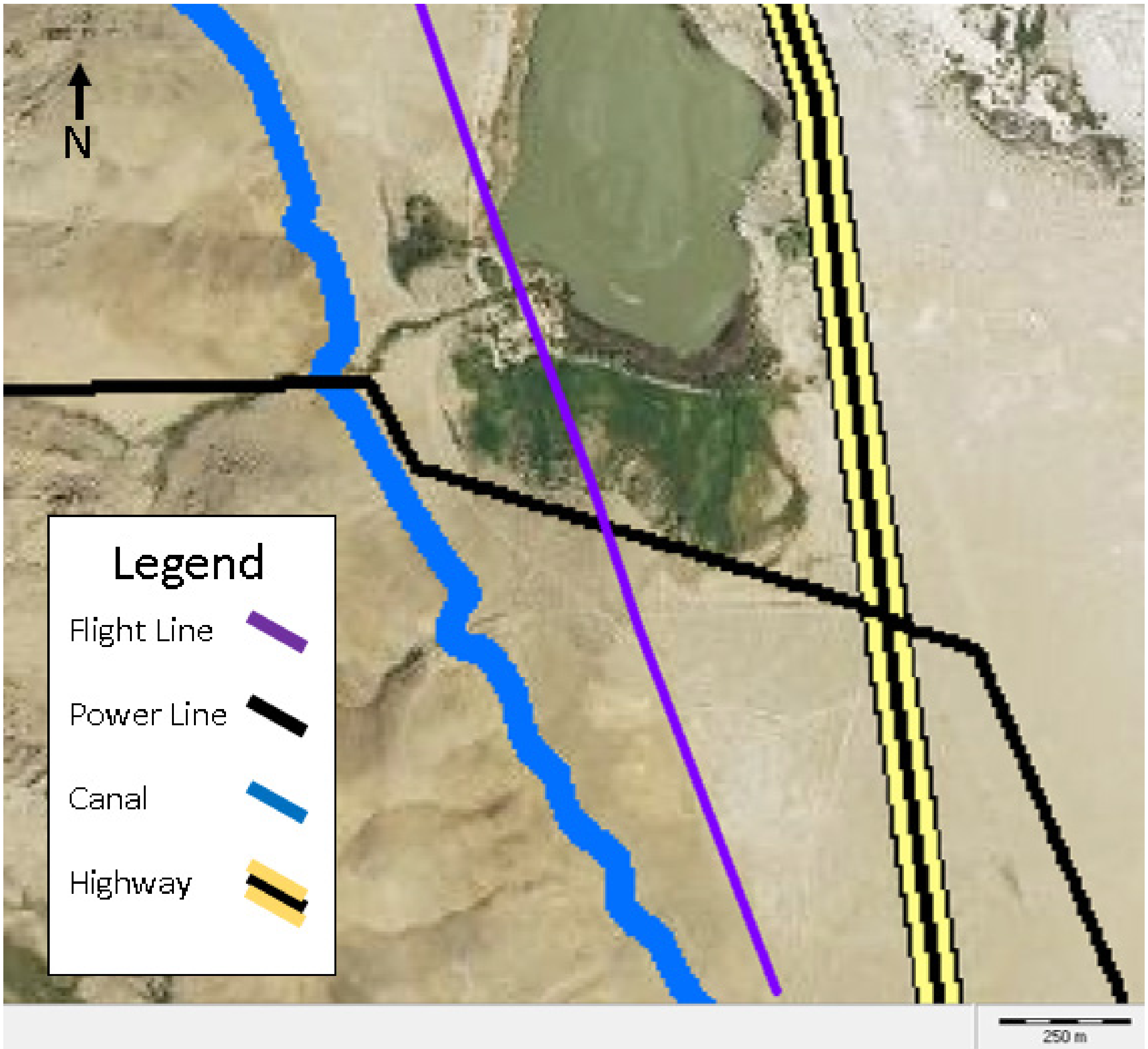


Figure 4-6: Example locations of electromagnetic coupling with pipelines or power lines.

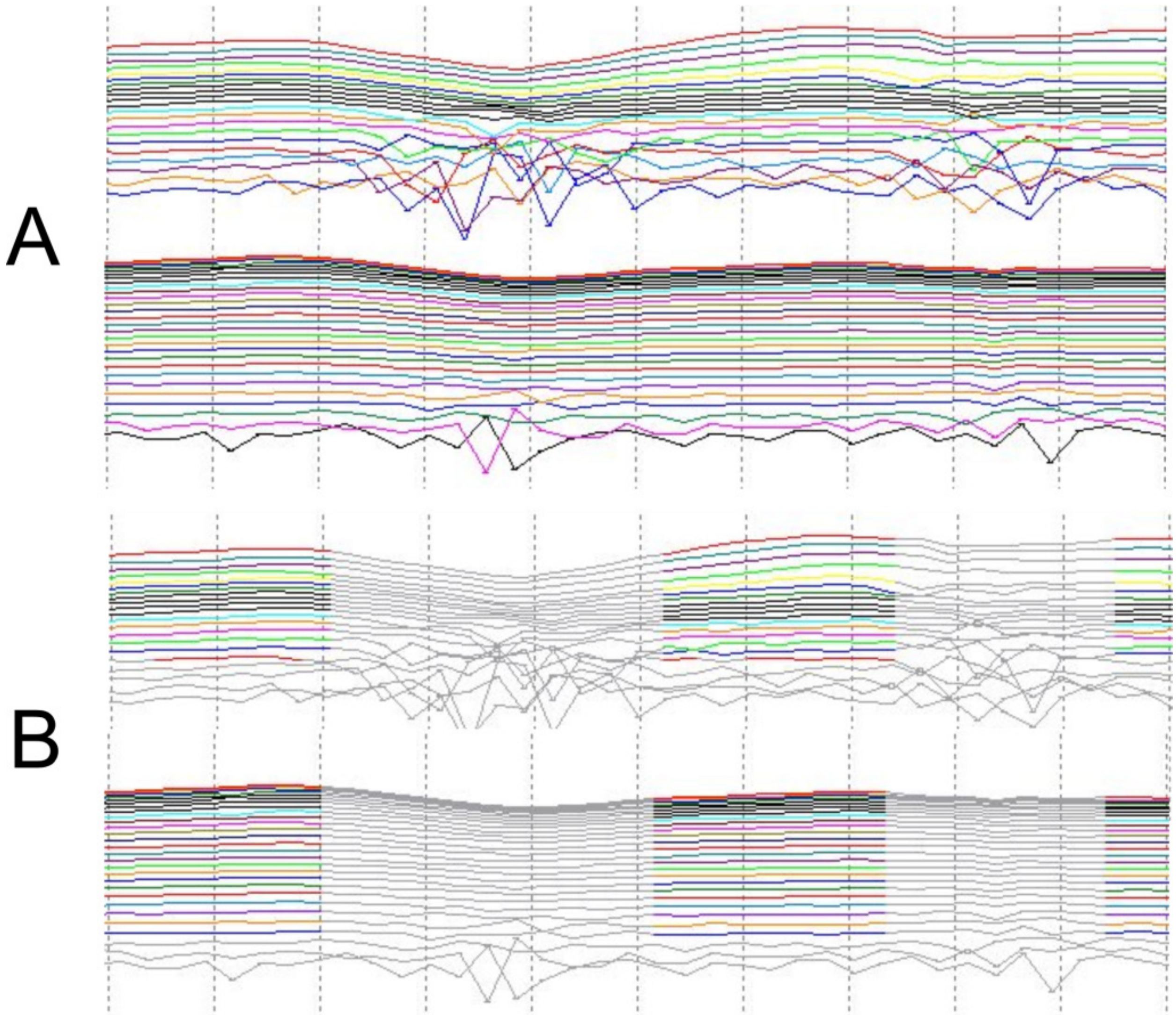


Figure 4-7: A) Example of AEM data from the BGMA AEM survey affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

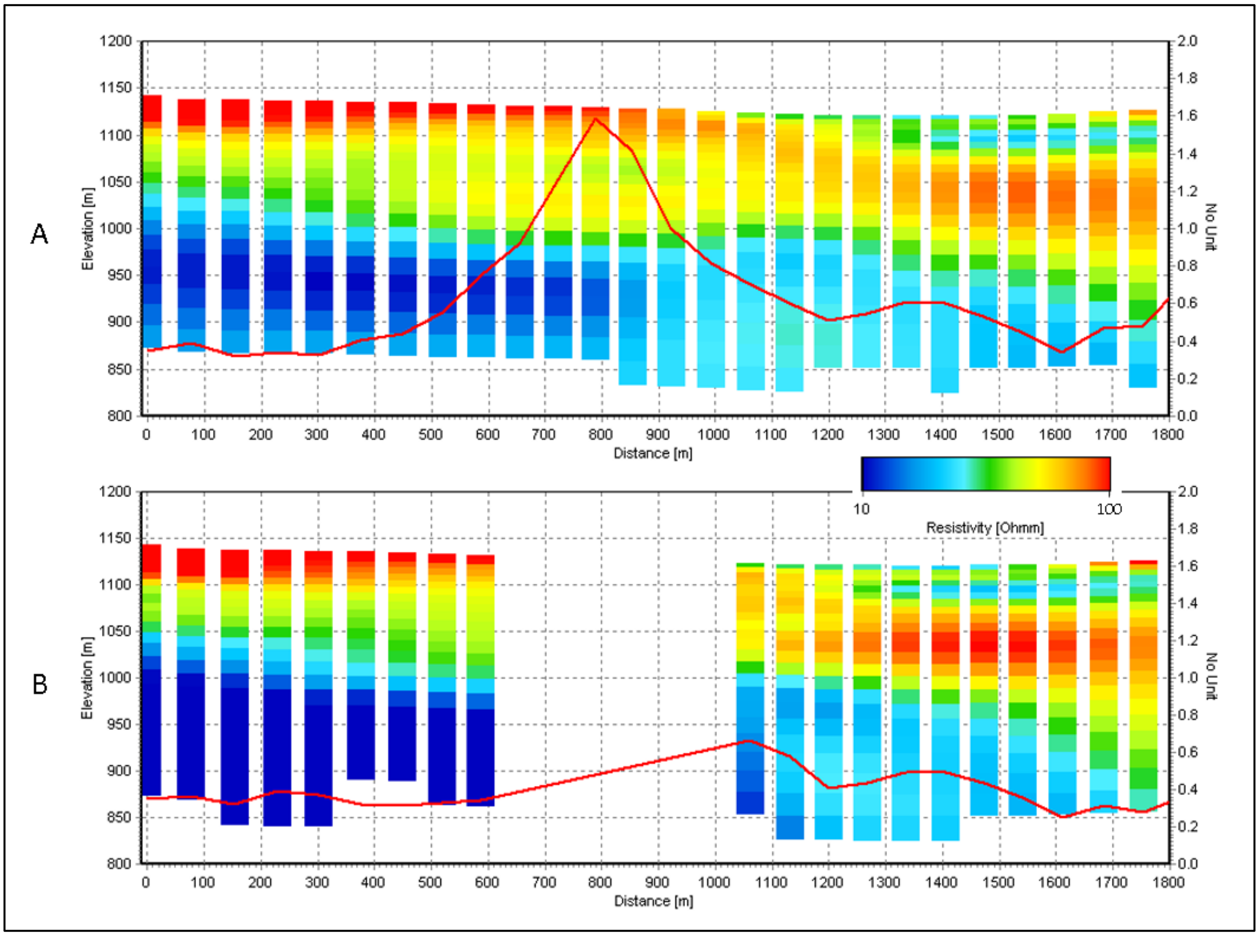


Figure 4-8: A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

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 BGMA survey are presented in Figure 4-9. The BGMA-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.

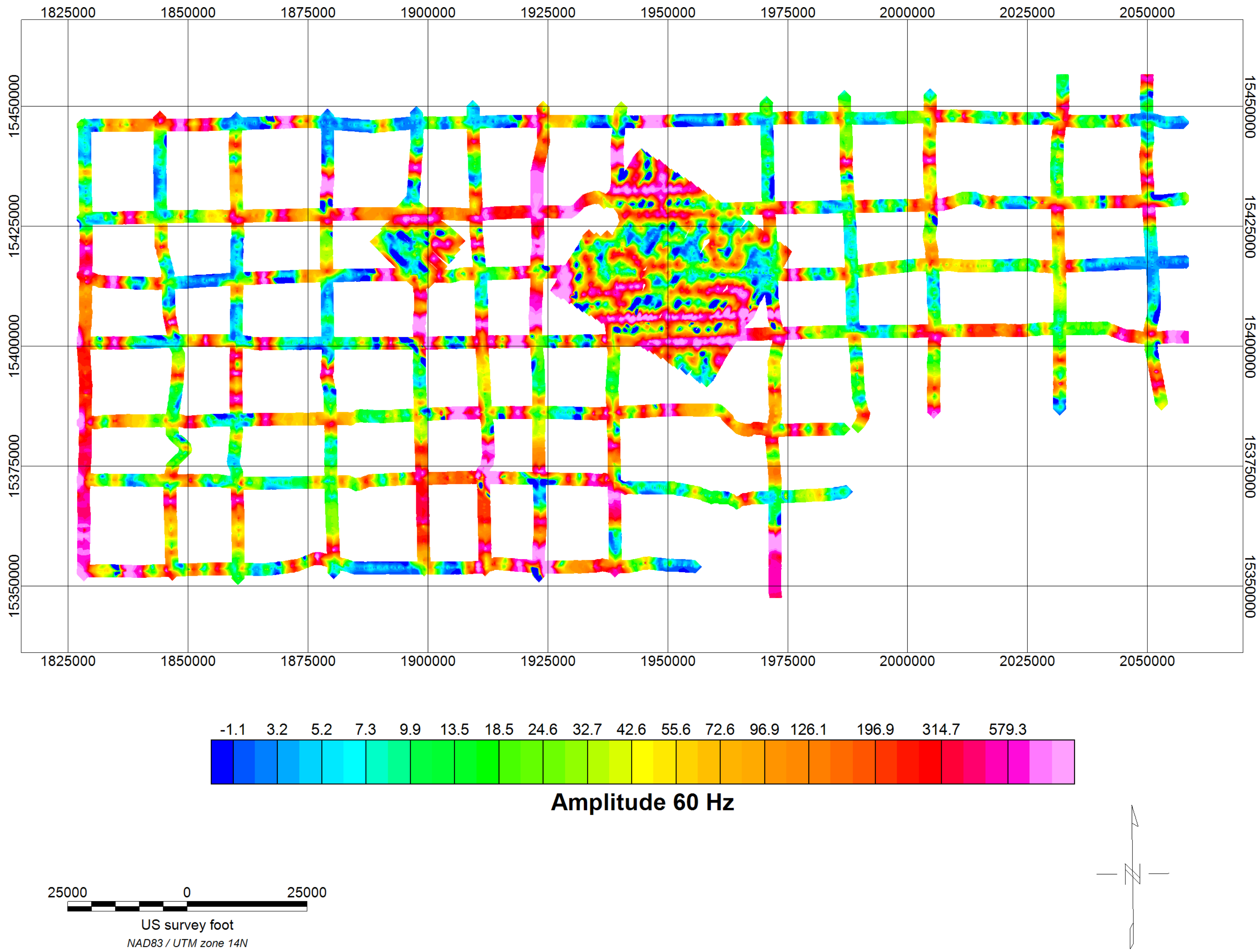


Figure 4-9: Power Line Noise Intensity (PLNI) map of the BGMA project area.

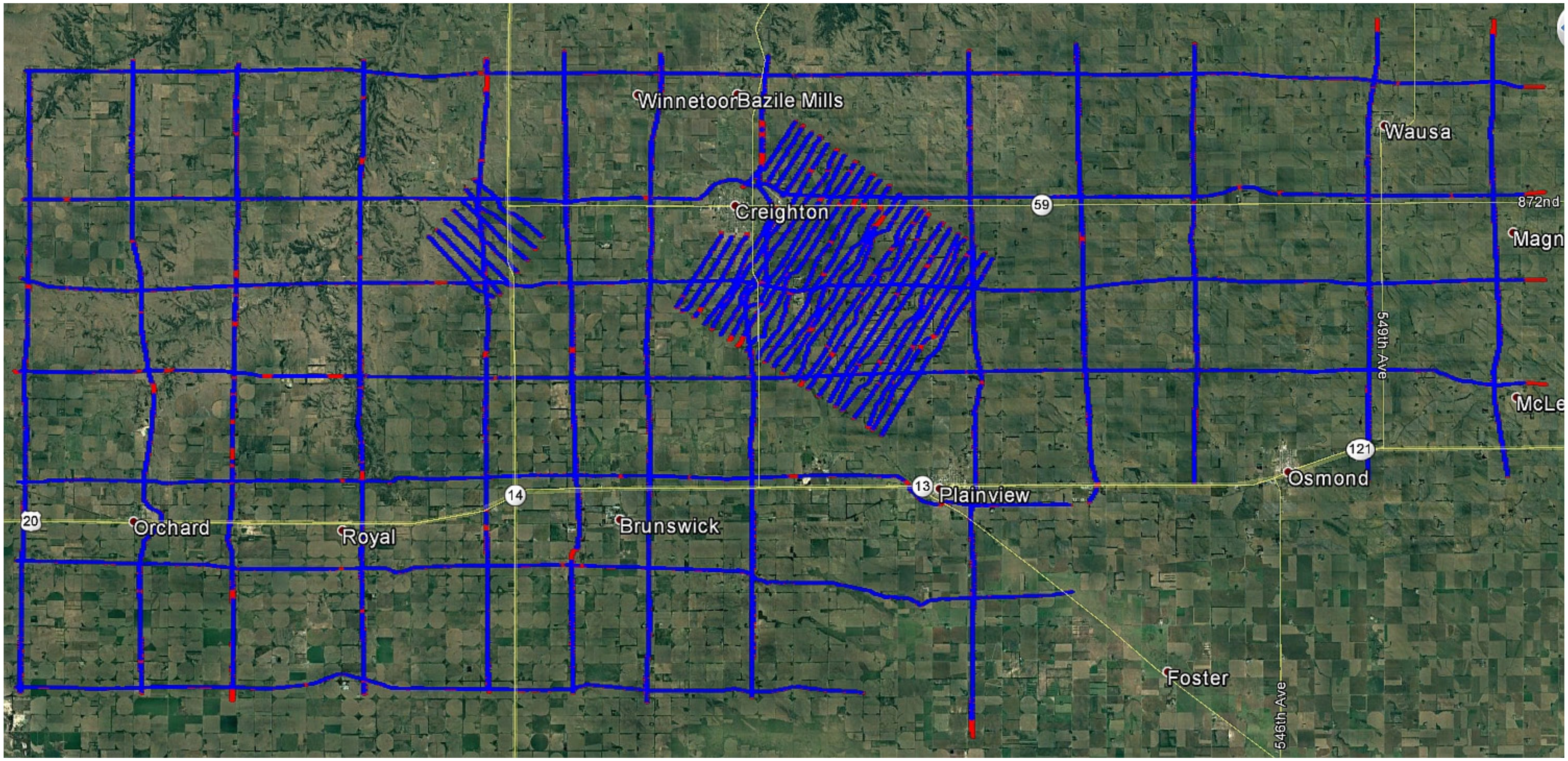


Figure 4-10: Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the BGMA project area. Where blue lines are not present indicates decoupled (removed) data. Google Earth kmz's of the inverted data locations as well as the flight lines are included in Appendix 14\KMZ.

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

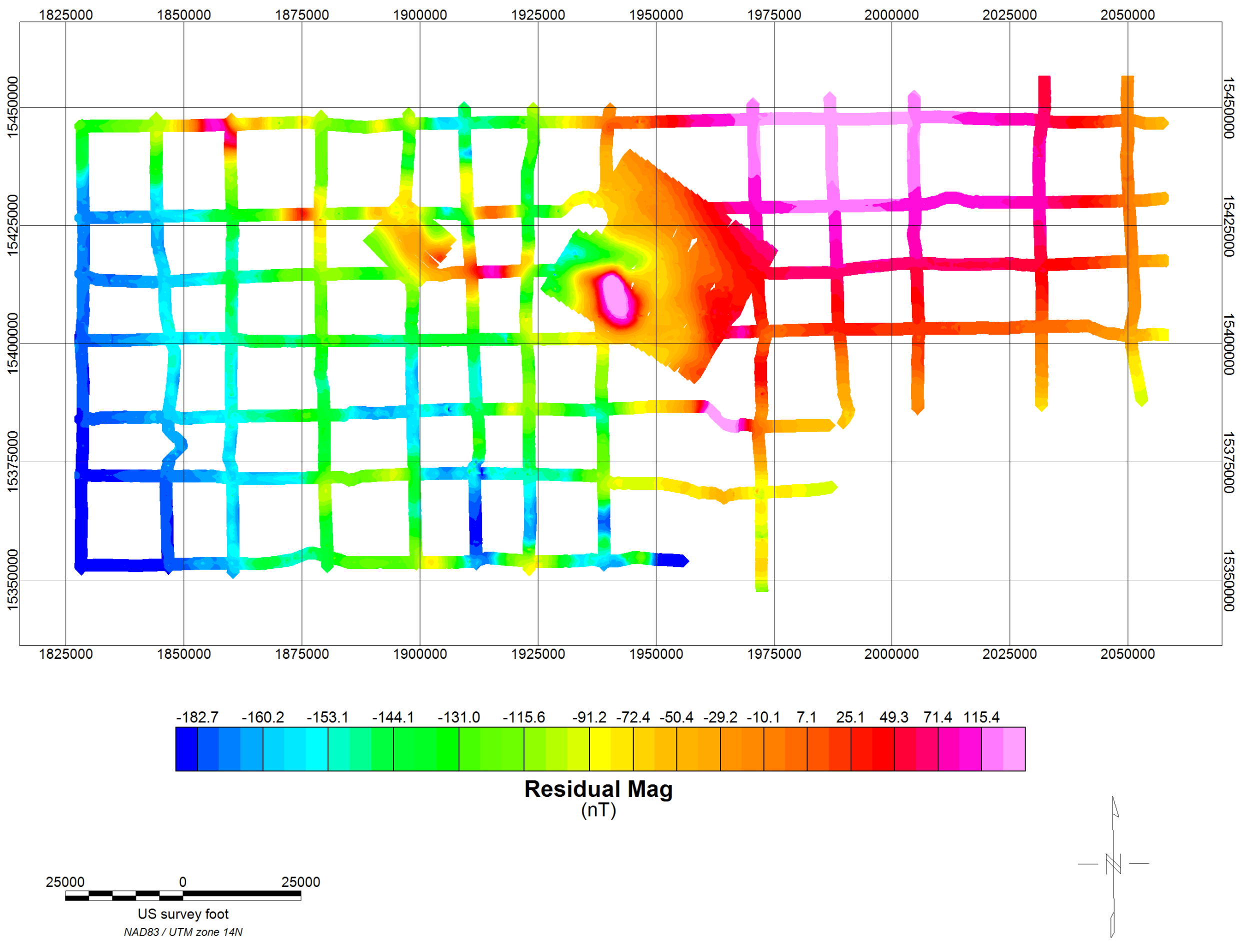


Figure 4-11: Magnetic Total Field intensity data for the BGMA survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

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 BGMA 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 under the Creighton area.

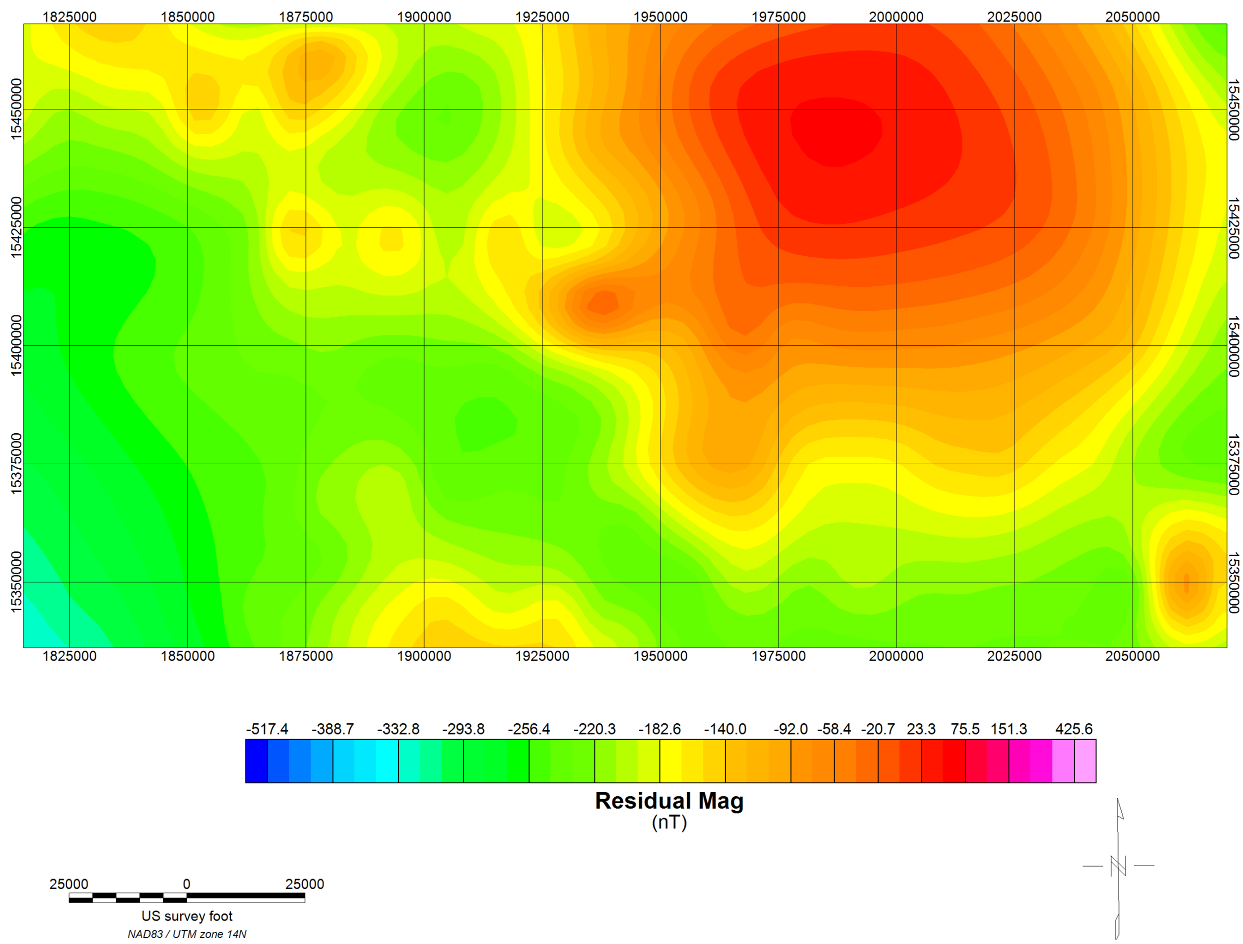


Figure 4-12: USGS magnetic Total Field intensity data for the BGMA survey area corrected for diurnal drift, with IGRF removed (Sweeney and Hill, 2005). The data was collected on an approximately 5 mile line spacing and upward continued to a reference elevation of 1000 ft.

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 BGMA AEM 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).

Figure 4-14 presents a histogram of the BGMA SCI inversion data/model residuals.

Table 4-4: Thickness and depth to bottom for each layer in the Spatially Constrained Inversion (SCI) 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			

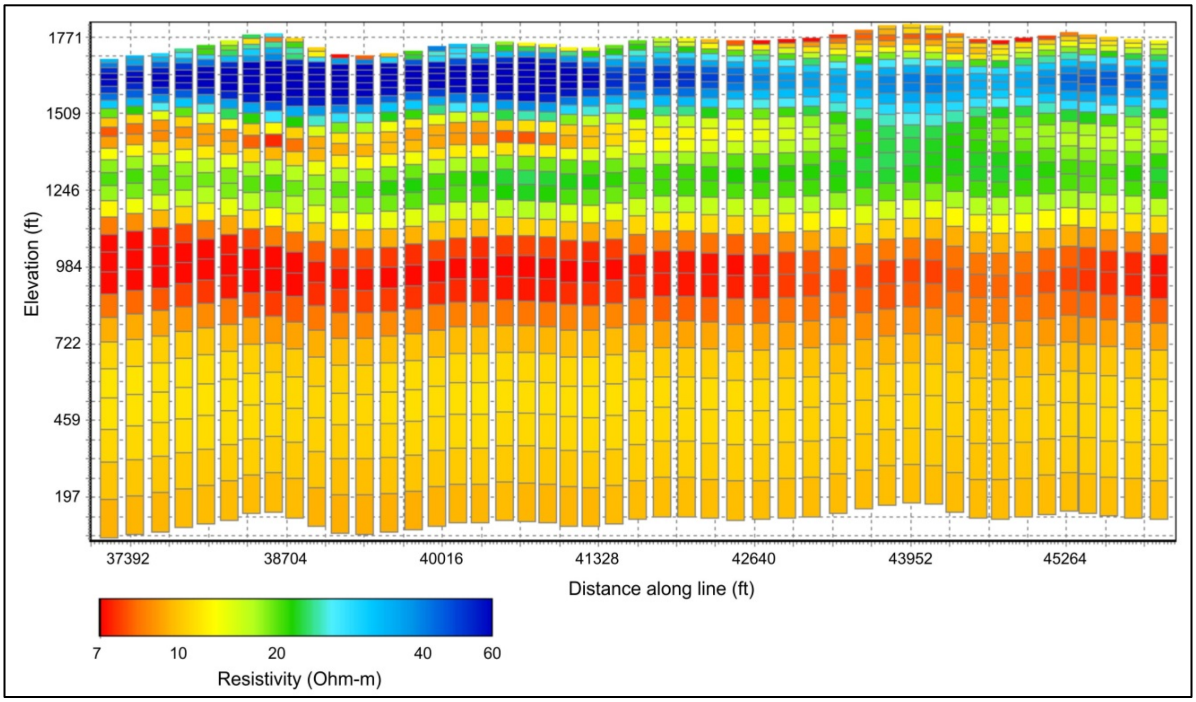


Figure 4-13: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

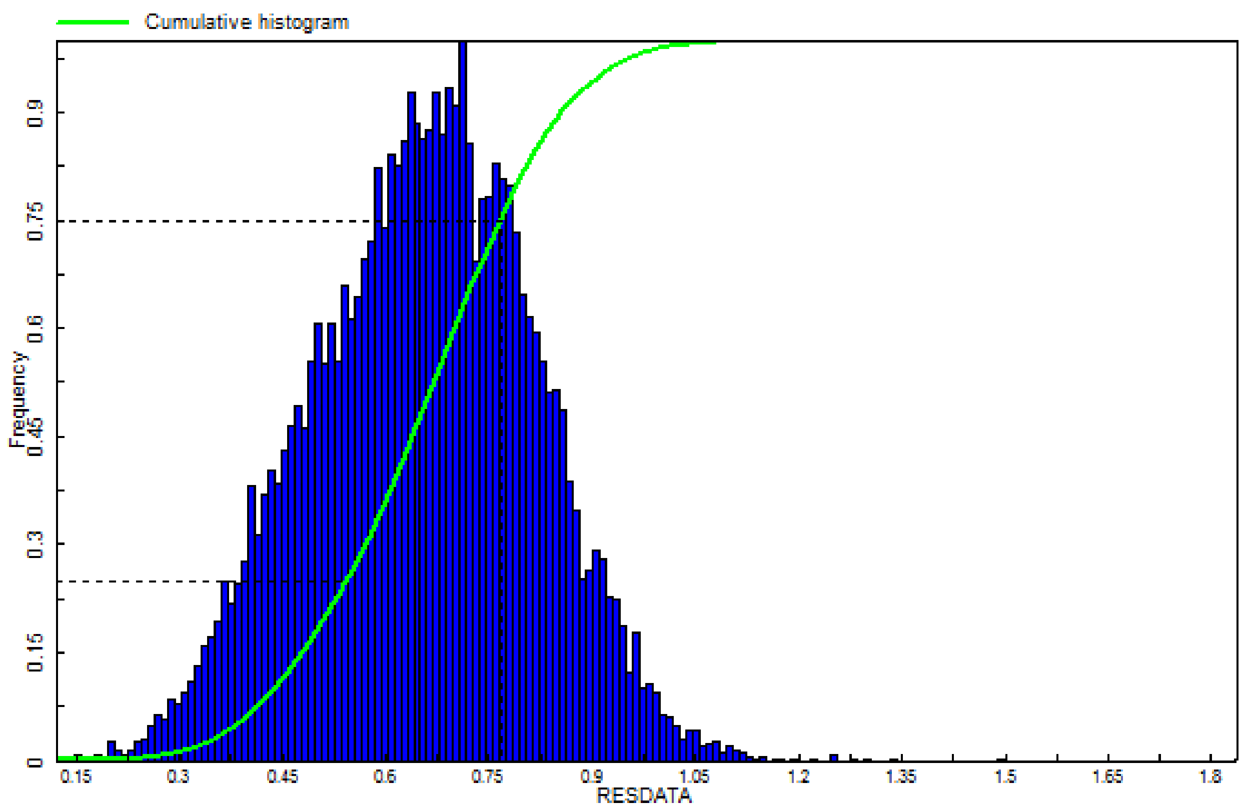


Figure 4-14: Data/model residual histogram for the BGMA SCI inversion results.

5 AEM Results and Interpretation

This section provides the details on the process involved in the interpretation of the BGMA 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. This included lines that composed the 3-mile reconnaissance grid lines and the Creighton Water System flight lines. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. Table 5-1 lists the original flown lines and the new combined lines.

Table 5-1. Combination of flight lines within the Bazile Groundwater Management Area survey

Original Source Lines	Direction	New Line
L124701, L124702, L124703, and L133701	East-West	L124700
L124901, L124902, L124903, L124904, and L133901	East-West	L124900
L125101, L125102, L125103, and L118301	East-West	L125100
L125301, L125302, and L118501	East-West	L125300
L125501, and L125502	East-West	L125500
L125701, and L125702	East-West	L125700
L125901, and L125902	East-West	L125902
L143002, L148601, and L148602	North-South	L148600
L144601, and L149201	North-South	L149200
L149401, and L149601	North-South	L149400
L127501, and L132301	South West- North East	L127500
L127701, and L132501	South West- North East	L127700
L127901, and L132701	South West- North East	L127900
L128101, and L132901	South West- North East	L128100

The BGMA survey area encompassed an additional 107.62 line-miles of AEM data collected in 2014 by the LENRD and the ENWRA (Carney et al. 2015a) (Figure 4-5 in previous section). The 2014 AEM data contains valuable information that can be utilized in the interpretation of the BGMA and the Creighton Water System survey area. The 2014 AEM data was combined with the 2016 AEM data along the lines that the data abutted and continued the reconnaissance lines that were planned in the BGMA or that were contained within the BGMA AEM survey area. This combination did not include reinverting the 2014 data, but included merging the 2014 inversions into the 2016 database. Details on the inversion of the 2014 AEM data can be found in Carney et al. (2015a). Table 5-2 summarizes the 2014 AEM data that was combined with the 2016 BGMA AEM data. When looking at the combination of the two separate data sets that were collected by different systems at different times and inverted separately, it is important to note that both data sets were properly calibrated and any system bias was removed prior to inversion. Inspection of the profiles created from the combined lines displaying inverted resistivity at the same color scale can indicate an issue with calibration and incomplete bias removal. Figure 5-1 is a north-south line that was combined from the 2016 BGMA SkyTEM 304 AEM inversions (north end) and the 2014 SkyTEM 508 AEM inversions (south end). Inspection of Figure 5-1 shows a small break in the data coverage at the meeting point of the two datasets; however, the resistivity values continue across the line until the top of the ***Kc*** is encountered in the 2016 SkyTEM304M inversions. This is due the differences of the DOI of the SkyTEM304M and the SkyTEM 508. Figure 5-2 is an east-west line that was combined from the 2016 BGMA SkyTEM304M AEM inversions (west end) and the 2014 SkyTEM 508 AEM inversions (east end). For Figure 5-2 the data do overlap about one another. Again, we see a clear continuing of the resistivity values across the combined line until we get to the top of the ***Kc***. This is due again to the difference in DOI of the SkyTEM304M versus the deeper imaging SkyTEM508.

Table 5-2. Combination of 2014 AEM data (Carney et al. 2015a) flight lines within the 2016 Bazile Groundwater Management Area survey lines

2016 Lines	2014 Lines	Direction	New Line
L125500	L100301	East-West	L125500301
L125700	L100401	East-West	L125700401
L125900	L100501	East-West	L125900501
	L200101	North-South	
L148801	L200201	North-South	L148801201
L149001	L200301	North-South	L149001301
	L200401	North-South	
L149200	L200501	North-South	L149200501
L149400	L200601	North-South	L149400601

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, BGMA AEM) a Digital Elevation Model (DEM) was constructed for the BGMA survey. The data was downloaded from the National Elevation dataset (NED) located at the National Map Website (U.S. Geological Survey, 2016) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates are North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88). The 100 ft grid cell size was used throughout the project and resulting products. Figure 5-3 is a map of the DEM showing a vertical relief of 642 ft with a minimum elevation of 1409 ft and a maximum elevation of 2051 ft. This DEM was used to reference all elevations within the AEM datasets.

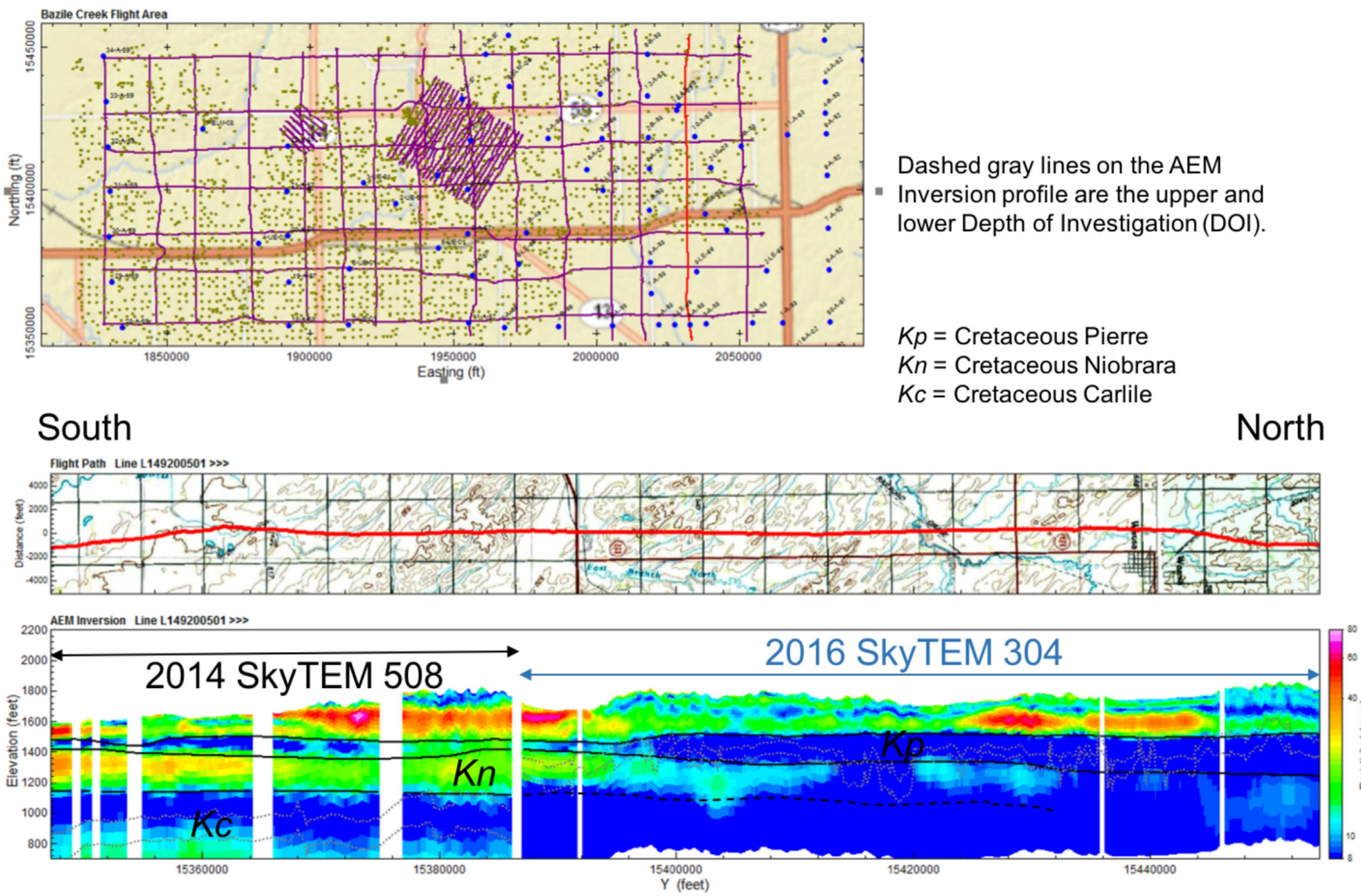


Figure 5-1. Example of a map and profile view of a north-south flight line L149200501 that was combined from the 2014 Eastern Nebraska Water Resources Assessment (ENWRA) AEM and the 2016 BGMA AEM. The top map shows all the flight lines flown in the BGMA from 2014 and 2016 with the red line indicating the viewed profiles. The blue dots represent CSD test holes and the brown dots represent the Nebraska DNR registered wells. The second map is a flight line positioned on the U.S. Geological Survey 100K topography at the same horizontal scale as the AEM inversions profile. The bottom profile displays the resistivity values of the 2014 ENWRA SkyTEM 508 and the 2016 BGMA SkyTEM 304 inversions. Geological interpretations on the profile include the Cretaceous Pierre (*Kp*), Niobrara (*Kn*), and Carlile (*Kc*). The dashed black line shows the inferred location of the *Kn* and *Kc* contact in the SkyTEM304M inversions. The dotted gray lines represent the upper and lower depths of investigation from the inversions.

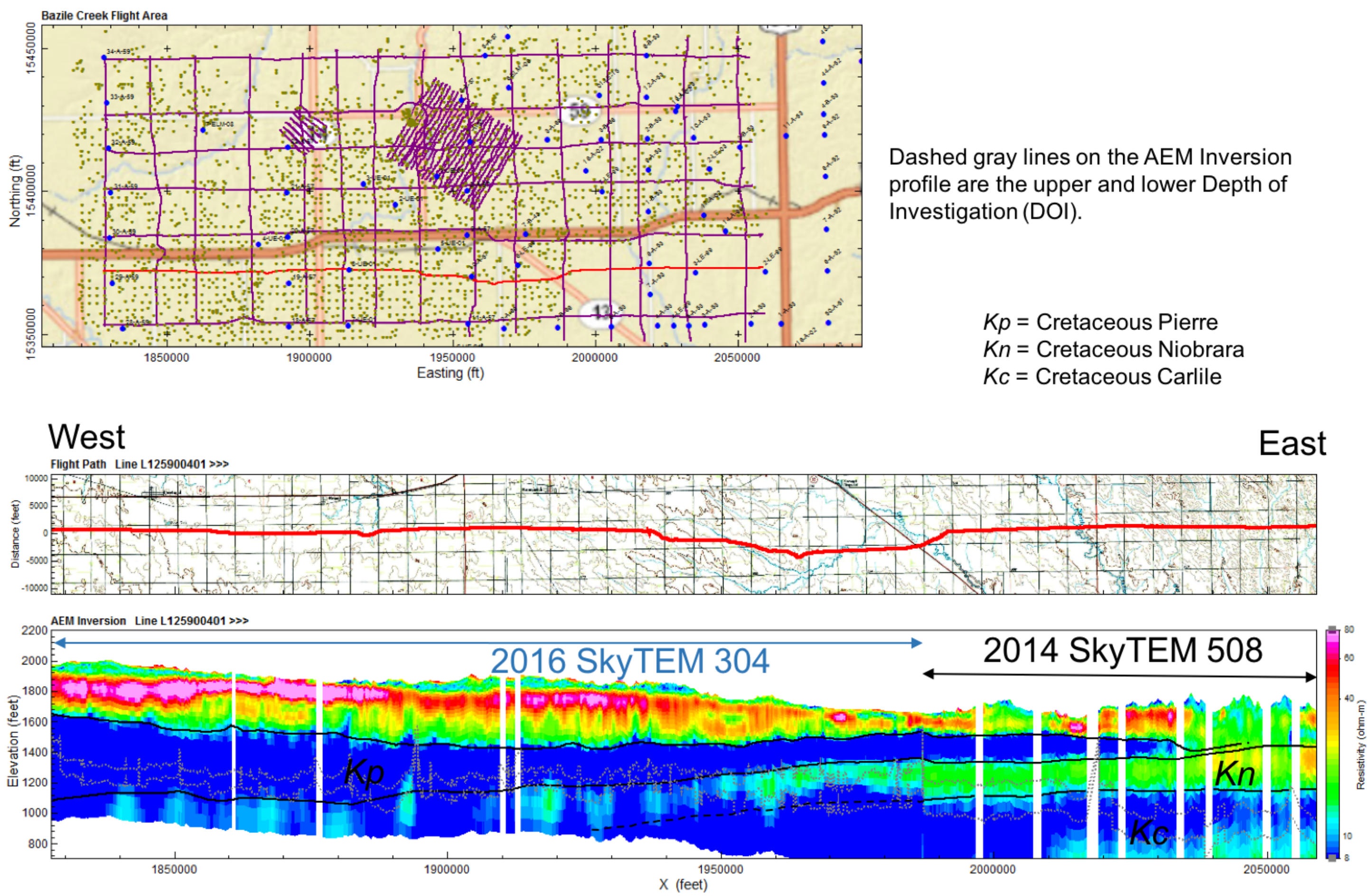


Figure 5-2. Example of a map and profile view of an east-west flight line L125900401 that was combined from the 2014 Eastern Nebraska Water Resources Assessment (ENWRA) AEM and the 2016 BGMA AEM. The top map shows all the flight lines flown in the BGMA from 2014 and 2016 with the red line indicating the viewed profiles. The blue dots represent CSD test holes and the brown dots represent the Nebraska DNR registered wells. The second map is a flight line positioned on the U.S. Geological Survey 100K topography at the same horizontal scale as the AEM inversions profile. The bottom profile displays the resistivity values of the 2014 ENWRA SkyTEM 508 and the 2016 BGMA SkyTEM304M inversions. Geological interpretations on the profile include the Cretaceous Pierre (*Kp*), Niobrara (*Kn*), and Carlile (*Kc*). The dashed black line shows the inferred location of the *Kn* and *Kc* contact in the SkyTEM304 inversions. The dotted gray lines represent the upper and lower depths of investigation from the inversions.

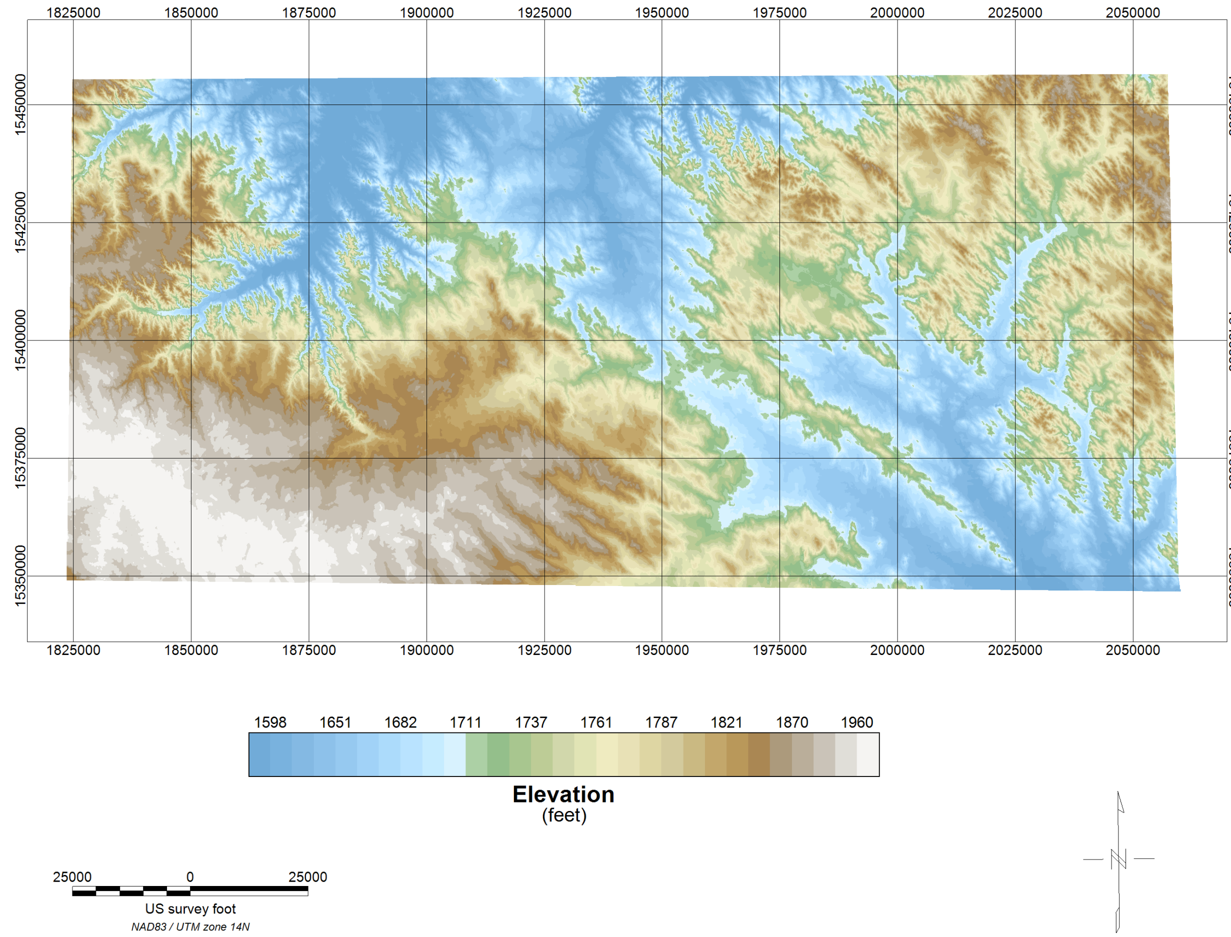


Figure 5-3. Map of the Digital Elevation Model for the BGMA. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2016). North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

5.1.3 Create Interpretative 2D Profiles

After final combination of the AEM data, characterization of the subsurface was performed in cross-section format using Encom PA (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 data related to the area being interpreted. The first step in the interpretation is digitizing the contacts between the geologic units including: Quaternary (***Q***), Tertiary Ogallala (***To***), Cretaceous Pierre (***Kp***), and Cretaceous Niobrara (***Kn***). The interpreted geological units included the ***Q**, **To**, **Kp**,* and ***Kn*** from the upper surface to the DOI. The interpretive process benefited from the use of CSD, NE-DNR, and West Knox Rural Water System borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (Burchett, 1986) and other geological maps in the project area (Burchett et al. 1988). Interpretations of the ***Kc**, **Kgg***, and ***Kd*** were part of the 2014 AEM data from Carney et al. (2015a) and are included in the final interpreted database in Appendix 14, but those units were not interpreted in the 2016 BGMA AEM data due to the shallower depth of imaging by the SkyTEM 304M.

The interpretation began with picking the ***Kp*** contact, then the ***Kn,*** and then finally the ***To*** interface. The process was iteratively in the area of the eroded ***Kp*** sitting on the ***Kn*** in the southeast corner of the BGMA survey area.

The interpretation of the ***Kp*** included examining the AEM profile section 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 ***Kp*** due to that stratigraphic unit not being considered an aquifer composed predominantly of shale containing clay minerals. Many of the CSD boreholes have stratigraphic calls that assist in the location of the ***Kp***. For the profiles, the clipping distance from the flight line was set independently for the CSD boreholes and the NE-DNR boreholes. Typically, the CSD clipping distance was set to one mile or 5,280 ft, and the NE-DNR boreholes was set to 1,000 ft. The inversion DOI was also inspected when interpretation of the profiles, but was almost always below the top of the ***Kp*** in the BGMA flight area.

Figure 5-4 is an eight-mile-long segment of the north-south line L147001 on the far western extent of the BGMA flight area. Figure 5-4 illustrates the interpretation of the top of the ***Kp,*** top of the ***To,*** and the ***Q***. Figure 5-4 also indicates the strong resistivity contrast between the ***Kp*** and the ***To*** in this area of the BGMA. The CSD boreholes in this area suggest a small amount of Tertiary White River Group Chadron formation (***Tc***); however, there was no indication that the ***Tc*** was detectable in the AEM inversions. This may be due to the thin and discontinuous nature of the deposits and the fine-grained nature of the ***Tc*** as indicated by the CSD lithology logs. It is important to note that these CSD logs are within one mile of the flight line and not directly on the flight line and changes can occur within the one mile distance. In Figure 5-4 the NE-DNR boreholes typically end at the ***Kp*** surface or just slightly penetrate the surface with lithology indicated as clay, clayey shale/claystone, or shale. The interpretation of the ***To*** included examination of the CSD and NE-DNR boreholes and comparison with the AEM resistivities. Unlike the ***Kp/To*** and ***Kp/Q*** surface there is not a strong resistivity contrast between the ***Q*** and the ***To***. To this end the borehole information is critical in the determination of an estimated top of the ***To***. The following characteristics were used to locate the ***To*** top: 1) ***To*** indicated on the CSD borehole stratigraphic logs; 2) indication of sandstone in the CSD borehole lithology logs; 3) indication of sandstone in the NE-DNR lithology logs; and a generally lower electrical resistivity than the overlying ***Q*** alluvial deposits. Patterns in the resistivity were also used to match the difference in the ***Q*** and the ***To***. An example of that can be seen in the area of the Figure 5-4 on the left side or southern portion of the line segment. A resistive body of material is deposited from approximately 1,750 – 1,900 ft in elevation. This package of material extends approximately 4.5 miles north or to the right of the figure. The CSD and the NE-DNR lithology logs indicate unconsolidated sands and sand and gravel with minor silt or silty sands. This package of material is consistent with ***Q*** paleochannel deposits composed of coarse material. It is important to note that the ***To*** top surface is an estimated surface based on the information summarized in this report. To be more confident in the interpretation of the ***To*** top field checks and additional drilling and laboratory analysis would need to be completed to verify that the deposits are Tertiary rather than Quaternary in age. It is the author's view that this would not provide a substantially better understanding of the aquifer systems in the area. More discussion on the hydrogeologic environment will be included in following sections. It is important to also note that there are some inconsistencies in the interpretation of the ***To*** within the CSD stratigraphic logs. A good example of that can be seen in the comparison of *29-A-59* and *30-A-59* on Figure 5-4. *29-A-59* indicates that the ***To*** begins at a point of sand and gravel to a sand only change in the lithology log, while the stratigraphic log from *30-A-59* indicates that the ***To*** begins at the bottom of the thick sand deposit. Understanding that these logs are up to one mile from the flight line and that there are known variations in both the ***To*** and ***Q*** deposits. It is still inconsistent that paleochannel deposits are not continuous across this area. Again, this has a limited impact on the understanding of the hydrology of the area as these are coarse deposits and are in connection with each other and would appear as the same aquifer regardless of their geological age.

Figure 5-5 is a 13.5-mile segment of line L149400601. This line is composed of the merged 2014 AEM inversions (Carney et al., 2015a) and the BGMA 2016 AEM inversions. This line indicates an area where the ***Kp*** is eroded off and the ***Kn*** is the bedrock/base of aquifer unit in the area. The ***To*** is also eroded off much of this area and the ***Q*** deposits are in direct contact with the ***Kp*** and the ***Kn***. These lines also indicate the deeper ***Kc*** that underlies the ***Kn*** regionally. The ***Kc*** is clearly mapped in the 2014 AEM but is below the DOI in the area collected in 2016 (Section 5.1.1). The CSD boreholes indicate two distinct stratigraphic situations on either end of the line segment in Figure 5-5. *2-A-53* shows ***Q*** alluvium sitting on a thin layer of ***To*** deposited on the ***Kn***. The AEM doesn't indicate a ***To*** deposit in the area of *2-A-53* and was not interpreted in this area. The ***Q*** deposits are alluvial or outwash related with a layer of loess on top. The resistive nature of the ***Kn*** is indicated by the AEM. Adjusting the resistivity color scale in this area aided in the interpretation of the top of the ***Kn***. *3-B-53* indicates a differing geological environment with ***Q*** glacial till deposited on a thin layer of ***To*** sitting on the ***Kp***. Again, the ***To*** interpreted by CSD is not detected in the AEM. The strong resistivity contrast of the ***Kp*** makes the interpretation of the top of the ***Kp*** relatively straightforward. The southern edge of the ***Kp*** is also clearly identifiable in the AEM resistivity inversions. This is an important transition in the geological environment as the ***Kn*** can locally contain fractures that can provide a water resource when hydrogeologically connected to surface water.

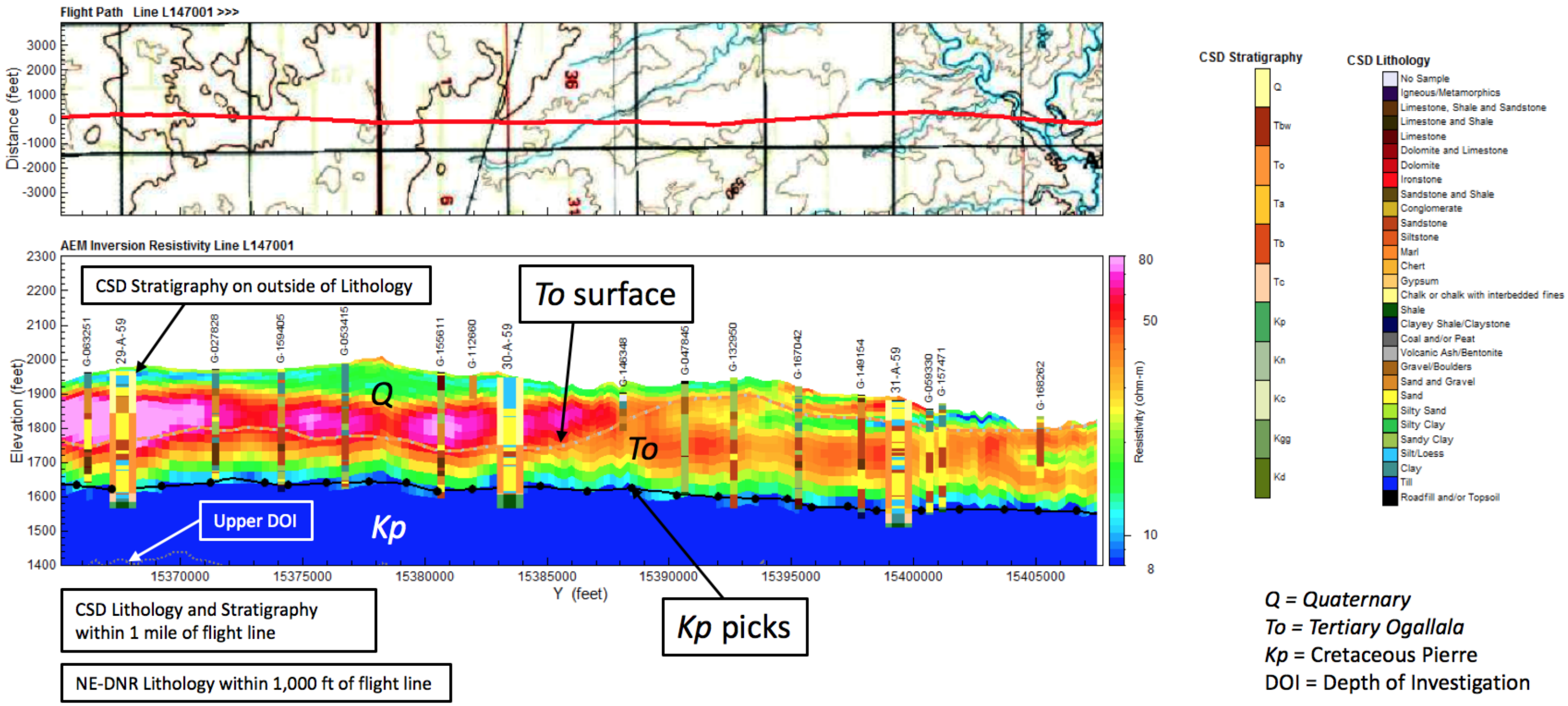


Figure 5-4. Eight-mile-long segment of north-south line L147001 on the far western extent of the BGMA. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

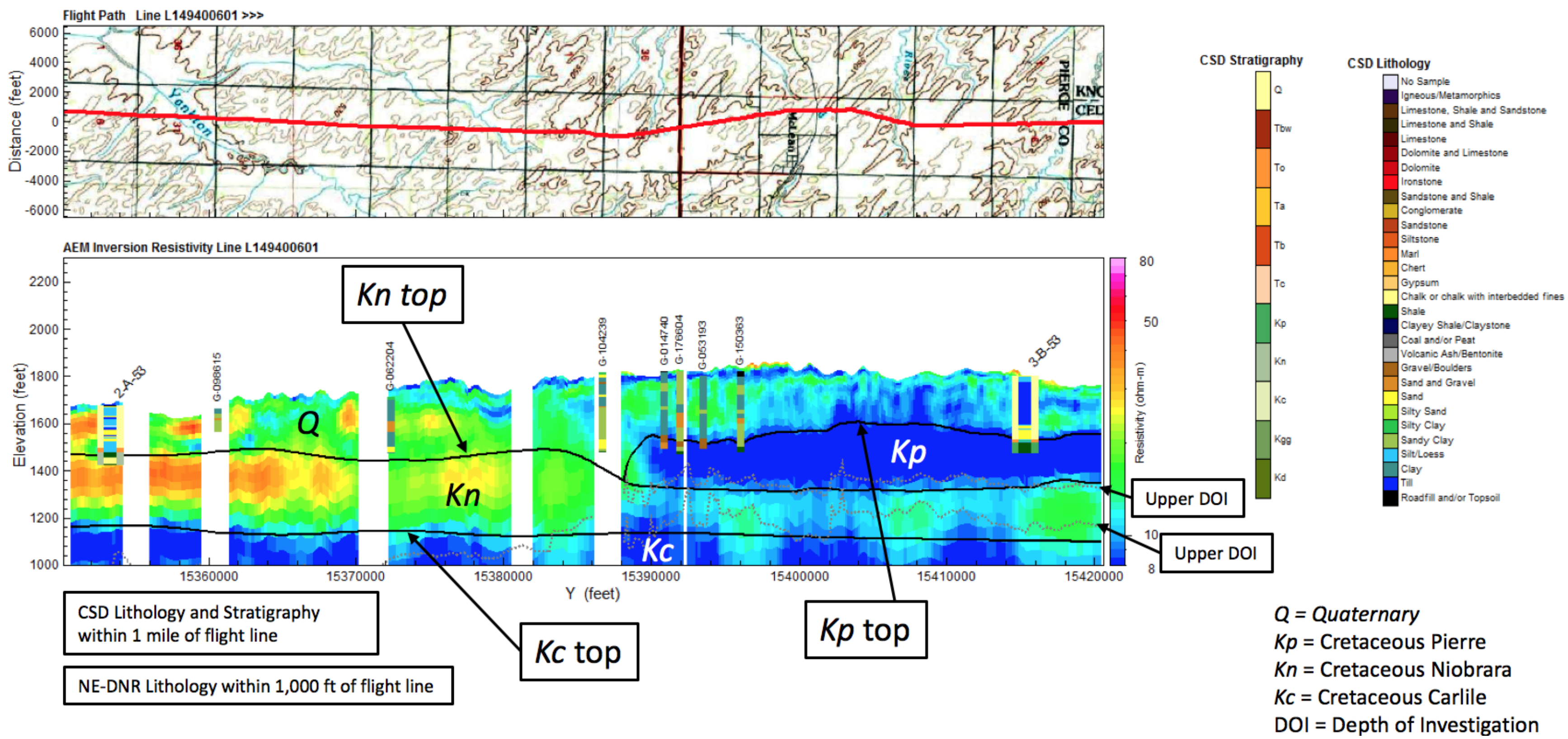


Figure 5-5. A 13.5-mile segment of line L149400601 on the eastern extent of the BGMA. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

Figure 5-6 is a five-mile segment of line L124900 that goes just north of the Creighton Municipal Airport north of the town of Creighton and crosses Bazile Creek. In this segment, there are no CSD boreholes utilized in the interpretation but several NE-DNR lithology logs exist. As discussed above the boreholes are projected onto the AEM inversion profile. The original elevation of the borehole is preserved. In an area of variable topography, the boreholes can be displayed above or below the surface elevation of the AEM inversions. As seen above in the previous examples the interpretation of the ***Kp*** surface is straightforward due to the large resistivity contrast in the ***Q*** deposits and the ***Kp***. The configuration of the ***Kp*** in this area shows that the erosion of Bazile Creek has removed much of the Q deposits and has exposed the ***Kp*** in Bazile Creek. Also of note is a resistive zone in the **K*p*** that is interpreted as a sandy zone in the ***Kp***. These sandy zones exist within the ***Kp*** and are composed of generally fine-grained sands and silts (Korus and Joeckel, 2011). It is not known if there is the possibility of any extractable water within this zone, nor the water quality. A drill hole would need to be located in this deposit to further evaluate the possibility of this zone being an aquifer. The ***Q*** deposits illustrated in Figure 5-6 show high resistivity indicating coarse sediments. This is also indicated by the NE-DNR lithology logs.

Figure 5-7 is a 2.5-mile line L126101 that goes through the southern portion of the West Knox Rural Water District Flight block. As seen above in the previous examples, the interpretation of the ***Kp*** surface is straightforward due to the large resistivity contrast in the ***To*** deposits and the ***Kp***. Utilizing the information from CSD borehole *22-A-57*, it can be interpreted that the ***To*** is close to the surface in this area and has a relatively thin layer of ***Q*** deposits. The interpretation of the ***To*** is again an estimate in the area and should only be used as a guideline. The AEM resistivity inversions are indicating a layered deposit of sands/sandstones and silts and clays. This is also indicated in the CSD and NE-DNR lithology logs. Of note in this area is the presence of a moderately conductive layer approximately 20 ohm-m that exists in the upper 100 ft of the profile. The deposit is relativity flat, but does indicate a draping appearance on the topography that may indicate a windblown deposit.

The above examples illustrate the interpretive process that was used on the profiles provided within this report. Each flight line with interpretation including the Quaternary/Tertiary Aquifer material mapping (Section 5.2.1) are included as Appendices. Table 5-3 is a summary of the appendices that contain the interpreted profiles.

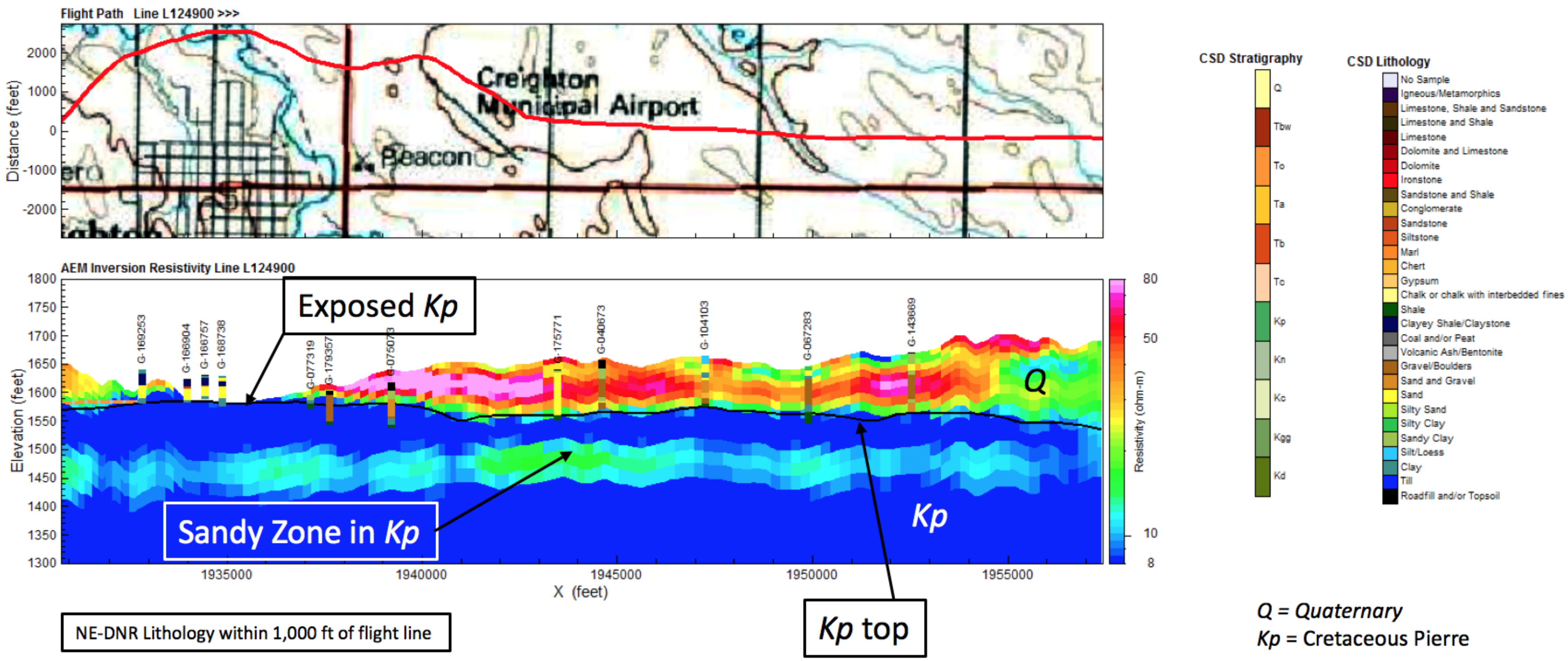


Figure 5-6. A 5-mile segment of line L124900 that goes just north of Creighton and the Creighton Municipal Airport and crosses Bazile Creek. Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

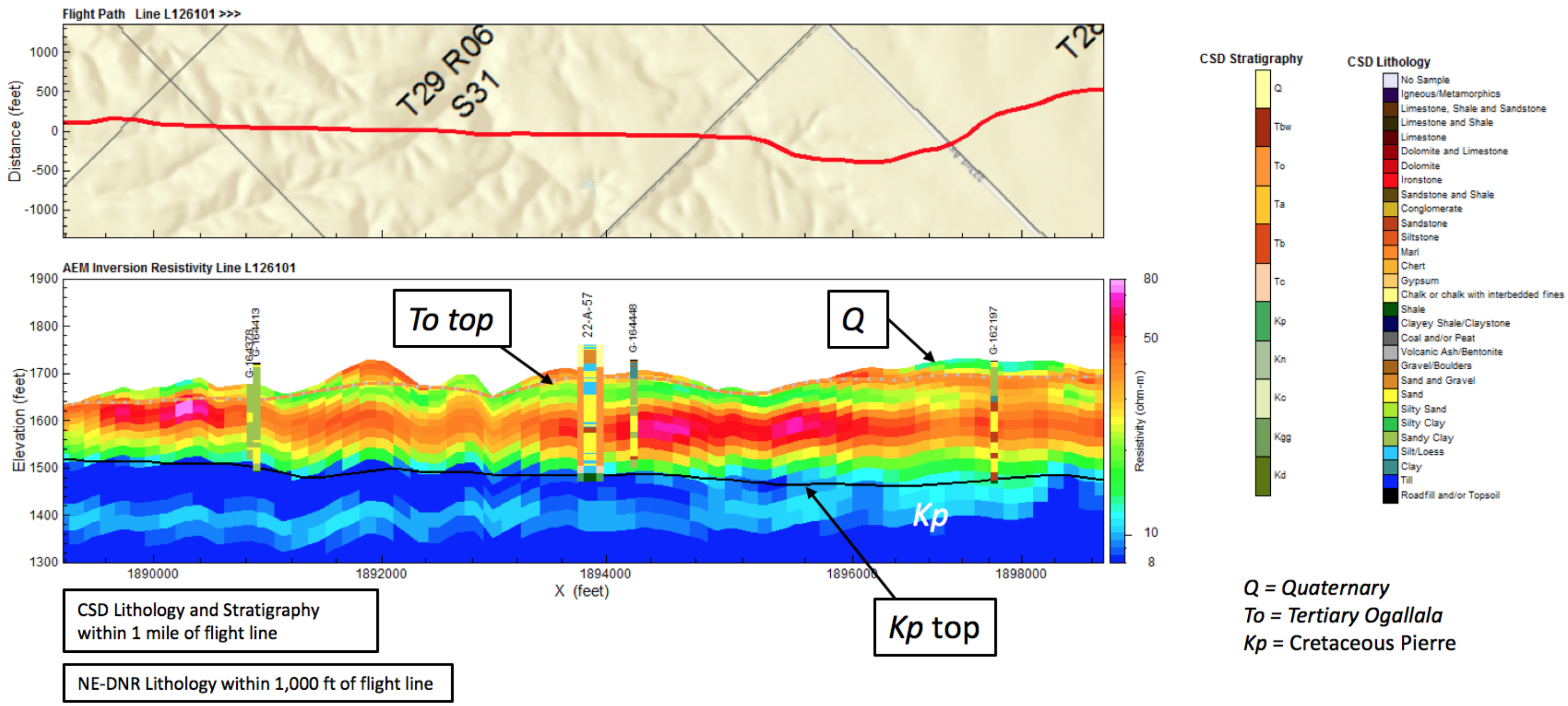


Figure 5-7. 2.5-mile line L126101 that goes that goes through the southern portion of the West Knox Rural Water District flight block. CSD and Nebraska DNR borehole lithology and stratigraphy logs are indicated on the AEM inverted earth models. Interpretations are indicated by lines labeled with stratigraphic names.

Table 5-3. Summary of the interpreted profiles for the BGMA AEM inversions.

Appendix	Flight Area	Resistivity Profile	Interpretation Profile	Flight Map	Air Photo Map	Topo Map
1	BGMA Reconnaissance Lines		X	X		X
2	BGMA Reconnaissance Lines	X	X			X
5	Creighton Water System		X	X	X	
6	Creighton Water System	X	X			X
9	West Knox Rural Water System		X	X	X	
10	West Knox Rural Water System	X	X		X	

5.1.4 Create Interpretative Surface Grids

BGMA 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 imported to a Geosoft Oasis montaj (OM) database. The interpreted elevation data were then gridded for each formation independently using the OM minimum curvature gridding (MCG) algorithm with a 500 ft cell size, a blanking distance of 2,500 ft, and the cells to extend beyond set to 50.

For the ***Kp*** top surface 38 CSD boreholes and 934 NE-DNR holes were used in addition to the 2,628 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. CSD and NE-DNR 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 ***Kp*** surface was then regridded at a 100 ft cell size and compared with the surface DEM which was also at 100 ft cell size. Were the ***Kp*** surface was higher in elevation then the DEM the KP surface as set to the DEM minus three feet. This process was required due to the outcrop of the ***Kp*** in the northwestern area of the BGMA. The AEM and the boreholes did not have the spatial resolution to properly represent the ***Kp*** outcrop and the original ***Kp*** surface did not reflect the complexity of the outcropping ***Kp***. The grid was then clipped to the BGMA area. Figure 5-8 is a map of the elevation of the top of the ***Kp*** within the BGMA.

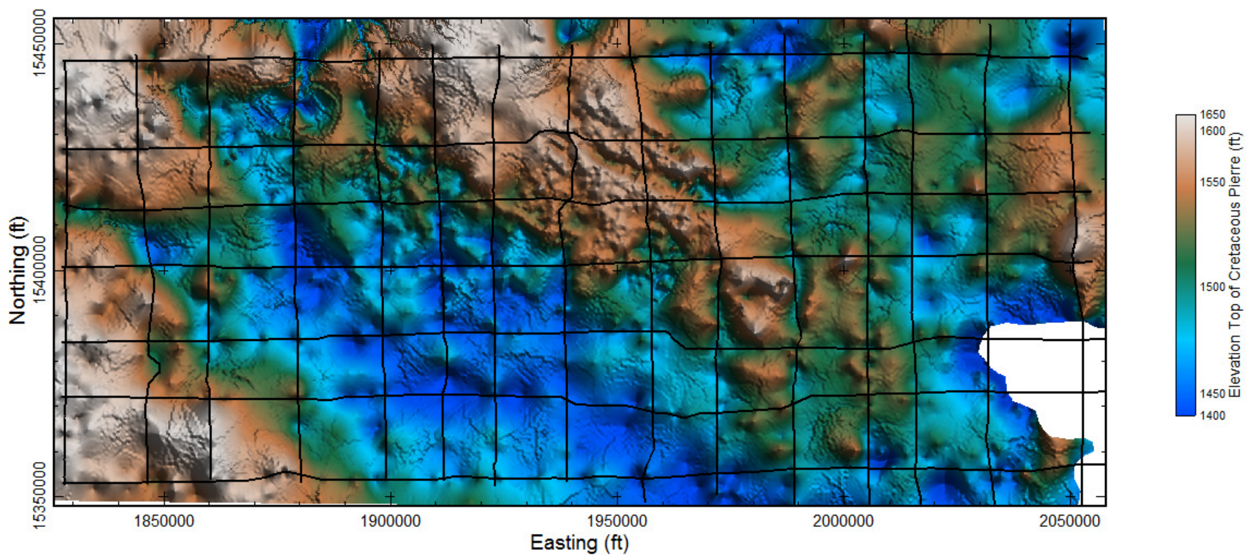


Figure 5-8. Map of the elevation of the top of the Cretaceous Pierre (*Kp*) and the reconnaissance flight lines within the BGMA. The projection is NAD83 and the elevation values are referenced to NAVD 88.

To define the ***Kn*** top surface 7 CSD boreholes and 19 NE-DNR holes were used in addition to the 1,368 AEM picks. Using the above specifications in the previous paragraph 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. CSD and NE-DNR 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. Unlike the ***Kp***, the ***Kn*** surface was left at a 500 ft grid cell size as no topographic corrections were required. The grid was then clipped to the BGMA area. Figure 5-9 is a map of the elevation of the top of the Kn within the BGMA.

The bedrock or the base of the Quaternary (***Q***) and Tertiary Ogallala (***To***) aquifer throughout the BGMA is a combination of the ***Kp*** and ***Kn*** surfaces. The ***Kp*** is eroded away on the southeast corner of the BGMA (Figure 5-8) and the ***Kn*** surface represents the base of aquifer in the southeast corner (Figure 5-9). 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 (Figure 5-10) at a 100 ft grid cell size. The grid was then clipped to the BGMA area.

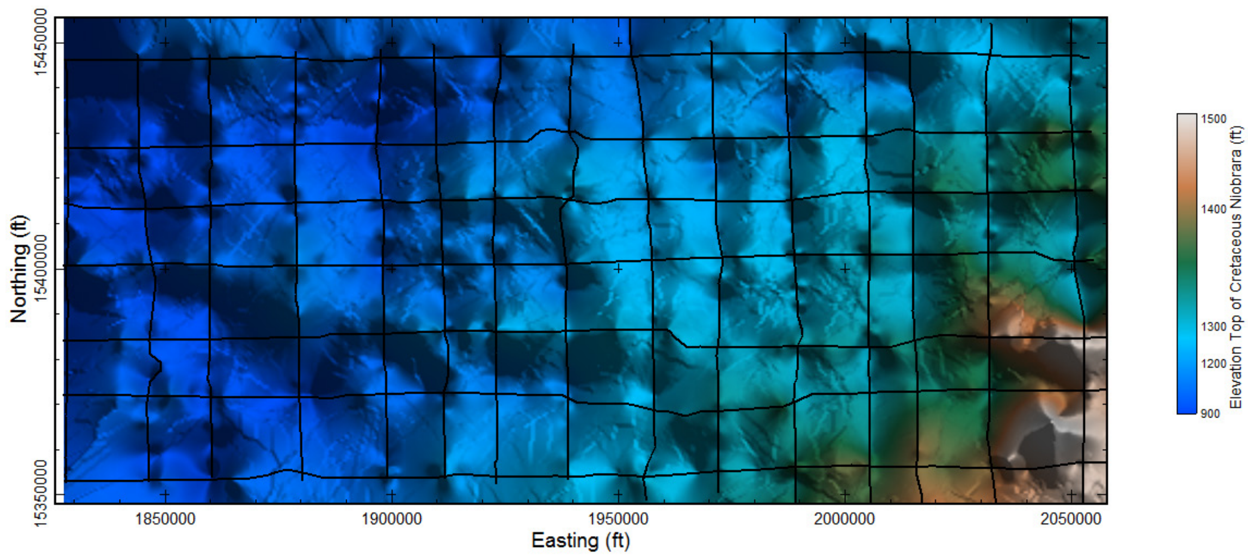


Figure 5-9. Map of the elevation of the top of the Cretaceous Niobrara *(Kn*) and the reconnaissance flight lines within the BGMA. The projection is NAD83 and the elevation values are referenced to NAVD 88.

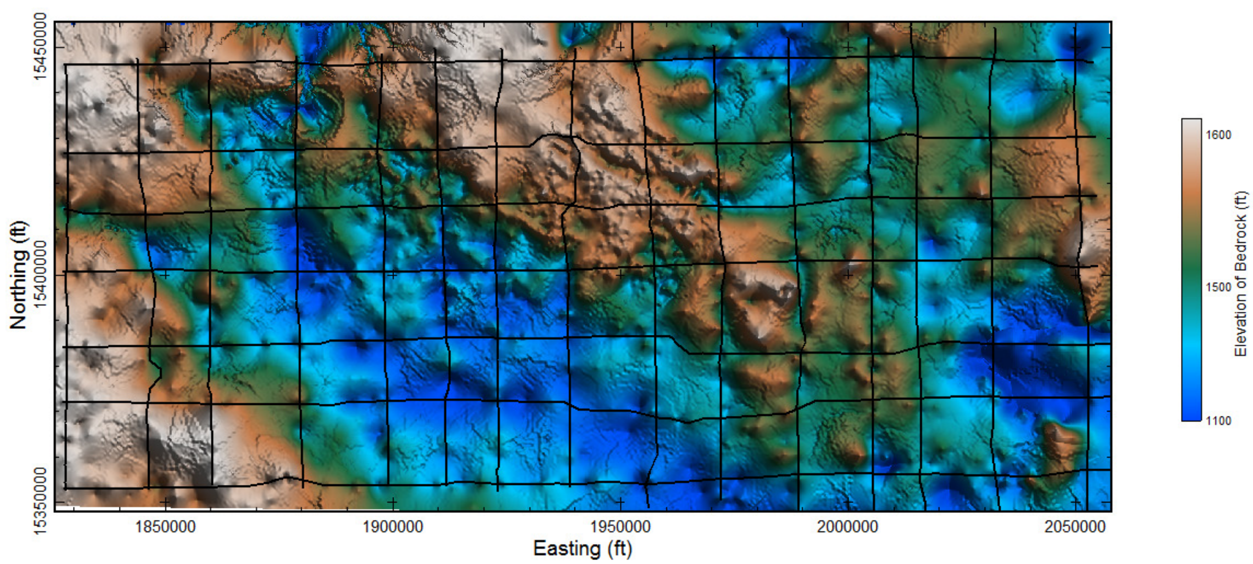


Figure 5-10. Map of the elevation of the top of the bedrock or the base of the Quaternary (*Q*) and Tertiary Ogallala (*To*) aquifer composed of the Cretaceous Pierre (*Kp*) and Niobrara (*Kn*) with the reconnaissance flight lines within the BGMA. The projection is NAD83 and the elevation values are referenced to NAVD 88.

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. These ranges include less than 12 ohm-m, representing non-aquifer materials (“aquitard”- primarily glacial till, loess), 12-20 ohm-m, representing marginal aquifer deposits with potential for interlayered silt and clay, 20-50 ohm-m, indicating the Quaternary system’s principal aquifer, and 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 regarding the selection of these threshold ranges and in Carney et al. (2015a)). Results of these interpretations can be found in Appendices 1-12 for the BGMA reconnaissance lines, the West Knox Rural Water System flight lines, and the Creighton Water System flight lines. As noted above, Table 5-3 is a summary of the appendices that contain the interpreted profiles.

To assist in the approximation of the saturated materials along the surveyed AEM flight lines, the 1995 CSD statewide water table (Nebraska CSD, 1995) was mapped into the cross-sections. It should be noted that this inclusion provides only a generalized characterization of the saturated thickness of the aquifer as the CSD's dataset is two decades old at the time of the 2016 BGMA AEM survey and local conditions likely deviate in areas with variable topography. The water table in the BGMA area is close to the surface in some of the areas. To this end a topographic correction was required to adjust the water table height to be below the surface topography. The original water table contour lines were gridded at a 1,000 ft cell size using the OM MCG and a blanking distance of 5,000 ft. The cells were set to extend beyond to 50. The resulting grid was then regridded at a 100 ft cell size and compared with the DEM of the BGMA. In areas where the water table was greater than the topography the water table was set to an elevation of the topography minus 3 feet. The grid was then clipped to the BGMA area. The result is presented in Figure 5-11.

Voxel grids were completed for the two dense flight blocks (the West Knox Rural Water System and the Creighton Water System) within the BGMA 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 grids were calculated for the two dense flight block areas the bedrock/base of aquifer system was then truncated/clipped from the voxel grids using the bedrock/base of aquifer grid explained above.

The resulting grids are from the surface down to the bedrock/base of the ***Q / To*** 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 14\Voxel. In order to calculate the material that is saturated another surface needs to be clipped from the voxel grids. Using the 1995 water table surface, the voxel grids were clipped again from the water table to the surface. These subset voxel grids represent the area from the bedrock/ base of aquifer system up to the 1995 water table. These subset grids are also located in Appendix 14\Voxel.

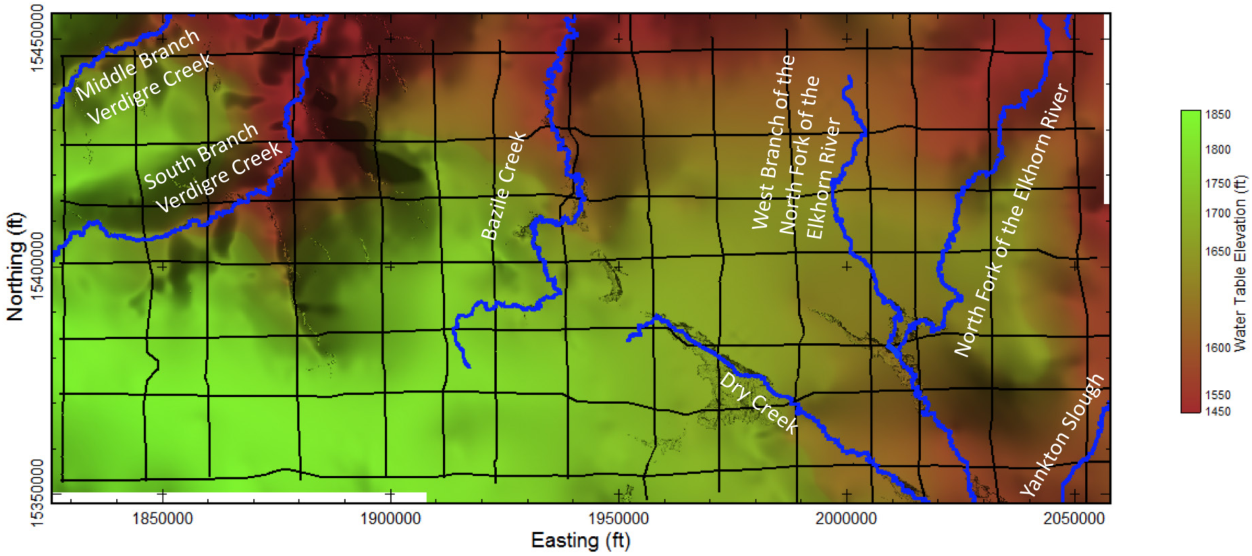


Figure 5-11. Map of the elevation of the water table (Nebraska CSD, 1995) with the reconnaissance flight lines within the BGMA. Steams are indicated on the map. The projection is NAD83 and the elevation values are referenced to NAVD 88.

The resulting grids are from the surface down to the bedrock/base of the ***Q / To*** 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 14. In order to calculate the material that is saturated another surface needs to be clipped from the voxel grids. Using the 1995 water table surface, the voxel grids were clipped again from the water table to the surface. These subset voxel grids represent the area from the bedrock/ base of aquifer system up to the 1995 water table. These subset grids are also located in Appendix 14.

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 BGMA 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 the ENWRA project area (Carney et al., 2015a). The original analysis that was completed as part of Carney et al. (2015a) included the area within the BGMA. 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 5-12.

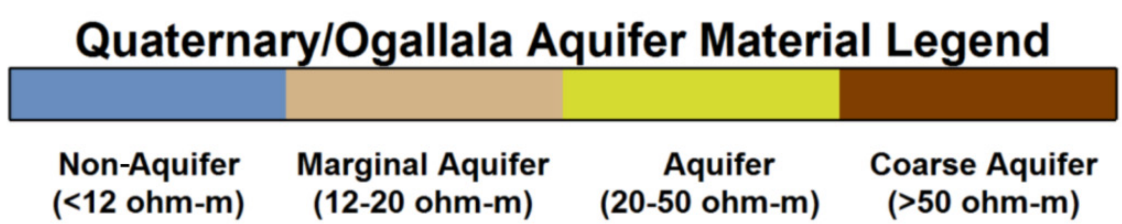


Figure 5-12. Plot displaying the resistivities by major aquifer material color categories (blue- non-aquifer material, tan- marginal aquifer, yellow- aquifer, brown- sand-rich, coarse intervals of the aquifer material).

5.2.2 Bedrock Resistivity Thresholds

The bedrock in the BGMA analyzed in this study includes the ***Kp*** and ***Kn*** formations. These were included to demonstrate the overall distribution in resistivity of bedrock materials across the entire BGMA. The median resistivity values for each unit are 9 ohm-m for the ***Kp*** and 38 ohm-m for the ***Kn*** (Carney et al., 2015a). The low resistivity character of the ***Kp*** made the interpretation of the ***Kp*** upper surface relatively straight forward and allowed the detailed mapping of the ***Kp*** and ***Kn*** contact on the southeastern corner of the BGMA.

5.2.3 Comparison of AEM Inversion Resistivity to Borehole Geophysical Resistivity Logs

Five CSD borehole geophysical resistivity logs were selected from the BGMA for comparison with the AEM inversions: Test hole *7-ELM-08* from the LNNRD; test hole *21-A-57* from the UENRD; and test holes *3-LE-99*, *1-LE-03*, and *01-LE-15* from the LENRD. Since the resistivity logs within the CSD database are of various vintages and conducted by various staff with differing equipment, a critical examination of the absolute values of the resistivity needs to include an awareness of errors in calibration and in the proper operation of the equipment. There is a long-standing issue with using geophysical logs as ground truths when comparing to AEM inversions that are well calibrated using modern techniques. Throughout much of the geophysical logging at the time it was acquired, the relative deflections of the resistivity measurements were all that was required or expected from a geophysical log. Operators were seldom trained in the proper operation of a calibrated sonde or in the ability to recognize high contact resistance of a cable head. This has led to many geophysical logs that are uncalibrated within the CSD database. Note that these logs still have scientific merit in their ability to relatively indicate an increase or a decrease in the formation resistivity. The logs used herein are for qualitative comparison to the AEM because detailed calibration and corrections would need to be carried out for the resistivity values in the logs to be directly used as numerical constraints in the inversion of the AEM data (Ley-Copper and Davis, 2010).

Figure 5-13 is a plot of *7-ELM-08* 16-inch normal resistivity log plotted on the inverted AEM resistivity for line L147401. The AEM and the geophysical log are plotted on the same resistivity color scale as indicated on Figure 5-13 of 8 to 80 ohm-m log scale. *7-ELM-08* is located 353 ft from line L147401 and the borehole geophysical log is projected on to the closest point of the AEM resistivity. Figure 5-14 is a graph of the *7-ELM-08* 16-inch normal resistivity log and lithology plotted with the AEM sounding closest to the test hole. The agreement in the resistivity is good in the area with the geophysical log containing more detail as would be expected. The AEM is illuminating the sand zone from approximately 70 ft to 195 ft. The geophysical log is picking up the details of the silts within the sand that the AEM cannot differentiate. The aquafer material mapping indicates that the material from approximately 70 ft to 165 ft is categorized as aquifer material and the zone from approximately 165 ft to 195 ft is categorized as marginal-aquifer material.

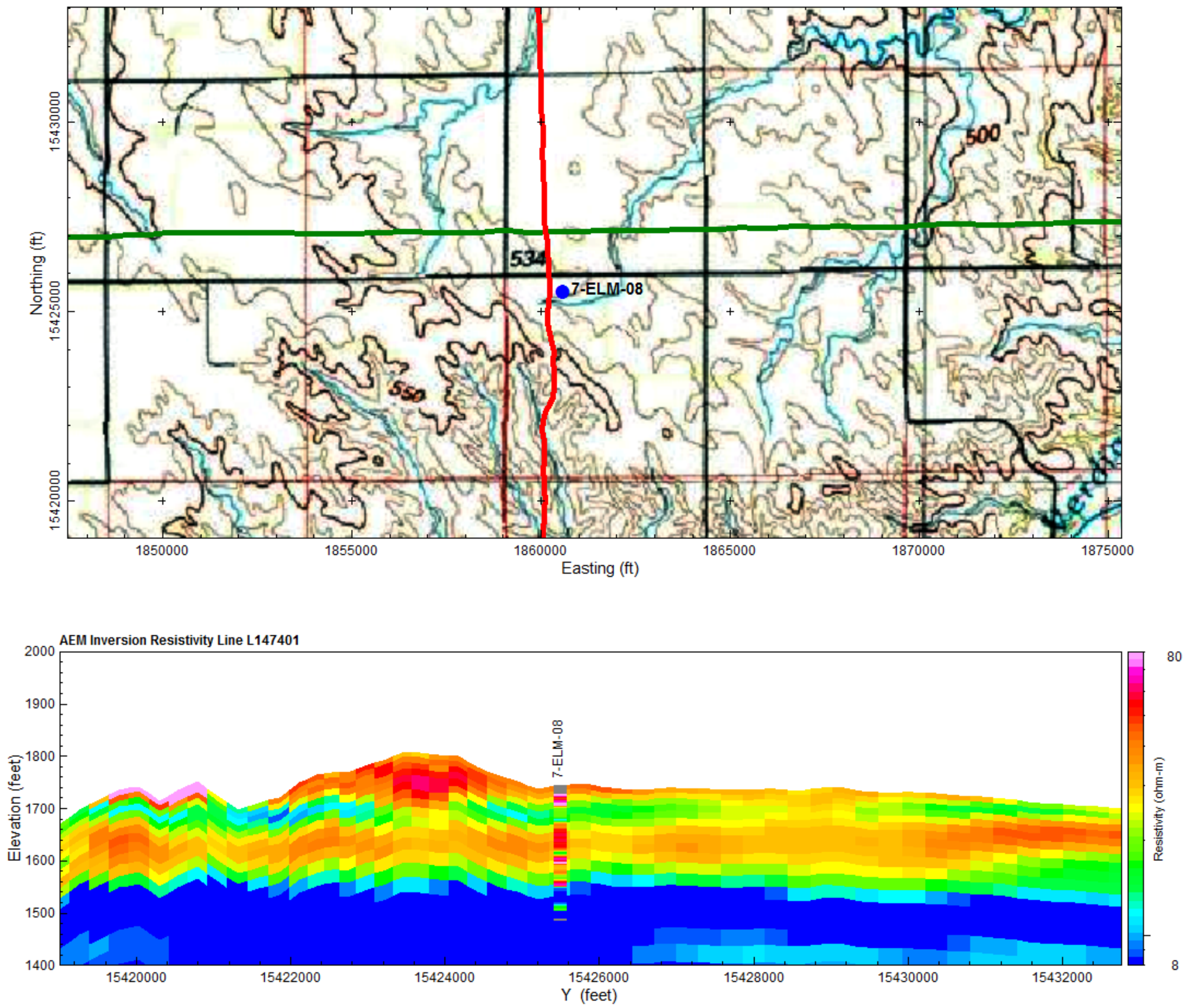


Figure 5-13. Upper map - plot of the location of *7-ELM-08* (blue dot) relative to Line L147401 (red line) plotted on a U.S Geological Survey 100K topo map. Green lines indicate other flight lines within the Bazile Groundwater Management Area. The lower profile shows the *7-ELM-08* 16-inch normal resistivity log values projected on the inverted airborne electromagnetic resistivity values using the same color scale.

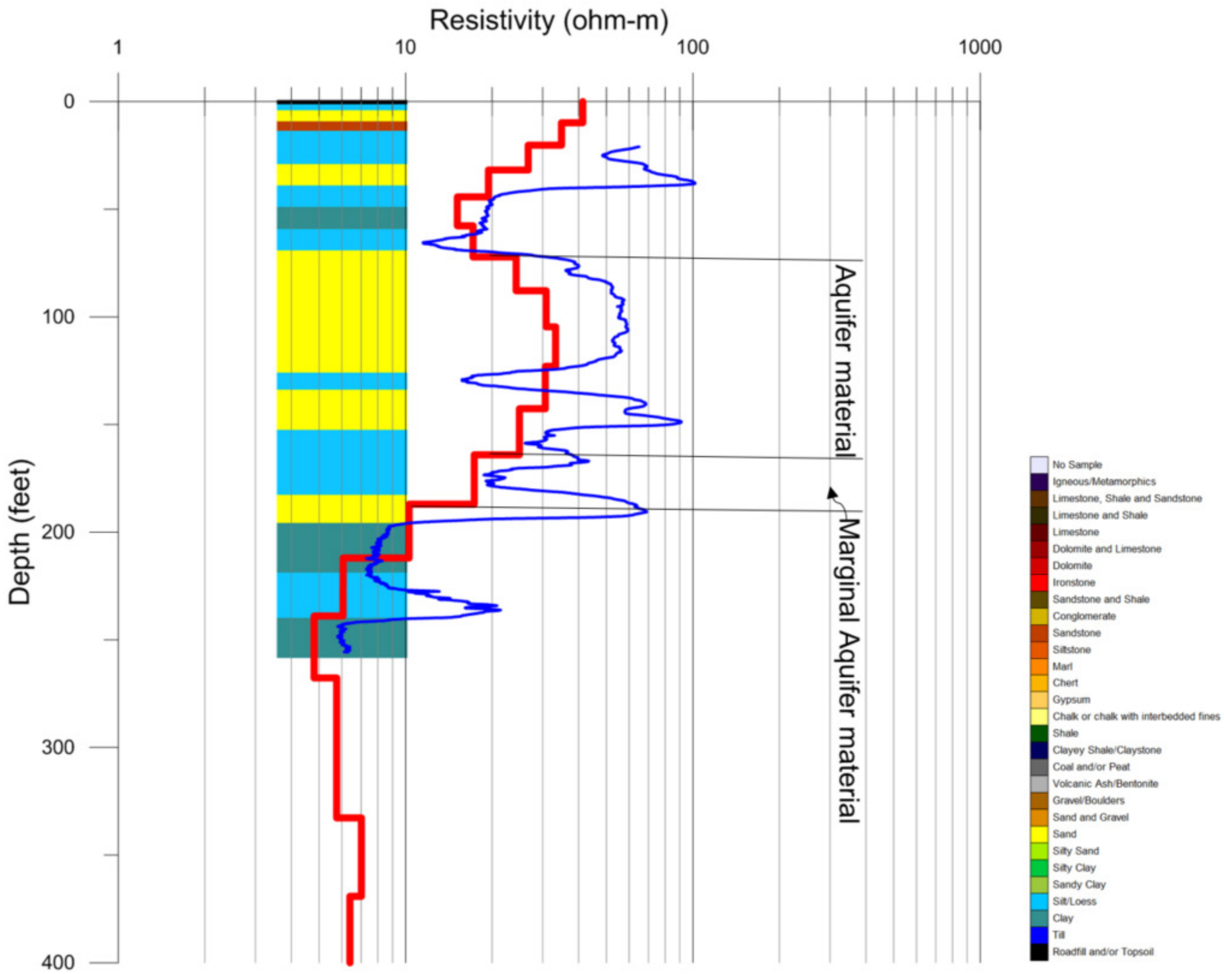


Figure 5-14. Graph of the *7-ELM-08* 16-inch normal resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *7-ELM-08* as well as the aquifer material categories for the major sand zone within the test hole.

Figure 5-15 is a plot of *21-A-57* resistivity log plotted on the inverted AEM resistivity for line L125300. The AEM and the geophysical log are plotted on the same resistivity color scale as indicated on Figure 5-15 of 8 to 80 ohm-m log scale. *21-A-57* is located 1,116 ft from line L125300 and the borehole geophysical log is projected on to the closest point of the AEM resistivity. The elevation of the top of *21-A-57* is higher than the AEM flight line due to the distance between the flight line and the test hole. Figure 5-16 is a graph of the *21-A-57* resistivity log and lithology plotted with the AEM sounding closest to the test hole. The agreement in the resistivity is good in the area with the geophysical log containing more detail as would be expected. The AEM is illuminating the sand and sandstone zone from approximately 30 ft to 268 ft. The geophysical log is picking up the details of the silts within the sand that the AEM cannot differentiate. The aquifer material mapping indicates that the material from approximately 30 ft to 205 ft is categorized as aquifer material and the zone from approximately 205 ft to 268 ft is categorized as marginal-aquifer material. The area at the top of *21-A-57* indicates a difference with the AEM. This may be due to the 1,116 ft difference in location and the elevation difference.

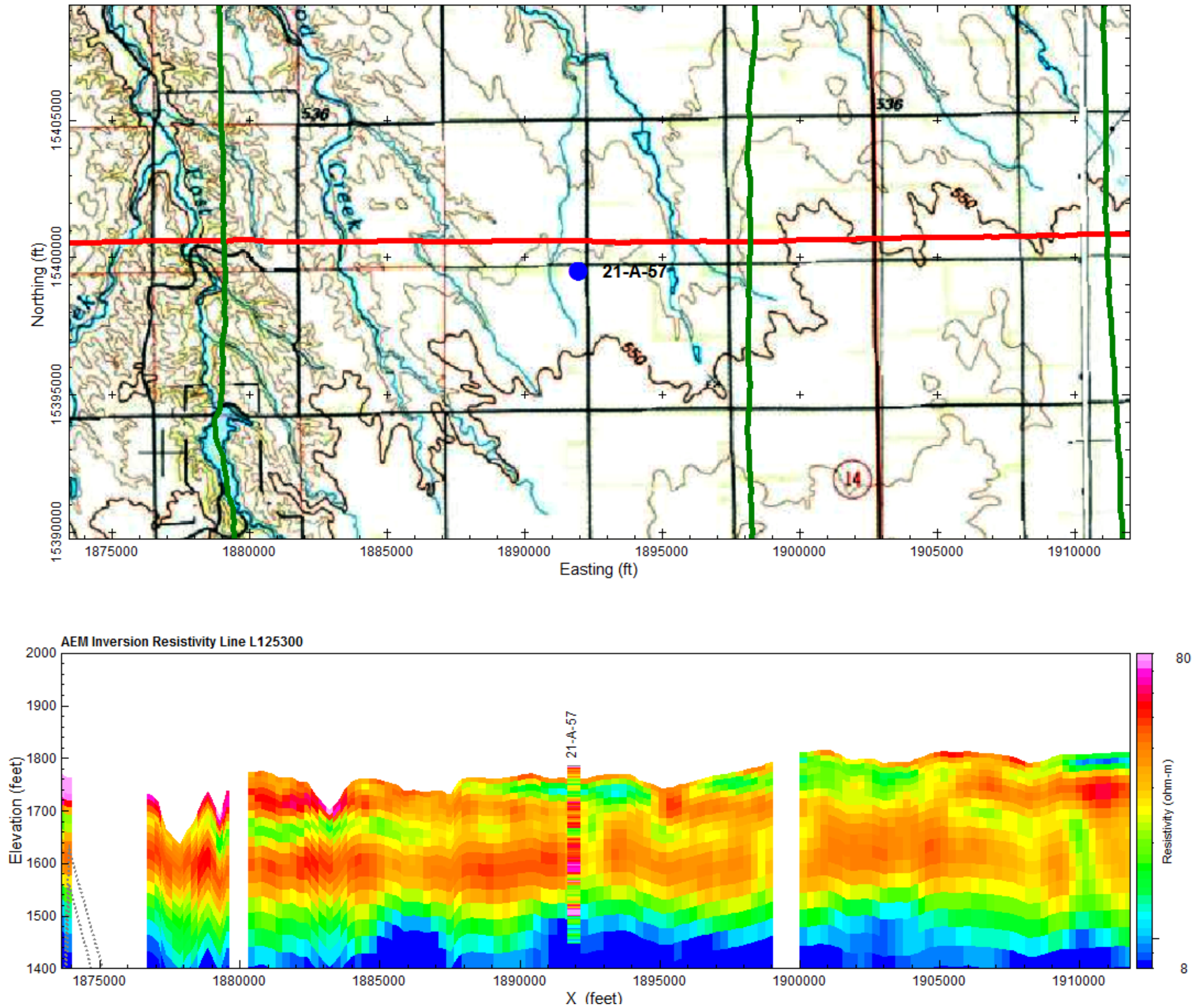


Figure 5-15. Upper map - plot of the location of *21-A-57* (blue dot) relative to Line L125300 (red line) plotted on a U.S Geological Survey 100K topo map. Green lines indicate other flight lines within the Bazile Groundwater Management Area. Lower Profile shows the *21-A-57* resistivity log values projected on the inverted airborne electromagnetic resistivity values using the same color scale.

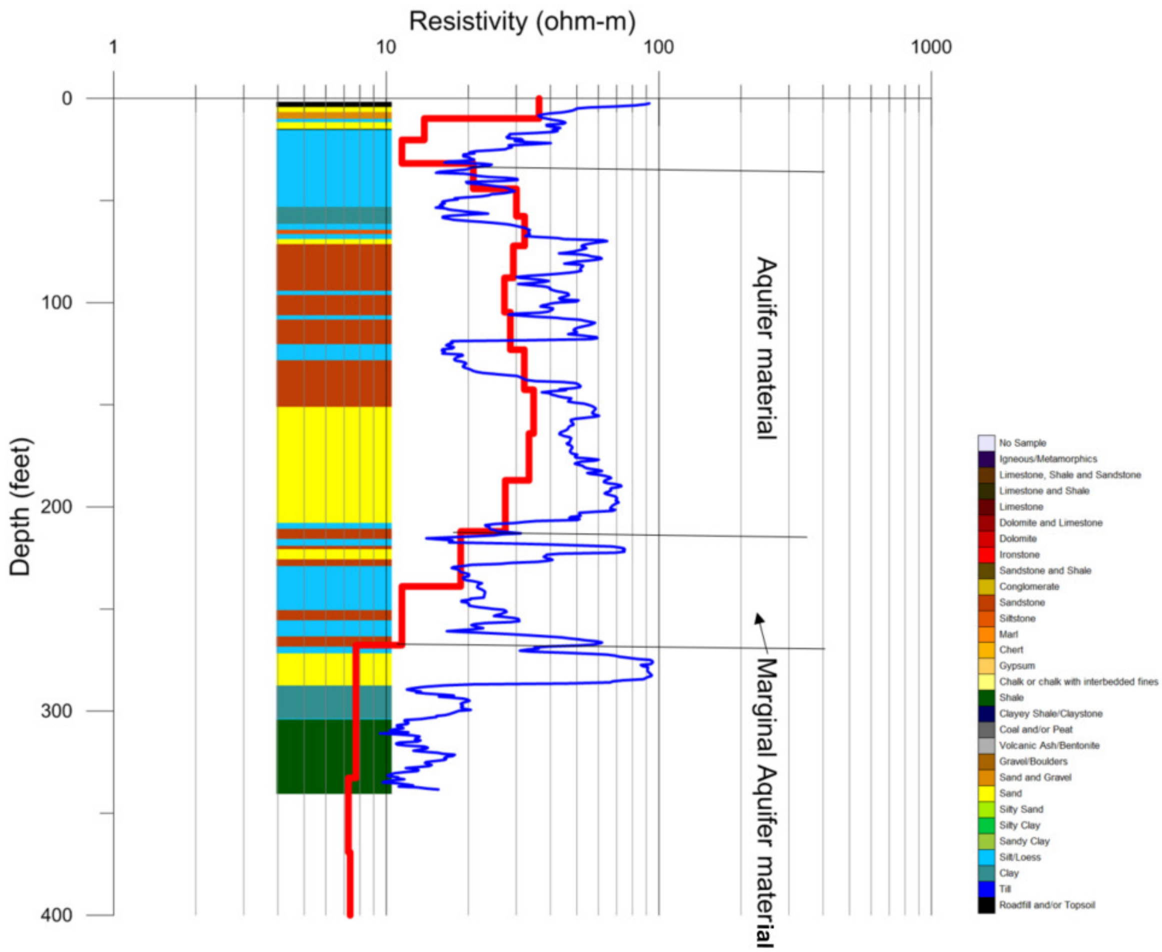


Figure 5-16. Graph of the *21-A-57* resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *21-A-57* as well as the aquifer material categories for the major sand zone within the test hole.

Figure 5-17 is a plot of *3-LE-99* 16-inch normal resistivity log plotted on the inverted AEM resistivity for line L125900401. The AEM and the geophysical log are plotted on the same resistivity color scale as indicated on Figure 5-17 of 8 to 80 ohm-m log scale. *3-LE-99* is located 1,772 ft from line L125900401 and the borehole geophysical log is projected on to the closest point of the AEM resistivity. Figure 5-18 is a graph of the *3-LE-99* resistivity log and lithology plotted with the AEM sounding closest to the test hole. The agreement in the resistivity is marginal in the area with the geophysical log containing more detail as would be expected. The AEM is illuminating the sand zone from approximately 25 ft to 140 ft and a marginal zone from approximately 210 ft to 360. The geophysical log is picking up the layers at different depths and a silt zone from approximately 145 ft to 195 ft. The geophysical log is also indicating high resistivity values for the area showing a zone that is in excess of 1,000 ohm-m. These values are much higher than other logs and AEM data collected in the same area (Carney et al., 2015). The aquifer material mapping indicates that the material from approximately 25 ft to 140 ft is categorized as aquifer material and the zone from approximately 140 ft to the bottom is categorized as marginal-aquifer material. This is overall a comparison of marginal quality. This may be due to the distance between the test hole and the AEM but also there are some issues with the geophysical log indicated by the high resistivity values. The one similarity is that the AEM and *3-LE-99* indicate a sand zone in the upper 150 ft of the area.

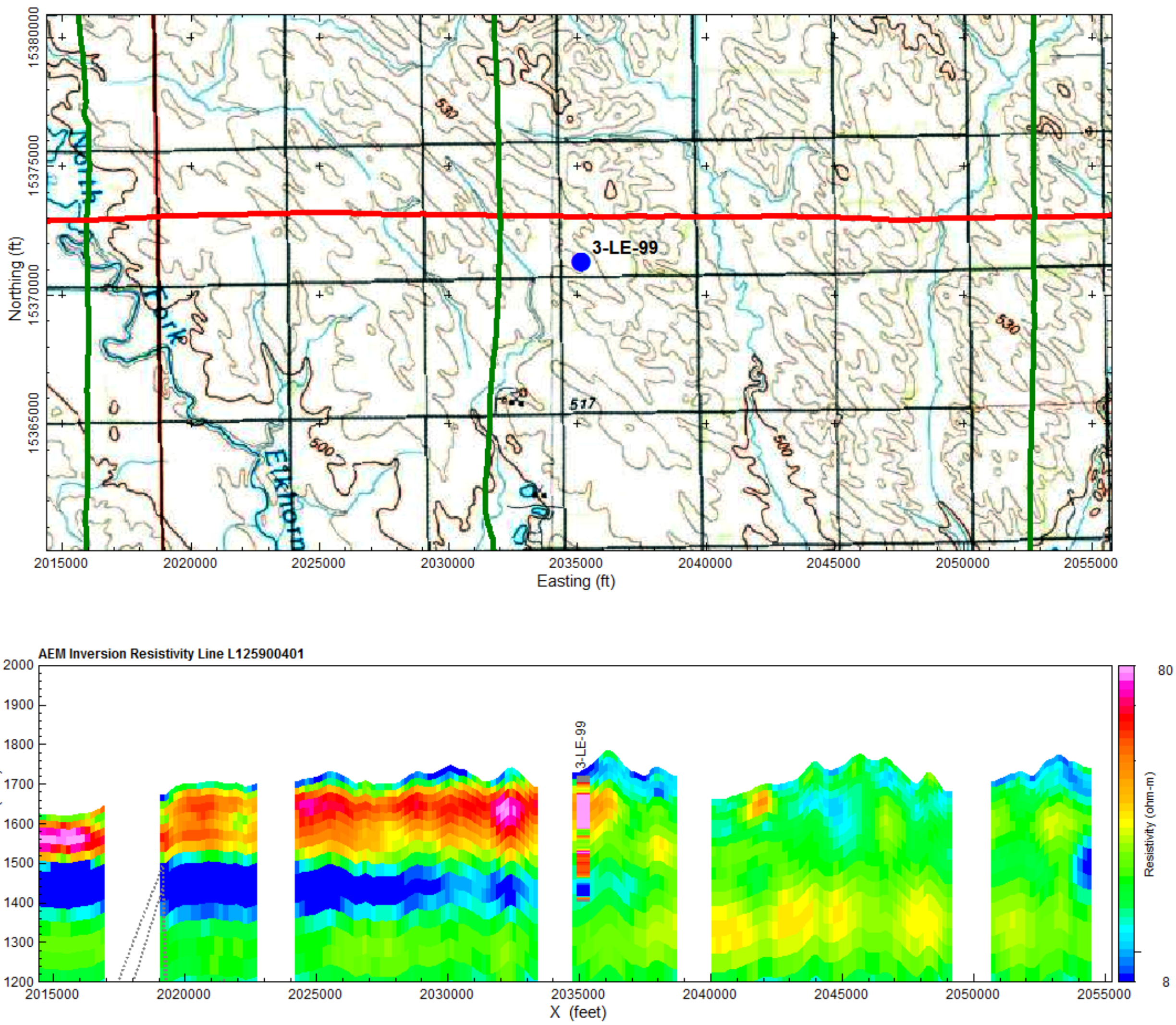


Figure 5-17. Upper map - plot of the location of *3-LE-99* (blue dot) relative to Line L125900401 (red line) plotted on a U.S Geological Survey 100K topo map. Green lines indicate other flight lines within the Bazile Groundwater Management Area. The lower profile shows the *3-LE-99* resistivity log values projected on the inverted airborne electromagnetic resistivity values using the same color scale.

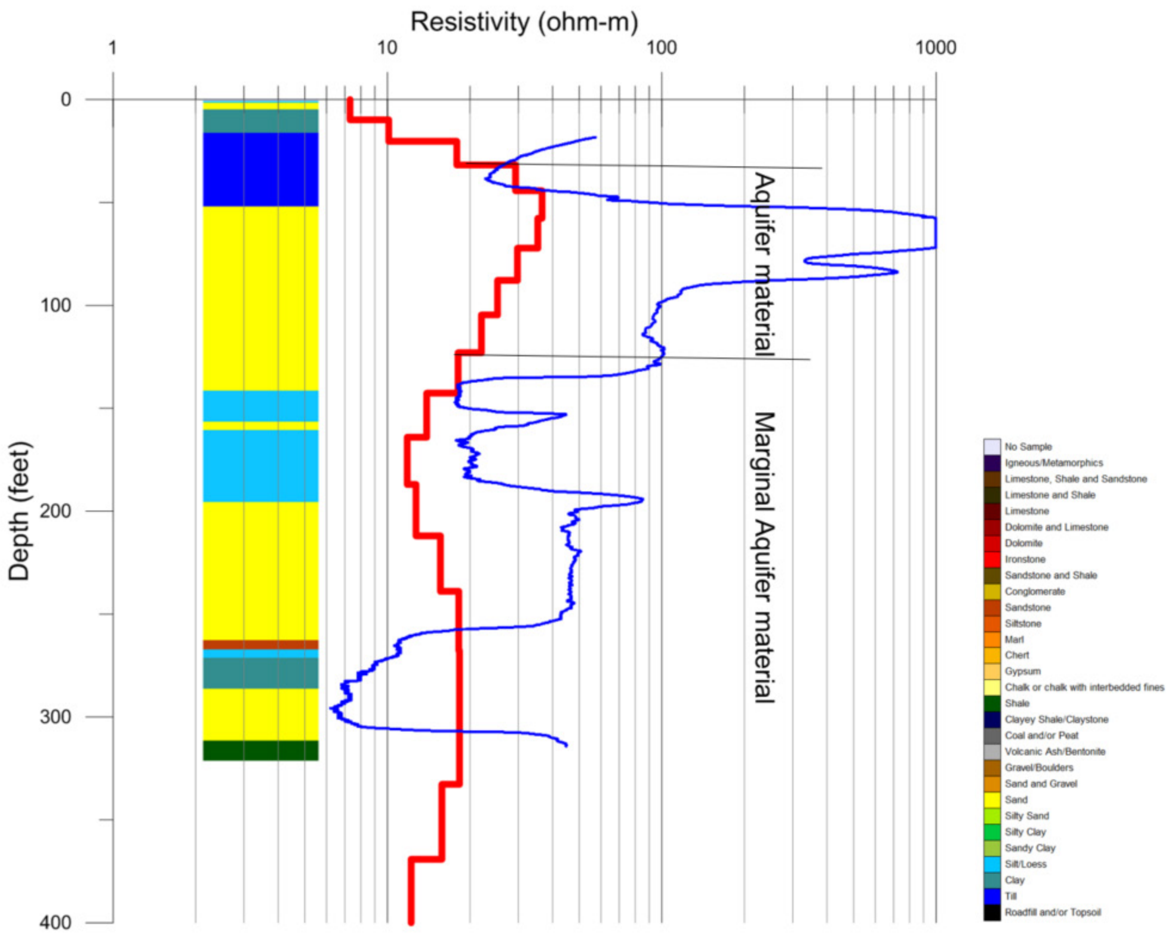


Figure 5-18. Graph of the *3-LE-99* resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *3-LE-99* as well as the aquifer material categories for the major sand zone within the test hole.

Figure 5-19 is a plot of *1-LE-03* 16-inch normal resistivity log plotted on the inverted AEM resistivity for line L124900. The AEM and the geophysical log are plotted on the same resistivity color scale as indicated on Figure 5-19 of 8 to 80 ohm-m log scale. *1-LE-03* is located 1,200 ft from line L124900 and the borehole geophysical log is projected to the closest point of the AEM resistivity profile. Figure 5-20 is a graph of the *1-LE-03* resistivity log and lithology plotted with the AEM sounding closest to the test hole. The agreement in the resistivity is marginal in the area with the geophysical log containing more detail as would be expected. The AEM is illuminating the sand zone from approximately 70 ft to 195 ft with a marginal aquifer zone above and below. The geophysical log is picking up the sand zone in a narrower zone from 125 ft to 180 ft. The geophysical log is also indicating high resistivity values for the area showing a zone that is in excess of 400 ohm-m. These values are much higher than other logs and AEM data collected in the same area (Carney et al., 2015a). The aquifer material mapping indicates that the material from approximately 70 ft to 195 ft is categorized as aquifer material. This is overall a marginal comparison. This may be due to the distance between the test hole and the AEM and the sand zone thins toward the south, but also there are some issues with the geophysical log indicated by the high resistivity values. Both the AEM and the test hole indicate there is a sand zone in the area, but they show a different thickness.

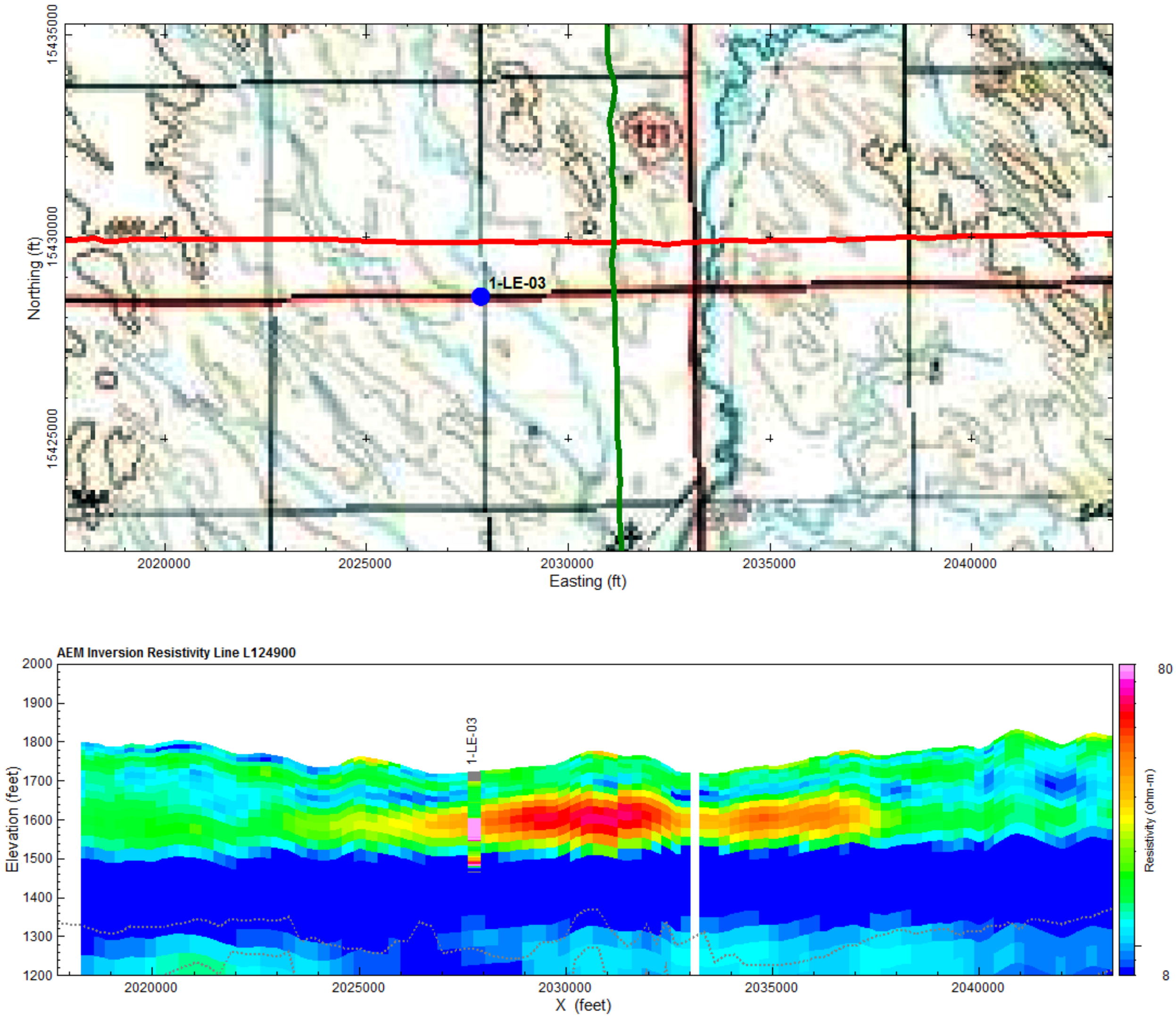


Figure 5-19. Upper map - plot of the location of *1-LE-03* (blue dot) relative to Line L124900 (red line) plotted on a U.S Geological Survey 100K topo map. Green lines indicate other flight lines within the Bazile Groundwater Management Area. The lower profile shows the *1-LE-03* resistivity log values projected on the inverted airborne electromagnetic resistivity values using the same color scale.

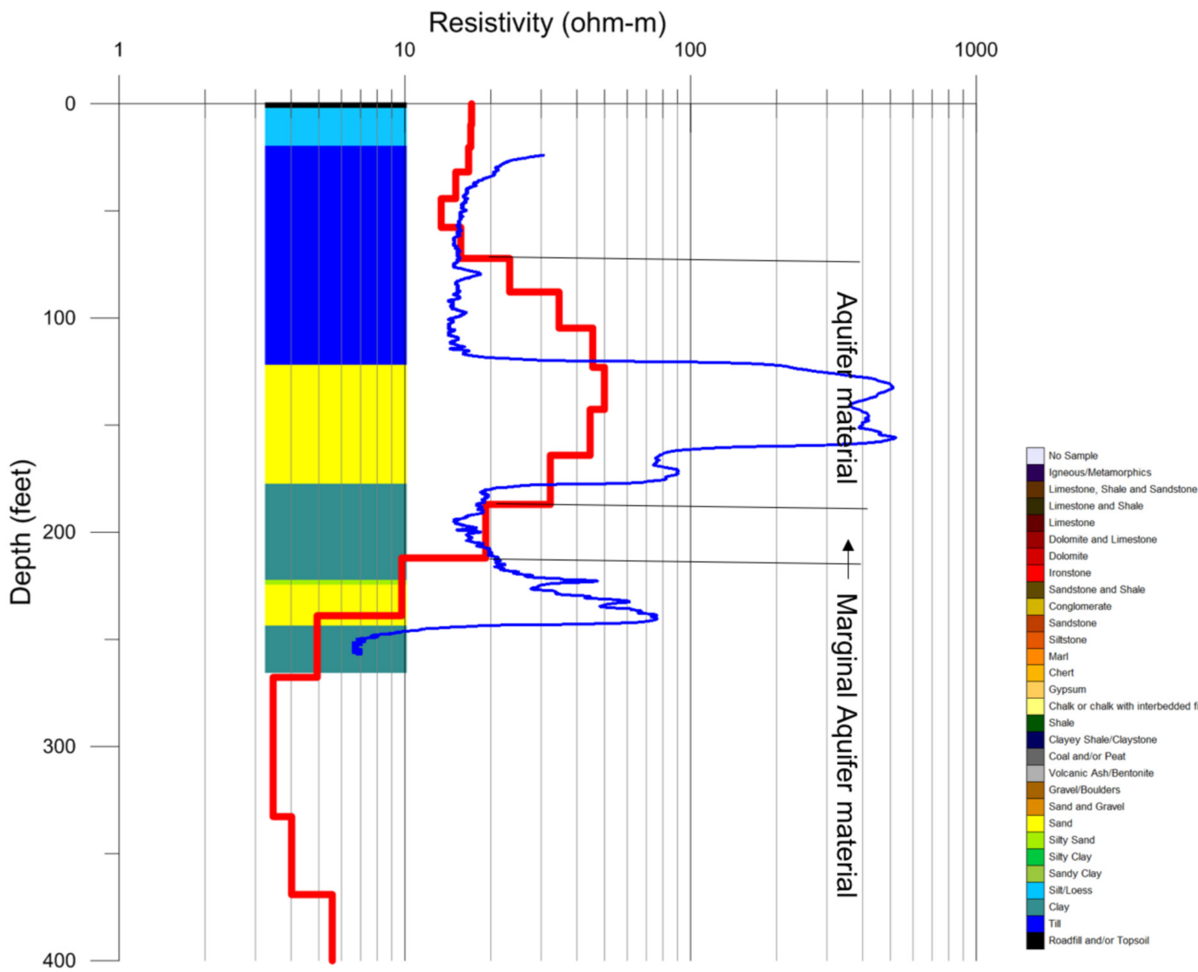
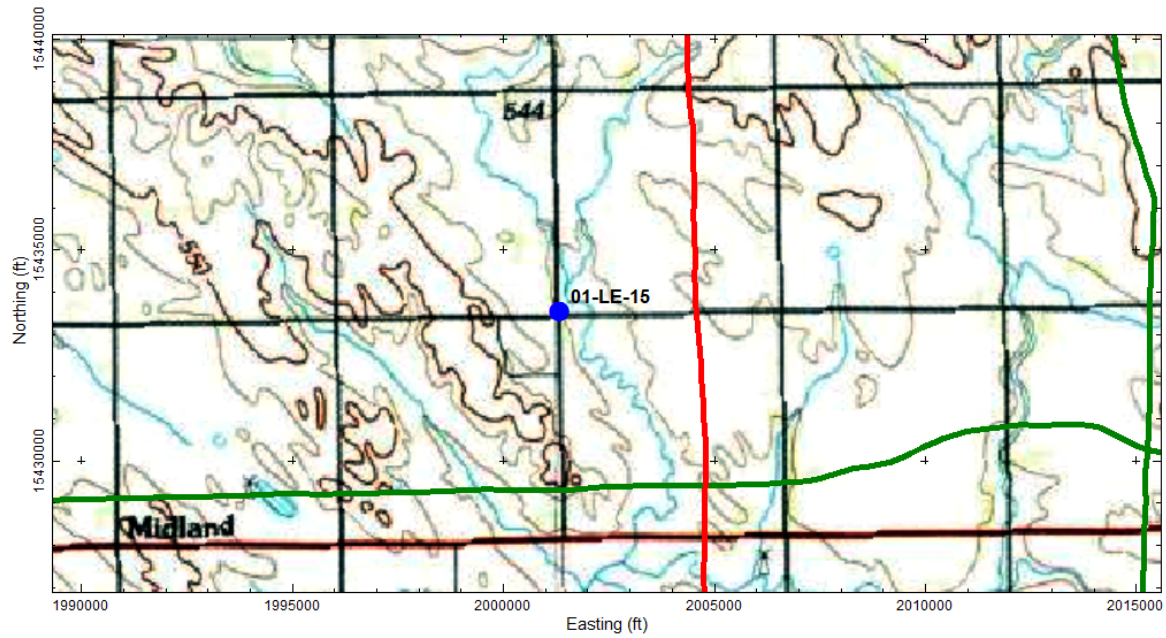


Figure 5-20. Graph of the *1-LE-03* resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *1-LE-03* as well as the aquifer material categories for the major sand zone within the test hole.

Figure 5-21 is a plot of *01-LE-15* 16-inch normal resistivity log plotted on the inverted AEM resistivity for line L149001301. The AEM and the geophysical log are plotted on the same resistivity color scale as indicated on Figure 5-21 of 8 to 80 ohm-m log scale. *01-LE-15* is located 3,229 ft from line L149001301 and the borehole geophysical log is projected to the closest point of the AEM resistivity. Figure 5-22 is a graph of the *01-LE-15* resistivity log and lithology plotted with the AEM sounding closest to the test hole. The agreement in the resistivity is good in the area with the geophysical log containing more detail as would be expected. The AEM is illuminating the sand zone from approximately 85 ft to 235 ft with a marginal aquifer zone above and below. The geophysical log is picking up the sand zone in a slightly narrower zone from approximately 85 ft to 212 ft. The geophysical log is also indicating resistivity values for the zone on the order of 100 ohm-m. These values are higher than many other logs and AEM data collected in the same area (Carney et al., 2015a). The aquifer material mapping indicates that the material from approximately 85 ft to 235 ft is categorized as aquifer material. This is an overall good comparison. The top of the sand unit matches well and the slight difference at the bottom is most probably due to the distance between the test hole and the AEM survey line.



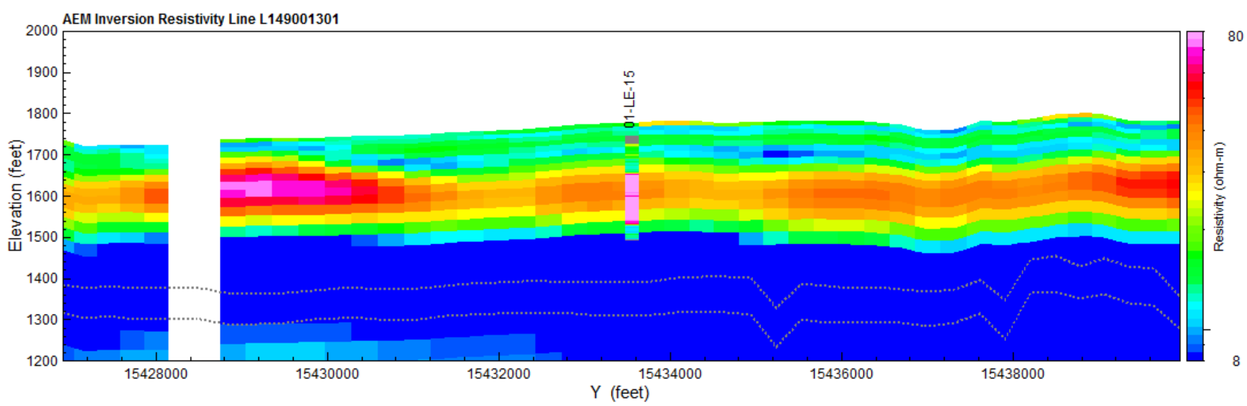


Figure 5-21. Upper map - plot of the location of *01-LE-15* (blue dot) relative to Line L149001301 (red line) plotted on a U.S Geological Survey 100K topo map. Green lines indicate other flight lines within the Bazile Groundwater Management Area. Lower Profile shows the 01-LE-15 resistivity log values projected on the inverted airborne electromagnetic resistivity values using the same color scale.

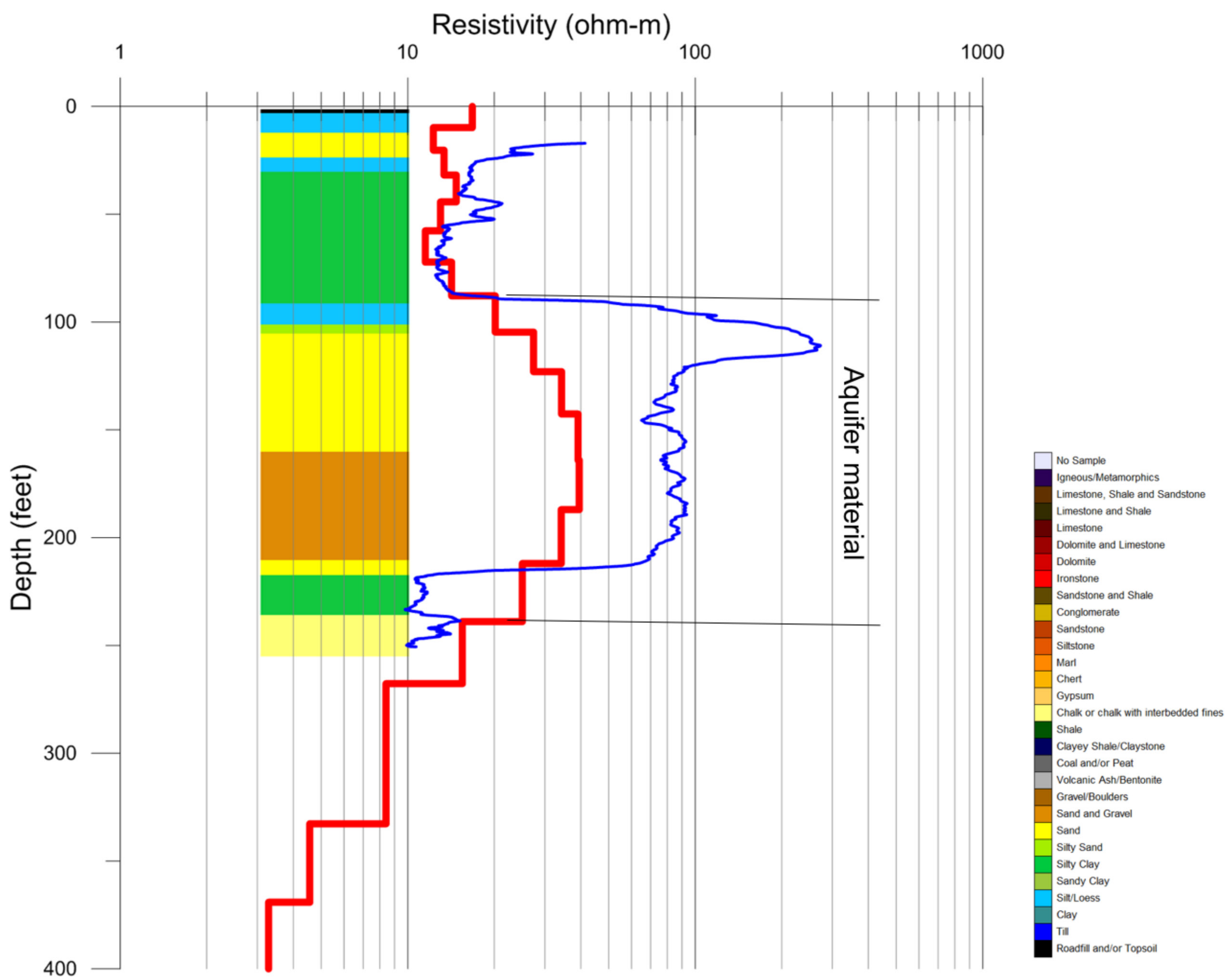


Figure 5-22. Graph of the *01-LE-15* resistivity log values (blue line) and the inverted airborne electromagnetic resistivity values (red line). Also indicated is the lithology log from *01-LE-15* as well as the aquifer material categories for the major sand zone within the test hole.

5.3 Hydrogeological Framework of the Bazile Groundwater Management Area

The AEM reveals considerable variability in the Quaternary and Tertiary deposits across the northern BGMA. "Quaternary and Tertiary Ogallala Aquifer system" is a term used in the interpretative section of this report to describe all unconsolidated and semi-consolidated materials overlying the Cretaceous bedrock, thus including aquifer and non-aquifer material alike. Figure 5-23 displays in 3D the overall distribution of materials (as described in the previous section) across the BGMA. The subsurface distribution of materials can be generally characterized into four somewhat overlapping, but distinct, areas with smaller localized depositional features distributed at various locations within the survey area. These areas include the Quaternary and Ogallala Aquifer Area, the shallow ***Kp*** area, the glacial area, and the ***Kn*** bedrock area. The approximate location is given in Figure 5-24.

5.3.1 The Quaternary and Ogallala Aquifer Area

The Quaternary and Ogallala Aquifer Area of the BGMA 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 varying thickness of ***To*** which is also dominated by aquifer materials. The combined aquifer system overlies the ***Kp***. The surface of the ***Kp*** has been eroded prior to and after the deposition of the ***To*** in the area and acts like an aquiclude for the above aquifer system. The map of the elevation of the top of the ***Kp*** can be found in Figure 5-8 in Section 5.1.4. Within the aquifer system there are areas of non-aquifer and marginal aquifer materials. These areas are typically confined to near surface loess deposits, basal silts and clays, and some continuous layers of fine grained material. These layers can locally act as aquiclude and prevent recharge or serve as locally confining units Figure 5-25 is a 3D image of several of these layers of marginal and non-aquifer materials found in the southern area of the BGMA. Figure 5-26 is a profile view of line L125900501 showing the southernmost line of the BGMA survey. Within the aquifer system there is an area that shows coarse aquifer material that is deposited above the ***To*** contact that has a trend from the west to the south east. This trend is interpreted as deposits from paleochannel systems (Figure 5-27). In profile view (Figure 5-28) line L125900401 illustrates the coarse aquifer material within this region of the western portion of the BGMA. A disadvantage of the reconnaissance lines is that they have only identified these deposits in the area of the AEM acquisition the complete extent of these deposits cannot be determining expediently without further AEM acquisition or exhaustive interpretation from added boreholes. Appendices 1 and 2 contain interpreted profiles that illustrate the details of the Quaternary and Ogallala Aquifer Area of the BGMA. Appendices 3 and 4 contain 3D images of the BGMA area that have been rotated and various angles to allow viewing of the overall distribution of materials. The Quaternary and Ogallala Aquifer Area of the BGMA contains areas of saturated thickness up to 300 ft.

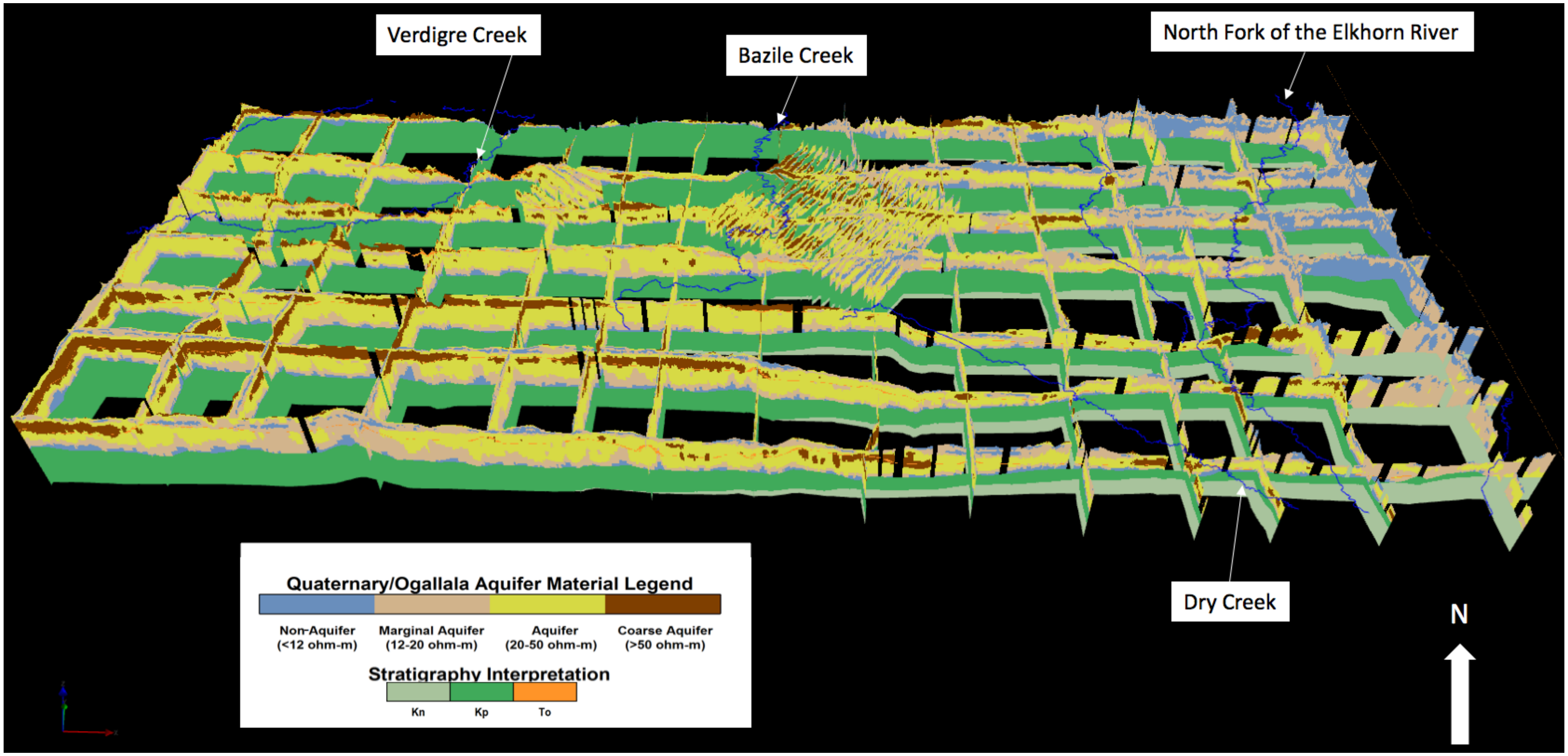


Figure 5-23. 3D map looking to the north of the interpreted distributions of material within the Bazile Groundwater Management Area. Major steams are labeled. Vertical exaggeration is 20x. Geological units include Ogallala (*To*), Cretaceous Pierre (*Kp*), and Cretaceous Niobrara (*Kn*).

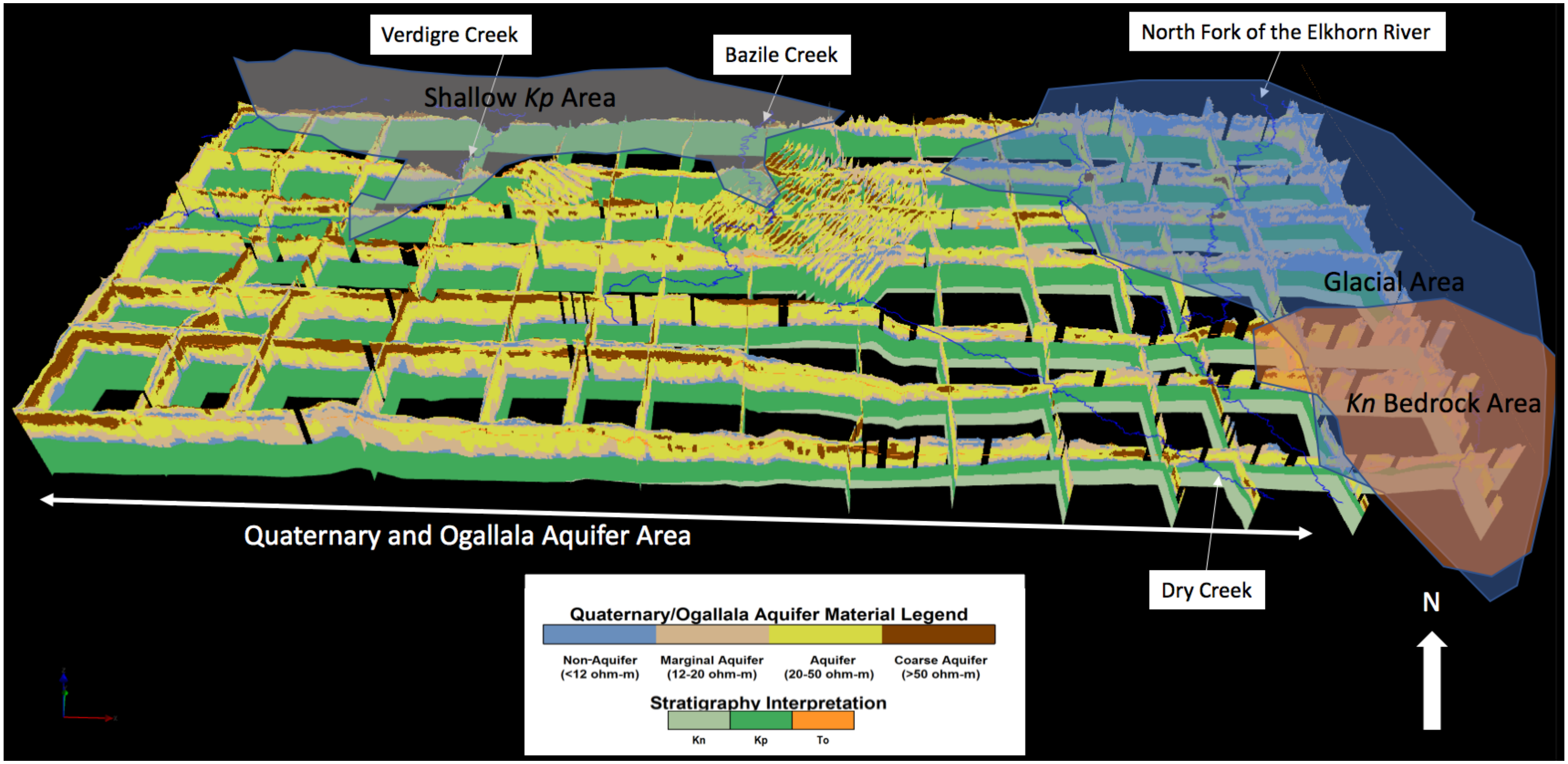


Figure 5-24. 3D map looking to the north of the interpreted distributions of material within the Bazile Groundwater Management Area with the four distinct areas indicated. Major steams are labeled. Vertical exaggeration is 20x. Geological units include Ogallala (*To*), Cretaceous Pierre (*Kp*), and Cretaceous Niobrara (*Kn*).

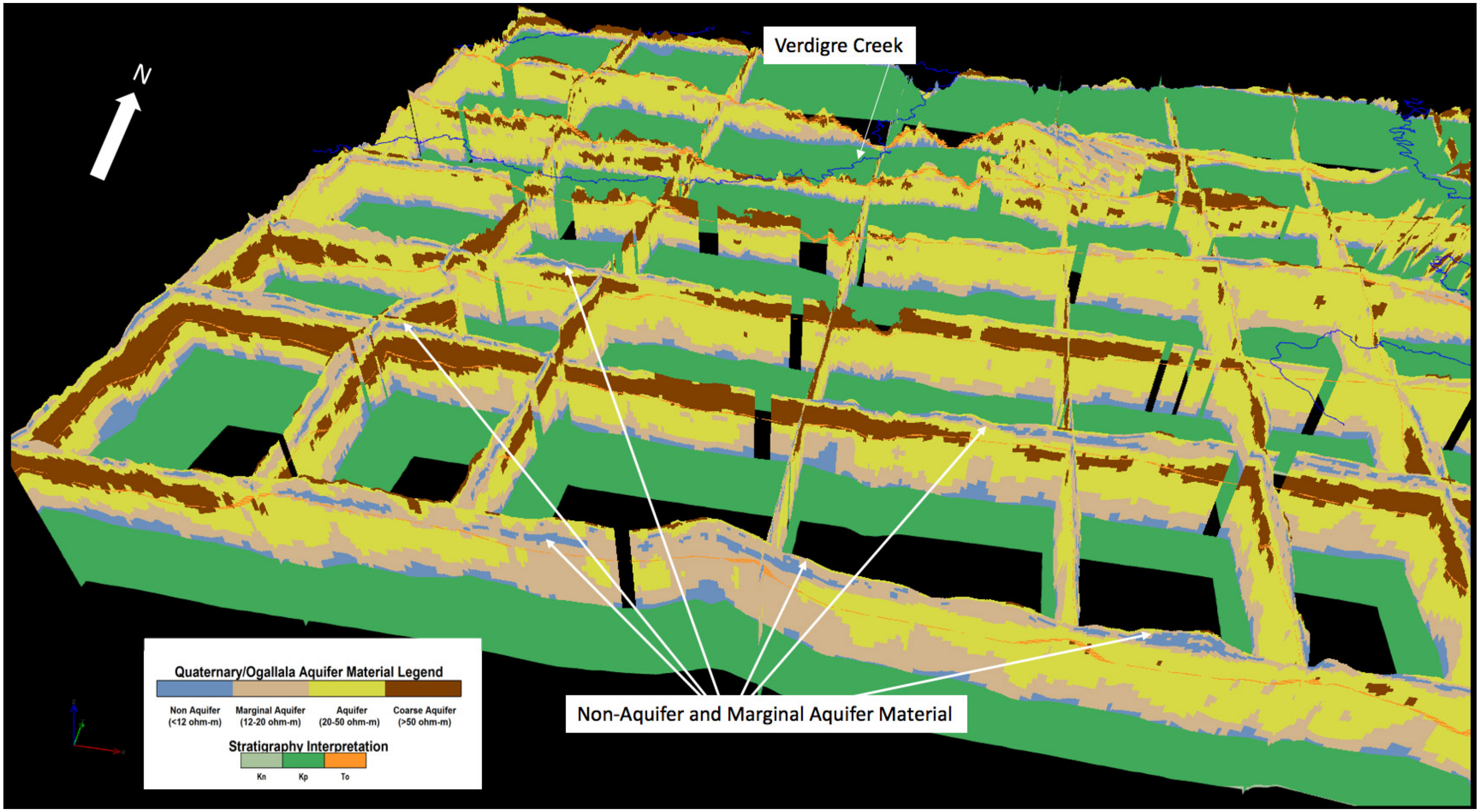


Figure 5-25. 3D map zoom looking to the northwest of the southwestern portion of the Bazile Groundwater Management Area illustrating the presence of non-aquifer and marginal aquifer materials with the majority of aquifer and coarse aquifer material. Vertical exaggeration is 20x. Geological units include Ogallala (*To*), Cretaceous Pierre (*Kp*), and Cretaceous Niobrara (*Kn*).

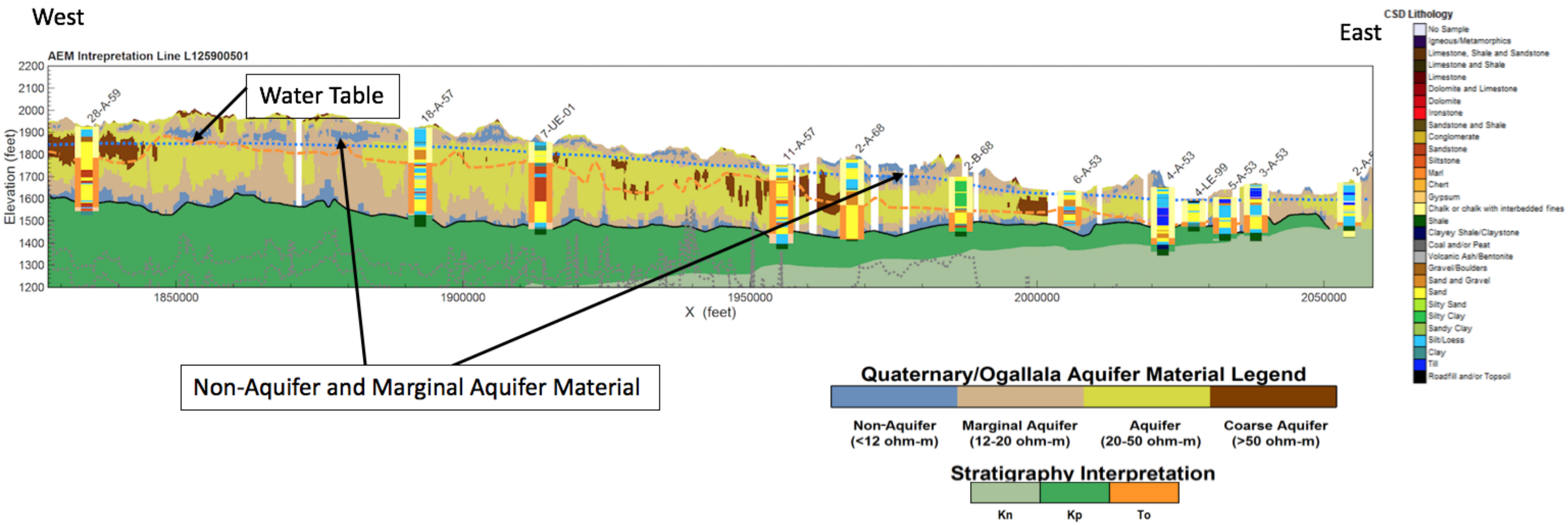


Figure 5-26. Profile view of line L125900501 with the non-aquifer and marginal aquifer materials indicated sitting on top of aquifer and coarse materials. Conservation and Survey Divisions wells are projected on the profile. The profile indicates the water table as a dashed blue line; the top of the Tertiary Ogallala (*To*) is indicated by a dashed orange line; the top of the Cretaceous Pierre (*Kp*) is indicated with a black line; the Cretaceous Niobrara (*Kn*) is indicated by the light green; and the inversion depth of investigations are indicated by dashed gray lines. Gaps in the profile indicate areas of no airborne electromagnetic data coverage.

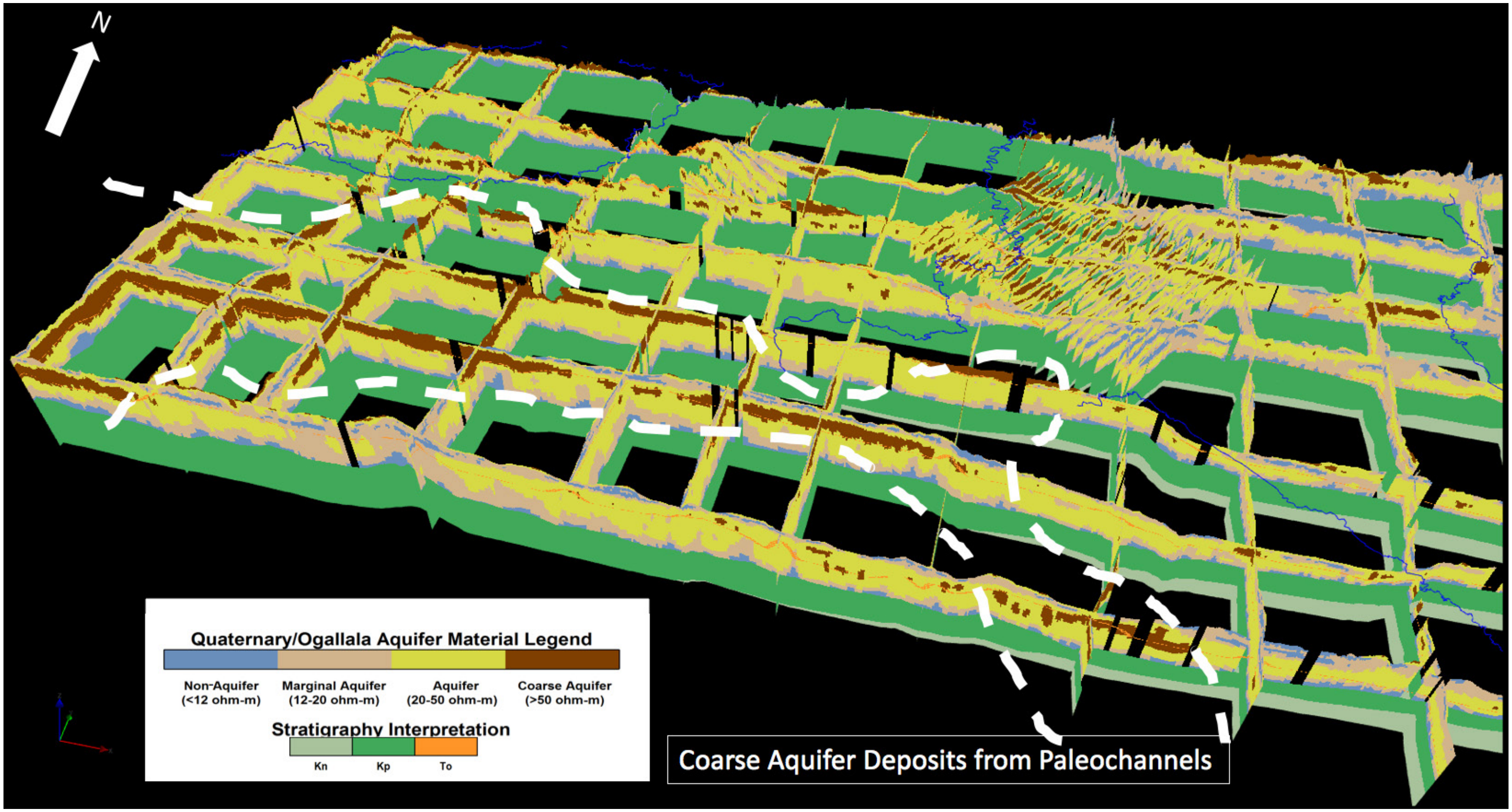


Figure 5-27. 3D map zoom looking to the northwest of the southwestern portion of the Bazile Groundwater Management Area illustrating the presence of coarse aquifer materials indicate deposits from paleochannels (white dashed line). Vertical exaggeration is 20x. Geological units include Ogallala (*To*), Cretaceous Pierre (*Kp*), and Cretaceous Niobrara (*Kn*).

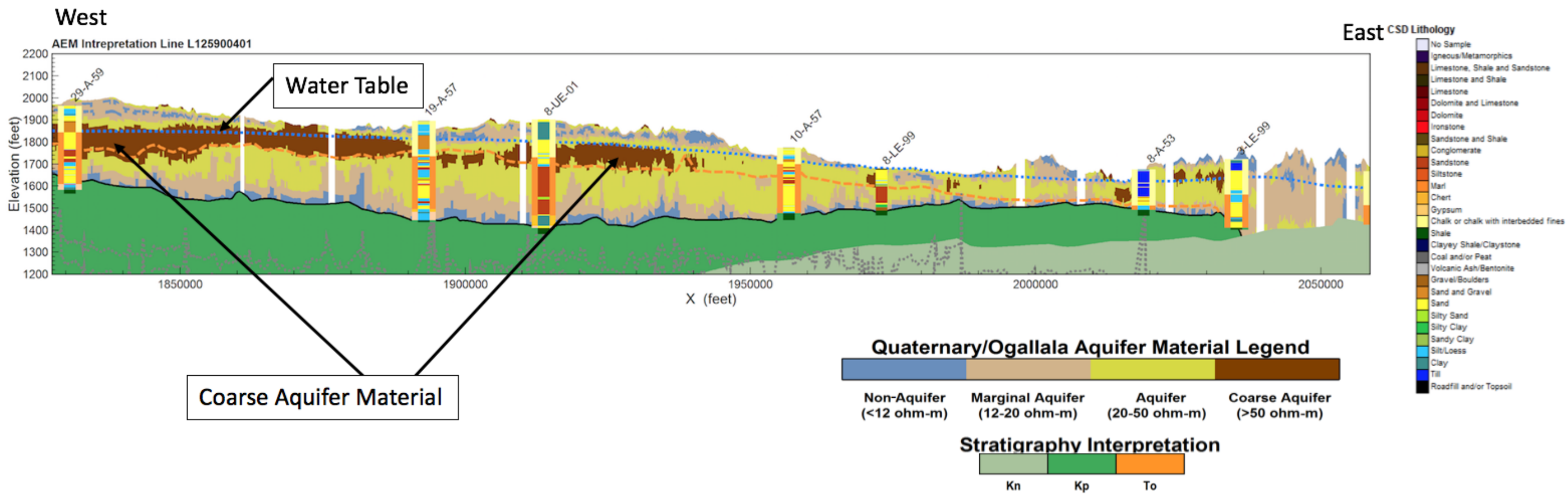


Figure 5-28. Profile view of line L125900401 showing the coarse aquifer material associated with the paleochannel deposits. CSD wells are projected on the profile. The profile indicates the water table as a dashed blue line; the top of the Tertiary Ogallala (*To*) is indicated by a dashed orange line; the top of the Cretaceous Pierre (*Kp*) is indicated with a black line; the Cretaceous Niobrara (*Kn*) is indicated by the light green; and the inversion depth of investigations are indicated by dashed gray lines. Gaps in the profile indicate areas of no airborne electromagnetic data coverage.

5.3.2 The "Shallow Kp" Area

The shallow ***Kp*** area is located in northwestern extent of the BGMA and is characterized by the bedrock/base of aquifer unit ***Kp*** being close to the surface. These areas can have both ***To*** and ***Q*** deposits but typically only have ***Q*** deposits siting on the ***Kp***. Figure 5-29 is a map of the location of the ***Kp*** that is within 50 ft of the surface. The patterns are obviously related to the erosion of the drainages to the north, including Bazile and Verdigre Creeks, as well as an area of shallow ***Kp*** that exists between the two major drainages. The areas of shallow ***Kp*** limit the saturated thickness. Figure 5-30 is a profile of line L124700 on the northern extend of the BGMA. The western end of the profile indicates the shallow ***Kp*** and the limited saturated thickness. The streams in Figure 5-30 show incision into the ***Kp***. This is also illustrated by overlaying the NE-DNR registered well locations (Figure 5-31) showing limited wells in the shallow ***Kp*** area.

5.3.3 The "Glacial" Area

The glacial area is located in the northeastern and eastern areas of the BGMA. This area is characterized by Quaternary glacial deposits overlaying pre-Pleistocene Quaternary alluvial deposits or thin ***To*** deposits overlying bedrock of ***Kp*** or ***Kn***. The glacial deposits of the area may be overlain by loess deposits or recent alluvial deposits. Within the glacial sequence there are potentials for multiple advances and moraines as well as multiple occurrences of tunnel valleys or outwash deposits (Carney et al., 2015a; Carney et al., 2015b; Korus et al., 2016). Hydrogeologically, the key to the area is the presences of separated zones of aquifer materials and how those zones are connected to surface water and subsequently compartmentalized by zones of marginal or non-aquifer materials. These zones of marginal aquifer material still can yield water to a well but are typically composed of interlayered fine sands or thin sand layers and have abundant fine grained material composed of silt, clay, and till. The reconnaissance lines that were collected in 2014 and in 2016 shed light on the arrangement of these complicated deposits in the BGMA. Figure 5-32 is a 3D map view looking to the west, of the eastern end of the BGMA, displaying the distribution of materials. Within Figure 5-32 there are several zones that indicate that the aquifer material contains coarse aquifer material zones. These areas can be seen to extend into several of the reconnaissance lines. These deposits of aquifer material are finite zones that are separated by extensive zones of marginal and non-aquifer materials. Figure 5-33 provides another view of the eastern end of the BGMA's distribution of all aquifer materials. The finite nature of the aquifer material zones can be seen at the points the reconnaissance lines cross each other. The one disadvantage of the reconnaissance lines is that they have only identified these deposits in the area of the AEM acquisition. The complete extent of these deposits cannot be determined expediently without additional data such as further AEM acquisition or exhaustive interpretation with added boreholes. Figure 5-34 is a profile of the east-west line L125100 showing on the eastern end the presence of the glacial deposits. The CSD boreholes *3-A-68*, *3-B-68*, *2-B-53*, *10-A-53*, and *3-B-53* all indicate till in the ***Q*** section of the stratigraphy. What is interesting to note is that the zone of aquifer materials and coarse aquifer materials between *3-A-68* and *3-B-68* as well as the zone of aquifer materials and coarse aquifer materials between *2-B-53* and *10-A-53* would not have been detected by the CSD drilling alone.

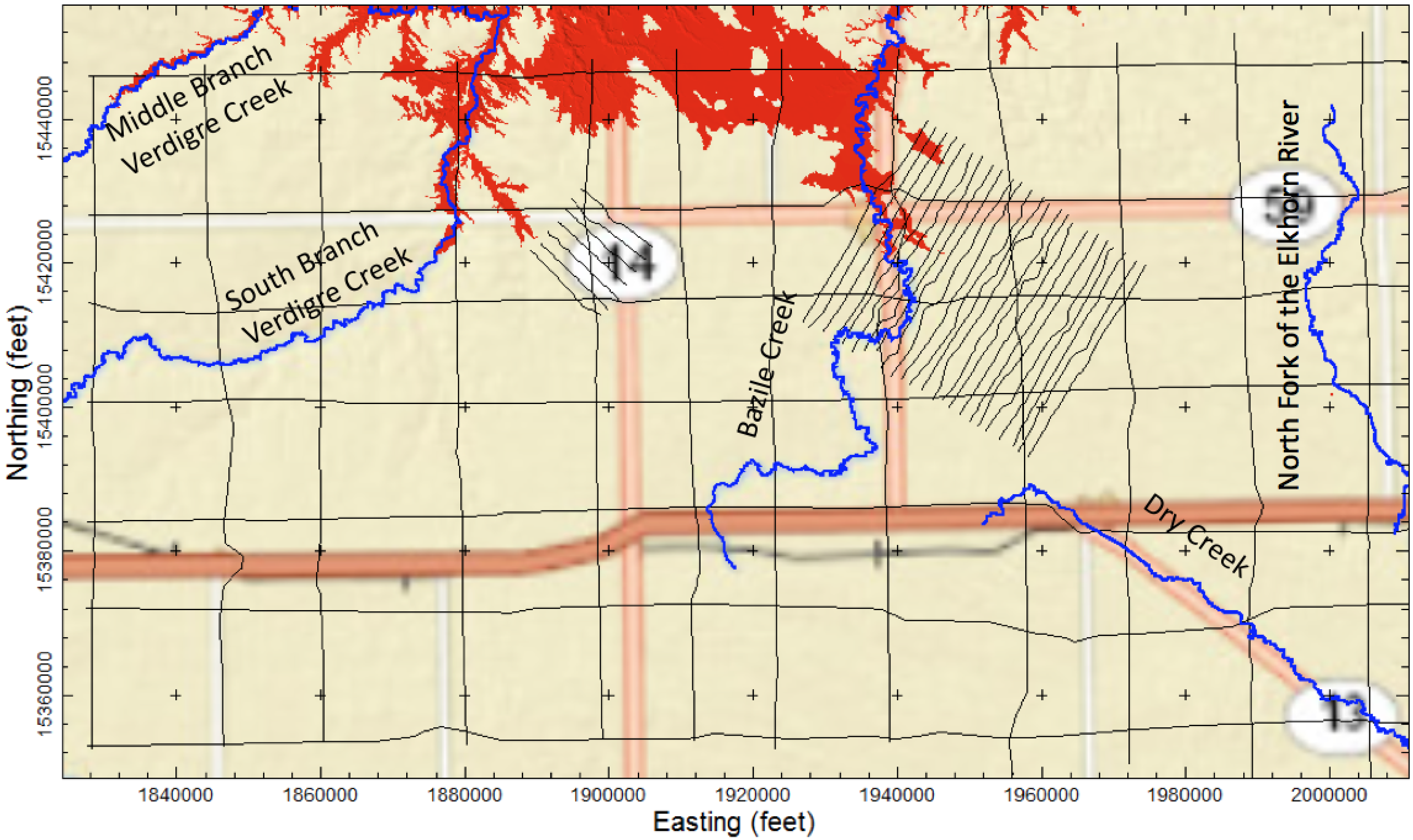


Figure 5-29. Map of the shallow, less than 50 ft depth, Cretaceous Pierre (*Kp*) (red) in the area of the northwestern extent of the Bazile Groundwater Management Area. Major drainages are labeled and indicated by a blue line. The airborne electromagnetic flight lines are indicated by thin black lines. North American Datum of 1983 (NAD 83) UTM Zone 14 North.

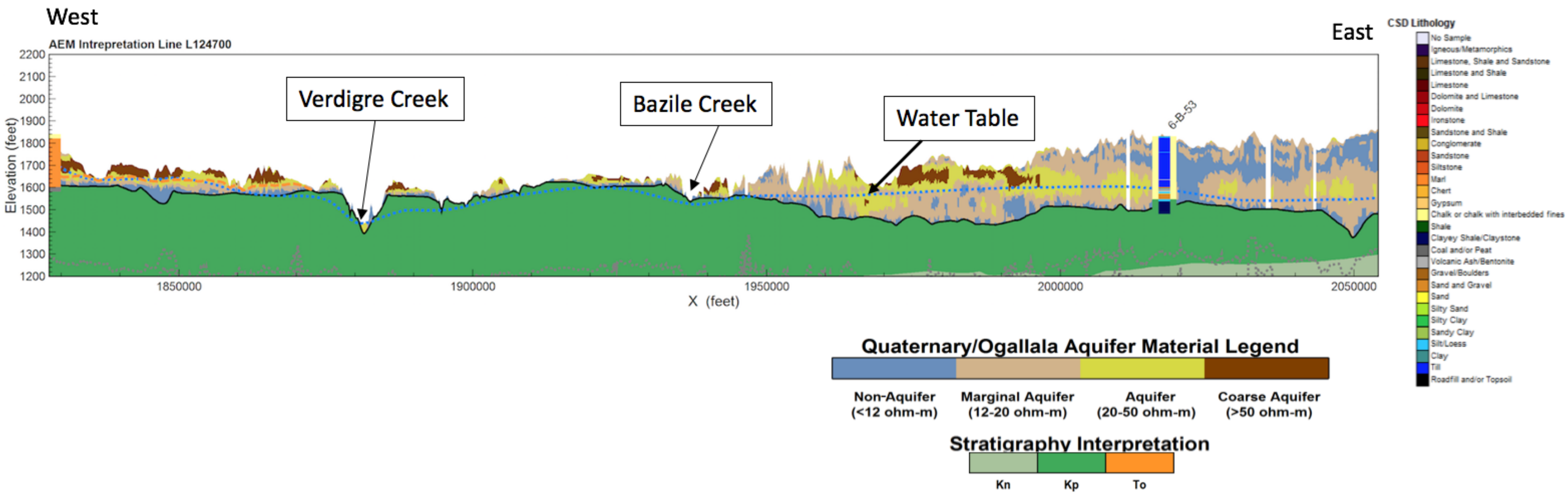


Figure 5-30. Profile view of line L124700 on the northern extent of the Bazile Groundwater Management Area showing the shallow Cretaceous Pierre (*Kp*). Verdigre and Bazile Creek are located and illustrate the erosion of the drainages into the bedrock. Conservation and Survey Divisions wells are projected on the profile. The profile indicates the water table as a dashed blue line; the top of the Tertiary Ogallala (*To*) is indicated by a dashed orange line; the top of the Cretaceous Pierre (*Kp*) is indicated with a black line; the Cretaceous Niobrara (*Kn*) is indicated by the light green; and the inversion depth of investigations are indicated by dashed gray lines. Gaps in the profile indicate areas of no airborne electromagnetic data coverage.

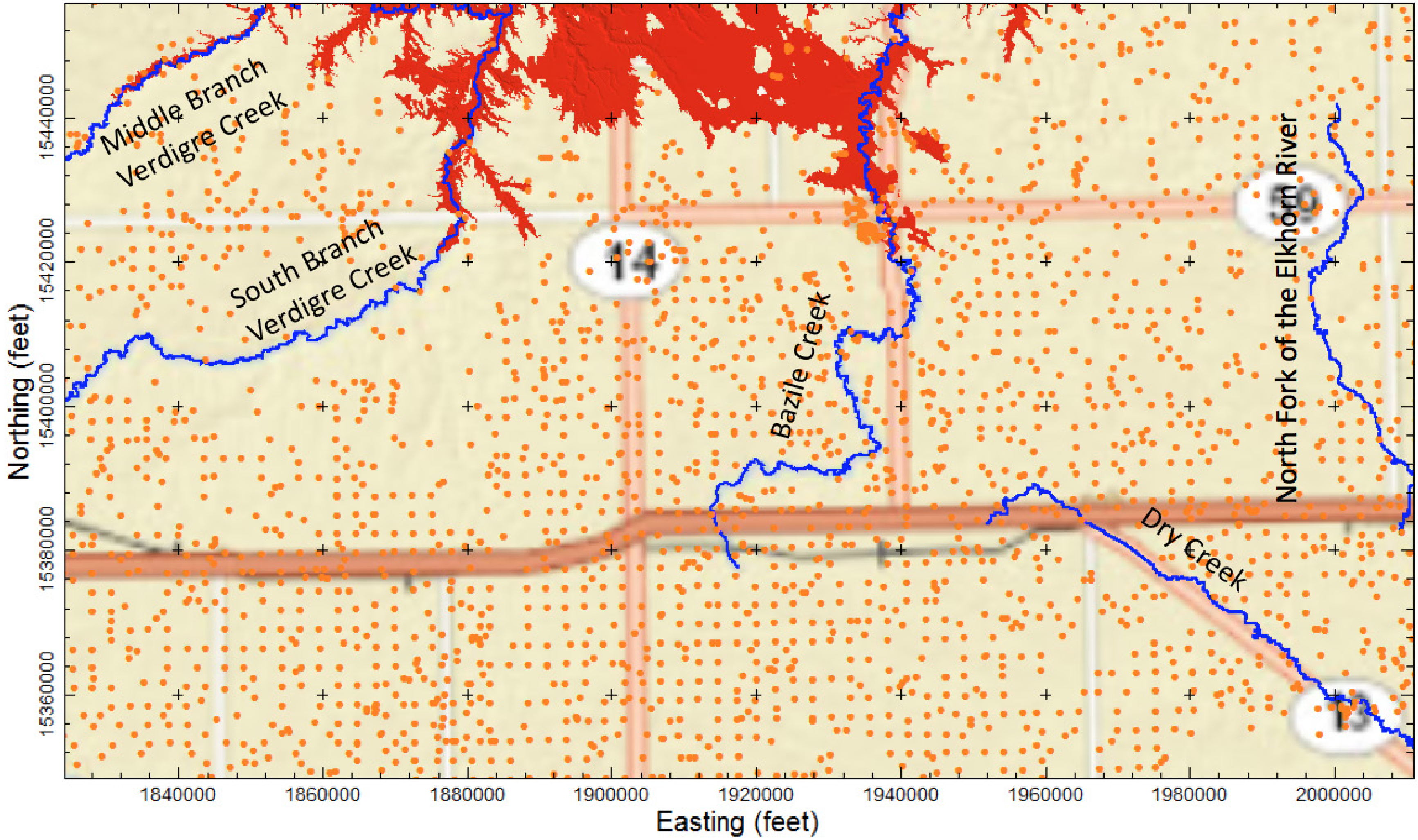


Figure 5-31. Map of the shallow, less than 50 ft depth, Cretaceous Pierre (*Kp*) (red) in the area of the northwestern extent of the Bazile Groundwater Management Area. Major drainages are labeled and indicated by a blue line. Locations of Nebraska Department of natural Resources registered wells are indicated by orange dots. Map projection is NAD83, UTM Zone 14 North.

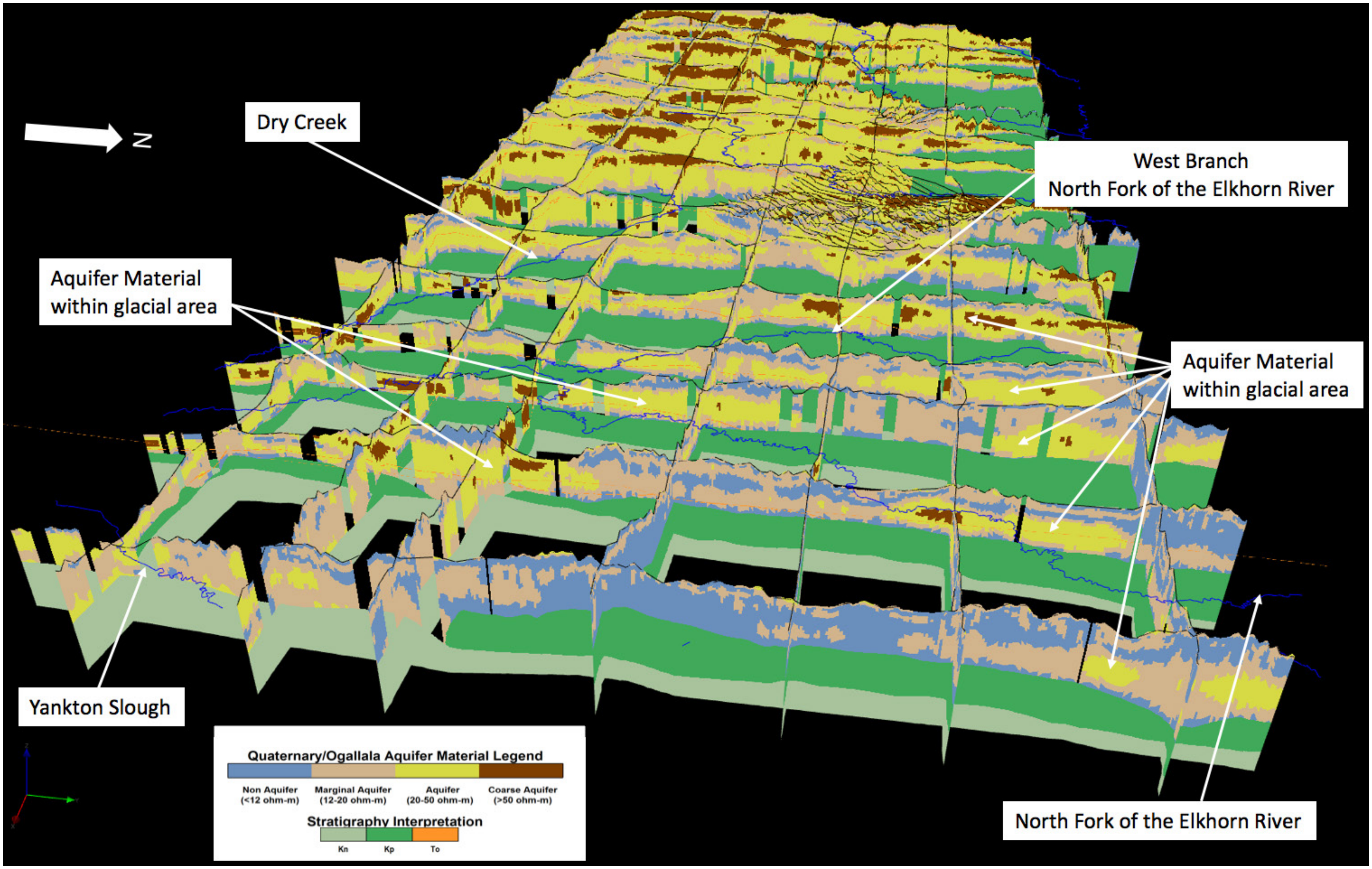


Figure 5-32. 3D map view looking to the west, of the eastern end of the Bazile Groundwater Management Area, displaying the distribution of materials within the glacial area. The vertical exaggeration is 20x. Geological units include Ogallala (*To*), Cretaceous Pierre (*Kp*), and Cretaceous Niobrara (*Kn*).

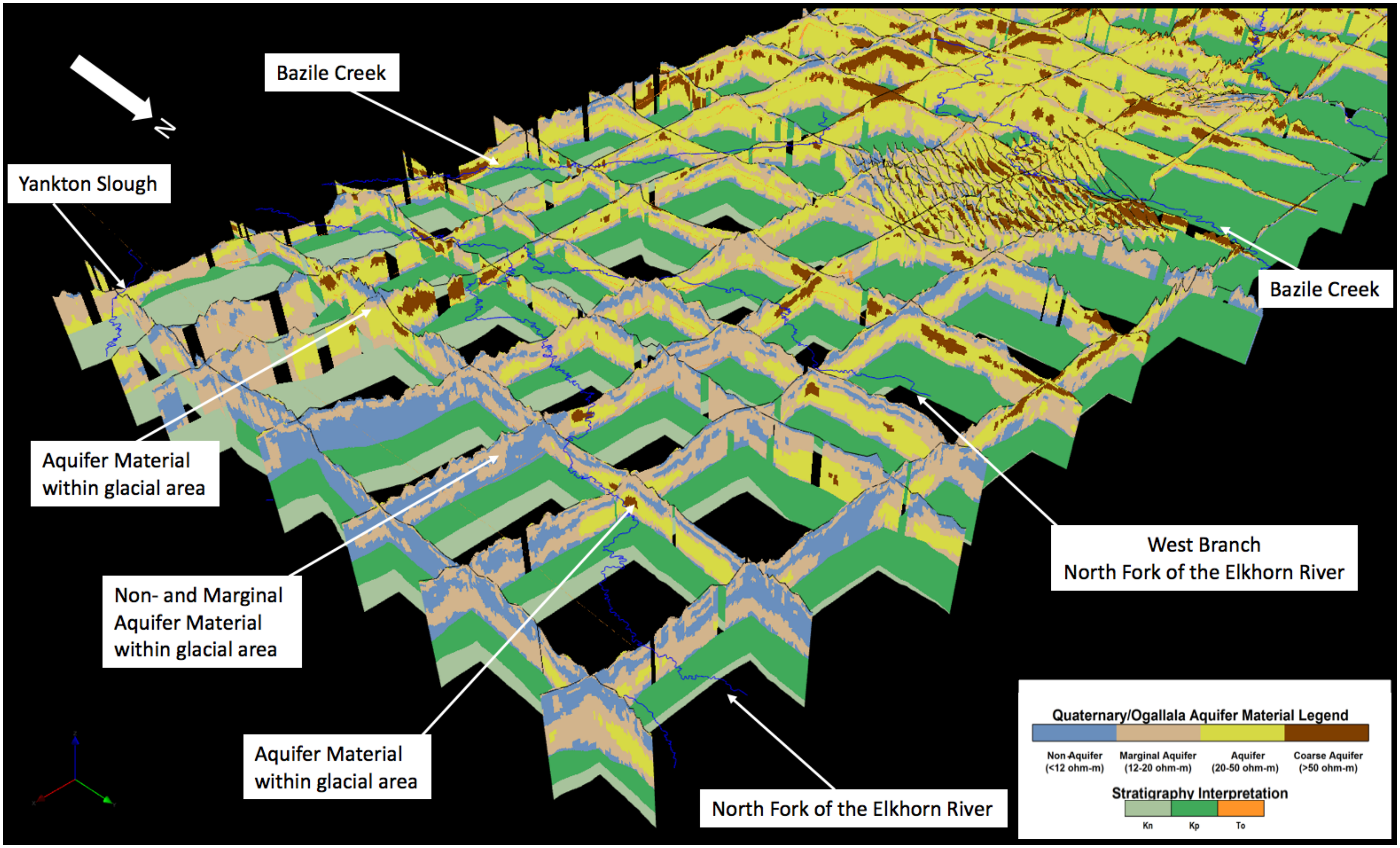


Figure 5-33. 3D map view looking to the southwest from the north east of the eastern end of the Bazile Groundwater Management Area, displaying the distribution of materials within the glacial area. The vertical exaggeration is 20x. Geological units include Ogallala (*To*), Cretaceous Pierre (*Kp*), and Cretaceous Niobrara (*Kn*).

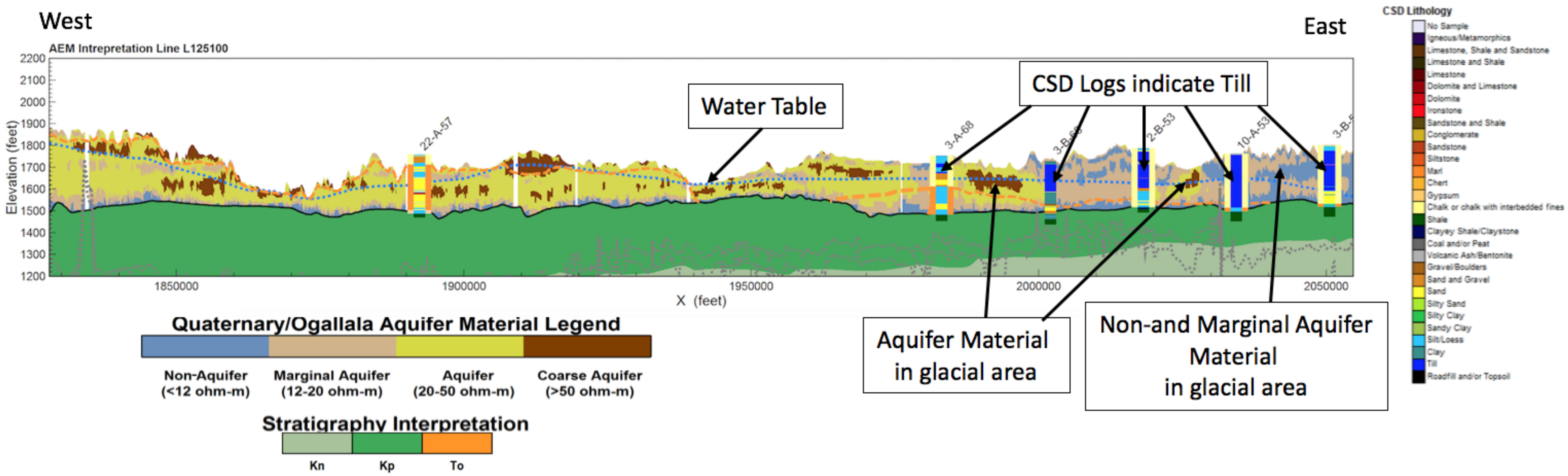


Figure 5-34. Profile view of line L125100 in the BGMA showing the glacial area. CSD wells are projected on the profile. The profile indicates the water table as a dashed blue line; the top of the Tertiary Ogallala (*To*) is indicated by a dashed orange line; the top of the Cretaceous Pierre (*Kp*) is indicated with a black line; the Cretaceous Niobrara (*Kn*) is indicated by the light green; and the inversion depth of investigations are indicated by dashed gray lines. Gaps in the profile indicate areas of no airborne electromagnetic data coverage.

5.3.4 The Kn Bedrock Area

As indicated above the glacial area is located in the northeastern and eastern areas of the BGMA. This area is characterized by Quaternary glacial deposits overlaying pre-Pleistocene Quaternary alluvial deposits or thin ***To*** deposits overlying bedrock of ***Kp*** or ***Kn***. The far southeastern corner of the BGMA is the location that the ***Kp*** has been removed by erosion from the underlying ***Kn***. The edge of this erosional surface was determined from the AEM inversions, CSD boreholes, and NE-DNR boreholes as indicated in Section 5.2.3 on the construction of the ***Kp*** and ***Kn*** surfaces. Figure 5-35 is a 3D view looking to the northwest from the south east of the area of the eroded ***Kp***. The importance of this area is that the character of the ***Kp*** is as an aquiclude and the ***Kn*** may contain fractures that will hold water (see Section 2.1 Geology). Figure 5-36 is another 3D view of the southeastern end of the BGMA looking to the southeast from the east. It is again easy to detect the change in the bedrock in this area of the BGMA. Figure 5-37 is a profile of the north-south line L149400601 composed of 2014 and 2016 AEM inversions. The profile indicates clearly the end of the ***Kp***.

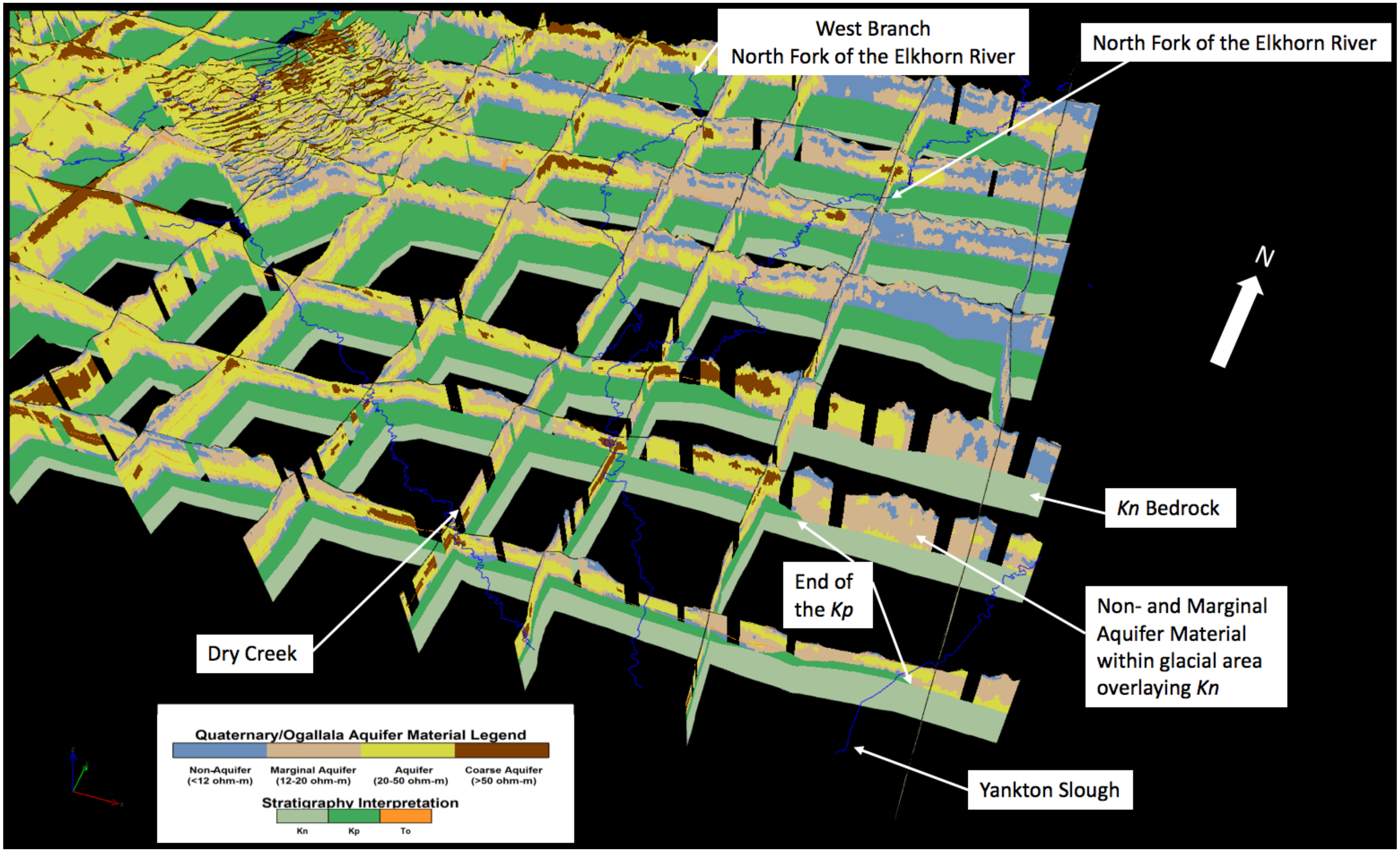


Figure 5-35. 3D map view looking to the northwest from the south of the southeastern corner of the BGMA, displaying the distribution of materials within the glacial area and the change in the bedrock. The vertical exaggeration is 20x. Geological units include Ogallala (*To*), Cretaceous Pierre (*Kp*), and Cretaceous Niobrara (*Kn*).

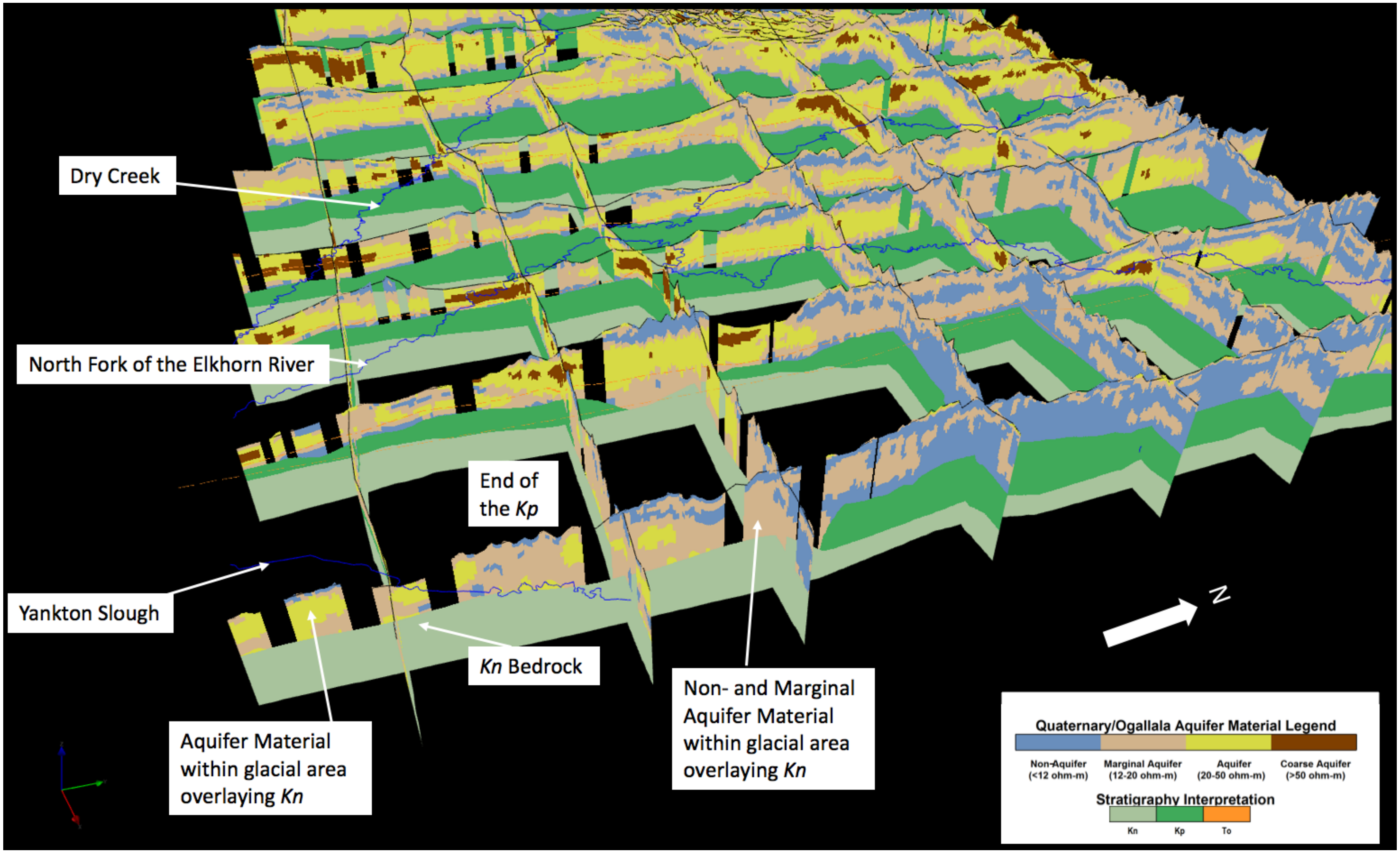


Figure 5-36. 3D map view looking to the southwest from the east of the southeastern corner of the Bazile Groundwater Management Area, displaying the distribution of materials within the glacial area and the change in the bedrock. The vertical exaggeration is 20x. Geological units include Ogallala (*To*), Cretaceous Pierre (*Kp*), and Cretaceous Niobrara (*Kn*).

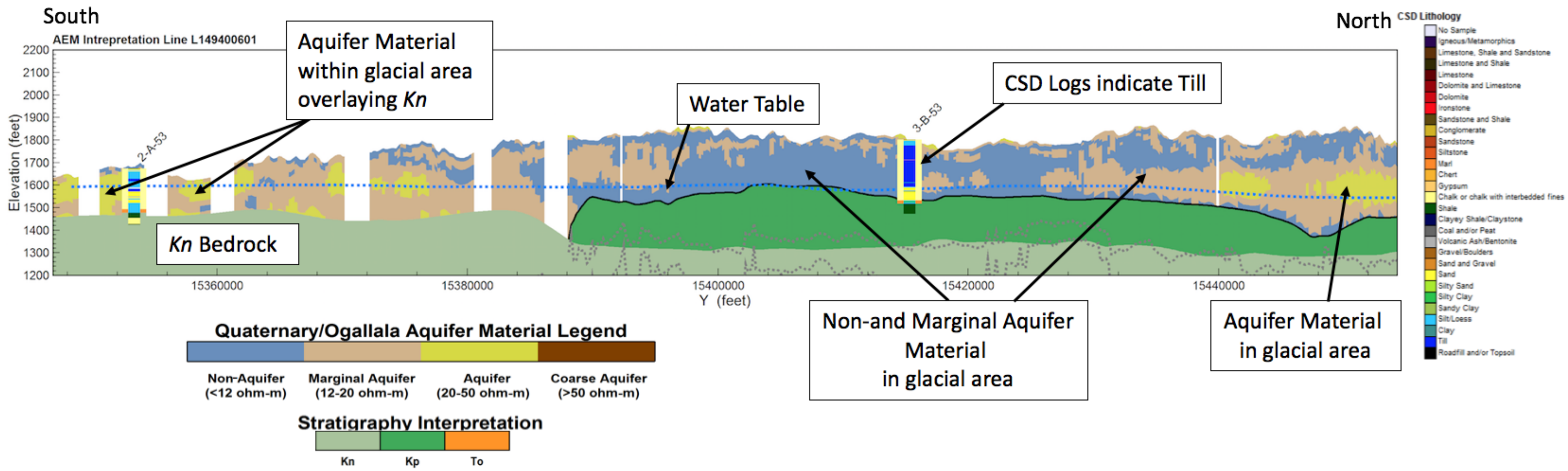


Figure 5-37. Profile view of line L149400601 on the eastern extent of the Bazile Groundwater Management Area showing the glacial area and the changing bedrock. CSD wells are projected on the profile. The profile indicates the water table as a dashed blue line; the top of the Tertiary Ogallala (*To*) is indicated by a dashed orange line; the top of the Cretaceous Pierre (*Kp*) is indicated with a black line; the Cretaceous Niobrara (*Kn*) is indicated by the light green; and the inversion depth of investigations are indicated by dashed gray lines. Gaps in the profile indicate areas of no airborne electromagnetic data coverage.

5.4 Hydrogeological Framework of the Creighton Water System Area

The Creighton Water System Area is within the Quaternary and Tertiary Ogallala Aquifer system region defined above (Section 5.3.1). Figure 5-38 is a map of the AEM survey lines included within the Creighton Water System survey area and also indicates the location of the NE-DNR registered wells and Bazile Creek. The area is composed of mostly aquifer materials. The area on the east side of Bazile Creek shows little to no ***To*** present. The area is dominated by aquifer materials and coarse aquifer materials that thin considerably around Bazile Creek with the ***Kp*** close to the surface. Some of the coarse aquifer materials within the ***To*** may be sandstones, but inspection of the NE-DNR wells indicate it is an aquifer in the area. The area in the northern portion of the Creighton Water System survey has no AEM data collected due to avoidance of the town of Creighton. Figure 5-39 is a 3D view of the Creighton Water System survey area showing the profiles in 3D. Much of the area is aquifer (yellow color in section) and coarse aquifer (brown color in section) material types. There is some non-aquifer and marginal aquifer materials present on the eastern side of the Creighton Water System survey area. The ***Kp*** bedrock surface is shown for the area as a gray surface in Figure 5-39. It is better observed in Figure 5-40 which is a map view of the ***Kp*** surface in the Creighton Water System survey area. An eroded northwest-southeast trending channel can be seen in the ***Kp*** surface. Figure 5-41 is another 3D view of the Creighton Water System survey area including a voxel model of the coarse aquifer material shown in 3D. This figure allows for the inspection of the aquifer material relationships within the Bazile Creek area. To inspect the relationship of these materials relative to saturation they need to be examined relative to the water table. As indicated above in Section 5.1 the water table was prepared for the area using the 1995 CSD regional water table and may not reflect the current configuration of the water table in the area. Figure 5-42 is a 3D image of the Creighton Water System survey area including the voxel model of the coarse aquifer material with the water table represented by a transparent surface. Inspection of Figure 5-42 indicates that some of the coarse aquifer material is above the water table and may not be saturated. However, it also shows that much of this coarse material is close to the surface and may serve as a conduit for recharge. For detailed examination of the relationship of the aquifer materials to the surface and Bazile Creek, the individual profiles should be inspected. For example, Figure 5-43 is a profile of line L128301 which cuts from the southwest to the northeast and crosses a meander in Bazile Creek in two places. To the west of Bazile Creek there is the estimated top of the ***To*** indicated by NE-DNR well *G-066419* by the presence of sandstone. The section is thinning to the east, close to NE-DNR well *G-165852* which also shows a thinning of the sandstone. To the east of *G-165852* the coarse material comes to the surface and is sitting above the water table. Much of the area within the Creighton Water System survey area has similar characteristics. Individual profiles for the interpreted resistivity sections can be found in Appendices 5 and 6. 2D and 3D plots of the Creighton area can be found in Appendices 7 and 8.

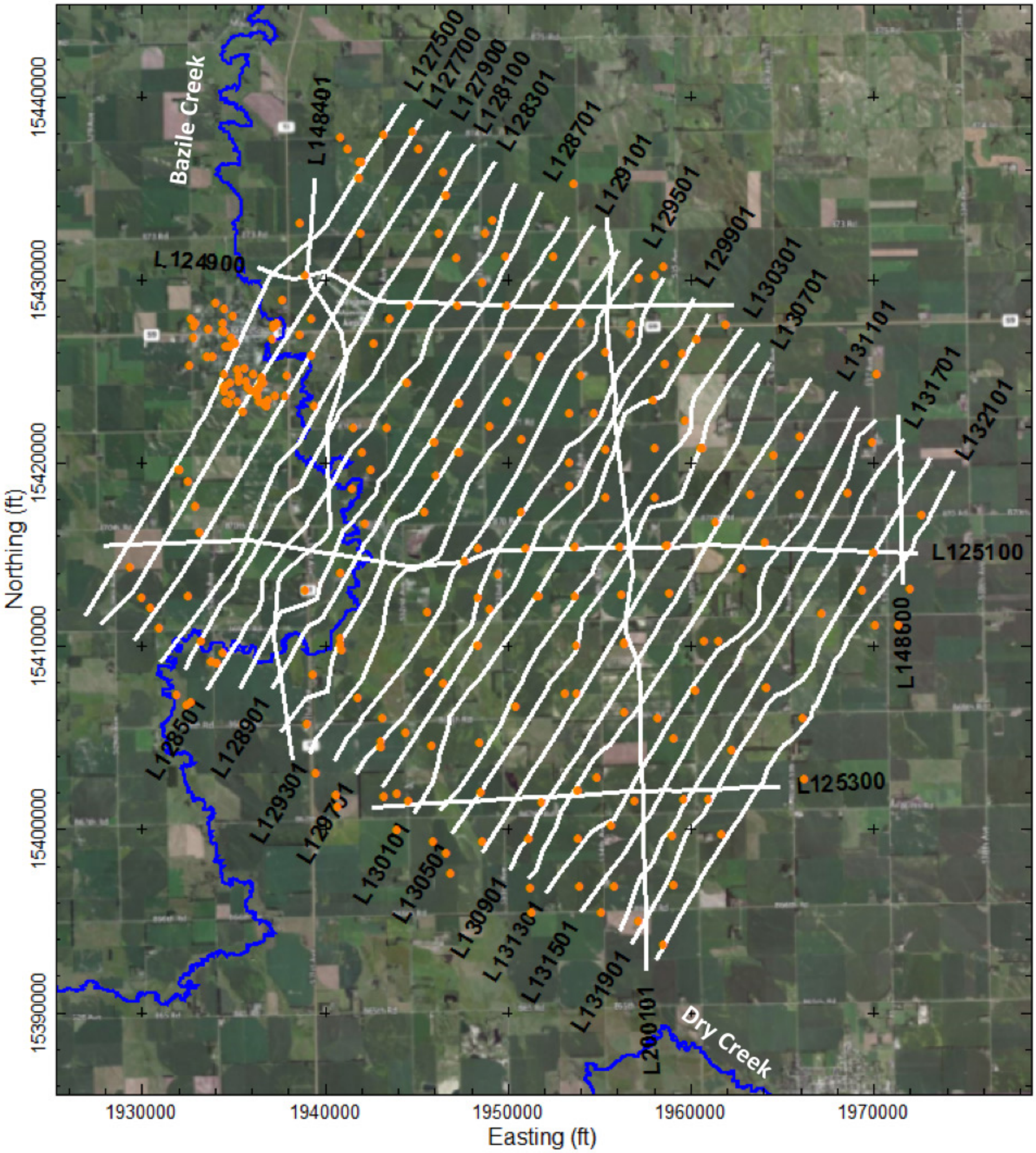


Figure 5-38. Map of the AEM flight lines within the Creighton Water System survey area. The orange dots indicate the locations of the Nebraska DNR registered wells. The meandering blue lines are Bazile and Dry creeks. The image projection is NAD 83, UTM Zone 14 North.

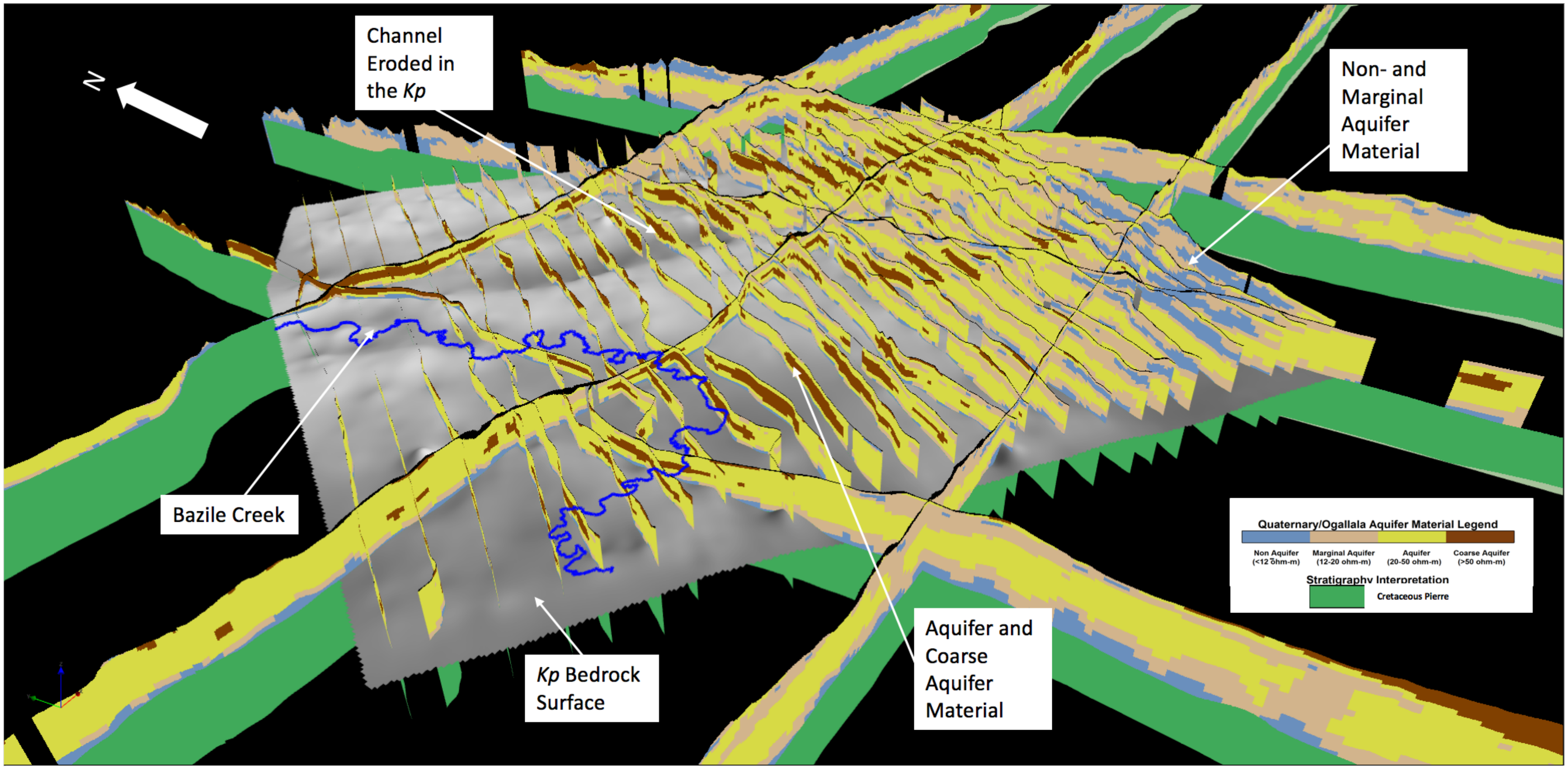


Figure 5-39. 3D map view looking to the east from the west of the western side of the Creighton Water System survey area, displaying the profiles and the distribution of materials within the area and the Cretaceous Pierre (*Kp*) bedrock surface. The vertical exaggeration is 10x.

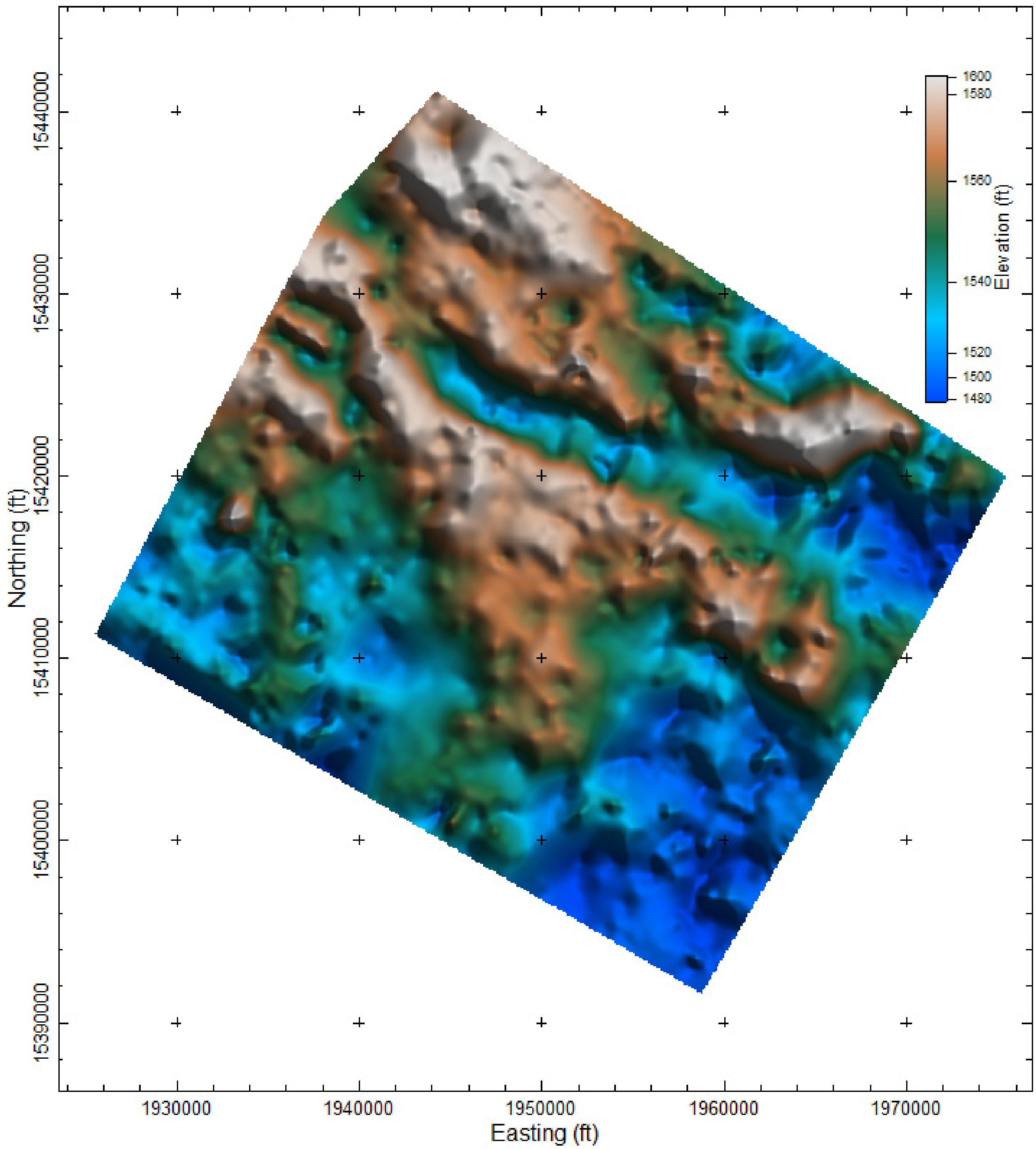


Figure 5-40. Map of the elevation of the Cretaceous Pierre (*Kp*) bedrock surface in the Creighton Water System survey area. The map projection is NAD 83, UTM Zone 14 North.

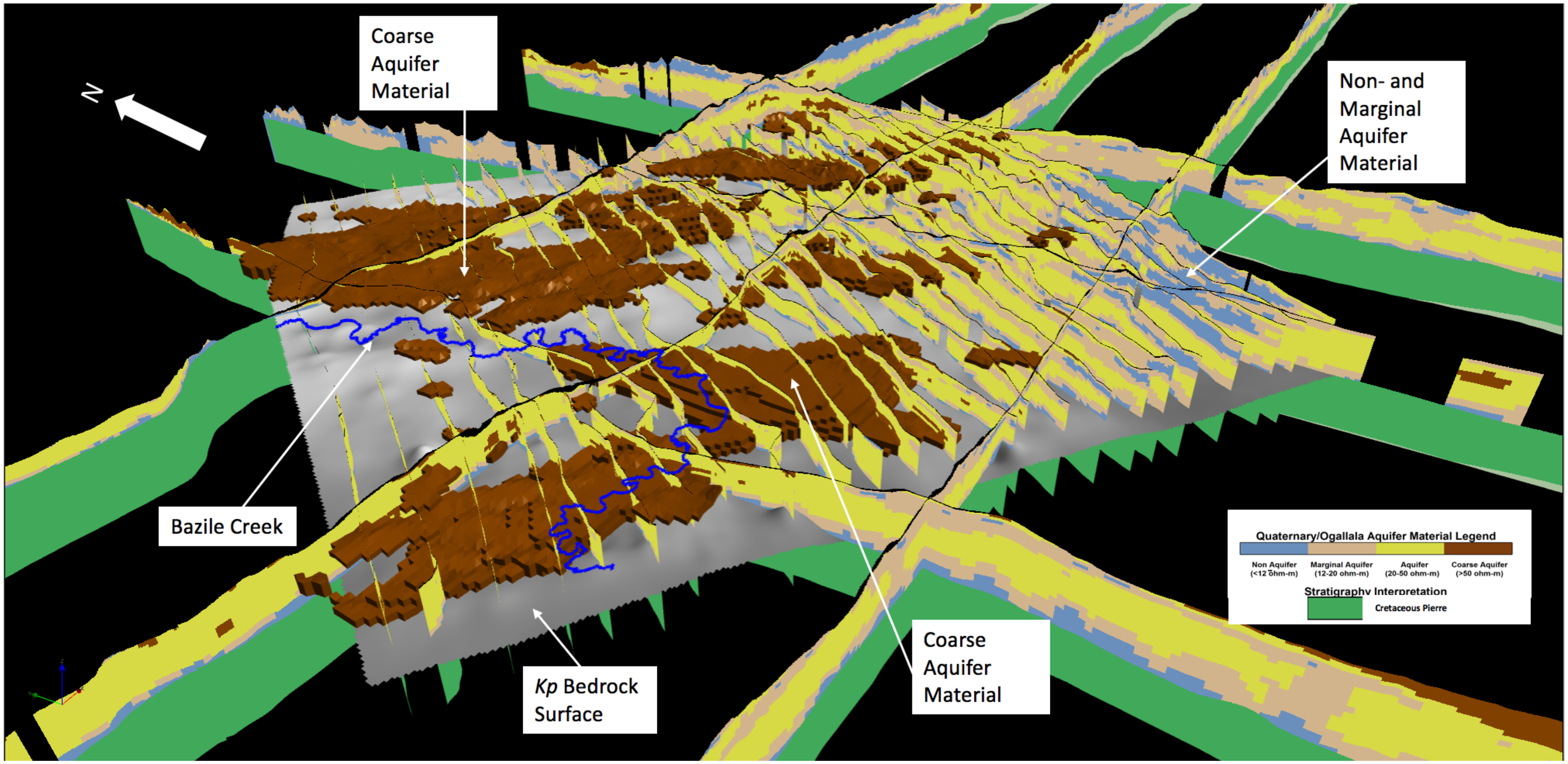


Figure 5-41. 3D map view looking to the northeast from the western side of the Creighton Water System survey area, displaying the profiles and the distribution of materials within the area and the Cretaceous Pierre (*Kp*) bedrock surface. The voxel model volume of the coarse aquifer materials is indicated in 3D (brown colored material). The vertical exaggeration is 10x.

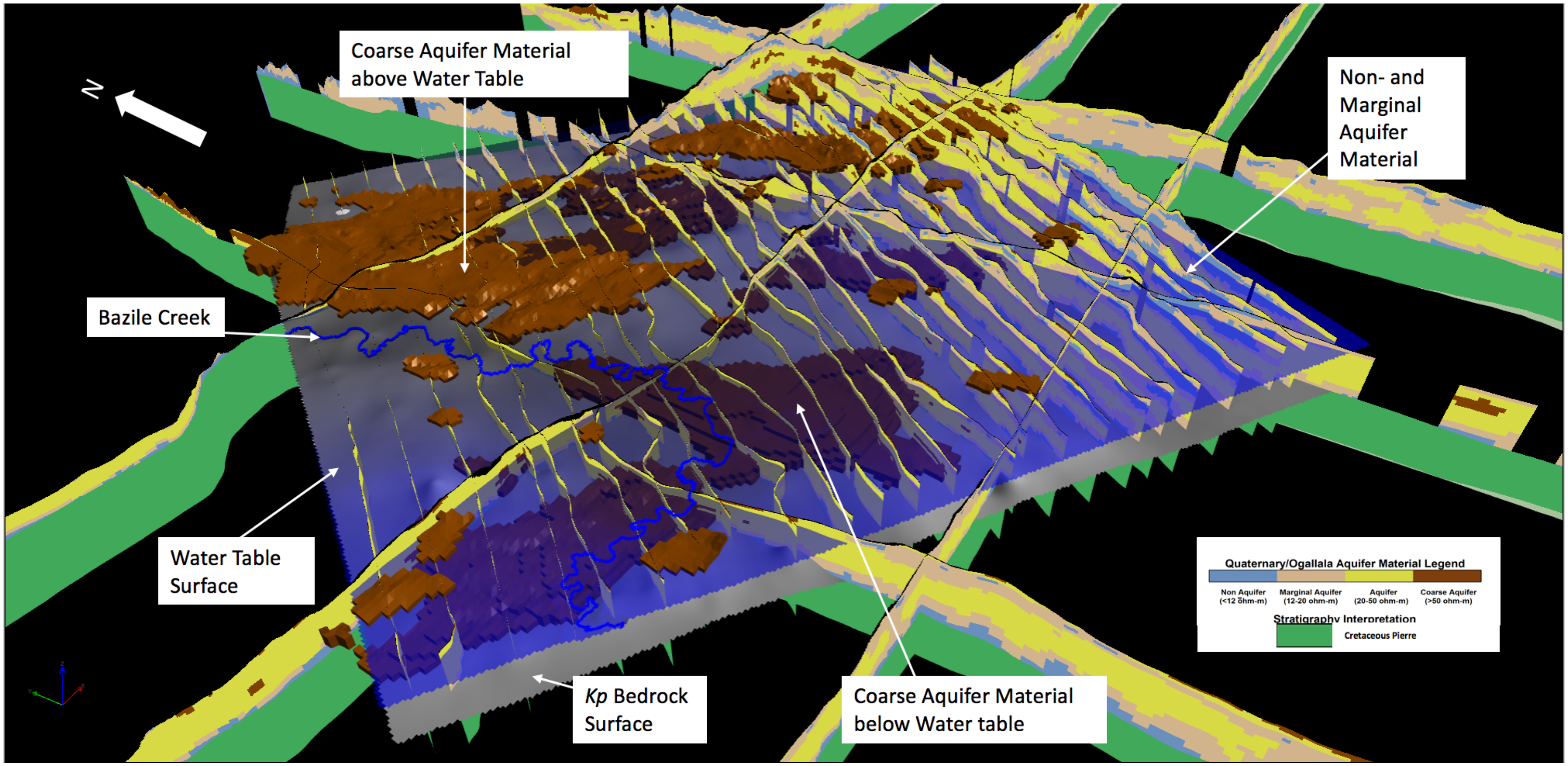


Figure 5-42. 3D map view looking to the northeast from the western side of the Creighton Water System AEM survey area, displaying the profiles and the distribution of materials within the area and the Cretaceous Pierre (*Kp*) bedrock surface. The voxel model volume of the coarse aquifer materials above (brown) and below (purple) the water table are indicated in 3D with the water table surface. The vertical exaggeration is 10x.

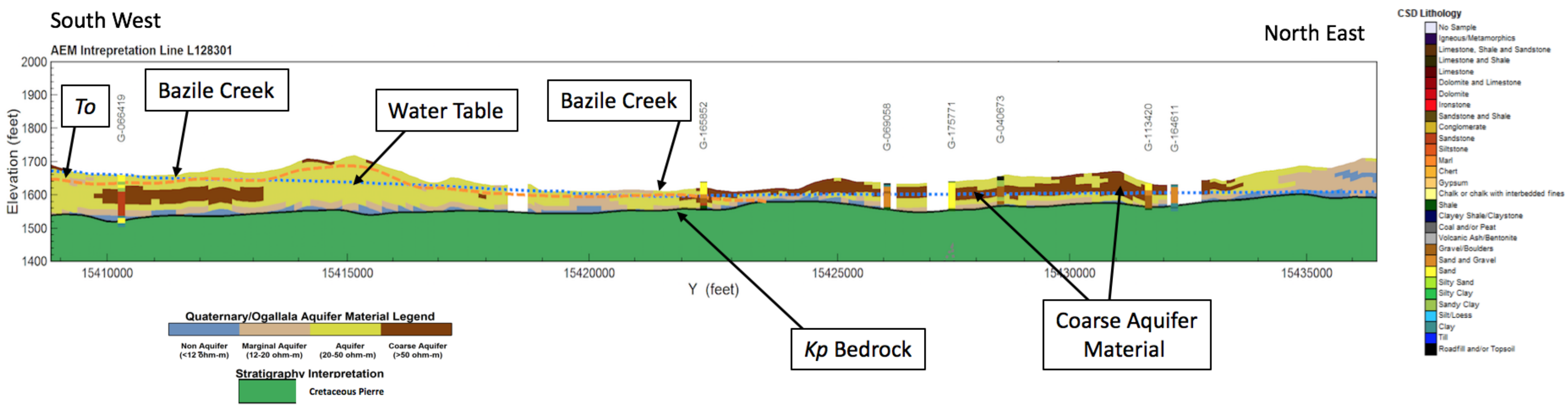


Figure 5-43. Profile view of line L128301 within the Creighton Water System survey area showing the distribution of materials along the profile. Nebraska Department of Natural Resources wells are projected on the profile. The position of Bazile Creek is indicated by arrows. The profile indicates the water table as a dashed blue line; the top of the Tertiary Ogallala (*To*) is indicated by a dashed orange line; the top of the Cretaceous Pierre (*Kp*) is indicated with a black line; gaps in the profile indicate areas of no airborne electromagnetic data coverage.

5.5 Hydrogeological Framework of the West Knox Rural Water System Area

The West Knox Rural Water System survey area is within the Quaternary and Tertiary Ogallala Aquifer system region defined above. Figure 5-44 is a map of the AEM survey lines included within the West Knox Rural Water System survey area. The map also is indicating the location of the NE-DNR registered wells, one CSD borehole *22-A-57*, and the 13 GWA West Knox Rural Water System test holes. The area is characterized by being composed of mostly aquifer materials composed of predominately of ***To*** with ***Q*** deposits overlaying the ***To***. Figure 5-45 is a 3D view of the West Knox Rural Water System survey area showing the profiles in 3D. Much of the area is aquifer (yellow colored material) with minor coarse aquifer (brown colored material) material types. There are non-aquifer and marginal aquifer materials present on the top of some of the profiles and at the bottom of the sections above the ***Kp*** bedrock. The ***Kp*** bedrock surface is shown for the area as a gray surface in Figure 5-45. Figure 5-46 is a map view of the elevation of the ***Kp*** surface in the West Knox Rural Water System survey area. Figure 5-47 is a 3D image of the West Knox Rural Water System survey area including the voxel model of the coarse aquifer material with the water table represented by a transparent blue surface. Figure 5-47 indicates that some of the aquifer material is above the water table and may not be saturated. Figure 5-48 is a profile of line L126101 this line runs from the southwest to the northeast and is at the southwestern extent of the West Knox Rural Water System survey area. The area is interpreted to be predominantly ***To*** with the aquifer material dominant. There are minor indications of coarse aquifer materials within the sections. The CSD boreholes within one-mile, NE-DNR boreholes within 1,000 feet, and the West Knox Rural Water System boreholes within 800 ft are indicated on the profile. The CSD borehole *22-A-57* and the NE-DNR well *G-162197* match the AEM material mapping in the area. Those two wells also indicate minor amounts of sandstone in the section. NE-DNR well *G-164378* and West Knox Rural Water System test holes *TH5-12*, *TH3-12*, *TH9-12*, and *TH10-12* do not match well and are indicating silty sand, sandy clay, silty clay with limited amounts of sand. These discrepancies may be due drilling techniques and sample description. Much of the area within the West Knox Rural Water System survey area has similar characteristics and is dominated by sandy aquifer material. Attention needs to be paid to the water table as that will impact the amount of saturated thickness in the area. The water table is higher to the northeast of the West Knox Rural Water System survey area. Individual profiles for the interpreted resistivity sections can be found in Appendices 9 and 10. 2D and 3D plots of the West Knox Rural Water System survey area can be found in Appendices 11 and 12.

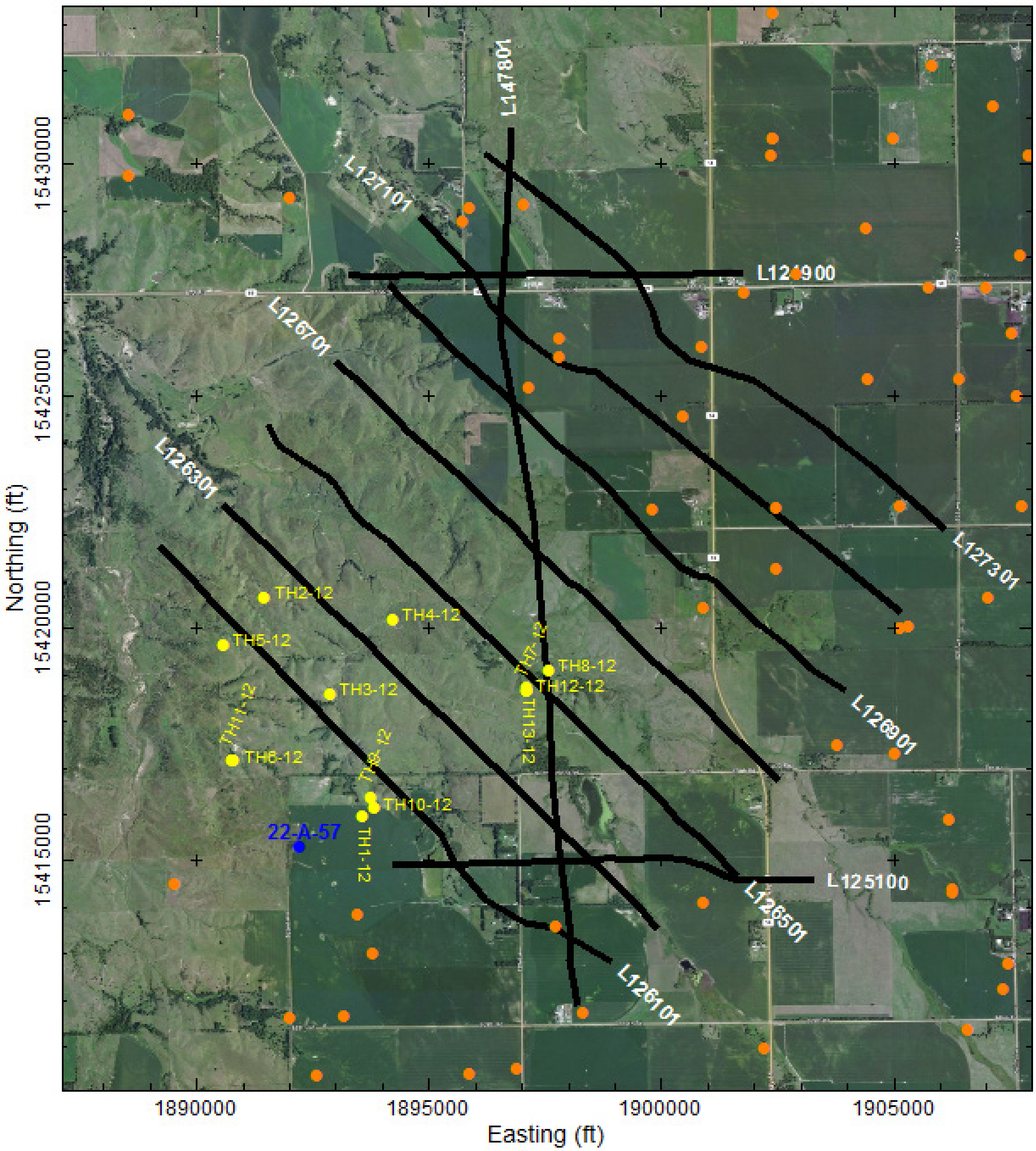


Figure 5-44. Map of the airborne electromagnetic flight lines within the West Knox Rural Water System survey area. The orange dots indicate the locations of the Nebraska Department of Natural Resources registered wells. The blue dot indicates the location of the only Conservation and Survey Division borehole in the West Knox Rural Water System survey area, *22-A-57*. The yellow dots indicate the location of the GWA West Knox Rural Water System Test wells. Image projection is NAD83, UTM Zone 14 North.

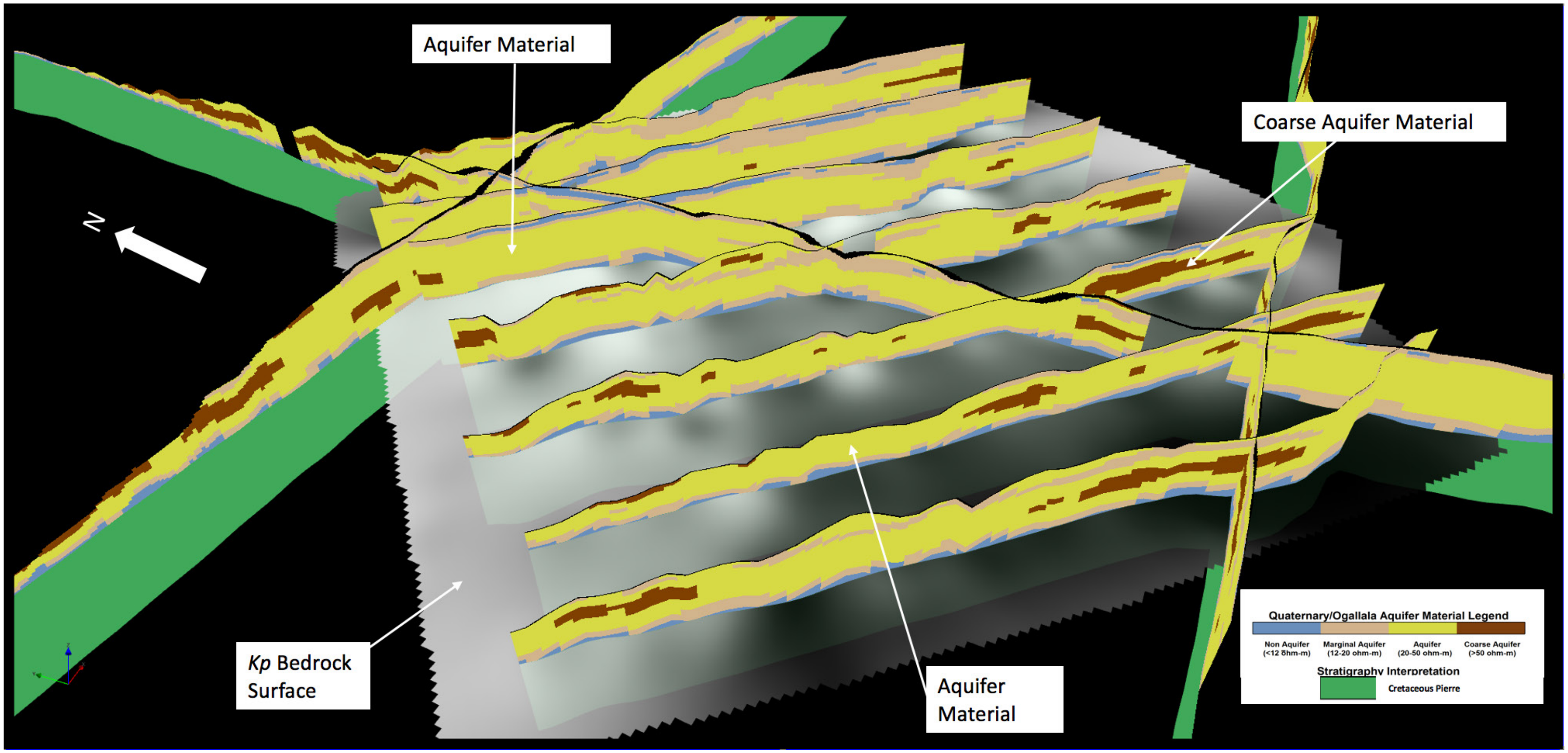


Figure 5-45. 3D map view looking to the east from the western side of the West Knox Rural Water System survey area displaying the profiles and the distribution of materials within the area and the Cretaceous Pierre (*Kp*) bedrock surface. Gaps in the profiles indicate areas of no airborne electromagnetic data collection. The vertical exaggeration is 5x.

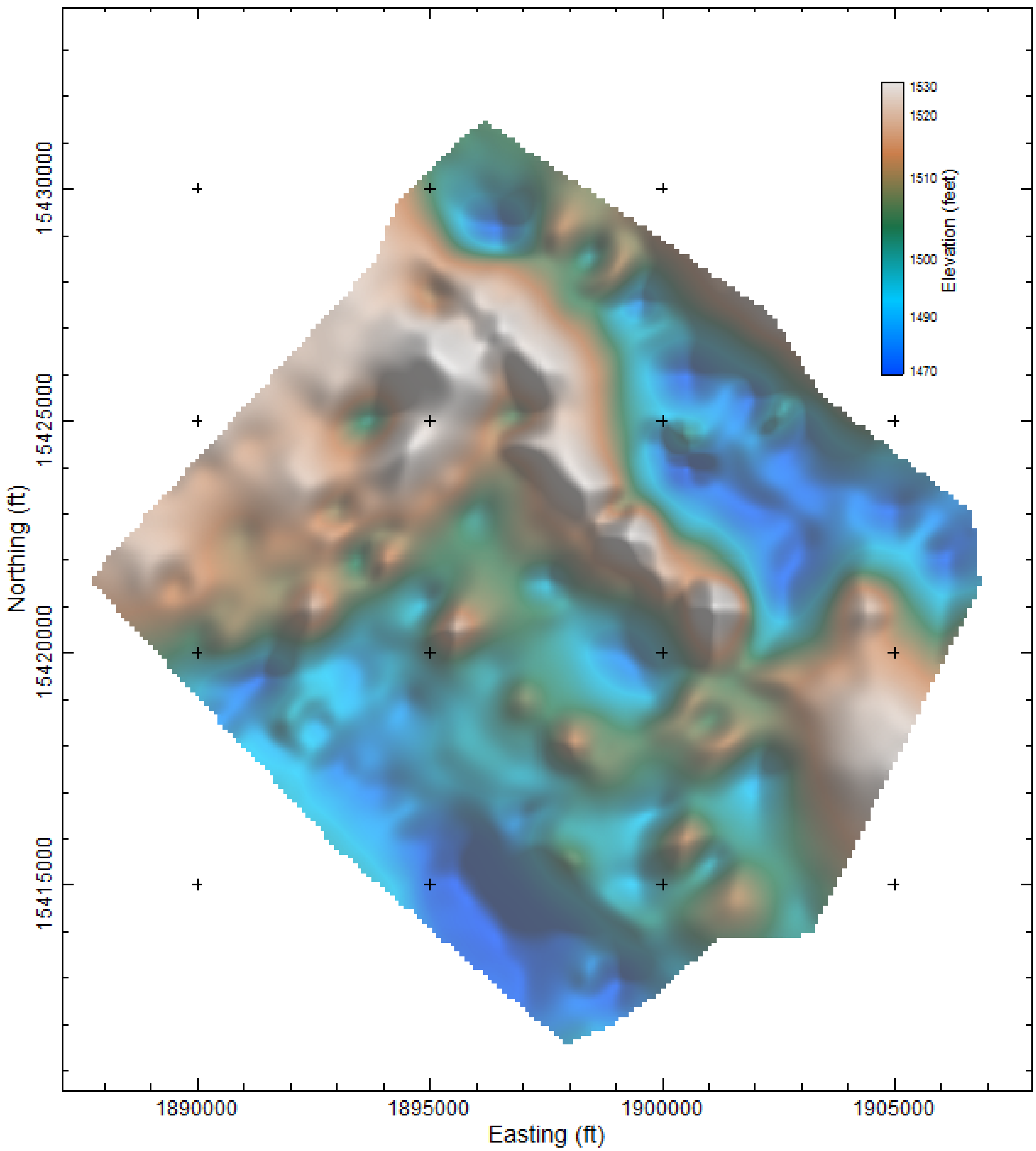


Figure 5-46. Map of the elevation of the Cretaceous Pierre (*Kp*) bedrock surface in the West Knox Rural Water System survey area. Map projection is NAD83, UTM Zone 14 North.

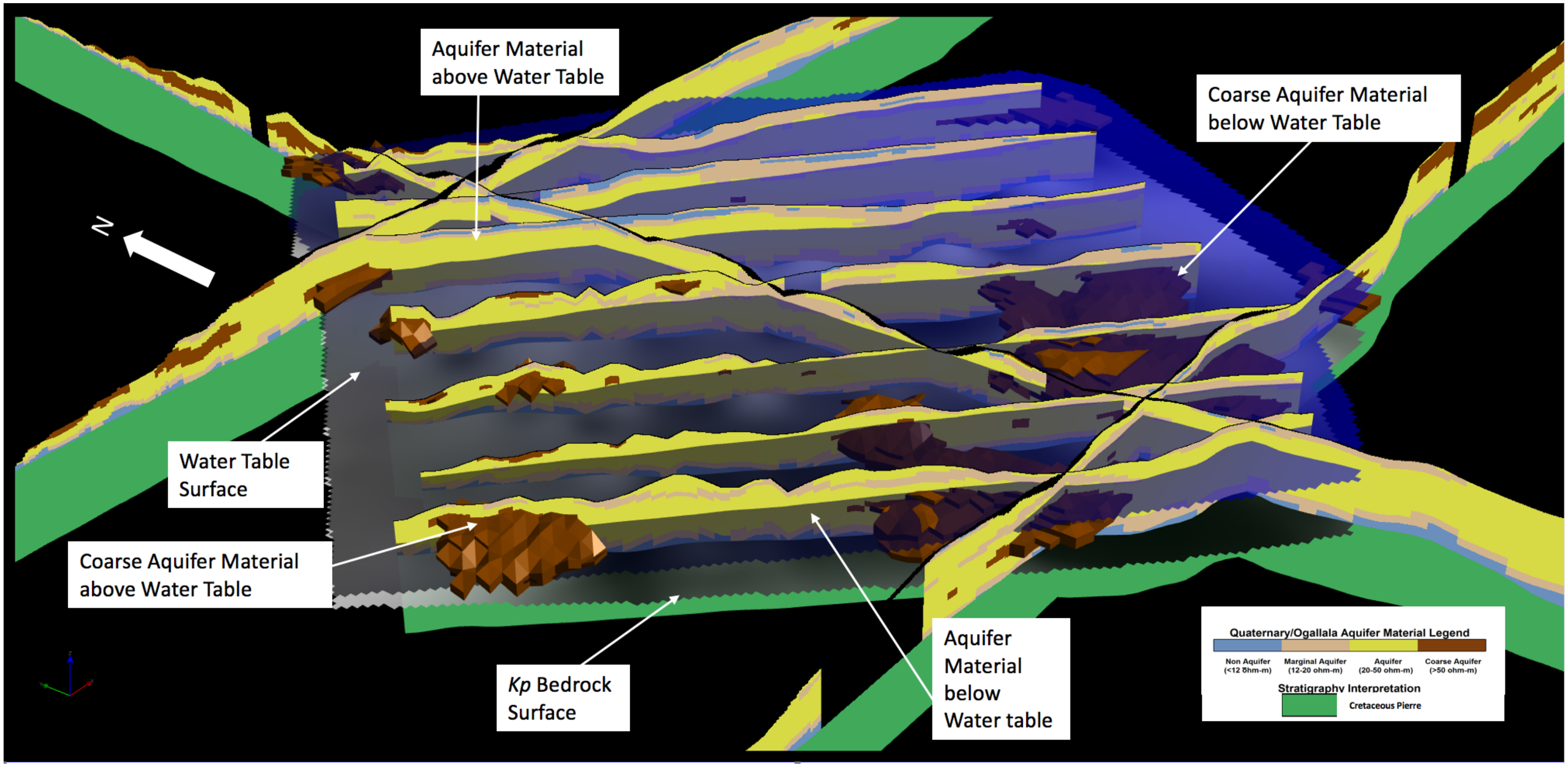


Figure 5-47. 3D map view looking to the east from the western side of the West Knox Rural Water System survey displaying the profiles and the distribution of materials area within the area and the Cretaceous Pierre (*Kp*) bedrock surface. The voxel model volume of the coarse aquifer materials is indicated in 3D with the water table surface (coarse materials above the water table in brown; below the water table in purple). The vertical exaggeration is 5x.

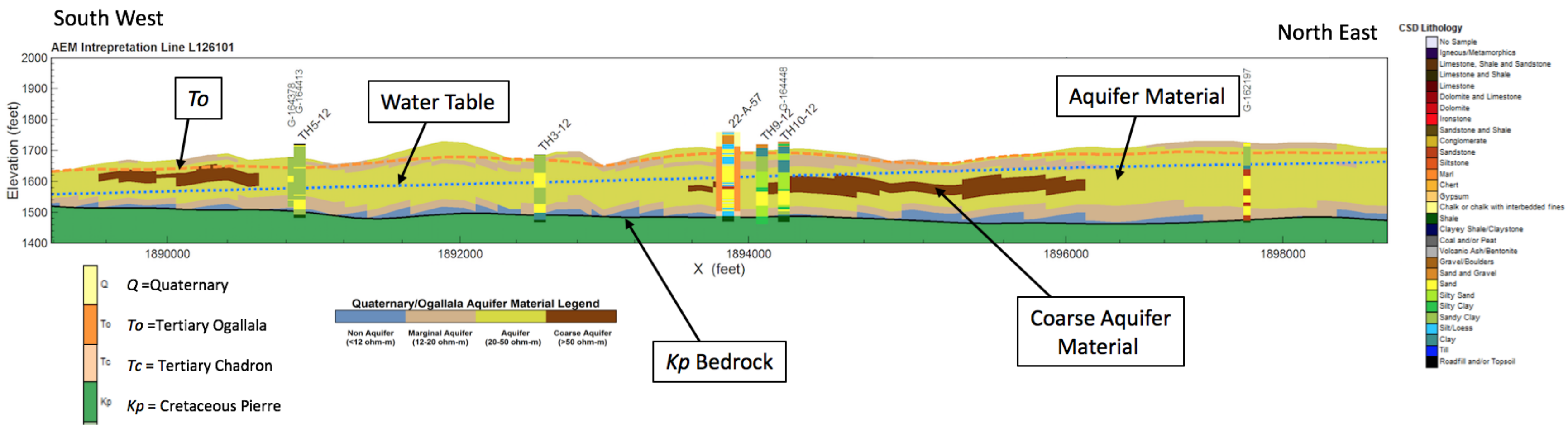


Figure 5-48. Profile view of line L126101 within the Knox Rural Water system survey area showing the distribution of materials along the profile. Nebraska Department of Natural Resources wells are projected on the profile as well as the West Knox Rural Water System Test holes. The profile indicates the water table as a dashed blue line; the top of the Tertiary Ogallala (*To*) is indicated by a dashed orange line; the top of the Cretaceous Pierre (*Kp*) is indicated with a black line.

5.6 Estimation of Aquifer Volume and Water in Storage for the Creighton Water System AEM Survey Area

Three-dimensional 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 Creighton Water System AEM survey area was mapped at high resolution for this purpose. Approximately 47.5 square miles (approximately 30,410 acres) of AEM data were collected and interpreted (Figure 1-2).

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 5.2. Figure 5-12 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 5-49 shows the distribution of the volumes of all saturated Quaternary/Ogallala 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 town of Creighton is not included in this calculation nor in Figure 5-49, Figure 5-50, and Figure 5-51. Note that the images in figures 5-49, 5-50, and 5-51 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 14\PA_Sessions.

Figure 5-50 shows the volume and distribution of the aquifer and coarse aquifer material in the survey area revealing that most of the area has good aquifer material.

Figure 5-51 shows only the volume and distribution of the coarse aquifer material below the water table which accounts for only 13% of the combined value of the aquifer and coarse aquifer material.

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.

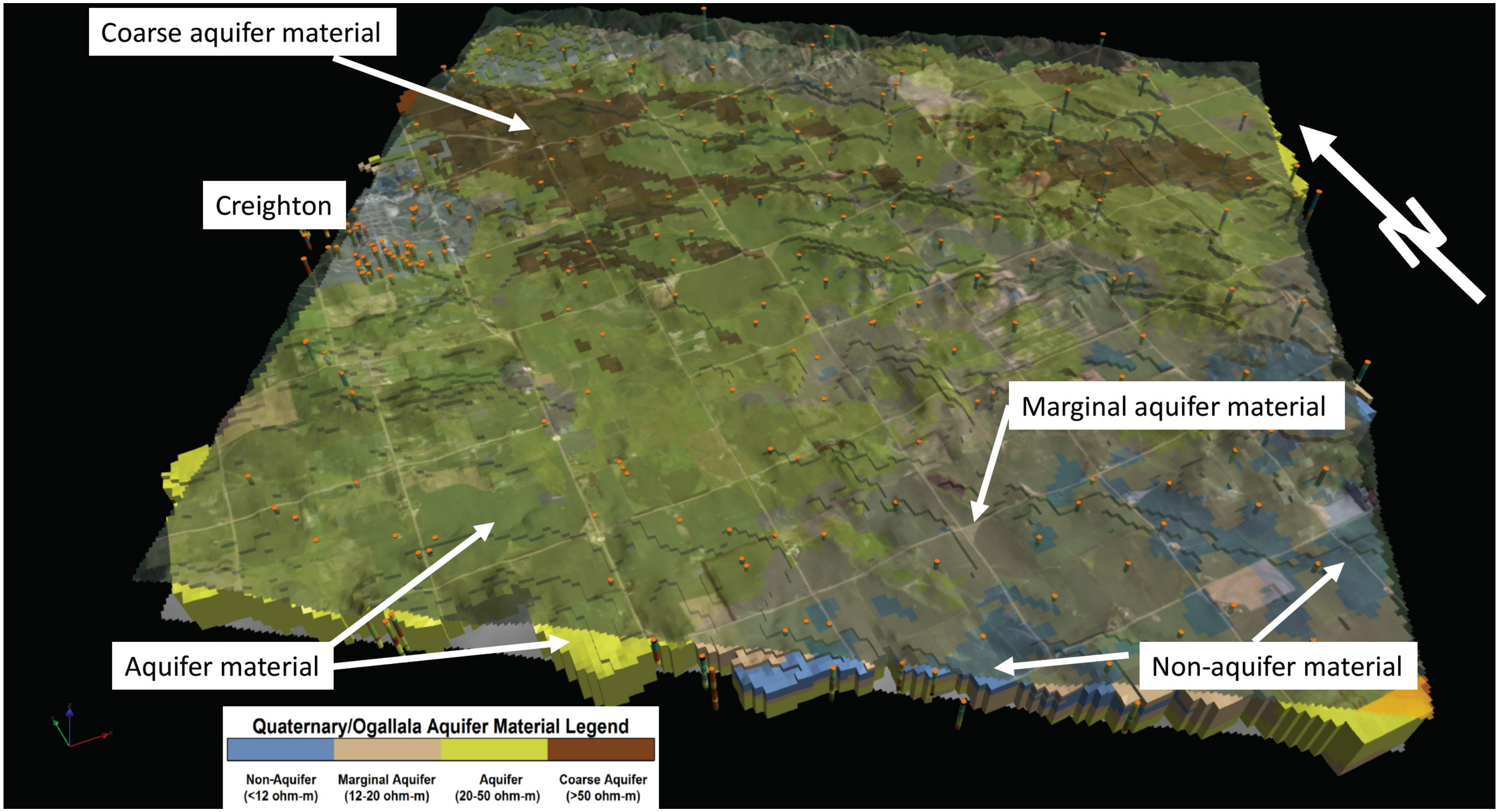


Figure 5-49. 3D voxel showing the volume and interpreted distribution of the non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material of the Quaternary/Ogallala looking to the north within the Creighton Water System survey area. Vertical exaggeration is 15x.

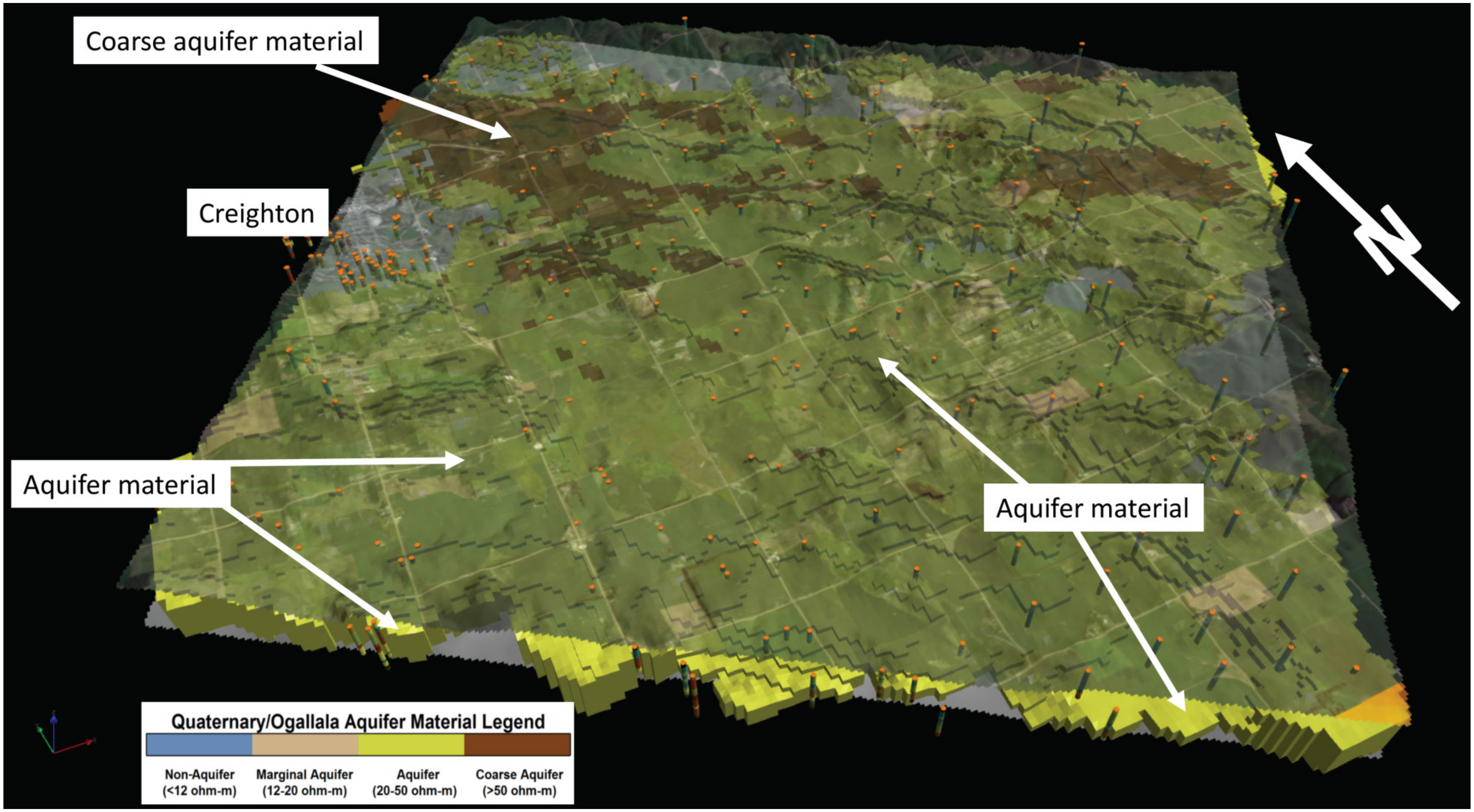


Figure 5-50. 3D voxel showing the volume and interpreted distribution of the aquifer material and coarse aquifer material of the Quaternary/Ogallala looking to the north within the Creighton Water System survey area. Vertical exaggeration is 15x.

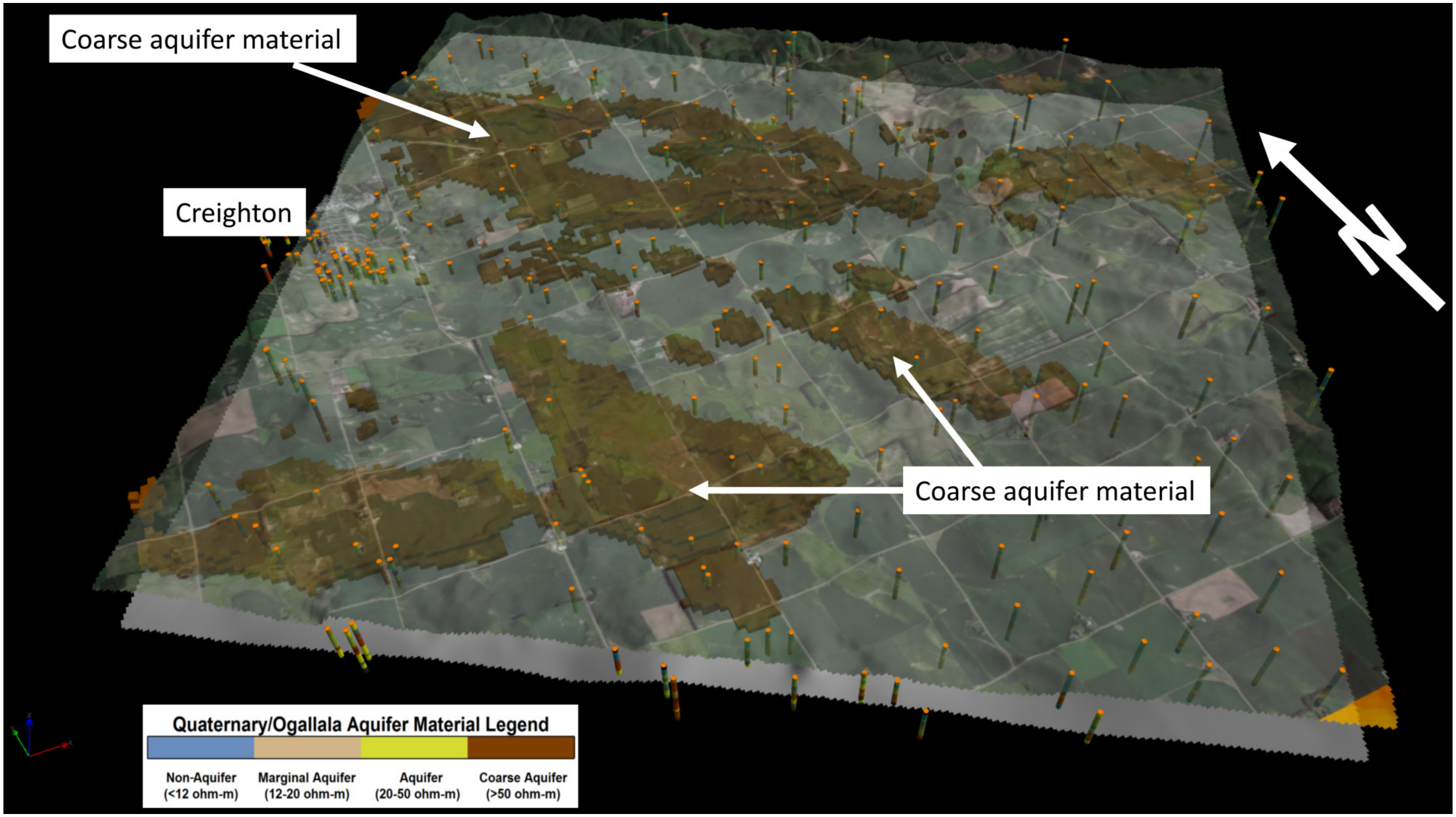


Figure 5-51. 3D voxel showing the volume and interpreted distribution of the coarse aquifer material of the Quaternary/Ogallala looking to the north within the Creighton Water System survey area. Vertical exaggeration is 15x.

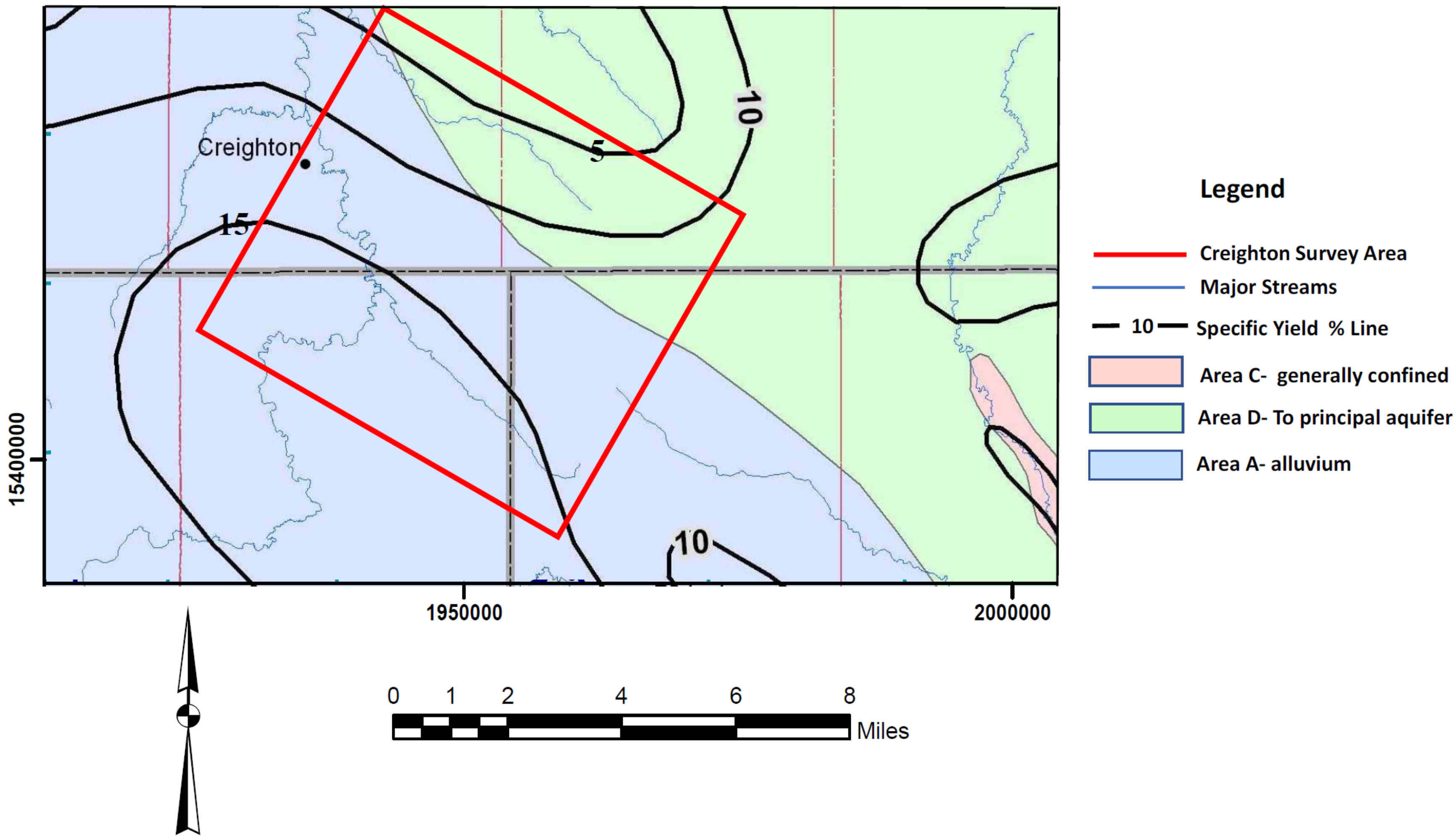


Figure 5-52. Specific yield map of the Creighton Water System survey area adapted from Olafsen-Lackey (2005). Lines of equal specific yield percent value are drawn as contours within and near the Survey area which is bounded by the red box.

Specific yield values were selected by estimating values (Figure 5-52) 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 from the Creighton Water System 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 (Heath, 1983), 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 0.05 to 0.2 with an average of 0.10 (Olafsen-Lackey, 2005). This takes into consideration the finer grained material of the ***To*** on the western side of the Creighton Water System survey area and the finer grained Quaternary deposits on the eastern side. Coarse aquifer materials exist as localized deposits in the survey area. Estimates of specific yield for the coarse aquifer material (>50 ohm-m) ranges from 0.13 to 0.17 with an average of 0.15 (Olafsen-Lackey, 2005).

Table 5-4 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 158,333 acre-ft and contains 63,333 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 482,282 acre-ft and contains 168,798 acre-ft, aquifer material has an estimated volume of 1,782,523 acre-ft and contains an estimated volume of 356,504 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 357,775 acre-ft for a total of 89,443 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 678,078 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 Creighton Water System survey area will yield approximately 1,266 acre-ft, marginal aquifer materials will yield approximately 8,440 acre-ft, aquifer materials will yield 35,650 acre-ft, and the coarse aquifer material will yield approximately 13,416 acre-ft. A total of 57,506 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 5-4. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-4 are conservative estimates and the amount released from the decline in pressure are not considered.

Table 5-4. Estimates of groundwater in storage and extractable water content in all aquifer materials underlying the Creighton Water System 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	6,897,000,000	158,333	0.40	63,333	0.02	1266
Marginal	21,008,240,625	482,282	0.35	168,798	0.05	8440
Aquifer	77,646,709,375	1,782,523	0.20	356,504	0.10	35,650
Coarse	15,584,690,625	357,775	0.25	89,443	0.15	13,416
TOTAL	121,136,640,625	2,780,913		678,078		57,506

5.7 Estimation of Aquifer Volume and Water in Storage for the West Knox Rural Water System AEM Survey Area

Three-dimensional 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 West Knox Rural Water System survey area was mapped at high resolution for this purpose. Approximately 7.8 square miles (approximately 4,992 acres) of AEM data was collected and interpreted (Figure 1-2).

The criteria for determining the basis for the range of resistivity values used in calculating the volumes of interpreted aquifer material are provided in Section 5.2. Figure 5-12 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 5-53 shows the distribution of the volumes of all saturated Quaternary/Ogallala 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.

Figure 5-54 shows the volume and distribution of the aquifer and coarse aquifer material in the survey area revealing that most of the area has good aquifer material.

Figure 5-55 shows only the volume and distribution of the coarse aquifer material below the water table which accounts for only approximately 6 percent of the combined value of the aquifer and coarse aquifer material.

Note that the images in figures 5-53, 5-54, and 5-55 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 14\PA_Sessions.

All aquifer materials including non-aquifer material, marginal aquifer material, and coarse aquifer materials 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 used for 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.

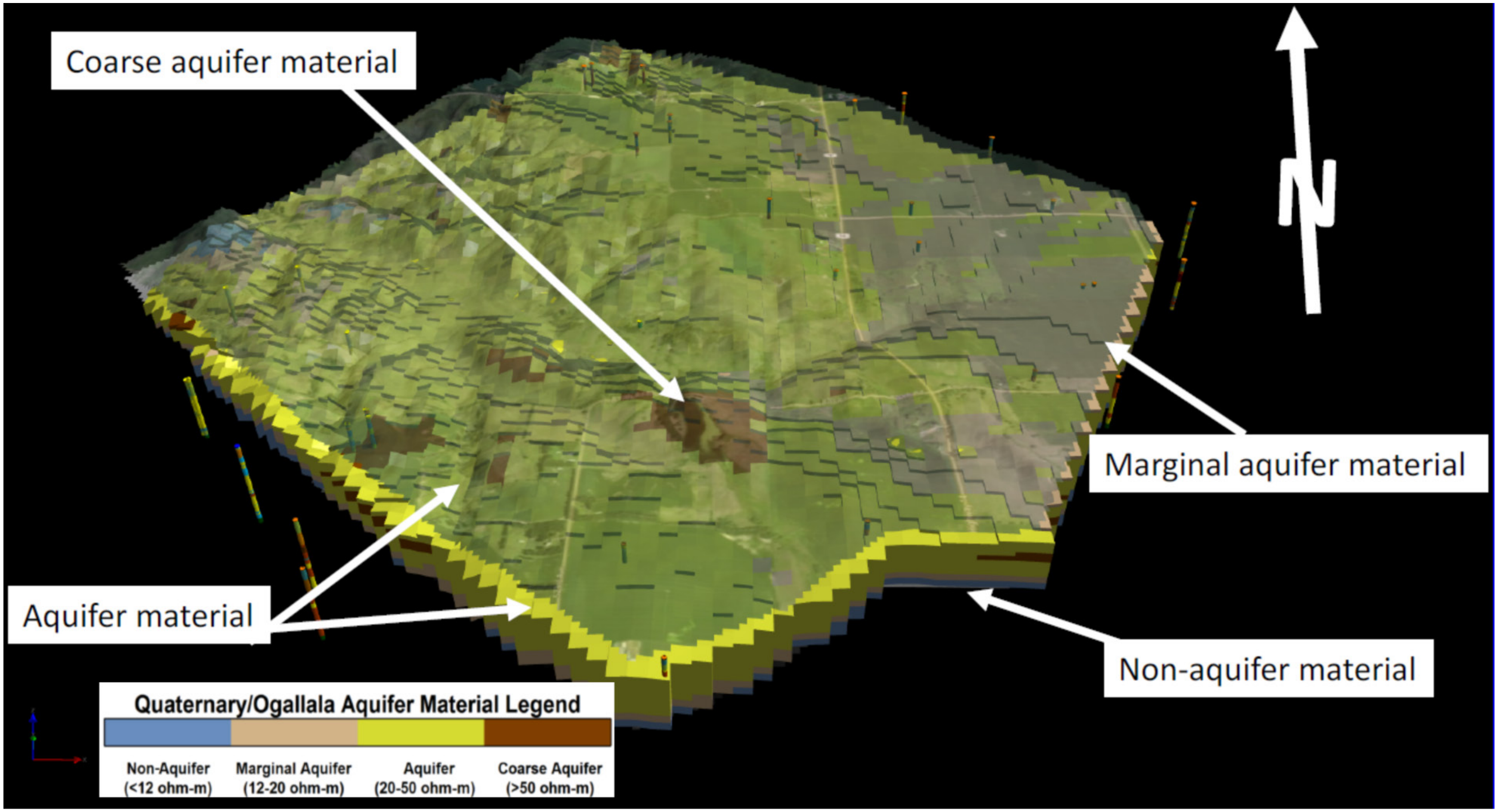


Figure 5-53. 3D voxel showing the volume and interpreted distribution of the non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material of the Quaternary/Ogallala looking to the north within the West Knox Rural Water System survey area. Vertical exaggeration is 15x.

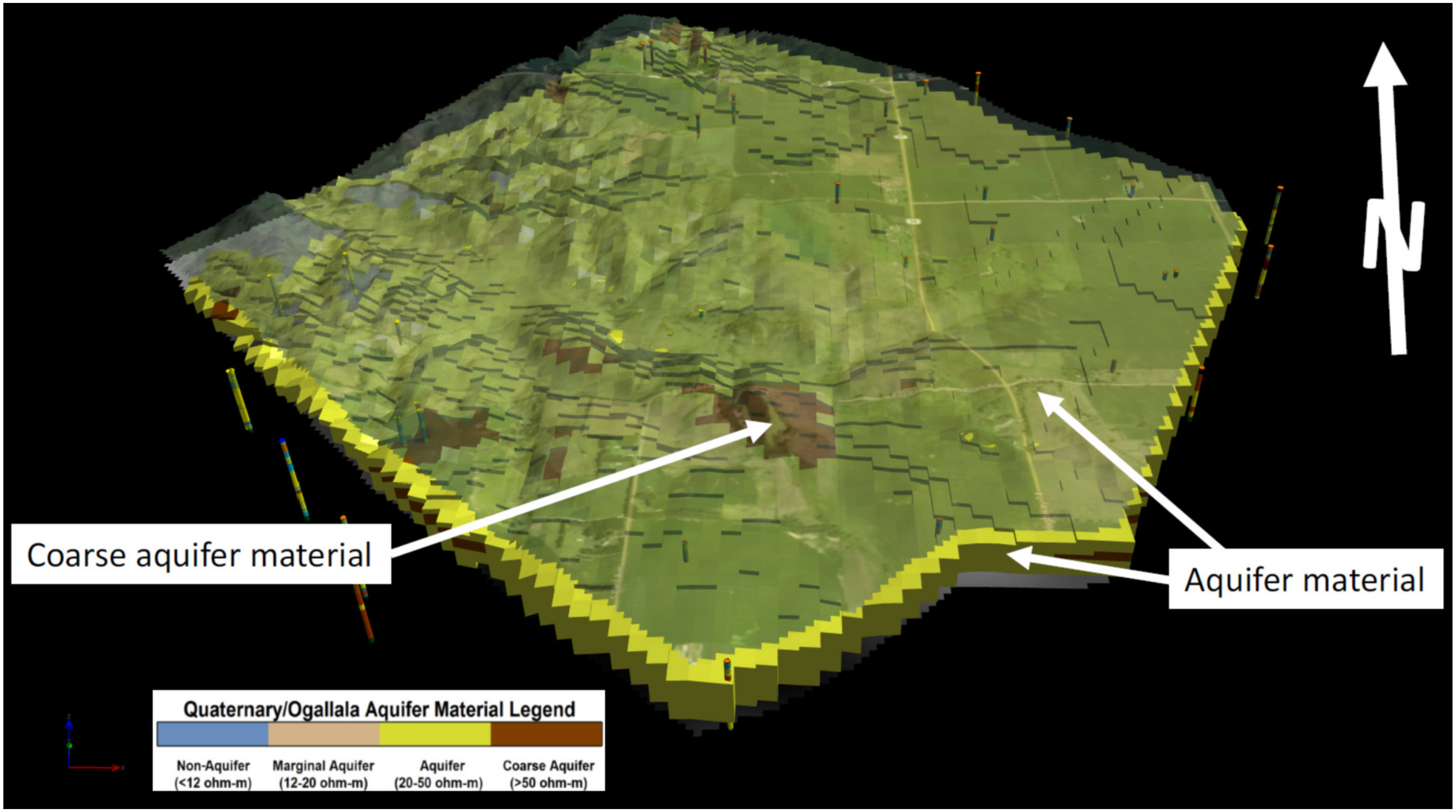


Figure 5-54. 3D voxel showing the volume and interpreted distribution of the aquifer material and coarse aquifer material of the Quaternary/Ogallala looking to the north within the West Knox Rural Water System survey area. Vertical exaggeration is 15x.

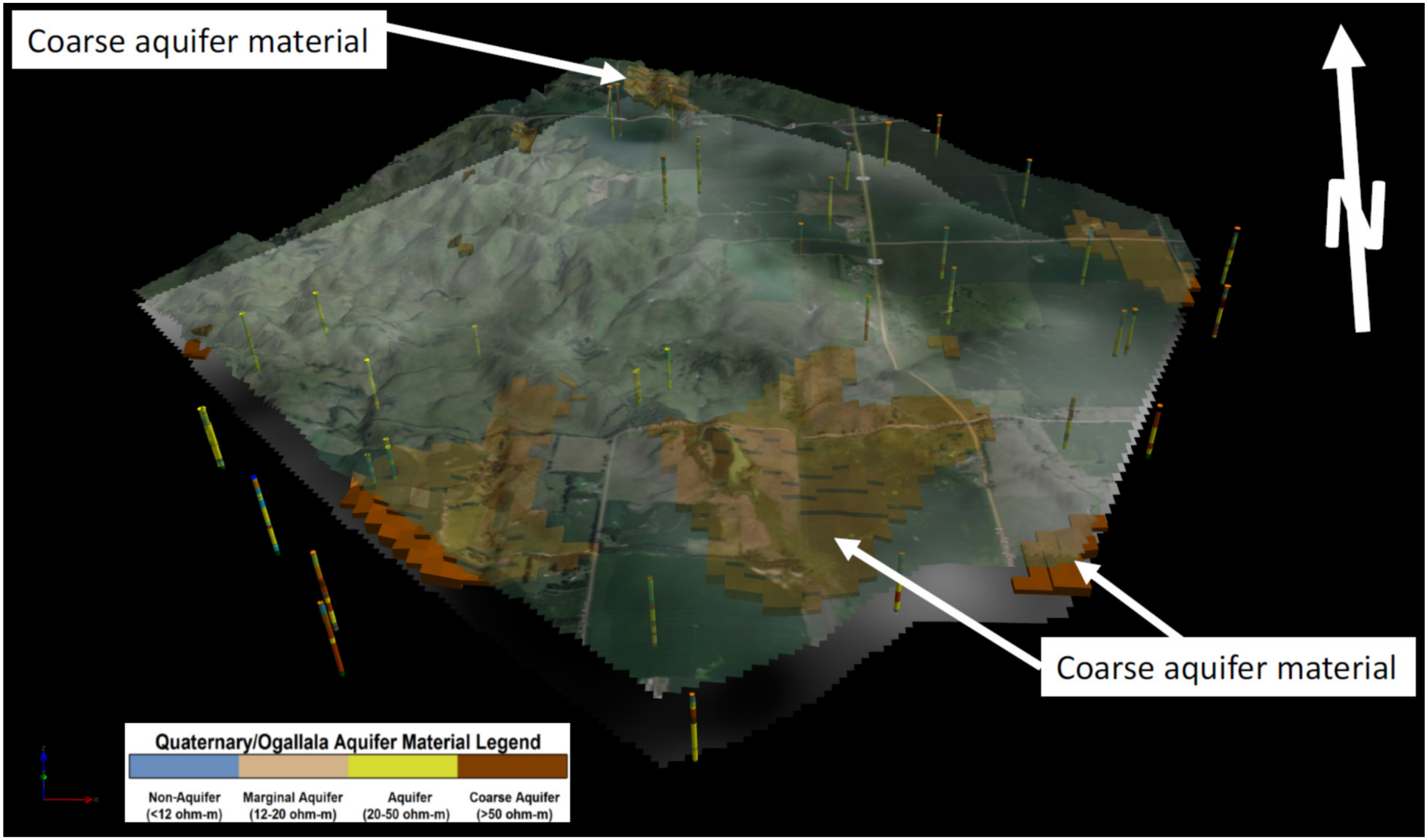


Figure 5-55. 3D voxel showing the volume and interpreted distribution of the coarse aquifer material of the Quaternary/Ogallala looking to the north within the West Knox Rural Water System survey area. Vertical exaggeration is 15x.

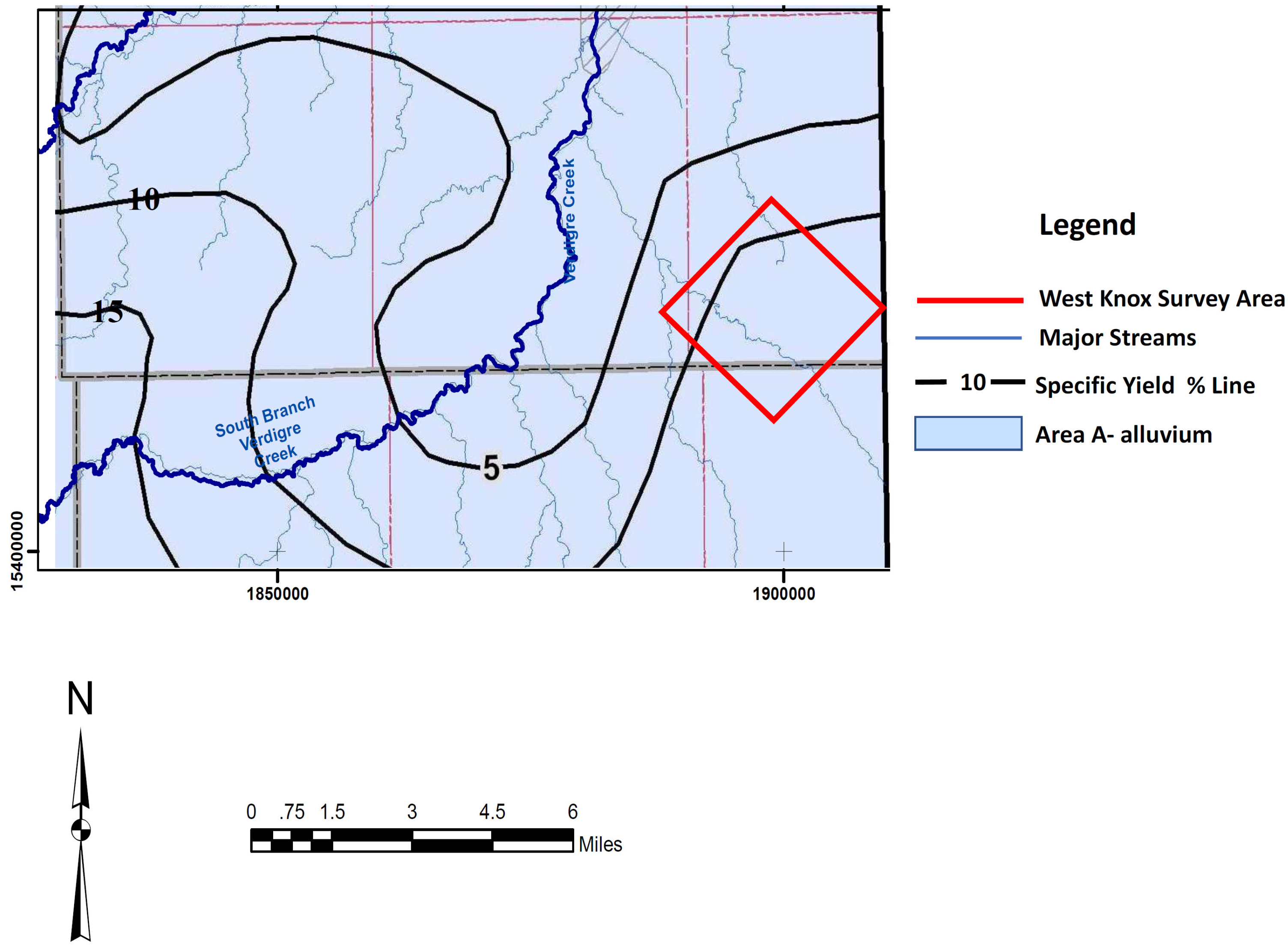


Figure 5-56. Specific yield map of the West Knox Rural Water System survey area adapted from Olafsen-Lackey (2005). Lines of equal specific yield percent value are drawn as contours within and near the survey area which is bounded by the red box.

Specific yield values were selected by estimating values (Figure 5-56) from Olafsen-Lackey (2005) and personal communication (Susan Olafsen-Lackey, UNL-CSD, Northeast Research and Extension Center, January 5, 2017). Aquifer test information was available from the LNNRD contractor letter from GWA on wells drilled within the West Knox Rural Water System Area (personal comm. Terry Julesgard, LNNRD May 12, 2016)), but was not used because the duration of the test was only 4 hours and could not be used for determination of specific yield. Estimates of specific yield were made for all aquifer materials. Specific yield for non-aquifer materials (<12 ohm-m) was selected to be 0.02 (Heath, 1983), for marginal aquifer materials (12-20 ohm-m) 0.05 was selected (Heath, 1983). The aquifer material (20-50 ohm-m) ranges from 0.05 to 0.2 with an average of 0.10 (Olafsen-Lackey, 2005). This takes into consideration the finer grained material of the ***To***, which makes up all of the saturated aquifer materials within West Knox Rural Water System survey area. Coarse aquifer materials exist as localized deposits in the survey area. Estimates of specific yield for the coarse aquifer (>50 ohm-m) material ranges from 0.13 to 0.17 with an average of 0.15 (Olafsen-Lackey, 2005).

Table 5-5 shows the results of calculations for the amount of groundwater in storage calculated by multiplying the volume of all aquifer materials below the water table by the estimated porosity. The following calculation from values in the table shows the non-aquifer material has an estimated volume of 110,490 acre-ft and contains 44,196 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 118,818 acre-ft and contains 41,586 acre-ft, and aquifer material has an estimated volume of 403,659 acre-ft and contains an estimated volume of 90,731 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 24,085 acre-ft for a total of 6,021 acre-ft of groundwater in storage. The amount of groundwater in storage for both material groups is 182,534 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 West Knox Rural Water System survey area will yield approximately 884 acre-ft. marginal aquifer materials will yield 2,079 acre-ft, aquifer materials will yield 8,073 acre-ft and the coarse aquifer material will yield approximately 903 acre-ft. A total of 11,939 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 overly 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 5-5. However, too much uncertainty exists in developing an average level of head above the top of the aquifer across the entire project area, as well as defining a representative storativity term for the confined or semi-confined aquifers. Thus, the volumes listed in Table 5-5 are only conservative estimates and the amount released from the decline in pressure are not considered.

Table 5-5. Estimates of groundwater in storage and extractable water content in all aquifer materials underlying the West Knox Rural Water System 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	4,812,948,750	110,490	0.40	44,196	0.02	884
Marginal	5,175,736,837	118,818	0.35	41,586	0.05	2,079
Aquifer	17,583,414,387	403,659	0.20	90,731	0.10	8,073
Coarse	1,049,171,825	24,085	0.25	6,021	0.15	903
TOTAL	28,621,271,800	657,053		182,534		11,939

5.8 Recharge Areas within the BGMA AEM Survey Area

Three-dimensional 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 BGMA area including the Creighton Water System survey area and West Knox Rural Water System survey area are summarized in Sections 5.3, Section 5.4, and Section 5.5. 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 those depths, based on the physics of the electromagnetic exploration technique. These first layer maps show all aquifer materials including non-aquifer material, marginal aquifer material, aquifer material, and coarse aquifer material. 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 is able to transmit the largest volume of water and the non-aquifer material being the least able to transmit water. In the report by Gosselin (1991), a description of five soil associations (selected from all soil associations in the area), and their ability to transmit water to the aquifer, was provided. Gosselin (1991) discussed the ability of the soils to transmit very little to upwards of 25% of the precipitation that falls upon the land surface. The information from the interpreted aquifer materials maps and the information from Gosselin (1991) provides the bases of the information utilized in this section which is divided into the BGMA reconnaissance line area, the Creighton Water System survey area, and the West Knox Rural Water System survey area.

5.8.1 BGMA Reconnaissance Area

The results of the interpretation of the aquifer materials of the BGMA survey area are explained in detail in Section 5.3. A total of 643.9 line-miles of AEM data were acquired for the entire project area including the Creighton Water System survey area and the West Knox Rural Water System survey area. Each BGMA AEM flight line in Figure 5-57 shows the interpreted aquifer material for the first model layer (0 – 10 ft) as a color from the Quaternary/Ogallala Aquifer Material legend. Areas of coarse aquifer material (brown colored material) will have the highest potential to transmit the largest amount of water to the groundwater system with the aquifer material potentially transmitting slightly less precipitation downward as both units are permeable and transmissive. 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 3 miles 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. There are four examples within the drawn circles on Figure 5-57 that show groupings of similar materials and different recharge potential.

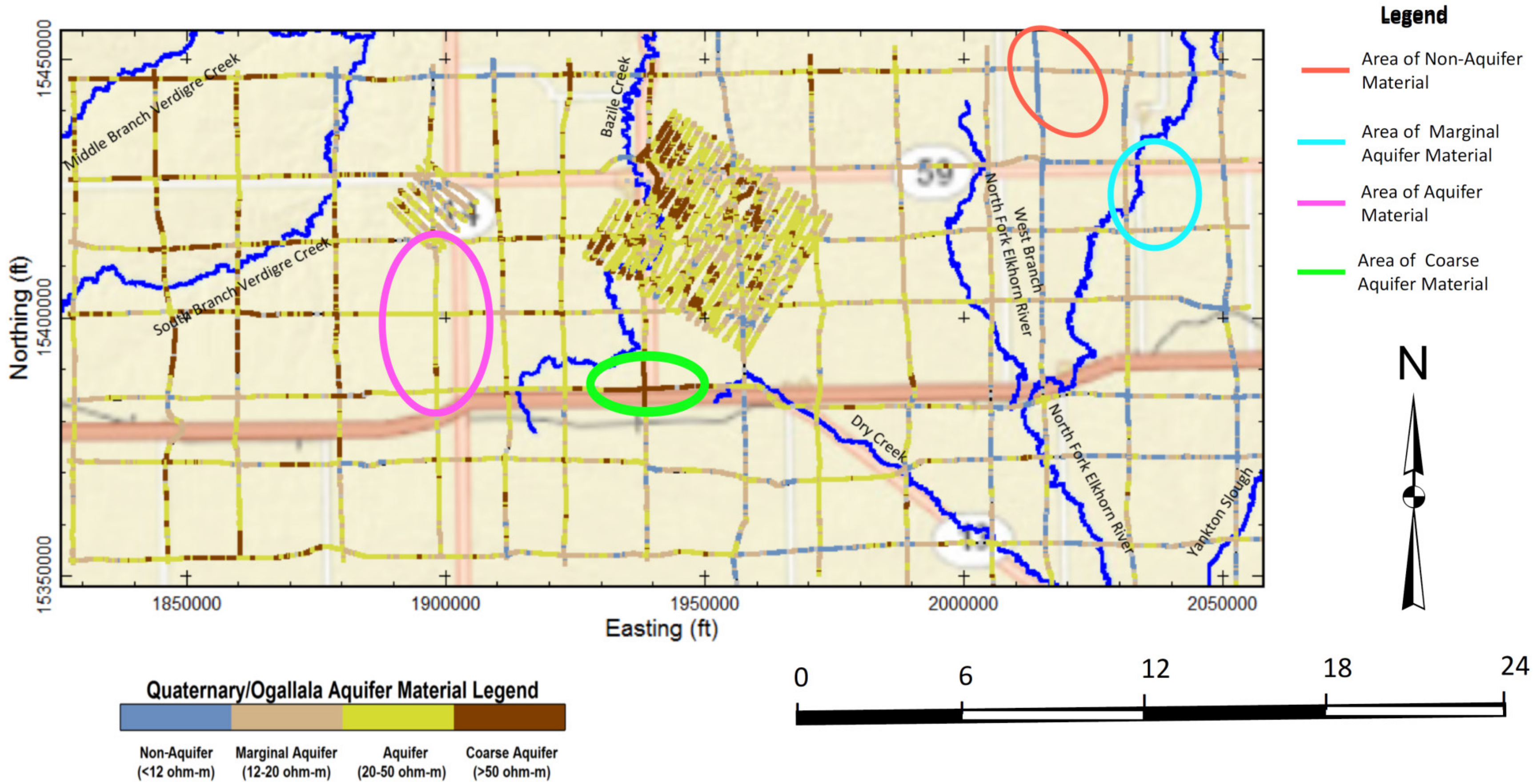


Figure 5-57. Map of aquifer materials for the first 0 to 10 feet, by flight line, displayed over the Bazile Groundwater Management Area. Circles of different colors show areas of different aquifer material types. This is an example of how to use the map by selecting an area where the dominant color is continuous along the flight line (s). Map projection is NAD 83, UTM Zone 14 North.

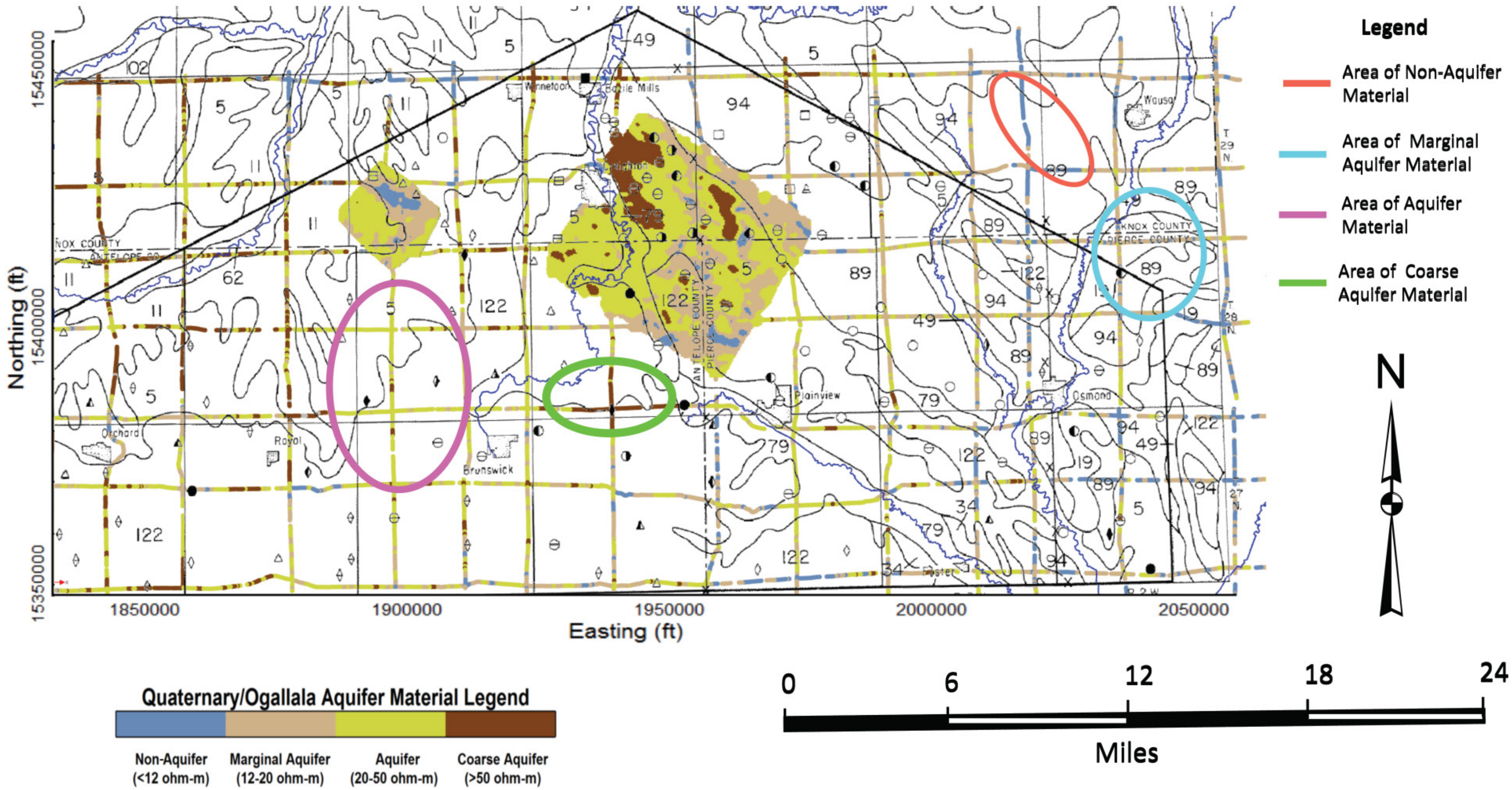


Figure 5-58. Map with aquifer materials interpolated across the block flight lines for the first 0 to 10 feet overlain on the Bazile Groundwater Management Area with the soils map modified from Gosselin (1991). Circles of different colors show areas of different aquifer materials. The magenta and green circles are in area of the soils mapped as having transmissive soils. The blue and red circles are in areas where the soils map and the interpreted aquifer materials are not coincident. Map projection is NAD 83, UTM Zone 14 North.

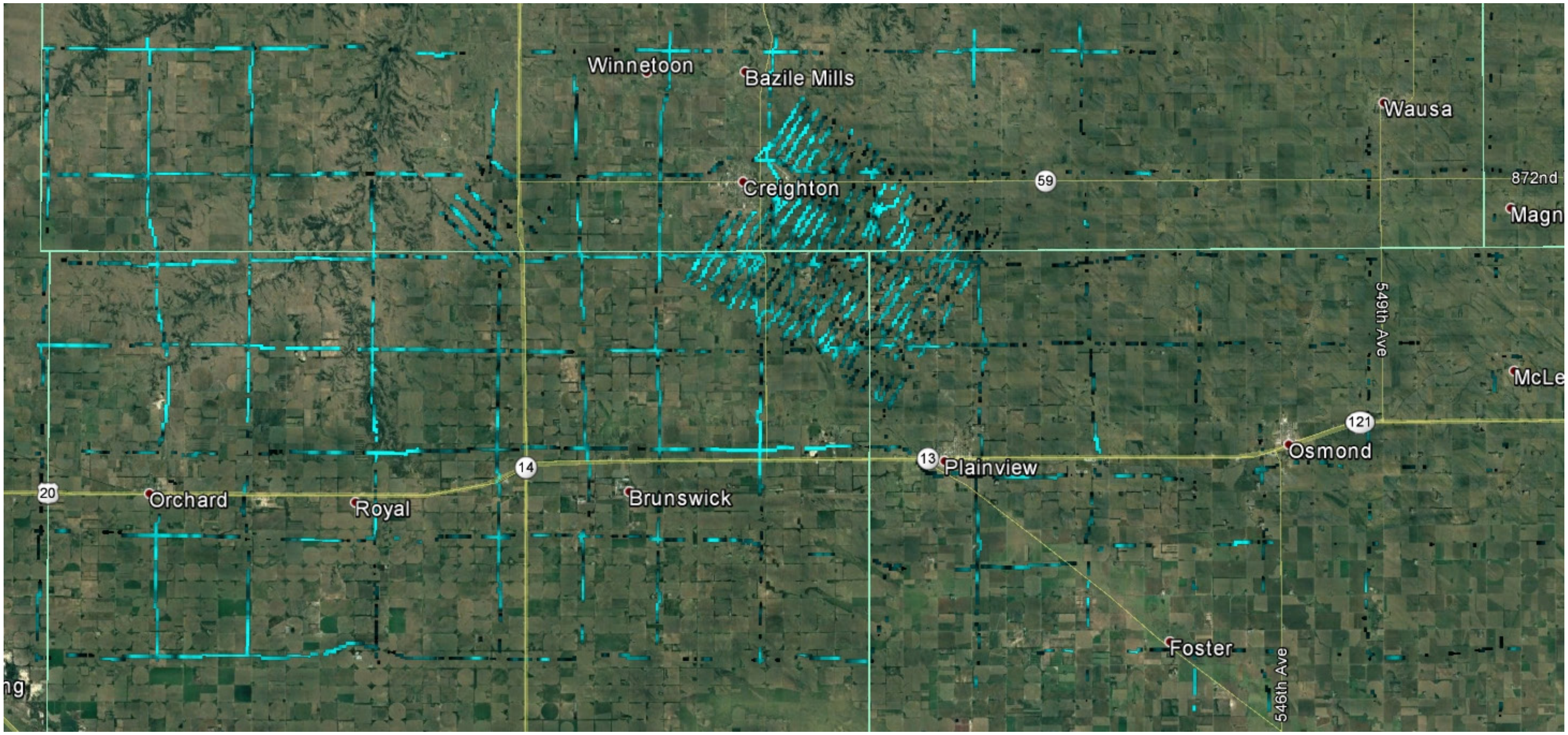


Figure 5-59. Potential aquifer and coarse material recharge zones within the BGMA AEM survey area displayed as a kmz in Google Earth. This kmz is included as a deliverable in Appendix 14\KMZ.

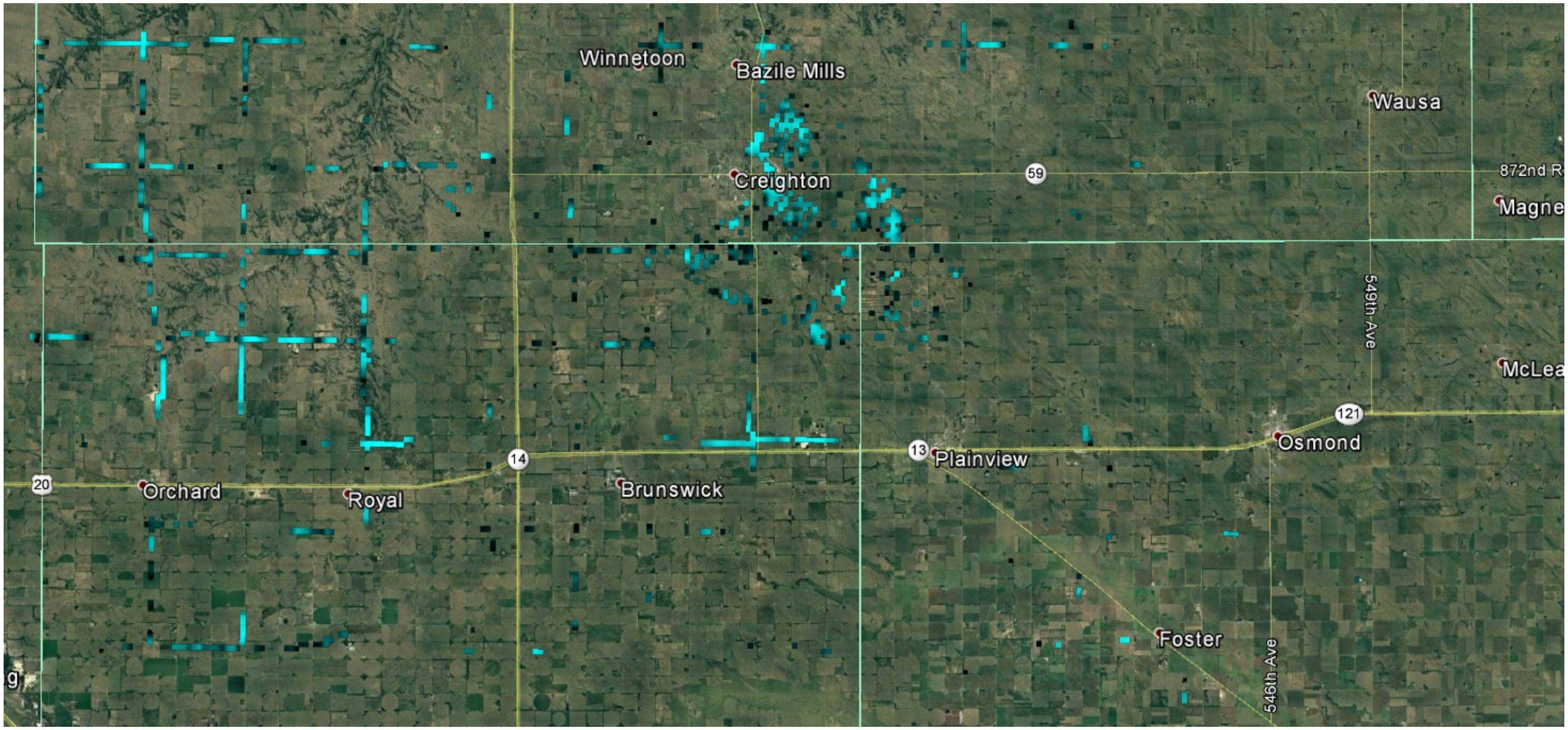


Figure 5-60. Potential coarse aquifer material recharge zones in the BGMA AEM survey area displayed as a kmz in Google Earth. This kmz is included as a deliverable in Appendix 14\KMZ.

Figure 5-58 compares the results of the interpreted AEM aquifer materials map with the soils map adapted from Gosselin (1991). There are areas on the map where the aquifer materials show a change in character that is nearly coincident with the soil association boundary. This is not consistent throughout the BGMA survey area.

Figure 5-58 shows a clear relationship between Gosselin's (1991) soils permeability and the first 0 to 10 feet of the AEM aquifer materials that can be used for evaluating where potential recharge areas might exist. There are some detailed inconsistencies that may be due to the different depths that the AEM images versus the very near-surface soils maps. Typically soils maps sample shallower than the 10 foot level, while in the AEM modeling, the first model layer presents an average of the 0 to 10 feet zone. Remember that the resolution of the AEM is a function of the frequency of the system used and the configuration of the inversion model layers. Section 4.3 discusses the system timing and Section 4.5 discusses the inversion process.

Google Earth KMZ displays of the potential recharge zones within the BGMA AEM survey area are presented in Figure 5-59 (surface aquifer and coarse aquifer material) and Figure 5-60 (surface coarse aquifer material only). Both these kmz's are included as deliverables in Appendix 14/KMZ.

5.8.2 Creighton Water System Survey Area

The Creighton Water System 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 Creighton block survey, approximately 47.5 square miles (approximately 30,410 acres) of AEM data were collected and interpreted. The closely spaced flight lines (0.25 mile) within the Creighton Water System survey area allowed for nearly continuous mapping of the different aquifer material types. Figure 5-61 is a map displaying the AEM-inferred aquifer materials in the first model layer, 0 to 10 ft. There is some 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.

A comparison between the AEM-inferred aquifer materials in the first 10 feet to the soils map from Gosselin (1991) is provided in Figure 5-62. Boundaries of different AEM-inferred aquifer materials compared to the boundaries of the soil associations are indicated in Figure 5-62. Note the location of the boundary of Soils Group 5-89 relative to the extent of the aquifer and coarse aquifer material. This image is an examples of where the different materials are reasonably coincident with the soil types.

Google Earth displays of the surface aquifer and coarse aquifer material are presented in Figure 5-63. The image on the left (a) shows both the aquifer material and the coarse aquifer surface material. The image on the right (b) shows only the coarse aquifer surface material. Both these kmz's are included as deliverables in Appendix 14/KMZ.

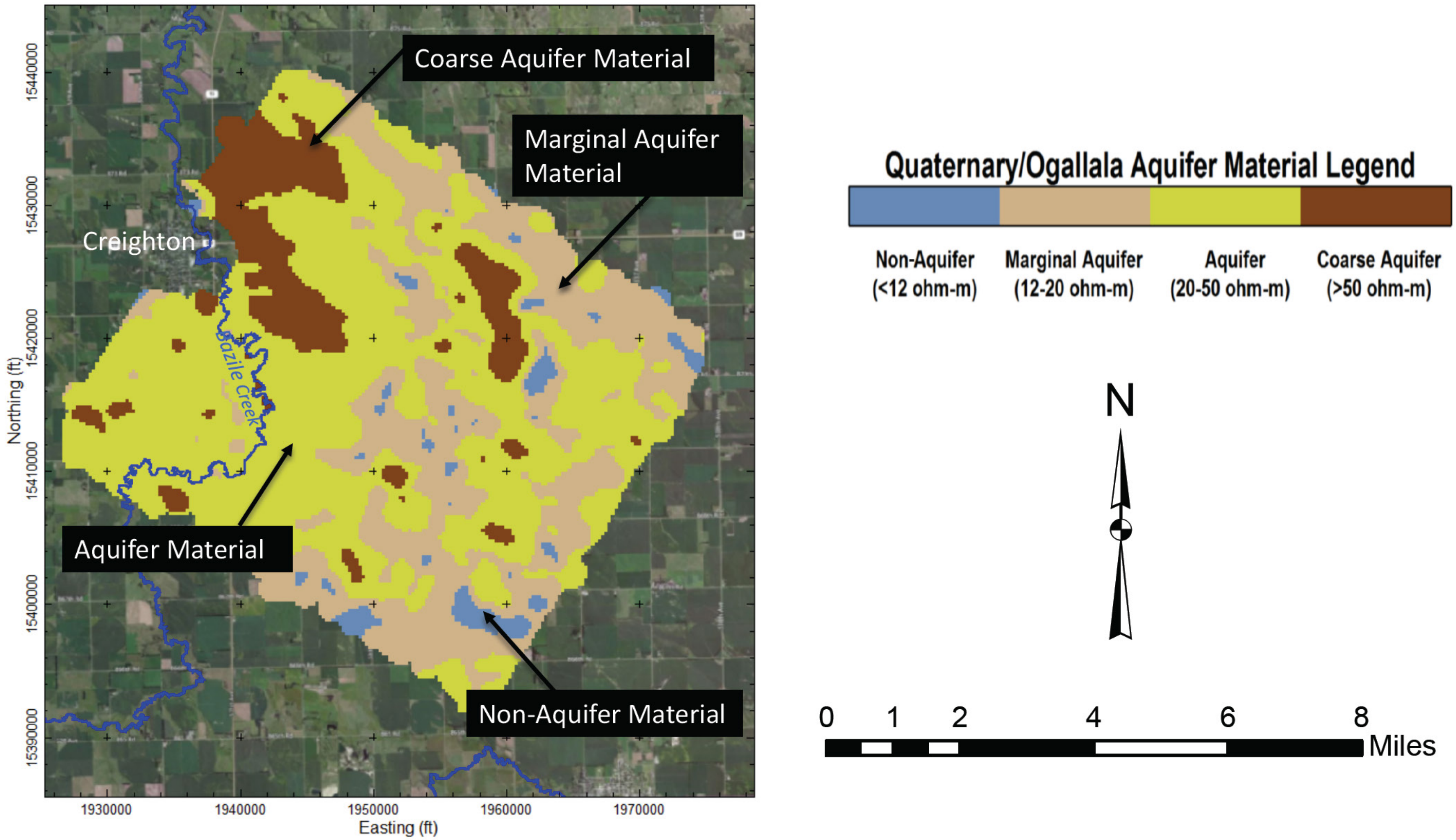


Figure 5-61. Map of aquifer materials within the Creighton Water System survey area. The aquifer materials displayed are from the surface down to 10 feet below the surface. The yellow and brown colored areas mark the potential recharge zones. Map projection is NAD 83, UTM Zone 14 North.

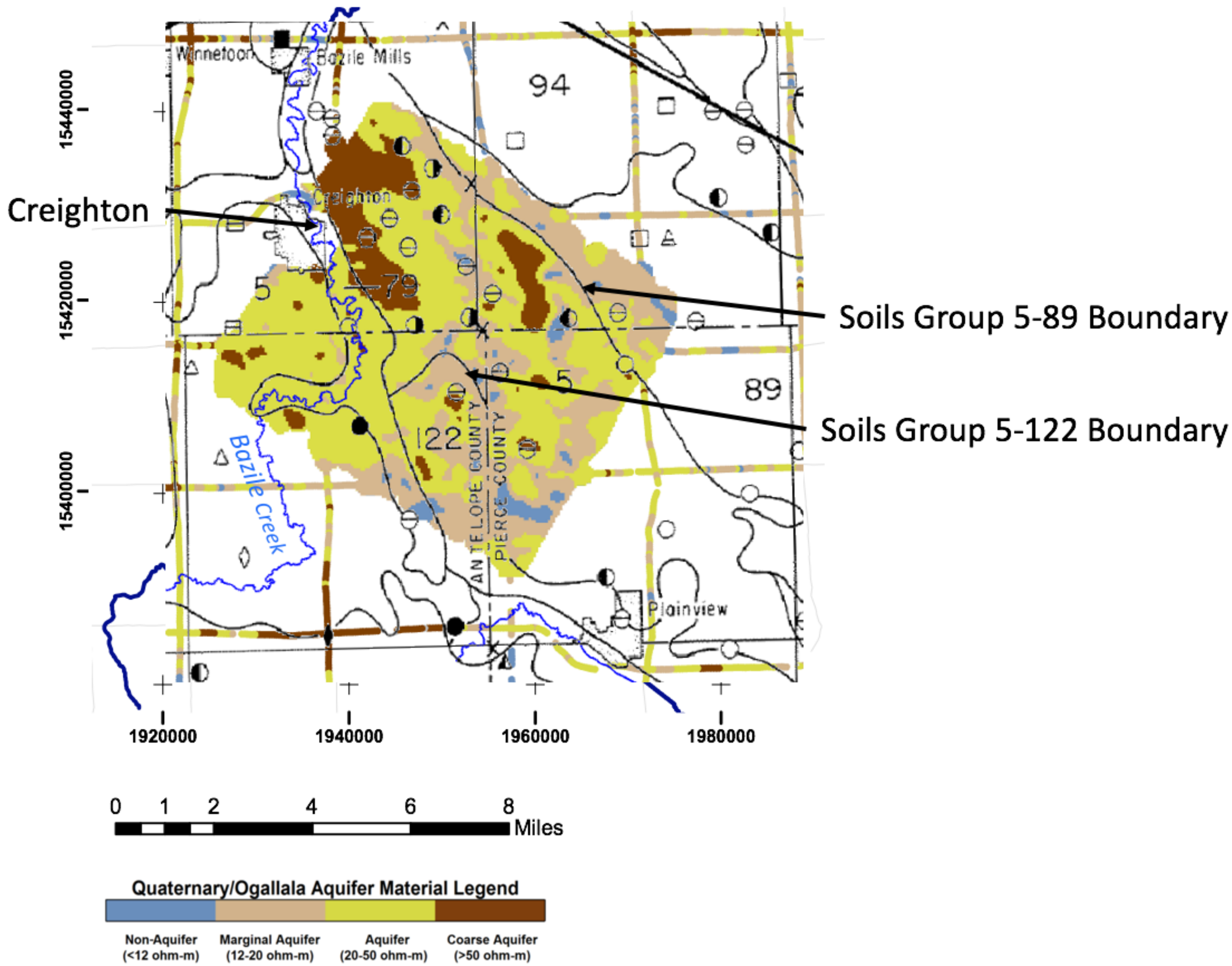


Figure 5-62. The same map as in Figure 5-61 (with the addition of a few nearby BGMA reconnaissance fight lines) showing the aquifer materials overlaid on the soils map modified from Gosselin (1991). Note the location of the soils group 5-89 boundary relative to the AEM-inferred aquifer materials. Map projection is NAD 83, UTM Zone 14 North.

a. b.

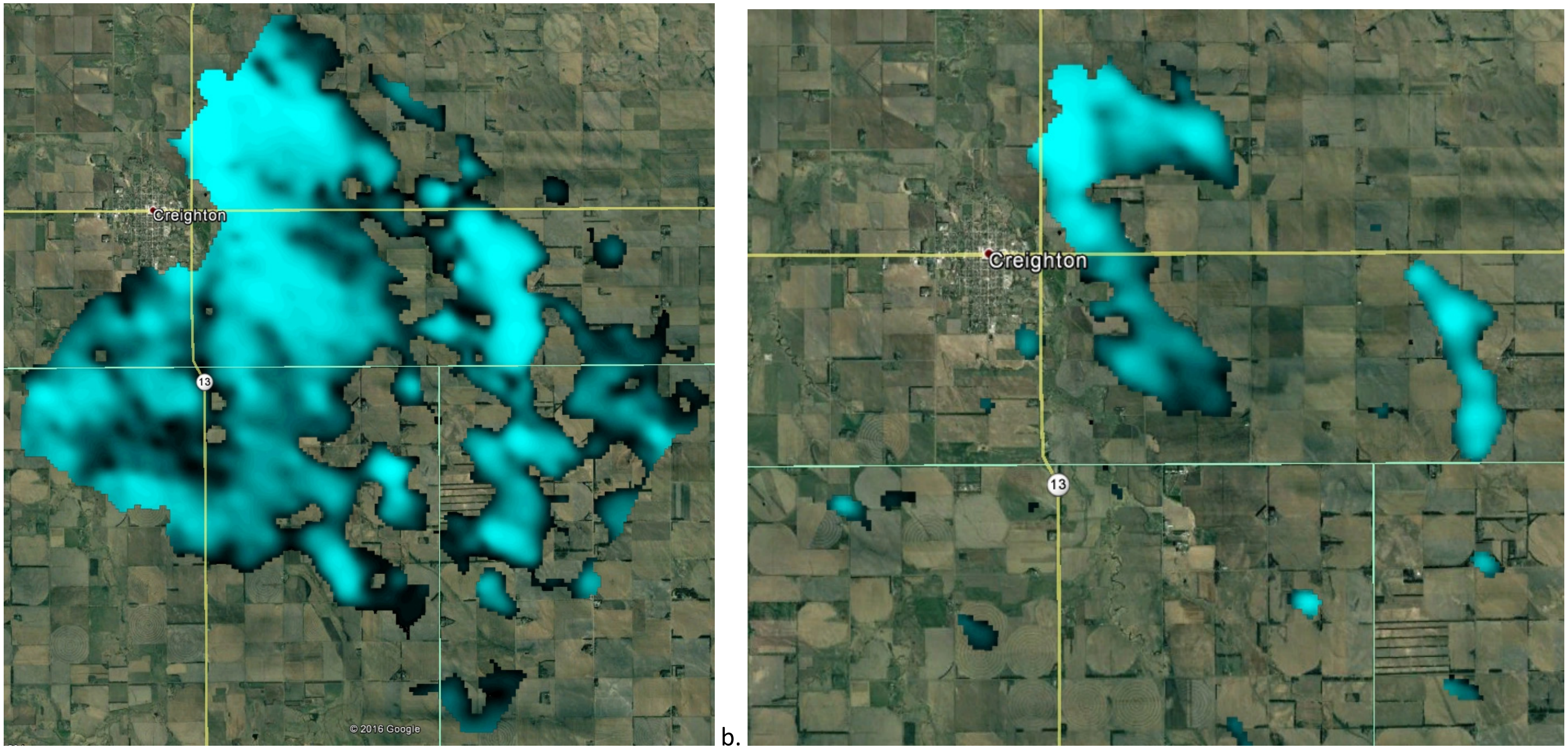


Figure 5-63. Potential aquifer recharge material in the Creighton Water System AEM survey area displayed as kmz's in Google Earth. a. KMZ of aquifer and coarse aquifer material; b. KMZ of coarse aquifer material only. Both these kmz's are included as deliverables in Appendix 14/KMZ.

5.8.3 West Knox Rural Water System Survey Area

The West Knox Rural Water System survey area was mapped in a similar manner to the Creighton Water System area – at a high resolution in order to construct a detailed 3D hydrogeologic framework. Approximately 7.8 square miles (approximately 4992 acres) of AEM data were collected, processed, and interpreted. As with the Creighton Water System Survey area, the closely spaced flight lines (here about 0.33 mile apart) covering the West Knox survey area allowed for nearly continuous mapping of the aquifer materials in the survey area. Also as with Creighton, part of that framework was the delineation of potential recharge zones in the West Knox area. Figure 5-64 is an AEM-interpreted aquifer materials map for the near surface (0-10 feet). Note that about half of the mapped area (the southwestern half) displays a yellow color indicating aquifer material, the other half being non-aquifer (blue) and marginal aquifer (tan) materials. There is apparently no coarse (brown) aquifer materials at the land surface in this area.

The areas with the yellow-colored aquifer materials in Figure 5-64 are the potential recharge areas in the West Knox Rural Water System area that will transmit the largest amount of water to the groundwater system. The blue-and tan-colored areas representing non-aquifer and marginal aquifer materials will transmit the least amount of water to the subsurface.

Figure 5-65 provides a comparison between the AEM-inferred aquifer materials and the soils map from Gosselin (1991). Notice the coincident location of the soils group 11-5 boundary with the yellow-colored AEM-inferred aquifer materials distribution on the map. Also, note the pockets of coarse aquifer material (brown-colored material) on the reconnaissance lines east of the West Knox Rural Water System survey area close to the 5-122 soils group boundary.

Thus the first layer (0 to 10 ft) of the interpreted AEM earth model of aquifer materials can be used to investigate areas of higher likelihood of aquifer recharge based on the locations of the coarse aquifer and aquifer materials areas. It is important to note that thin soils in the areas may have an impact on the recharge that is not indicated by the aquifer material mapping alone. On top of the potential of some soils to reduce recharge, land use and surface topography also need to be considered. To augment these maps with a better understanding of recharge further investigations on infiltration would need to be completed. However, the 0 to 10 foot maps do indicate areas that would allow recharge into the hydrogeological section if infiltration was through the soils was possible.

The Google Earth display presented in Figure 5-66.shows potential surface recharge material in the West Knox Rural Water System area. The image shows surface aquifer material in the survey area. This kmz is included as a deliverable in Appendix 14/KMZ.

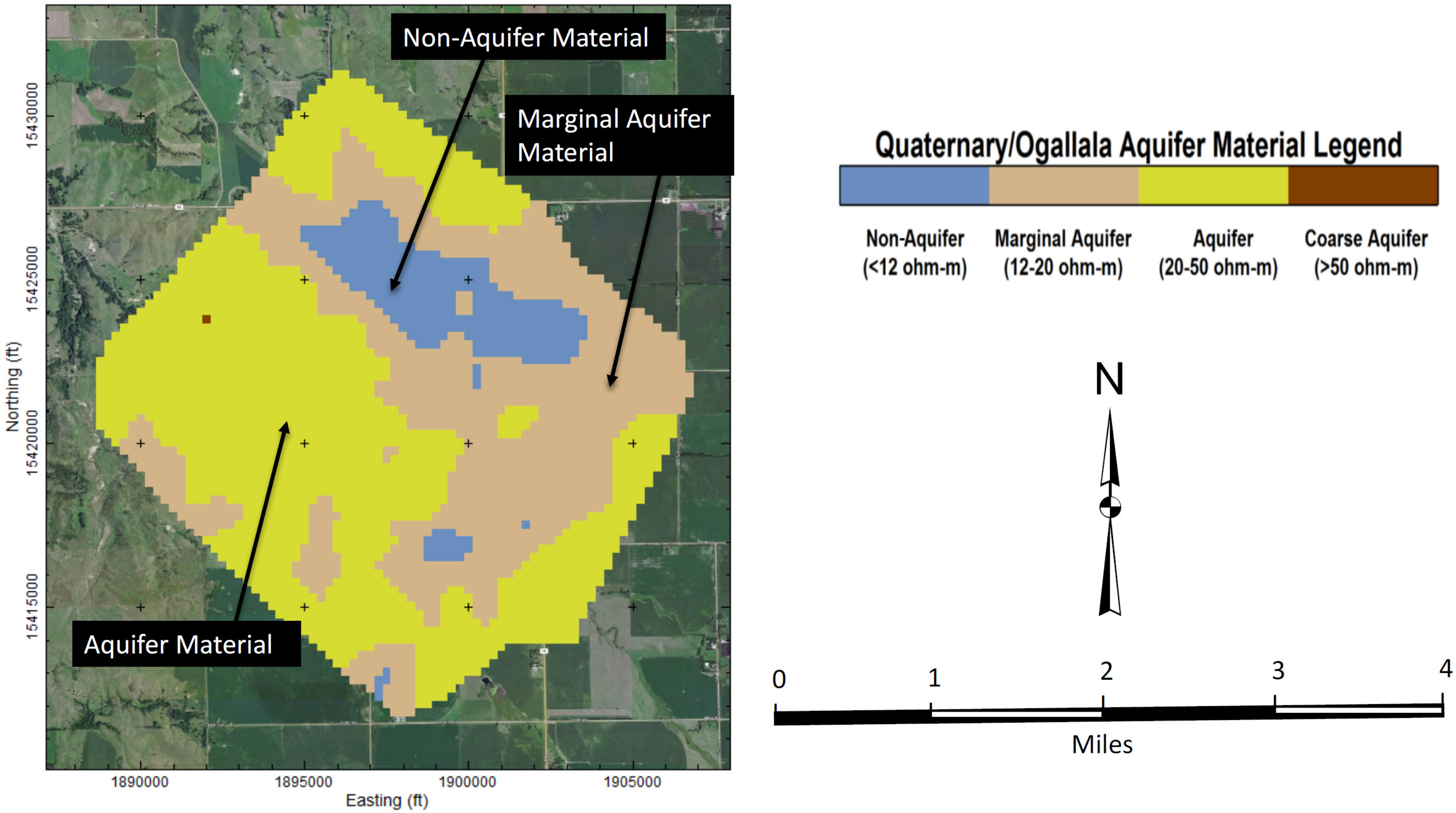


Figure 5-64. Map of aquifer materials within the West Knox Rural Water System survey area. The aquifer materials displayed are from the surface down to 10 feet below the surface. The yellow colored areas mark the potential recharge zones. Map projection is NAD 83, UTM Zone 14 North.

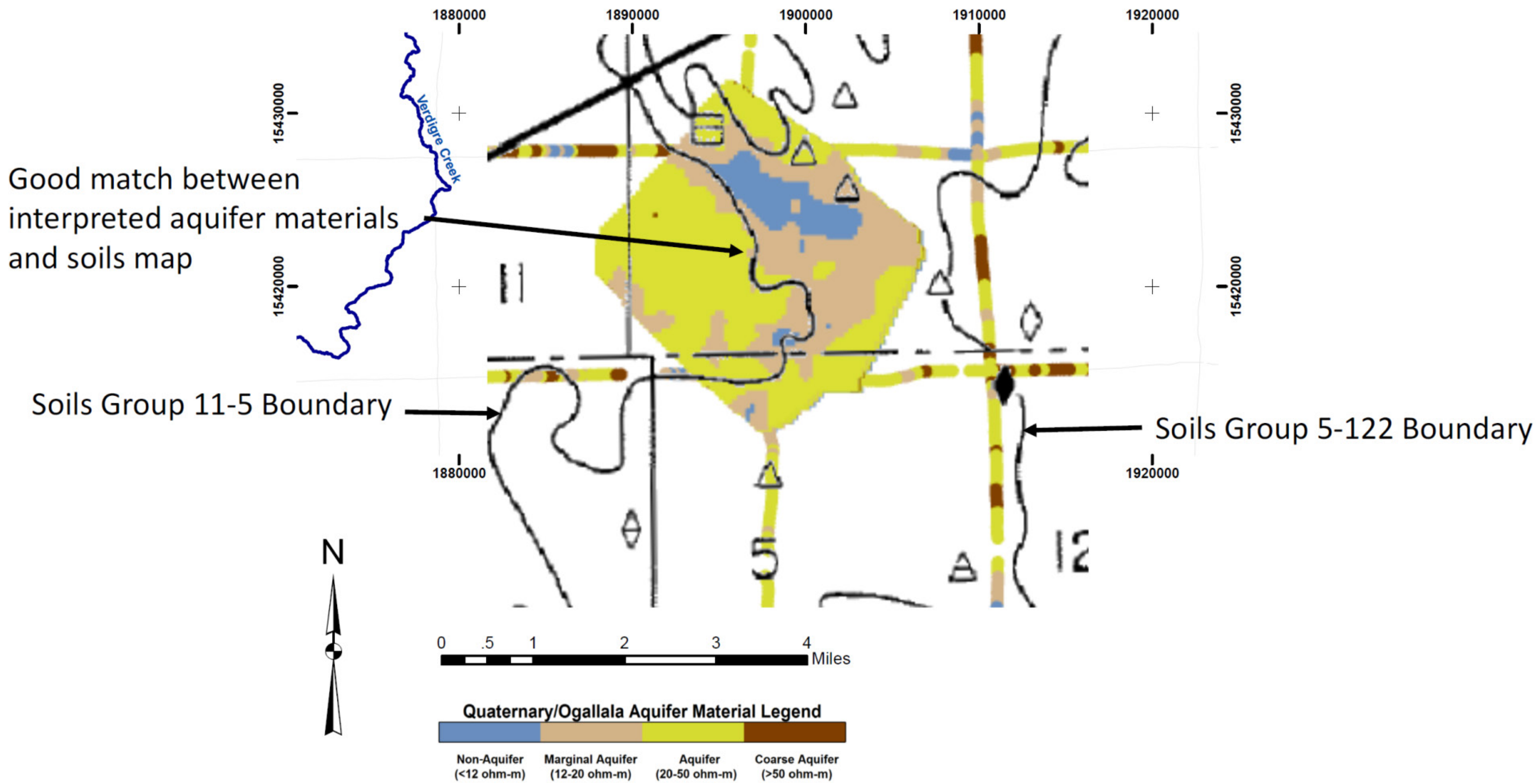


Figure 5-65. The same map as in Figure 5-64 (with the addition of a few nearby BGMA reconnaissance fight lines) showing the aquifer materials overlaid on the soils map modified from Gosselin (1991). Note the location of the soils group 11-5 boundary relative to the AEM-inferred aquifer material. Also, note the pockets of coarse aquifer material (brown-colored material) on the reconnaissance lines east of the West Knox Rural Water System survey area close to the 5-122 soils group boundary. Map projection is NAD 83, UTM Zone 14 North.

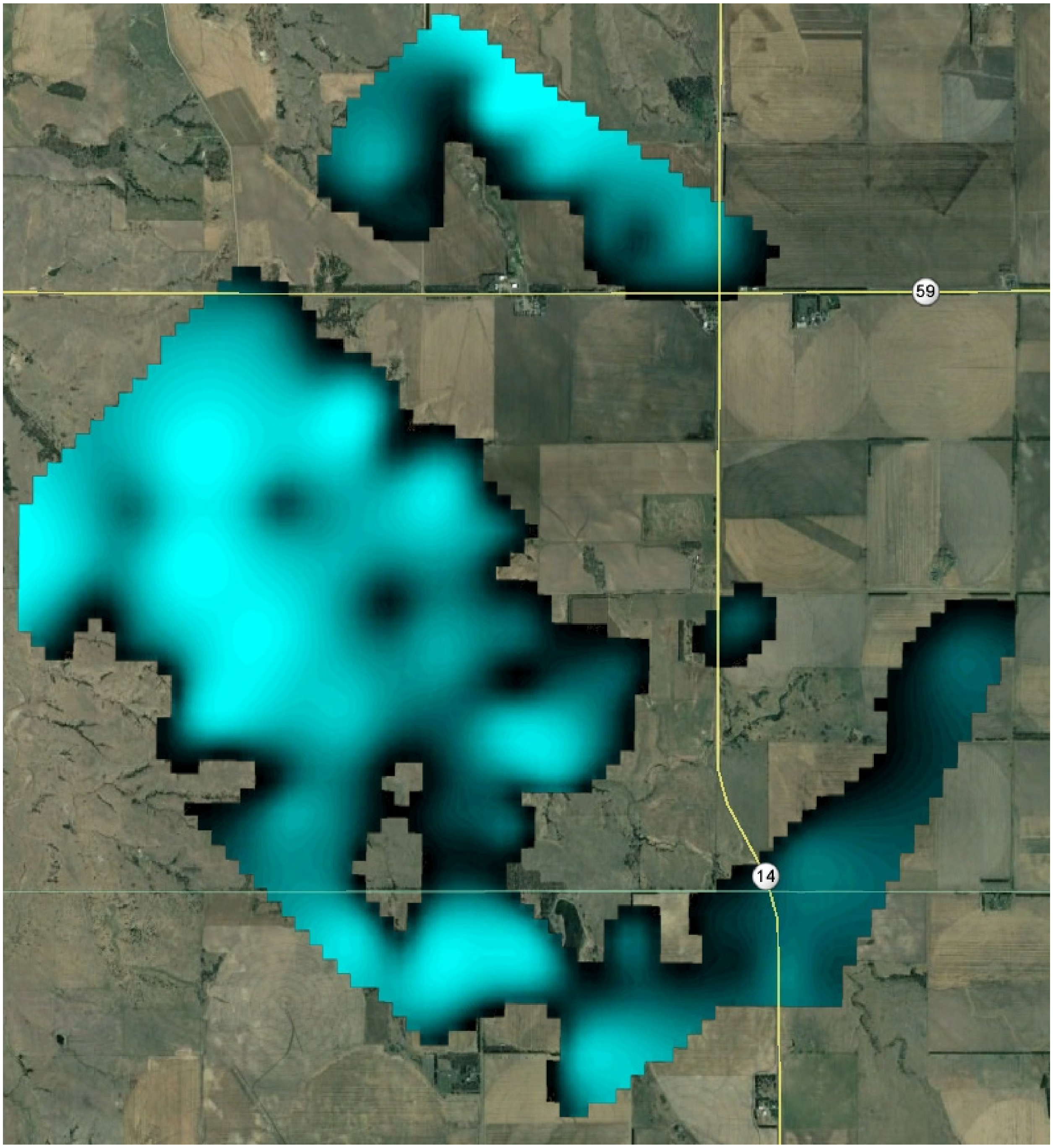


Figure 5-66. Potential aquifer material recharge area in the West Knox Rural Water System AEM survey block displayed as a kmz in Google Earth. The image displays detected aquifer material within the flight area. This kmz is included as a deliverable in Appendix 14\KMZ.

5.9 Key AEM Findings

5.9.1 Boreholes

As discussed above, borehole information was used to analyze the AEM inversion results. These included CSD (Within the BGMA, a total of 58 CSD holes contained lithology information, 50 holes contained stratigraphy information, and 30 holes contained geophysical information) and NE-DNR (A total of 2,934 registered wells contained usable lithology information), and West Knox Rural Water System boreholes (A total of 13 wells contained lithology information, and 11 wells contained geophysical information) were utilized in the analysis of the AEM inversion results.

5.9.2 Merging 2014 and 2016 AEM Databases

The BGMA survey area encompassed an additional 107.62 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 BGMA and the Creighton Water System. 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.

5.9.3 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***), Tertiary Ogallala (***To***), Cretaceous Pierre (***Kp***), and Cretaceous Niobrara (***Kn***). The interpretive process benefited from the use of CSD, NE-DNR, and West Knox Rural Water System 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 as Appendices by flight area as well as the interpretative surface grids.

5.9.4 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.

5.9.5 Hydrogeological Framework of the BGMA

The AEM reveals considerable variability in the Quaternary and Tertiary deposits across the northern BGMA. The subsurface distribution of materials can be generally characterized into four somewhat overlapping, but distinct, areas with smaller localized depositional features distributed at various locations within the survey area. These areas include the Quaternary and Ogallala Aquifer Area, the shallow ***Kp*** area, the glacial area, and the ***Kn*** bedrock area. The Quaternary and Ogallala Aquifer Area of the BGMA contains areas of saturated alluvium thickness up to 300 ft. The shallow ***Kp*** area is located in northwestern extent of the BGMA and is characterized by the bedrock/base of aquifer unit ***Kp*** being close to the surface. The glacial area is located in the northeastern and eastern areas of the BGMA and is characterized by ***Q*** glacial deposits overlaying pre-Pleistocene ***Q*** alluvial deposits or thin ***To*** deposits overlying bedrock of ***Kp*** or ***Kn***. The importance of the ***Kn*** bedrock area is that the character of the ***Kp*** is as an aquiclude and the ***Kn*** may contain fractures that will hold water

5.9.6 Hydrogeological Framework of the Creighton Water System Area

The Creighton Water System Area is within the Quaternary and Tertiary Ogallala Aquifer system region. The area is composed of mostly aquifer materials. The area on the east side of Bazile Creek shows little to no ***To*** present. The area is dominated by aquifer materials and coarse aquifer materials that thin considerably around Bazile Creek with the ***Kp*** close to the surface. Some of the coarse aquifer material is above the water table and may not be saturated. However, it also shows that much of this coarse material is close to the surface and may serve as a conduit for recharge.

5.9.7 Hydrogeological Framework of the West Knox Rural Water System Area

The West Knox Rural Water System survey area is also within the Quaternary and Tertiary Ogallala Aquifer system region. The area is characterized by being composed of mostly aquifer materials composed of predominately of ***To*** with ***Q*** deposits overlaying the ***To***. Much of the area is aquifer material with minor coarse aquifer material types. There are non-aquifer and marginal aquifer materials present on the top of some of the AEM profiles and at the bottom of the sections above the ***Kp*** bedrock.

5.9.8 Creighton Water System Estimation of Aquifer Volume and Water in Storage

The non-aquifer material has an estimated volume of 158,333 acre-ft and contains 63,333 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 482,282 acre-ft and contains 168,798 acre-ft, aquifer material has an estimated volume of 1,782,523 acre-ft and contains an estimated volume of 356,504 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 357,775 acre-ft for a total of 89,443 acre-ft of groundwater in storage. The amount of groundwater in storage for all material groups is 678,078 acre-ft. Non aquifer materials in the Creighton survey area will yield approximately 1,266 acre-ft, marginal aquifer materials will yield approximately 8,440 acre-ft, aquifer materials will yield 35,650 acre-ft, and the coarse aquifer material will yield approximately 13,416 acre-ft. A total of 57,506 acre-ft is available from the combined aquifer and coarse aquifer materials.

5.9.9 West Knox Rural Water System Estimation of Aquifer Volume and Water in Storage

The non-aquifer material has an estimated volume of 110,490 acre-ft and contains 44,196 acre-ft of groundwater in storage, marginal aquifer material has an estimated volume of 118,818 acre-ft and contains 41,586 acre-ft, and aquifer material has an estimated volume of 403,659 acre-ft and contains an estimated volume of 90,731 acre-ft of groundwater in storage. The coarse aquifer material contains an estimated volume of 24,085 acre-ft for a total of 6,021 acre-ft of groundwater in storage. The amount of groundwater in storage for both material groups is 182,534 acre-ft. Non aquifer materials in the West Knox survey area will yield approximately 884 acre-ft. marginal aquifer materials will yield 2,079 acre-ft, aquifer materials will yield 8,073 acre-ft and the coarse aquifer material will yield approximately 903 acre-ft. A total of 11,939 acre-ft is available from the combined aquifer and coarse aquifer materials.

5.9.10 Potential Recharge Zones within the BGMA

There are locations where the AEM flight lines intersect and both lines show either aquifer or coarse aquifer material. These locations should be considered as higher likelihood for better recharge because of the 2D spatial nature of the aquifer material distribution. The opposite is also true – there are locations within the BGMA where two flight lines intersect and both lines show non-aquifer or marginal material; those areas will likely not be optimal recharge locations. An overlay of the AEM-inferred aquifer materials on soil maps of the area from Gosselin (1991) suggest areas where the interpreted aquifer materials and the soil types are very similar and some other areas where they are not similar. This may be due to the shallow nature of soil sampling and/or the averaging of the first 10 feet due to the nature of the AEM technique.

5.9.11 Potential Recharge Zones within the Creighton Water System AEM Survey Area

A display of the AEM-inferred aquifer materials in the first 10 ft indicates that while there is some heterogeneity in the aquifer materials, it is quite easy to identify the areas of aquifer materials that will transmit the most (aquifer and coarse aquifer materials), and the least (non-aquifer and marginal aquifer materials), amounts of water from the surface down to the groundwater system. An overlay of the AEM-interpreted aquifer materials on the Gosselin (1991) soil maps show strong correlation between the interpreted aquifer materials and the boundaries of the 5-89 and 5-122 soil groups.

5.9.12 Potential Recharge Zones within the West Knox Rural Water System AEM Survey Area

An examination of the AEM-interpreted aquifer materials within the West Knox AEM survey block indicates that about half of the mapped area (the southwestern half) displays aquifer material suitable for recharge and the other half is identified as non-aquifer and marginal aquifer material types. There is apparently no coarse aquifer material at the land surface in this area. When these materials are overlain on the soil maps (Gosselin, 1991), there are coincident locations of the interpreted aquifer materials and the 11-5 soils group boundary. It should be noted that coarse aquifer material can be identified just east of the West Knox AEM survey block along several BGMA reconnaissance flight lines.

5.10 Recommendations

Recommendations provided to the client in this section are based on the interpretation and understanding gained from adding the AEM data to existing information and from discussions with the clients about their needs.

AGF is providing a hydrogeologic framework report that includes maps of aquifer materials and their relationships to current test holes and production groundwater wells, estimates of water storage capacity and water availability, and maps of estimated potential recharge areas.

5.10.1 Additional AEM Mapping.

The aquifer maps provided in this report represent general frameworks based on the BGMA AEM reconnaissance lines flown and the detailed frameworks developed for the Creighton Water System AEM survey area and the West Knox Rural Water System AEM survey area.

a. The detail provided in the hydrogeological interpretation of the Creighton Water System and the West Knox Rural Water System AEM survey areas allowed for confident development of hydrogeologic frameworks for each of these areas. The interpretations match particularly well with the CSD and NE-DNR test holes. If additional high resolution information is needed within the BGMA to resolve questions of resource management, it is recommended that additional areas of closely spaced lines or “block flights” be collected in order to develop detailed frameworks similar to those developed for the Creighton and West Knox Rural water systems survey area.

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

b. Since groundwater flowing into and out of the BGMA generally flows from west to east, understanding the hydrogeology of the areas up gradient from the BGMA would give useful information on the hydraulic connection between the aquifers. It is therefore recommended that additional reconnaissance lines be collected west, south, and possibly east of the current BGMA project area. In addition, the AEM data could be used for identification of additional sites for water supply and monitoring wells for water level and water quality data collection.

   The additional AEM data collection and interpretation could also be used to show the hydrological connections between aquifers and streams. Data collection along streams can provide information directly within the streambed. The additional studies on groundwater-surface water relationships could possibly be quantified as to impacts on stream flow and groundwater increases or losses. A good example of future work would be mapping in and around Verdigre Creek, a priority watershed.

5.10.2 Siting new test holes and production wells.

The framework maps and profiles provided in this report provide insight in 3D on the relationship between current test holes and production groundwater wells. All of the available well data for the BGMA were 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 can be sited in optimal locations for the purpose intended. This is efficient and saves money by planning the new locations with details not previously available.

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. Care should be taken to locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution. It is possible that new wells will need to be sited outside the current BGMA project area using future AEM data interpretation derived from the reconnaissance or detailed block surveys recommended above.

5.10.3 Aquifer testing and borehole logging.

Additional aquifer tests are recommended to improve estimates of aquifer characteristics. Aquifer Tests can be designed based on the AEM survey. Existing production wells could be used in conjunction with three or more installed water level observation wells.

Additional test holes with detailed well calibrated geophysical logging for aquifer characteristics is recommended. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, and induction logs. Plus, there are new technologies for collecting detailed aquifer characteristics from a borehole such as 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.

5.10.4 Recharge Zones.

The new hydrogeologic framework provides approximate areas of recharge from the ground surface to the groundwater aquifer. The discussions in Section 5.8, it is clear that the most detailed information for this purpose was obtained from the closely-spaced block flights in the Creighton and West Knox Rural water systems areas where nearly continuous data was collected. It is recommended that if detailed information is required for understanding recharge throughout the BGMA, then additional AEM data be collected and interpreted for closely-spaced flight lines utilizing an AEM system that has very high 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, water retention, etc. to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer.

6 Description of Data Delivered

6.1 Tables Describing Included Data Files

Table 6-1 describes the data columns in the ASCII *.xyz file BGMA_EM_MAG_UTM14n_feet.xyz as well as the Geosoft database file BGMA_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 BGMA_SCI_INV.gdb files and BGMA_SCI_INV.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 BGMA_InterpSurfaces_v1.gdb and BGMA_InterpSurfaces_v1.xyz. Table 6-6 describes the data columns of those files.

Table 6-7 describes the raw data files included in Appendix 14 – Deliverables. As discussed above, nine (9) flights were required to acquire the BGMA AEM data (Figure 4-5). Grouped by flight date, there are four (4) data flies included in Appendix 14 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 has 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”) and the ‘mask’ file (with the extension “*.lin”) which correlates the flight dates, flight numbers, and assigned line numbers.

ESRI Arc View Binary Grids of the surfaces that were used in the interpretation (DEM, water table) and derived from the interpretation (top of geological units) of the AEM and borehole are listed in Table 6-8.

Voxel grids were completed for the two dense flight blocks within the BGMA survey area including the West Knox Rural Water System and the Creighton Water System. The voxel grids were made using a 250 ft grid cell size and the model layer thickness (Table 4-4 in the previous section). The voxel grids were clipped below the bedrock surface interpreted from the AEM and the boreholes detailed in section 5.2.3. The bedrock surface grid “*BGMA_Bedrock_BaseofAquifer_top_elevation_ft.flt*” was used to clip the voxels, 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 West Knox Rural Water System and the Creighton Water System voxels.

In summary, the following are included as deliverables:

- Raw EM Mag data Geosoft database and xyz
- SCI inversion Geosoft database and xyz
- Borehole Geosoft databases and xyz
- Interpretations Geosoft database and xyz
- Raw Data Files - SkyTEM files *.geo, *skb, *.lin
- ESRI ArcView files – surface, topo, etc
- 3D voxel models as ASCII xyz for the Creighton and Knox flight blocks

KMZs for BGMA Reconnaissance, Creighton Water System, and West Knox Rural Water System flight lines (Discussed in Section 6.2)

Profile Analyst sessions for the Profiles and 3D voxels for Creighton Water System and West Knox Rural Water System (Discussed in Section 6.3)

Table 6-1: Channel name, description, and units for BGMA_EM_MAG_UTM14n_feet.gdb and BGMA_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 BGMA_SCI_Inv.gdb and BGMA_SCI_Inv.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]
NUMDATA	Number of data points	
RECORD	Data Record	
SEGMENTS	Number of segments in inversions	
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_1 THROUGH RHO_I_29	Inverted resistivity of each later	Ohm-m
RHO_I_STD1 THROUGH RHO_I_STD29	Standard deviation of inverted resistivity	Ohm-m
SIGMA_I_1 THROUGH SIGMA_I_29	Conductivity	S/m
DEP_BOT_1_M THROUGH DEP_BOT_29_M	Depth to the bottom of individual layers	Meters [m]
DEP_TOP_1_M THROUGH DEP_TOP_29_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_1_FT THROUGH DEP_BOT_29_FT	Depth to the bottom of individual layers	Feet [ft]
DEP_TOP_1_FT THROUGH DEP_TOP_29_FT	Depth to the top of individual layers	Feet [ft]
THK_1_M THROUGH THK_29_M	Thickness of individual layers	Meters [m]

Table 6-3: Files containing borehole information.

Database (*.xyz, *.gdb)	Description
Bazile_CSD_Geolog_Collar.	Geophysical logs from CSD wells
Bazile_CSD_Geolog_Data.	
Bazile_CSD_Lith_Collar.	Lithology logs from CSD wells
Bazile_CSD_Lith_Lith.	
Bazile_CSD_Strat_Collar.	Stratigraphy logs from CSD wells
Bazile_CSD_Strat_Strat.	
KnoxCountyLith_Collar.	Lithology logs from Knox County Wells
KnoxCountyLith_Lith.	
KnoxCountyGeolog_Collar.	Geophysical logs from Knox County Wells
KnoxCountyGeolog_Data.	

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

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

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

Parameter	Description	Unit	Type of Log
DH_East	Easting of boreholes, NAD83, UTM Zone 14	Feet [ft]	All
DH_North	Northing of boreholes, NAD83, UTM Zone 14	Feet [ft]	All
DH_RL	Elevation of top of borehole	Feet [ft]	All
DH_From	End of interval	Feet[ft]	Strat, Lith
DH_To	Start of interval	Feet [ft]	Strat, Lith
DH_Strat_Code	Code used to indicate type of stratigraphy		Strat
DH_Soil_Code	Code used to indicate type of lithology		Lith
DH_Description	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 65in	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 BGMA_InterpSurfaces_v1.gdb and BGMA_InterpSurfaces_v1.xyz.

Parameter	Description	Unit
X_ft	Easting NAD83, UTM Zone 14	Feet [ft]
Y_ft	Northing NAD83, UTM Zone 14	Feet [ft]
Z_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
Distance	Down line distance from start of flight line	Feet [ft]
RHO[0] through RHO[28]	Array of Inverted model resistivities of each later	Ohm-m
RHO_STD[0] through RHO_STD[28]	Array of standard deviations of inverted model resistivities of each layer	
RESDATA	Inversion model residuals of each individual sounding	
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_1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
AquiferTyp[0] through AquiferTyp[28]	Array of Aquifer Material types: 0 - Bedrock; 1 - Non-Aquifer Material; 2 - Marginal Aquifer Material; 3 - Aquifer Material; 4 - Coarse Aquifer Material	Integer Array
Top_AqMat1	Elevation of top of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Bot_AqMat1	Elevation of bottom of upper Aquifer Material (20 - 50 ohm-m)	Feet [ft]
Top_AqMat2	Elevation of top of 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_CoarseAquifMat	Elevation of top of Coarse Aquifer Material (>50 ohm-m)	Feet [ft]
Bot_CoarseAquifMat	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]
Kp	Elevation of the top of the Cretaceous Pierre shale.	Feet [ft]
Kn	Elevation of the top of the Cretaceous Niobrara Formation.	Feet [ft]
Kc_Kgg	Elevation of the top of the Cretaceous Carlile, Graneros Shale.	Feet [ft]
Kd	Elevation of the top of the Cretaceous Dakota Formation.	Feet [ft]
Penn	Elevation of the top of the Pennsylvanian units.	Feet [ft]
M	Elevation of the top of the Mississippian units.	Feet [ft]
***	No data or unit not detected	

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	20160725_BGMA_Linefile.lin	Production file listing dates, flights, and assigned line numbers

Table 6-8: Files containing ESRI ArcView Binary Grids

Grid File Name	Description	Grid Cell Size (feet)
BGMA_Bedrock_BaseofAquifer_top_elevation_ft.flt	Grid of the Bedrock composed of Kp and Kn which is also the Base of the Aquifer elevation NAVD88 (feet)	100
BGMA_DEM_Elevation_ft.flt	Grid of the Digital Elevation Model (DEM) downloaded from the National Elevation Dataset (NED) August 2016 NAVD88 (feet)	100
BGMA_Kn_top_elevation_ft.flt	Grid of the top of the Kn elevation NAVD88 (feet)	500
BGMA_Kp_top_elevation_ft.flt	Grid of the top of the Kp elevation NAVD88 (feet)	100
Knox_surface_resistivity.flt	Grid of the 0-10 ft resistivity layer of the West Knox Rural Water System (ohm-m)	250
Creighton_surface_resisitivity.flt	Grid of the 0-10 ft resistivity layer of the Creighton Water System (ohm-m)	250

Table 6-9. Channel name, description, and units for Knox_voxel_Resitivity.* and Creighton_voxel_Resitivity.*xyz and *.gdb.

Parameter	Description	Unit
X	Easting NAD83, UTM Zone 14	Feet [ft]
Y	Northing NAD83, UTM Zone 14	Feet [ft]
Depth	Depth negative down surface at 0.0	Feet [ft]
Knox_ or Creighton_Resistivity	Voxel cell resistivity value	Ohm-m
Elevation	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, a Google Earth .kmz file was created to view the geophysical AEM flight line locations and interpreted geologic data. Unique .kmz files were created for each individual flight line in 10-mile segments or shorter, as well as a .kmz file for all flight lines. Within the specialized kmz files, the AEM flight line is shown as well as place marks at each location where there are interpreted geologic results. The attribute data for each unique place mark contains location information plus the elevations of tops and bottoms of aquifer material and coarse aquifer material as well as bedrock, the water table (1995), and the elevations of the tops of the Tertiary Ogallala and the Cretaceous Pierre and Niobrara formations. These .kmz files are located within the “BGMA Report/Appendix 14/KMZ/BGMA_Prof” folder. Also in this folder is a “GoogleE_Readme_BGMA.pdf” file that provides instructions in regards to the “Settings” changes that need to be made in Google Earth, and how to use the .kmz files in Google Earth including a legend of what attributes are displayed when an AEM sounding location is clicked. This file is repeated below as a convenience. An example of the kmz is presented in Figure 6-1.

6.2.1 Included README for “BGMA_v1.kmz”

Data Files - Please copy the folder *BGMA_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 and personal data.

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

STEP 5: The BGMA_v1.kmz file within the folder named *BGMA_Prof* can now be opened and viewed in Google Earth (Figure 6-1).

Data Displayed:

Easting_ft – Easting coordinate in NAD83, UTM 14N, in feet

North_ft – Northing coordinate in NAD83, UTM 14N, in feet

Elev_ft – Elevation in feet

WatrTbl_ft – Water table elevation, in feet

Top_AqMat1 – Elevation of Top of Upper Aquifer Material zone, in feet

Bot_AqMat1 – Elevation of Bottom of Upper Aquifer Material zone, in feet

Top_AqMat2 – Elevation of Top of Lower Aquifer Material zone, in feet

Bot_AqMat2 – Elevation of Bottom of Lower Aquifer Material zone, in feet

Top_CorsAq – Elevation of Top of Coarse Aquifer Material zone, in feet

Bot_CorsAq – Elevation of Bottom of Coarse Aquifer Material zone, in feet

Bedrock – Elevation of Bedrock surface, in feet

To – Elevation of Top of Tertiary Ogallala Formation, in feet

Kp – Elevation of Top of Cretaceous Pierre Formation, in feet

Kn – Elevation of Top of Cretaceous Niobrara Formation, in feet

Profile – Link to Interpreted AEM profile images

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

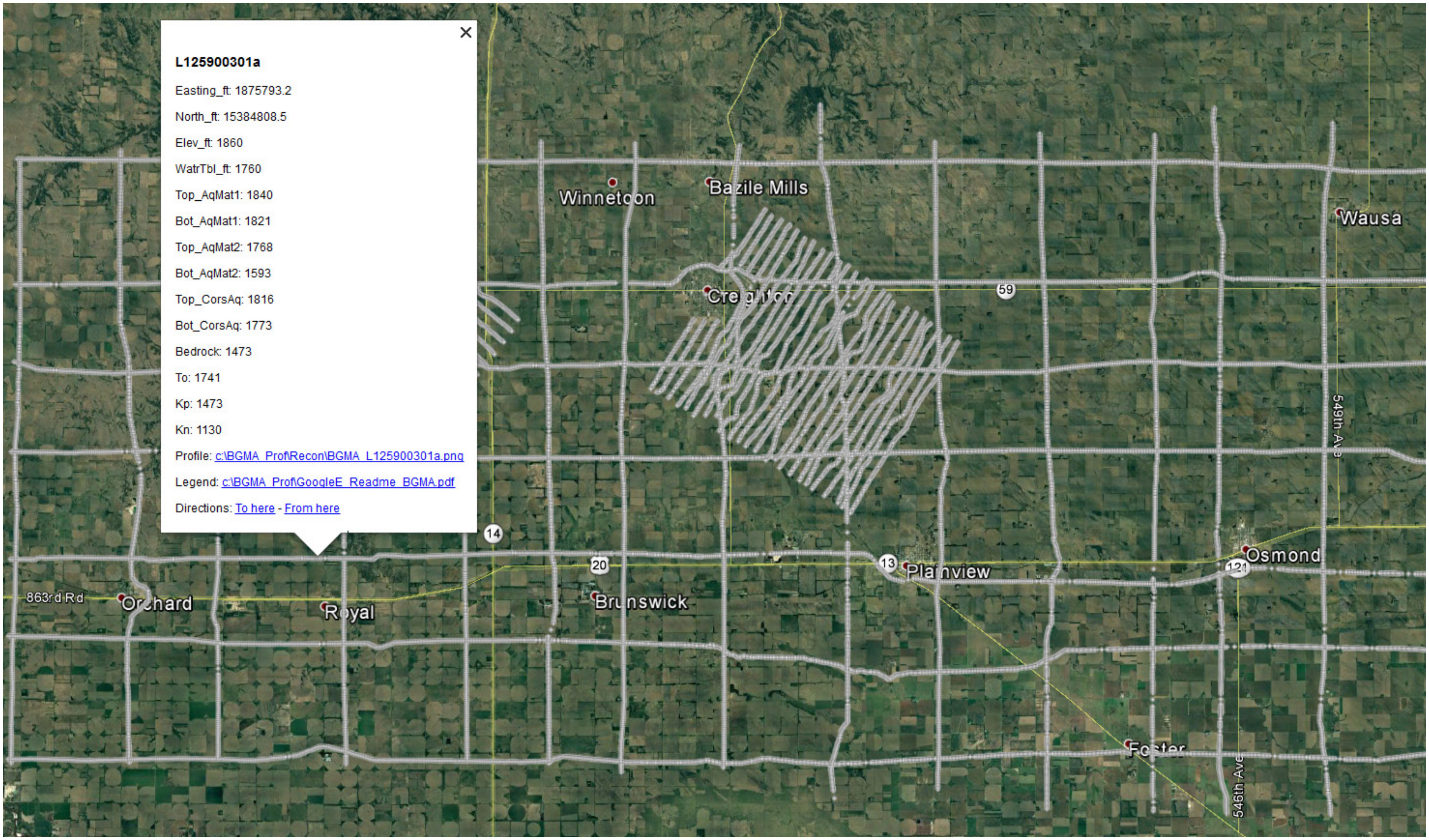


Figure 6-1. Example of Google Earth image for BGMA kmz.

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 14\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
Bazile Groundwater Management Area	2D	BGMA_ Resistivity_Interp_Profiles.egs
Bazile Groundwater Management Area	3D	BGMA_3D_FenceDiagrams.egs
West Knox Rural Water System	3D	Knox_3D_Voxel.egs
Creighton Water System	3D	Creighton_3D_Voxel.egs

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