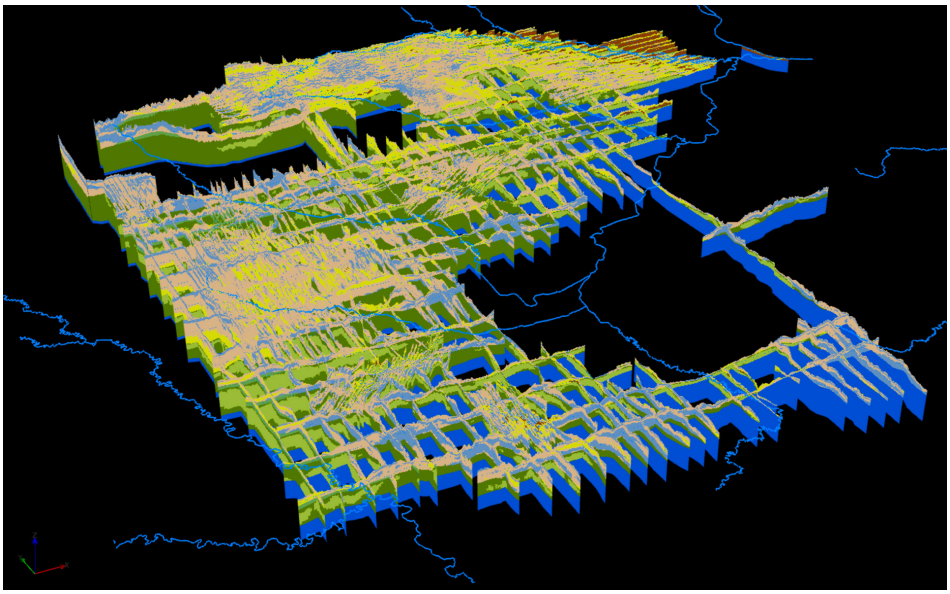
December 4, 2019

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



Prepared for the:
Lower Platte South Natural Resources District
3125 Portia Street
Lincoln, NE 68521

Submitted by:
Aqua Geo Frameworks, LLC
130360 County Road D
Mitchell, NE 69357

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

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

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

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



Executive Summary

Aqua Geo Frameworks, LLC. (AGF) is pleased to submit this report titled "Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Regions of the Eastern Nebraska Water Resources Assessment Area" Chapter on the Lower Platte South Natural Resources District.

An understanding of the hydrogeological framework in the survey area is desired to assist in resource management. AGF entered into an agreement with the Eastern Nebraska Water Resources Assessment (ENWRA) to collect, process, and interpret airborne electromagnetic (AEM) data, in conjunction with other available background information, to develop a 3D hydrogeologic framework of the Lower Platte South Natural Resources District (LPSNRD) project area and to recommend future work to enhance groundwater management activities.

The scope of work for this project was as follows:

1. SCOPE OF WORK

1.1 An AEM survey utilizing the SkyTEM304M system was flown over the LPSNRD project area. These flights have been provided as preliminary AEM inversions and the final AEM data and inversions are included as a product attached to this data report.

1.2 AGF began project planning upon signing of the project between AGF and the ENWRA. This work included flight plans, database development, and review of hydrogeologic and geologic work for the area. The LPSNRD assisted in providing information such as power line maps, test hole databases, and related aquifer characteristic studies, if available.

Upon conclusion of the design process the LPSNRD reconnaissance flight lines had a maximum length of approximately 35 miles (56 km) in the north-south direction and about 29 miles (47 km) in the east-west direction. The reconnaissance flight lines were separated by approximately 1.0 miles (1.62 km) in both east-west and north-south directions and block flight lines were separated by about 650 feet to 1,000 feet (200 m – 300 m).

1.4 AGF acquired AEM data over the LPSNRD, commencing 17 June 2018 and finishing on 12 July 2018, to support development of the hydrogeological framework. During this time frame data were collected in other adjacent NRD's surrounding LPSNRD. Approximately 1,990 line-miles (3,225 line-kilometers) were acquired over the LPSNRD AEM survey area. Status reports of the flying were provided to the Contract Representative of ENWRA daily, including the areas flown, production rates, and flight plan for the following day.

1.5 AGF processed and conducted quality assurance and quality control (QA/QC) procedures on all data collected from the acquisition system. AGF delivered preliminary data and inversions on June 19 - July 13, 2018. After final processing approximately 1,711-line-miles (2,773-line kilometers) were retained for inversion amounting to a retention rate of 86.0%. This high rate is the result of careful flight line planning and design given the infrastructure that was encountered during the acquisition

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

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

2. KEY FINDINGS

2.1 Boreholes - Information from boreholes was used to analyze the AEM inversion results and was critical for all areas in the LPSNRD. The CSD (Nebraska Conservation and Survey Division) and the NE-DNR (Nebraska Department of Natural Resources) registered wells were used extensively in the interpretation of the geological contacts. In many areas the wells encountered saltwater which is characterized by the AEM but is seldom indicated in the CSD or NE-DNR wells. The dependence on just boreholes for geologic interpretation also has its limitations due to errors in the entry of the logs into the database, improperly located or documented wells, and improper stratigraphic/lithology picks, and/or other errors. These errors in the boreholes are usually encountered in the NE-DNR registered wells. Very rarely are inconsistencies encountered in the oldest of the NE- CSD wells. The limited errors in the CSD wells may very well be due to poor positioning from a time before GPS and modern survey methods. As a guide in the interpretation of the AEM***,*** a bedrock surface was prepared using the of CSD and NE-DNR borehole logs and surface maps of the geologic outcrops. As in all surveys of this nature, the use of boreholes with AEM needs to be approached in a thoughtful and considered manner as to the value of information from an individual borehole.

2.2 Digitizing Interpreted Geological Contacts - Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q),*** Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, Nebraska Oil and Gas Conservation Commission (NEOGCC), and NE-DNR borehole logs. Geologic maps of surface outcrops and geologic maps contributed to the understanding of geologic interpretation. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the ***Q*** aquifer material mapping is included in the appendices as well as interpretative surface grids. The surfaces in this study only include the data from 2018; No merging was done with previous studies conducted in the LPSNRD.

2.3 Resistivity/Lithology Relationship - Assessment of the sediment character in the Quaternary aquifer system and the bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. The resistivity relationship that was used in previous studies of Carney et al. (2015a, 2015b) were used in this project. The resistivity thresholds used were <12 ohm-m (Non-Aquifer Materials), 12-20 ohm-m (Marginal), 20-50 ohm-m (Aquifer Materials), and >50 ohm-m (Coarse Aquifer Materials (e.g. sand-rich intervals). This allowed for the aquifer material characterization of the ranges of resistivities present in the major geologic units described in this report.

2.4 Hydrogeological Framework of the LPSNRD - The 2018 LPSNRD AEM survey reveals variability in the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) deposits across the LPSNRD AEM survey area that make up the aquifer materials. The ***Q*** makes up the aquifer materials overlying the Cretaceous bedrock units of which the ***Kd*** Sandstone/Sand Dominant material is the aquifer material. Across the AEM survey area, the Aquifer Material and Coarse Aquifer Material exist in paleovalleys, glacial outwash and glaciotectonic deposits that are separated by ***Q*** Marginal and Non-Aquifer material deposits. These separating ***Q*** Marginal and Non-Aquifer Material deposits are glacial till and loess that can be more than 500 ft thick. ***Q*** Aquifer and Coarse Aquifer materials are thickest in the paleovalleys located across 2018 survey areas. There are significant amounts of saltwater within the ***Kd*** and ***IP*** as the saltwater can be widespread across some of the Block areas. This can be a future issue as wells get drilled deeper to supply domestic purposes or as groundwater is pumped, there may be upwelling of the saltwater. Areas of glaciotectonic movement of sediment can impact areas of the LPSNRD due to the mixing of aquifer materials causing the development of both water bearing materials as well boundaries to flow in unpredictable areas. These areas are where sands and gravel are thrust up on the top of tills as the glacier moved over previous deposits. They can be observed in areas where isolated sands and gravels are on top of till deposits. Note that a majority of these are above the water table. Many of the Block areas have limited groundwater well development in the ***Q*** due to the lack of water bearing sediments. In these areas the ***Kd*** Sandstone/Sand dominant materials are the primary and/or secondary source of groundwater to the wells. Note that many of the wells in the ***Kd*** have specific capacities of less than 5 gpm/ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Ceresco AEM Block of aquifer material below the 1995 CSD water table elevation is 89,321 acre-ft. The amount of extractable groundwater from Aquifer Material is 4,466 acre-ft and Coarse Aquifer Material is 162.1 acre-ft. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 980 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Davey Raymond AEM Block of Aquifer Material below the 1995 CSD water table elevation is 11,373 acre-ft. The amount of extractable groundwater from Aquifer Material is 568 acre-ft and Coarse Aquifer Material is 0 acre-ft. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 1,1050 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Denton AEM Block of Aquifer Material below the 1995 CSD water table elevation is 8,698 acre-ft. The amount of extractable groundwater from Aquifer Material is 246 acre-ft and coarse aquifer material is 56. While these materials will produce water, the yields and specific capacity will be reduced. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 782 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Dwight South AEM Block of Aquifer Material below the 1995 CSD water table elevation is 20,316 acre-ft. The amount of extractable groundwater from Aquifer Material is 1,015 acre-ft and Coarse Aquifer material is 0. While these materials will produce water, the yields and specific capacity will be reduced. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 847 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Emerald Pleasant Dale AEM Block of Aquifer Material below the 1995 CSD water table elevation is 20,593 acre-ft. The amount of extractable groundwater from Aquifer Material is 1,029 acre-ft and Coarse Aquifer material is 0. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 4,062 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Garland Malcolm AEM Block of Aquifer Material below the 1995 CSD water table elevation is 361,105 acre-ft. The amount of extractable groundwater from Aquifer Material is 18,055 acre-ft and Coarse Aquifer material is 0. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 3,121 acre-ft.

2.5 Potential Recharge Zones within the LPSNRD AEM Survey Area - Within the LPSNRD Reconnaissance AEM flight area, the highest rate of recharge can be expected along the river-stream valleys due to the presence of Aquifer and Coarse Aquifer materials and the uplands having deposits of Aquifer and Coarse Aquifer materials from the land surface down to the water table and beyond. Areas with Aquifer and Coarse Aquifer materials at the surface can also become conduits for infiltration of nitrates into the groundwater system. These areas exist in the river and stream areas and uplands of the AEM survey area where the reconnaissance lines are the basis for this determination. It should be noted that in these areas, the results shown in the interpreted recharge maps are based on actual AEM data. A potential solution for any nonpoint source water quality contamination is adding additional fresh surface water as recharge to select areas of rangeland that can dilute any potential nitrate contaminant problem occurring from cropland. Additional work can be done to identify where the best locations are for these type of management efforts, but this is limited in the LPSNRD due to the abundance of fine-grained material throughout the area.

The use of Block flights for the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcom 2018 AEM survey areas illustrate the preferred method of using AEM to identify areas where the potential for recharge to the aquifer can be higher and lower. Locations where the flight lines are closely spaced showing either Aquifer or Coarse Aquifer Material at the land surface should be considered as locations for higher likelihood for recharge because of the 2D and 3D spatial nature of the aquifer material distribution. The opposite is also true where AEM data analysis shows Non-Aquifer or Marginal Aquifer Material. Those areas will likely not be optimal recharge locations. The areas throughout the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcom AEM survey areas have mixed potential recharge that is limited across most of the area due to the ***Q*** dominance of the Non-Aquifer and Marginal Aquifer materials at, or just below, the ground surface.

2.6. Hydrologic Connection Between Groundwater and Surface Water in the LPSNRD AEM Survey Area - The AEM data and interpretation provides detailed empirical data for determining earth materials on the surface and at depth that are related to aquifer characteristics. The ***Q*** aquifer materials are a guide, with Coarse Aquifer and Aquifer Materials being the most able to recharge, store, and provide groundwater flow. The Marginal Aquifer Material provides limited groundwater flow with poor recharge and the Non-Aquifer Material provides virtually no groundwater flow. The areas mapped and discussed in this report show areas that contain large amounts of Marginal and Non-Aquifer deposits. These areas can be boundary conditions between different parts of the groundwater system and the surface water of the area. Any planning or detailed analysis related to groundwater and surface water relationships should take this information into account.

2.7 Saltwater Areas in the LPSNRD AEM Survey Area -The AEM easily detects conductive materials in the subsurface. The addition of saltwater to earth materials lowers the bulk resistivity. In many of the areas of the LPSNRD low resistivities below 4 ohm-m are detected. These areas are most certainly impacted by saltwater that are long no to exist in the areas. The maps developed in this study can be used to further delineate control areas to avoid the interception of saltwater.

3. RECOMMENDATIONS

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

3.1 Preparing the Results from AEM Hydrogeological Investigations for Groundwater Modeling - The LPSNRD has acquired AEM data for groundwater management purposes over the past 12 years. With the completion of this current study, it is recommended that additional work be undertaken to integrate the previous studies into a unified geologic model to describe the subsurface in detail. The output from this work can be used for monitoring well placement for water quantity and quality studies, provide detailed groundwater flow path studies for water quality that can estimate time and direction of flow, provide detailed estimates groundwater surface water relationships and create optimal datasets for use in groundwater models and assist in their use. With the investment in the AEM that the LPSNRD has undertaken this next step will provide a final product that can be easily accessed by the staff and public for future groundwater management.

3.2 Additional AEM Mapping - No additional AEM reconnaissance mapping is required for the LPSNRD at this time. Block data acquisition should only be considered depending on management needs of the LPSNRD for the purpose of infilling areas where the reconnaissance surveys did not provide enough detail to clearly define the hydrostratigraphy.

3.3 Update the Water Table map - The groundwater data used in the analyses presented in this report utilized the 1995 CSD water table map which is now 24 years old. Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. The areas of glacial till and loess covering the parts of the district will need great care in developing a water level map of potentiometric heads due to the confined to semiconfined nature of the area. Use of the data collected in this survey and future surveys will provide the best possible water table and conditions map for the district.

3.4 Planning new test holes and production wells – The AEM hydrogeological framework profiles, maps, and surfaces provided in this report provide great insight in 3D on the relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the LPSNRD area was used in building the framework maps and profiles. Additional information from previous groundwater reports were helpful in this work. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in more optimal locations. The location of new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution. A good example of this would be confined aquifers with large volumes of coarse aquifer and aquifer material with minimal sedimentary boundary conditions. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the LPSNRD.

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

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailing aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR) at a reduced cost when compared to traditional aquifer tests. This is a quick and effective way to characterize porosity and water content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth.

3.6 Recharge Zones - The LPSNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. Reconnaissance-level AEM investigations provide limited detailed information between the lines for understanding recharge throughout the survey area. It is recommended that future work integrate new soils and land use maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer. A potential solution to water quality, quantity, and stream depletions is adding additional fresh surface water as recharge to select areas of rangeland or other areas. Additional work can be done to identify where the best locations are for these type of management efforts. This information can and has been used in Nebraska to improve Well Head Protection Areas by refining the estimated travel time estimates and the boundary areas.

3.7 Managed Aquifer Recharge – The areas which may have potential for managed aquifer recharge (MAR) are limited at best. However, additional detailed work focusing on this effort can provide potential sites. The detailed analysis suggested for this purpose would need to determine where viable opportunities for the LPSNRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping in new block flight locations and along the streams in the LPSNRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the LPSNRD for storage and release of water for stream flow and other uses.

3.8 Updating previous groundwater reports and Groundwater Management Plans - The groundwater reports and management plans should be updated with the AEM information. The addition of estimates of groundwater in storage, recharge areas, hydrologic connection to streams and consideration of managed aquifer recharge sites will greatly improve and groundwater management plan.

3.9 Assist the LPSNRD staff with additional interpretation and data analysis for groundwater management needs - The AEM reports provided to the district are complete, but there is always a need to extract and analyze the AEM data in conjunction with a particular management need or area. Examples include using the AEM data to define areas for management practices related to water quality problems, use the AEM data to site water well development, assist groundwater modelers with input

data sets for groundwater modeling, and define hydrologic connections between groundwater and surface water to name a few.

3.10 Development of Water Quality Maps using the AEM - While the AEM detected areas of saltwater within the LPSNRD, no characterization of the water quality was calculated. In many other areas of the US and the world, AEM has successfully been used to calculate the 3D distribution of water quality. To accomplish this, strategically placed drill holes and water quality sampling field campaigns need to be conducted to be used to calibrate the AEM resistivity distributions of the water quality. These control points provide the volumetric mixing relationships that are needed to deconvolve the pore water resistivity from the matrix or formation/earth materials resistivity. The LPSNRD has a valuable resource in the AEM data that can then be further utilized with limited sampling and new test hole drilling to provide a district-wide water quality map.

4. DELIVERABLES

In summary, the following are included as deliverables:

- Raw Data Files - SkyTEM files *.gex, *skb, *.lin
- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz in array and an individual column format by model layer
- Interpretations as ASCII *.xyz
- ESRI ArcView grid files – surface, topo, *.flt, *.grd, etc
- Voxel Grids of the AEM Block areas *.xyz
- 2D Profiles and 3D fence diagrams of the AEM survey lines

Google Earth KMZs for LPSNRD AEM flight lines and interpretations

Table of Contents

1 Introduction 1
1.1 Purpose of Current Project 1
1.2 Background 4
1.3 Description of the LPSNRD 2018 AEM Project Area 5
2 Geophysical Methodology, Acquisition and Processing 7
2.1 Geophysical Methodology 7
2.2 Flight Planning/Utility Mapping 8
2.3 AEM Survey Instrumentation 9
2.4 Data Acquisition 11
2.4.1 Primary Field Compensation 14
2.4.2 Automatic Processing 14
2.4.3 Manual Processing and Laterally-Constrained Inversions 14
2.4.4 Power Line Noise Intensity (PLNI) 17
2.4.5 Magnetic Field Data 17
2.5 Spatially-Constrained Inversion 20
2.6 Merge AEM Databases from Different Flights and Inversions 27
3 AEM Results and Interpretation 30
3.1 Interpretive Process 30
3.1.1 Construct the Project Digital Elevation Model 30
3.1.2 Borehole Derived Bedrock Surface 37
3.1.3 Create Interpretative 2D Profiles 39
3.1.4 Create Interpretative Surface Grids 46
3.1.5 Resistivity/Lithology Relationship in the Quaternary Aquifer System 110
3.1.6 Resistivity/Lithology Relationship in the Bedrock 111
3.1.7 Create 3D Interpretative Voxel Grids 111
3.1.8 Comparison of Borehole Resistivity Logs to Inverted AEM Resistivity Soundings 113
3.2 Hydrogeological Framework of the LPSNRD 2018 AEM Survey Area 116
3.2.1 The Hydrogeologic Framework of the LPSNRD Reconnaissance Survey Area 116
3.2.2 Hydrogeologic Framework of the Ceresco Block Survey Area 143
3.2.3 Hydrogeologic Framework of the Davey Raymond Block AEM Survey Area 168
3.2.4 Hydrogeologic Framework of the Denton Block AEM Survey Area 200

3.2.5 Hydrogeologic Framework of the Dwight South Block AEM Survey Area 230
3.2.6 Hydrogeologic Framework of the Emerald Pleasant Dale Block AEM Survey Area 263
3.2.7 Hydrogeologic Framework of the Garland Malcolm Block AEM Survey Area 292
3.2.8 Estimation of Aquifer Volume and Water in Storage for the LPSNRD Ceresco, Davey Raymond, Denton, Dwight South and Garland Malcolm AEM Block Areas 329
3.3 Recharge Areas in the LPSNRD AEM Survey Area 349
3.4 Key AEM Findings 358
3.4.1 Boreholes 358
3.4.2 Digitizing Interpreted Geological Contacts 358
3.4.3 Resistivity/Lithology Relationship 358
3.4.4 Hydrogeological Framework of the LPSNRD 359
3.4.5 Potential Recharge Zones within the LPSNRD AEM Survey Area 360
3.4.6 Hydrologic Connection Between Groundwater and Surface Water in the LPSNRD AEM Survey Area 360
3.4.7 Saltwater Areas in the LPSNRD AEM Survey Area 361
3.5 Recommendations 361
3.5.1 Preparing the Results from AEM Hydrogeological Investigations for Groundwater Modeling 361
3.5.2 Additional AEM Mapping 361
3.5.3 Update the Water Table map 362
3.5.4 Planning new test holes and production wells 362
3.5.5 Aquifer testing and borehole logging 362
3.5.6 Recharge Zones 363
3.5.7 Managed Aquifer Recharge 363
3.5.8 Updating previous groundwater reports and Groundwater Management Plans 363
3.5.9 Assist the LPSNRD staff with additional interpretation and data analysis for groundwater management needs 363
3.5.10 Development of water quality maps using the AEM 364
4 Description of Data Delivered 365
4.1 Tables Describing Included Data Files 365
4.2 Description of Included Google Earth KMZ Data and Profiles 375
4.2.1 Included README for the LPSNRD Interpretation KMZ's 375
5 References 385

Appendix 1. LPSNRD AEM Flight Line 2D Profiles and Surfaces

Appendix 2. LPSNRD 3D Images

Appendix 3. Data Deliverables

List of Figures

Figure 1-1. Map of the LPSNRD in eastern Nebraska 2

Figure 1-2. The LPSNRD 2018 AEM survey flight lines including the AEM Block flight areas 3

Figure 1-3. Map of LPSNRD groundwater management areas 6

Figure 2-1. Schematic of an airborne electromagnetic survey 7

Figure 2-2. A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model. 8

Figure 2-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 2-1 10

Figure 2-4. Photo of the SkyTEM304M system in suspension beneath the helicopter 10

Figure 2-5. LPSNRD 2018 AEM flight lines grouped by acquisition date 13

Figure 2-6. Example locations of electromagnetic coupling with pipelines or power lines. 15

Figure 2-7. A) Example of AEM data affected by electromagnetic coupling in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing. 16

Figure 2-8. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed. 17

Figure 2-9. Power Line Noise Intensity (PLNI) map of the LPSNRD 2018 project area. 18

Figure 2-10. Residual magnetic Total Field intensity data for the LPSNRD 2018 survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed. 19

Figure 2-11. Locations of inverted data along AEM flight lines in the LPSNRD 2018 AEM survey area 21

Figure 2-12. An example of an AEM profile illustrating increasing model layer thicknesses with depth. . 22

Figure 2-13. SCI inversion groups for the P-MRNRD, LPNNRD, and LPSNRD AEM data. 24

Figure 2-14. Data/model residual histogram for the LPSNRD SCI inversion results 25

Figure 2-15. Map of data residuals for the LPSNRD 2018 SCI inversion results 26

Figure 3-1. Map of the Digital Elevation Model for the 2018 LPSNRD study area 31

Figure 3-2. Map of the Digital Elevation Model for the Ceresco Block AEM survey area 32

Figure 3-3. Map of the Digital Elevation Model for the Davey Raymond Block 33

Figure 3-4. Map of the Digital Elevation Model for the Denton Block 34

Figure 3-5. Map of the Digital Elevation Model for the Dwight South Block 35
Figure 3-6. Map of the Digital Elevation Model for the Emerald Pleasant Dale Block 36
Figure 3-7. Map of the Digital Elevation Model for the Garland Malcolm Block 37
Figure 3-8. 28-mile-long east-west line, L304601, flown north of Davey, Nebraska 42
Figure 3-9. 34-mile-long north-south line, L413700 42
Figure 3-10. 4-mile-long east-west line, L302501 43
Figure 3-11. 8-mile-long southwest-northeast line, L305901 43
Figure 3-12. 4-mile-long north-south line, L411901 44
Figure 3-13. 4-mile-long north-south line, L400701 44
Figure 3-14. 6-mile-long east-west line, L307701 45
Figure 3-15. 5-mile-long southwest-northeast line, L304300 45
Figure 3-16. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***) within the 2018 LPSNRD AEM survey area 48
Figure 3-17. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the 2018 LPSNRD AEM survey area 49
Figure 3-18. Map of the elevation of the top of the Undifferentiated Pennsylvanian (***IP***) within the 2018 LPSNRD AEM survey area 50
Figure 3-19. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the Ceresco Block survey area 51
Figure 3-20. Map of the elevation of the top of the Undifferentiated Pennsylvanian (***IP***) within the Ceresco Block survey area 52
Figure 3-21. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the Davey Raymond Block survey area 53
Figure 3-22. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Davey Raymond Block survey area. 54
Figure 3-23. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the Denton Block survey area 55
Figure 3-24. Map of the elevation of the top of the Undifferentiated Pennsylvanian (***IP***) within the Denton Block survey area 56
Figure 3-25. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***) within the Dwight South Block survey area 57
Figure 3-26. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the Dwight South Block survey area 58
Figure 3-27. Map of the elevation of the top of the Undifferentiated Pennsylvanian (***IP***) within the Dwight South Block survey area 59
Figure 3-28. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the Emerald Pleasant Dale Block survey area 60

Figure 3-29. Map of the elevation of the top of the Undifferentiated Pennsylvanian (***IP***) within the Emerald Pleasant Dale Block survey area 61

Figure 3-30. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***) within the Garland Malcolm Block survey area 62

Figure 3-31. Map of the elevation of the top of the Cretaceous Dakota Group (***Kd***) within the Garland Malcolm Block survey area 63

Figure 3-32. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Garland Malcolm Block survey area 64

Figure 3-33. 3D fence diagram of the southern reconnaissance lines and borehole lithology looking to the east 65

Figure 3-34. Map of the elevation of the top of the bedrock within the LPSNRD AEM survey area..... 66

Figure 3-35. Map of the elevation of the top of the bedrock within the Ceresco Block AEM survey area 67

Figure 3-36. Map of the elevation of the top of the bedrock within the Denton Block AEM survey area. 68

Figure 3-37. Map of the elevation of the top of the bedrock within the Dwight South Block AEM survey area 69

Figure 3-38. Map of the elevation of the top of the bedrock within the Emerald Pleasant Dale Block AEM survey area..... 70

Figure 3-39. Map of the elevation of the top of the bedrock within the Garland Malcolm Block AEM survey area..... 71

Figure 3-40. Map of the thickness (in feet) of Quaternary (***Q***) deposits within the LPSNRD AEM survey area 72

Figure 3-41. Map of the thickness (in feet) of Quaternary (***Q***) deposits within the Ceresco Block AEM survey area..... 73

Figure 3-42. Map of the thickness (in feet) of Quaternary (***Q***) deposits within the Davey Raymond Block AEM survey area 74

Figure 3-43. Map of the thickness (in feet) of Quaternary (***Q***) deposits within the Denton Block AEM survey area..... 75

Figure 3-44. Map of the thickness (in feet) of Quaternary (***Q***) deposits within the Dwight South Block AEM survey area 76

Figure 3-45. Map of the thickness (in feet) of Quaternary (***Q***) deposits within the Emerald Pleasant Dale Block AEM survey area..... 77

Figure 3-46. Map of the thickness (in feet) of Quaternary (***Q***) deposits within the Garland Malcom Block AEM survey area 78

Figure 3-47. Map of the thickness (in feet) of the Greenhorn Limestone/Graneros Shale (***Kgg***) within the LPSNRD AEM survey area 79

Figure 3-48. Map of the thickness (in feet) of the top of the Greenhorn Limestone/Graneros Shale (***Kgg***) within the Dwight South Block AEM survey area 80

Figure 3-49. Map of the thickness (in feet) of the top of the Greenhorn Limestone/Graneros Shale (***Kgg***) within the Garland Malcolm Block AEM survey area 81

Figure 3-50. Map of the thickness (in feet) of the Cretaceous Dakota Group (***Kd***) within the LPSNRD AEM survey area 82

Figure 3-51. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (***Kd***) within the Ceresco Block AEM survey area 83

Figure 3-52. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (***Kd***) within the Davey Raymond Block AEM survey area 84

Figure 3-53. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (***Kd***) within the Denton Block AEM survey area 85

Figure 3-54. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (***Kd***) within the Dwight South Block AEM survey area 86

Figure 3-55. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (***Kd***) within the Emerald Pleasant Dale Block AEM survey area 87

Figure 3-56. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (***Kd***) within the Garland Malcolm Block AEM survey area 88

Figure 3-57. Map of the elevation (in feet) of the 1995 CSD water table within the 2018 LPSNRD AEM survey area 89

Figure 3-58. Map of the elevation (in feet) of the 1995 CSD water table within the Ceresco Block AEM survey area 90

Figure 3-59. Map of the elevation (in feet) of the 1995 CSD water table within the Davey Raymond Block AEM survey area 91

Figure 3-60. Map of the elevation (in feet) of the 1995 CSD water table within the Denton Block AEM survey area 92

Figure 3-61. Map of the elevation (in feet) of the 1995 CSD water table within the Dwight South Block AEM survey area 93

Figure 3-62. Map of the elevation (in feet) of the 1995 CSD water table within the Emerald Pleasant Dale Block AEM survey area 94

Figure 3-63. Map of the elevation (in feet) of the 1995 CSD water table within the Garland Malcolm Block AEM survey area 95

Figure 3-64. Map of the saturated thickness of Quaternary (***Q***) materials within the 2018 LPSNRD AEM survey area 96

Figure 3-65. Map of the saturated thickness of Quaternary (***Q***) materials within the Ceresco Block AEM survey area 97

Figure 3-66. Map of the saturated thickness of Quaternary (***Q***) materials within the Davey Raymond Block AEM survey area 98

Figure 3-67. Map of the saturated thickness of Quaternary (***Q***) materials within the Denton Block AEM survey area 99

Figure 3-68. Map of the saturated thickness of Quaternary (***Q***) materials within the Dwight South Block AEM survey area 100

Figure 3-69. Map of the saturated thickness of Quaternary (***Q***) materials within the Emerald Pleasant Dale Block AEM survey area 101

Figure 3-70. Map of the saturated thickness of Quaternary (***Q***) materials within the Garland Malcolm Block AEM survey area..... 102

Figure 3-71. Map of the saturated thickness of Cretaceous Dakota Group (***Kd***) within the 2018 LPSNRD AEM survey area 103

Figure 3-72. Map of the saturated thickness of Cretaceous Dakota Group (***Kd***) within the Ceresco Block AEM survey area 104

Figure 3-73. Map of the saturated thickness of Cretaceous Dakota Group (***Kd***) within the Davey Raymond Block AEM survey area..... 105

Figure 3-74. Map of the saturated thickness of Cretaceous Dakota Group (***Kd***) within the Denton Block AEM survey area 106

Figure 3-75. Map of the saturated thickness of Cretaceous Dakota Group (***Kd***) within the Dwight South Block AEM survey area..... 107

Figure 3-76. Map of the saturated thickness of Cretaceous Dakota Group (***Kd***) within the Emerald Pleasant Dale Block AEM survey area..... 108

Figure 3-77. Map of the saturated thickness of Cretaceous Dakota Group (***Kd***) within the Garland Malcolm Block AEM survey area..... 109

Figure 3-78. Plot displaying the resistivities by major aquifer material categories: non-aquifer materials, marginal aquifer materials, aquifer materials, coarse aquifer materials 110

Figure 3-79. Exploded solid model of the aquifer material types for the Garland Malcolm Block of the Quaternary (***Q***) both unsaturated and saturated, Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), and the two types of Cretaceous Dakota Group (***Kd***) separated from the undifferentiated Pennsylvanian (***IP***)..... 112

Figure 3-80. Graph of the *02-LPN-15* 16-inch short normal and 64-inch long normal resistivity logs values and the inverted airborne electromagnetic resistivity values for flight line L504800..... 114

Figure 3-81. Graph of the *03-LPN-15* 16-inch short normal resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L502900 115

Figure 3-82. Map showing the CSD bedrock geology map for the entire project area 120

Figure 3-83. 3D fence diagram of the LPSNRD 2018 lines looking north showing ***Q*** aquifer materials, ***Kgg***, ***Kd***, and ***IP*** units 121

Figure 3-84. 3D fence diagram of the LPSNRD 2018 lines looking south showing ***Q*** aquifer materials, ***Kgg***, ***Kd***, and ***IP*** units 122

Figure 3-85. Map of the total ***Q*** aquifer material thickness of the AEM LPSNRD 2018 Reconnaissance survey area..... 123

Figure 3-86. Map of the total ***Kd*** thickness of the AEM LPSNRD 2018 Reconnaissance survey area..... 124

Figure 3-87. 3D fence diagram of the LPSNRD 2018 Reconnaissance lines looking east showing ***Q*** aquifer materials 125

Figure 3-88. Interpreted north-south line, L413700, crosses the Salt Creek just west of the town of Waverly 126

Figure 3-89. Interpreted north-south line, L403801, near the towns of Garland, Malcom, Emerald, and Pleasant Dale, Nebraska, displays the subsurface deposits of geologic units of the uplands including three paleochannels that appear across the line from south to north 127

Figure 3-90. Interpreted north-south line L412100 lies ~3 miles west of the Lincoln airport..... 128

Figure 3-91. Interpreted east-west line, L307501, is approximately 1 mile east of Lincoln north of Highway 34, Nebraska 129

Figure 3-92. Map of the elevation of the top surface of the bedrock composed of ***Kgg***, ***Kd***, and ***IP*** within the 2018 LPSNRD Reconnaissance AEM survey area..... 130

Figure 3-93. Map of the saturated thickness of ***Q*** aquifer materials within the 2018 LPSNRD Reconnaissance survey area 131

Figure 3-94. Map of the saturated ***Q*** aquifer thickness for the LPSNRD 2018 Reconnaissance AEM survey area plus the specific capacity of wells screened within the ***Q*** 132

Figure 3-95. Map of the top surface of the ***Kgg*** within the 2018 LPSNRD Reconnaissance AEM survey area 133

Figure 3-96. Map of the Total Thickness of the ***Kgg*** within the 2018 LPSNRD Reconnaissance AEM survey area 134

Figure 3-97. Map of the top surface elevation of the of the ***Kd*** within the 2018 LPSNRD Reconnaissance AEM survey area 135

Figure 3-98. Map of the saturated thickness of the ***Kd*** within the 2018 LPSNRD Reconnaissance AEM survey area..... 136

Figure 3-99. Map of the saturated ***Kd*** aquifer thickness for the LPSNRD 2018 Reconnaissance AEM survey area plus the specific capacity of wells screened within the ***Kd***..... 137

Figure 3-100. Depositional environment of the Cretaceous Dakota Group (***Kd***) sediments in eastern Nebraska and western Iowa (Witzke and Ludvigson, 1994)..... 138

Figure 3-101. Map of the top surface elevation of the of the ***IP*** within the 2018 LPSNRD Reconnaissance AEM survey area 139

Figure 3-102. Map showing where saltwater is present within the project area and these areas represent where a value of 4 ohm/m which indicates the presence of saltwater 140

Figure 3-103. Map of wells including the values of specific conductance in µS/cm from groundwater samples taken from wells 141

Figure 3-104. Map of wells including the values of Total Dissolved Solids in mg/l from groundwater samples taken from wells 142

Figure 3-105. Location map of the Ceresco Block indicating numbered AEM flight lines, local roads, and streams..... 146

Figure 3-106. Map showing the ground surface elevation with flight lines in the Ceresco Block..... 147

Figure 3-107. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Ceresco Block AEM survey area..... 148

Figure 3-108. Profile of the east-west line L409001 showing Q. Note that the ***Q*** aquifer materials and the ***Kd*** sandstone/sand materials are in contact and have a hydrologic connection 149

Figure 3-109. Map of the total thickness of the ***Q*** (Quaternary) deposits within the 2018 Ceresco Block AEM survey area 150

Figure 3-110. Map of the elevation of the top of bedrock in the 2018 Ceresco Block AEM survey area 151

Figure 3-111. Map of the 1995 CSD water table (NE-CSD, 1995) in the Ceresco Block..... 152

Figure 3-112. Map of saturated thickness of the ***Q*** saturated aquifer and coarse aquifer materials within the 2018 Ceresco Block AEM survey area..... 153

Figure 3-113. Map of the elevation of the top of the ***Kd*** in the 2018 Ceresco Block AEM survey area ... 154

Figure 3-114. Map of the total thickness of the ***Kd*** within the 2018 Ceresco Block AEM survey area 155

Figure 3-115. Interpreted profile of the north-south line L302001 showing the relationship the ***Q***, ***Kd,*** and ***IP*** of the AEM interpretations across the area 156

Figure 3-116. Interpreted profile of the north-south line L303001 showing the relationship the ***Q***, ***Kd,*** and ***IP*** of the AEM interpretations across the area 157

Figure 3-117. 3D exploded voxel model of the Ceresco Block showing ***Q***, ***Kd***, ***IP*** 158

Figure 3-118. Map of saturated Quaternary (***Q***) Aquifer and Coarse Aquifer Materials for the Ceresco Block..... 159

Figure 3-119. Map of saturated thickness of Quaternary (***Q***) deposits and the Specific Capacity measured in wells completed in the *Q* deposits..... 160

Figure 3-120. View of 3D voxel model looking northwest showing the ***Q***, ***Kd***, ***IP*** of the Ceresco Block AEM survey area..... 161

Figure 3-121. View to the west showing a 3D voxel of both ***Q*** Aquifer and Coarse Aquifer Material and the underlying bedrock units with the unsaturated ***Q*** materials shown as a 3D fence diagram 162

Figure 3-122. A view to the northwest of a 3D voxel of the ***Q*** Aquifer and Coarse Aquifer Material overlying a surface depicting the elevation of the top of the ***Kd*** Sandstone/Sand Dominant material .. 163

Figure 3-123. A view to the west of a 3D voxel of the ***Q*** Aquifer and Coarse Aquifer Material overlying a surface depicting the elevation of the top of the ***Kd*** Sandstone/Sand Dominant material 164

Figure 3-124. Map of the saturated thickness of the ***Kd*** Sandstone/Sand Dominant in the 2018 Ceresco Block AEM survey area..... 165

Figure 3-125. Map of the saturated thickness of the ***Kd*** Sandstone/Sand Dominant material in the 2018 Ceresco Block AEM survey area with specific capacity indicated..... 166

Figure 3-126. View of 3D voxel model looking north showing the saltwater water areas in the Block colored red..... 167

Figure 3-127. Location map of the Davey Raymond Block indicating numbered AEM flight lines, local roads, and streams..... 171

Figure 3-128. Map showing the ground surface elevation of flight lines in the Davey Raymond Block .. 172

Figure 3-129. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Davey Raymond Block AEM survey area 173

Figure 3-130. Profile of the east-west line L305701 showing the ***Q*** aquifer materials and the ***Kd*** sandstone/sand materials are in contact and have a minimal hydrologic connection 174

Figure 3-131. Map of the total thickness of the ***Q*** deposits within the 2018 Davey Raymond Block AEM survey area 175

Figure 3-132. Map of the elevation of the top of bedrock within the 2018 Davey Raymond Block AEM survey area 176

Figure 3-133. Map of total thickness of the Quaternary (***Q***) within the 2018 Davey Raymond Block AEM survey area 177

Figure 3-134. Map of the elevation of the 1995 CSD water table (NE-CSD, 1995) for the Davey Raymond Block 178

Figure 3-135. Map of saturated thickness of the Quaternary (***Q***) within the 2018 Davey Raymond Block AEM survey area 179

Figure 3-136. Map of saturated thickness for ***Q*** deposits and specific capacity of wells completed in the ***Q*** shows the relationship between specific capacity in gpm/ft and the saturated thickness 180

Figure 3-137. Map of the elevation of the top of the ***Kd*** within the 2018 Davey Raymond Block AEM survey area 181

Figure 3-138. Map of the total thickness of the ***Kd*** within the 2018 Davey Raymond Block AEM survey area 182

Figure 3-139. Map of the saturated thickness of the ***Kd*** within the 2018 Davey Raymond Block AEM survey area 183

Figure 3-140. Map of saturated thickness for ***Kd*** deposits and specific capacity of wells completed in the ***Kd*** shows the relationship between specific capacity in gpm/ft and the saturated thickness 184

Figure 3-141. Interpreted profile of the north-south line L306400 showing the relationship the ***Q***, ***Kd,*** and ***IP*** of the AEM interpretations across the area 185

Figure 3-142. Interpreted profile of the north-south line L304603 showing the relationship the ***Q***, ***Kd***, and ***IP*** of the AEM interpretations across the area 186

Figure 3-143. 3D exploded voxel model of the Davey Raymond Block showing Unsaturated ***Q***, Saturated ***Q,*** Unsaturated ***Kd***, Saturated ***Kd,*** and ***IP*** 187

Figure 3-144. Map of ***Q*** Non-Aquifer and Marginal Aquifer materials total thickness for the Davey Raymond Block 188

Figure 3-145. Map of total thickness of ***Q*** deposits of Aquifer and Coarse Aquifer materials 189

Figure 3-146. Map of total saturated thickness of ***Q*** deposits of Aquifer and Coarse Aquifer materials 190

Figure 3-147. View of 3D voxel model of ***Q*** saturated Aquifer and Coarse Aquifer Material with a fence diagram of unsaturated ***Q*** Marginal and Non-Aquifer material 191

Figure 3-148. View to the north showing a 3D voxel of saturated and unsaturated ***Q*** Aquifer and Coarse Aquifer Material 192

Figure 3-149. View to the north of 3D voxel of saturated ***Q*** Aquifer and Coarse Aquifer Material 193

Figure 3-150. Map of the total thickness of the Sandstone/Sand Dominant portion of the ***Kd*** in the 2018 Davey Raymond Block AEM survey area 194

Figure 3-151. Map of the saturated thickness of the Cretaceous Dakota Group (***Kd***) Sandstone/Sand Dominant material in the 2018 Davey Raymond Block AEM survey area 195

Figure 3-152. View of 3D voxel model of ***Kd*** Sandstone/Sand dominant and Shale/Clay or Saltwater Dominant materials looking northwest 196

Figure 3-153. View of 3D voxel model of ***Kd*** Sandstone/Sand dominant looking west 197

Figure 3-154. View of 3D voxel model looking north showing the saltwater water areas in the Block colored red 198

Figure 3-155. Close up view of 3D voxel model looking northeast showing the saltwater water areas in the Block colored red 199

Figure 3-156. Location map of the Denton Block indicating numbered AEM flight lines, local roads, and streams 203

Figure 3-157. Map showing the ground surface elevation with flight lines in the Denton Block 204

Figure 3-158. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Denton Block AEM survey area 205

Figure 3-159. Profile presents 2D profile L411000, located west of the town of Denton, Nebraska 206

Figure 3-160. Map of the 1995 CSD water table (NE-CSD, 1995) over the Denton Block 207

Figure 3-161. Map of the total thickness of the Quaternary (***Q***) deposits within the 2018 Denton Block AEM survey area 208

Figure 3-162. Map of elevation of top of bedrock within the 2018 Denton Block AEM survey area 209

Figure 3-163. Map of saturated thickness of the ***Q*** within the 2018 Denton Block AEM survey area 210

Figure 3-164. Map of saturated thickness for ***Q*** deposits and specific capacity of wells completed in the ***Q*** shows the relationship between specific capacity in gpm/ft and the saturated thickness 211

Figure 3-165. Map of elevation of top of the ***Kd*** within the 2018 Denton Block AEM survey area 212

Figure 3-166. Map of the total thickness of the Cretaceous Dakota Group (***Kd***) within the 2018 Denton Block AEM survey area 213

Figure 3-167. Map of saturated thickness for ***Kd*** deposits and specific capacity of wells completed in the ***Kd*** shows the relationship between specific capacity in gpm/ft and the saturated thickness 214

Figure 3-168. Interpreted profile of the north-south line L311100 showing the relationship the ***Q***, ***Kd***, and ***IP*** of the AEM interpretations across the area 215

Figure 3-169. Interpreted profile of the north-south line L407000 showing the relationship the ***Q***, ***Kd,*** and ***IP*** of the AEM interpretations across the area 216

Figure 3-170. 3D exploded voxel model looking northwest of the Denton Block showing Unsaturated ***Q***, Saturated ***Q,*** Saturated ***Kd***, and ***IP*** 217

Figure 3-171. Map of Quaternary (***Q***) Non-Aquifer and Marginal Aquifer Materials total thickness for the Denton Block 218

Figure 3-172. Map of total thickness of ***Q*** deposits of Aquifer and Coarse Aquifer Materials in the Denton Block 219

Figure 3-173. Map of total saturated thickness of ***Q*** deposits of Aquifer and Coarse Aquifer Materials 220

Figure 3-174. View of shows a 3D voxel model of ***Q*** saturated Aquifer and Coarse Aquifer Material with a 3D fence diagram of unsaturated *Q* aquifer materials 221

Figure 3-175. View to the north showing a 3D voxel model of saturated ***Q*** aquifer and the coarse aquifer material with fence diagram of all other materials, ***Kd,*** and ***IP*** 222

Figure 3-176. View to the northwest of a 3D voxel of the ***Q*** Non- Aquifer Material and all other units as a 3D Fence Diagram 223

Figure 3-177. Map of the total thickness of the Sandstone/Sand Dominant portion of the ***Kd*** in the 2018 Denton Block AEM survey area 224

Figure 3-178. View of 3D voxel model of ***Kd*** Sandstone/Sand dominant materials looking north 225

Figure 3-179. View of 3D voxel model of ***Kd*** Sandstone/Sand dominant to the northwest 226

Figure 3-180. View of 3D voxel model, looking north, showing the saltwater areas in Denton Block..... 227

Figure 3-181. View of 3D Fence Diagram of All units and 3D voxel model looking northwest in the Denton Block showing the saltwater water areas 228

Figure 3-182. Map of the saltwater thickness in the Denton Block area, varying from 5 to 544 feet 229

Figure 3-183. Location map of the Dwight South Block AEM survey area showing numbered AEM flight lines, local roads, and streams 233

Figure 3-184. Map showing the ground surface elevation with flight lines in the Dwight South Block... 234

Figure 3-185. 3D fence diagram looking south of interpreted AEM hydrostratigraphic profiles within the 2018 Dwight South Block AEM survey area 235

Figure 3-186. The bedrock geology map shows the ***Kgg*** lying upon the ***Kd*** in the northwest part of the Block 236

Figure 3-187. Profile of the north-south line L400301 showing the ***Q*** aquifer materials, ***Kgg***, and ***Kd*** ... 237

Figure 3-188. Map of the CSD 1995 water table (NE-CSD, 1995) for the area showing that the water table has little slope 238

Figure 3-189. Map of the total thickness of the Quaternary (***Q***) deposits within the 2018 Dwight South Block AEM survey area 239

Figure 3-190. Map of the elevation of the top of bedrock within the 2018 Dwight South Block AEM survey area 240

Figure 3-191. Map of saturated thickness of ***Q*** within the 2018 Dwight South Block AEM survey area . 241

Figure 3-192. Map shows the relationship between the saturated thickness of ***Q*** and the specific capacity in gpm/ft for wells completed in the ***Q*** 242

Figure 3-193. Map of the elevation of the top of the ***Kgg*** within the 2018 Dwight South Block AEM survey area 243

Figure 3-194. Map of the total thickness of ***Kgg*** within the 2018 Dwight South Block AEM survey area 244

Figure 3-195. Map of the elevation of the top of the ***Kd*** within the 2018 Dwight South Block AEM survey area 245

Figure 3-196. Map of the total thickness of ***Kd*** within the 2018 Dwight South Block AEM survey area.. 246

Figure 3-197. Map of the saturated thickness of the ***Kd*** within the 2018 Dwight South Block AEM survey area 247

Figure 3-198. Map shows the relationship between the saturated thickness of ***Kd*** and the specific capacities in gpm/ft for wells completed in the ***Kd*** 248

Figure 3-199. Map shows the top elevation for the ***IP*** shows the surface to be a gently sloping surface from the high in the south to the low in the north 249

Figure 3-200. Interpreted profile of the north-south line L303800 showing the relationship the ***Q***, ***Kd*** and ***IP*** of the AEM interpretations across the area 250

Figure 3-201. Interpreted profile of the north-south line L304201 showing the relationship the ***Q***, **Kgg**, ***Kd***, and ***IP*** of the AEM interpretations across the area 251

Figure 3-202. 3D exploded voxel model looking northwest of the Dwight South Block showing Unsaturated ***Q***, Saturated ***Q***, ***Kgg***, *Saturated* ***Kd***, and ***IP*** 252

Figure 3-203. Map of Quaternary (***Q***) non-aquifer and marginal aquifer materials total thickness for the Dwight South Block 253

Figure 3-204. Map of total thickness of ***Q*** deposits of aquifer and coarse aquifer materials in the Dwight South Block 254

Figure 3-205. Map of total saturated thickness of ***Q*** deposits of aquifer and coarse aquifer materials in the Dwight South Block 255

Figure 3-206. View to the northwest that shows a 3D fence diagram of ***Q*** aquifer materials looking northwest in the Dwight South Block 256

Figure 3-207. View to the east showing a 3D fence diagram of ***Q*** aquifer materials looking northwest in the Dwight South Block 257

Figure 3-208. Map of the total thickness of the Sandstone/Sand Dominant portion of the ***Kd*** in the 2018 Dwight South Block AEM survey area 258

Figure 3-209. View of 3D voxel model looking north of ***Q*** aquifer material which is a small volume in the north lying on the ***Kd*** looking north 259

Figure 3-210. View of Dwight South 3D voxel model similar the Figure 3-209 looking west 260

Figure 3-211. View of 3D fence diagram looking north showing the saltwater areas in the Dwight South Block 261

Figure 3-212. View of 3D fence diagram looking northwest showing the saltwater water areas in the Dwight South Block 262

Figure 3-213. Location map of the Emerald Pleasant Dale Block AEM survey area showing numbered AEM flight lines, local roads, and streams 266

Figure 3-214. Map shows the ground surface elevation map over the Emerald Pleasant Dale Block 267

Figure 3-215. 3D Fence Diagram with a 3D voxel model of the ***Q*** aquifer materials, ***Kd***, and ***IP*** of the Emerald Pleasant Dale Block AEM survey area 268

Figure 3-216. 2D profile L309701 is a north-south line in the center of Emerald Pleasant Dale Block AEM survey area 269

Figure 3-217. Map shows top elevation for the ***IP*** is shown on and shows the surface to be a gently sloping surface from the high in the south to the low in the north 270

Figure 3-218. Map of the total thickness of the Quaternary (***Q***) deposits within the 2018 Emerald Pleasant Dale Block AEM survey area 271

Figure 3-219. Map of the elevation of the top of bedrock within the 2018 Emerald Pleasant Dale Block AEM survey area 272

Figure 3-220. Map of saturated thickness of the ***Q*** within the 2018 Emerald Pleasant Dale Block AEM survey area 273

Figure 3-221. Map shows the relationship between the saturated thickness of ***Q*** and the specific capacity in gpm/ft for wells completed in the ***Q*** in the Emerald Pleasant Dale Block 274

Figure 3-222. Map of the elevation of top of ***Kd*** in the Emerald Pleasant Dale Block which ranges in elevation from 1,088 to 1,336 feet 275

Figure 3-223. Map of the total thickness of the Cretaceous Dakota Group (***Kd***) within the 2018 Emerald Pleasant Dale Block AEM survey area 276

Figure 3-224. Map of the saturated thickness of the ***Kd*** within the 2018 Emerald Pleasant Dale Block AEM survey area 277

Figure 3-225. Map of the saturated thickness compared to the specific capacity for the ***Kd*** wells of the area within the 2018 Emerald Pleasant Dale Block AEM survey area 278

Figure 3-226. Interpreted profile of the north-south line L307901 showing the relationship the ***Q*** and ***Kd*** of the AEM interpretations across the Emerald Pleasant Dale survey area 279

Figure 3-227. Interpreted profile of the north-south line L307701 showing the relationship the ***Q***, ***Kd,*** and ***IP*** of the AEM interpretations across the Emerald Pleasant Dale survey area 280

Figure 3-228. 3D exploded voxel model looking northwest of the Emerald Pleasant Dale Block showing Unsaturated ***Q***, Saturated ***Q***, Saturated ***Kd,*** and ***IP*** 281

Figure 3-229. Map of ***Q*** Non-Aquifer and Marginal Aquifer materials total thickness for the Emerald Pleasant Dale Block 282

Figure 3-230. Map of thickness of ***Q*** deposits of saturated Non-Aquifer, Marginal Aquifer materials ... 283

Figure 3-231. Map of total thickness of ***Q*** deposits of Aquifer and Coarse Aquifer Materials in the Emerald Pleasant Dale Block 284

Figure 3-232. Map of saturated thickness of ***Q*** deposits of Aquifer and Coarse Aquifer Materials in the Emerald Pleasant Dale Block 285

Figure 3-233. View looking west of a 3D voxel model of the ***Q*** Aquifer and Coarse Aquifer Material lying upon the ***Kd*** and ***IP*** with a 3D fence diagram showing ***Q*** Marginal and Non-Aquifer Material of the Emerald Pleasant Dale Block AEM survey area 286

Figure 3-234. Map of the thickness for ***Kd*** Sandstone/Sand Dominant deposits which is present across nearly the whole of the Emerald Pleasant Dale survey area 287

Figure 3-235. View of 3D voxel model looking north showing the saturated thickness for ***Kd*** Sandstone/Sand Dominant material and Shale/Clay or Saltwater Dominant with a 3D fence diagram of all Q materials in the Emerald Pleasant Dale Block 288

Figure 3-236. 3D voxel model looking north showing the thickness for ***Q*** Non-Aquifer Material, with a 3D fence diagram of unsaturated ***Q*** materials, ***Kd***, and ***IP*** 289

Figure 3-237. 3D voxel model looking north showing the saltwater areas in the Emerald Pleasant Dale Block 290

Figure 3-238. Thickness map of saltwater affected areas which is present across nearly the of the Emerald Pleasant Dale Block AEM survey area based on the voxel. model 291

Figure 3-239. Location map of the Garland Malcolm Block AEM survey area showing numbered AEM flight lines, local roads, and streams 296

Figure 3-240. Ground surface elevation map shows there are rolling hills surrounding Oak Creek, Middle Oak Creek, West Oak Creek, Elk Creek, Middle Creek, and Branched Oak Lake 297

Figure 3-241. 3D fence diagram with a voxel model of the ***Q*** aquifer materials, ***Kgg***, ***Kd,*** and ***IP*** of the Garland Malcolm Block AEM survey area 298

Figure 3-242. The bedrock geology map shows the ***Kgg*** lying upon the ***Kd*** in the northwest part of the Garland Malcolm Block 299

Figure 3-243. 2D profile L414001 is a north-south line in the center of the Garland Malcolm Block AEM survey area 300

Figure 3-244. Map of the surface elevation for the *IP* as a gently sloping surface from all sides to the center of the Garland Malcolm Block survey area 301

Figure 3-245. Map showing the CSD 1995 (NE-CSD, 1995) water table for the area and has a gradual slope from north to south 302

Figure 3-246. Map of the total thickness of the ***Q*** deposits within the 2018 Garland Malcolm Block AEM survey area 303

Figure 3-247. Map of the elevation of the top of bedrock within the 2018 Garland Malcolm Block AEM survey area 304

Figure 3-248. Map of saturated thickness for all ***Q*** Aquifer Material for the Garland Malcolm Block 305

Figure 3-249. Map of the relationship between the saturated thickness of ***Q*** and the specific capacity in gpm/ft for wells completed in the ***Q*** 306

Figure 3-250. Map of the elevation of the top of ***Kgg*** in the Garland Malcolm Block and ranges in elevation from 1,240 to 1,412 feet 307

Figure 3-251. Map of the total thickness of the ***Kgg*** within the 2018 Garland Malcolm Block AEM survey area 308

Figure 3-252. Map of the elevation of top of ***Kd*** in the Garland Malcolm Block which ranges from 1,015 to 1,374 feet 309

Figure 3-253. Map of the total thickness of the ***Kd*** within the 2018 Garland Malcolm Block AEM survey area 310

Figure 3-254. Map of saturated ***Kd*** thickness for the Garland Malcolm Block 311

Figure 3-255. Map of the relationship between the saturated thickness of ***Kd*** and the specific capacity in gpm/ft for wells completed in the ***Kd*** 312

Figure 3-256. Interpreted 2D profile L306801 is an east-west line south of Garland, Nebraska 313

Figure 3-257. Interpreted 2D profile L304300 is an east-west profile in the northernmost diagonal line north of Garland, Nebraska 314

Figure 3-258. Interpreted 2D profile L402600 is a north-south profile just west of Garland, Nebraska . 315

Figure 3-259. 3D exploded voxel model of the Garland Malcolm Block looking northwest showing Unsaturated ***Q***, Saturated ***Q***, ***Kgg***, Saturated ***Kd***, and ***IP*** 316

Figure 3-260. Map of the distribution of ***Q*** Marginal and Non-Aquifer Materials total thickness in the Garland Malcolm Block 317

Figure 3-261. Map of the distribution of the saturated thickness of ***Q*** Marginal and Non-Aquifer materials in the Garland Malcolm Block 318

Figure 3-262. Map the thickness of the ***Q*** Aquifer and Coarse Aquifer Materials which are nearly continuous across the area except in the north with the thickest deposits spread across the southern part of the survey area 319

Figure 3-263. Map of the ***Q*** saturated Aquifer and Coarse Aquifer Materials in the Garland Malcolm Block which are thin and range in thickness from <25 to 277 feet 320

Figure 3-264. 3D fence diagram looking south of the ***Q*** Marginal and Non-Aquifer Material with a 3D voxel model of the ***Q*** Aquifer and Coarse Aquifer Materials lying upon the ***Kgg***, ***Kd,*** and ***IP*** of the Garland Malcolm Block AEM survey area 321

Figure 3-265. Map of the thickness for ***Kd*** Sandstone/Sand Dominant deposits which is discontinuous across the Garland Malcolm survey area 322

Figure 3-266. 3D voxel model view to the north showing the ***Q***, ***Kgg***, ***Kd***, and ***IP*** in the Garland Malcolm Block 323

Figure 3-267. 3D voxel model looking north showing the thickness for ***Kgg***, ***Kd***, and ***IP*** materials in the Garland Malcolm Block 324

Figure 3-268. 3D voxel model looking north showing the ***Q*** saturated thickness and ***Kgg***, ***Kd***, and ***IP*** materials in the Garland Malcolm Block 325

Figure 3-269. 3D voxel model looking northwest showing saltwater areas to be nearly continuous across the Garland Malcolm Block area and affecting the ***IP*** and ***Kd*** 326

Figure 3-270. 3D voxel model looking north showing saltwater areas to be nearly continuous across the Garland Malcolm Block area and affecting the ***IP*** and ***Kd*** 327

Figure 3-271. Thickness map of voxel model of the saltwater-affected areas present across most of the Garland Malcolm Block AEM survey area 328

Figure 3-272. Map of the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale and Garland Malcolm block locations 331

Figure 3-273. Resistivity ranges for interpreted Quaternary (***Q***) Non-Aquifer, Marginal Aquifer, Aquifer, and Coarse Aquifer Materials 332

Figure 3-274. 3D voxel model of the Ceresco AEM block area facing north showing Quaternary Unsaturated (***Q***), Quaternary Saturated (***Q***), Cretaceous Dakota Formation (***Kd***) aquifer materials, and Undifferentiated Pennsylvanian (***IP***) 333

Figure 3-275. Exploded 3D voxel model of the Davey Raymond AEM Block area facing north showing all unsaturated and saturated Quaternary (***Q***), unsaturated and saturated Cretaceous Dakota Formation (***Kd***) aquifer materials, and Undifferentiated Pennsylvanian (***IP***)..... 334

Figure 3-276. 3D voxel model of the Denton AEM Block area facing north showing all unsaturated and saturated Quaternary (***Q***), Cretaceous Dakota Formation (***Kd***) aquifer materials, and Undifferentiated Pennsylvanian (***IP***)..... 335

Figure 3-277. 3D voxel model of the Dwight South AEM block area facing north showing all unsaturated and saturated Quaternary (***Q***), Cretaceous Greenhorn-Graneros Formation (***Kgg***), Cretaceous Dakota Formation (***Kd***) aquifer materials, and Undifferentiated Pennsylvanian (***IP***)..... 336

Figure 3-278. 3D voxel model of the Emerald Pleasant Dale AEM block area facing north showing all unsaturated and saturated Quaternary (***Q***), Cretaceous Dakota Formation (***Kd***) aquifer materials, and Undifferentiated Pennsylvanian (***IP***)..... 337

Figure 3-279. 3D voxel model of the Garland Malcolm AEM block area facing north showing all unsaturated and saturated Quaternary (***Q***), Cretaceous Greenhorn Graneros Formation (***Kgg***), Cretaceous Dakota Formation (***Kd***) aquifer materials, and Undifferentiated Pennsylvanian (***IP***) 328

Figure 3-280. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 LPSNRD AEM survey area 350

Figure 3-281. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 LPSNRD Block AEM survey areas 351

Figure 3-282. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Ceresco Block AEM survey area 352

Figure 3-283. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Davey Raymond Block AEM survey area 353

Figure 3-284. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Denton Block AEM survey area 354

Figure 3-285. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Dwight South Block AEM survey area 355

Figure 3-286. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Emerald Pleasant Dale Block AEM survey area 356

Figure 3-287. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Garland Malcolm Block AEM survey area 357

Figure 4-1. KMZ of the full LPSNRD AEM survey area. Due to the size of the data set, this kmz has been divided into four (4) parts (Pt1, Pt2, Pt3, and Pt4) 377

Figure 4-2. KMZ locations of LPSNRD AEM Block survey areas 378

Figure 4-3. Example Google Earth image for the 2018 Denton Block Interpretation kmz showing location attributes 379

Figure 4-4. Example Google Earth image for the 2018 Dwight South Block Interpretation kmz showing location attributes..... 380

Figure 4-5. Example Google Earth image for the 2018 Ceresco Block Interpretation kmz showing location attributes 381

Figure 4-6. Example Google Earth image for the 2018 Davey Raymond Block Interpretation kmz showing location attributes 382

Figure 4-7. Example Google Earth image for the 2018 Emerald-Pleasant-Dale Block Interpretation kmz showing location attributes 383

Figure 4-8. Example Google Earth image for the 2018 Garland Malcolm Block Interpretation kmz showing location attributes 384

List of Tables

Table 2-1. Positions of instruments on the SkyTEM304M frame, using the center of the frame as the origin, in feet 11

Table 2-2. Positions of corners of the SkyTEM304M transmitter coil, using the center of the frame as the origin in feet 11

Table 2-3. LPSNRD AEM Data Acquisition Schedule and Totals 12

Table 2-4. Thickness and depth to bottom for each layer in the Spatially Constrained inversion (SCI) AEM earth models. The thickness of the model layers increase with depth as the resolution of the AEM technique decreases 23

Table 2-5. AEM flights included in each of the SCI inversion groups 23

Table 2-6. Combination of flight lines within the inversion areas 27

Table 3-1. ***Q*** aquifer materials underlying the Ceresco AEM Block Area 339

Table 3-2. Saturated ***Q*** aquifer materials underlying the Ceresco AEM Block Area 339

Table 3-3. Saturated ***Kd*** aquifer materials underlying the Ceresco AEM Block Area 340

Table 3-4. ***Q*** aquifer materials underlying the Davey Raymond AEM Block Area 340

Table 3-5. Saturated ***Q*** aquifer materials underlying the Davey Raymond AEM Block Area 341

Table 3-6. Total ***Kd*** aquifer materials underlying the Davey Raymond AEM Block Area 341

Table 3-7. Saturated ***Kd*** aquifer materials underlying the Davey Raymond AEM Block Area 342

Table 3-8. ***Q*** aquifer materials underlying the Denton AEM Block Area 342

Table 3-9. Saturated ***Q*** aquifer materials underlying the Denton AEM Block Area 343

Table 3-10. Saturated ***Kd*** aquifer materials underlying the Denton AEM Block Area 343

Table 3-11. ***Q*** aquifer materials underlying the Dwight South AEM Block Area 344

Table 3-12. Saturated ***Q*** aquifer materials underlying the Dwight South AEM Block Area 344

Table 3-13. Saturated ***Kd*** aquifer materials underlying the Dwight South AEM Block Area 345

Table 3-14. ***Q*** aquifer materials underlying the Emerald Pleasant Dale AEM Block Area 345

Table 3-15. Saturated ***Q*** aquifer materials underlying the Emerald Pleasant Dale AEM Block Area 346

Table 3-16. Saturated ***Kd*** aquifer materials underlying the Emerald Pleasant Dale AEM Block Area 346

Table 3-17. ***Q*** aquifer materials underlying the Garland Malcolm AEM Block Area 347

Table 3-18. Saturated ***Q*** aquifer materials underlying the Garland Malcolm AEM Block Area.....347

Table 3-19. Saturated ***Kd*** aquifer materials underlying the Garland Malcolm AEM Block Area 348

Table 4-1. Raw SkyTEM data files..... 366

Table 4-2. Channel name, description, and units for LPSNRD2018_EM_MAG_AUX.xyz with DEM, magnetic, DGPS, Inclinometer, altitude, and associated data..... 366

Table 4-3. Channel name, description, and units for LPSNRD2018_AEM_SCI_INV_v1.xyz with EM inversion results..... 367

Table 4-4. Channel name description and units for the interpretation results files LPSNRD2018_Interp_AqThk.xyz, Ceresco_AqThk.xyz, DaveyRaymond_AqThk.xyz, Denton_AqThk.xyz, DwightSouth_AqThk.xyz, EmeraldPleasantDale_AqThk.xyz, GarlandMalcolm_AqThk.xyz 368

Table 4-5. LPSNRD Inverted Model Structure with DEM and Layer Top-, Bottom-, and Mid-points in Depth and Elevation plus Inverted Cell Resistivities (LPSNRD_XYDEM_Dep_Elev_Rho.xyz) 370

Table 4-6. Channel name, description, and units for *_Quat_voxel.csv and *_Kd_voxel.csv. This is for the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, Garland Malcolm Blocks..... 370

Table 4-7. Files containing ESRI ArcView Binary Grids *.flt (Nebraska State Plane, NAD83, feet)..... 371

List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
A*m^2	Ampere meter squared
AEM	Airborne Electromagnetic
AGF	Aqua Geo Frameworks, LLC
dB/dt	Change in amplitude of magnetic field with time
BMP	Best management plan
CSD	Conservation and Survey Division
CWSPA	Community Water System Protection Area
DEM	Digital Elevation Model
DOI	Depth of Investigation
DGPS	Differential global positioning system
em, EM	Electromagnetic
ENWRA	Eastern Nebraska Water Resources Assessment
FT, ft	Feet
ft^3	cubic feet
GIS	Geographic Information System
gpm	Gallons per minute
Hr, hr	hours
Hz	Hertz (cycles per second)
IGRF	International Geomagnetic Reference Field
IP	undifferentiated Pennsylvanian units
Kc	Cretaceous Carlile Shale
Kd	Cretaceous Dakota Group
Kgg	Cretaceous Greenhorn Limestone and Graneros Shale
Km, km	Kilometers
KMZ, kmz	Keyhole Markup language Zipped file
LCI	Laterally-constrained Inversions
LENRD	Lower Elkhorn Natural Resources District
LPNNRD	Lower Platte North Natural Resources District
LPSNRD	Lower Platte South Natural Resources District
MAG	Magnetic (data); Magnetometer (instrument)
MCG	Minimum curvature gridding
mg/L	Milligram per liter
M, m	Meters
mi^2	Miles squared
NAD83	North American Datum of 1983
MAR	Managed Aquifer Recharge
NAVD88	North American Vertical Datum of 1988
NE	Nebraska
NED	National Elevation Dataset
NE-DNR	Nebraska Department of Natural Resources

NMR	Nuclear Magnetic Resonance
NNRD	Nemaha Natural Resources District
NOGCC	Nebraska Oil and Gas Conservation Commission
NRD	Natural Resources Districts
OM	Geosoft Oasis montaj
PFC	Primary Field Compensation
PLNI	Power Line Noise Intensity
P-MRNRD	Papio-Missouri River Natural Resources District
Q	Quaternary
Rx	Receiver
recon	Reconnaissance
SC	Specific Conductance
SCI	Spatially-Constrained Inversion
sec	second
STD	Standard Deviation
TEM	Transient Electromagnetic
TDEM	Time-Domain Electromagnetic
TDS	Total Dissolved Solids
Tx	Transmitter
UNL	University of Nebraska Lincoln
μS/cm	MicroSiemens per centimeter
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VE	Vertical Exaggeration
V/m^2	Volts per meter squared
X, x	The x-direction in a cartesian coordinate system
XRI	Exploration Resources International
Y, y	The y-direction in a cartesian coordinate system
Z, z	The z-direction (positive is up) in a cartesian coordinate system

1 Introduction

1.1 Purpose of Current Project

Sound management of groundwater and surface water in eastern Nebraska has become increasingly important in recent years. There are expanding pressures placed on the resource by the ever growing and dynamic demands for: agricultural production, population growth and urbanization, potential contamination from natural and anthropogenic sources, industrial and commercial needs; along with ever present changing climate.

The combination of these stresses on water resources has increased the need for detailed hydrogeologic frameworks of the subsurface. Groundwater management strategies and policies implemented to address water quality concerns is another effort that can be improved with better understanding of recharge, and its relationship with the underlying aquifers. The mapping of the subsurface related to groundwater flow and hydrologic connection between different aquifers and streams is also important in understanding water quality. Geographic regions that are identified as major contributors to recharge could be areas targeted for enhanced promotion of best management practices (BMP) to reduce or eliminate future contamination events. Additional uses of this survey will be to determine potential areas of Managed Aquifer Recharge (MAR) for addition to current supplies of groundwater in areas if need to replace depletions from development or supply future development. This data can be used to enhance the hydrogeologic framework for groundwater modeling for testing management scenarios at a regional level where boreholes are not sufficient or are of limited use. Where AEM block flights exist, this dense flight line data would be excellent for local groundwater models by having high resolution framework to build the model.

This report describes the general hydrogeologic conditions, assessed using data collected from this AEM survey. In addition to the AEM data, reports from previous studies, analysis of historic groundwater levels, and geologic descriptions from University of Nebraska-Lincoln Conservation and Survey Division (CSD) test holes, Nebraska Oil and Gas Conservation Commission (NOGCC), and drillers logs obtained from registered wells at the Nebraska Department of Natural Resources (NE-DNR) were used. The AEM survey data were collected along reconnaissance (recon) lines spaced approximately 1.0 miles apart and the block flight lines separated by about 650 ft to 1,000 ft (200 m – 300 m). This AEM survey was planned and selected by LPSNRD and AGF with assistance from scientists from CSD to assist in the development of a 3D hydrogeologic framework of this project area and recommend future work to enhance groundwater management activities. This work was supported by the Natural Resources Commission Water Sustainability Fund, the LPSNRD, and in-kind service from CSD.

A location map showing the LPSNRD is presented in Figure 1-1. A Google Earth image of the “As-Flown” flight lines are presented in Figure 1-2 and also included as a kmz in Appendix 3-Deliverables \KMZs\Flight Lines. These are discussed in detail in Section 2. The main AEM flight area was between Ashland, NE in the east and Seward, NE in the west and between Crete, NE in the south and Wahoo, NE in the north.

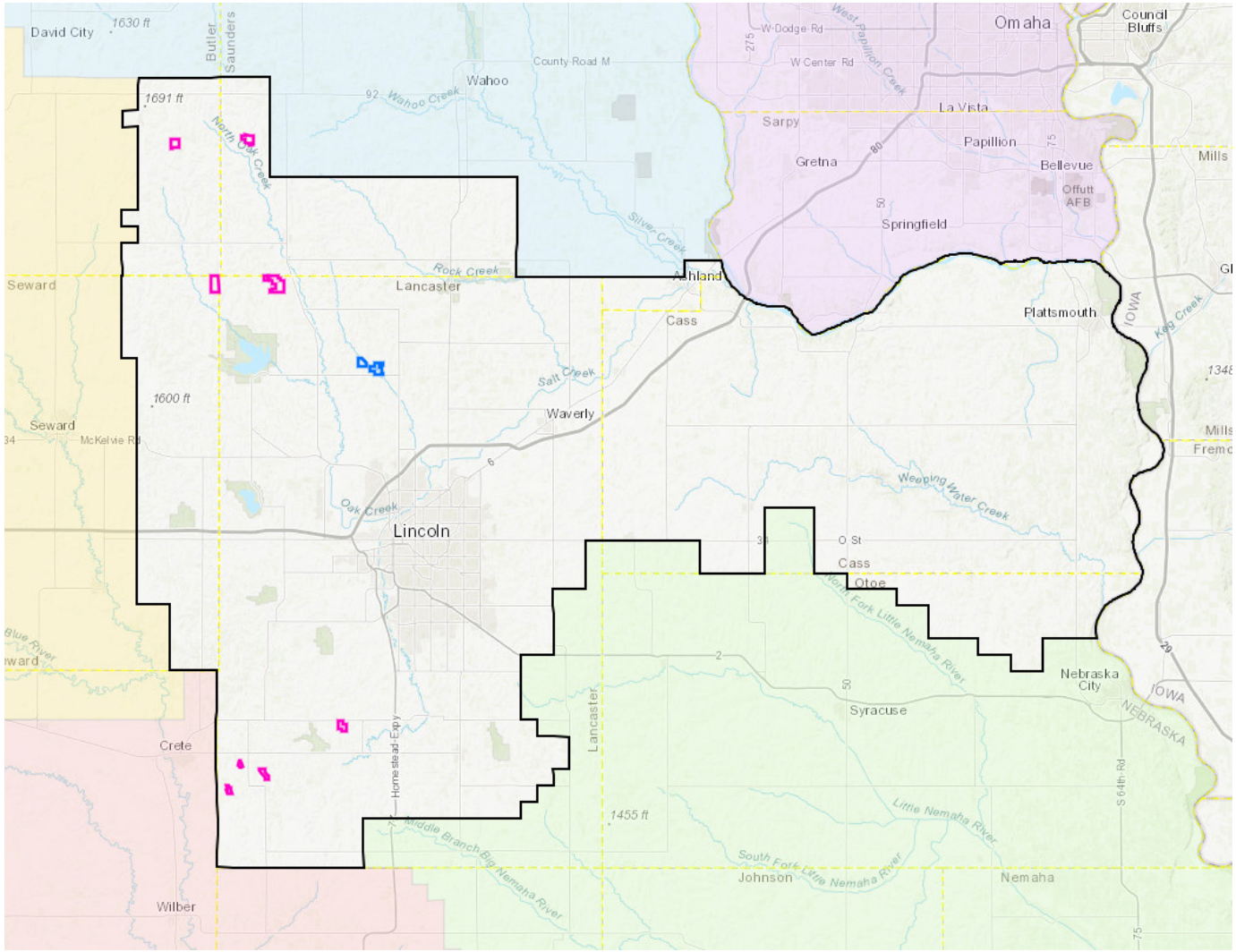


Figure 1-1. Map of the LPSNRD (black boundary) in eastern Nebraska. Purplish Pink-Papio-Missouri River NRD, Blue-Lower Platte North NRD, Yellow-Upper Big Blue NRD, Pink-Lower Big Blue NRD, and Green-Nemaha NRD (modified from https://lpsnrd.maps.arcgis.com/apps/MapJournal/index.html?appid=a07535d5d2f64bffbef4ca2ec6c8cd0e).

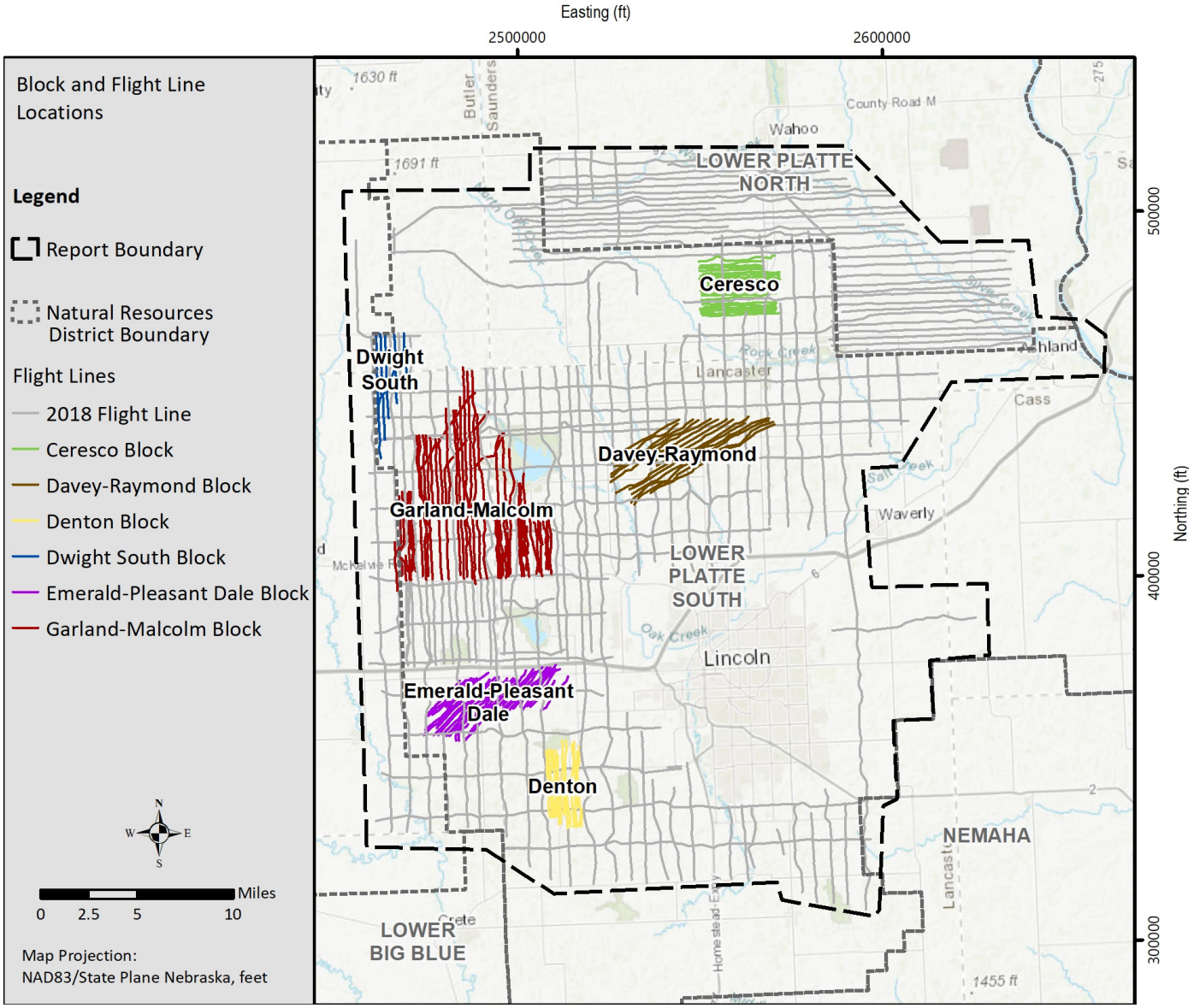


Figure 1-2. The LPSNRD 2018 AEM survey flight lines including the AEM Block flight areas.

1.2 Background

In 1995, the LPSNRD declared the entire District as Phase I for ground water quality and quantity, which implemented basic programs such as well permitting, cost-sharing on best management practices, and information and education programs (LPSNRD, 1995). This determination was based on a variety of studies by the LPSNRD, the U.S. Geological Survey (USGS), and private consultants. The conclusions from these studies indicated that the LPSNRD is underlain by several different and separate aquifer units, referred to in the Plan as Ground Water Reservoirs (GWRs), and designated these as specific areas of management for ground water quality and quantity. In addition, the Plan identified the Community Water System Protection Areas (CWSPA) surrounding approximately 30 communities in the LPSNRD as areas of management. The remainder of the LPSNRD was designated as the Remaining Area (RA), where ground water availability is highly variable and aquifer units must be managed on a case-by-case basis. The plan also directed that areas of management needed to be managed for both quality and quantity. Subsequent studies by the LPSNRD and private consultants delineated areas where ground water quality, particularly from nitrate contamination, was a concern, and these areas were designated as Phase II quality management areas, mostly in the early 2000s. In Phase II areas, additional requirements such as certification training for individuals applying nitrogen fertilizer were instituted. In the eastern portion of the LPSNRD, these included the Lower Salt Creek GWR, and the Otoe County Rural Water District #3/Weeping Water and Union CWSPAs. In addition, historically high nitrate levels in the Elmwood CWSPA resulted in a Phase III ground water quality management area designation; Phase III requirements include additional measures such as required soil sampling and restrictions on fertilizer application timing. The other CWSPAs in the eastern portion of the LPSNRD (Waverly, Alvo/Cass County Rural Water District #2, Eagle, and Cass County Rural Water District #1 South/Sanitary District #1/ Lake Waconda), although not designated as Phase II or III management areas, are characterized in most cases by limited aquifer units which increase their vulnerability to ground water quality and quantity problems. As a result of these concerns, all these areas were mapped during the 2016 AEM investigation (AGF, 2017).

The LPSNRD has been a user of AEM technology for many years in NE. In 2006 the ENWRA project was formed with sponsors from six NRDs (Lewis and Clark, Lower Elkhorn, Papio-Missouri River, Lower Platte North, Lower Platte South, and Nemaha) and cooperating agencies including the CSD and the USGS. The long-term goal of the project is to develop a geologic framework and water budget for the glaciated portion of eastern Nebraska. In March 2007, ENWRA funded a study where AEM methods were implemented by the USGS to characterize the hydrogeologic conditions in the Platte River valley near Ashland, as well as in areas underlain by glacial till near Firth and Oakland, Nebraska (Smith et al. 2008). The Firth area AEM survey was split between the LPSNRD and the NNRD. The NE-CSD report on the interpretation of AEM in the Firth area was released in 2013 (Korus et al., 2013). In 2009, the LPSNRD funded the USGS for the development of a 3D hydrostratigraphic framework of the subsurface near Sprague, Nebraska using an AEM survey (Smith et al., 2009; Divine and Korus, 2013). In 2013, the LPSNRD funded Exploration Resources International (XRI) to complete an AEM survey covering over 800 line-miles in Butler and Saunders counties near Valparaiso and Dwight, Nebraska (Carney et al., 2014). This survey revealed buried paleovalley aquifers beneath thick sequences of till. In 2014-2015 the

ENWRA funded XRI for a large-scale reconnaissance AEM survey over the glaciated portion of Nebraska, approximately 2,200 line-km of approximately 32 km spaced lines (Abraham et al., 2015; Carney et al., 2015a; Carney et al., 2015b). As mentioned above, in 2016 AGF flew an AEM survey over areas of interest for well head protection and groundwater availability in the LPSNRD (AGF, 2017). Through the previous work and the current work presented in this report much of the area of the LPSNRD has been mapped with AEM technology.

1.3 Description of the LPSNRD 2018 AEM Project Area

The LPSNRD spans approximately ~1527 square miles (mi^2) in eastern Nebraska. The elevation of the area ranges from 1,030 ft to 1,722 ft above sea level**.** It is underlain by parts of two of Nebraska's eight topographic regions—Rolling Hills and Valleys (Elder et al., 1951). There are 314,722 residents and Principal cities within the project area, based on 2010 population estimates, include (alphabetically) Ceresco (885), Denton (204), Davey (154), Garland (216), Lincoln (284,736), Malcolm (399), Pleasant Dale (210), and Raymond (183) (U.S. Census Bureau, 2013).

A map of the LPSNRD groundwater management areas is presented in Figure 1-3. Groundwater Quality management areas are shown on the map by the orange shaded areas are Phase II, Pink areas are Phase III, which include villages of Pleasant Dale and Davey in the 2018 AEM project area and orange hatched zone which is the low Salt Creek-Phase II groundwater water quality area within the boundary of the LPSNRD (modified from https://www.lpsnrd.org/, last accessed on November 28, 2019.).

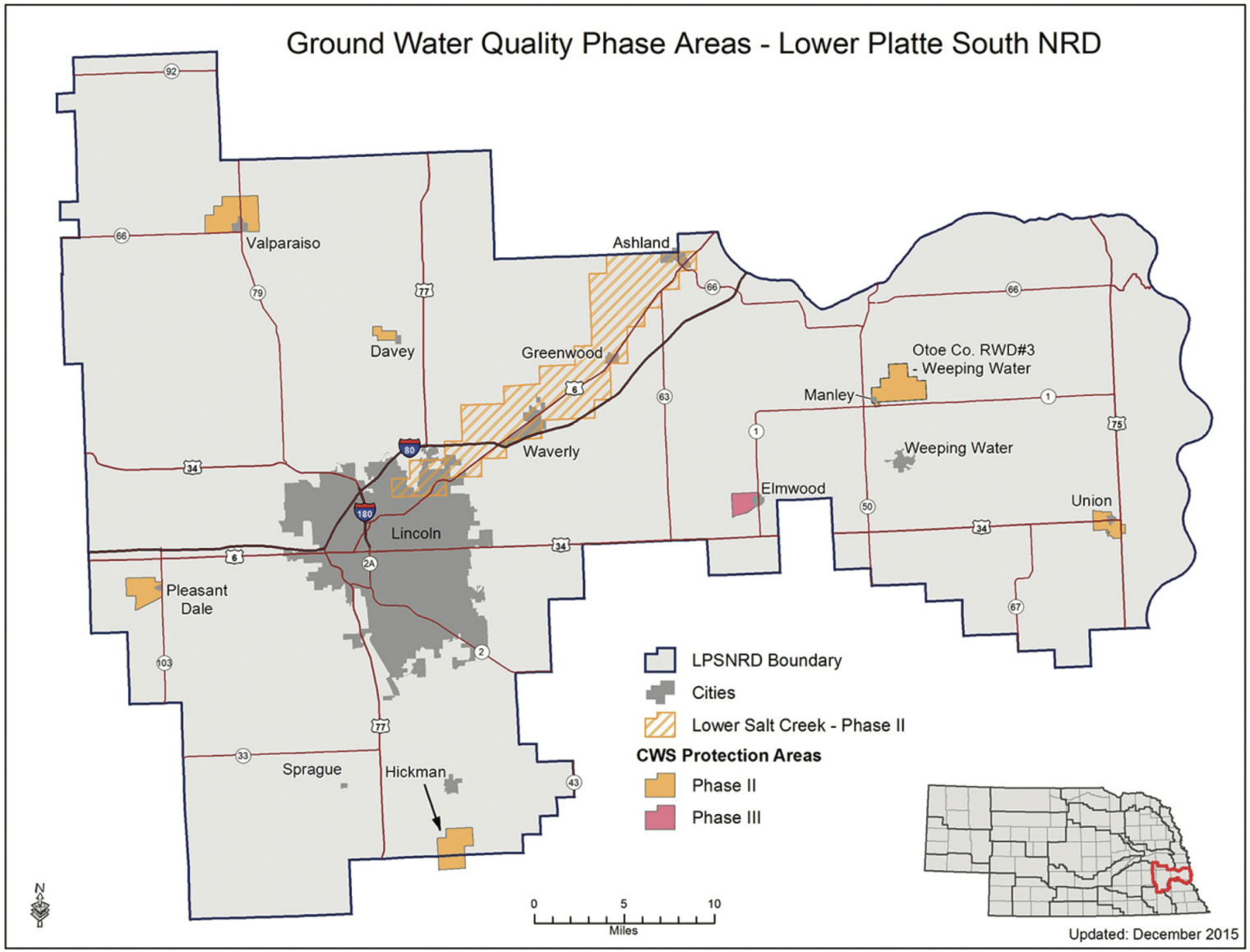


Figure 1-3. Map of LPSNRD groundwater management areas.

2 Geophysical Methodology, Acquisition and Processing

2.1 Geophysical Methodology

Airborne Transient Electromagnetic (TEM) or airborne Time-Domain Electromagnetic (TDEM), or generally AEM, investigations provide characterization of electrical properties of earth materials from the land surface downward using electromagnetic induction. Figure 2-1 gives a conceptual illustration of the airborne TEM method.

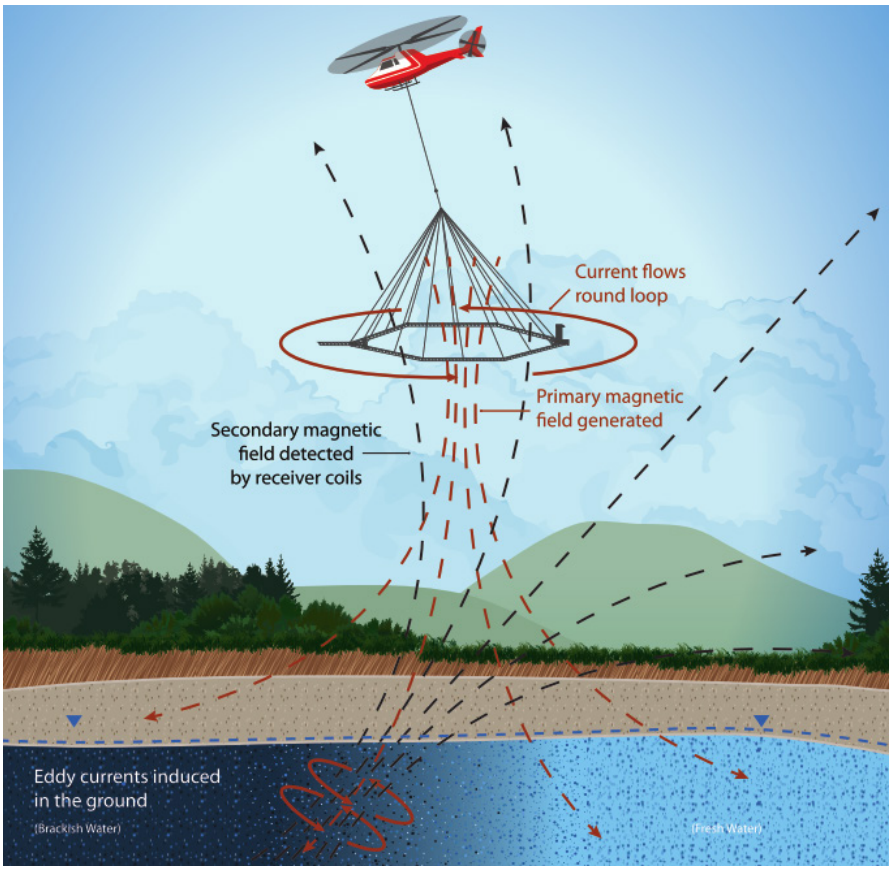


Figure 2-1. Schematic of an airborne electromagnetic survey, modified from Carney et al. (2015a).

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

current, the time rate of decay of the magnetic field, B, is determined (dB/dt). When compiled in time, these measurements constitute a "sounding" at that location. Each TEM measurement produces an EM sounding at one point on the surface.

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

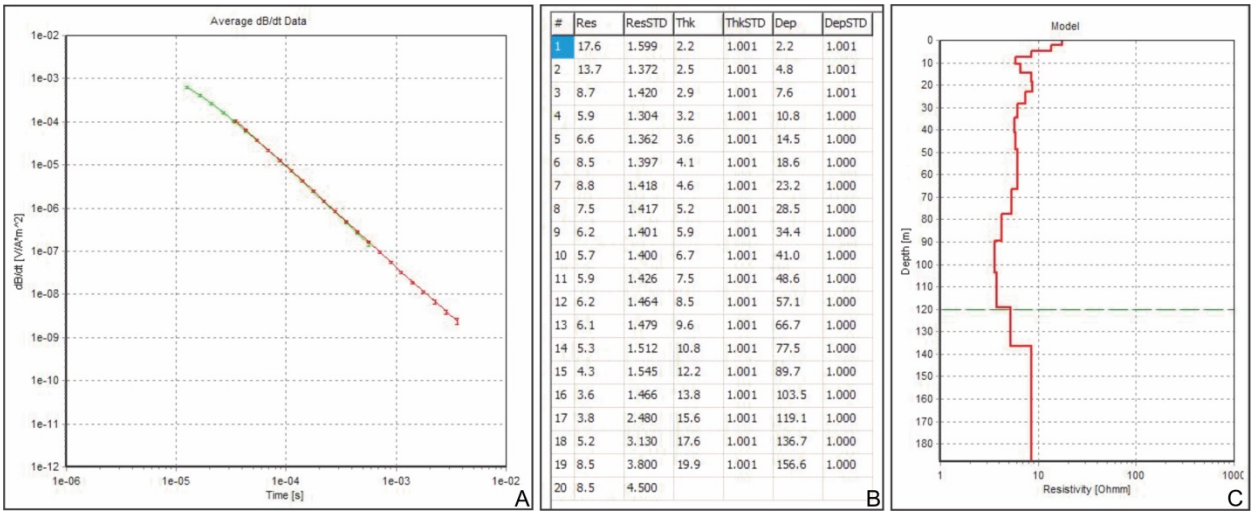


Figure 2-2. A) Example of a dB/dt sounding curve. B) Corresponding inverted model values. C) Corresponding resistivity earth model.

2.2 Flight Planning/Utility Mapping

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

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

The locations of the flight lines were converted from a regularly spaced grid to one with flight lines optimized to avoid electromagnetic coupling with the previously mentioned utilities. This was done by moving along each flight line in Google Earth to inspect the path for visible power lines, radio towers,

railroads, highways and roads, confined feeding operations and buildings, and any other obstructions that needed to be avoided during flight.

Upon conclusion of the design process the LPSNRD reconnaissance flight lines had a maximum length of approximately 35 miles (56 km) in the north-south direction and about 29 miles (47 km) in the east-west direction. The reconnaissance flight lines were separated by approximately 1.0 miles (1.62 km) in both east-west and north-south directions and block flight lines were separated by about 650 feet to 1,000 feet (200 m – 300 m).

2.3 AEM Survey Instrumentation

AEM data were acquired using the SkyTEM304M (304M) airborne electromagnetic system (SkyTem Airborne Surveys Worldwide, 2019). The 304M is a rigid frame, dual-magnetic moment (Low and High) TEM system. The area of the 304M Tx coil is 342 m^2 and the coil contains four (4) turns of wire. A peak current of nine (9) amps is passed through one turn of wire in the Tx for Low Moment measurements and a peak current of about 110 amps is passed through the four turns of wire for High Moment measurements. This results in peak Tx Low and High magnetic moments of ~3,000 Ampere-meter-squared ($A*m^2$) and ~150,000 $A*m^2$, respectively.

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

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

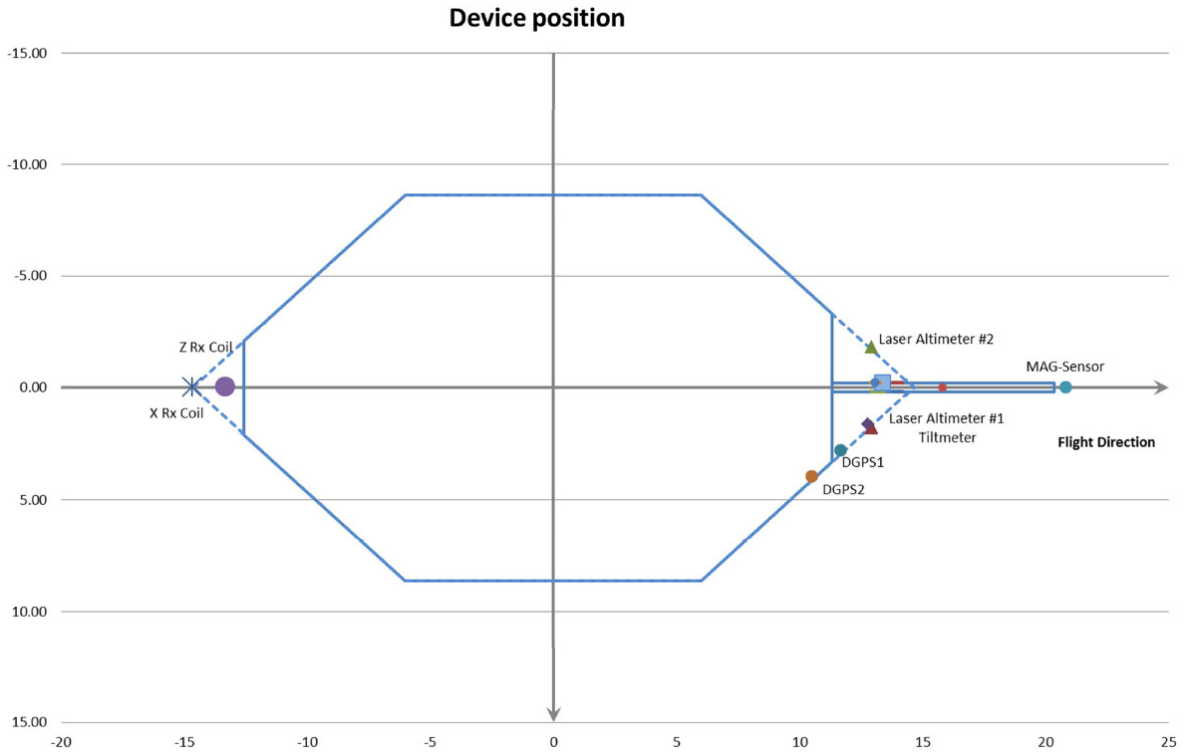


Figure 2-3. SkyTEM304M frame, including instrumentation locations and X and Y axes. Distances are in meters. Instrumentation locations listed in Table 2-1.



Figure 2-4. Photos of the SkyTEM304M system in suspension beneath the helicopter.

For this project, the 304M was flown at an average speed of 48 mi/hr (78 kilometers/hr) at an average flight height of 126.9 ft (38.7 m) above the land surface, using the sling-load cargo system of a Eurocopter AS350 helicopter. Figure 2-4 displays a couple of images of the 304M in operation.

Table 2-1. Positions of instruments on the SkyTEM304M frame, using the center of the frame as the origin, in feet.

	DGPS 1	DGPS 2	Inclinometer 1	Inclinometer 2	Altimeter 1	Altimeter 2	Magnetic Sensor	Rx Coil
X	38.31	34.47	41.95	41.95	42.44	42.44	67.24	-43.46
Y	9.15	12.96	5.38	-5.38	5.87	-5.87	0	0
Z	-0.52	-0.52	-0.39	-0.39	-0.39	-0.39	-1.71	-6.56

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

Tx Corners	1	2	3	4	5	6	7	8
X	-41.16	-19.78	18.83	37.19	39.19	18.83	-19.78	-41.16
Y	-6.89	-27.98	-28.18	-10.85	10.85	28.18	27.98	6.89

2.4 Data Acquisition

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

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

Approximately 1,990 line-miles (3,224 line-kilometers) were acquired over the LPSNRD AEM survey area between 17 June 2018 and finishing on 12 July 2018 (Table 2-3). A data acquisition map is presented in Figure 2-5 with the flight lines grouped by acquisition date.

Table 2-3. LPSNRD AEM Data Acquisition Schedule and Totals.

Date	# Flights	Feet	Miles	Km
17-Jun-18	1	255982	48.5	78.5
18-Jun-18	3	1086083	205.7	333.2
19-Jun-18	1	452287	85.7	138.8
22-Jun-18	3	1256053	237.9	385.4
23-Jun-18	3	1533188	290.4	470.4
24-Jun-18	3	1617342	306.3	496.2
26-Jun-18	2	552021	104.5	169.4
28-Jun-18	2	1045929	198.1	320.9
30-Jun-18	3	1352234	256.1	414.9
1-Jul-18	2	973801	184.4	298.8
2-Jul-18	1	313997	59.5	96.3
3-Jul-18	1	10723	2.0	3.3
4-Jul-18	1	44717	8.5	13.7
12-Jul-18	1	15319	2.9	4.7
Total	27	10509677	1990.5	3224.6



Figure 2-5. LPSNRD 2018 AEM flight lines grouped by acquisition date. Projection is Nebraska State Plane NAD83, feet.

2.4.1 Primary Field Compensation

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

2.4.2 Automatic Processing

The AEM data collected by the 304M were processed using Aarhus Workbench version 5.8.3.0 (Aarhus Geosoftware (http://www.aarhusgeosoftware.dk/aarhus-workbench-ib3ao) described in HydroGeophysics Group, Aarhus University (2011).

Automatic processing algorithms provided within the Workbench program are initially applied to the AEM data. DGPS locations were filtered using a stepwise, second-order polynomial filter of nine seconds with a beat time of 0.5 seconds, based on flight acquisition parameters. The AEM data are corrected for tilt deviations from level and so filters were also applied to both tilt meter readings with a median filter of three seconds and an average filter of two seconds. The altitude data were corrected using a series of two polynomial filters. The lengths of both eighth-order polynomial filters were set to 15 seconds with shift lengths of twelve (12) seconds. The lower and upper thresholds were 1 and 100 meters, respectively.

Trapezoidal spatial averaging filters were next applied to the AEM data. The times used to define the trapezoidal filters for the Low Moment were $1.0x10^{-5}$ sec, $1.0x10^{-4}$ sec, and $1.0x10^{-3}$ sec with widths of 4, 7, and 18 seconds. The times used to define the trapezoid for the High Moment were $1.0x10^{-4}$ sec, $1.0x10^{-3}$ sec, and $1.0x10^{-2}$ sec with widths of 10, 20, and 36 seconds. The trapezoid sounding distance was set to 1.0 seconds and the left/right setting, which requires the trapezoid to be complete on both sides, was turned on. The spike factor and minimum number of gates were both set to 20 percent for both soundings. Lastly, the locations of the averaged soundings were synchronized between the two moments.

2.4.3 Manual Processing and Laterally-Constrained Inversions

After the implementation of the automatic filtering, the AEM data were manually examined using a sliding two-minute time window. The data were examined for possible electromagnetic coupling with surface and buried utilities and metal, as well as for late time-gate noise. Data affected by these were removed. Examples of locating areas of EM coupling with pipelines or power lines and recognizing and removing coupled AEM data in Aarhus Workbench are shown in Figure 2-6 and Figure 2-7, respectively. Examples of two inversions, one without EM coupling and the other with EM coupling, are shown in Figure 2-8. Areas were also cut out where the system height was flown greater than 213 feet (65 m) above the ground surface which caused a decrease in the signal level. This problem was encountered at several locations along the major rivers and streams due to the tall cottonwood trees.

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

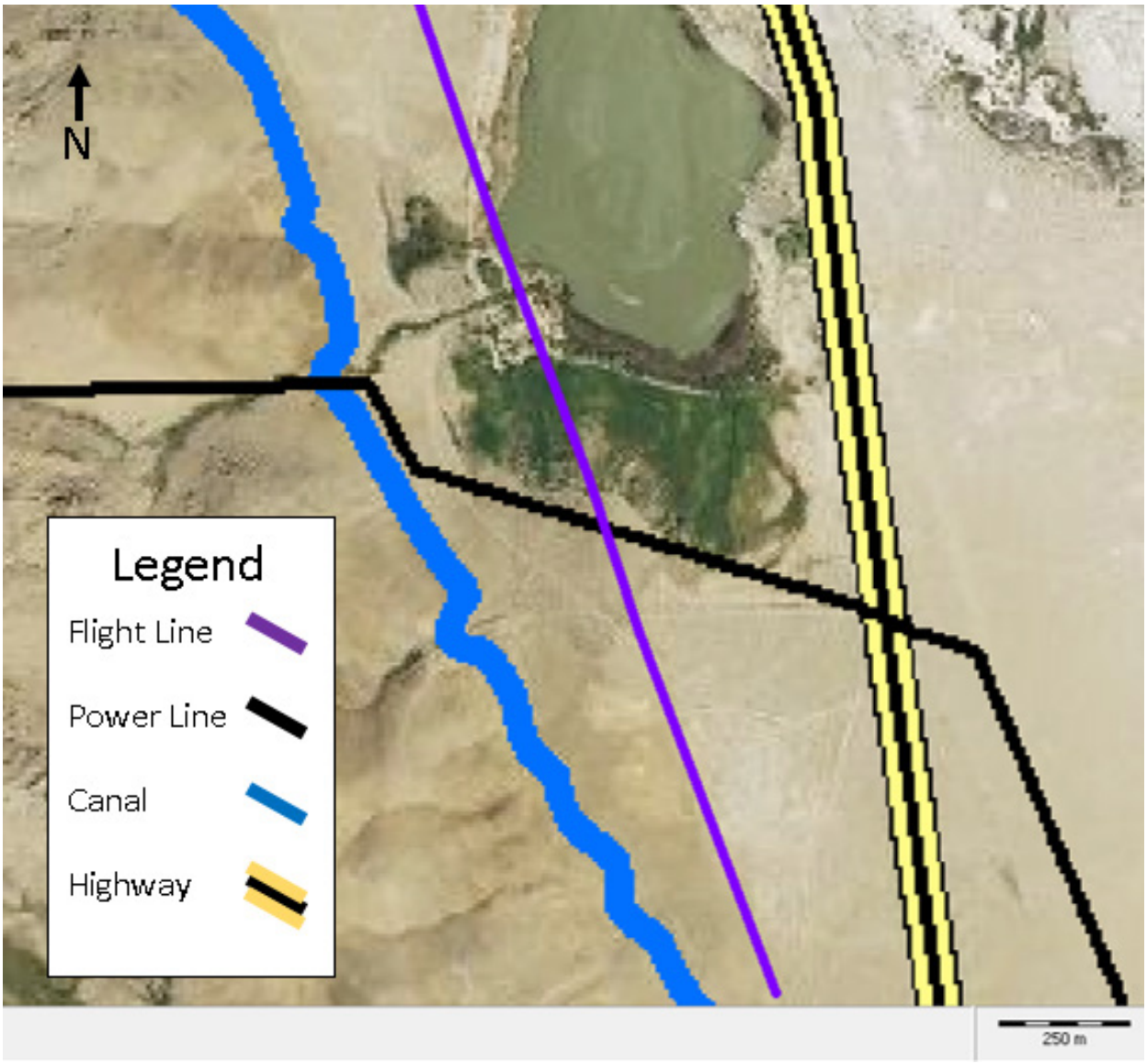


Figure 2-6. Example locations of electromagnetic coupling with pipelines or power lines.

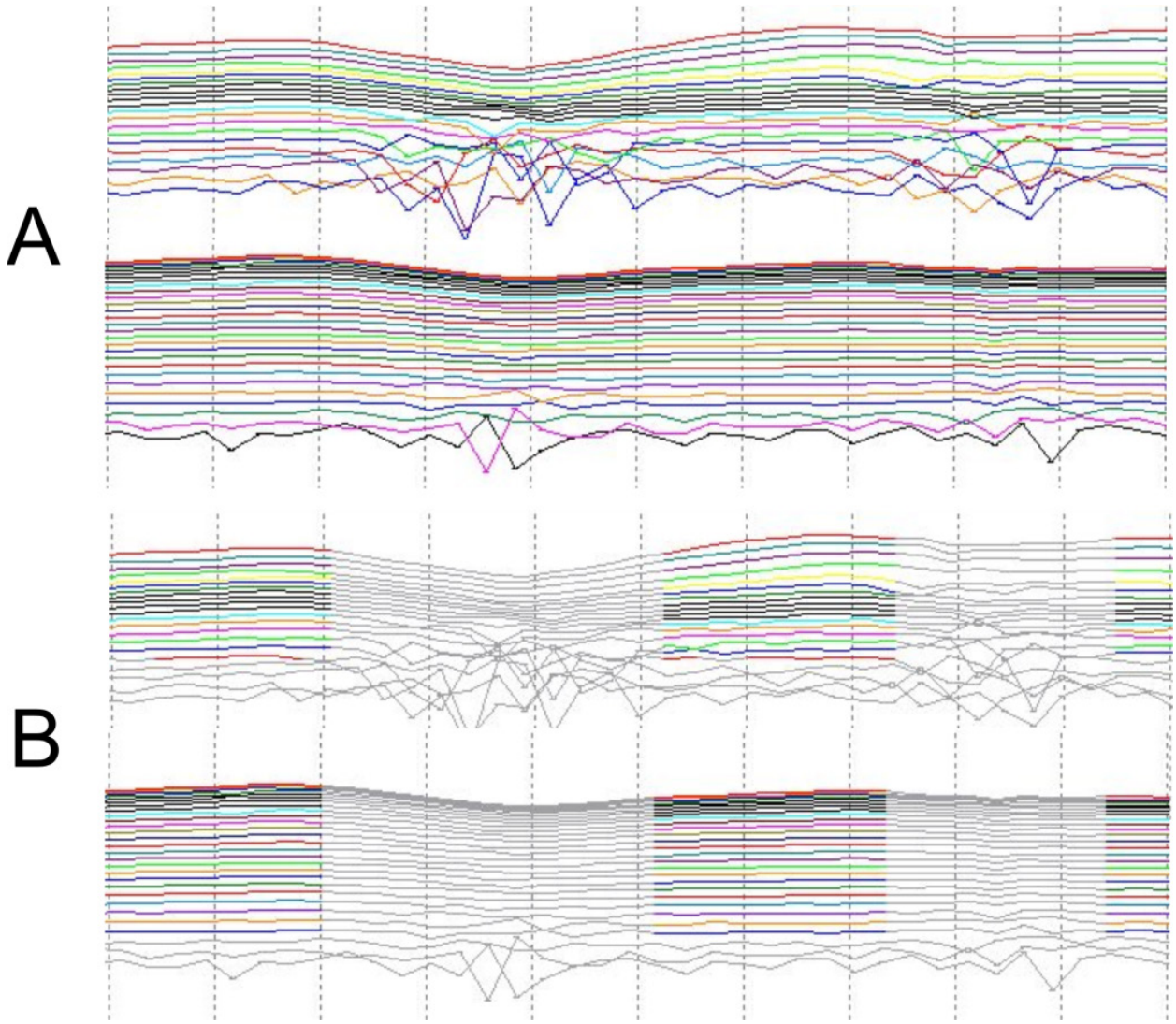


Figure 2-7. A) Example of AEM data affected by electromagnetic coupling as presented in the Aarhus Workbench editor. The top group of lines is the unedited data with the Low Moment on top and the High Moment on the bottom. The bottom group shows the same data after editing.

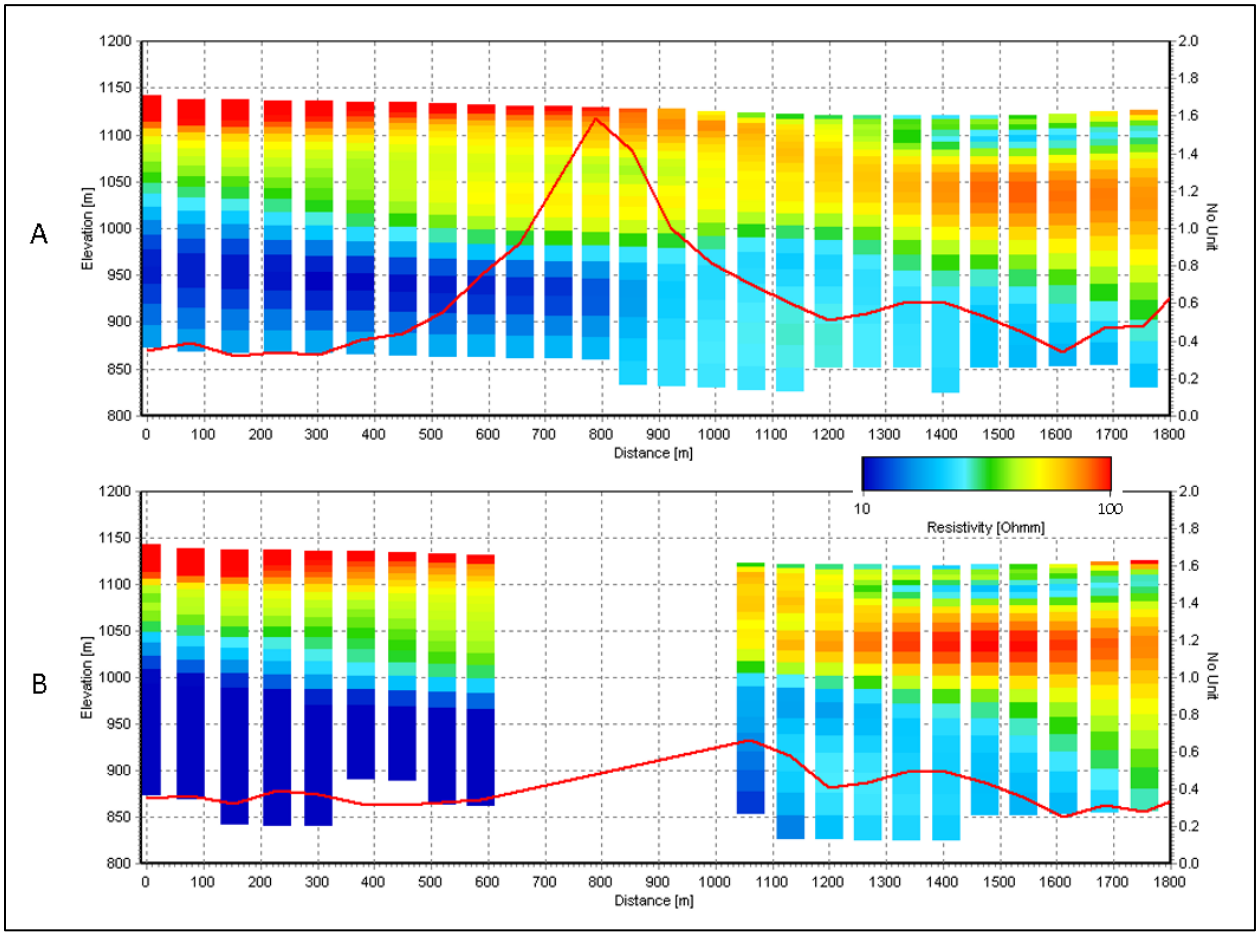


Figure 2-8. A) Example of Laterally-Constrained inversion results where AEM data affected by coupling with pipelines and power lines were not removed. B) Inversion results where AEM data affected by coupling were removed.

2.4.4 Power Line Noise Intensity (PLNI)

The Power Line Noise Intensity (PLNI) channel assists in identifying possible sources of noise from power lines. Pipelines, unless they are cathodically-protected, are not mapped by the PLNI. The PLNI is produced by performing a spectral frequency content analysis on the raw received Z-component SkyTEM data. For every Low Moment data block, a Fourier Transform is performed on the latest usable time gate data. The Fourier Transform is evaluated at the local power line transmission frequency (60 Hz) yielding the amplitude spectral density of the local power line noise. The PLNI data for the LPSNRD 2018 AEM survey is presented in Figure 2-9.

2.4.5 Magnetic Field Data

As discussed above, the SkyTEM 304M includes a Total Field magnetometer. The magnetic Total Field data can yield information about infrastructure as well as geology. Figure 2-10 shows the residual magnetic Total Field intensity data for the LPSNRD AEM survey area after correcting for diurnal drift and removing the International Geomagnetic Reference Field (IGRF). This data is used in decoupling efforts.

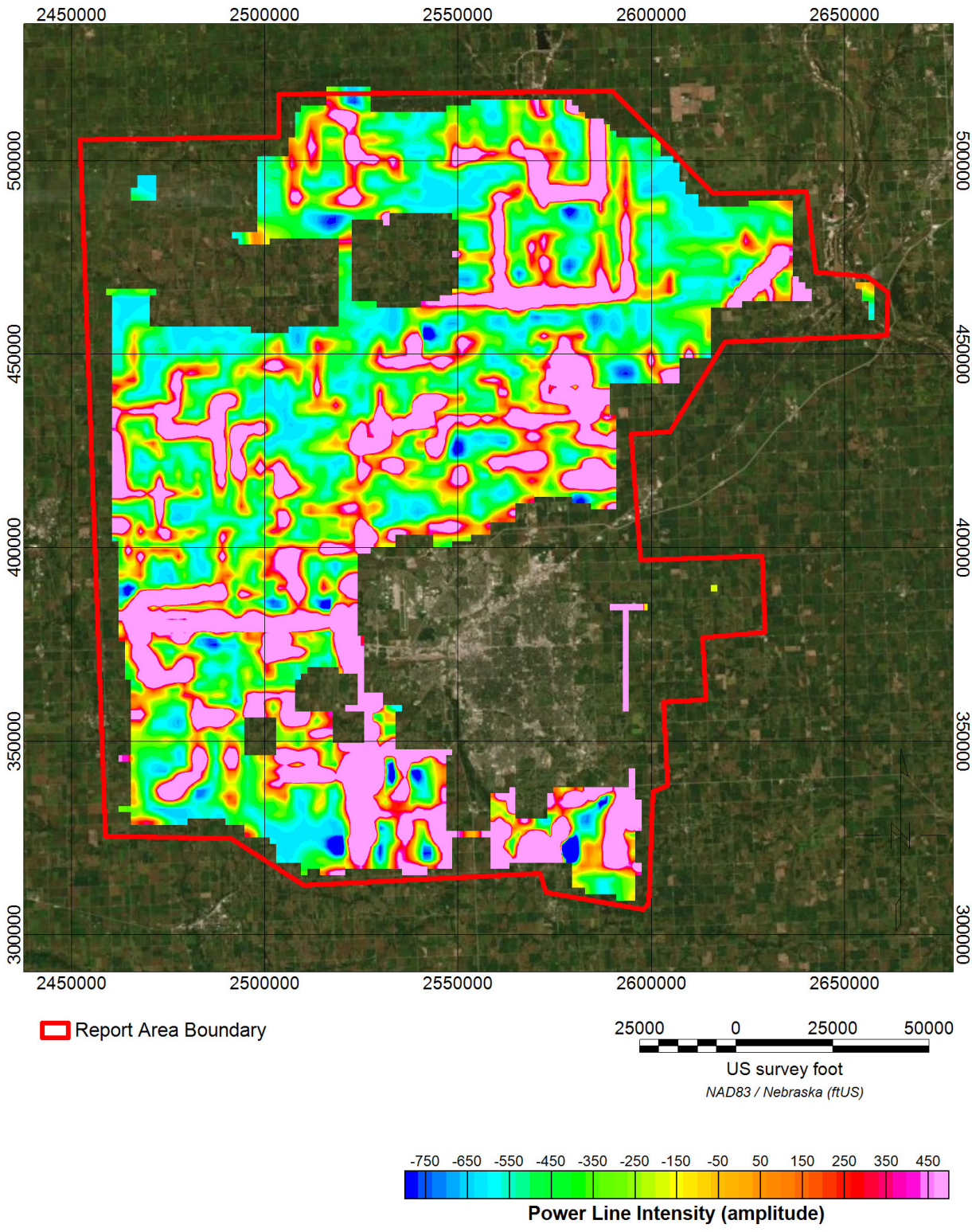


Figure 2-9. Power Line Noise Intensity (PLNI) map of the LPSNRD 2018 project area.

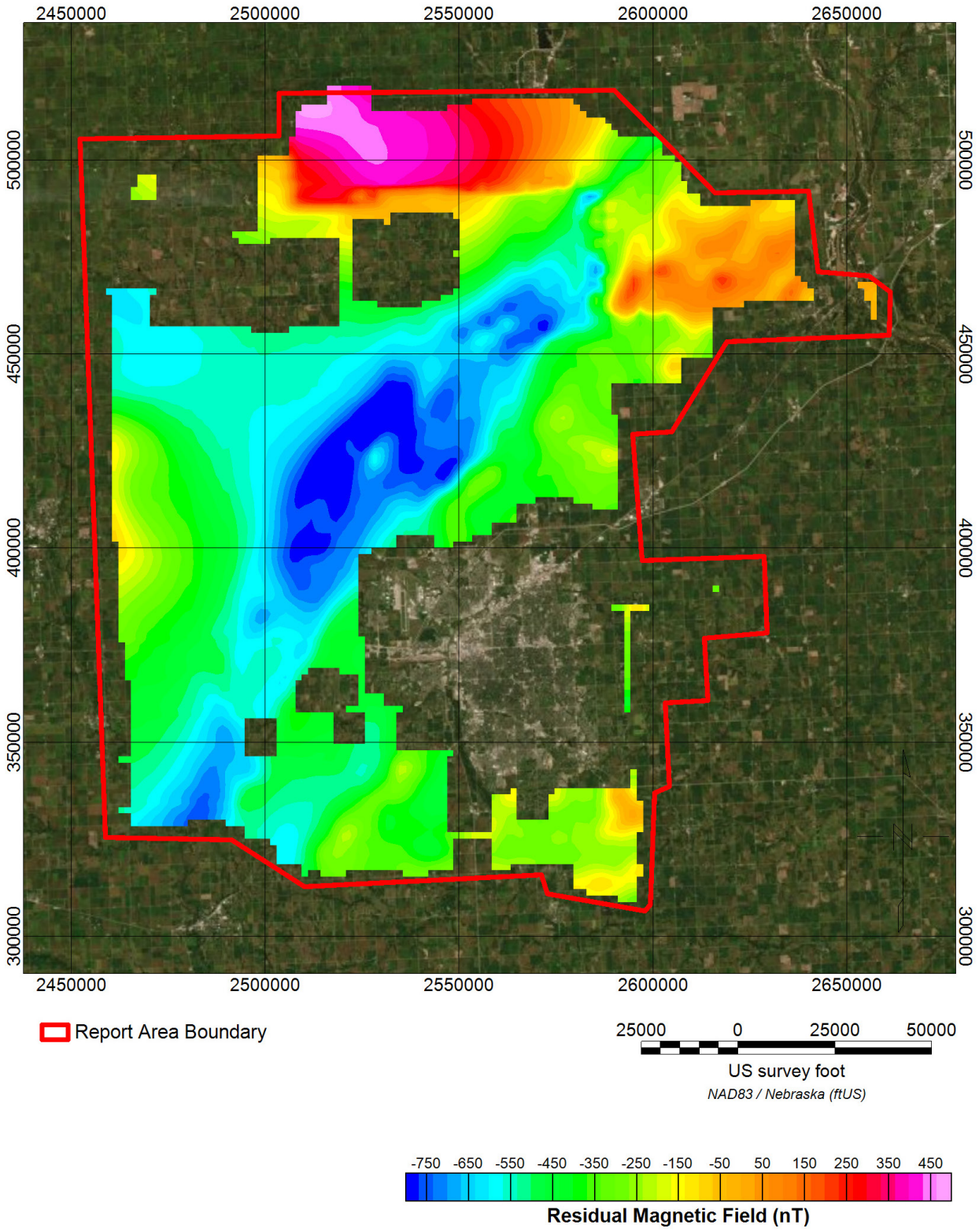


Figure 2-10. Residual magnetic Total Field intensity data for the LPSNRD 2018 survey area corrected for diurnal drift, with the International Geomagnetic Reference Field (IGRF) removed.

After final processing, 1,711-line-miles (2,772-line kilometers) were retained for inversion amounting to a retention rate of 86.0%. This high rate is the result of careful flight line planning and design given the infrastructure that was encountered during the acquisition. The LPSNRD-flight lines with blue colors representing the 86% of data retained for inversion and red lines representing data removed due to infrastructure and late time noise are presented in Figure 2-11.

2.5 Spatially-Constrained Inversion

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

The LPSNRD 2018 AEM data were inverted using a 40-layer model structure. The SCI inversions used smooth models, each with a starting resistivity of 10 Ohm-m (equivalent to a 10 ohm-m halfspace). The thicknesses of the first layers of the models were about 3 ft (1 m) with the thicknesses of the consecutive layers increasing by a factor of 1.08. The depths to the bottoms of the 39th layers were set to 1,148 ft, with thicknesses up to about 85 ft. The thicknesses of the layers increase with depth (Table 2-4 and Figure 2-12) as the resolution of the technique decreases. The spatial reference distance, ***s***, for the constraints were set to 308 ft with power laws of 0.75. The vertical and lateral constraints, ***ResVerSTD*** and ***ResLatStD***, were set to 2.4 and 1.4, respectively, for all layers.

The areas that were flown for the P-MRNRD, LPNNRD, and LPSNRD districts were inverted together with some areas of LENRD along the borders of the other NRD's. Seven groups of inversions, with about 10-15 flights each, were required to invert the AEM data. This process provided adequate overlap and allowed for full advantage to be taken with the SCI. Table 2-5 lists the SCI inversion groups and the flights that were included in each group and Figure 2-13 presents Google Earth images of the different inversion groups.



Figure 2-11. Locations of inverted data (blue lines) along the AEM flight lines (red lines) in the LPSNRD 2018 AEM survey area. Where blue lines are not present indicates decoupled (removed) data. 86.0% of the acquired data was retained for inversion and interpretation. Google Earth kmz's of the inverted data locations as well as the "as-flown" flight lines are included in Appendix 3\KMZ.

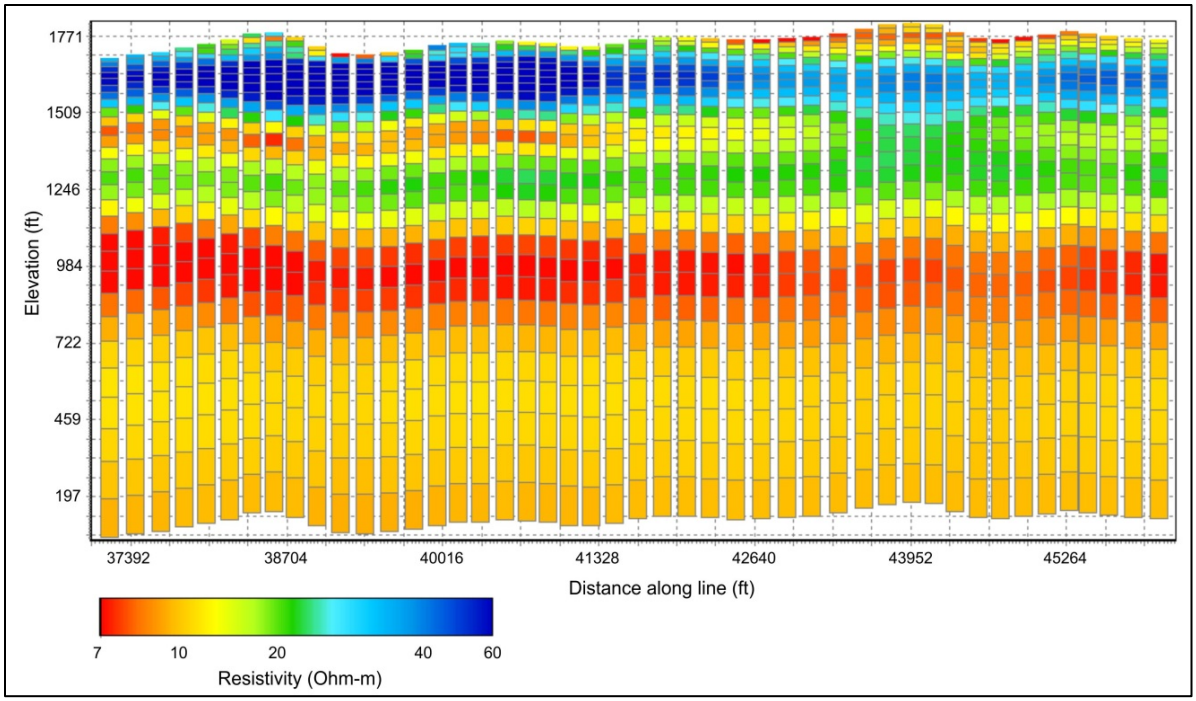


Figure 2-12: An example of an AEM profile illustrating increasing model layer thicknesses with depth.

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). The DOI provides a general estimate of the depth to which the AEM data are sensitive to changes in the resistivity distribution at depth (Christiansen and Auken, 2012). Two DOI's are calculated: an "Upper" DOI at a cumulative sensitivity of 1.2 and a "Lower" DOI set at a cumulative sensitivity of 0.6. A more detailed discussion on the DOI can be found in Asch et al. (2015).

Table 2-4: Thickness and depth to bottom for each layer in the Spatially Constrained Inversion (SCI) AEM earth models. The thickness of the model layers increase with depth as the resolution of the AEM technique decreases.

Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)	Layer	Depth to Bottom (ft)	Thickness (ft)	Depth to Bottom (m)	Thickness (m)
1	3.3	3.3	1.0	1.0	21	197.8	20.0	60.3	6.1
2	6.9	3.6	2.1	1.1	22	219.8	22.0	67.0	6.7
3	10.8	3.9	3.3	1.2	23	243.7	23.9	74.3	7.3
4	15.1	4.3	4.6	1.3	24	269.9	26.2	82.3	8.0
5	19.7	4.6	6.0	1.4	25	298.8	28.9	91.1	8.8
6	24.9	5.2	7.6	1.6	26	330.3	31.5	100.7	9.6
7	30.5	5.6	9.3	1.7	27	364.7	34.4	111.2	10.5
8	36.7	6.2	11.2	1.9	28	402.5	37.7	122.7	11.5
9	43.6	6.9	13.3	2.1	29	443.8	41.3	135.3	12.6
10	51.2	7.5	15.6	2.3	30	489.0	45.3	149.0	13.8
11	59.4	8.2	18.1	2.5	31	538.6	49.5	164.2	15.1
12	68.2	8.9	20.8	2.7	32	593.0	54.4	180.7	16.6
13	78.1	9.8	23.8	3.0	33	652.4	59.4	198.8	18.1
14	88.6	10.5	27.0	3.2	34	717.3	64.9	218.6	19.8
15	100.4	11.8	30.6	3.6	35	788.5	71.2	240.3	21.7
16	113.2	12.8	34.5	3.9	36	866.6	78.1	264.1	23.8
17	127.3	14.1	38.8	4.3	37	951.9	85.3	290.1	26.0
18	142.7	15.4	43.5	4.7	38	1045.3	93.5	318.6	28.5
19	159.4	16.7	48.6	5.1	39	1147.7	102.3	349.8	31.2
20	177.8	18.4	54.2	5.6					

Table 2-5. AEM flights included in each of the SCI inversion groups.

Group 1	0617FL2-0618FL1,2,3-0619FL1-0622FL1,2,3-0623FL1,2,3
Group 2	0622FL1,2,3-0623FL1,2,3-0624FL1,2,3-0626FL2-0628FL2,3-0630FL1
Group 3	0626FL1,2-0628FL1,2,3- 0630FL1,2,3- 0701FL1,2,3-0702FL1C-0704FL2
Group 4	0701FL3 - 0702FL1C,2A-0703FL1,2 - 0704FL1,2,3 - 0705FL2
Group 5	0703FL1,2-0704FL1,2,3-0705FL1-0706FL1,2-0707FL1
Group 6	0705FL1,2,3-0706FL1,2-0707FL1,2-0709FL1-0712FL1,2,3
Group 7	0711FL1-0714FL1,2-0718FL2-0720FL1

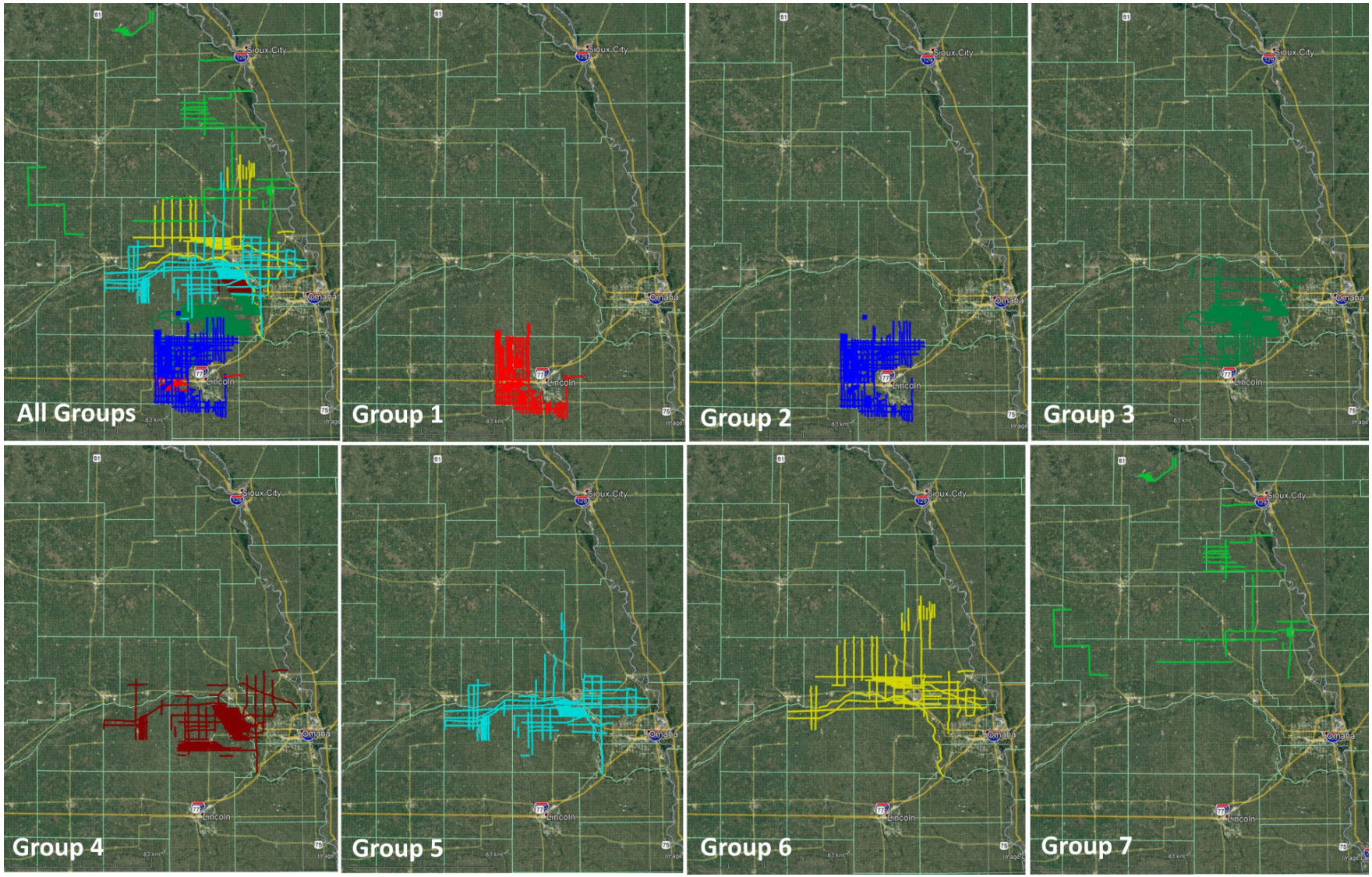


Figure 2-13. SCI inversion groups for the P-MRNRD, LPNNRD, and LPSNRD AEM data.

Figure 2-14 presents a histogram of the LPSNRD SCI inversion data/model residuals and a map of data to model error residuals comparison is presented in Figure 2-15.

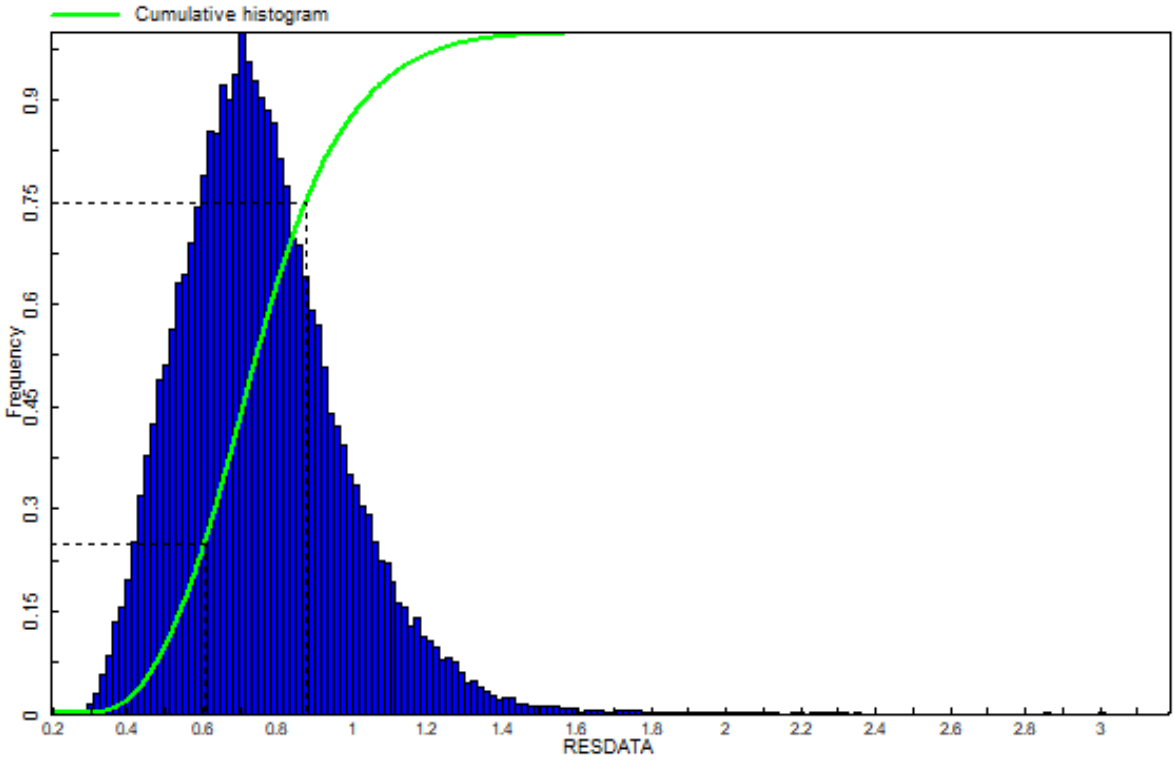


Figure 2-14: Data/model residual histogram for the LPSNRD 2018 SCI inversion results.

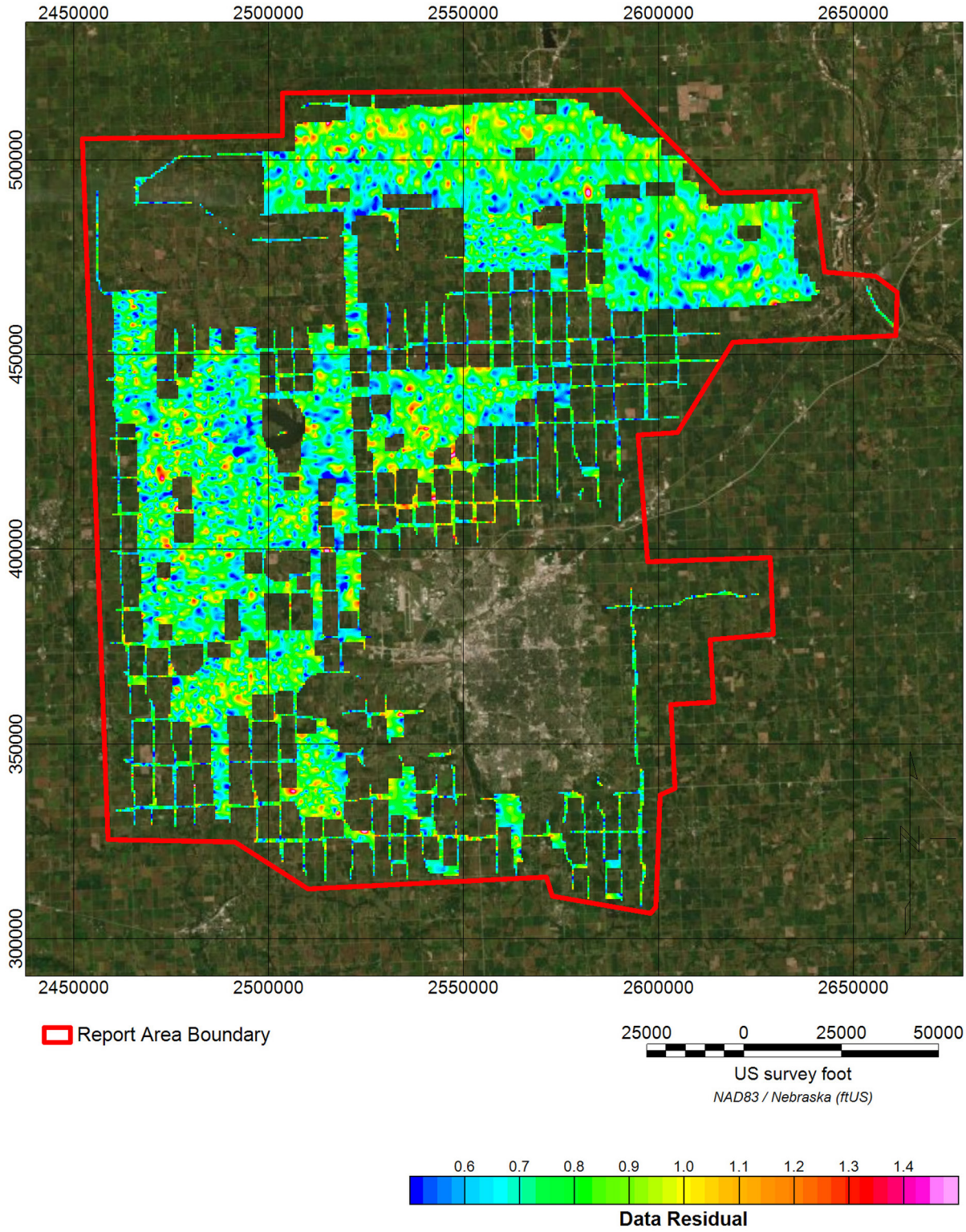


Figure 2-15. Map of data-inversion model residuals for the LPSNRD 2018 SCI inversion results.

2.6 Merge AEM Databases from Different Flights and Inversions

After the inversion process several lines segments were combined to form continuous lines within the survey area. This included lines that composed the block flights and reconnaissance grid lines. These continuous lines allow for improved viewing and interpretation of the AEM inversions results. As just discussed above, the areas that were flown for the P-MRNRD, LPNNRD, and LPSNRD AEM survey were inverted together with some areas of the LENRD. A consequence of this inversion procedure resulted in/provided multiple inversions of many lines. The lines that had multiple inversions were compared and the line-inversion with the lowest data-model residual was retained, and the other repeat line-inversions were deleted from the data base. At that point the segmented lines were merged to form continuous lines. Table 2-6 lists the original flown lines and the new combined lines.

Table 2-6. Combination of flight lines within the inversion areas.

Original Source Lines	New Line
Group 6 L160001.1, and Group 6 L160002	L160000
Group 3 L300101, Group 3 L507001, and Group 3 L508001	L300100
Group 3 L300201, Group 3 L507101, and Group 3 L508101	L300200
Group 3 L300301, and Group 3 L508201	L300300
Group 3 L300401, Group 3 L507301, and Group 3 L508301	L300400
Group 3 L300501, and Group 3 L508401	L300500
Group 3 L300601, and Group 3 L508601	L300600
Group 3 L300701, and Group 3 L508701	L300700
Group 3 L300801, and Group 3 L508901	L300800
Group 3 L301001, and Group 3 L509001	L301000
Group 3 L302101, and Group 3 L302102	L302100
Group 3 L302901, and Group 3 L509601	L302900
Group 3 L303701, and Group 3 L510001	L303700
Group 1 L303801, and Group 1 L303802	L303800
Group 1 L303901, Group 1 L304001, and Group 1 L304101	L303900
Group 1 L304301, and Group 1 L304302	L304300
Group 1 L305101, and Group 1 L305202	L305100
Group 1 L305301, and Group 1 L305401	L305300
Group 1 L305501, and Group 1 L305601	L305500
Group 1 L306001, and Group 1 L306101	L306000
Group 1 L306201, and Group 1 L306301	L306200
Group 1 L306401, and Group 1 L306501	L306400
Group 1 L306601, and Group 1 L306701	L306600
Group 1 L306901, and Group 1 L306902	L306900
Group 1 L307101, and Group 1 L307102	L307100
Group 2 L308301 and Group 2 L308401	L308300
Group 2 L308901, Group 2 L309001, and Group 2 L309002	L308900
Group 2 L309101, and Group 2 L309201	L309100
Group 2 L309301, and Group 2 L309401	L309300
Group 2 L310901, and Group 2 L310902	L310900
Group 2 L311101, and Group 2 L311201	L311100

Group 2 L311401, and Group 2 L311403	L311400
Original Source Lines	New Line
Group 1 L400811, and Group 1 L401301	L400800
Group 1 L400901, and Group 1 L401401	L400900
Group 1 L401101, Group 1 L402101, and Group 1 L402102	L401100
Group 1 L401501, and Group 1 L401901	L401500
Group 1 L402601, and Group 1 L402701	L402600
Group 1 L403001, Group 1 L403002, and Group 1 L403003	L403000
Group 3 L404101, and Group 1 L406801	L404100
Group 1 L404301, and Group 1 L404701	L404300
Group 3 L404501, and Group 1 L404801	L404500
Group 1 L404601, and Group 1 L404901	L404600
Group 1 L405201, and Group 1 L405301	L405200
Group 1 L405401, and Group 1 L405501	L405400
Group 1 L406001, and Group 1 L406201	L406000
Group 1 L406101, and Group 1 L406301	L406100
Group 3 L407801, and Group 1 L407901	L407800
Group 2 L407001, and Group 2 L407002	L407000
Group 2 L407601, and Group 1 L407602	L407600
Group 3 L409101, Group 3 L409102, Group 3 L409201, and Group 3 L413901	L409100
Group 2 L410201, Group 1 L405001, and Group 1 L406901	L410200
Group 2 L410601, and Group 2 L410701	L410600
Group 2 L410801, and Group 2 L410901	L410800
Group 2 L411001, and Group 2 L411101	L411000
Group 2 L411201, and Group 2 L411301	L411200
Group 3 L413801, Group 1 L414101, and Group 1 L402801	L413800
Group 2 L411401, and Group 2 L411501	L411400
Group 2 L411601, and Group 2 L411602	L411600
Group 2 L412101, and Group 3 L407401	L412100
Group 2 L412201, and Group 2 L412301	L412200
Group 2 L412401, and Group 2 L412501	L412400
Group 2 L413701, Group 3 L409701, and Group 3 L409702	L413700
Group 6 L500801, and Group 5 L700901	L500800
Group 6 L501100, Group 6 L701201, and Group 6 L908901	L501100
Group 5 L501401, Group 5 L501402, Group 5 L503101, and Group 5 L701101	L501400
Group 5 L501501, Group 5 L501601, Group 5 L501602, and Group 5 L701301	L501500
Group 5 L501901, and Group 5 L503201	L501900
Group 5 L502901, Group 5 L503001, Group 5 L701401, and Group 5 L702701	L502900
Group 4 L504201, and Group 4 L701501	L504200
Group 4 L6504401, Group 5 L504501, and Group 4 L702501	L504500
Group 5 L504801, and Group 5 L504901	L504800
Group 4 L505001, and Group 4 L701601	L505000
Group 4 L505601, and Group 4 L702601	L505600
Group 3 L505801, Group 3 L506001, Group 3 L506002, and Group 3 L701701	L505800
Group 3 L506101, Group 3 L506102, and Group 3 L701801	L506100
Group 3 L506301, Group 3 L506302, and Group 3 L701901	L506300

Group 3 L506501, and Group 3 L702001	L506500
Group 3 L506601, and Group 3 L702101	L506600
Group 3 L506701, and Group 3 L702201	L506700
Original Source Lines	New Line
Group 3 L506801, and Group 3 L702301	L506800
Group 3 L506901, and Group 3 L702401	L506900
Group 3 L507801, and Group 3 L507901	L507800
Group 5 L600401, and Group 5 L909001	L600400
Group 6 L601601, Group 5 L601701, and Group 5 L601702	L601600
Group 6 L601901, and Group 6 L1004801	L601900
Group 6 L602101, Group 6 L1004901, and Group 7 L1004902	L602100
Group 6 L602301, and Group 6 L1005001	L602300
Group 6 L602500, Group 4 L602601, and Group 6 L1005201	L602500
Group 6 L700701, and Group 6 L700702	L700700
Group 7 L700301, and Group 7 L906501	L700300
Group 7 L700501, and Group 7 L700502	L700500
Group 6 L800401, and Group 7 L800402	L800400
Group 5 L700801, and Group 6 L908801	L908800
Group 5 L600601, and Group 6 L1004001	L1004000
Group 5 L601201, and Group 6 L1004301	L1004300
Group 5 L601801, and Group 6 L1004701	L1004700
Group 7 L1004904, and Group 7 L1004905	L1004900

3 AEM Results and Interpretation

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

3.1 Interpretive Process

3.1.1 Construct the Project Digital Elevation Model

To ensure that the elevation used in the project is constant for all the data sources (i.e. Boreholes and AEM) a Digital Elevation Model (DEM) was constructed for the ENWRA area. The data was downloaded from the National Elevation dataset (NED) located at the National Map Website (U.S. Geological Survey, 2019) at a resolution of 1 arc-second or approximately 100 ft. The geographic coordinates are North American Datum of 1983 (NAD 83) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88). The 100 ft grid cell size was used throughout the project and resulting products. Figure 3-1 is a map of the DEM for the LPSNRD survey area having a vertical relief of 637 ft with a minimum elevation of 1,040 ft and a maximum elevation of 1,722 ft. This DEM was used to reference all elevations within the AEM and borehole datasets. Figure 3-2 is a DEM of the Ceresco Block and has a vertical relief of 264 ft with a minimum elevation of 1,168 ft and a maximum elevation of 1,432 ft. Figure 3-3 is a DEM of the Davey Raymond Block and has a vertical relief of 297 ft with a minimum elevation of 1,135 ft and a maximum elevation of 1,432 ft. Figure 3-4 is a DEM of the Denton Block and has a vertical relief of 289 ft with a minimum elevation of 1,174 ft and a maximum elevation of 1,463 ft. Figure 3-5 is a DEM of the Dwight South Block and has a vertical relief of 265 ft with a minimum elevation of 1,367 ft and a maximum elevation of 1,632 ft. Figure 3-6 is a DEM of the Emerald Pleasant Dale Block and has a vertical relief of 360 ft with a minimum elevation of 1,160 ft and a maximum elevation of 1,520 ft. Figure 3-7 is a DEM of the Garland Malcolm Block and has a vertical relief of 402 ft with a minimum elevation of 1,196 ft and a maximum elevation of 1,598 ft.

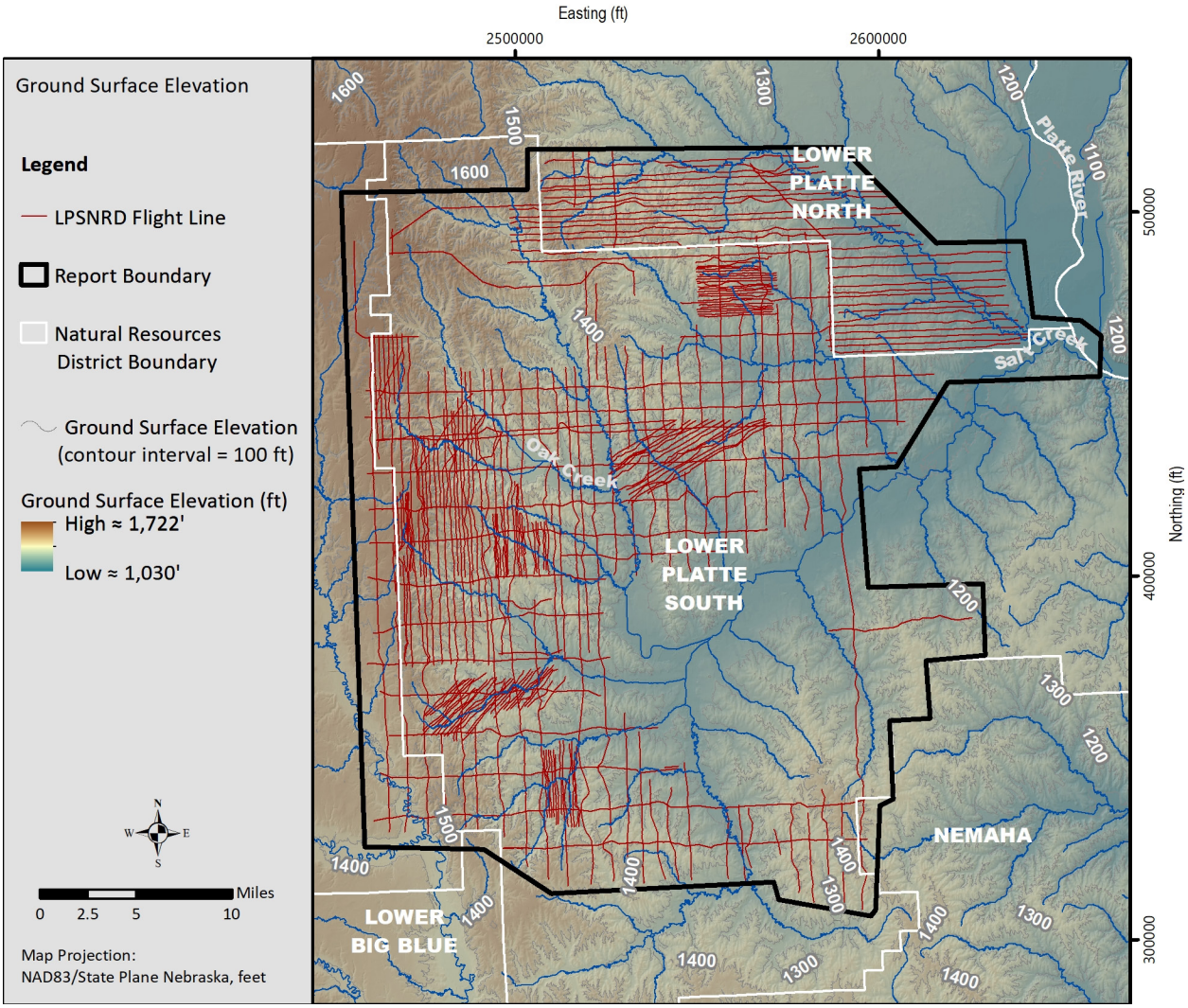


Figure 3-1. Map of the Digital Elevation Model for the 2018 LPSNRD study area. 2018 flight lines are indicated with maroon lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2019a). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

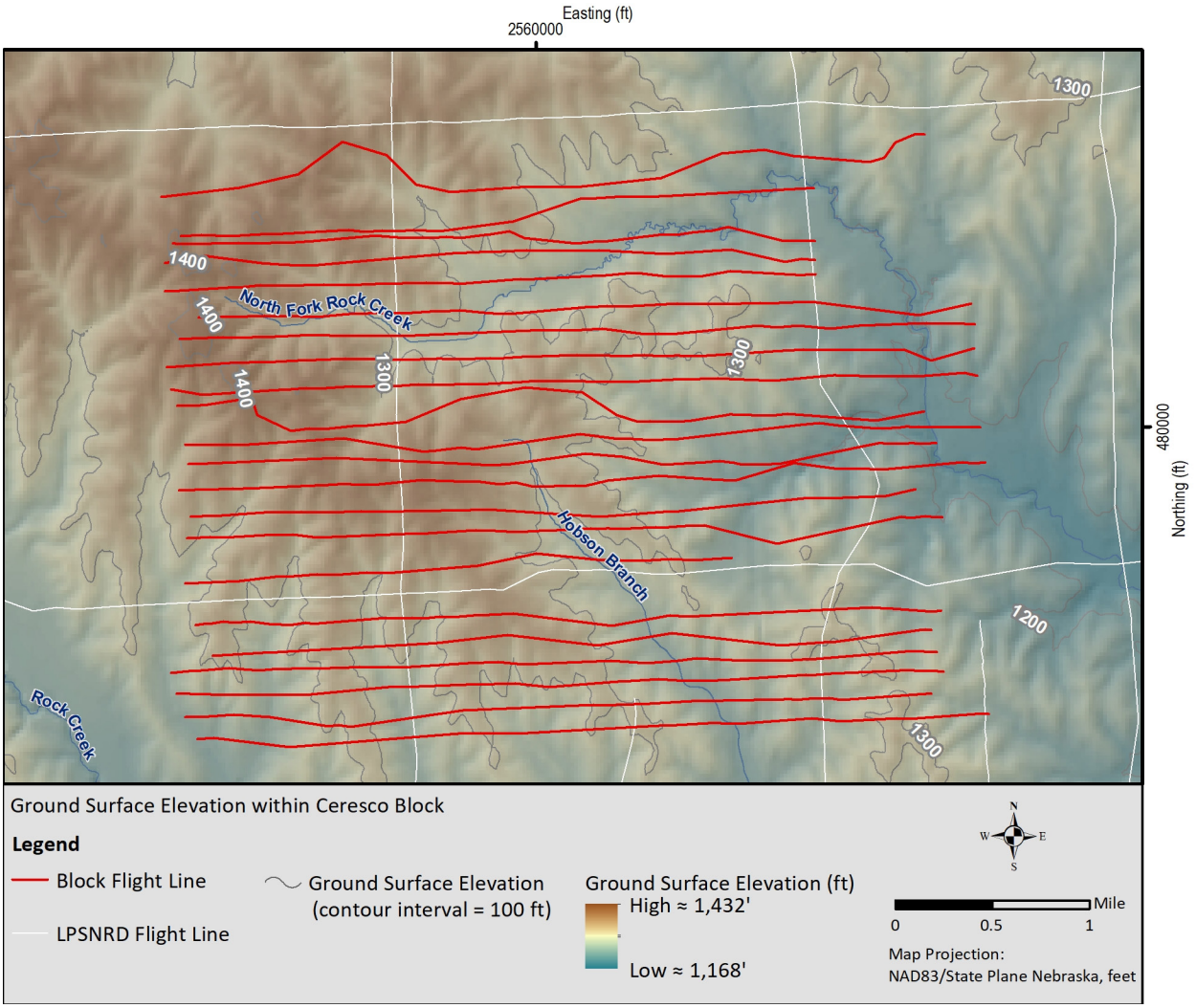


Figure 3-2. Map of the Digital Elevation Model for the Ceresco Block. Block flight lines are indicated with red lines and 2018 flight lines are indicated with white lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2019a). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

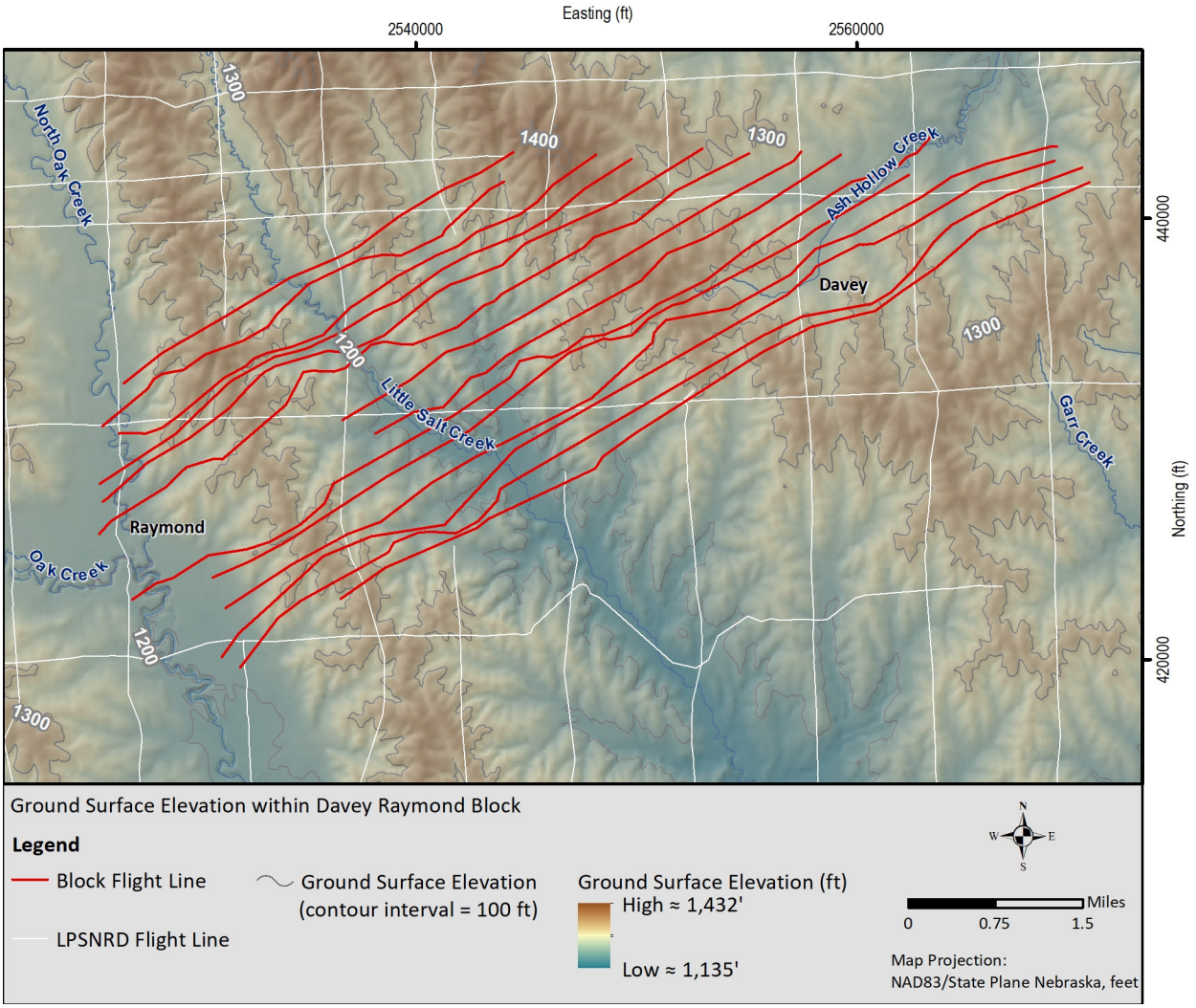


Figure 3-3. Map of the Digital Elevation Model for the Davey Raymond Block. Block flight lines are indicated with red lines and 2018 flight lines are indicated with white lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2019a). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

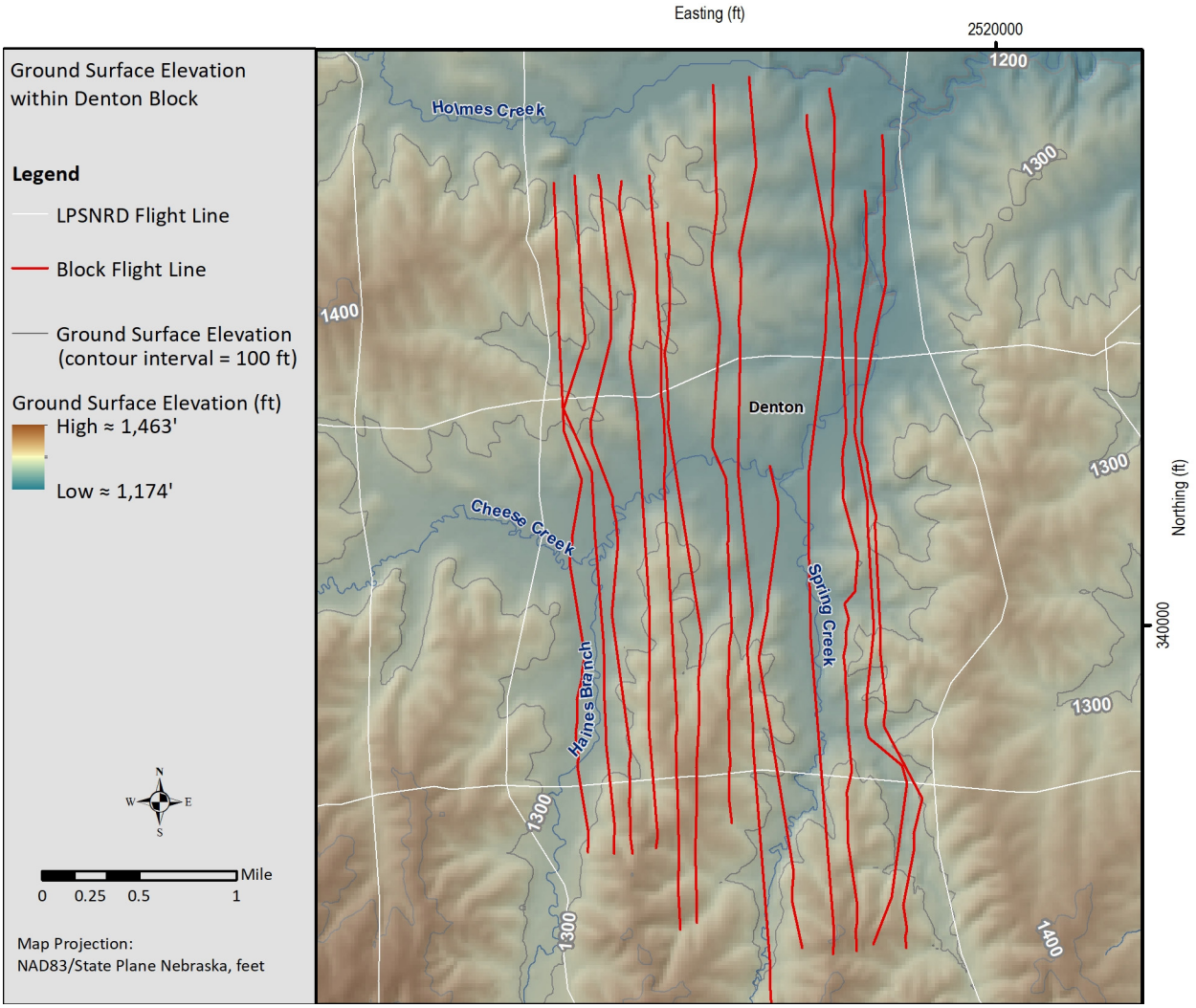


Figure 3-4. Map of the Digital Elevation Model for the Denton Block. Block flight lines are indicated with red lines and 2018 flight lines are indicated with white lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2019a). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

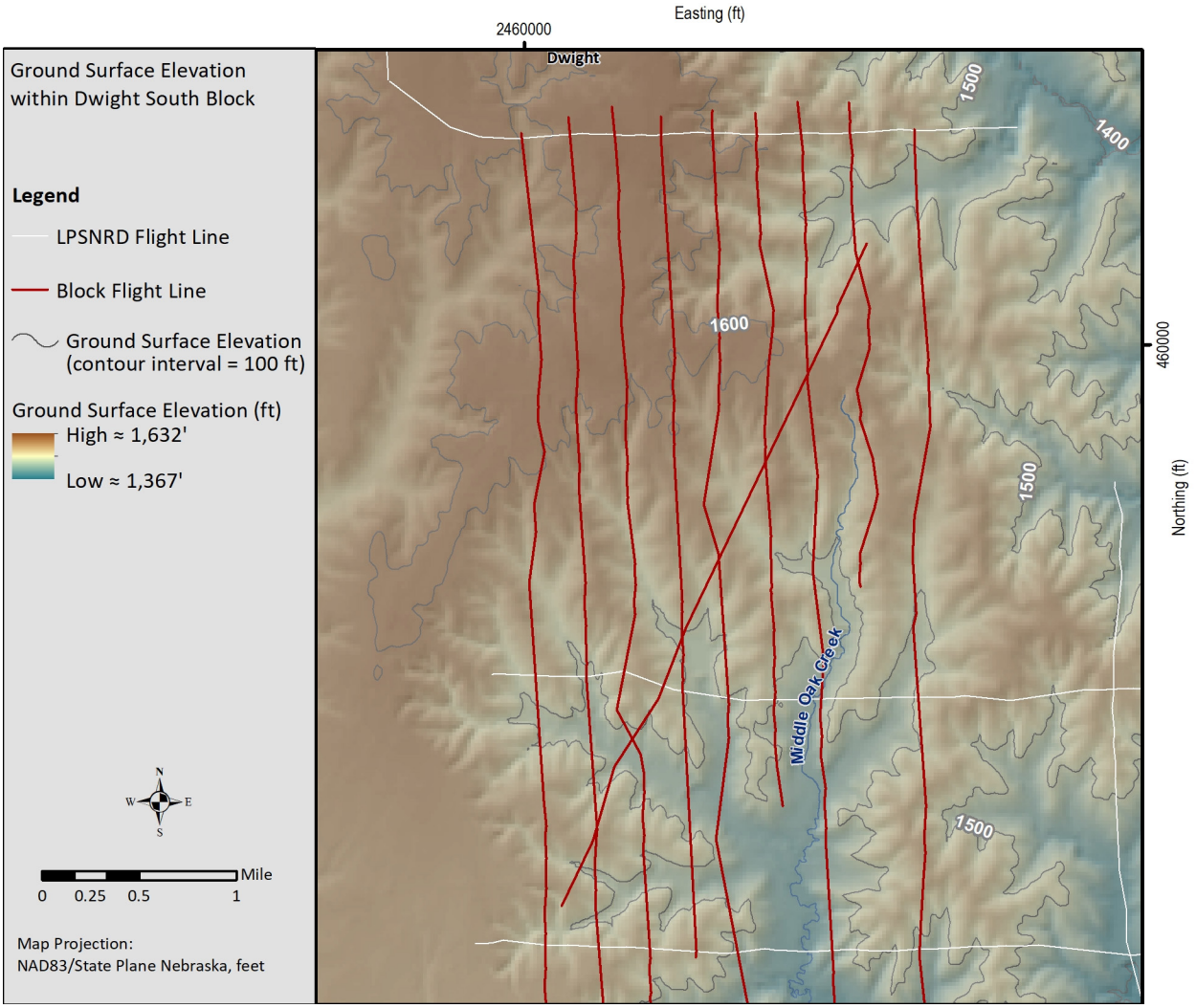


Figure 3-5. Map of the Digital Elevation Model for the Dwight South Block. Block flight lines are indicated with red lines and 2018 flight lines are indicated with white lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2019a). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

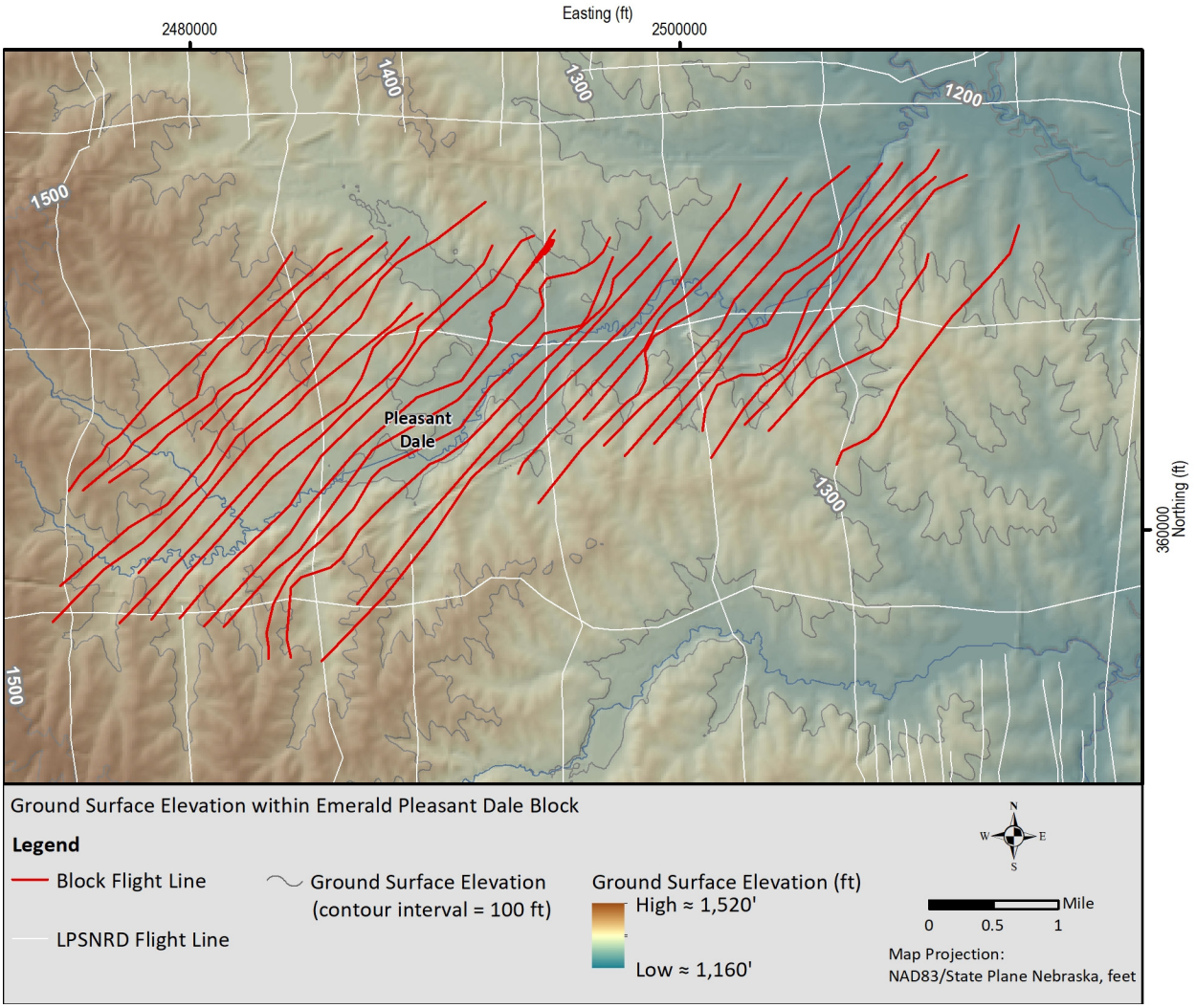


Figure 3-6. Map of the Digital Elevation Model for the Emerald Pleasant Dale Block. Block flight lines are indicated with red lines and 2018 flight lines are indicated with white lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2019a). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

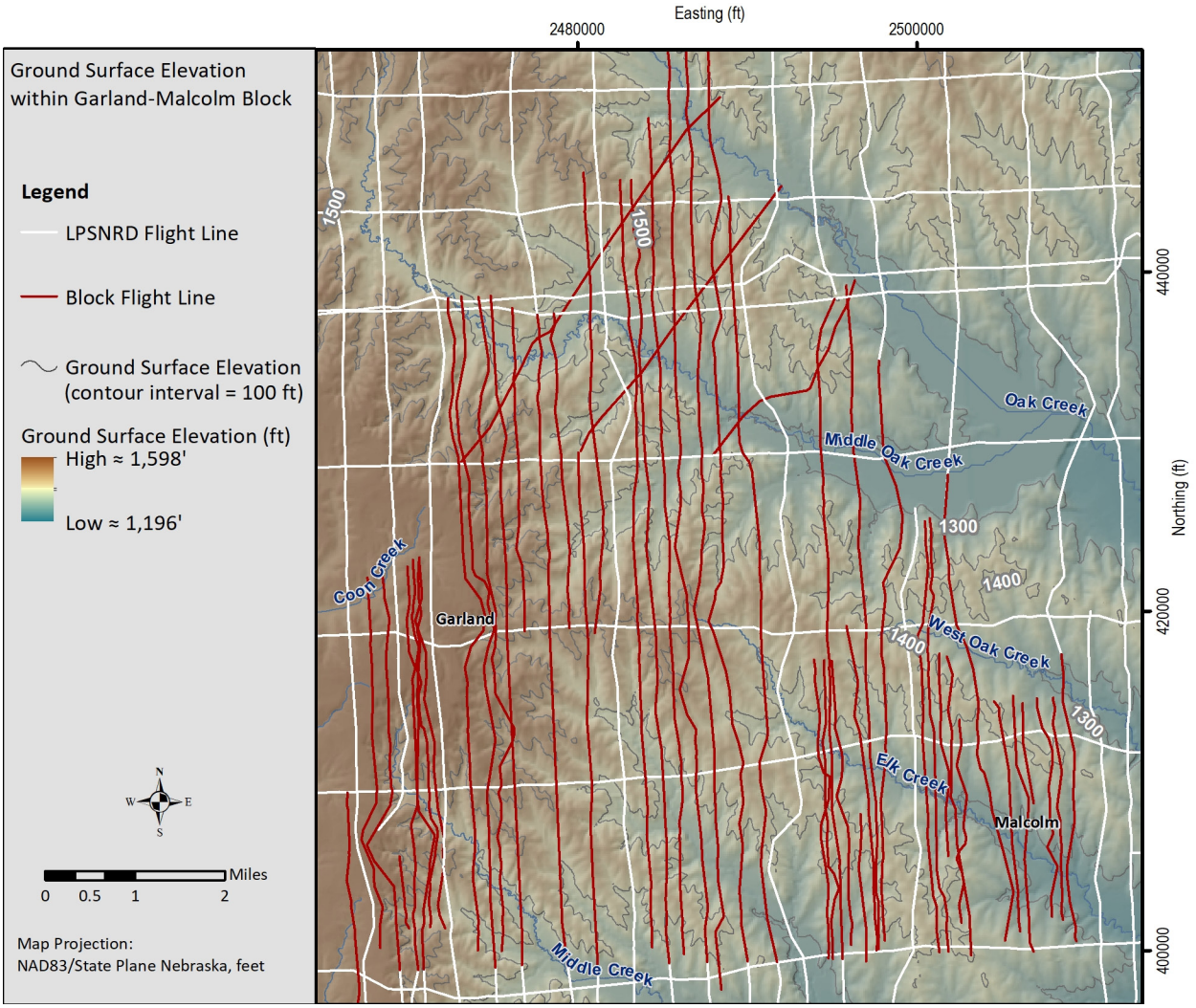


Figure 3-7. Map of the Digital Elevation Model for the Garland Malcolm Block. Block flight lines are indicated with red lines and 2018 flight lines are indicated with white lines. Data source is the one (1) arc-second National Elevation Dataset (U.S. Geological Survey, 2019a). North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

3.1.2 Borehole Derived Bedrock Surface

As a guide in the interpretation of the AEM a bedrock surface was prepared using the of CSD (UNL, 2019) and NE-DNR logs (NE-DNR, 2019). This work was included the following steps:

As a guide in the interpretation of the AEM, a bedrock surface was prepared using CSD and NE-DNR borehole logs. The process included the following steps:

- Consolidated the NE-DNR lithology tables used in previous AGF studies and the current study into one comprehensive dataset.

- Categorized each borehole's lithology description as either "Bedrock" or 'Unconsolidated' based on the description type. For example:
    - Sandstone, Shale, Siltstone, Limestone, Chalk = "Bedrock"
    - Clay, silt, gravel/boulders, etc. = "Unconsolidated"
- Reviewed the dataset and flagged those boreholes where an "Unconsolidated" lithologic description was underlying a "Bedrock" description.
- Revised categorized lithology, as needed, or flagged boreholes for removal from final dataset to be used for interpolation of the bedrock surface.
    - In general, those boreholes flagged for removal contained unclear lithologic descriptions, making it uncertain where the depth to the top of bedrock was located.
- Added the CSD borehole stratigraphy table to updated borehole lithology dataset, imported final dataset into ESRI's ArcCatalog, and exported as a borehole point shapefile. The borehole shapefile contained 7,203 data points.
- Extracted the project's 100 ft cell size DEM into the borehole point shapefile and calculated the top of bedrock elevation by subtracting the depth to the top of bedrock from the ground surface elevation.
- Interpolated the borehole point shapefile into a continuous raster dataset using the kriging geostatistical model and exported to a 300 ft cell size grid.
- Calculated the residuals of the actual measured top of bedrock elevation to the interpolated top of bedrock elevation.
- Reviewed any borehole where the residual was > 30 ft or < -30 ft. The value of 30 was used because it is a general representation of the degree of error while logging a borehole with mud rotary drilling techniques as it is approximately one drill stem length. Flagged those boreholes that appeared to be an anomaly.
    - Boreholes were flagged as an "anomaly" if the following was observed:
        - A borehole in a cluster of boreholes where the actual measured bedrock elevation varied more than ~ 75 ft from adjacent wells' actual measured bedrock elevation, or
        - a borehole's actual measured bedrock elevation varied more than ≈ 75 ft from an adjacent CSD well.
- Compared the interpolated top of bedrock elevation surface to bottom of Quaternary deposits in CSD boreholes. Areas where the top of bedrock elevation was below the bottom of Quaternary deposits were reviewed for either anomalous boreholes in the area, or over-smoothing of the 300 ft cell size.
- After reviewing and revising the borehole point shapefile, 285 data points that were flagged an "anomaly" were removed leaving 6,918 data points for a second bedrock surface interpolation.
- Re-interpolated the borehole point shapefile into a continuous raster dataset using the kriging geostatistical model and exported to a 300 ft cell size grid.
- The interpolated bedrock surface raster dataset was compared to the DEM and anywhere the bedrock surface was greater than the DEM was set to the elevation of the DEM.

- Calculated the residuals of the actual measured top of bedrock elevation to the interpolated top of bedrock elevation.
    - Found that ~ 535 boreholes had actual measured bedrock elevations differ more than 30 ft from the interpolated bedrock elevation.
    - The majority of these 535 points fell within the range of +/- 30 to +/-50 ft variation of actual versus interpolated top of bedrock elevation.
    - These relatively small differences between actual and interpolated bedrock elevation in these boreholes could be attributed to inconsistent logging of boreholes

This surface is utilized as a guide in the interpretation of the bedrock within the AEM data profiles described next.

3.1.3 Create Interpretative 2D Profiles

After final combination and clipping of the AEM data **in** the general area of the LPSNRD (described above in Section 2.6), characterization of the subsurface was performed in cross-section format using Datamine Discover PA (Datamine, 2019). During interpretation, the horizontal and vertical scale of the profiles were adjusted to facilitate viewing. The color scale of the resistivity data was also adjusted to illuminate subtle differences in the resistivity structure within the inverted AEM resistivity data related to the area being interpreted. The first step in the interpretation is digitizing the contacts between the geologic units including: Quaternary (***Q***), Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and the undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, NE-DNR, and NEOGCC borehole logs, which provided lithologic, stratigraphic, and geophysical information. The interpretations were simultaneously checked against the CSD's Nebraska bedrock geology map (Burchett, 1986), but may differ due to the final interpretation. Additionally, the bedrock borehole only surface as developed was used as a guide for the interpretation in areas of low electrical resistivity contrast and no boreholes.

The ***Kgg*** only occurred on the western portions of the survey area along the AEM Reconnaissance lines and in the Dwight South and Garland Malcolm AEM survey Blocks. The ***Kd*** exists throughout most of the LPSNRD survey area with the exception of the far southeast corner where the ***Q*** is sitting directly on the ***IP***. The CSD stratigraphic control was utilized to distinguish the ***Q*** from the underlining formations. The ***To*** and the ***Q*** are difficult units to differentiate due to the similarities in resistivity. The ***Kgg*** is typically observed as a resistor from the inclusion of the Greenhorn Limestone but is masked in many locations by the low resistivity Graneros Shale unit that causes a bulk averaging effect. Depending on the ***Kgg/Kd*** resistivity contrast, interpretations can be made. In much of the area of the LPSNRD survey, the Graneros Shale is an exposed unit, with the exception of the Greenhorn that is quarried within the Garland Malcolm Block.

The ***Kd*** general location is detectable when there are resistive sands/sandstones. Use of general thickness constraints can also assist in the interpretation of the ***Kd*** location. NEOGCC and CSD wells in the area also provide stratigraphic control assisting in the location of the geologic units. When the ***Kd*** is the Cretaceous bedrock unit, much greater care needs to be taken due to the poor resistivity contrast of

the ***Q*** and the ***Kd***. Many of the holes in the area indicate sand and or sand and gravel at the bottom of the *Q* while the *Kd* is sand and or sandstone. The resistivity contrast between the ***Q*** sand and the ***Kd*** sand is almost nonexistent. Use of CSD stratigraphy calls and the presence of sandstone and shale in the NE-DNR registered wells were used to pick the ***Q/Kd*** contact when no resistivity contrast was present. The borehole derived bedrock provided a useful interpretive tool to supplement the boreholes. The ***Kd*** interpretations are further complicated with the presence of saltwater. The saltwater lowers the bulk resistivity.

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

Figure 3-8 is an approximately 28-mile-long east-west line, L304601, that was flown north of Davey, Nebraska and through the north side of the Branched Oak Lake. Several CSD test holes are projected onto the line within ½ mile. The ***Q*** sediments are composed of glacial till and overlying loess. These ***Q*** materials are overlying the eroded ***Kgg***, mostly the Graneros Shale, on the west of the line. The ***Kd*** occurs over the full flight line and heavily eroded on the eastern end of the flight line. The color scale is set to a range that shows the resistive material within the ***Kd***. Within the ***Kd*** there is a very low resistivity area that is most likely related to saltwater. The ***IP*** is not easily seen in this profile but the CSD test holes indicate its position.

Figure 3-9 is an approximately 34-mile-long north-south line, L413700, that is just east of Lincoln, Nebraska. The line crosses I-80 and Salt Creek. Several CSD test holes are along the line. The bedrock is a combination of heavily eroded ***Kd*** and ***IP***. The ***Kd*** sandstones show up well as resistive bodies covered with a combination of glacial till and loess. Low resistivities are observed in much of the *IP* that may indicate the presence of saltwater.

Figure 3-10 is an approximately 4-mile-long east-west line, L302501, in the middle of the Ceresco Block. The line crosses Hwy 77 on the eastern end of the line but is short of crossing North Rock Creek. Several NE-DNR registered wells penetrate the ***Kd***. This line is dominated by high resistivity materials in the eastern middle section. The water table shows that much of the ***Q*** is unsaturated. The bedrock in the area is ***Kd***. The ***IP*** has low resistivity in the area. Several areas in the ***Kd*** show the change in resistivity associated with the Sand/Sandstone units versus the Clay/Shale units.

Figure 3-11 is an approximately 8-mile-long southwest-northeast line, L305901, within the Davey Raymond Block that is south of Raymond on the southwest side and north of Davey on the northeast side of the line. The line crosses Little Salt and Ash Hollow creeks. Several NE-DNR registered wells penetrate the ***Kd*** which is the bedrock in the area and indicate sandstone that correlates with increased resistivity in the AEM. The area around Little Salt Creek is has very low resistivity. The ***Q*** material is predominantly till but shows areas of higher resistivity but is mostly in the unsaturated area.

Figure 3-12 is an approximately 4-mile-long north-south line, L411901, within the Denton Block that is just west of Denton and crosses Haines Creek Branch. Several CSD test holes (plotted within ½ mile) and a couple of NE-DNR wells (plotted within ¼ mile) penetrate the ***Kd*** and one penetrates the ***IP***. While the ***Q*** is dominated by till in the area, it does show a resistive sand zone to the south that is located above the water table.

Figure 3-13 is an approximately 4-mile-long north-south line, L400701, in the middle of the Dwight South Block that is south of Dwight. Several NE-DNR wells (plotted within ¼ mile) penetrate the ***Kgg*** and the ***Kd***. The ***Kgg*** is heavily eroded and is only present on the south end of the line. On the north end, a resistive area correlates with a paleochannel mapped in 2013 by AEM (Carney et al., 2014). The ***Q*** material is predominantly loess on top of till. The resistive areas within the ***Kd*** correlate with sandstone within the NE-DNR registered wells.

Figure 3-14 is an approximately 6-mile long east-west line, L307701, on the northern end of the Emerald Pleasant Dale Block. The line is north of Pleasant Dale and southwest of Emerald, Nebraska and runs parallel to South Branch for three miles. Several NE-DNR registered wells are within ¼ mile of the flight line. The ***Kd*** is the bedrock in the area. Many of the NE-DNR registered wells are completed in the resistive part of the ***Kd*** that is indicated as sandstone. The lower part of the ***Kd*** as well as the ***IP*** show very low resistivities related to saltwater. The ***Q*** is dominated by low resistivity tills and loess.

Figure 3-15 is an approximately 5-mile-long southwest-northeast line, L304300, on the northern end of the Garland Malcolm Block. The line is north of Garland and crosses Middle Oak Creek and the northeastern end of the line terminates in the Oak Creek valley. The line also passes near a couple of the quarries in the Greenhorn limestone. A CSD well penetrates the ***Kgg*** and the ***Kd*** down to the ***IP*** in the area but slightly offline. The lower part of the ***Kd*** as well as the ***IP*** show very low resistivities related to saltwater. Several NE-DNR registered wells penetrated the ***Kd*** and indicate sandstone in some areas. Most of the Greenhorn Limestone is eroded off in this section but a small amount remains in the areas of the quarries as a resistor compared with the low resistivity of the Graneros Shale. The ***Q*** is dominated by low resistivity tills and loess.

The above profiles serve as examples of the interpretation of the AEM profiles. All of the 2D profiles for the complete study area can be found in Appendix 1 which show the relationship of the CSD test holes to the interpreted AEM.

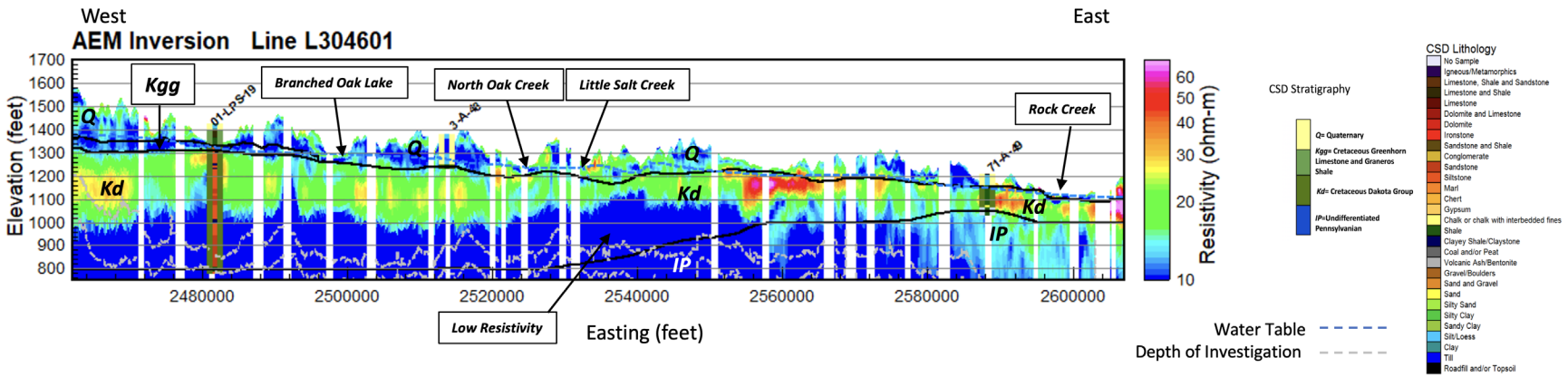


Figure 3-8. 28-mile-long east-west line, L304601, flown north of Davey, Nebraska. Borehole CSD lithology and stratigraphic logs are indicated on the AEM inverted earth models if they are within ½ mile. Interpretations of the top of the geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. Projection is North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

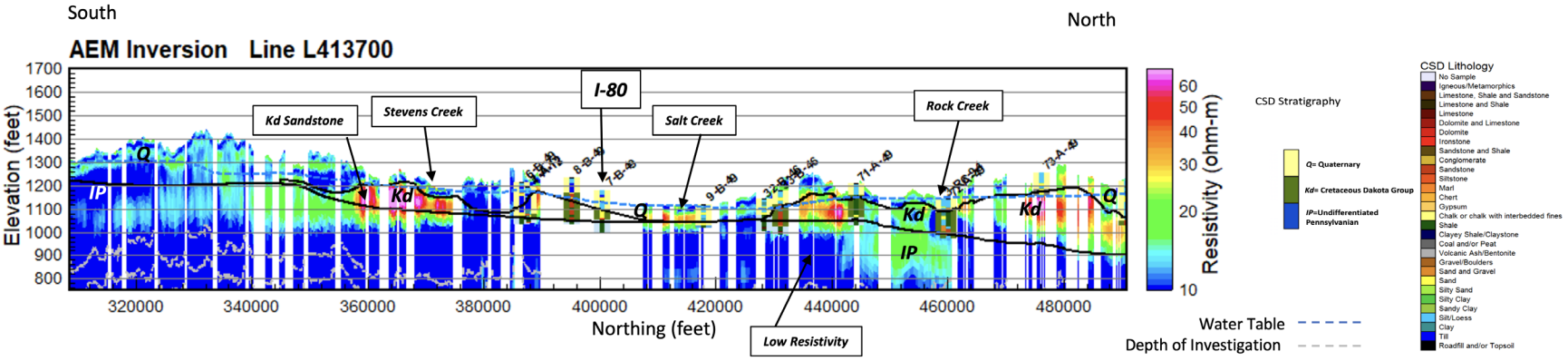


Figure 3-9. 34-mile-long north-south line, L413700. CSD (within ½ mile) boreholes lithology and stratigraphic logs are indicated on the AEM inverted earth model. Interpretations of the top of the geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. Projection is North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

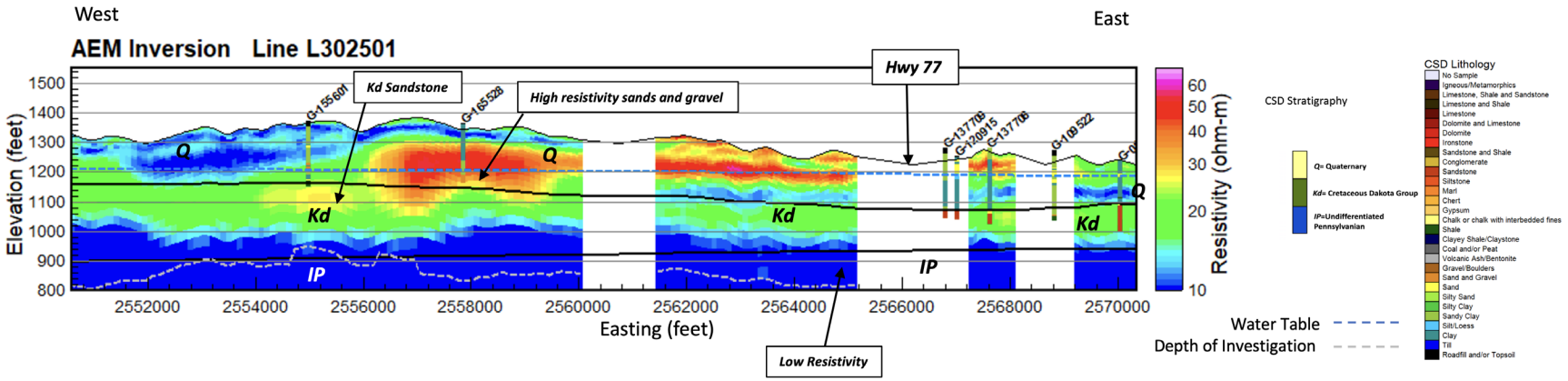


Figure 3-10. 4-mile-long east-west line, L302501. Nebraska DNR (within ¼ mile) boreholes lithology logs are indicated on the AEM inverted earth model. Interpretations of the top of the geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. Projection is North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

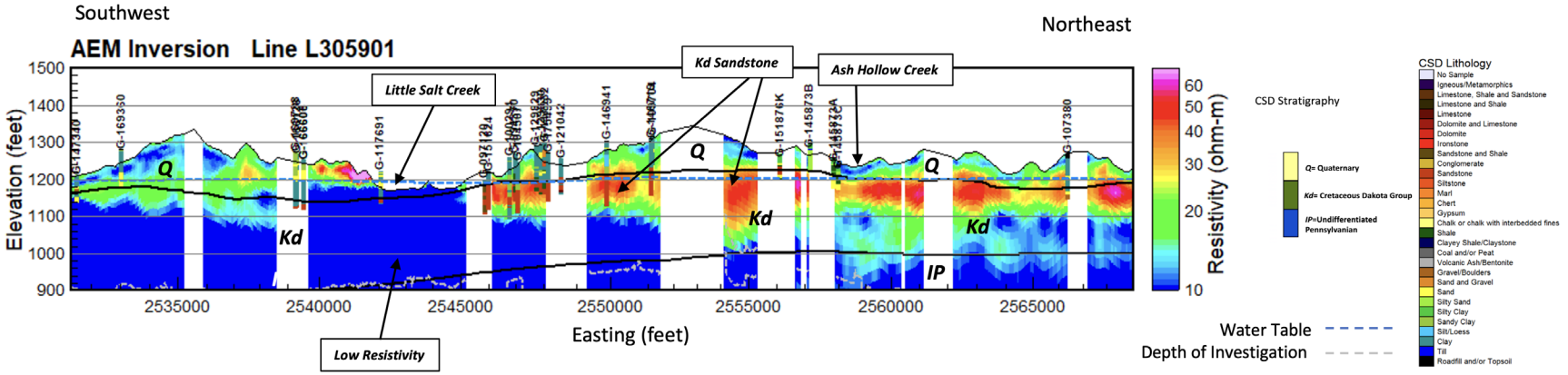


Figure 3-11. 8-mile-long southwest-northeast line, L305901. Nebraska DNR borehole lithology logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. Projection is North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

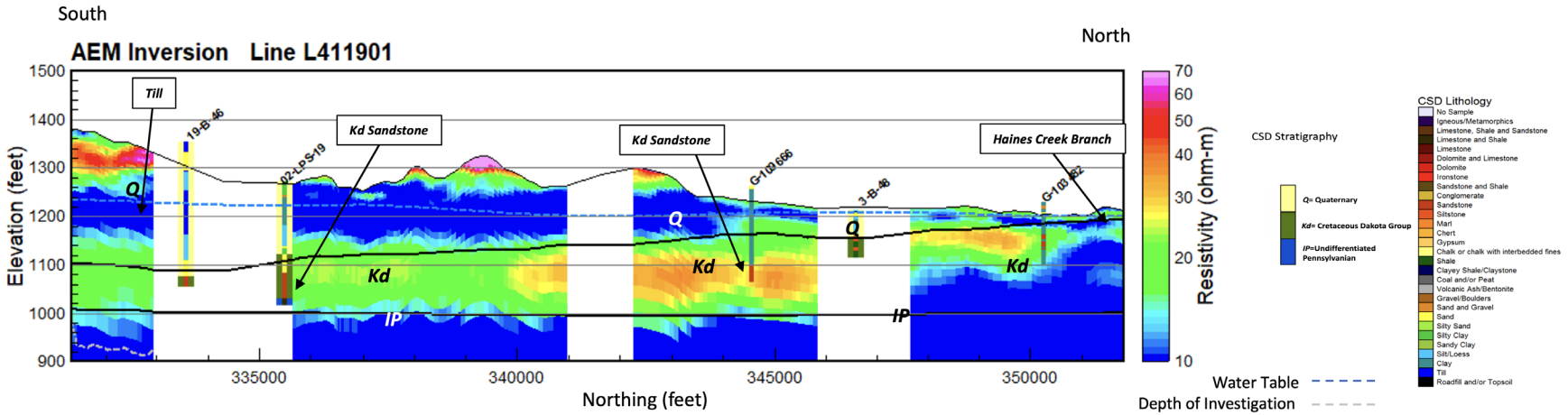


Figure 3-12. 4-mile-long north-south line, L411901. CSD and Nebraska DNR borehole lithology logs are indicated on the AEM inverted earth models if they are within ½ and ¼ mile of the flight line respectively. Interpretations of the top geological units are indicated by the black lines. Gaps indicate areas removed due to coupling. Projection is North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

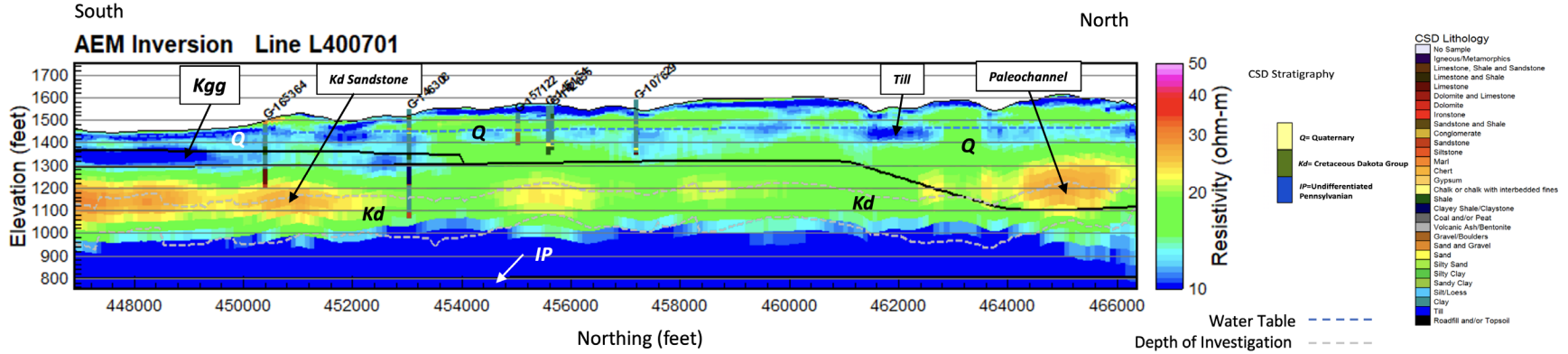


Figure 3-13. 4-mile-long north-south line, L400701. Nebraska DNR borehole lithology logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. Projection is North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

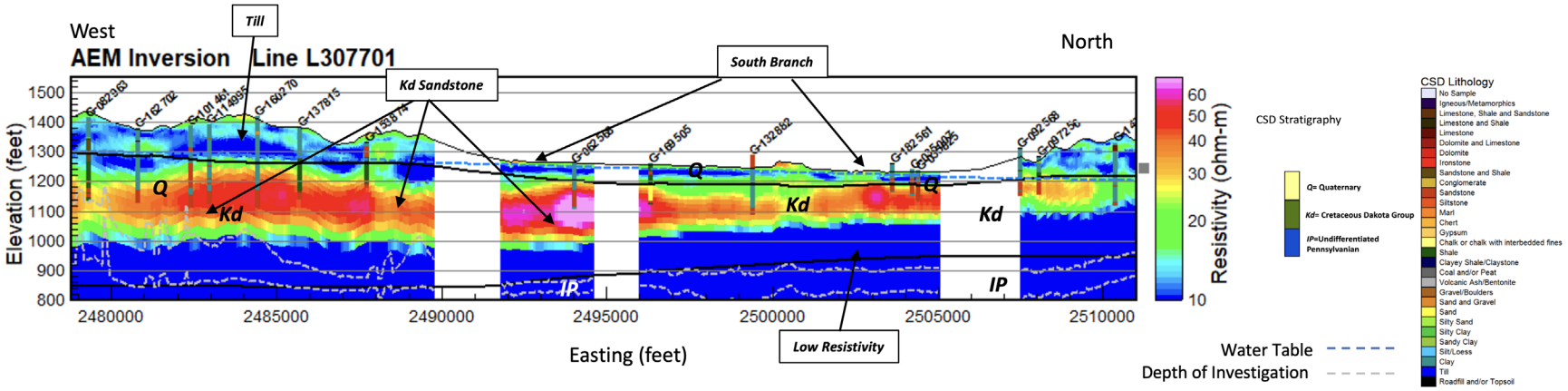


Figure 3-14. 6-mile-long east-west line, L307701. Nebraska DNR borehole lithology logs are indicated on the AEM inverted earth models if they are within ¼ mile of the flight line. Interpretations of the top geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. Projection is North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

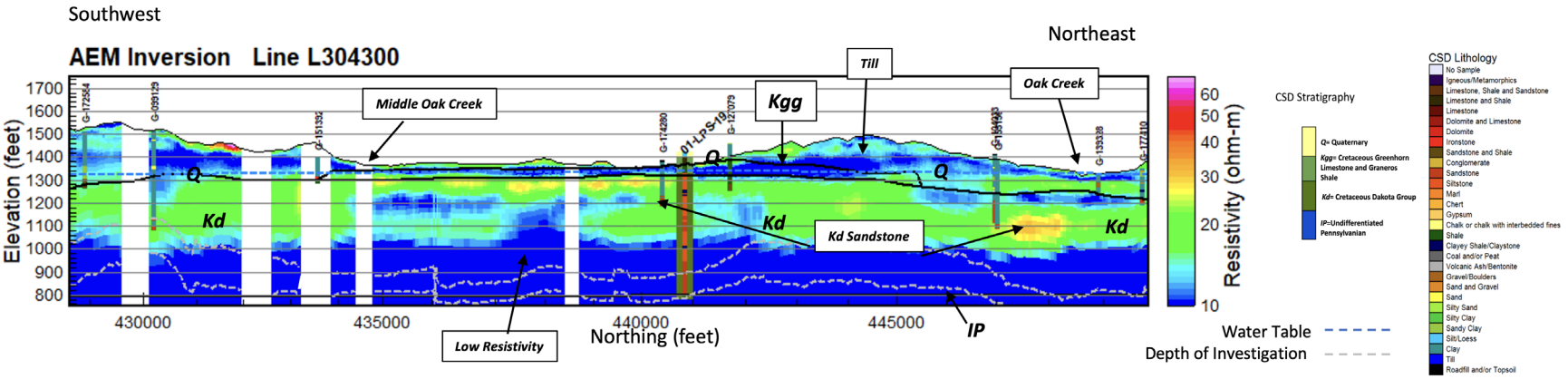


Figure 3-15. 5-mile-long southwest-northeast line, L304300. CSD and Nebraska DNR borehole lithology logs are indicated on the AEM inverted earth models if they are within ½ and ¼ mile of the flight line respectively. Interpretations of the top geologic units are indicated by the black lines. Gaps indicate areas removed due to coupling. Projection is North American Datum of 1983 (NAD 83) State Plane Nebraska (feet) and the elevation values are referenced to the North American Vertical Datum of 1988 (NAVD 88).

3.1.4 Create Interpretative Surface Grids

For the LSNNRD 2018 project area, Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcolm Block AEM survey areas geologic unit top elevation, geologic unit thickness, and geologic unit saturated thickness grids were produced. To create these grids, data such as a ground surface digital elevation model (DEM), water table elevation, Conservation and Survey Division (CSD) boreholes, and AEM interpreted point data of the survey area were imported and processed in ESRI's ArcMap along with the Spatial and Geostatistical Analyst extensions.

Raster grids of the elevation of the top of the Greenhorn Limestone/Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***) for the LPSNRD and the Block AEM survey areas were produced. To create the grids, approximately 107,000 data points with top elevation values were extracted from the AEM interpretation and input into a database. Additionally, approximately 150 CSD borehole and public well data points with depth to top of geologic units were added to the database and the database was input into ESRI's ArcMap for processing. The CSD borehole and public well data provided control in areas between flight lines. The elevation point data were interpolated into a continuous surface using the kriging geostatistical model and exported to a 100 ft cell size grid. Figure 3-16 to Figure 3-32 are maps of top elevation of ***Kgg, Kd,*** and ***IP*** within the 2018 LPSNRD AEM survey area and the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcolm Block AEM survey areas, respectively.

A raster grid of the elevation of the top of bedrock was produced for the 2018 LPSNRD and the Block AEM survey areas. First, a comparison was made between the geologic contacts interpreted on the geologic map (Burchett, 1986) and where the AEM data show the contact to exist. Small adjustments were made to the mapped contact based on this comparison. Next, the grids of the elevations of the tops of ***Kgg, Kd,*** and ***IP*** were masked to the extents of each unit based on the revised geologic map. Finally, the grids were mosaicked in ArcMap to create one continuous top of bedrock elevation grid. The 100 ft cell size for the top of bedrock elevation grids was retained for the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcolm Block areas. Figure 3-33 to Figure 3-40 are maps of the elevation of the top of the bedrock surface within the 2018 LPSNRD survey area and the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcolm Block AEM survey areas, respectively.

Quaternary deposits (***Q***), ***Kgg,*** and ***Kd*** thicknesses were calculated for the 2018 LPSNRD and the Block AEM survey areas using the top of elevation grids with ArcMap's raster calculator. For the ***Q*** thickness grid, the elevation of top of bedrock was subtracted from the DEM. For the ***Kgg*** thickness, the elevation of the top of ***Kd*** was subtracted from the elevation of the top of ***Kgg***, then the resultant grid was masked with the ***Kgg-Kd*** contact line polygon. Finally, for the ***Kd*** thickness, the elevation of the top of ***IP*** was subtracted from the elevation of the top of ***Kd***, then the resultant grid was masked with the ***Kd-IP*** contact line polygon. The grids produced for the 2018 LPSNRD and Block AEM survey areas were calculated using the 100 ft cell size. Figure 3-40 to Figure 3-56 are maps of ***Q, Kgg,*** and ***Kd*** thickness within the 2018 LPSNRD and Block AEM survey areas, respectively.

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 utilized. It should be noted that this inclusion provides only a generalized characterization of the saturated thickness of the aquifer as the CSD's dataset is two decades old at the time of the 2018 LPSNRD AEM survey and local conditions likely deviate in areas with variable topography. The water table in the LPSNRD area is close to the surface in some of the areas. To this end a topographic correction was required to ensure that the water table height was below the surface topography. The original water table contour lines were gridded at a 1,000 ft cell size using the Oasis Montaj Minimum Curvature Grid and a blanking distance of 5,000 ft. The cells were set 'to extend beyond' to 50. The resulting grid was then re-gridded at a 100 ft cell size and compared with the DEM (Figure 3-1) of the LPSNRD 2018 AEM survey area. In areas where the water table was greater than the topography, the water table was set to an elevation of the topography minus three feet. The grid was then clipped to a buffered boundary around the AEM survey area. A water table map was also prepared for the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcolm AEM survey areas (Figure 3-57 to Figure 3-63).

Saturated thicknesses of ***Q*** and ***Kd*** were calculated for the 2018 LPSNRD and the Block AEM survey areas with the top elevation and 1995 CSD water table grids using ArcMap's raster calculator. For the ***Q*** saturated thickness grid, the elevation of the top of bedrock was subtracted from the 1995 water table. For the ***Kd*** saturated thickness grid, the elevation of the top of ***IP*** was subtracted from the 1995 water table. Then the elevation of the top of Kd was subtracted from the 1995 water table. Finally, the resultant grids were subtracted from each other. The grids produced for the 2018 LPSNRD and Block survey areas were calculated using the 100 ft cell size top elevation grids. All resultant saturated thickness grids were masked, as necessary, to the geologic contact lines. Figure 3-64 to Figure 3-77 are maps of ***Q*** and ***Kd*** saturated thicknesses within the 2018 LPSNRD and Block AEM survey areas, respectively.

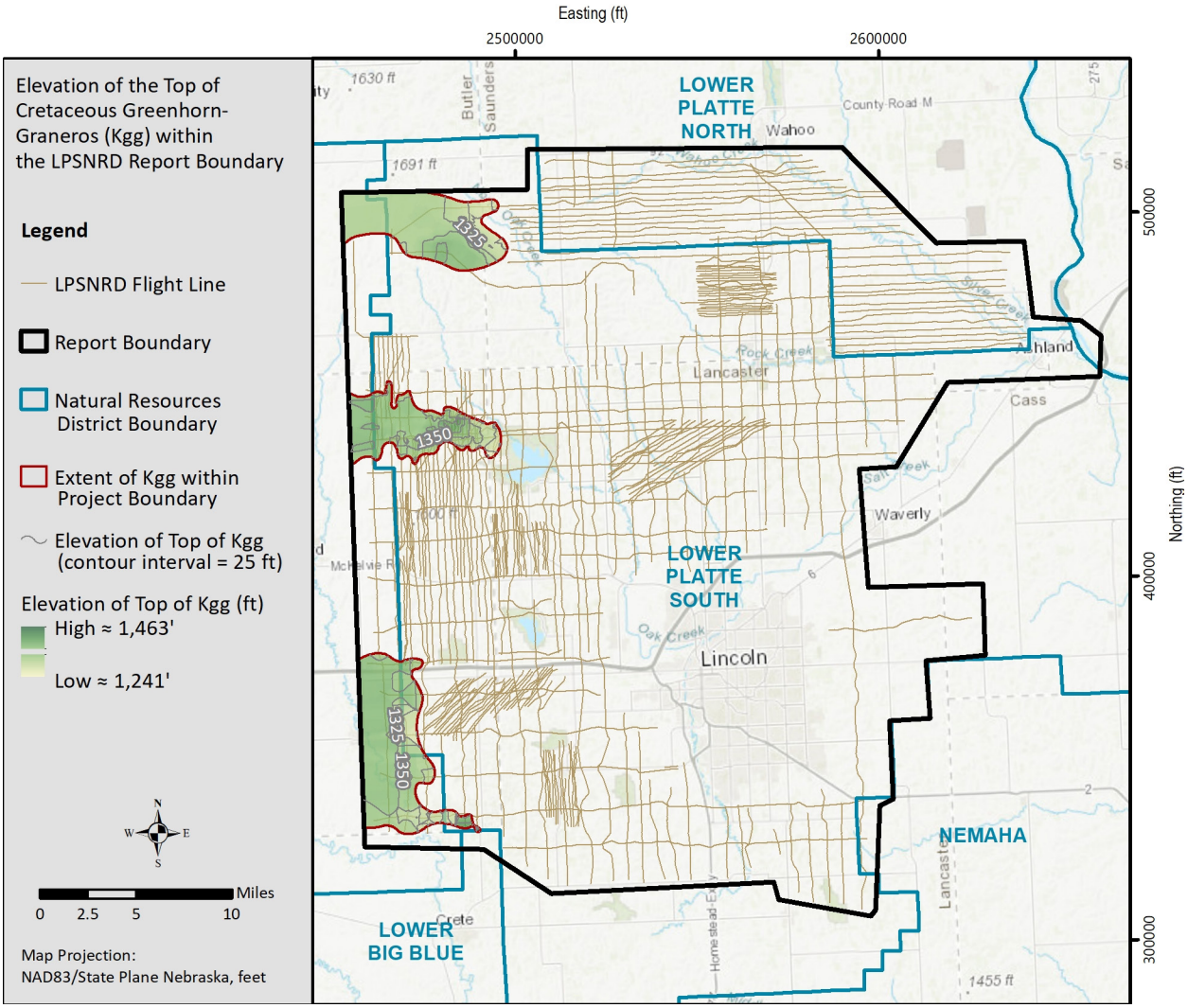


Figure 3-16. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the 2018 LPSNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

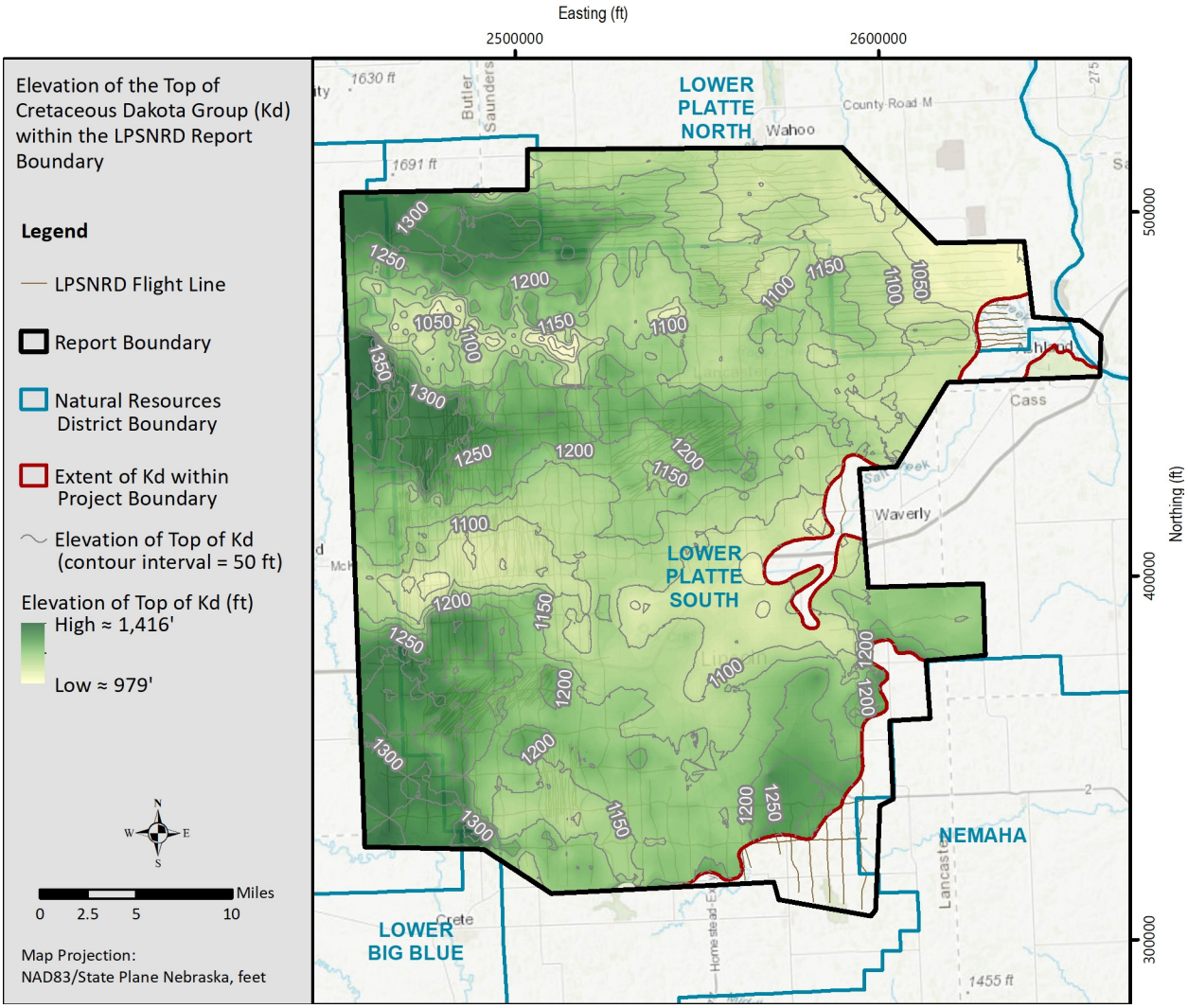


Figure 3-17. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the 2018 LPSNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

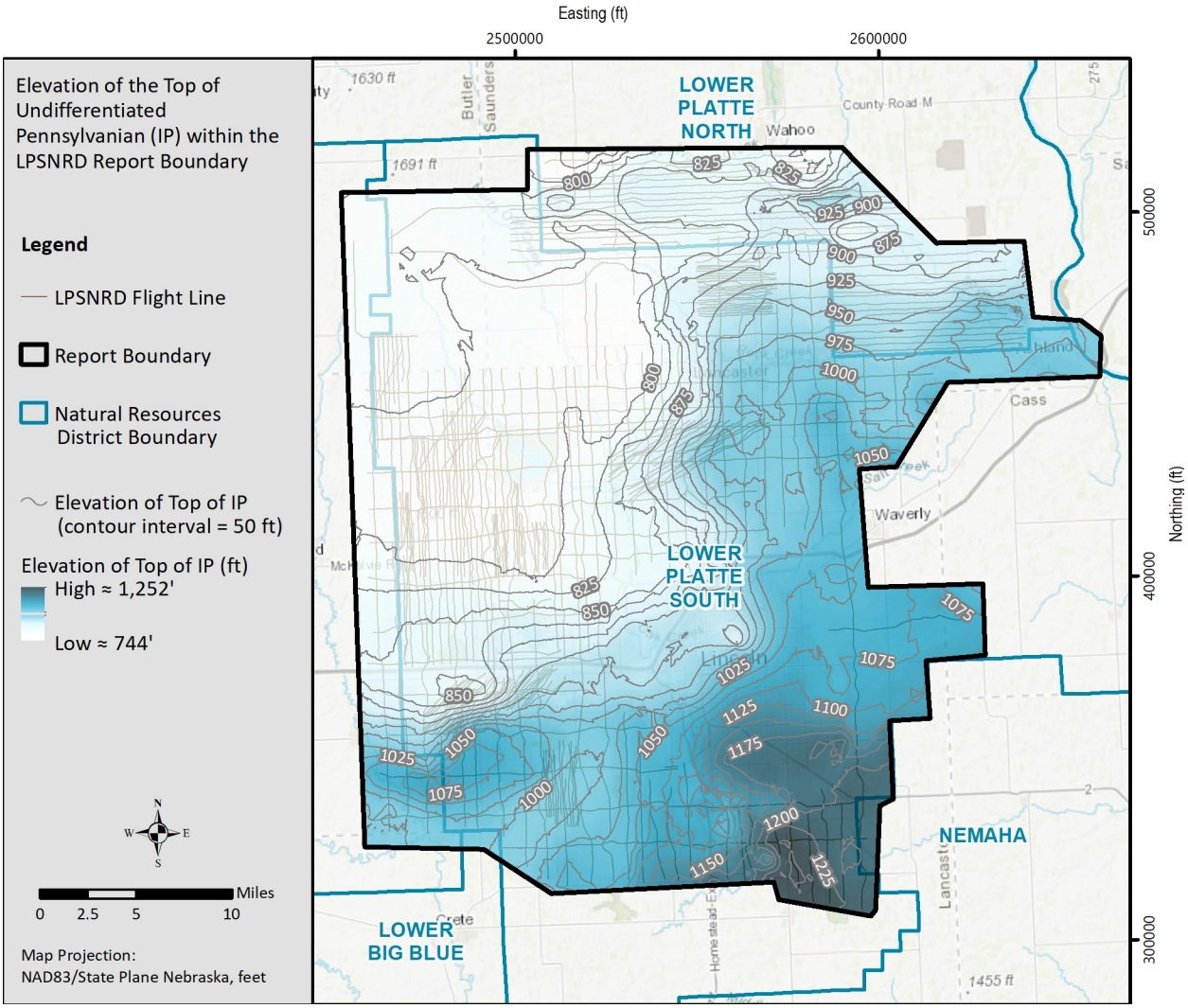


Figure 3-18. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the 2018 LPSNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

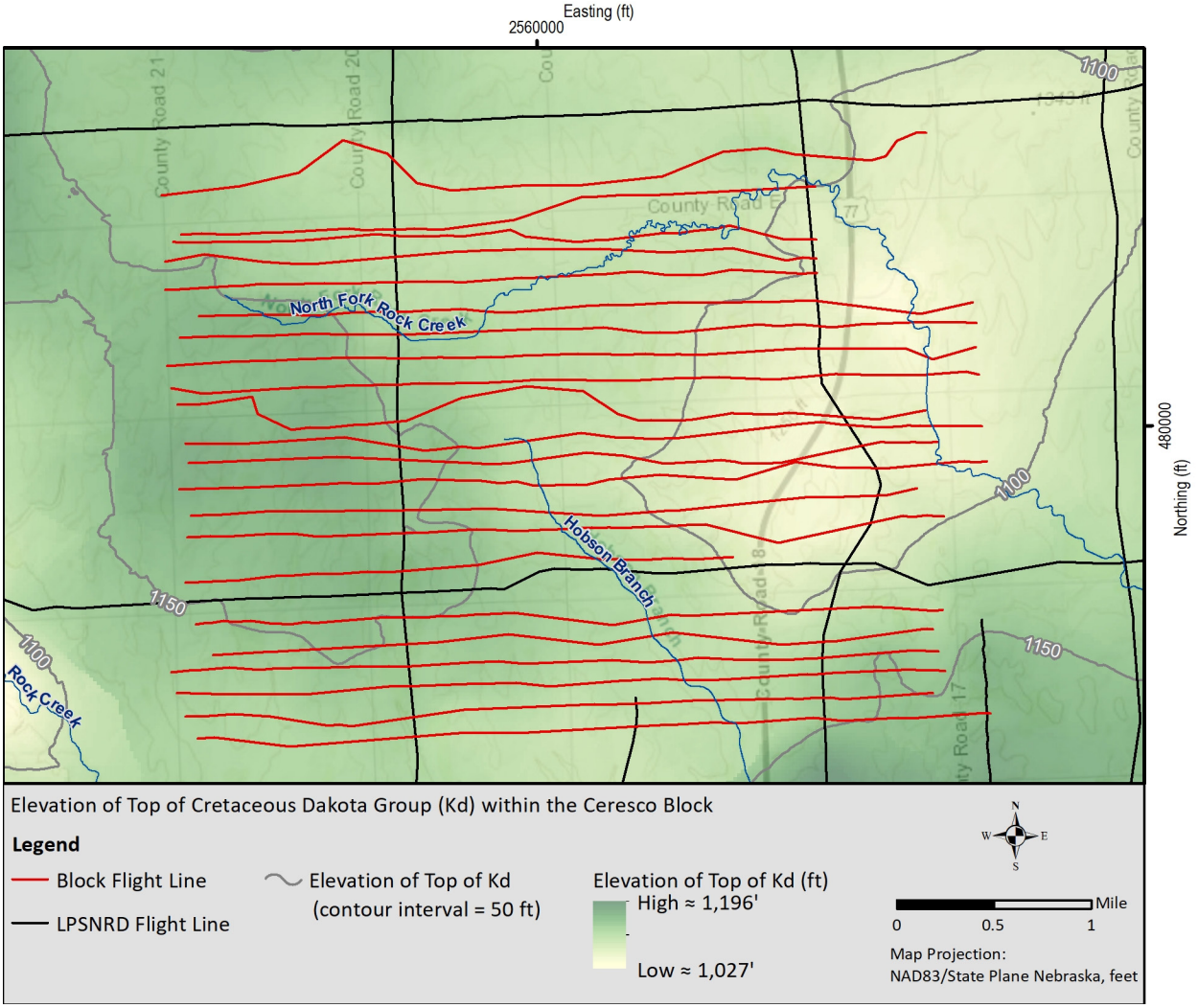


Figure 3-19. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Ceresco Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

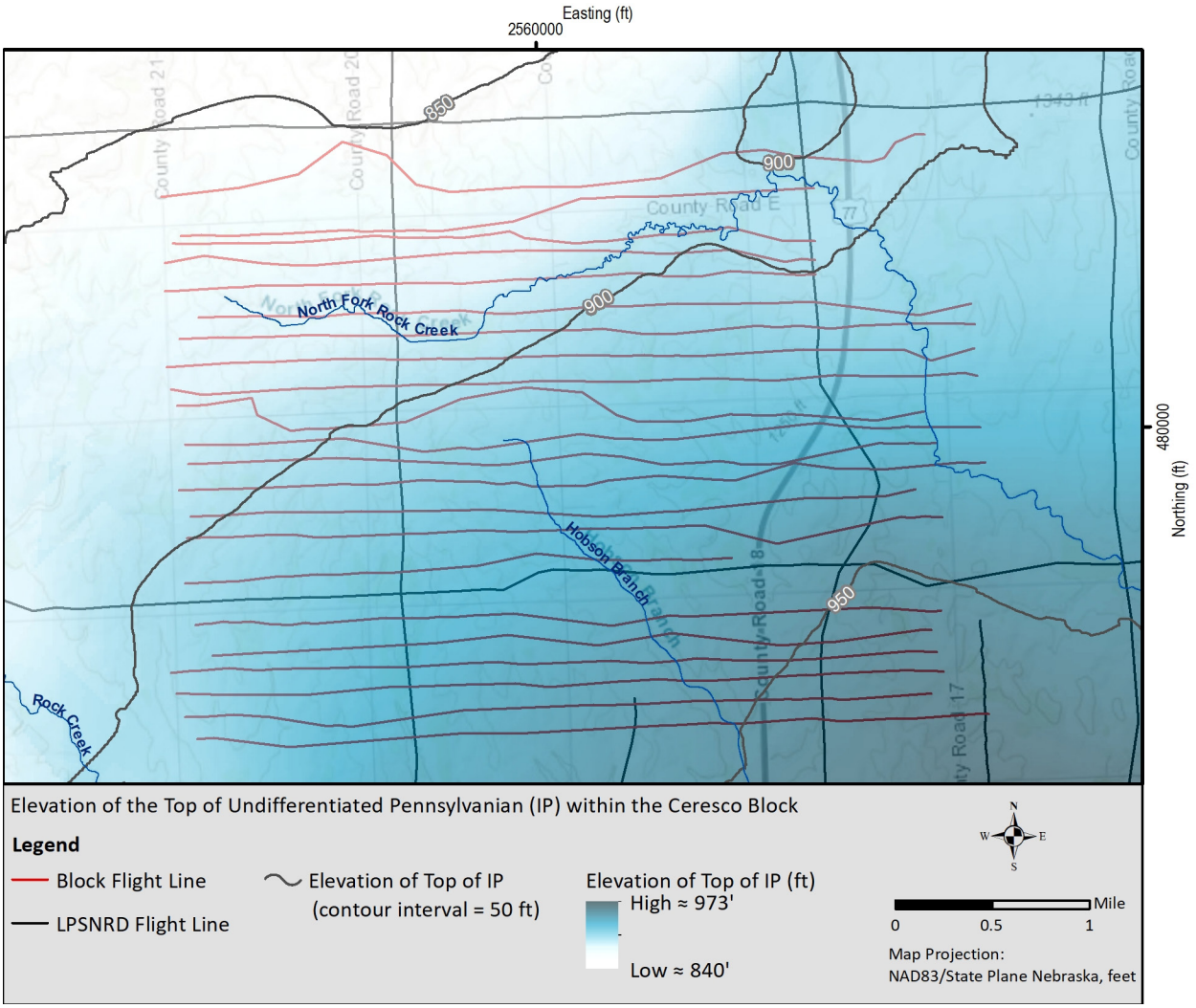


Figure 3-20. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Ceresco Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

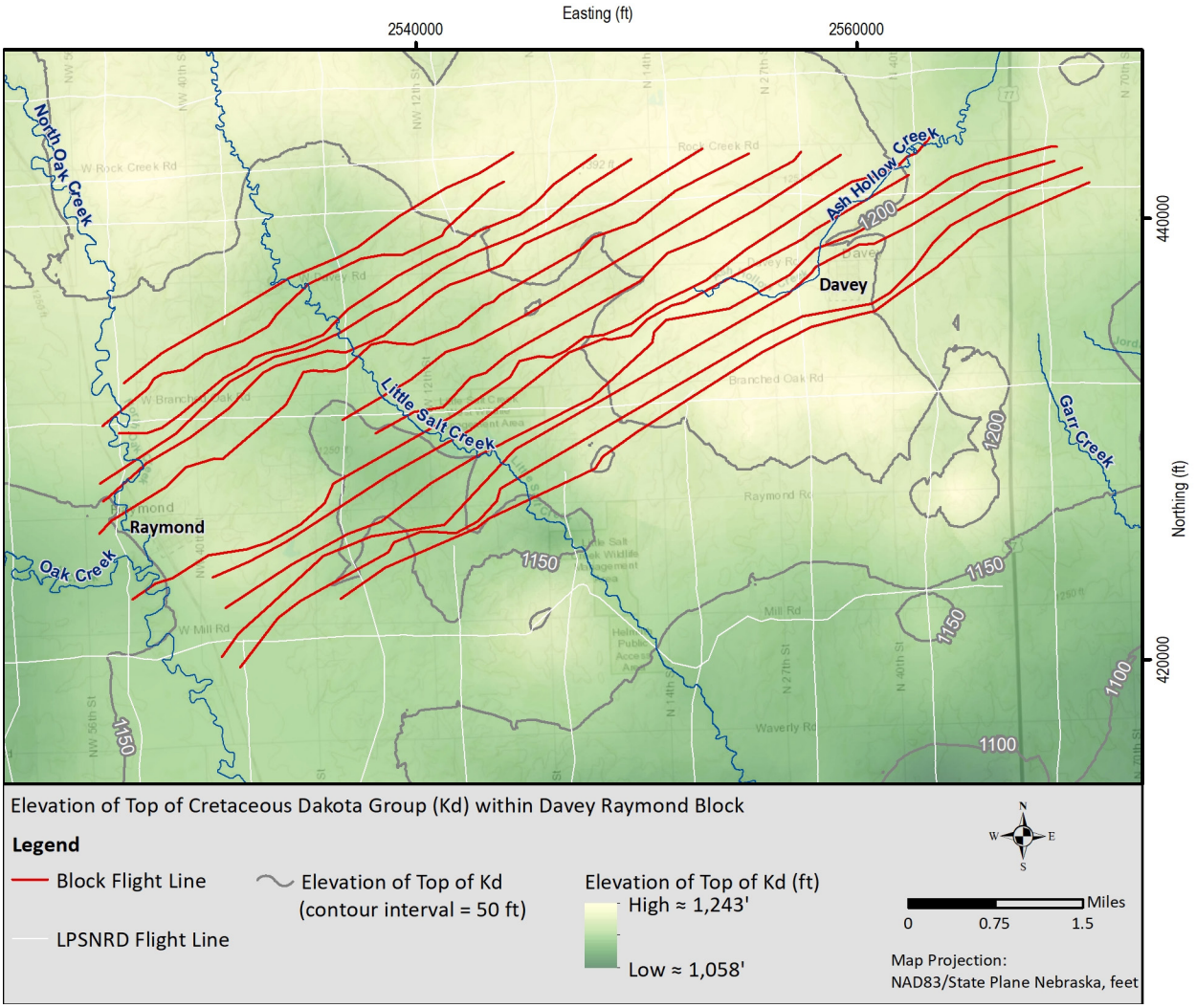


Figure 3-21. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Davey Raymond Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

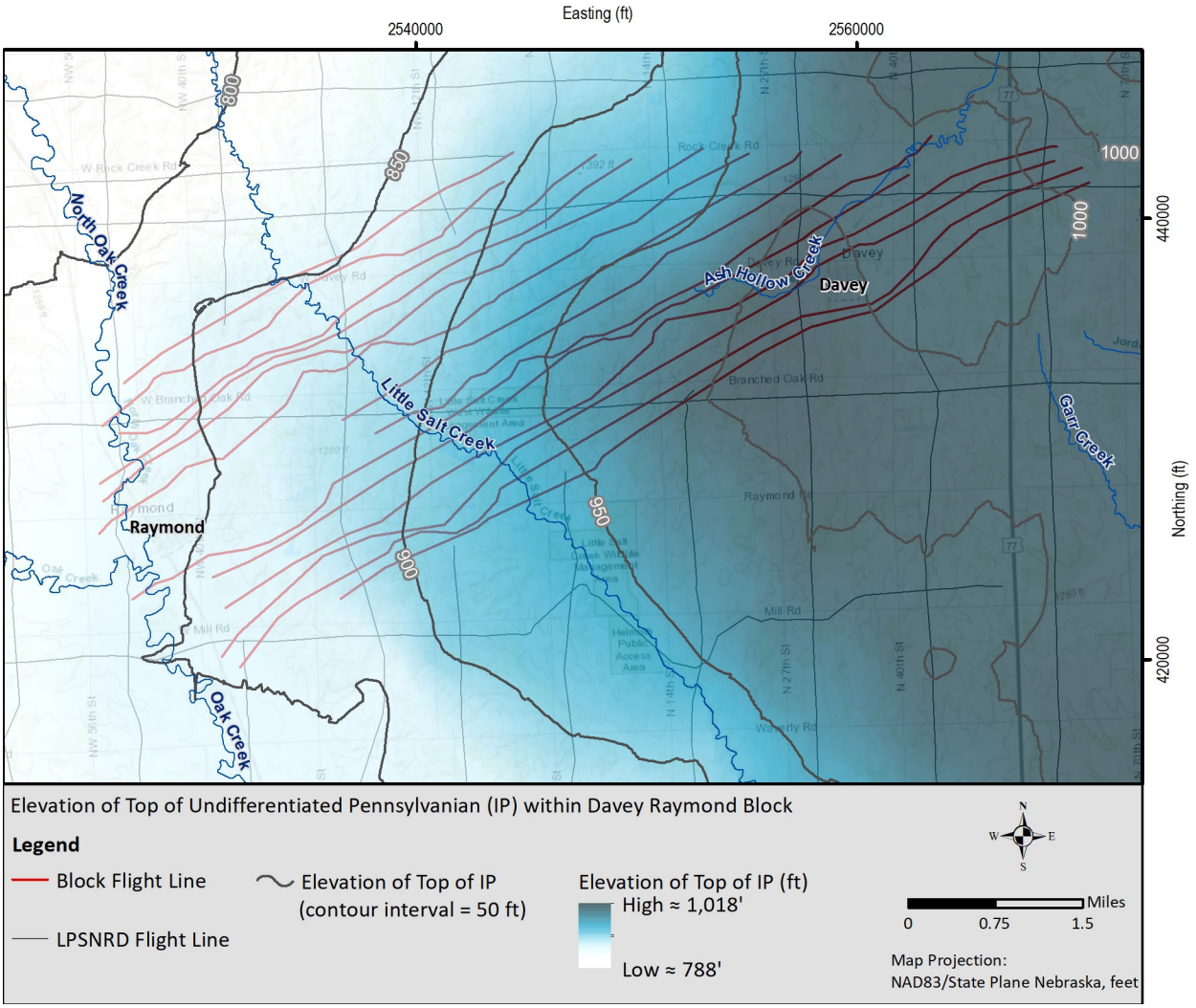


Figure 3-22. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Davey Raymond Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

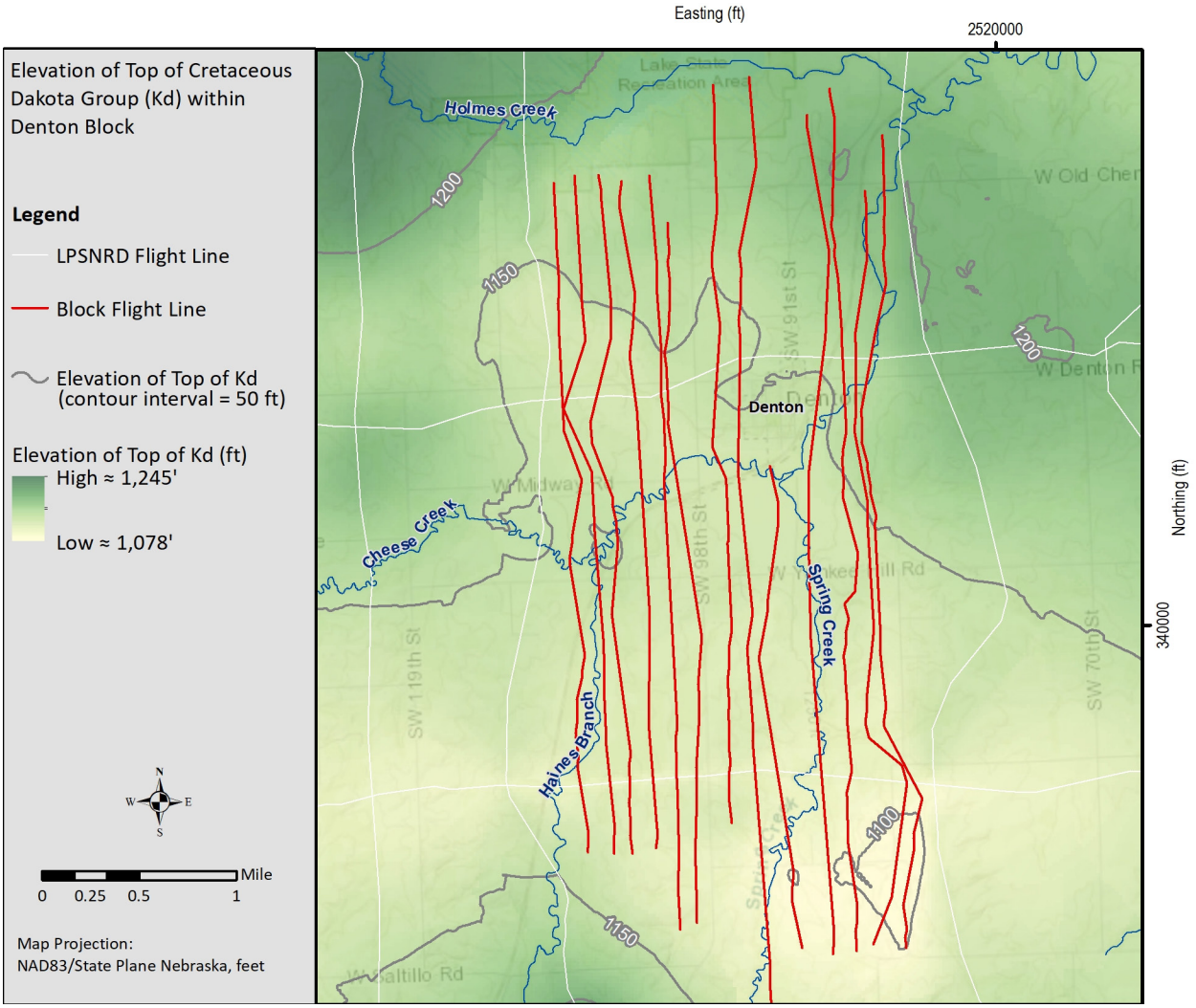


Figure 3-23. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Denton Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

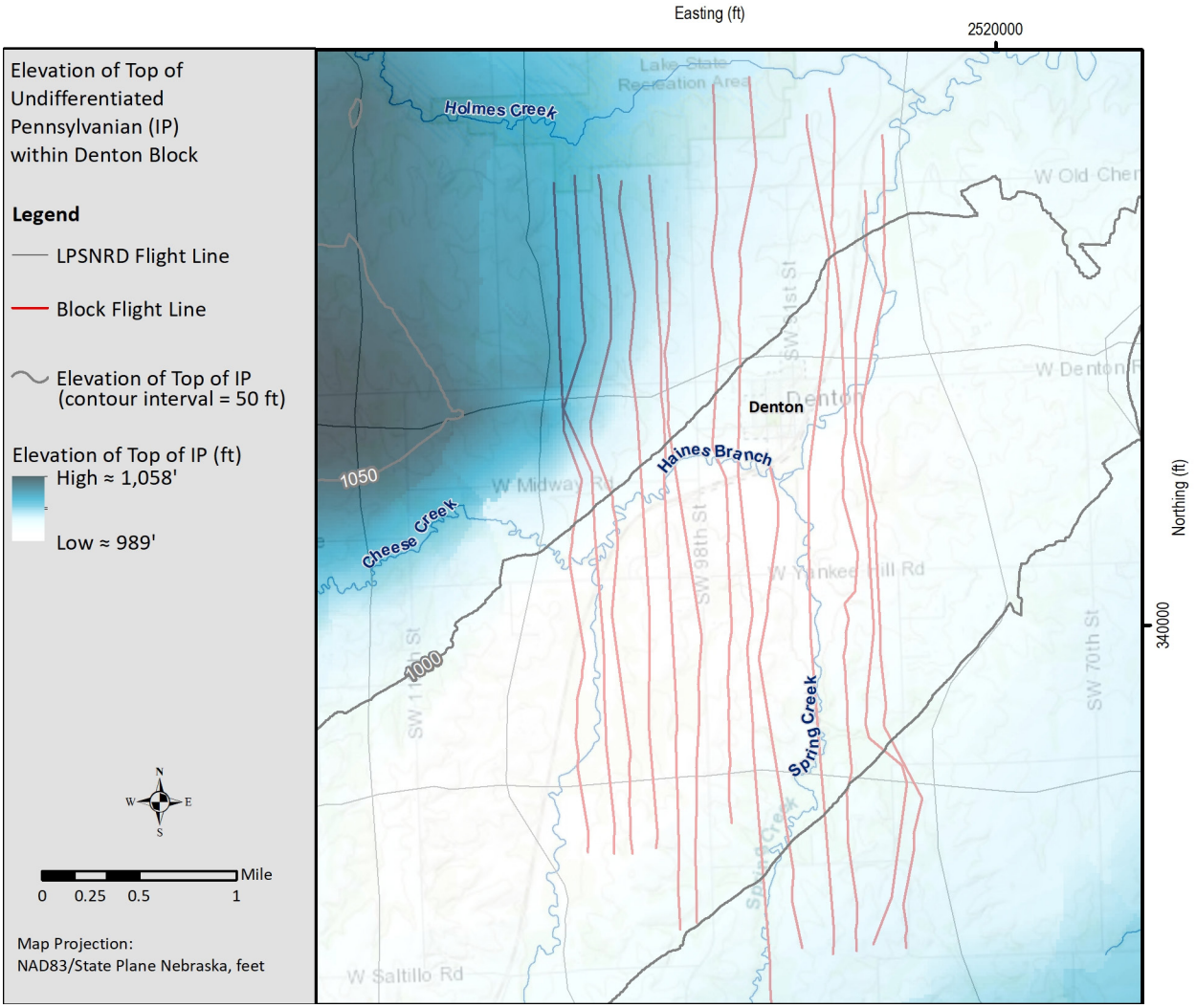


Figure 3-24. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Denton Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

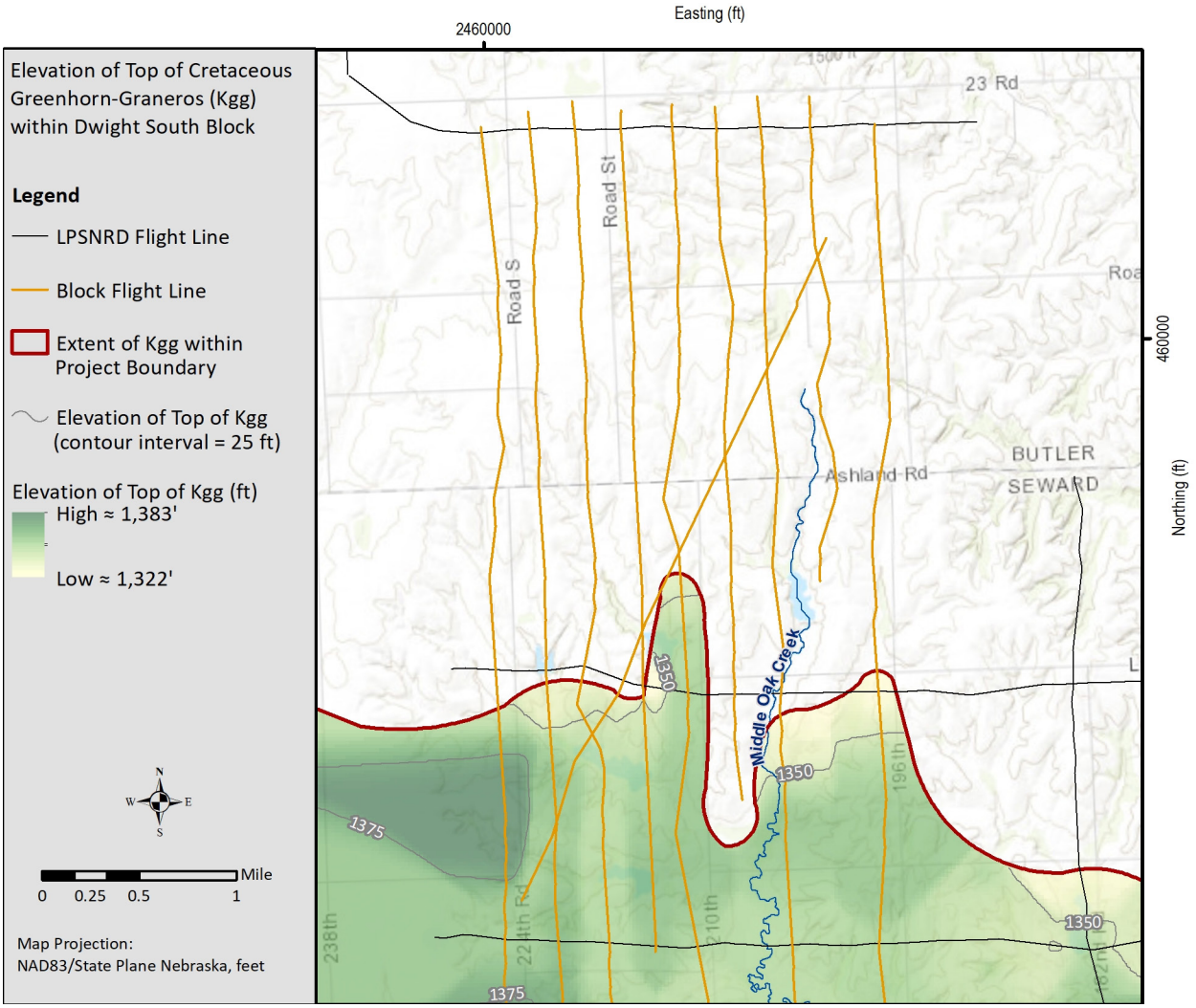


Figure 3-25. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the Dwight South Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

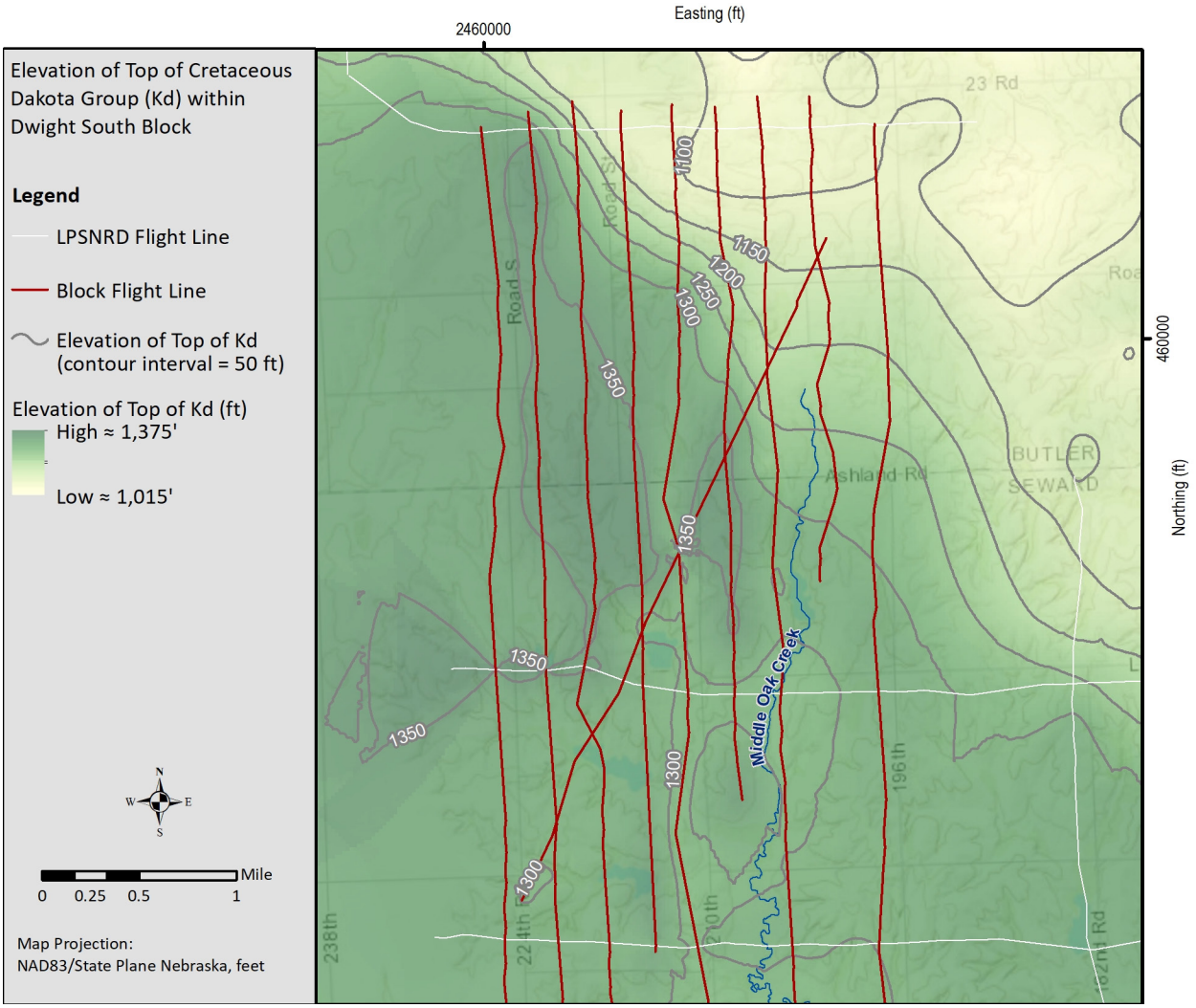


Figure 3-26. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Dwight South Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

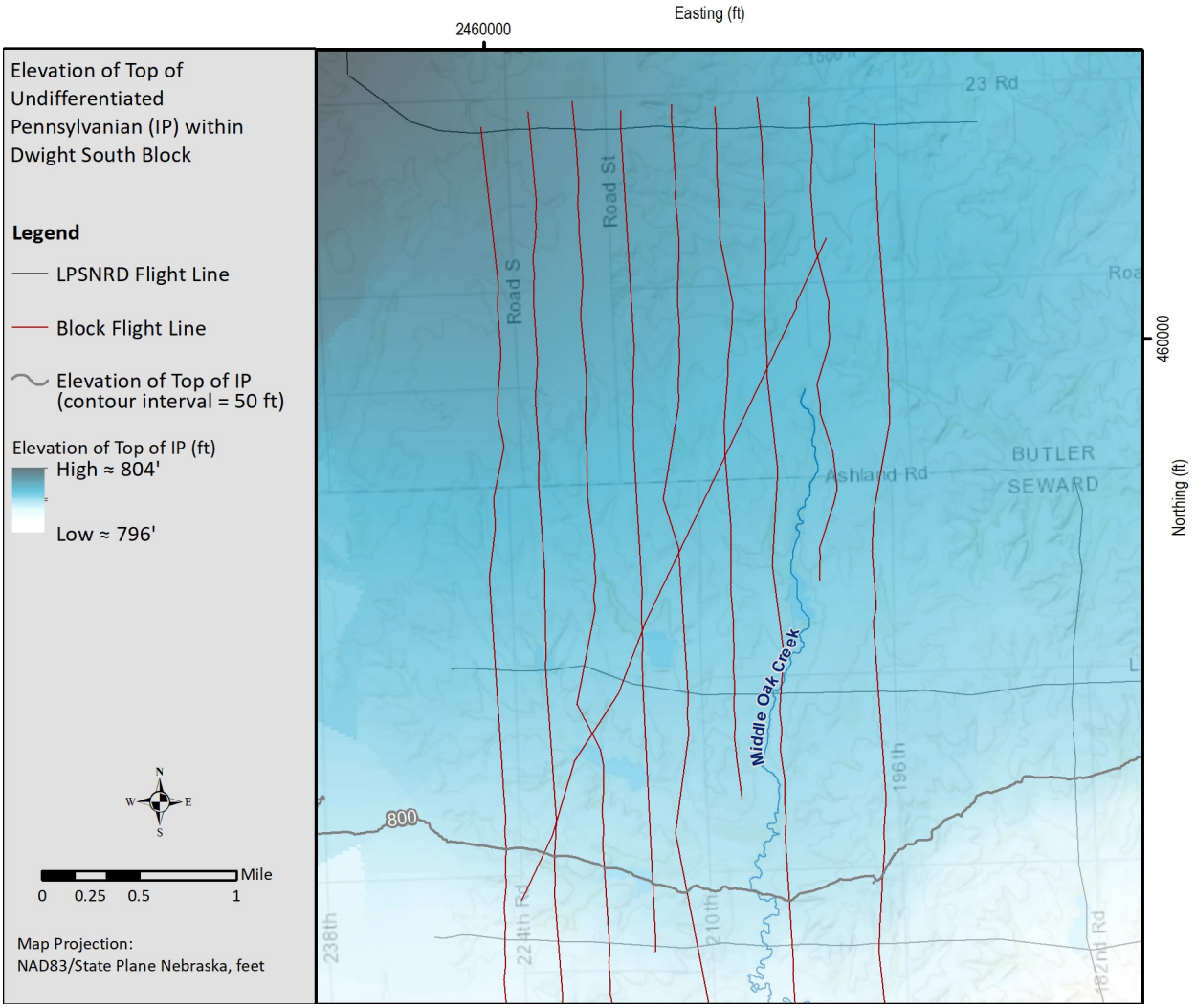


Figure 3-27. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Dwight South Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

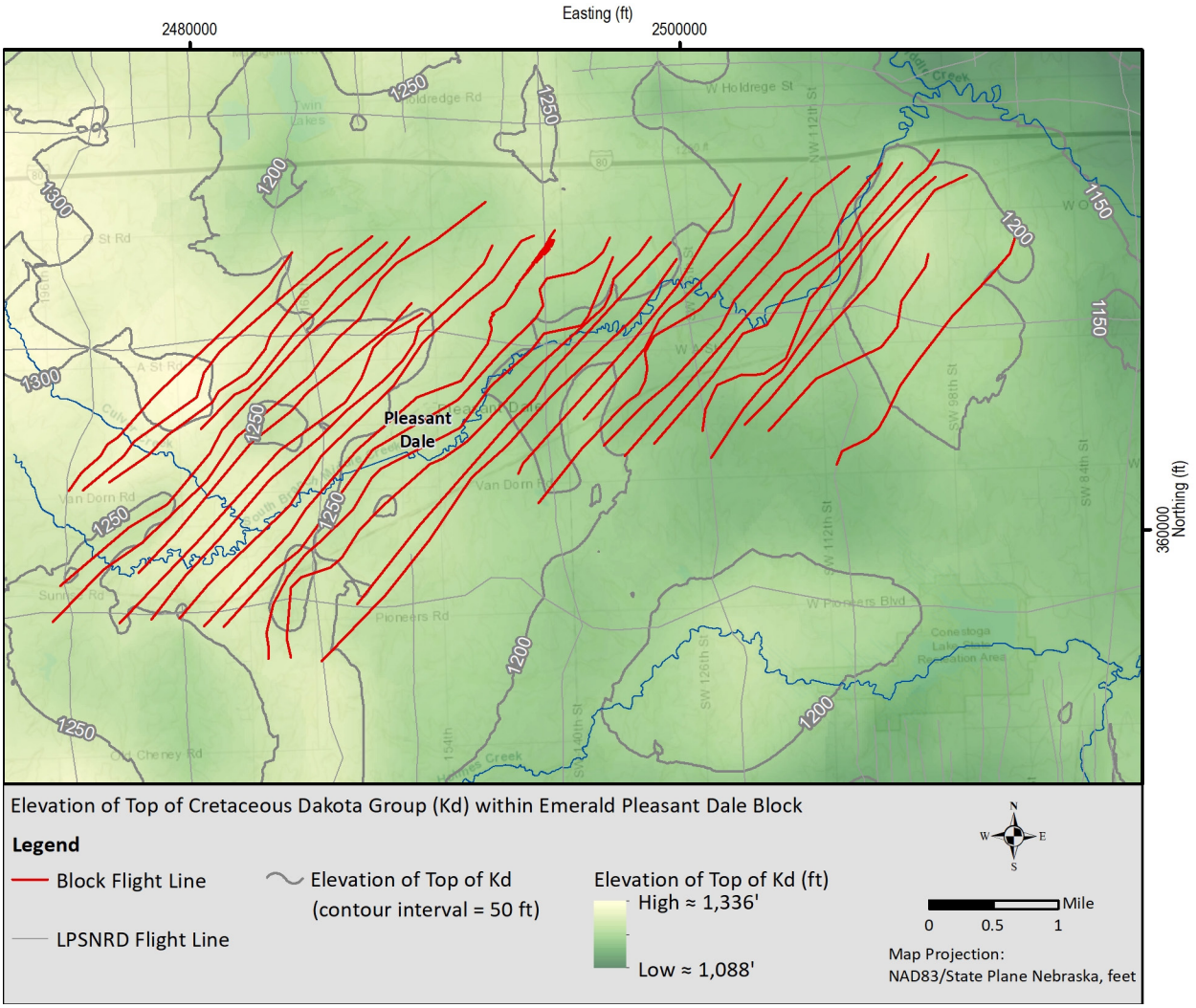


Figure 3-28. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Emerald Pleasant Dale Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

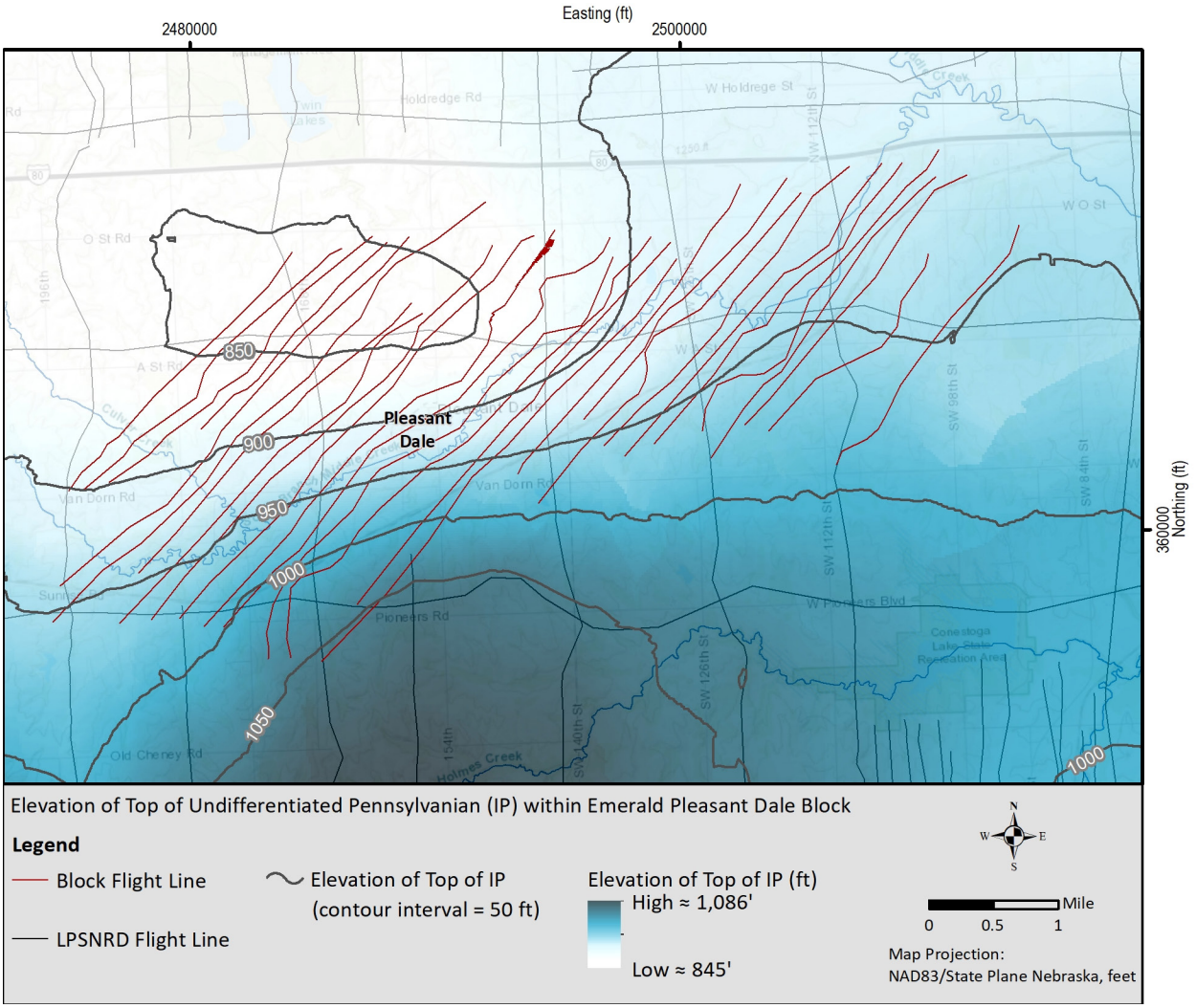


Figure 3-29. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Emerald Pleasant Dale Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

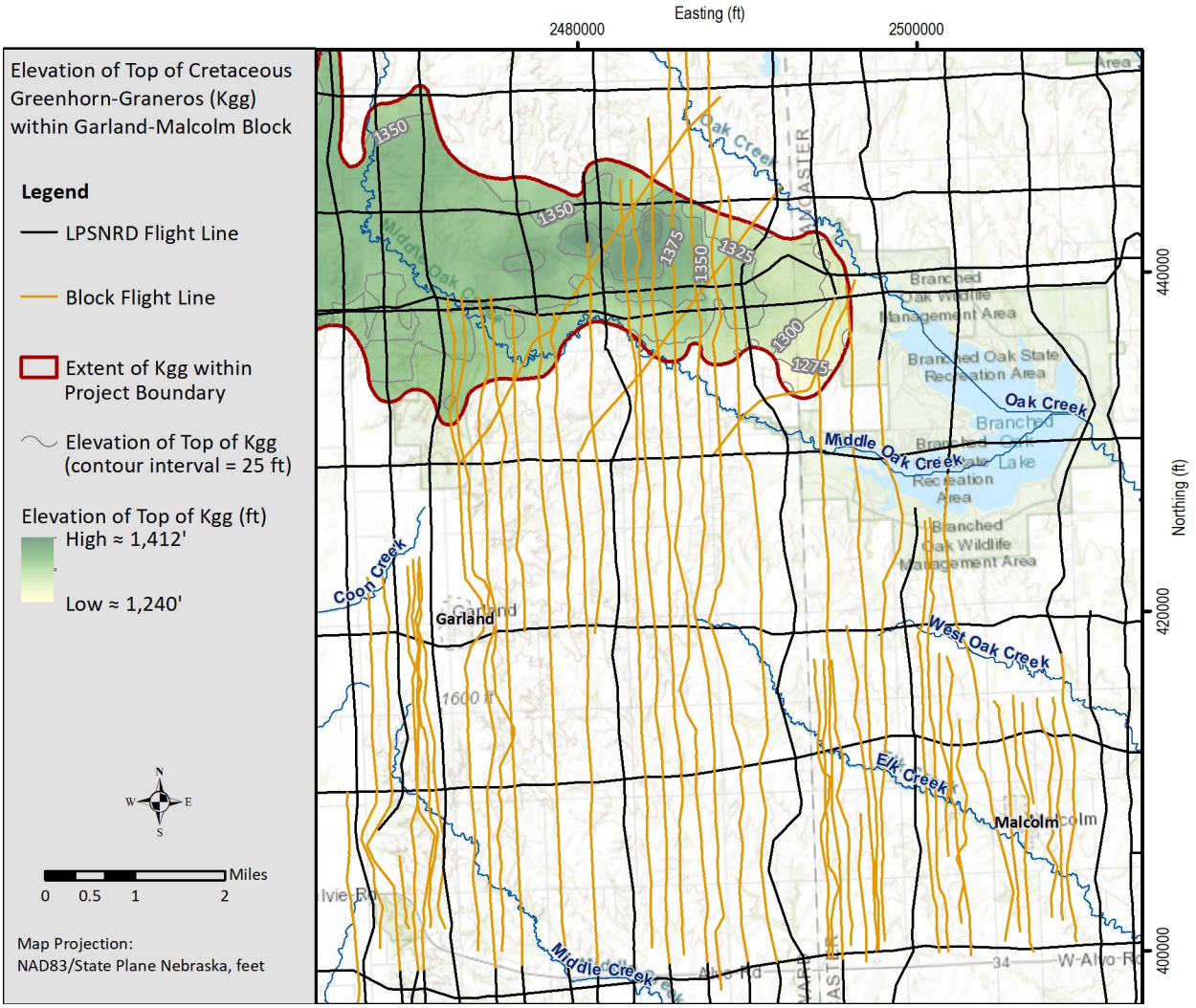


Figure 3-30. Map of the elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale (*Kgg*) within the Garland Malcolm Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

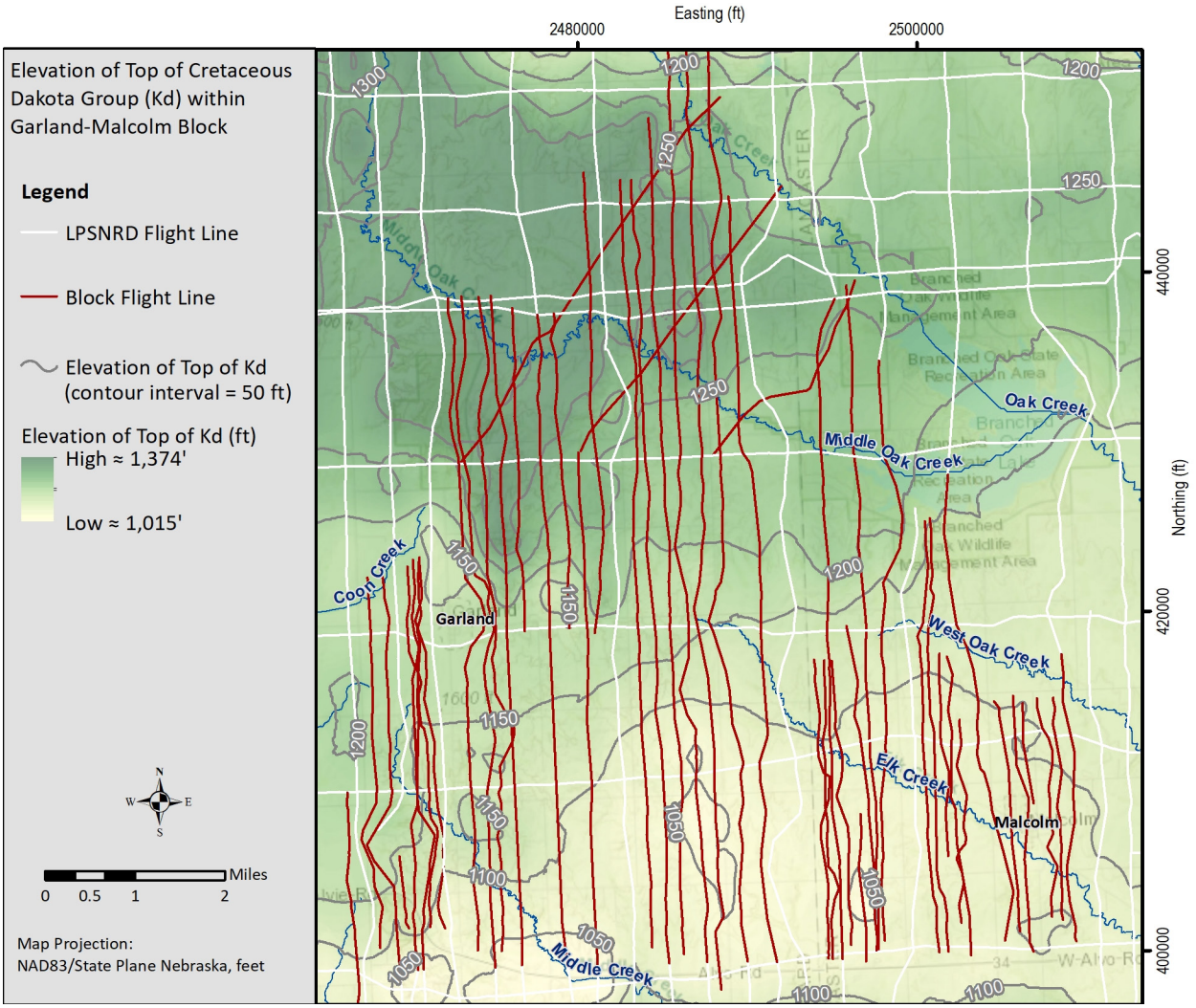


Figure 3-31. Map of the elevation of the top of the Cretaceous Dakota Group (*Kd*) within the Garland Malcolm Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

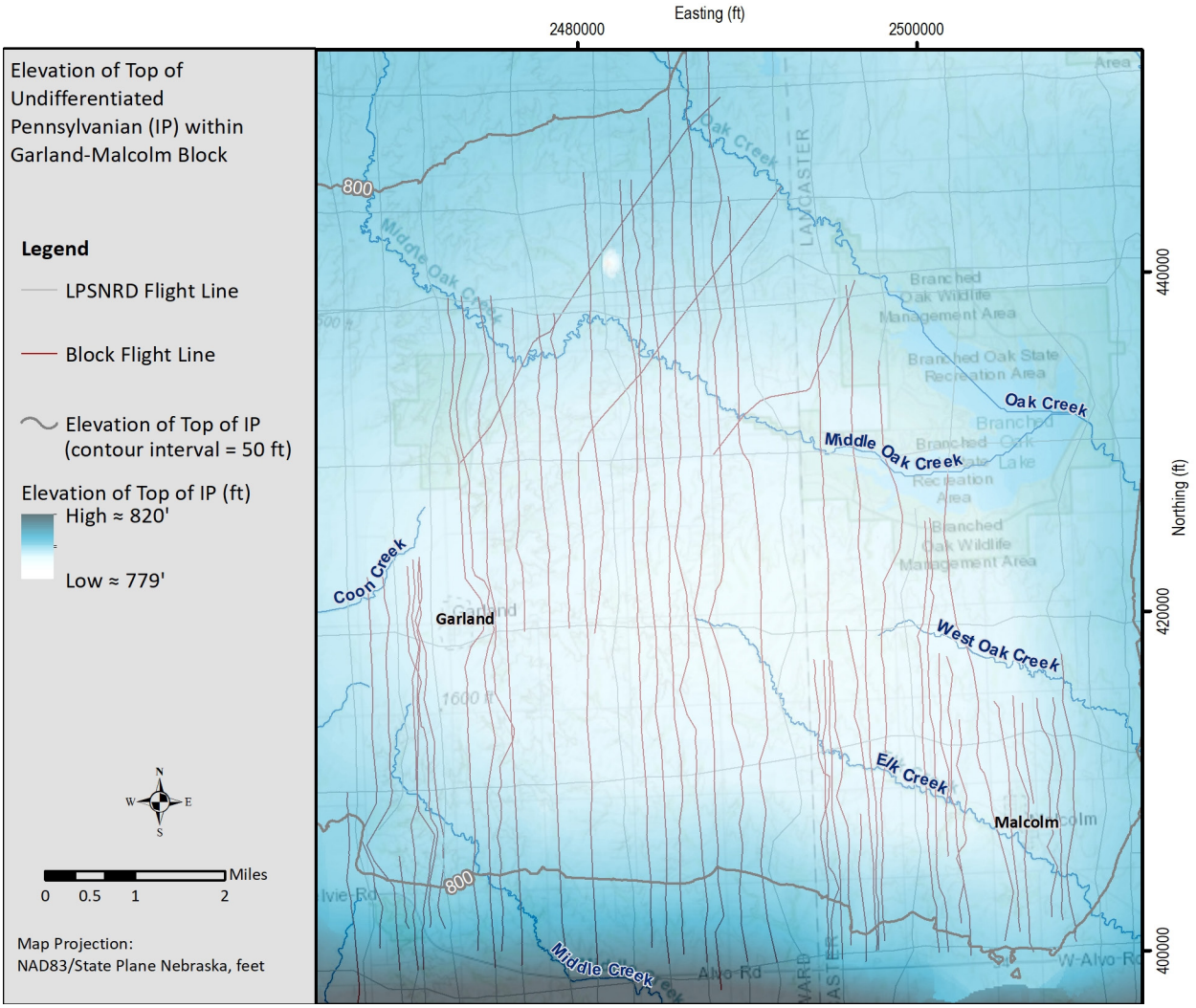


Figure 3-32. Map of the elevation of the top of the Undifferentiated Pennsylvanian (*IP*) within the Garland Malcolm Block survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

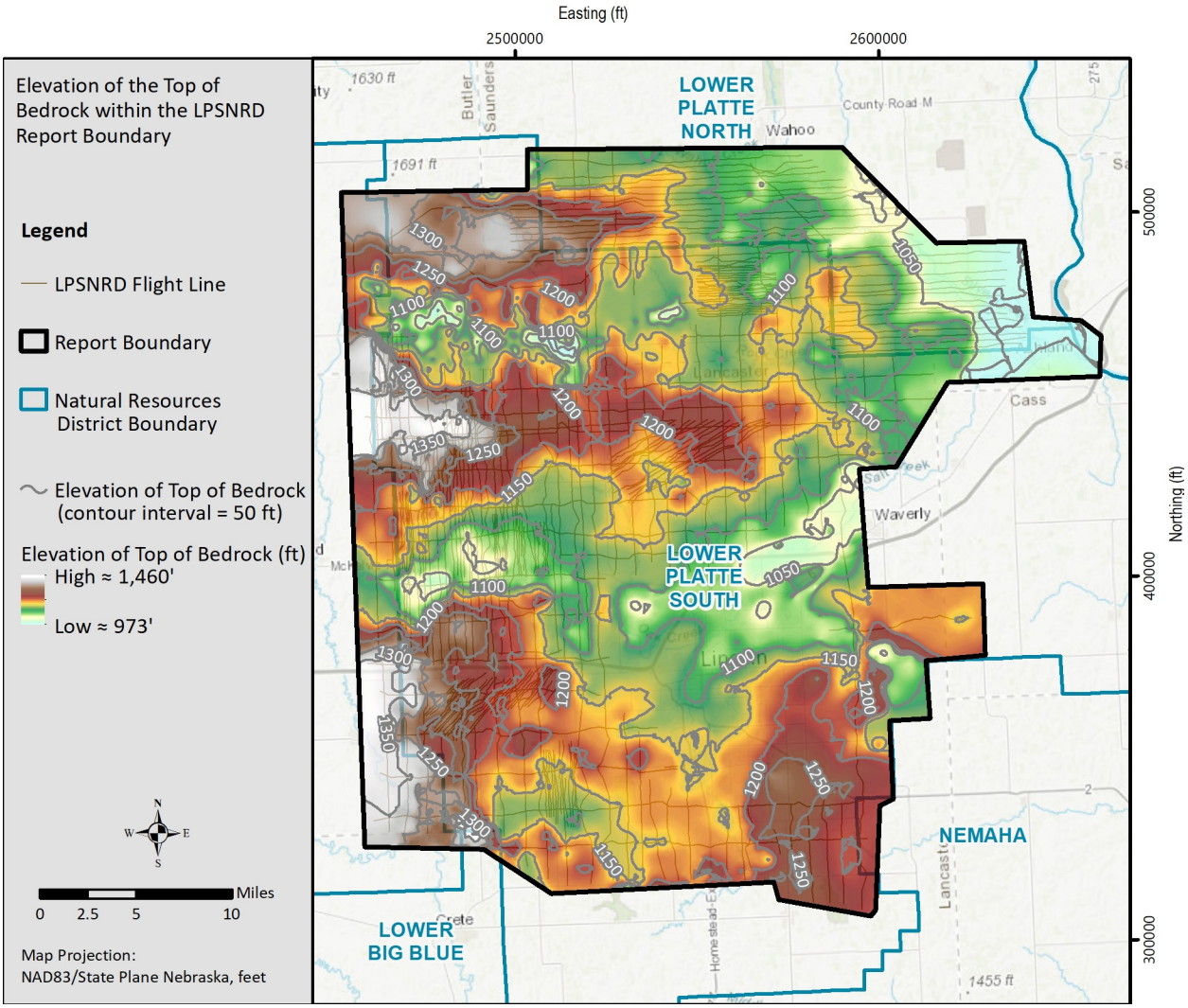


Figure 3-33. Map of the elevation of the top of the bedrock within the LPSNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

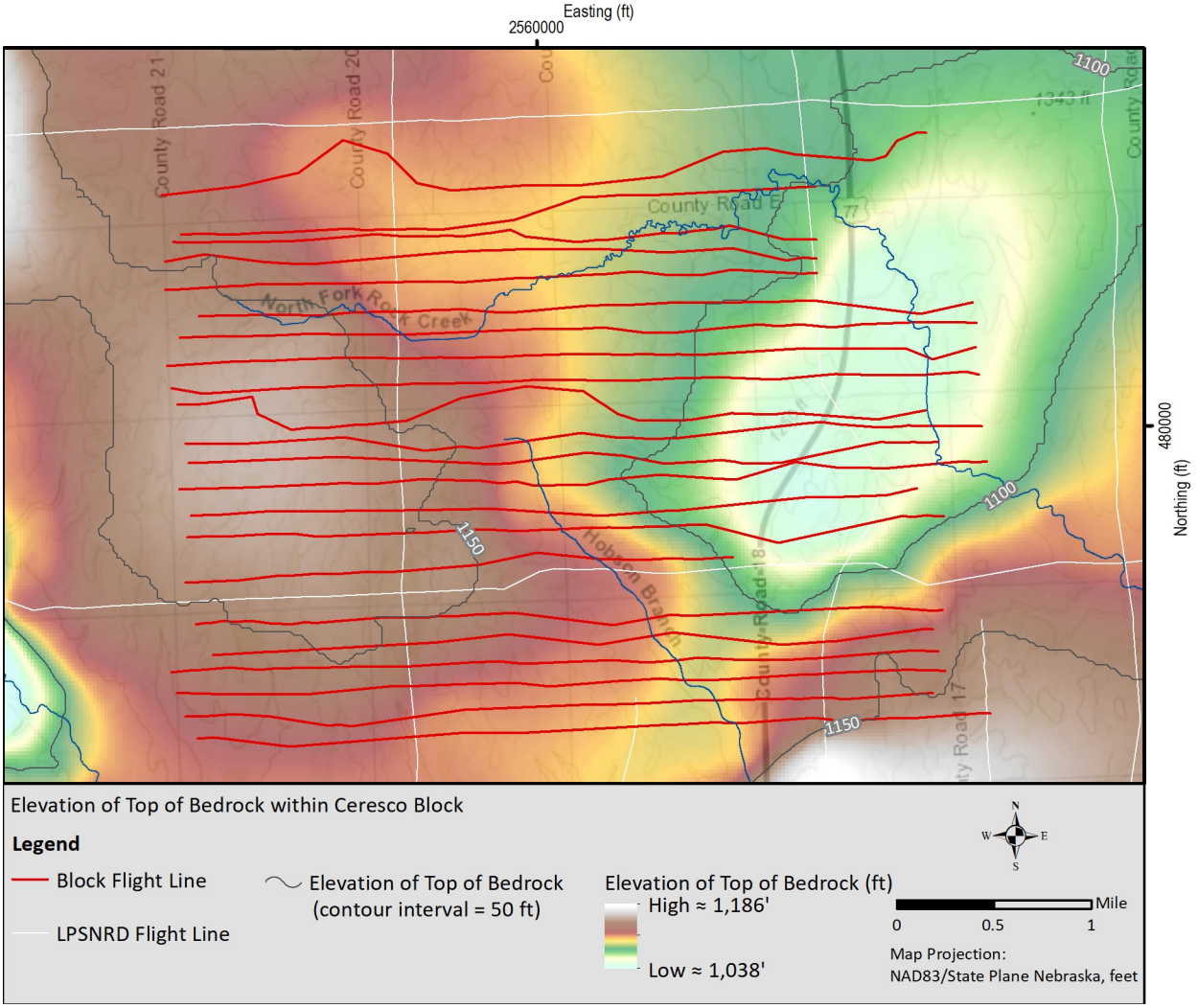


Figure 3-34. Map of the elevation of the top of the bedrock within the Ceresco Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

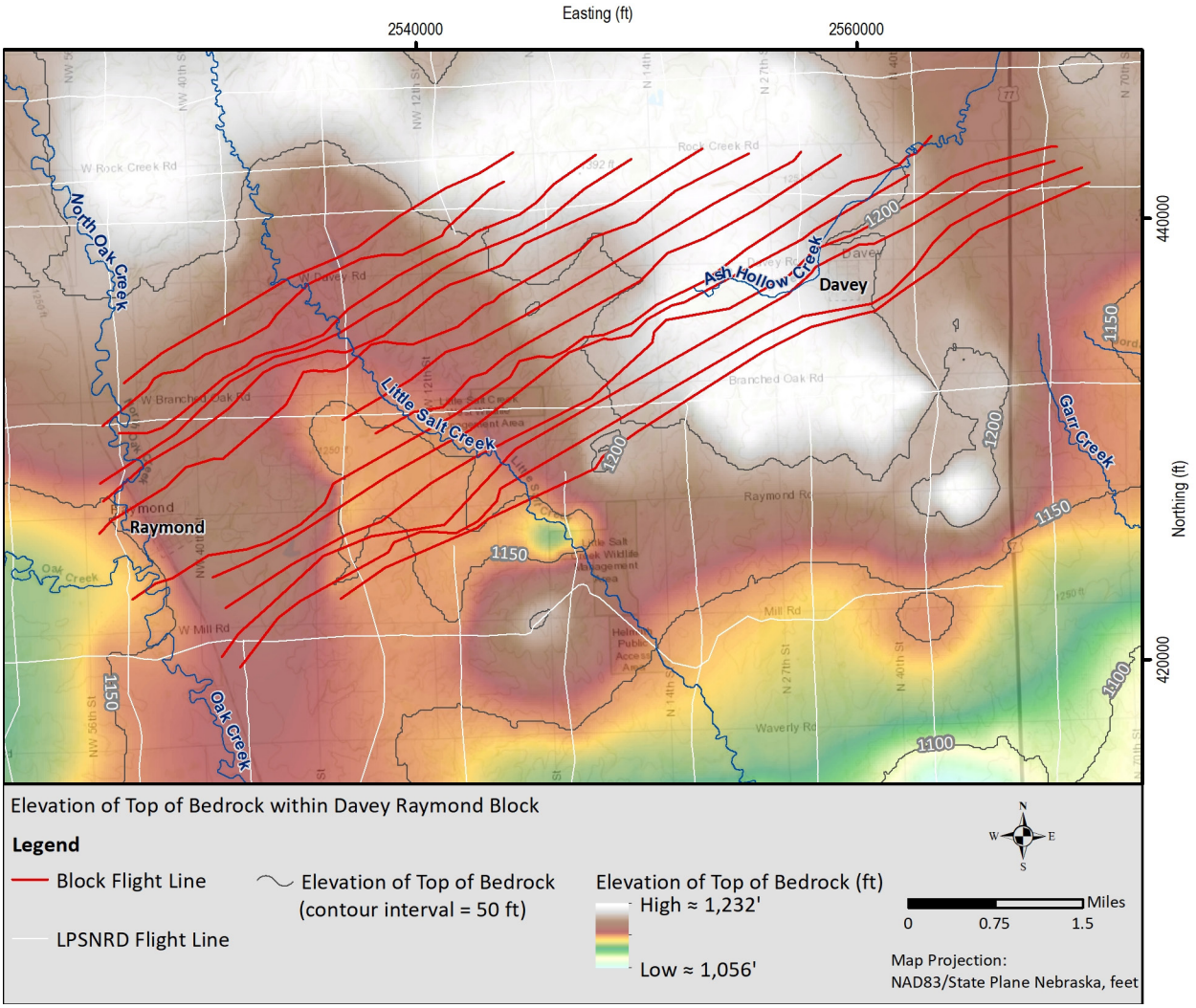


Figure 3-35. Map of the elevation of the top of the bedrock within the Davey Raymond Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

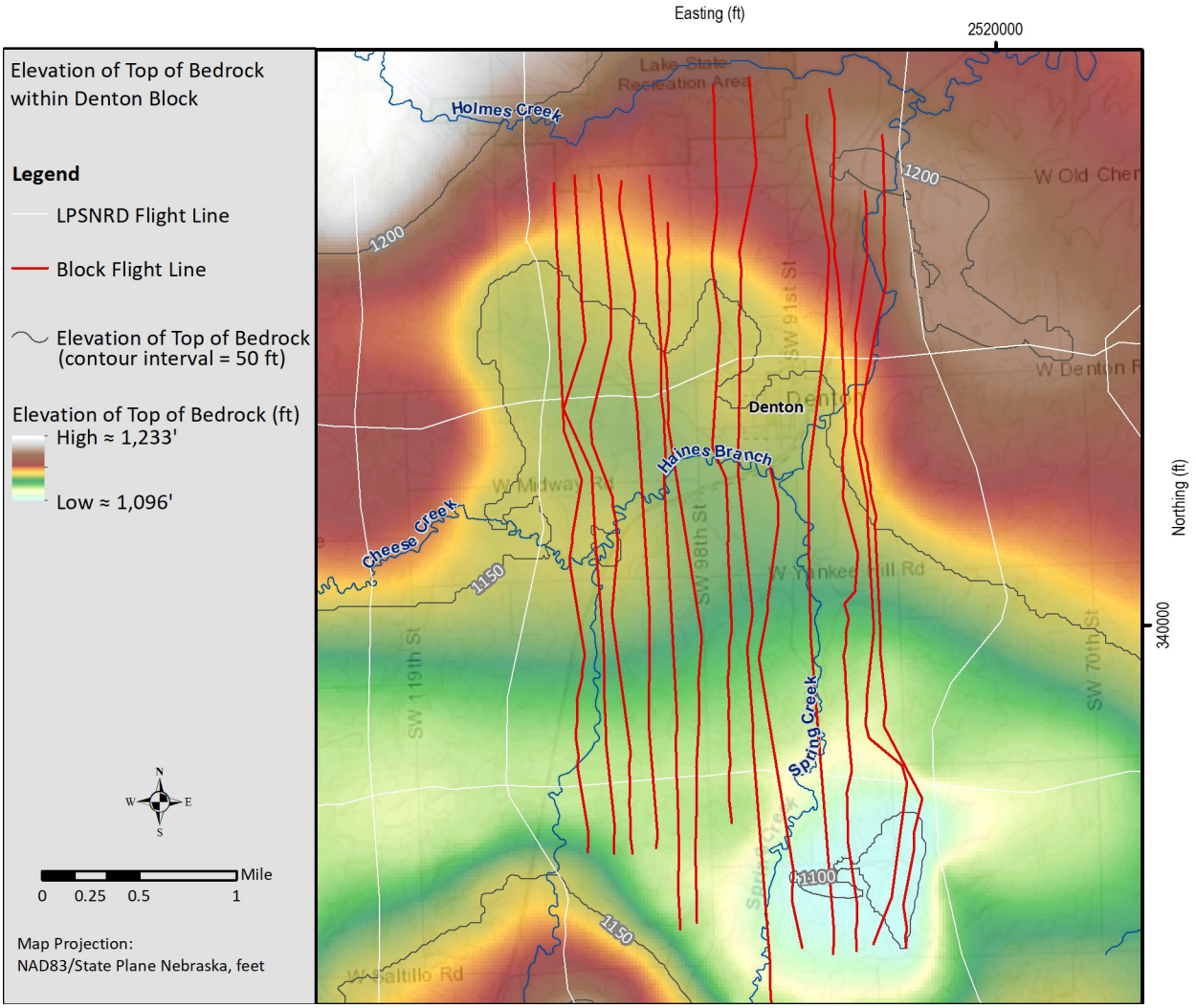


Figure 3-36. Map of the elevation of the top of the bedrock within the Denton Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

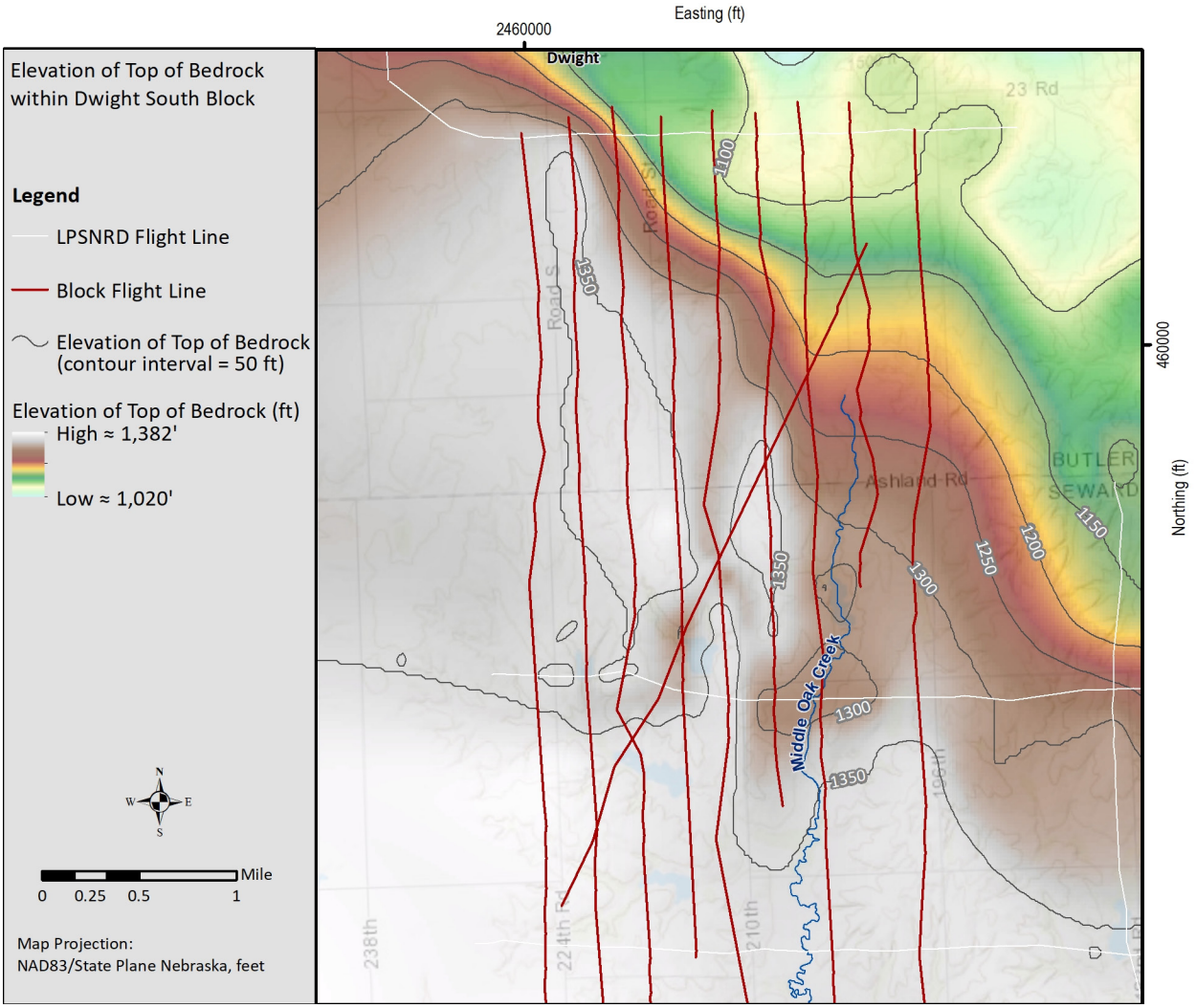


Figure 3-37. Map of the elevation of the top of the bedrock within the Dwight South Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

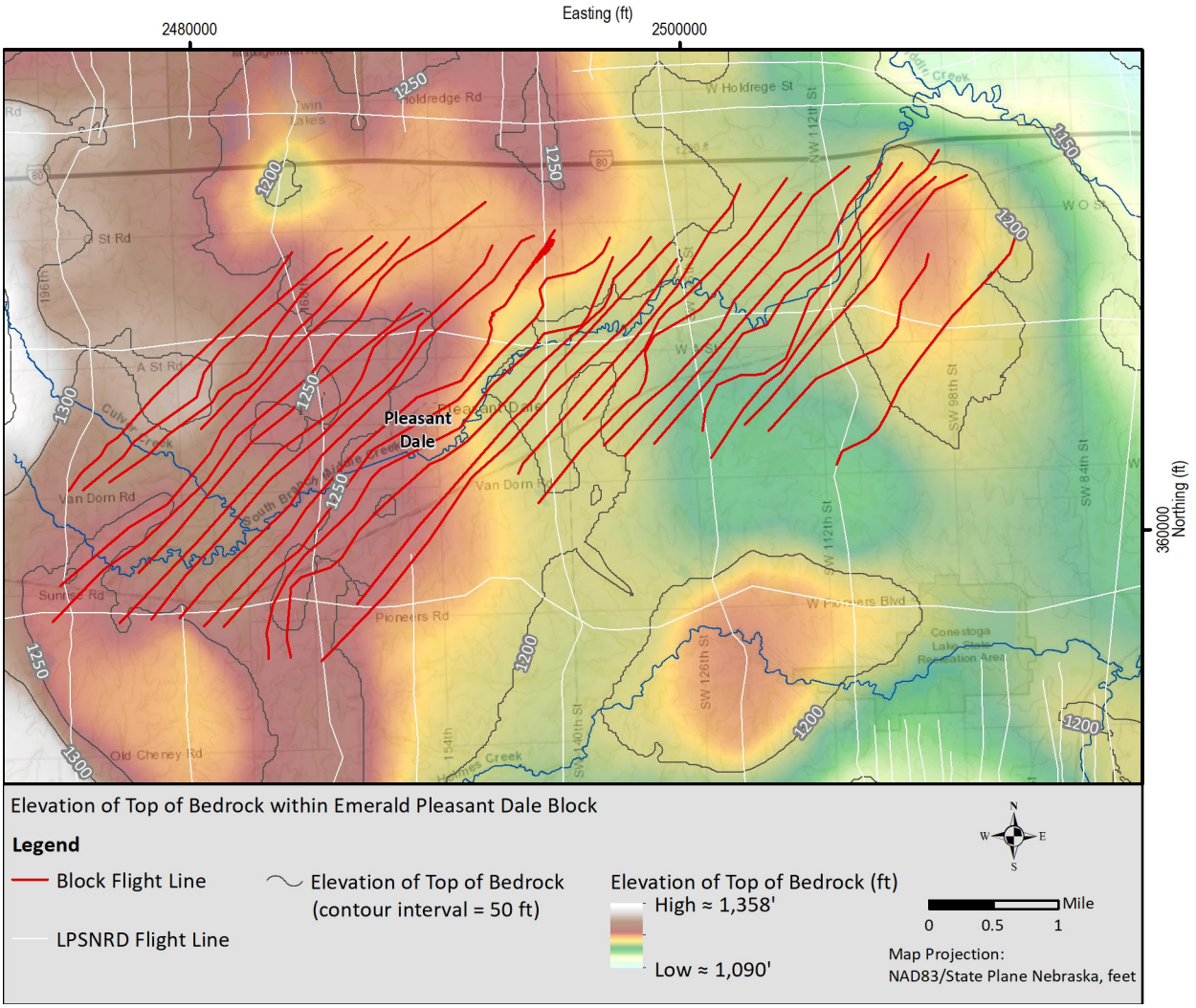


Figure 3-38. Map of the elevation of the top of the bedrock within the Emerald Pleasant Dale Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

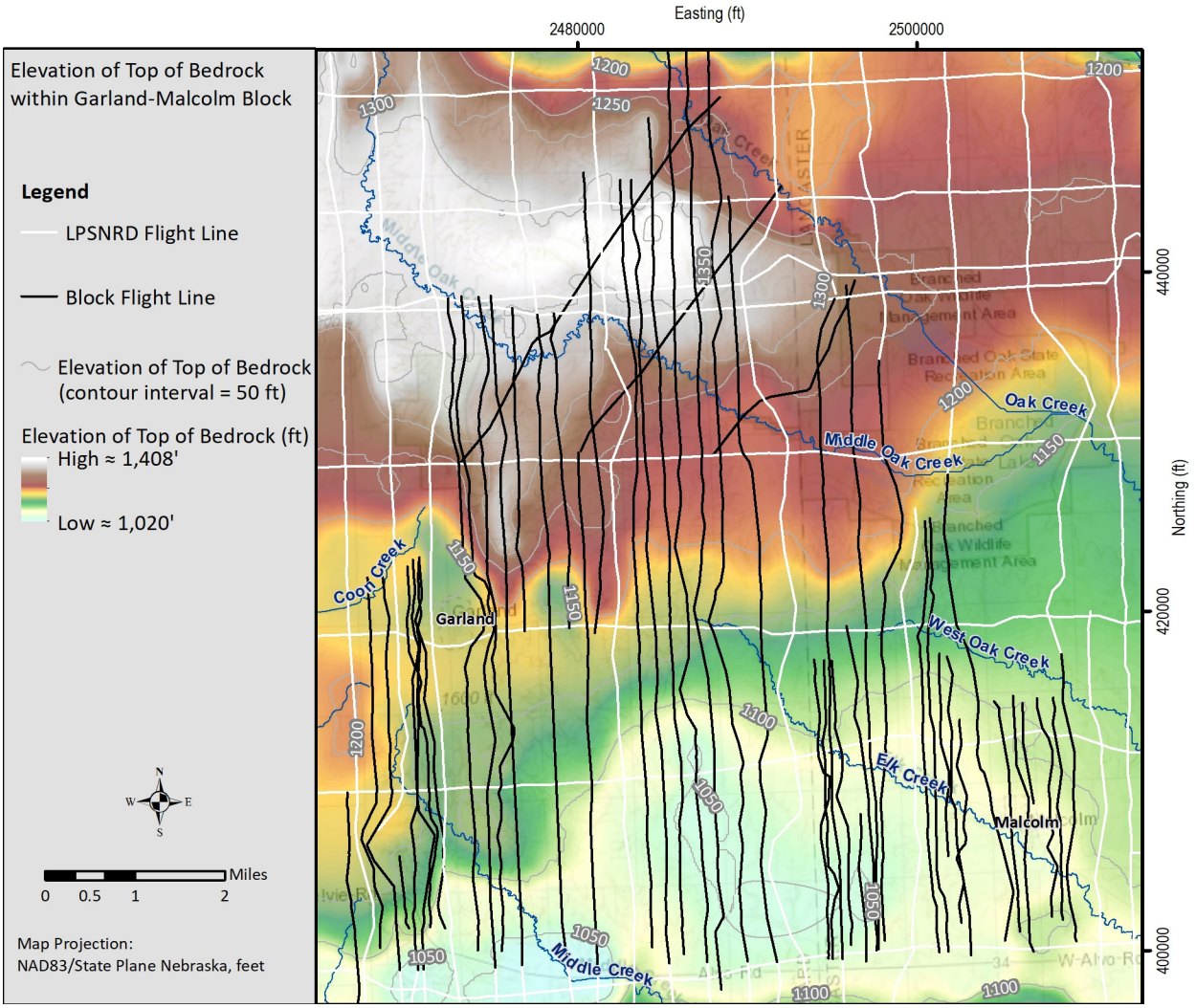


Figure 3-39. Map of the elevation of the top of the bedrock within the Garland Malcolm Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet) and the elevation values are referenced to NAVD 88 (feet).

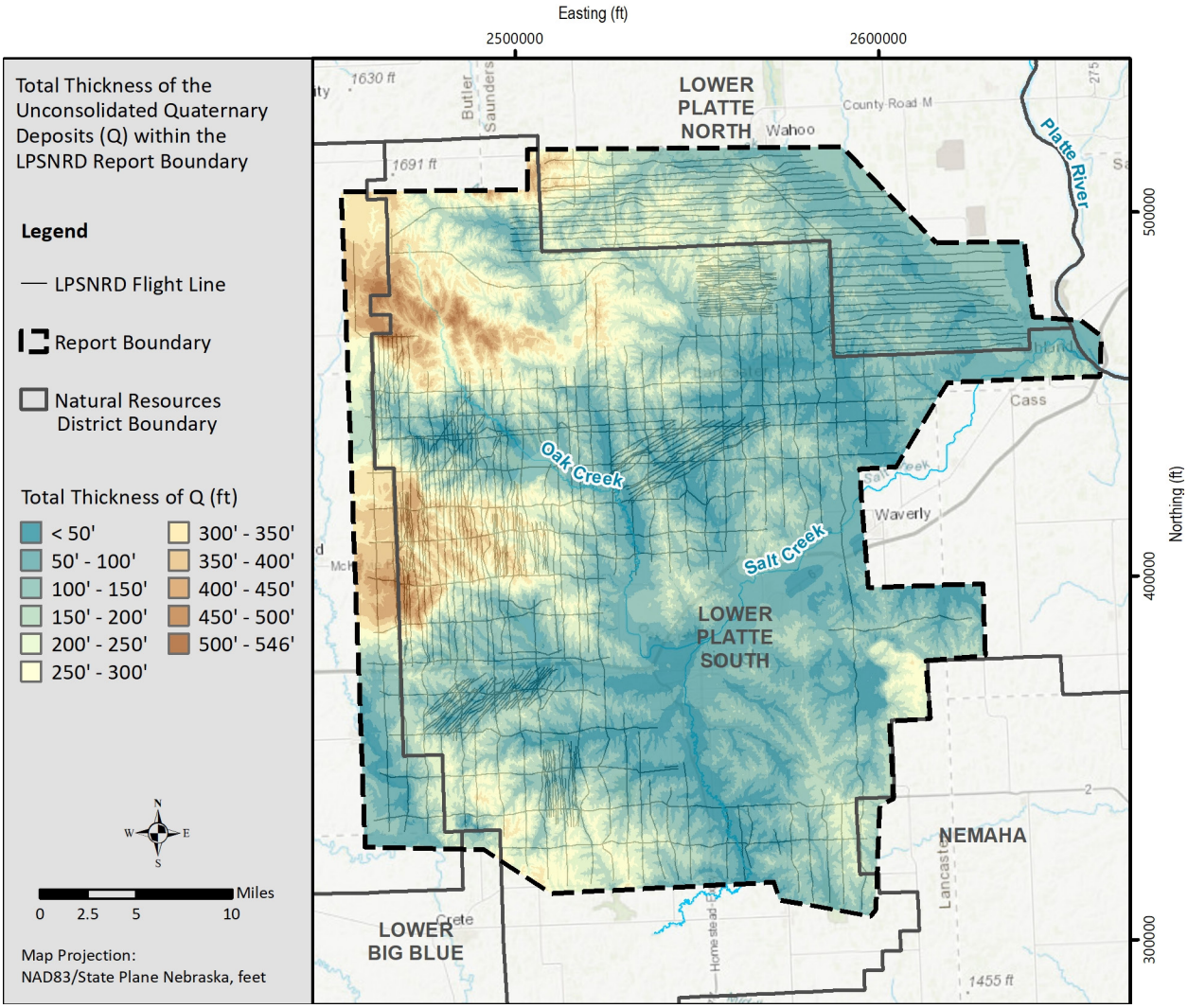


Figure 3-40. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the LPSNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

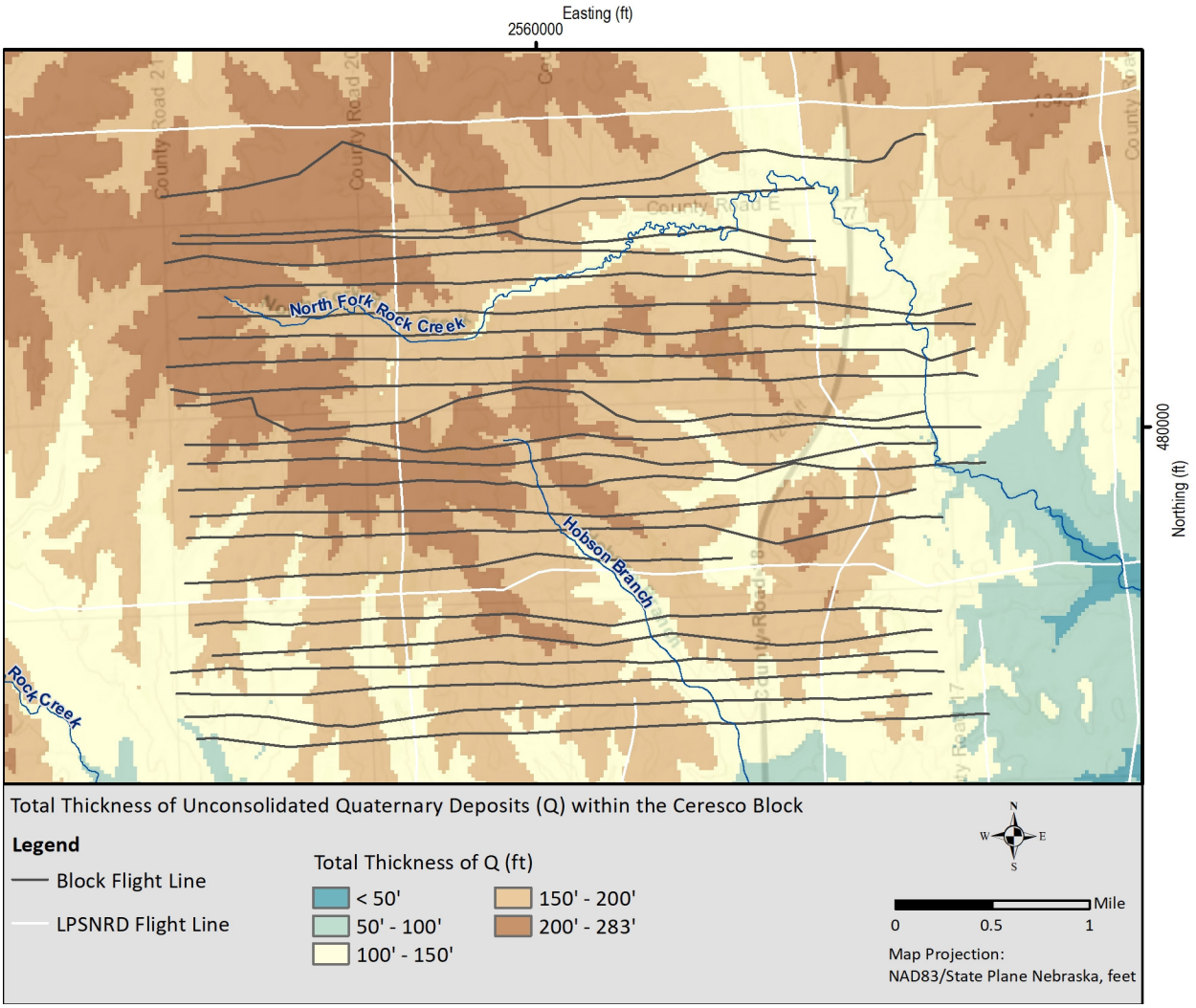


Figure 3-41. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the Ceresco Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

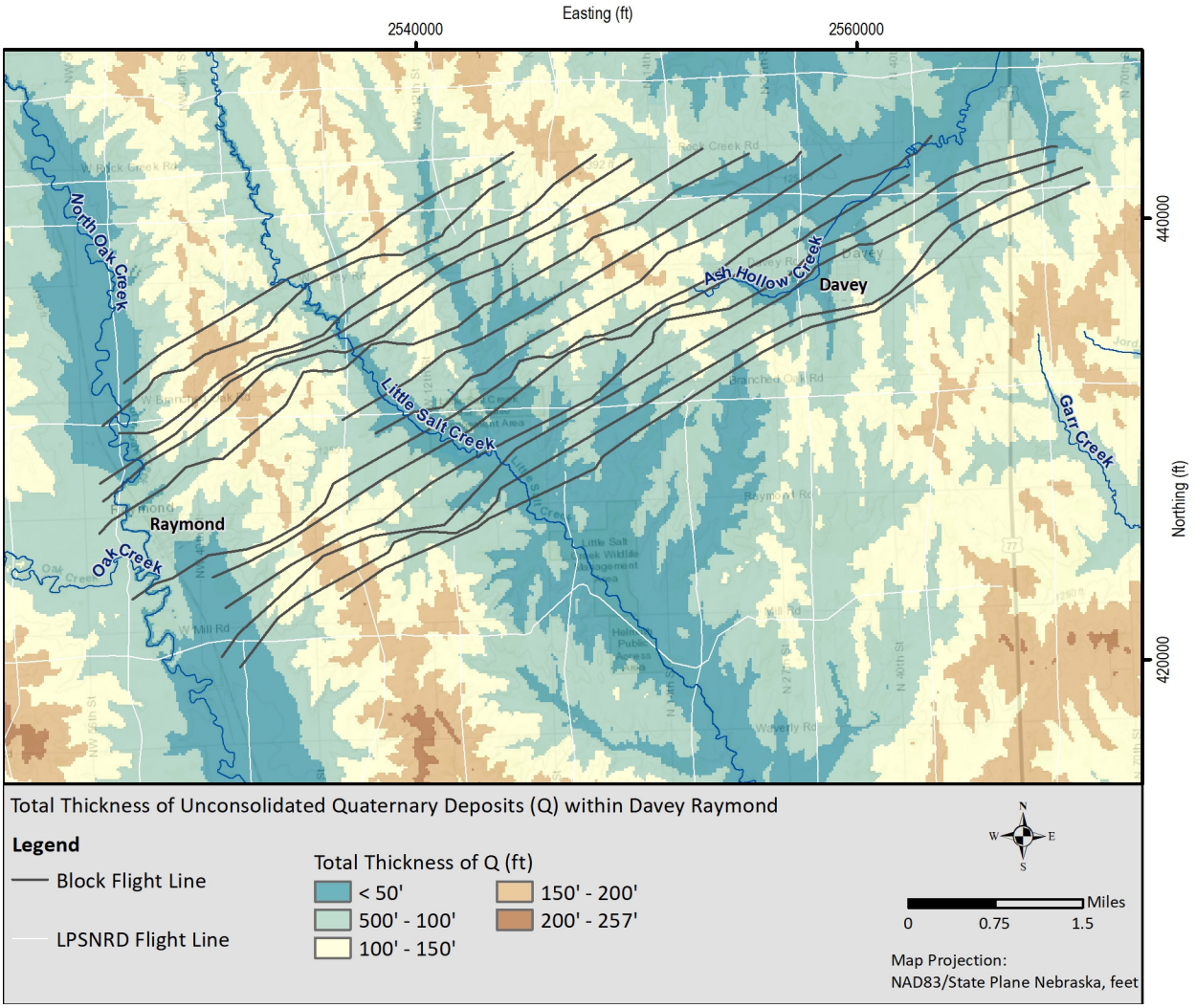


Figure 3-42. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the Davey Raymond Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

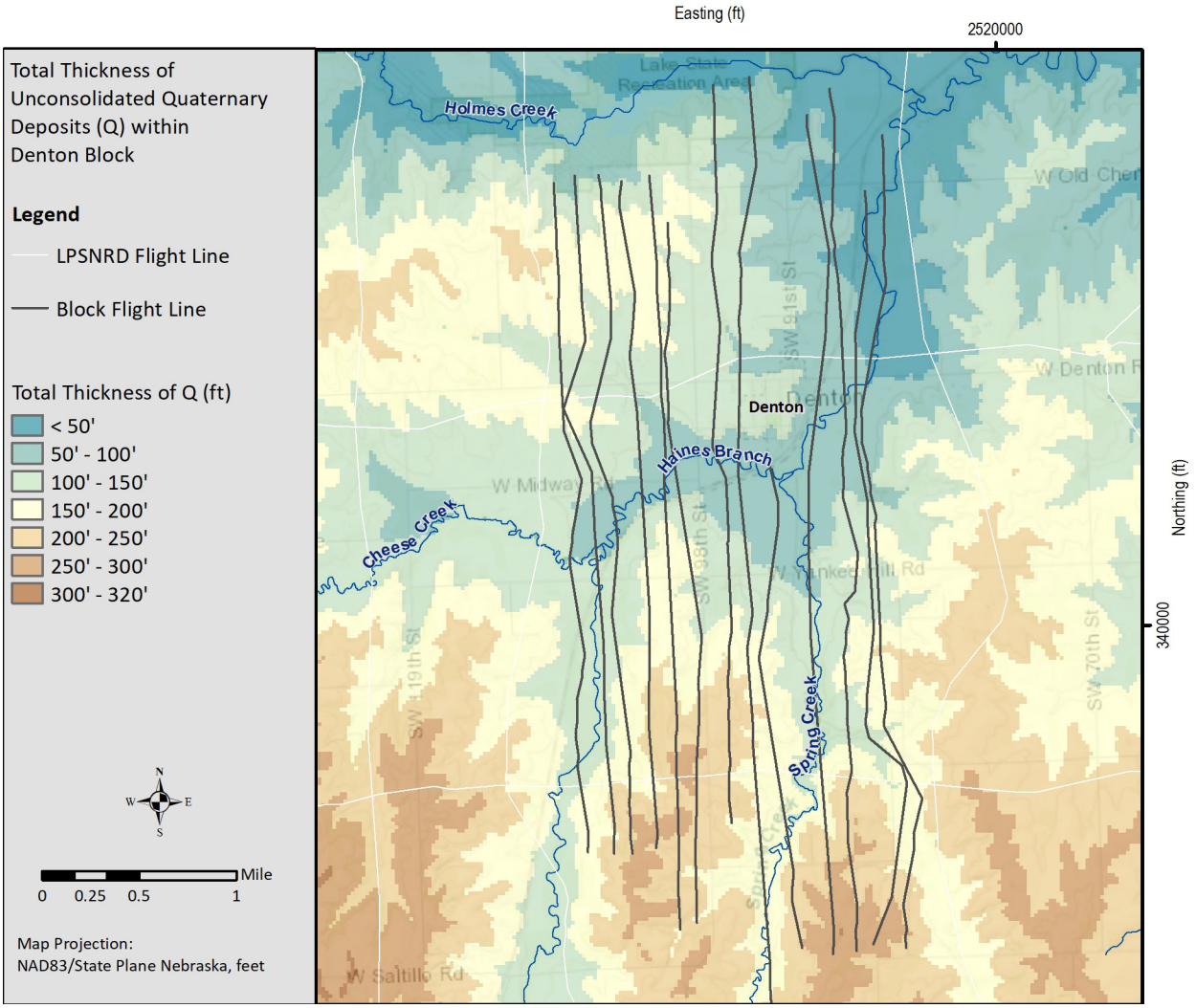


Figure 3-43. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the Denton Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

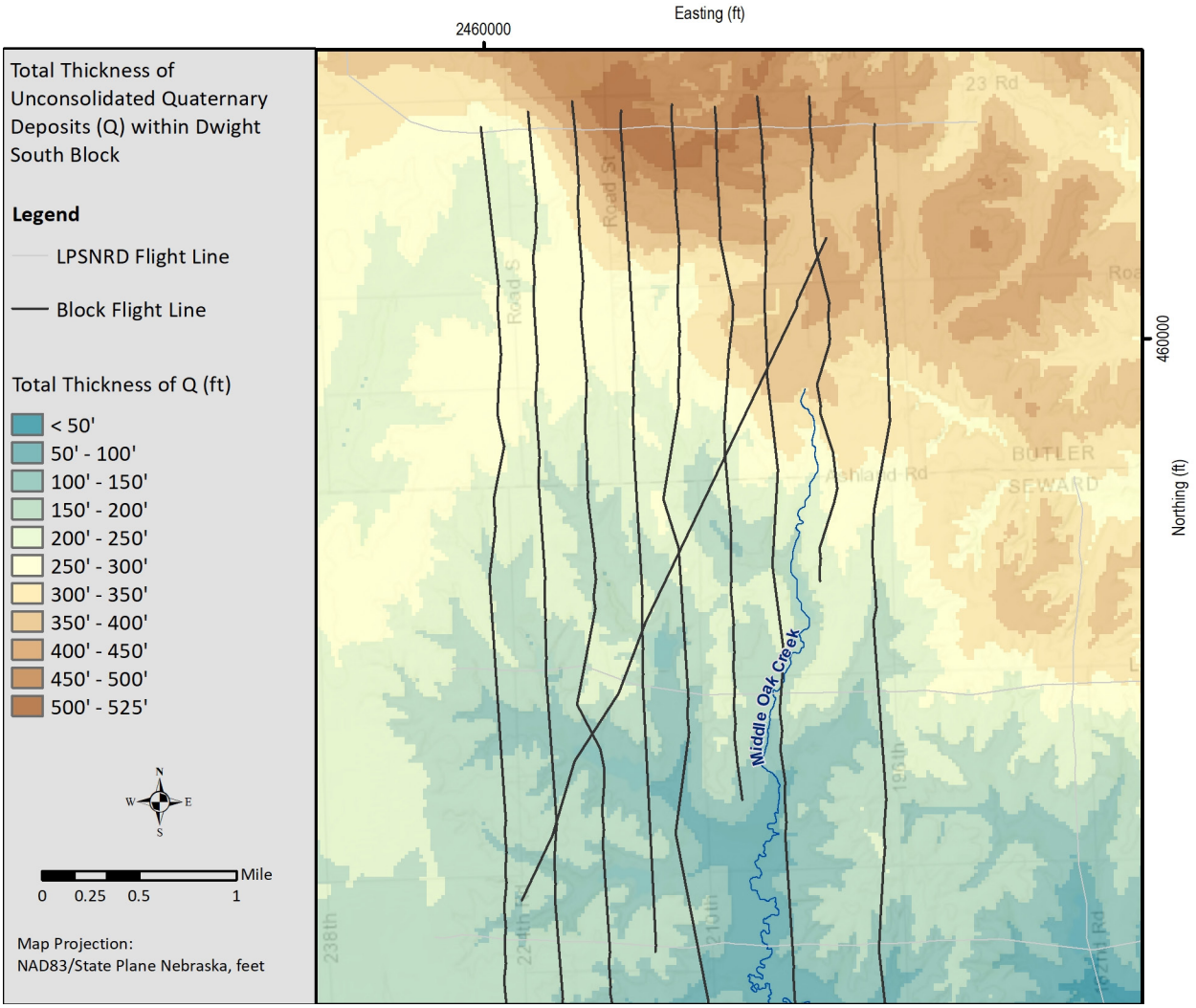


Figure 3-44. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the Dwight South Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

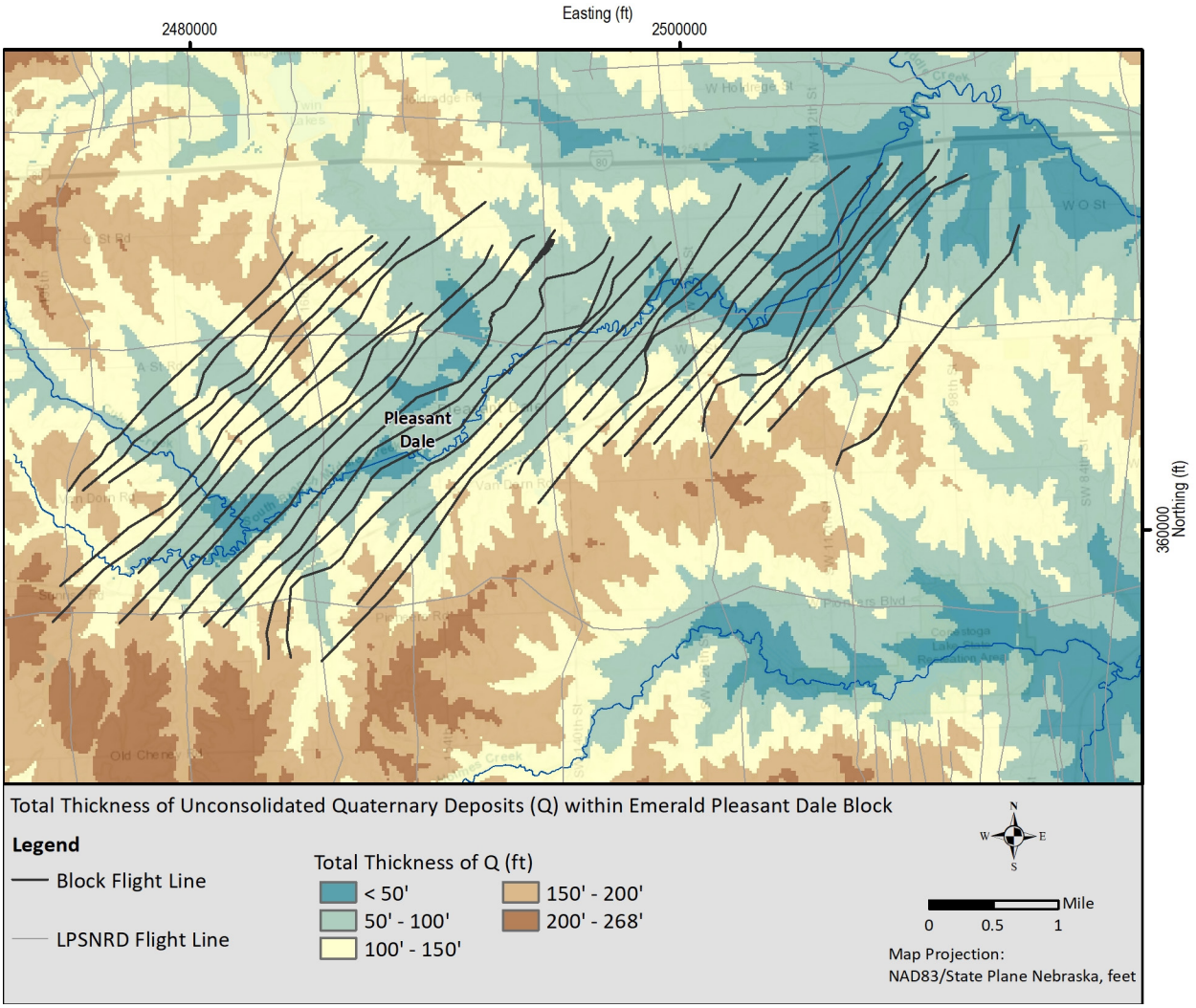


Figure 3-45. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the Emerald Pleasant Dale Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

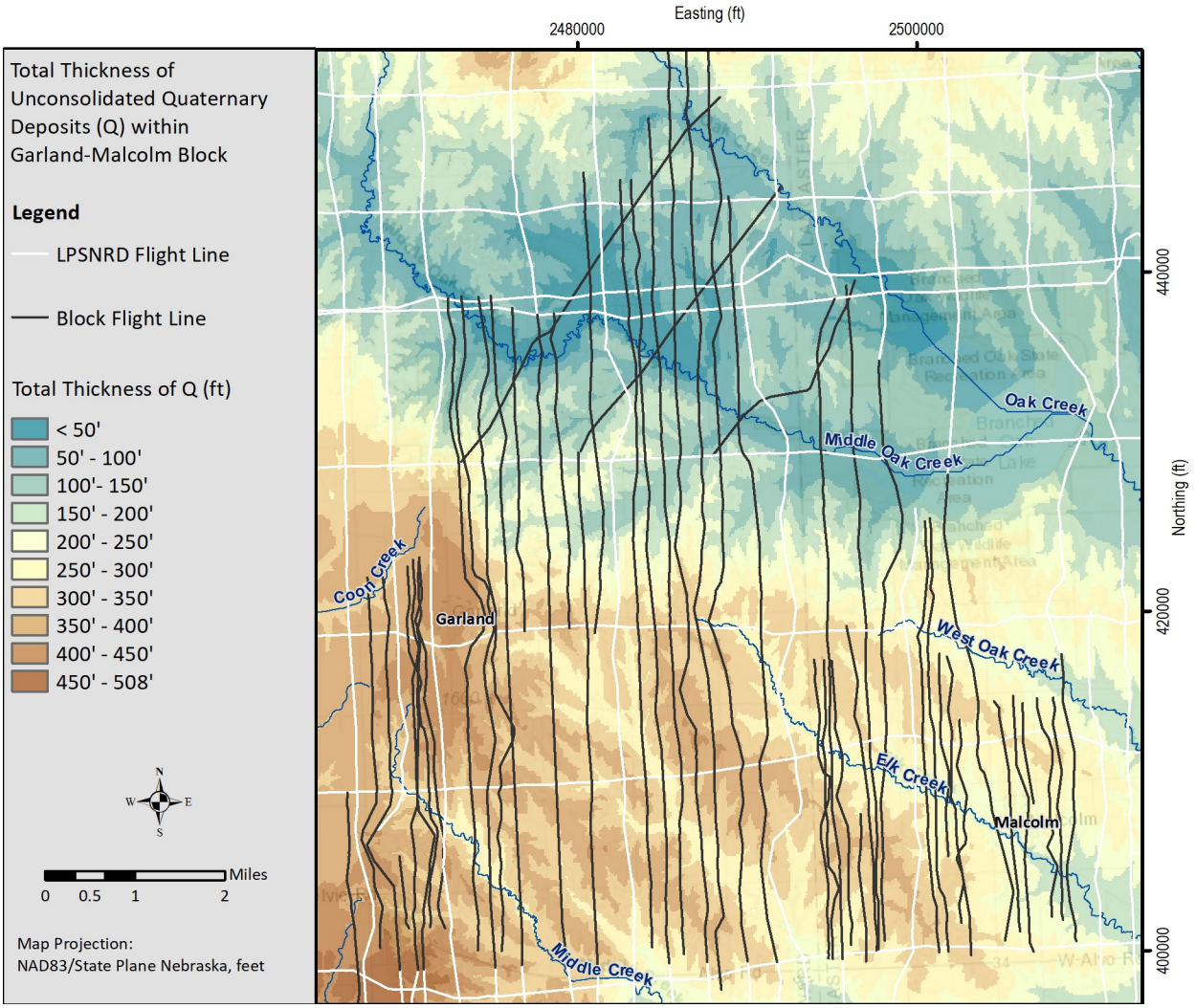


Figure 3-46. Map of the thickness (in feet) of Quaternary (*Q*) deposits within the Garland Malcom Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

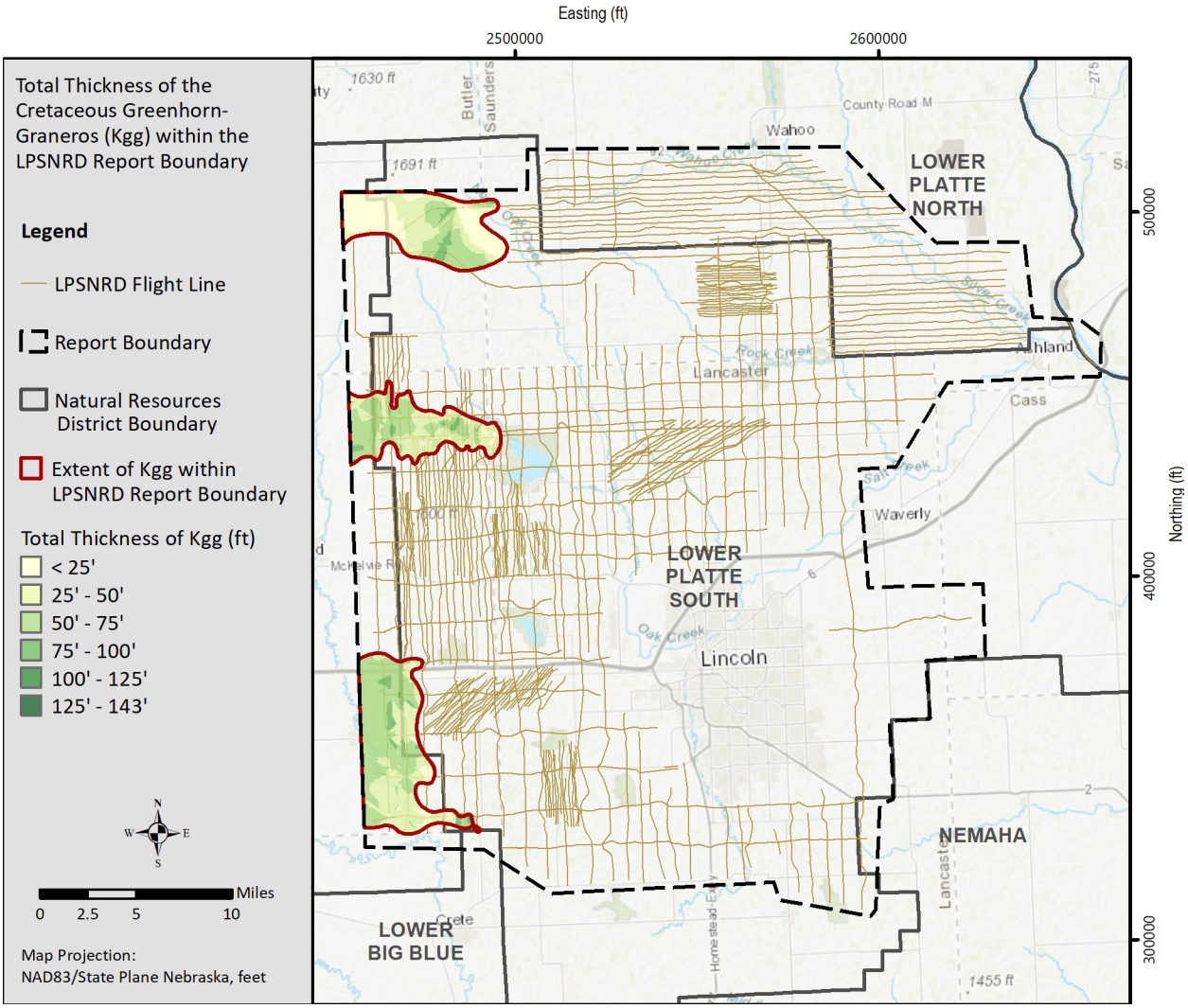


Figure 3-47. Map of the thickness (in feet) of the Greenhorn Limestone/Graneros Shale (*Kgg*) within the LPSNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

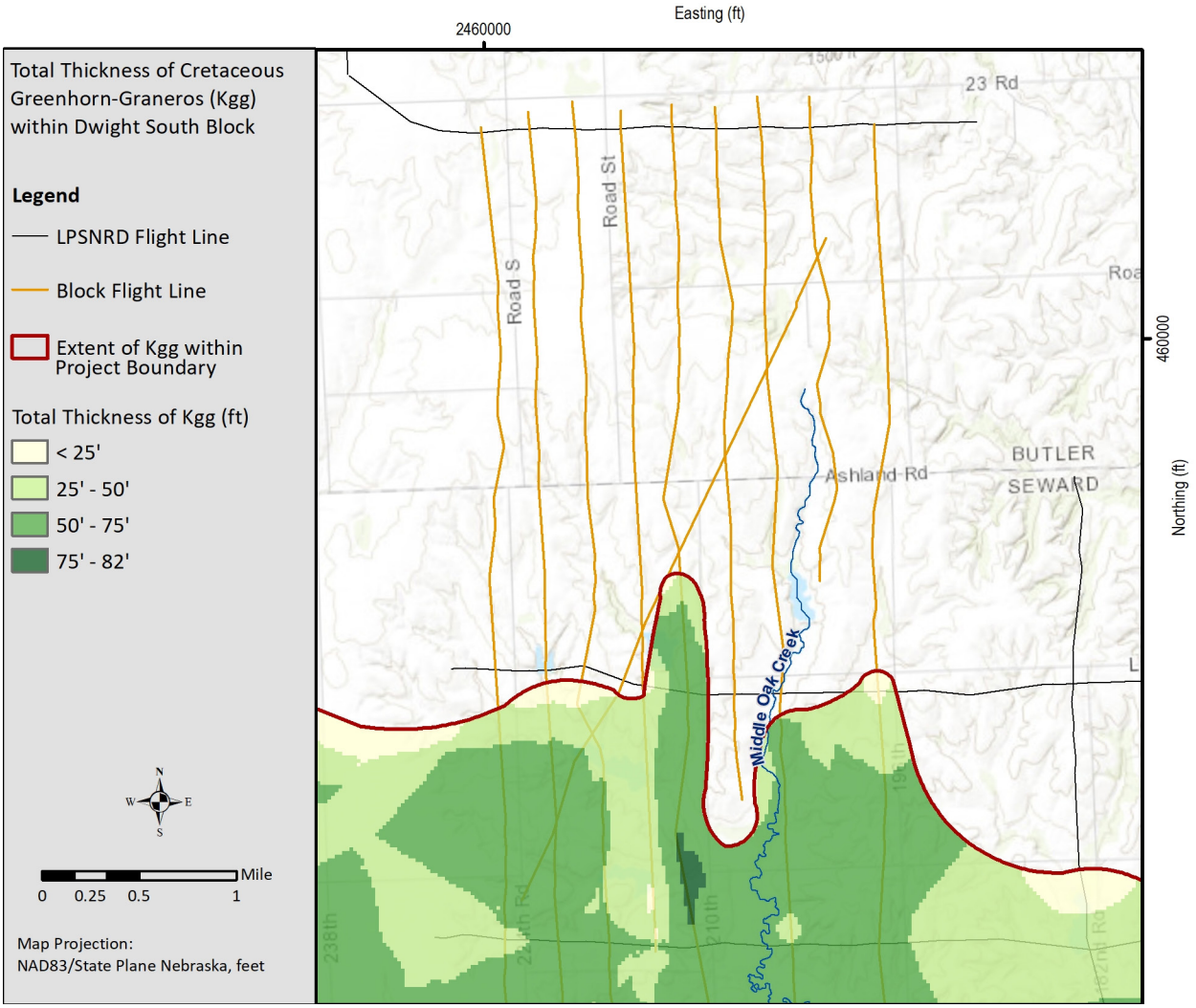


Figure 3-48. Map of the thickness (in feet) of the top of the Greenhorn Limestone/Graneros Shale (*Kgg*) within the Dwight South Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

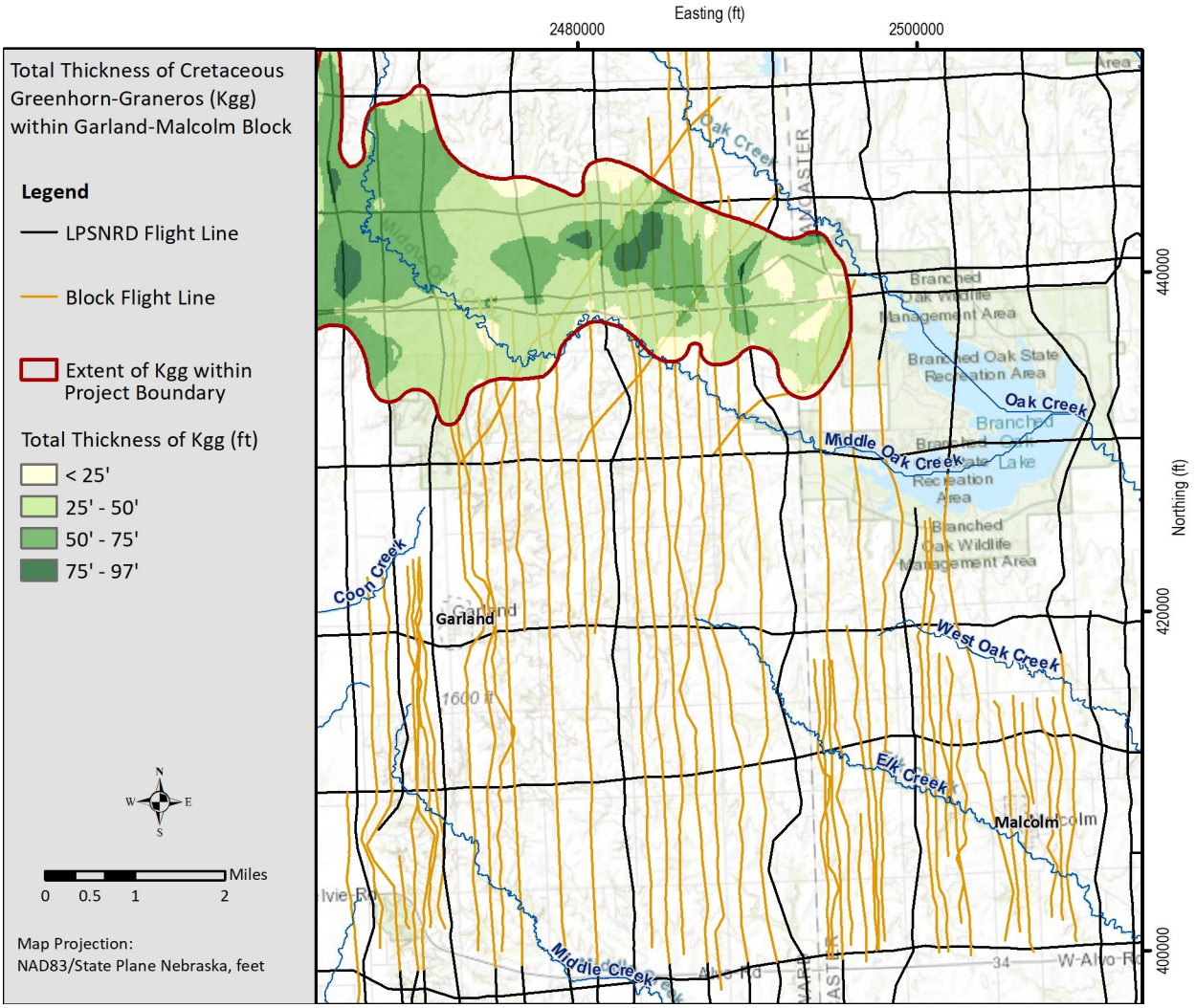


Figure 3-49. Map of the thickness (in feet) of the top of the Greenhorn Limestone/Graneros Shale (*Kgg*) within the Garland Malcolm Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

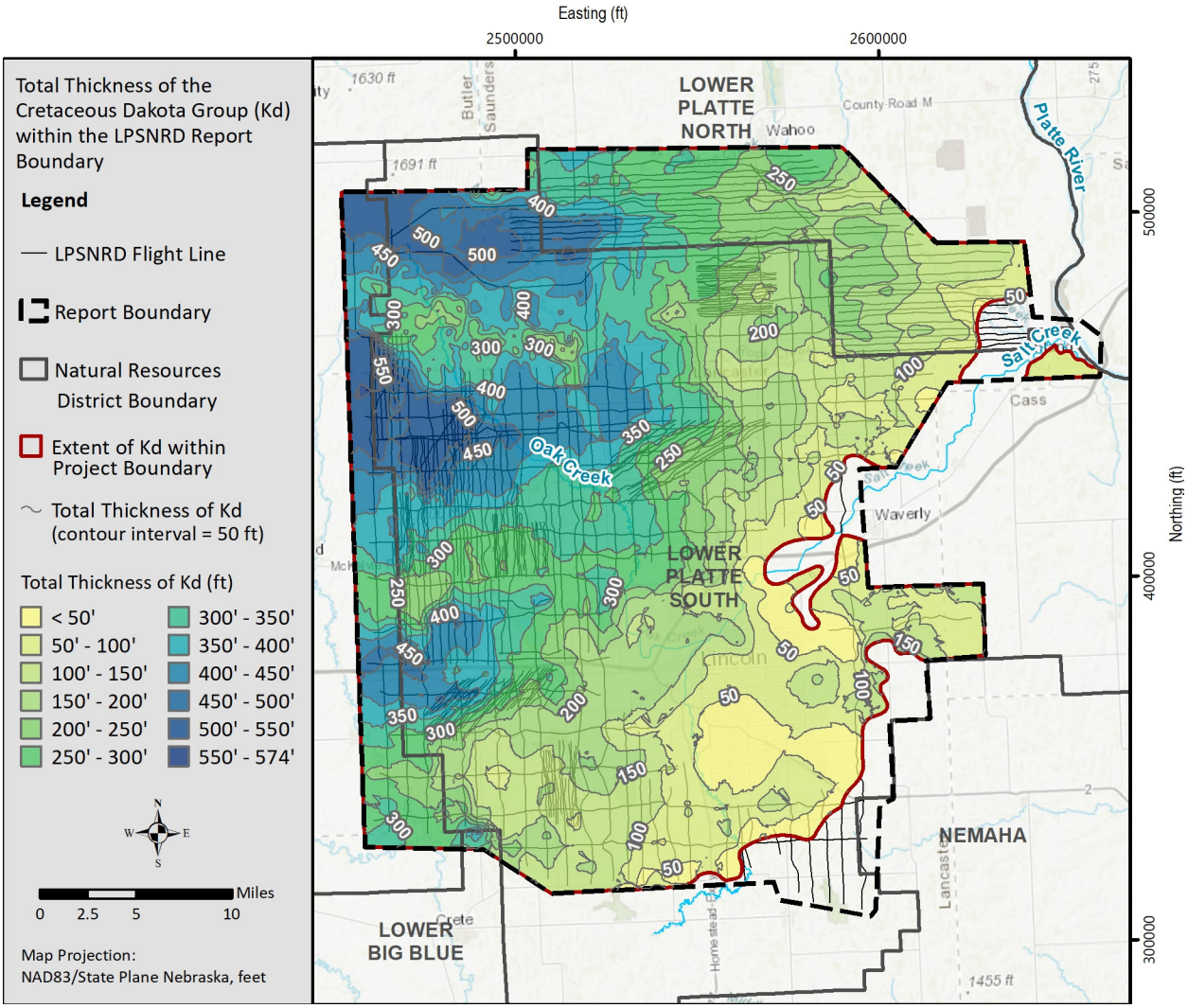


Figure 3-50. Map of the thickness (in feet) of the Cretaceous Dakota Group (*Kd*) within the LPSNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

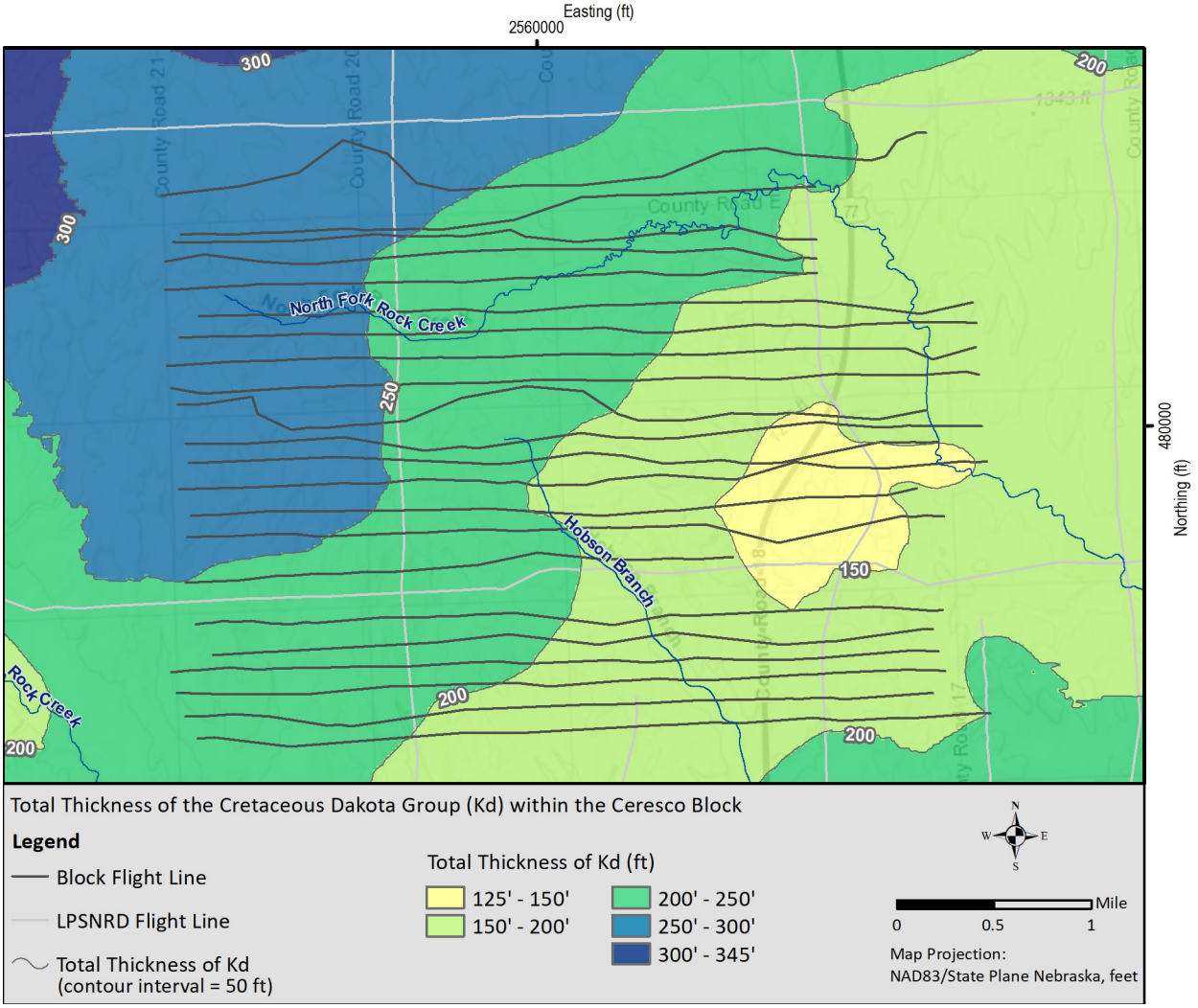


Figure 3-51. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the Ceresco Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

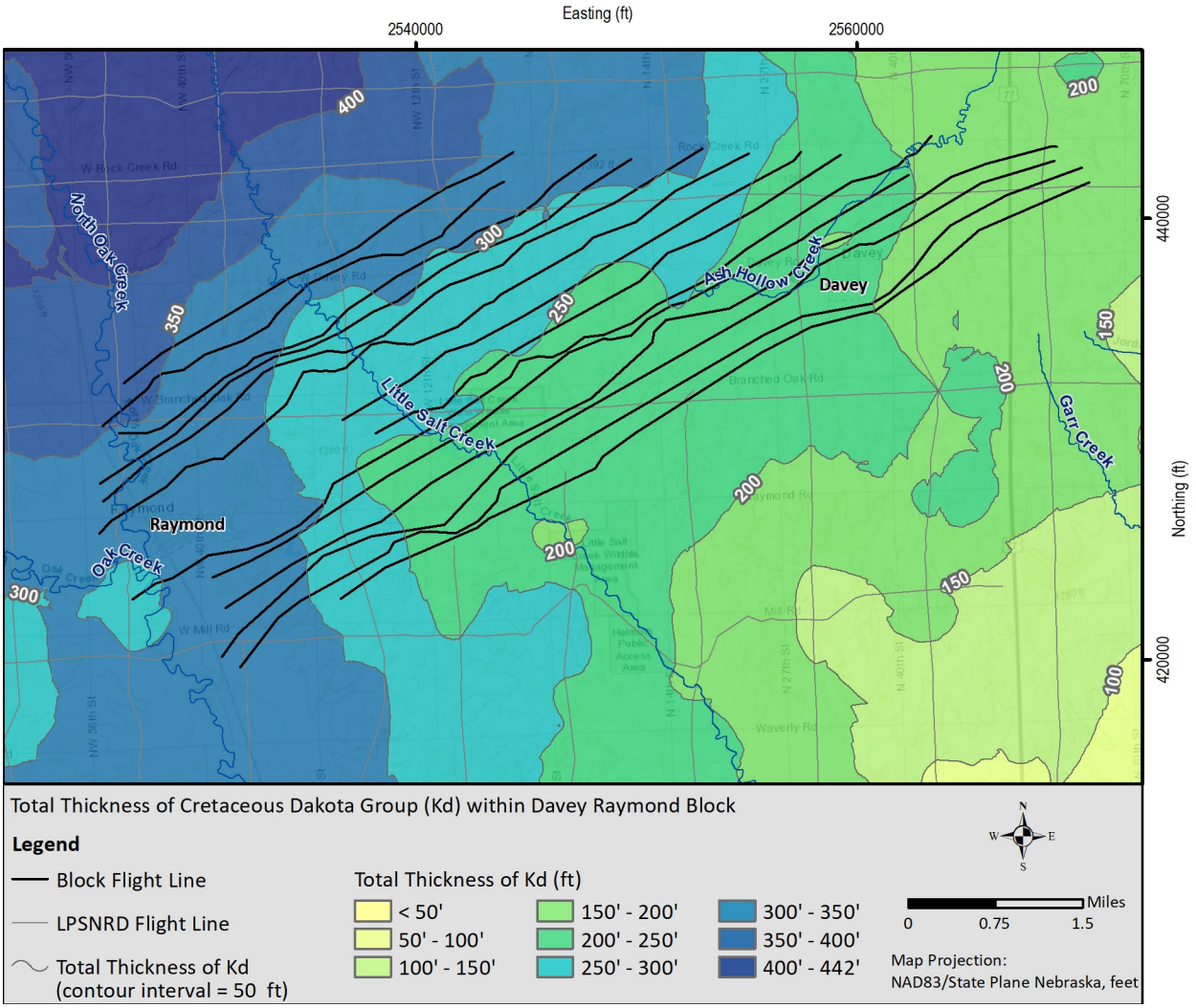


Figure 3-52. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the Davey Raymond Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

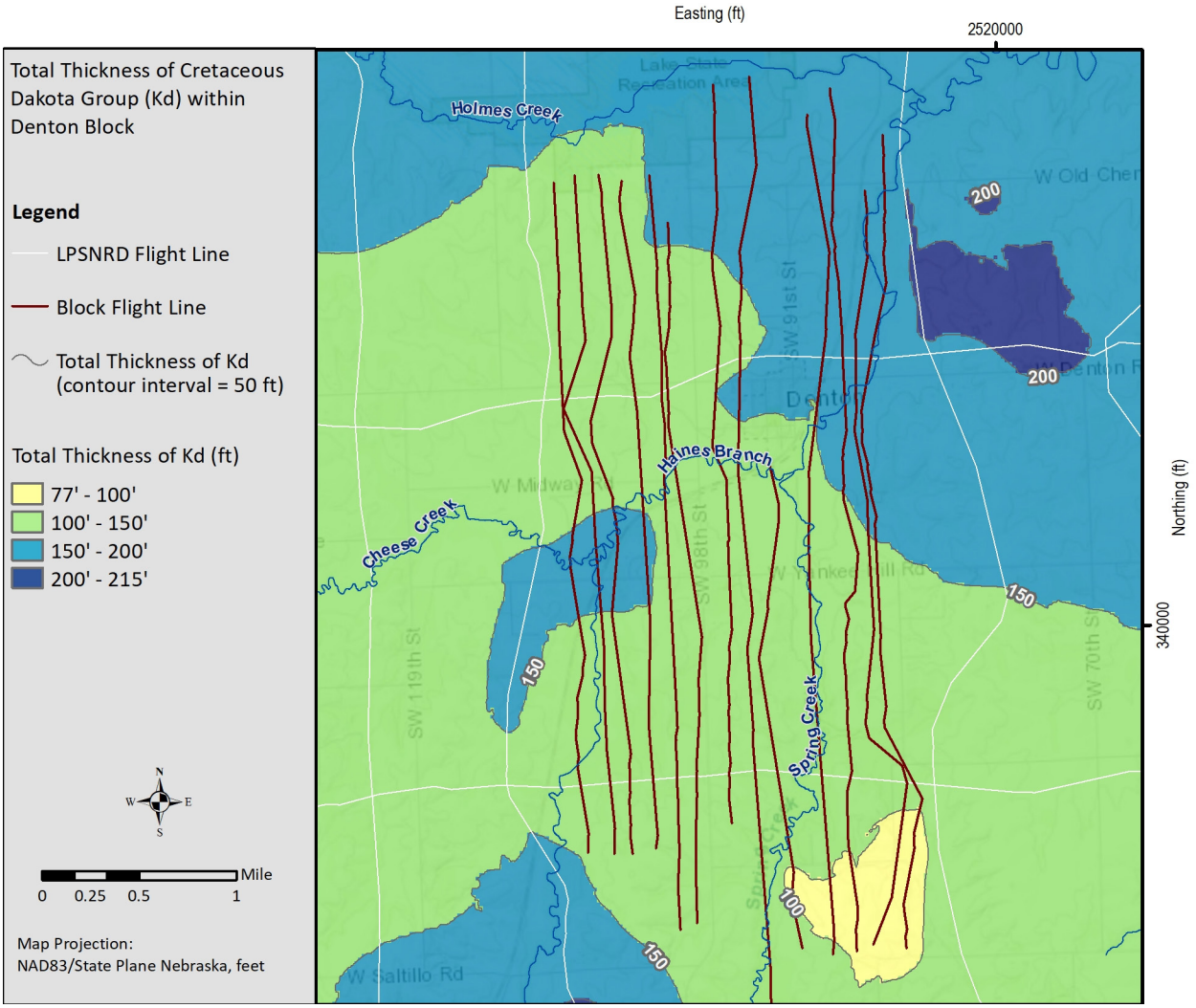


Figure 3-53. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the Denton Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

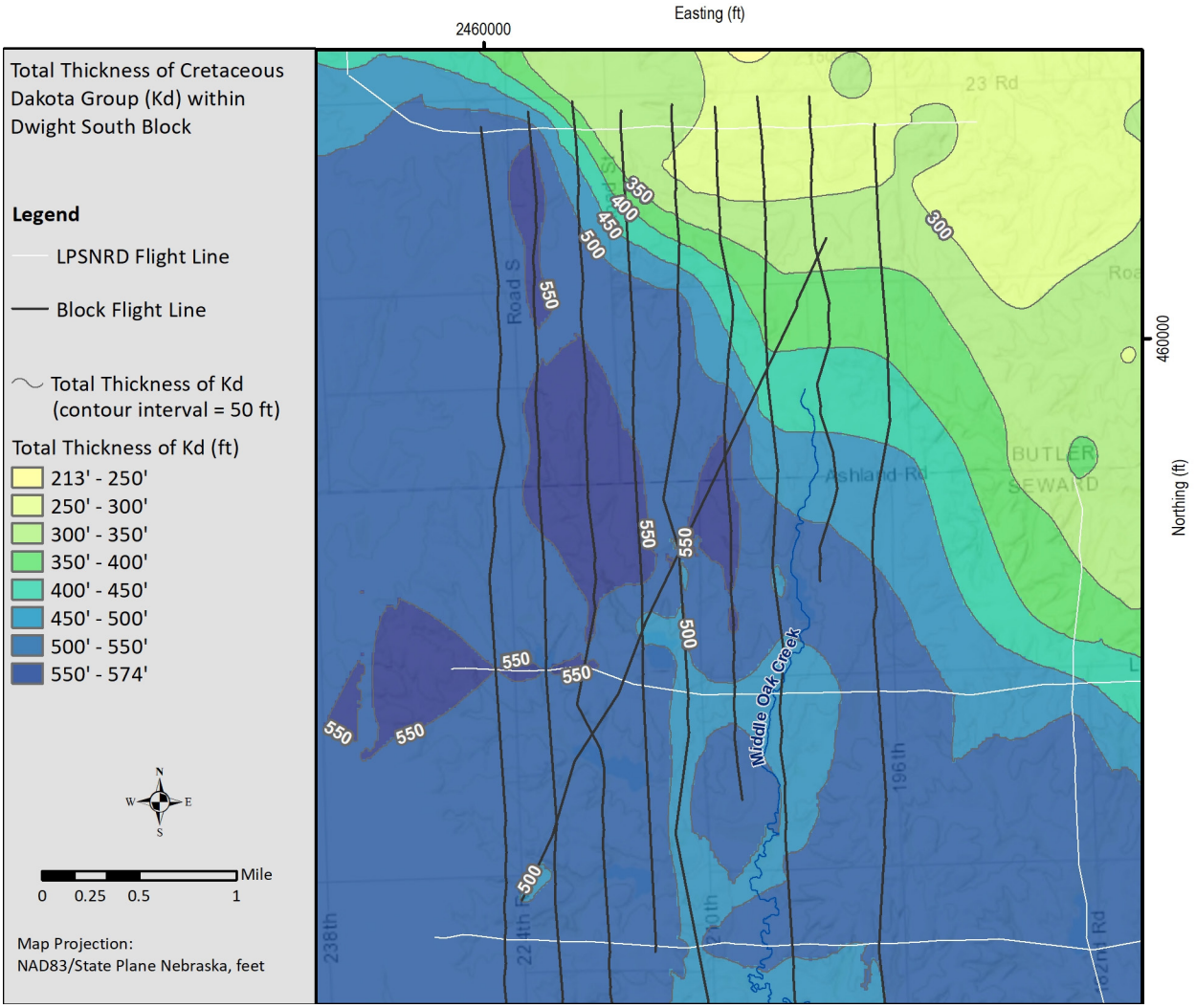


Figure 3-54. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the Dwight South Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

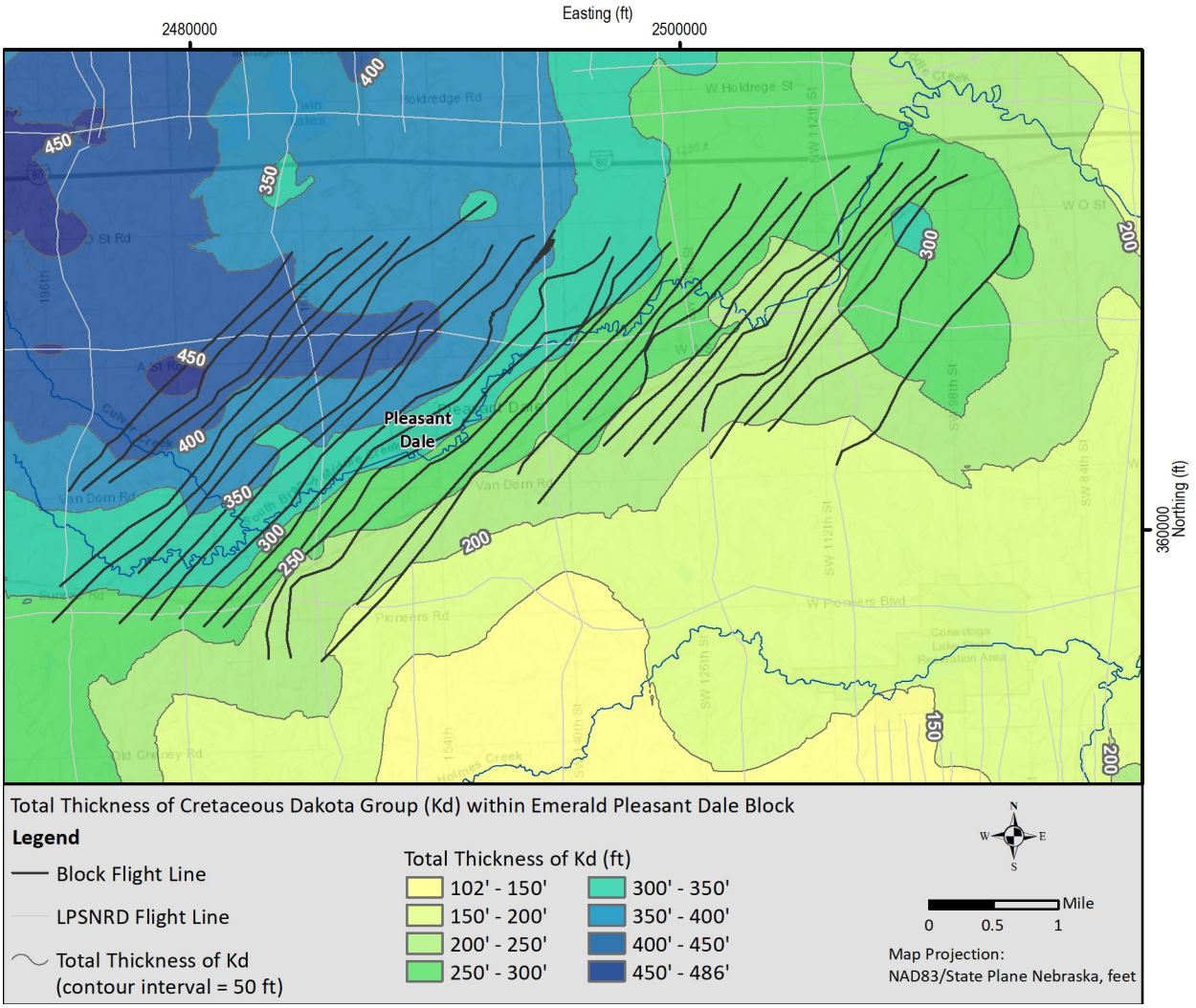


Figure 3-55. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the Emerald Pleasant Dale Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

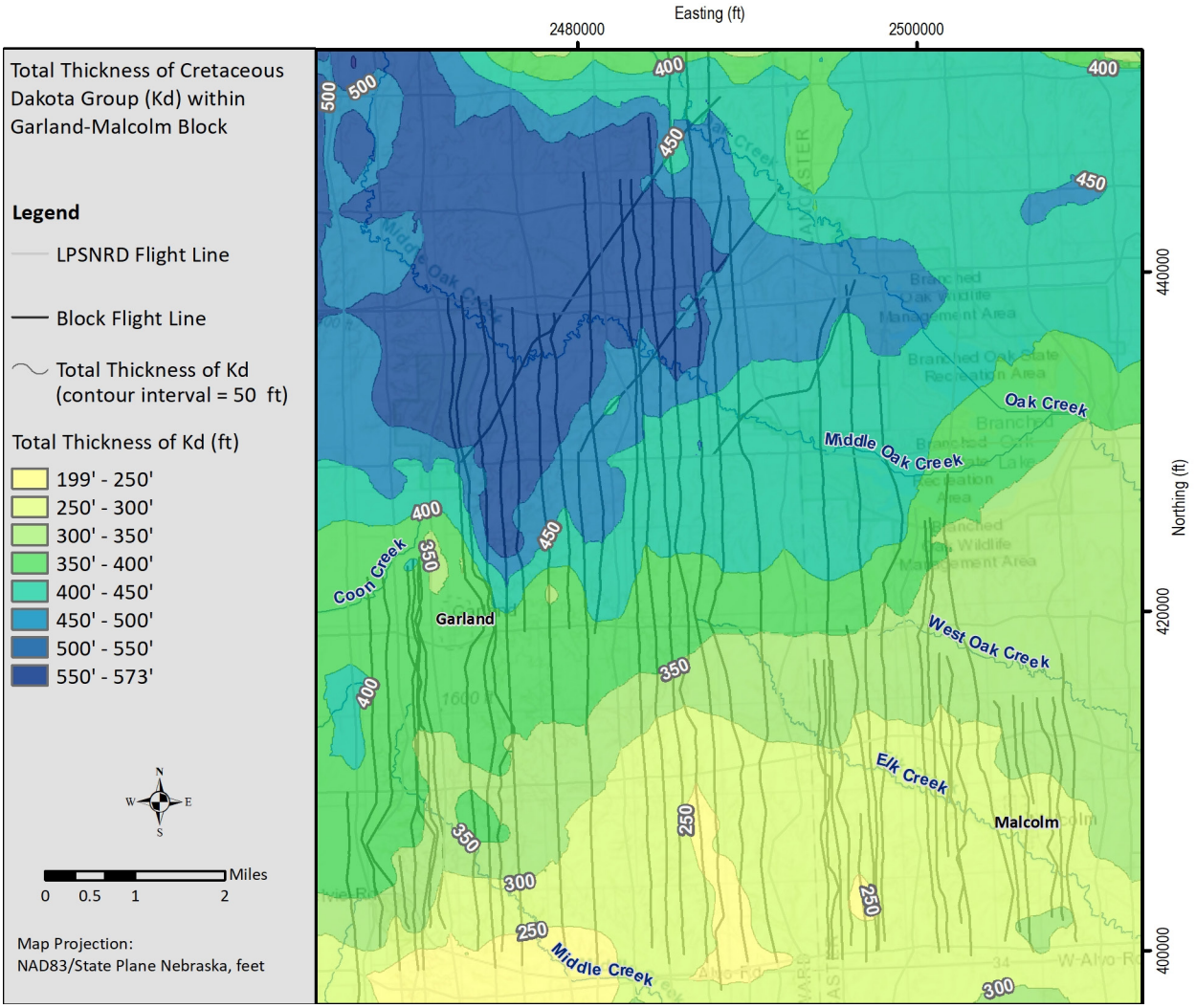


Figure 3-56. Map of the thickness (in feet) of the top of the Cretaceous Dakota Group (*Kd*) within the Garland Malcolm Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

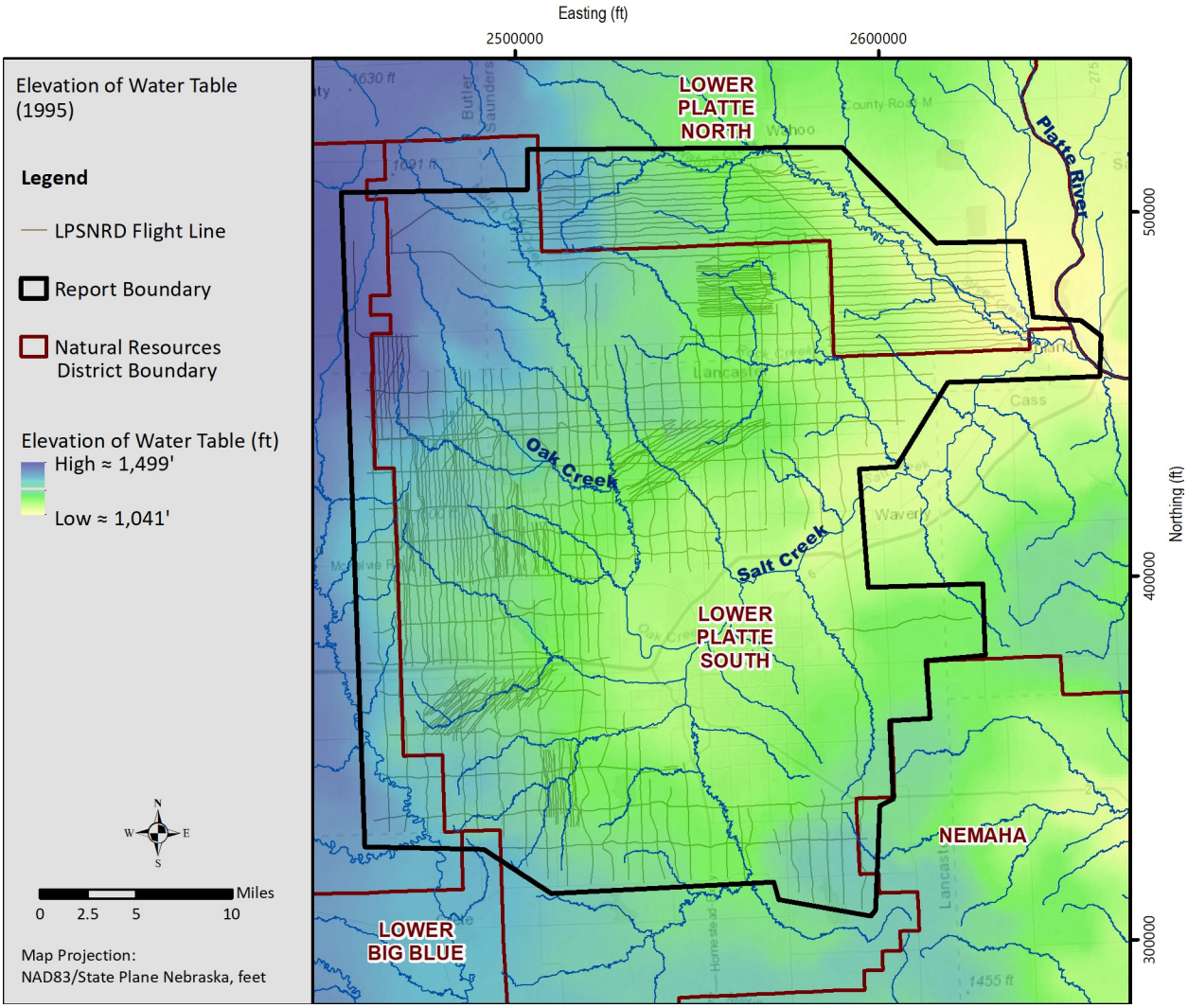


Figure 3-57. Map of the elevation (in feet) of the 1995 CSD water table within the 2018 LPSNRD AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

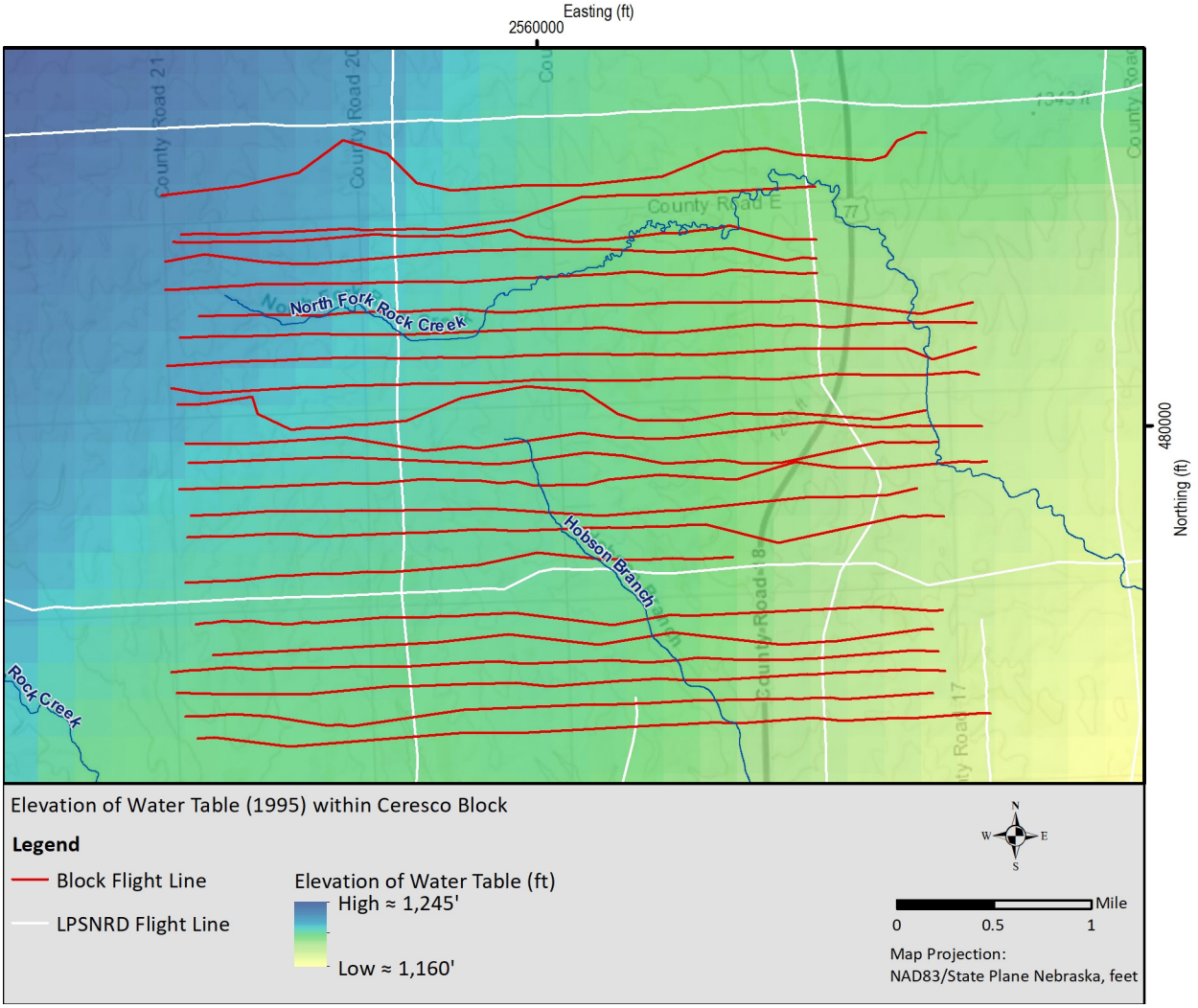


Figure 3-58. Map of the elevation (in feet) of the 1995 CSD water table within the Ceresco Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

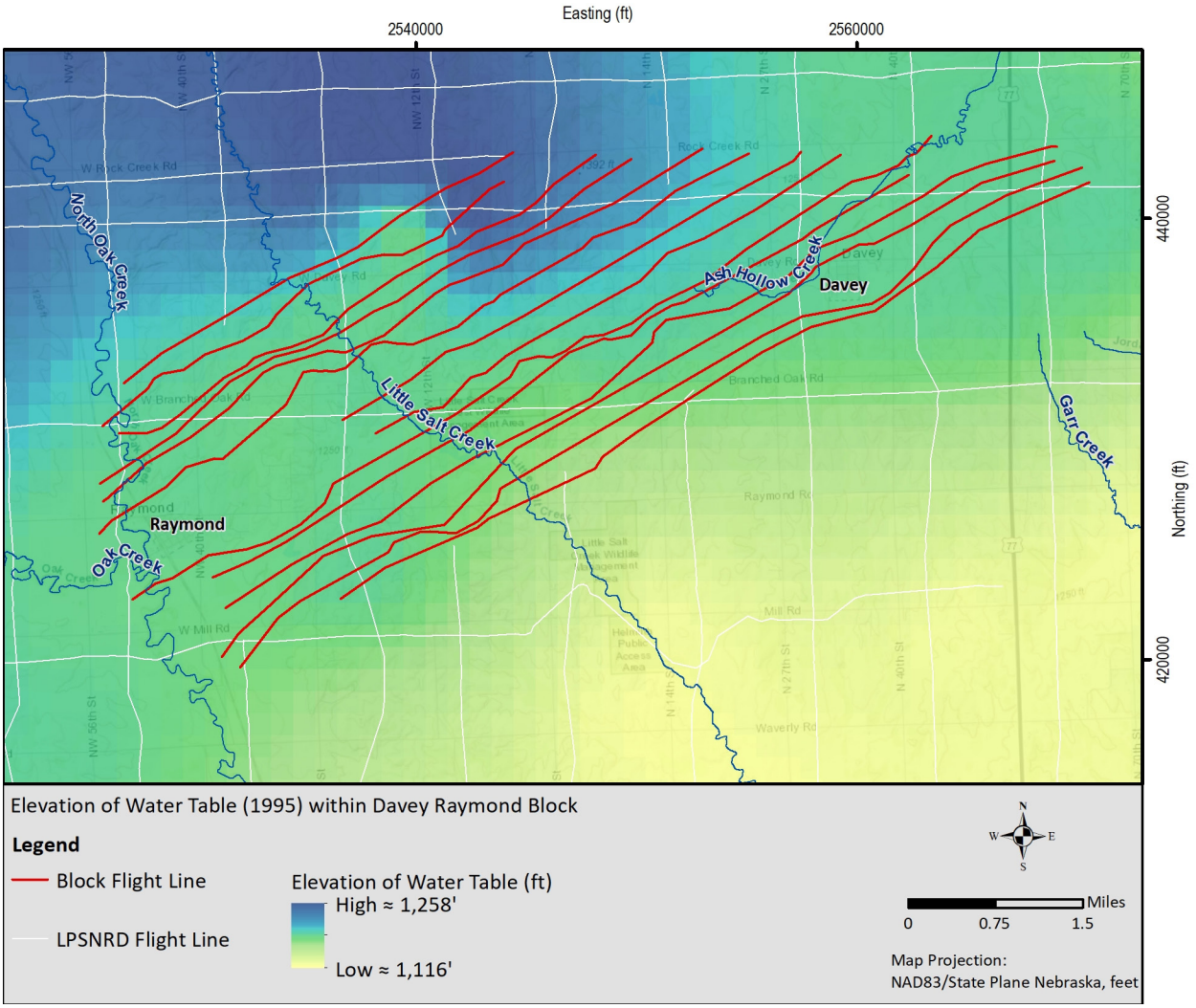


Figure 3-59. Map of the elevation (in feet) of the 1995 CSD water table within the Davey Raymond Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

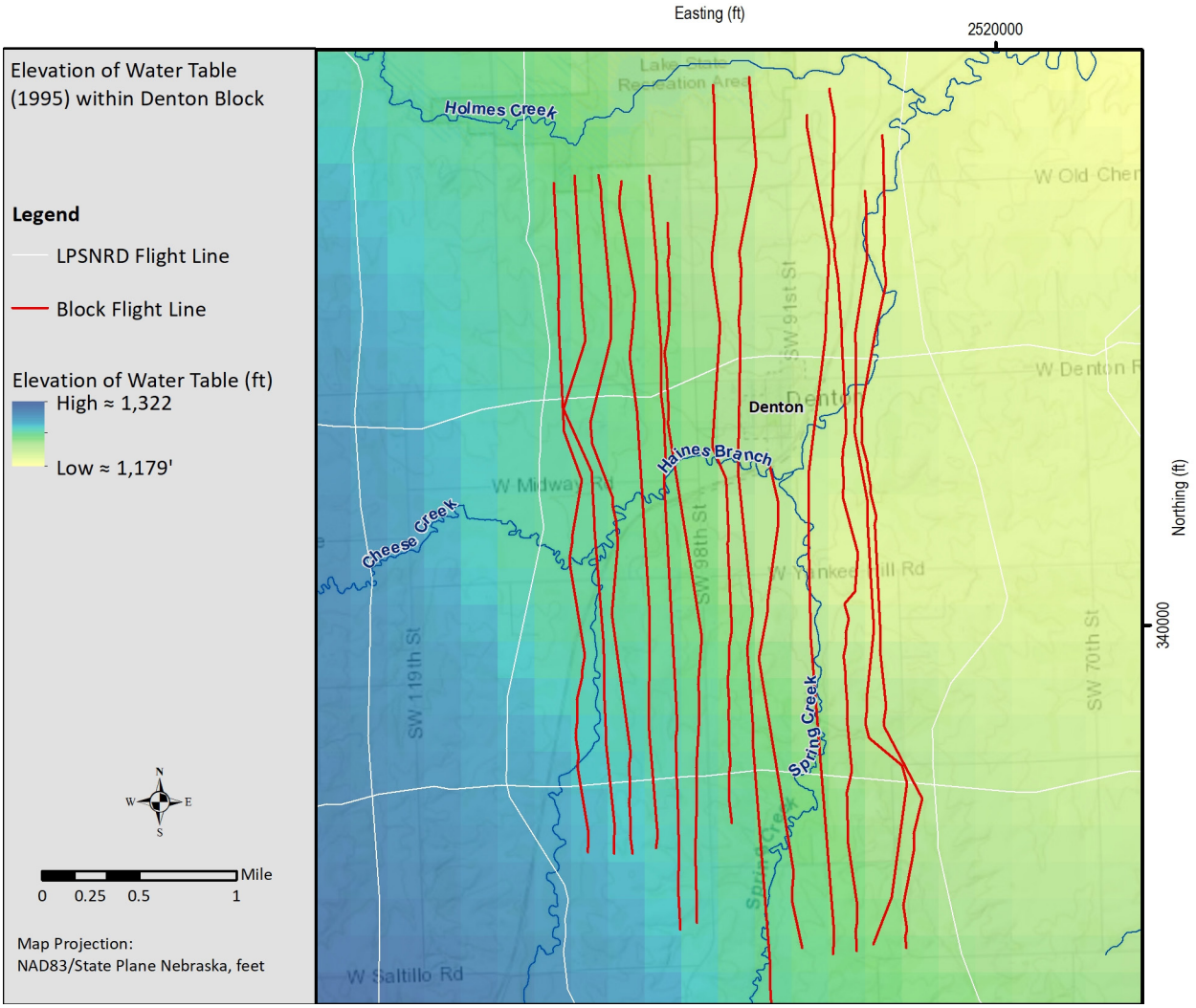


Figure 3-60. Map of the elevation (in feet) of the 1995 CSD water table within the Denton Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

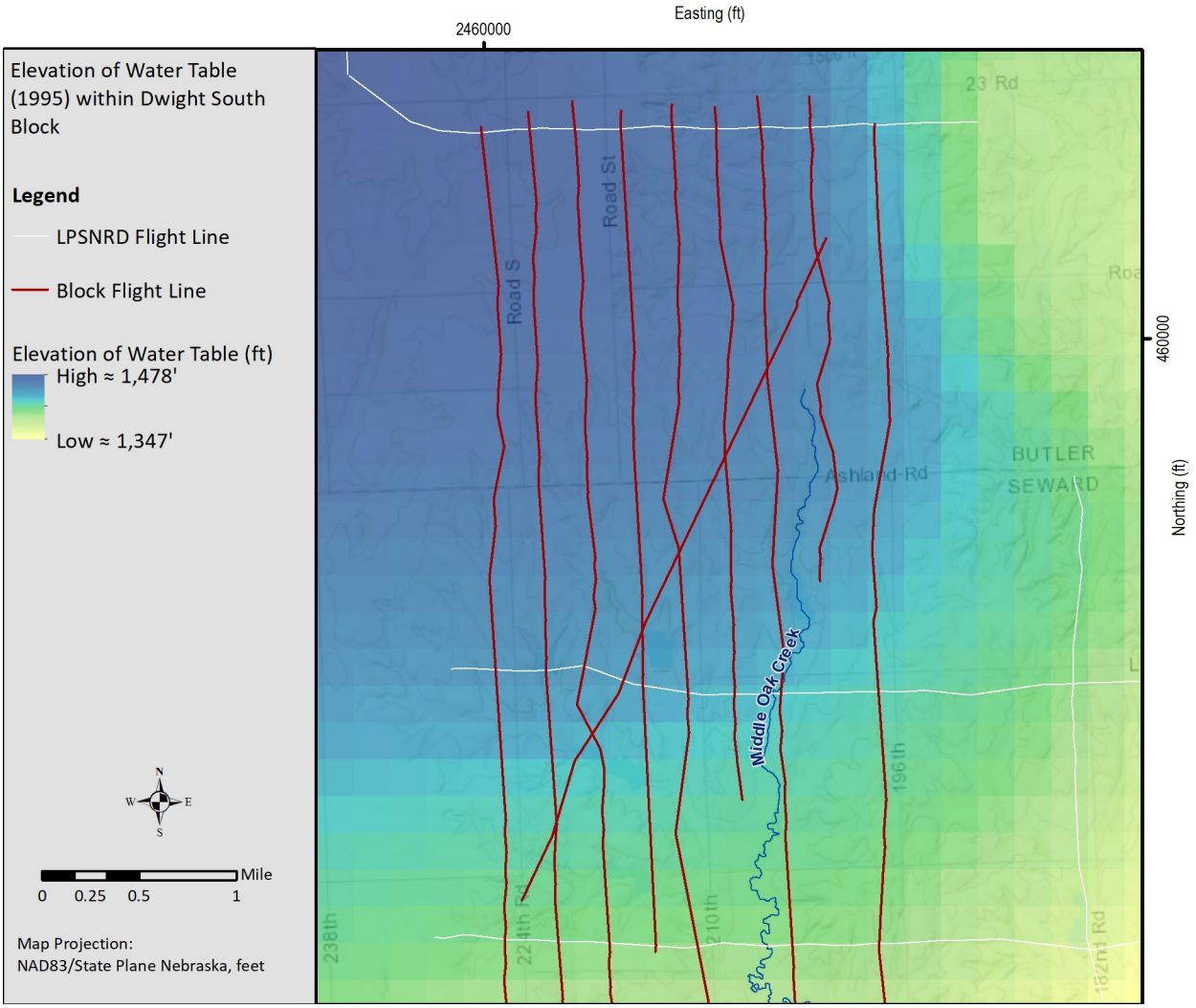


Figure 3-61. Map of the elevation (in feet) of the 1995 CSD water table within the Dwight South Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

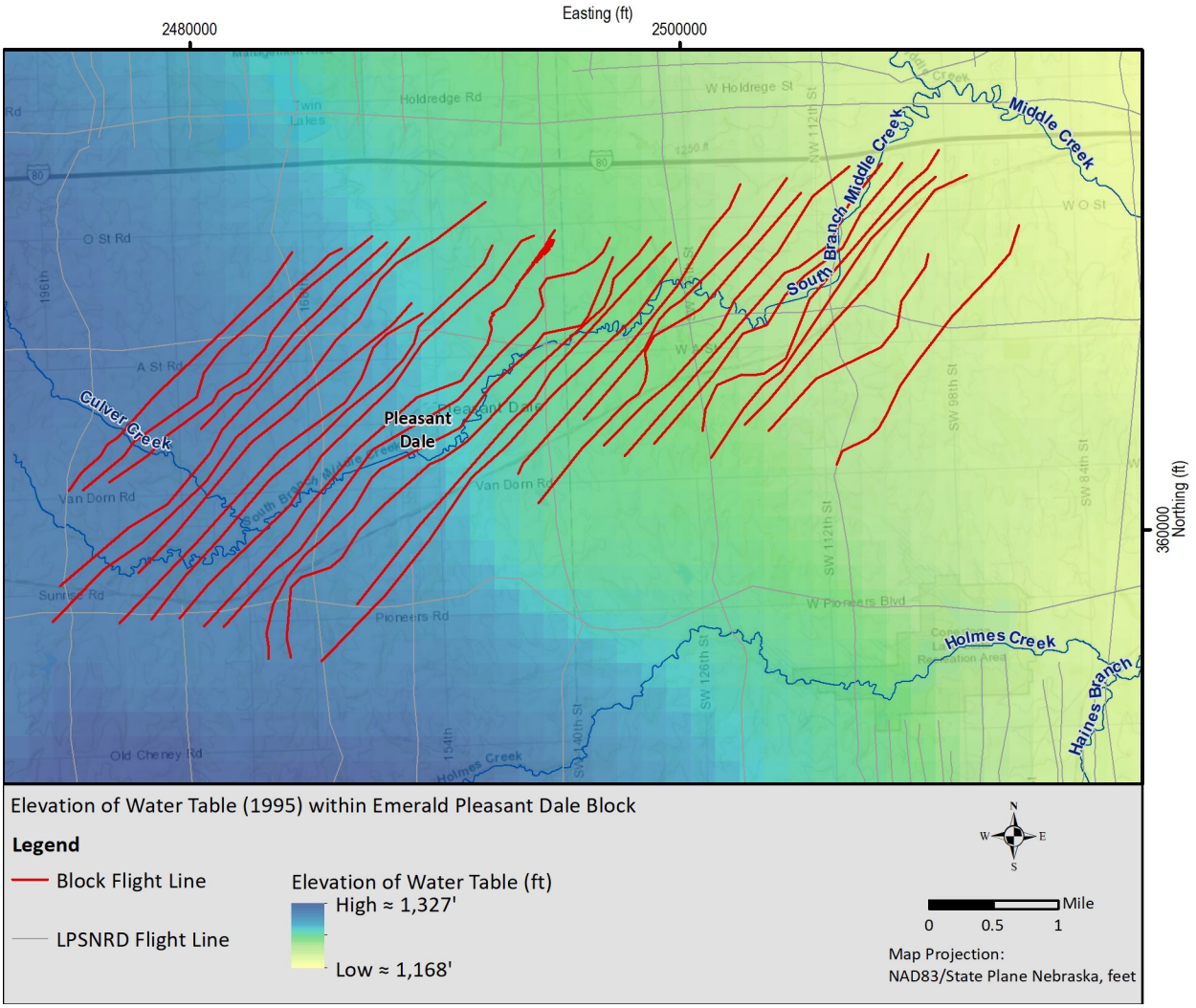


Figure 3-62. Map of the elevation (in feet) of the 1995 CSD water table within the Emerald Pleasant Dale Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

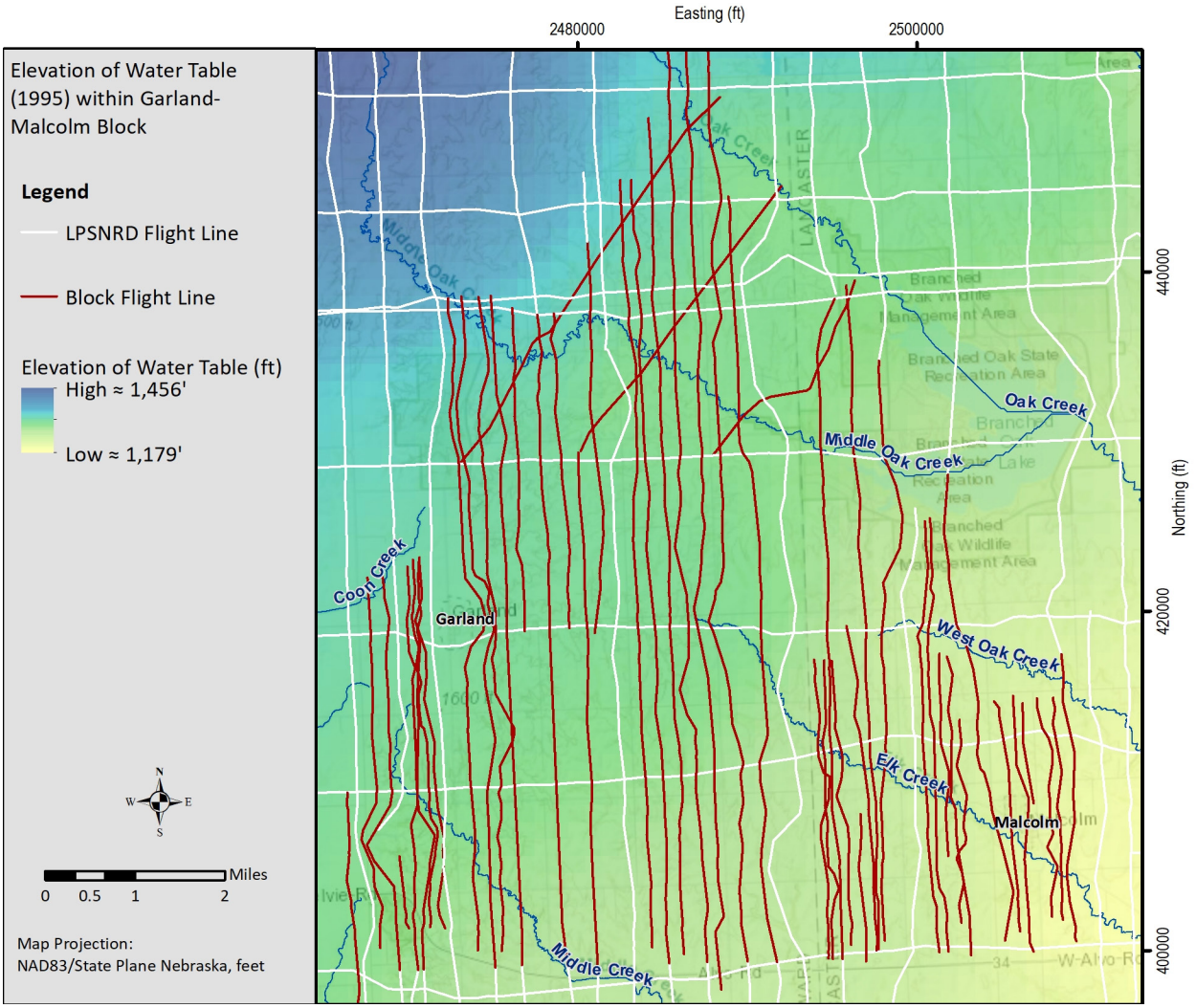


Figure 3-63. Map of the elevation (in feet) of the 1995 CSD water table within the Garland Malcolm Block AEM survey area. The projection is NAD83 State Plane Nebraska (feet).

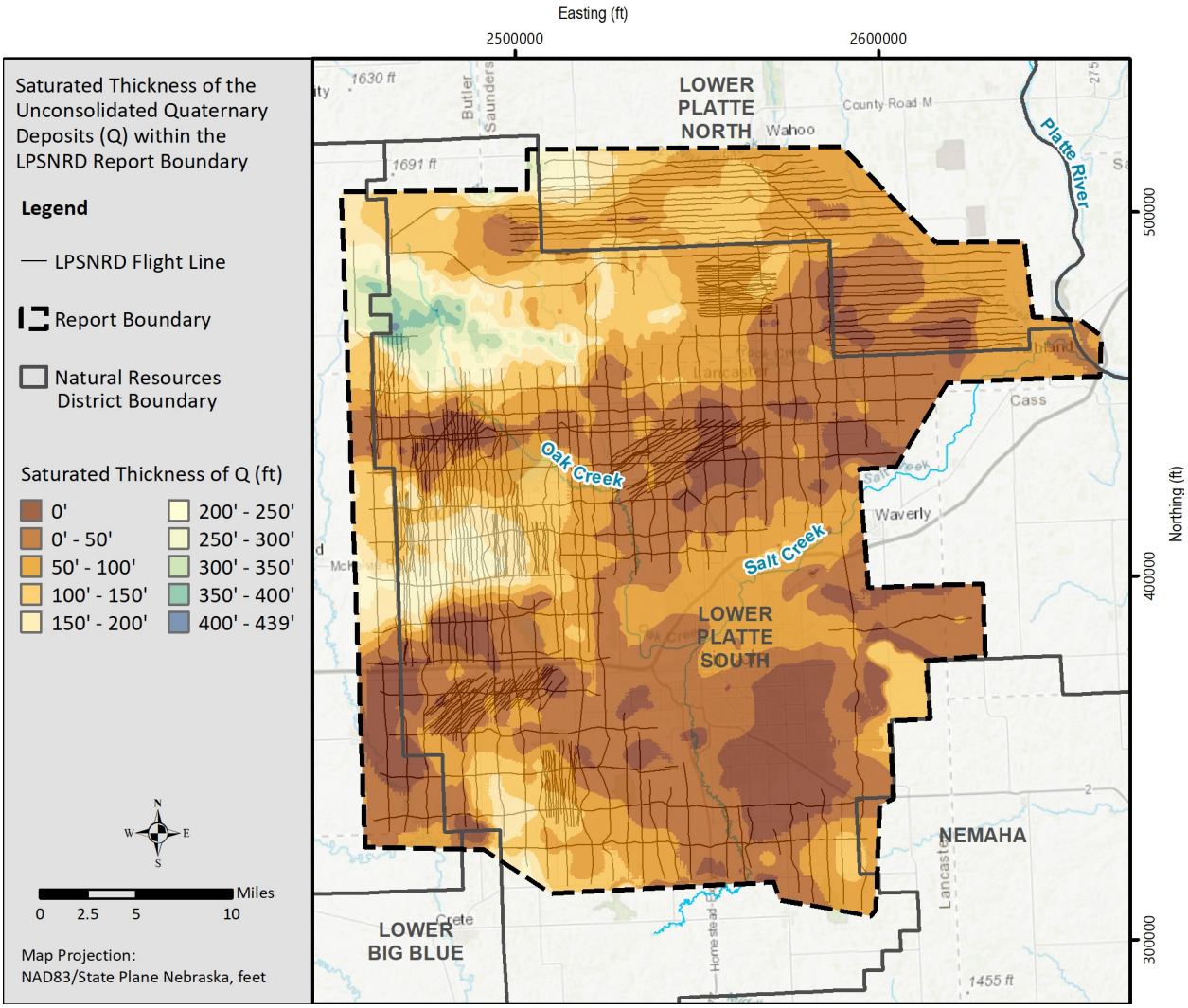


Figure 3-64. Map of the saturated thickness of Quaternary (*Q*) materials within the 2018 LPSNRD AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

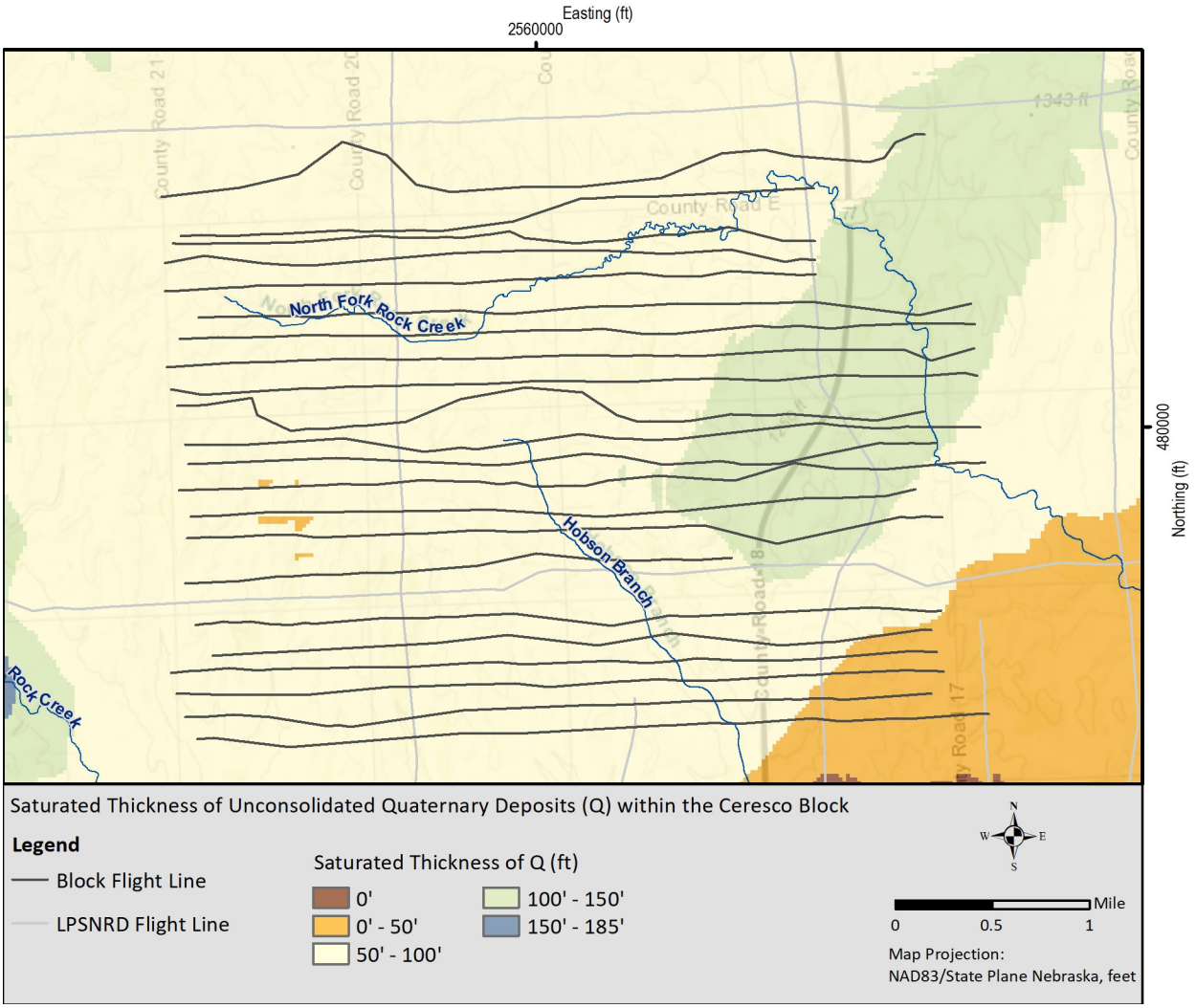


Figure 3-65. Map of the saturated thickness of Quaternary (*Q*) materials within the Ceresco Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

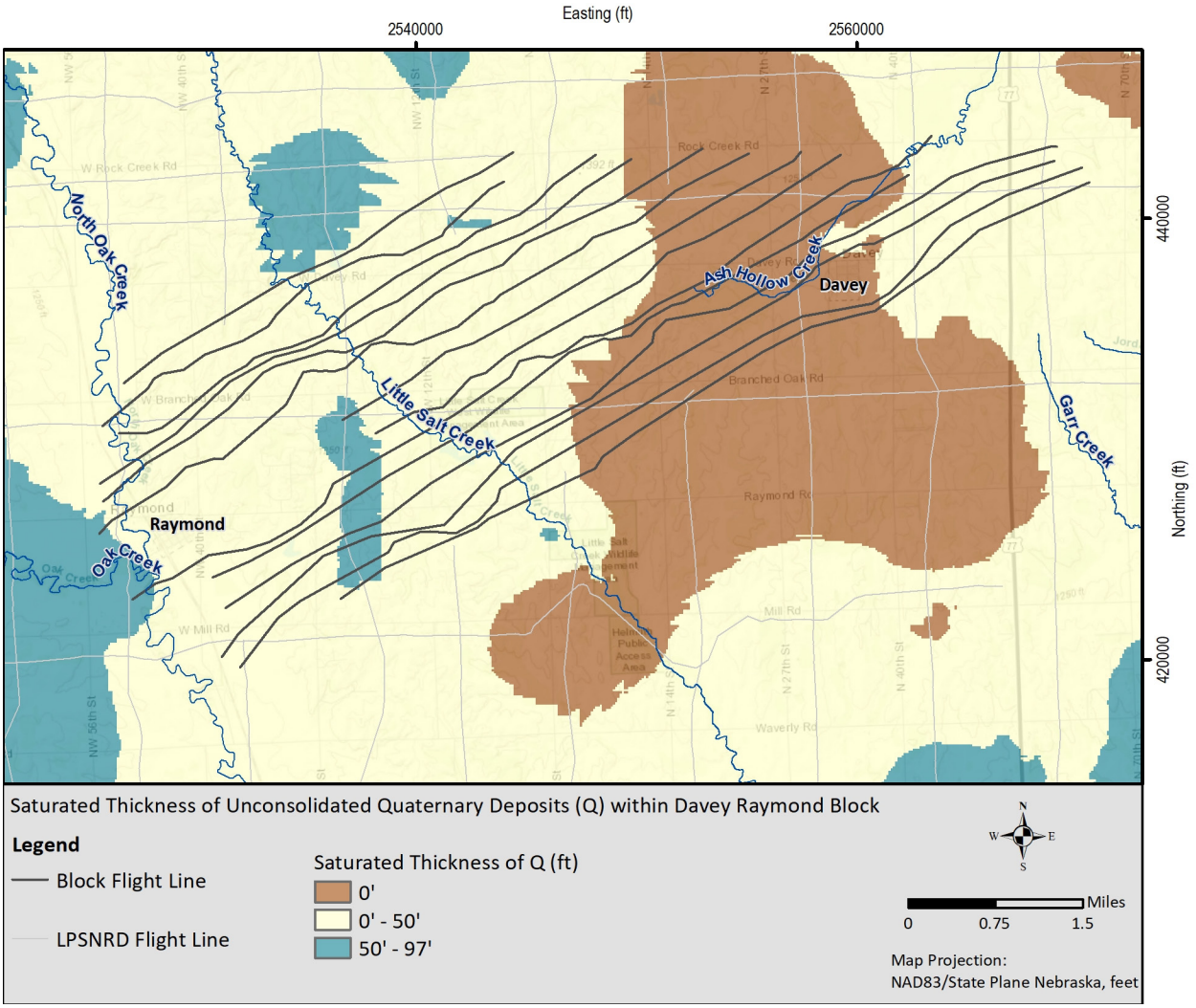


Figure 3-66. Map of the saturated thickness of Quaternary (*Q*) materials within the Davey Raymond Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

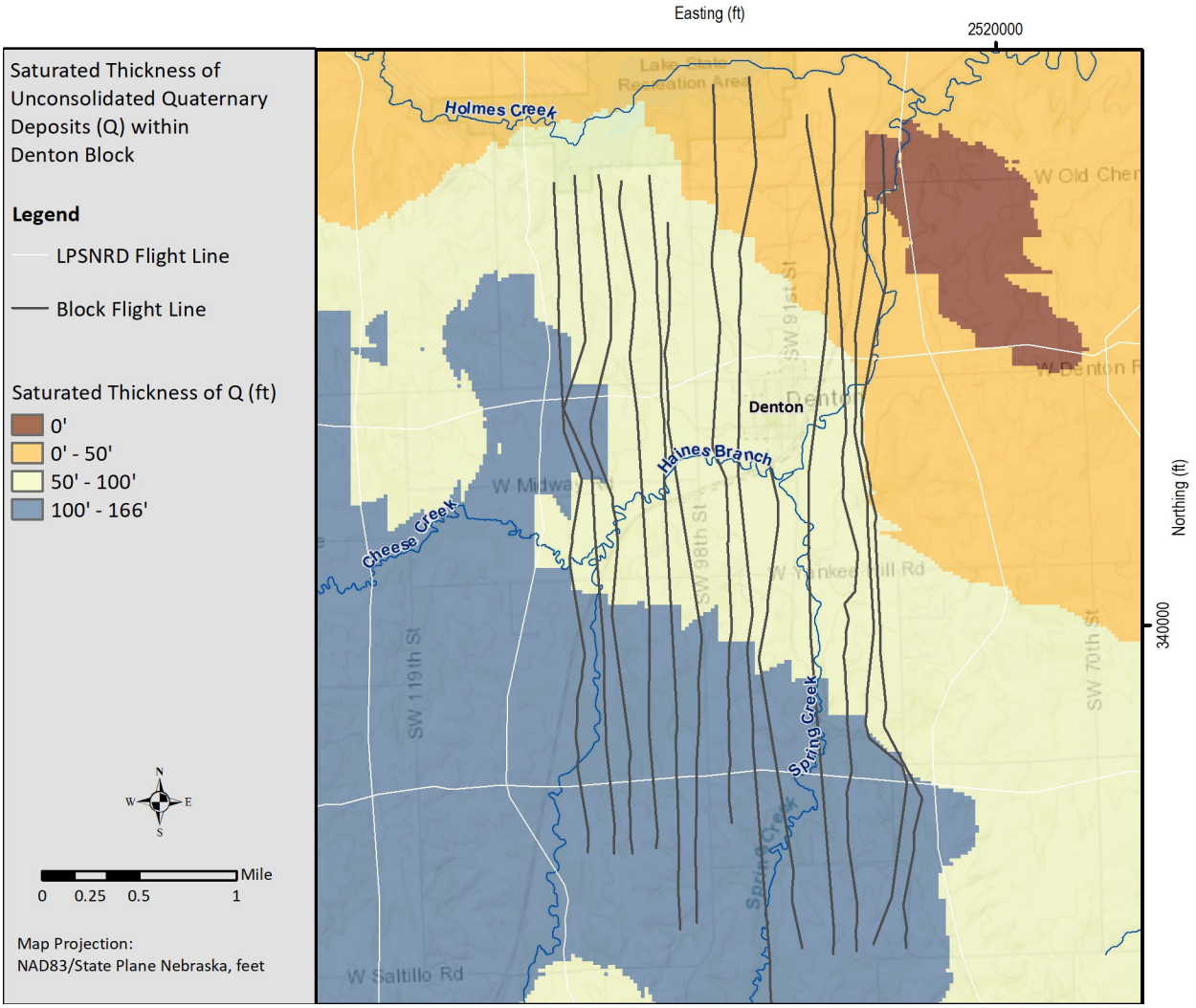


Figure 3-67. Map of the saturated thickness of Quaternary (*Q*) materials within the Denton Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

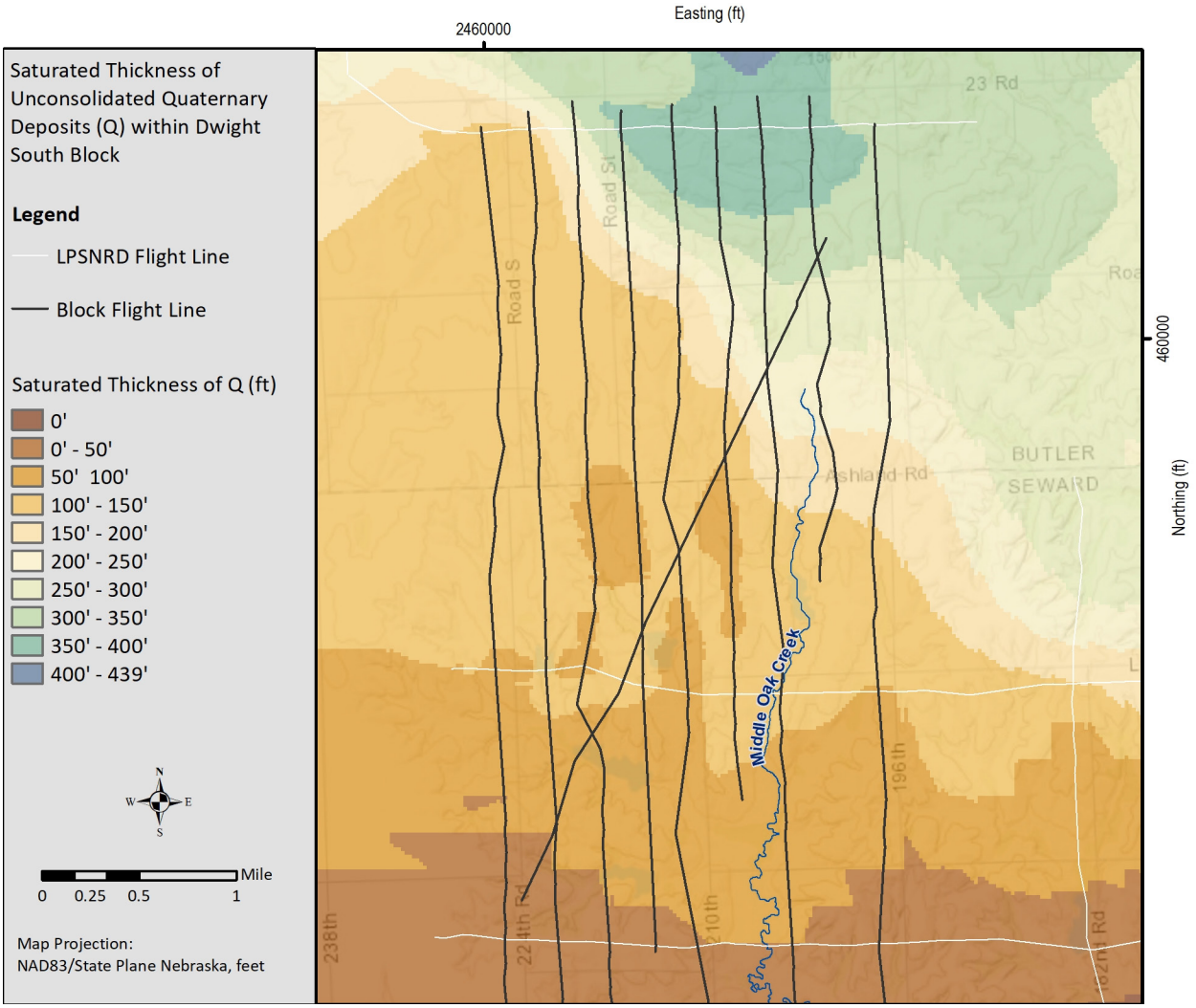


Figure 3-68. Map of the saturated thickness of Quaternary (*Q*) materials within the Dwight South Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

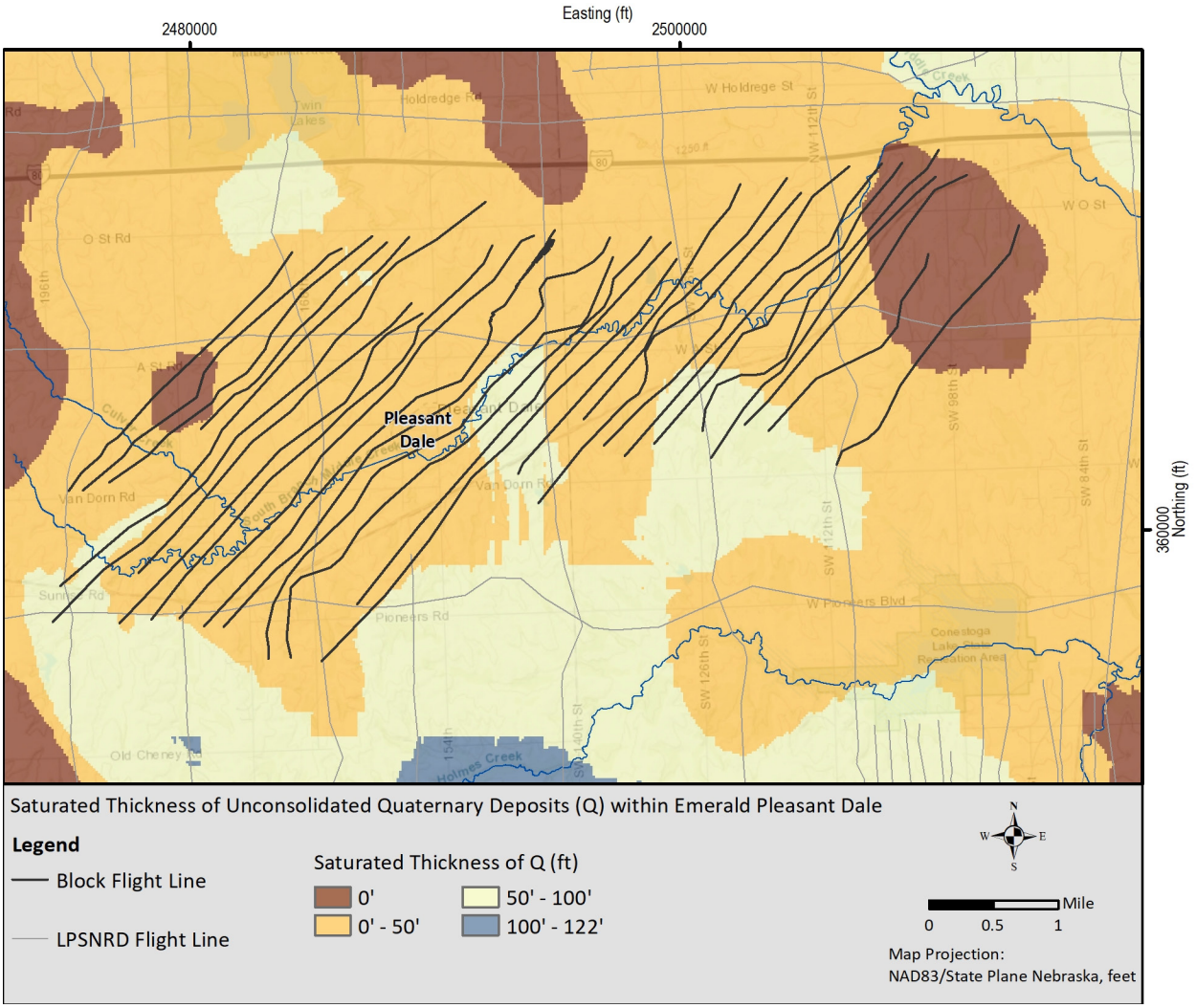


Figure 3-69. Map of the saturated thickness of Quaternary (*Q*) materials within the Emerald Pleasant Dale Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

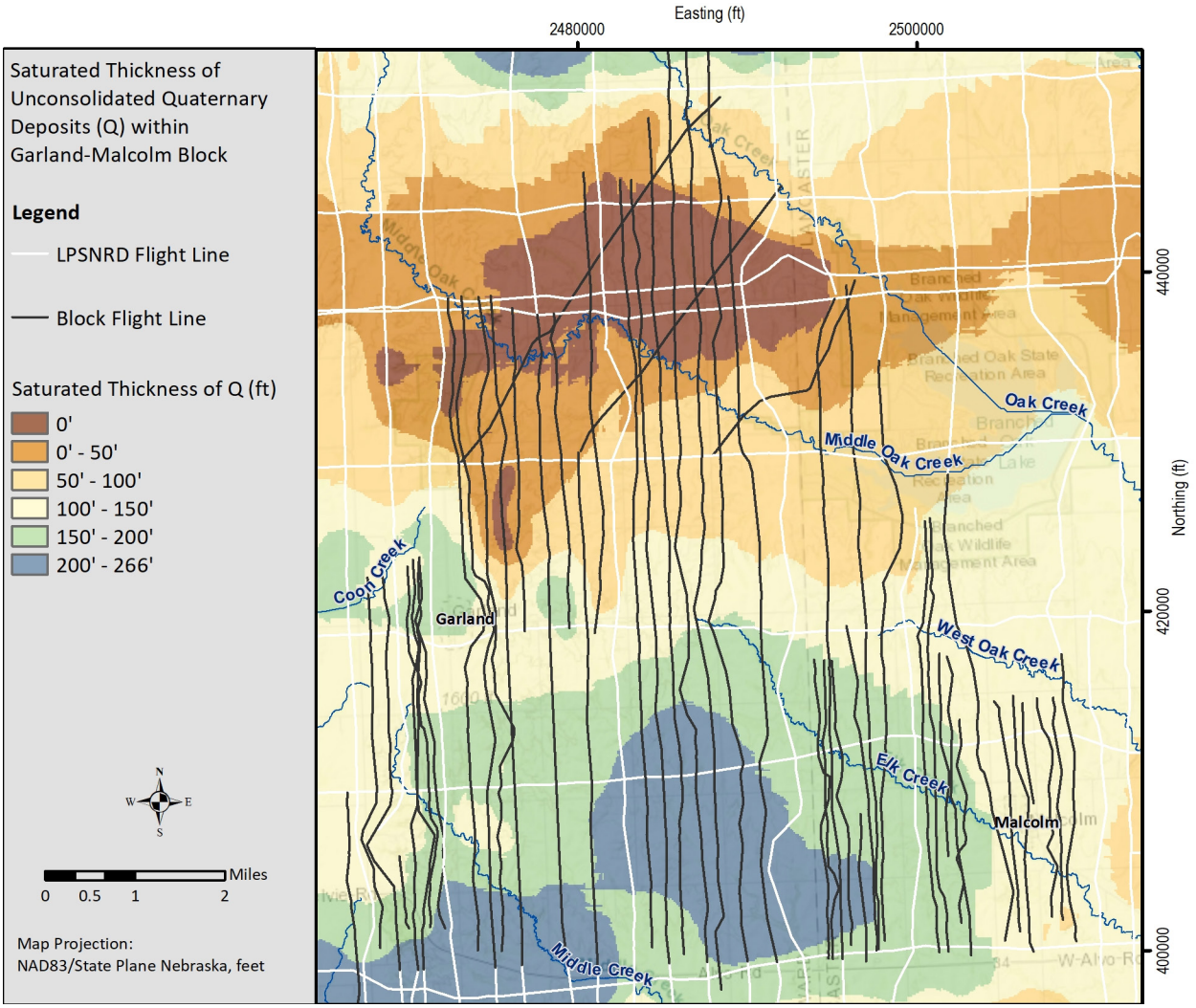


Figure 3-70. Map of the saturated thickness of Quaternary (*Q*) materials within the Garland Malcolm Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

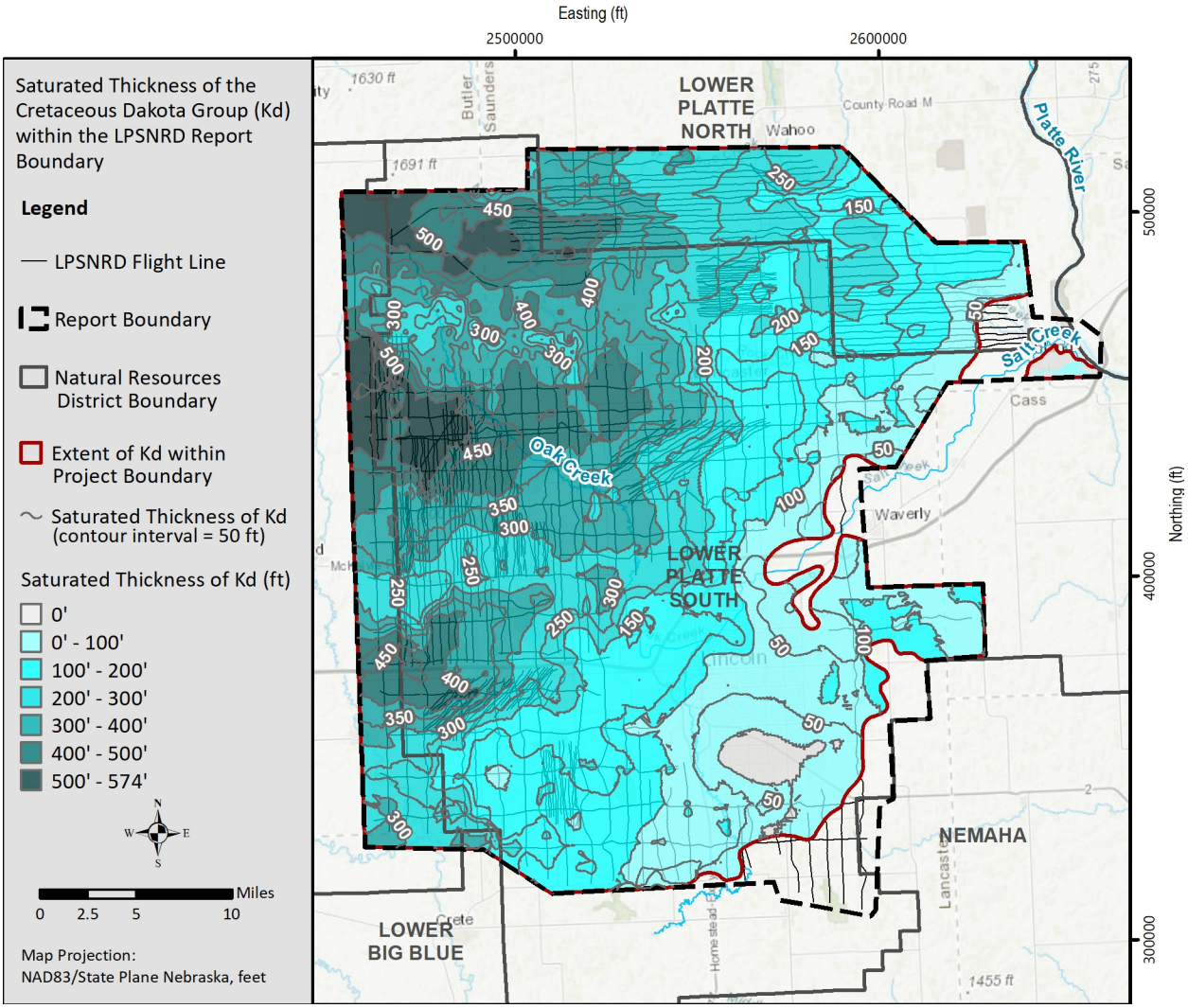


Figure 3-71. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the 2018 LPSNRD AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

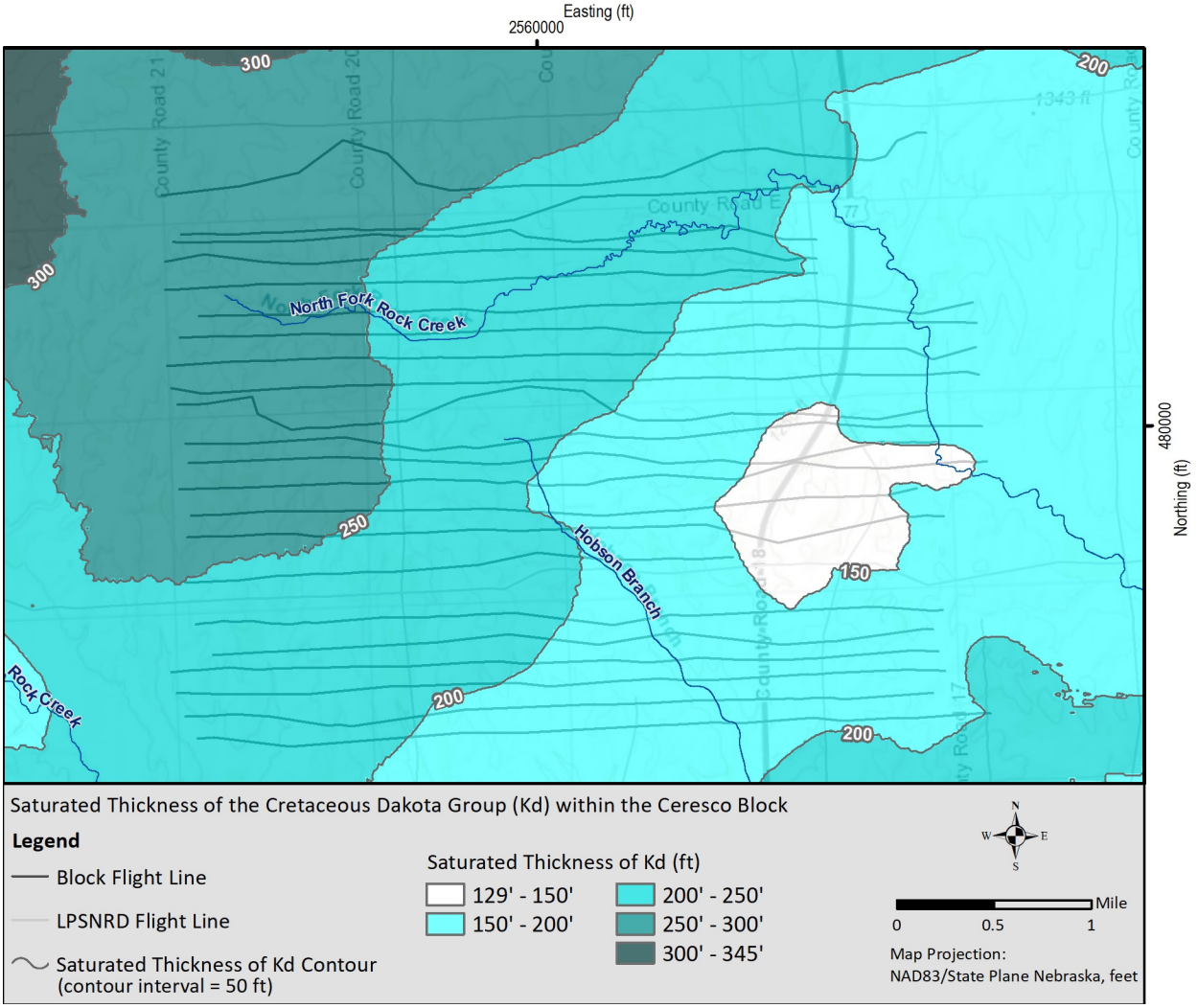


Figure 3-72. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the Ceresco Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

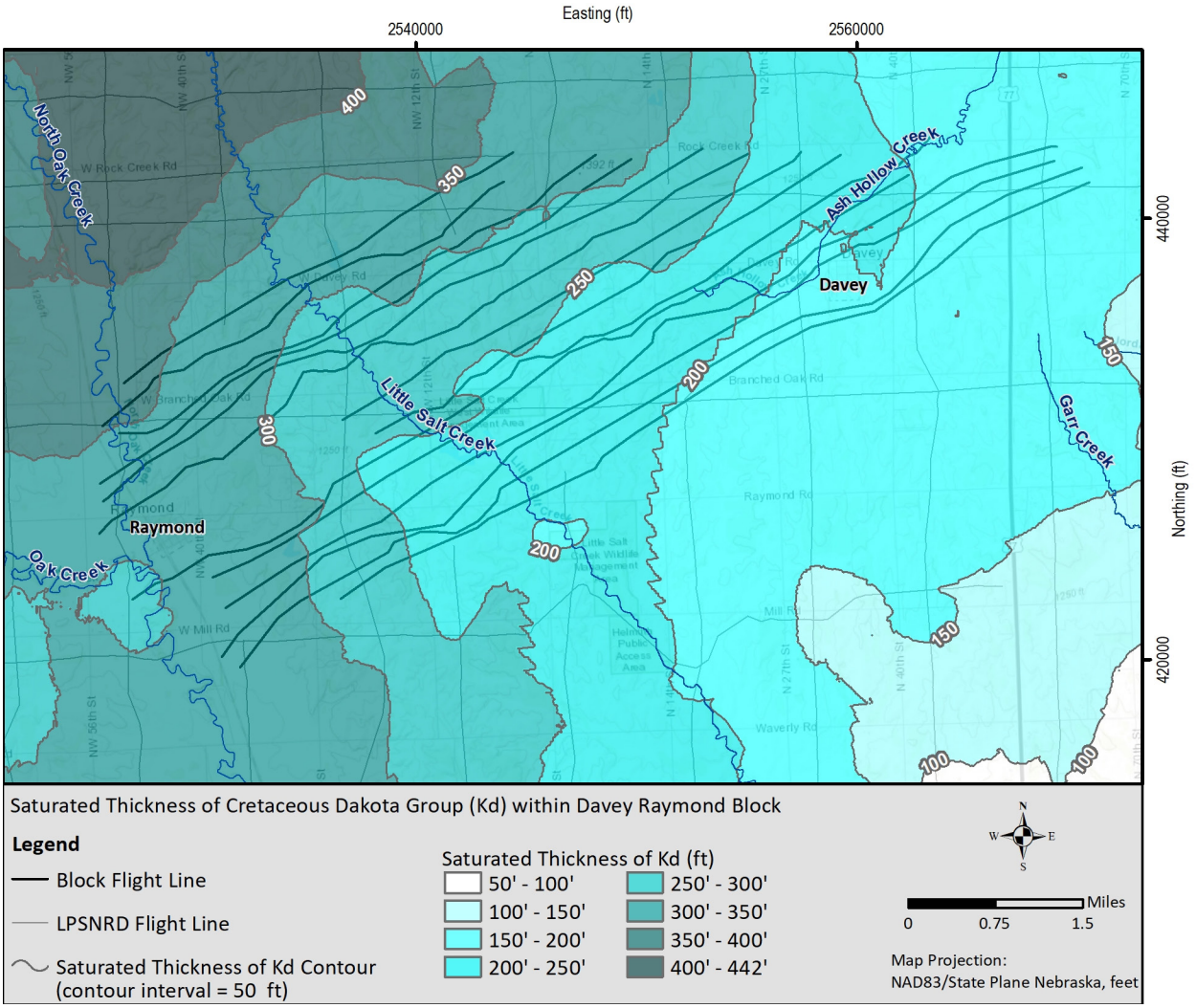


Figure 3-73. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the Davey Raymond Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

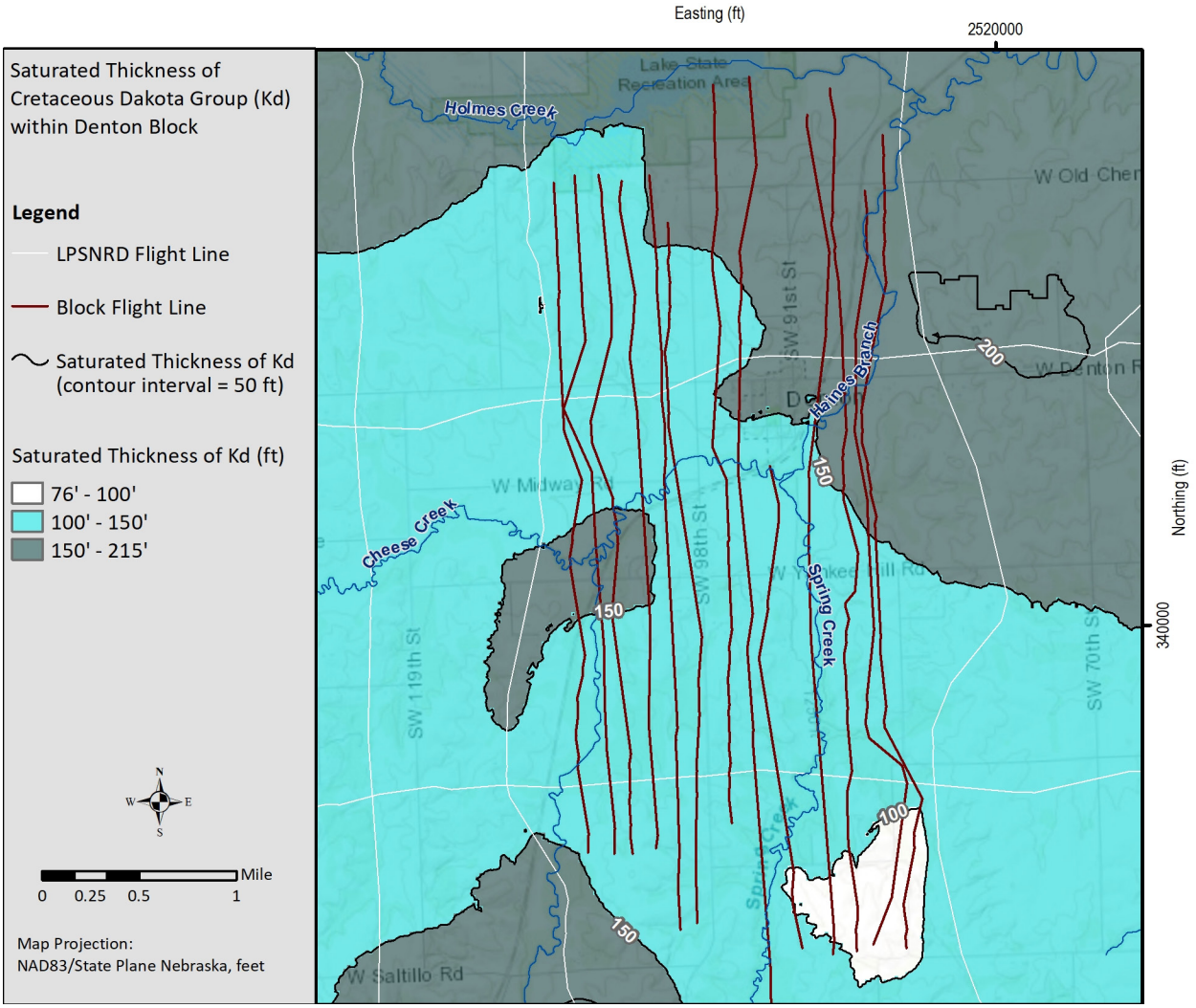


Figure 3-74. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the Denton Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

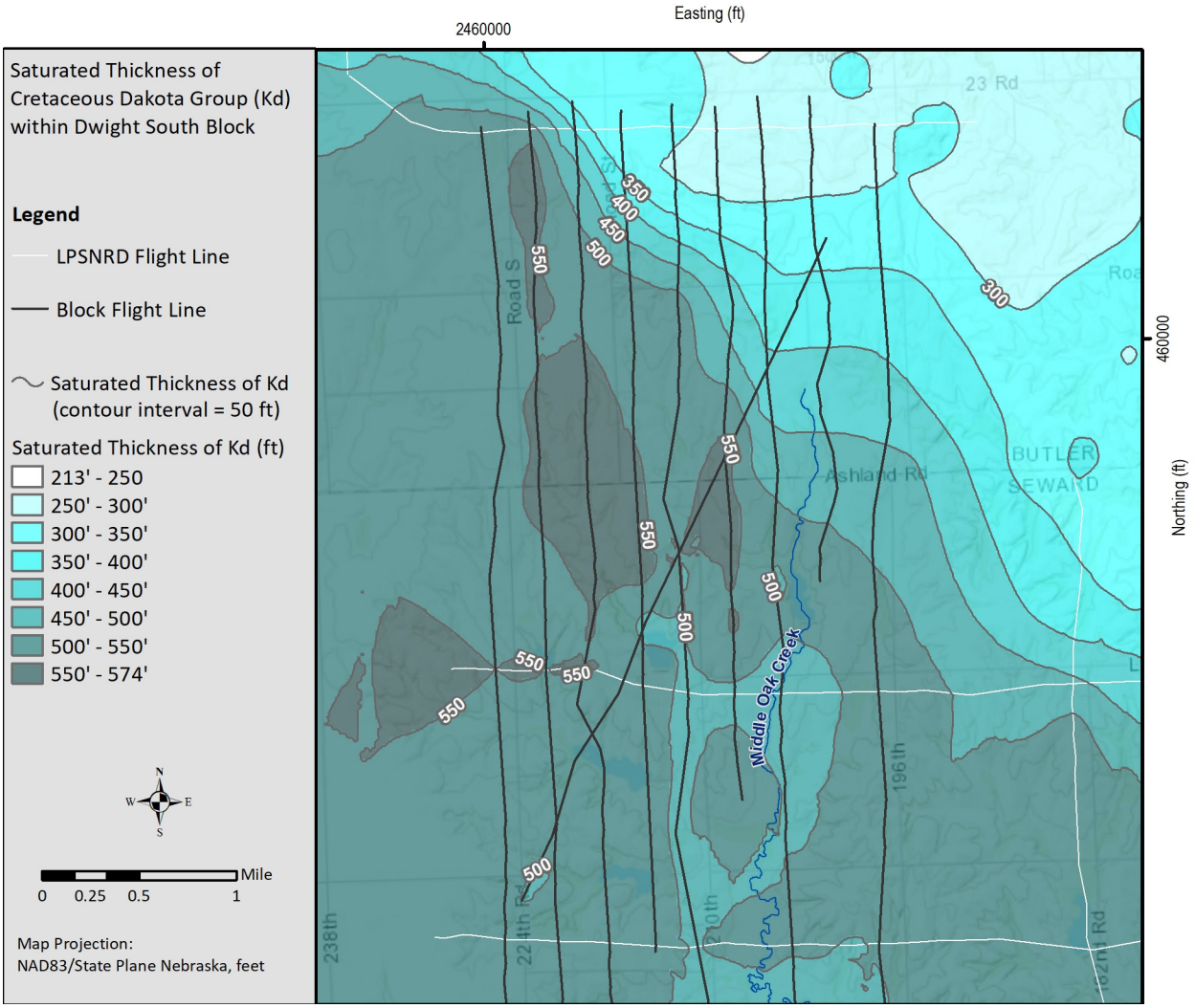


Figure 3-75. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the Dwight South Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

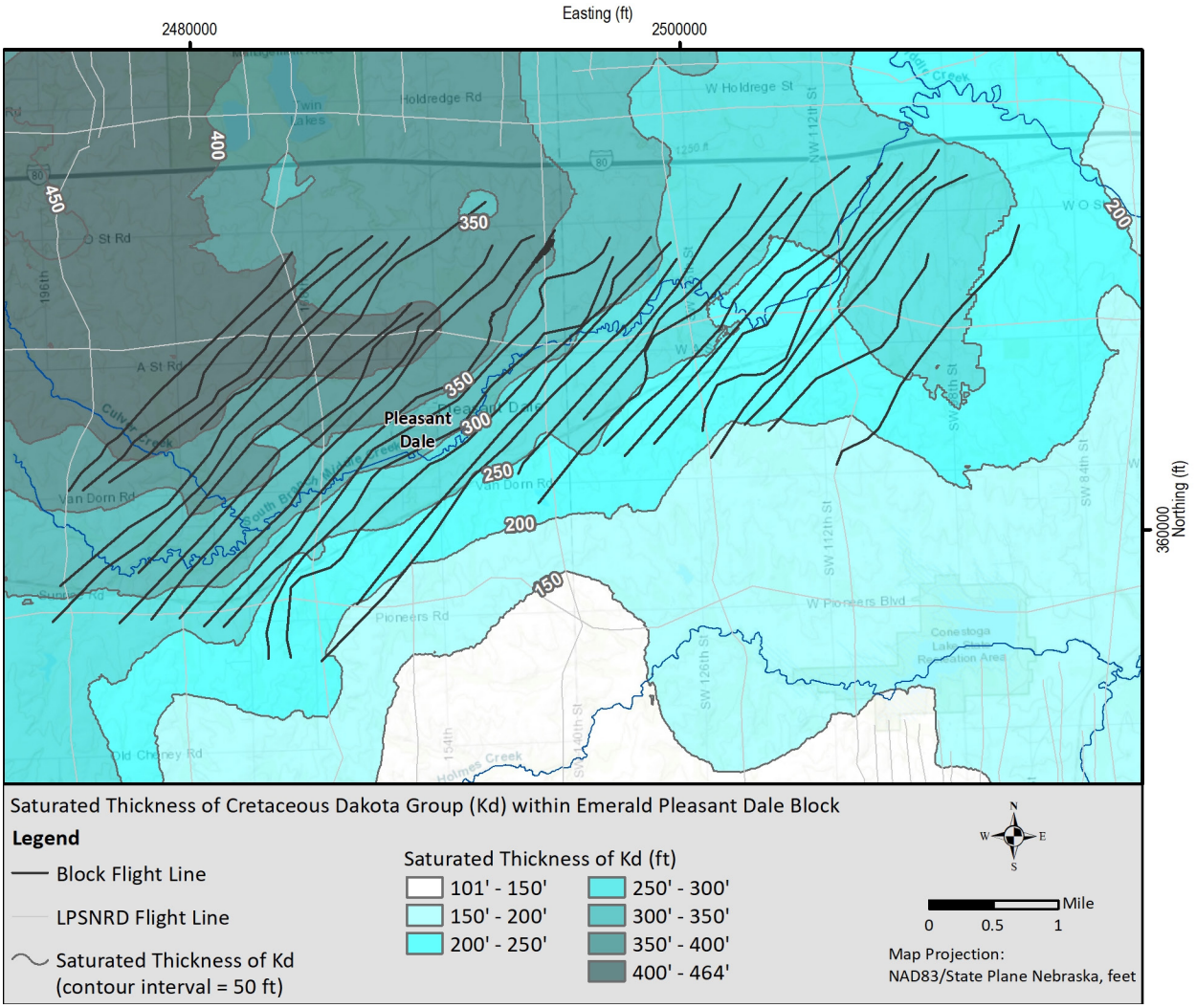


Figure 3-76. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the Emerald Pleasant Dale Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

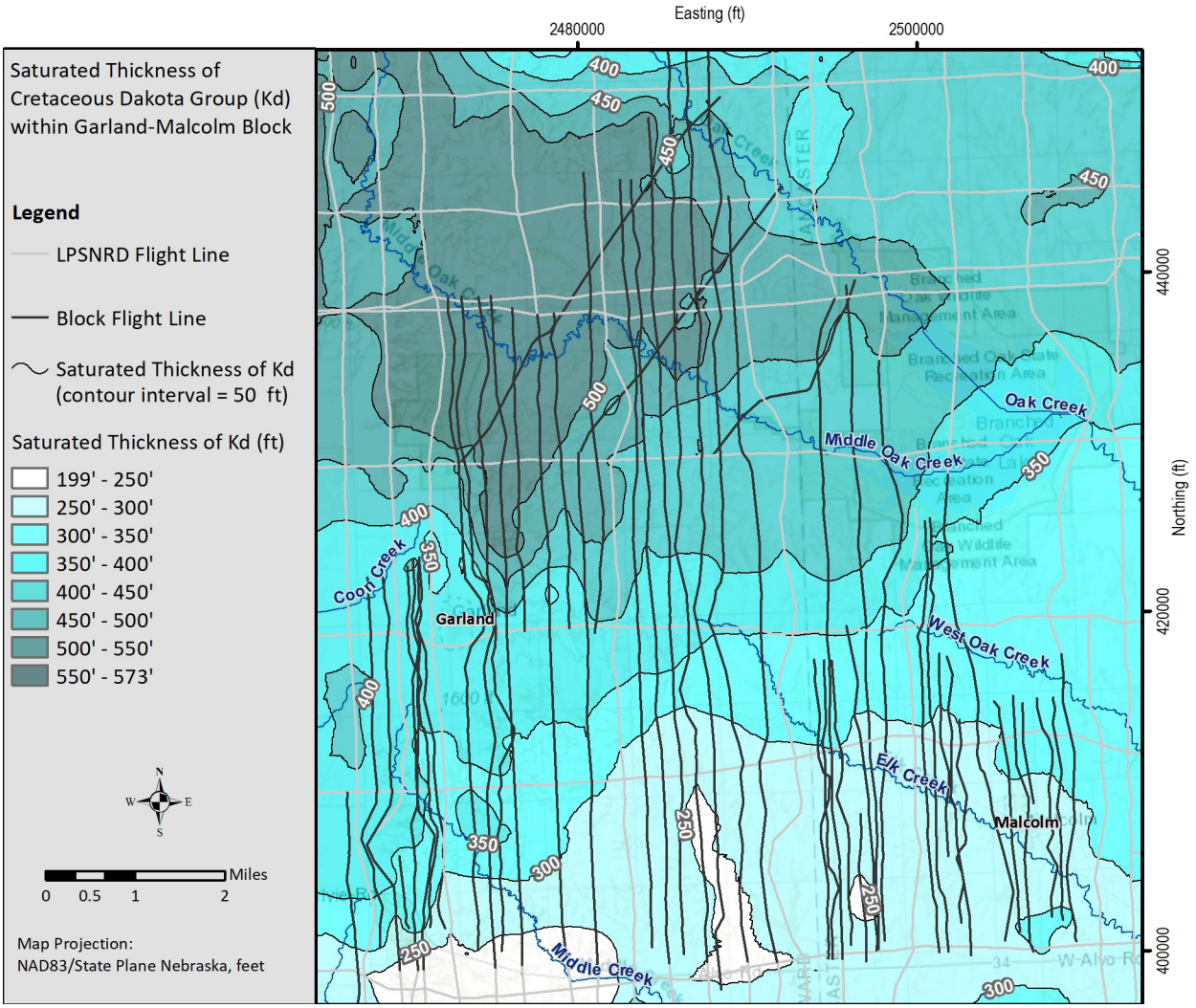


Figure 3-77. Map of the saturated thickness of Cretaceous Dakota Group (*Kd*) within the Garland Malcolm Block AEM survey area. Flight lines are indicated by the gray lines. The projection is NAD83 State Plane Nebraska (feet).

3.1.5 Resistivity/Lithology Relationship in the Quaternary Aquifer System

A critical aspect of a geophysical survey, for whatever purpose, is assessing the nature of the material detected by the geophysical method applied in the investigation. In regard to the LPSNRD survey, assessment of the sediment character in both the Quaternary aquifer system and the consolidated bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. A numerically robust assessment of the resistivity thresholds 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, 2015b). The original analysis that was completed as part of Carney et al. (2015a, 2015b) included, in the overall area, the LPSNRD. This analysis has been used in the current report for the categorization of the Quaternary aquifer system.

Data for this analysis was utilized from locations across the ENWRA reconnaissance line area (Carney et al., 2015a, 2015b). The relationship between resistivity and lithology type was assessed by performing an association function that linked nine lithologic descriptor codes for Quaternary/Tertiary Ogallala (***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 ENWRA area, 33 from the northern ENWRA 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, 2015b). A summary of the resistivities and the color scale is shown in Figure 3-78.

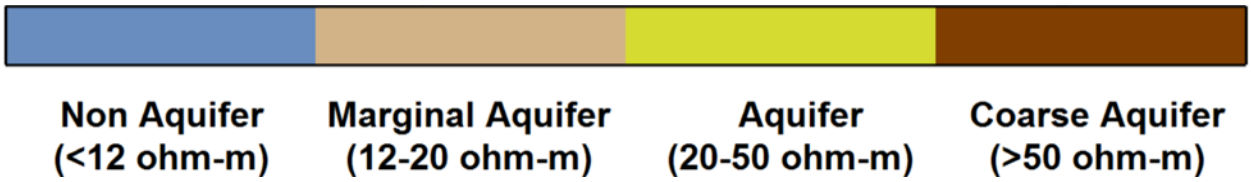


Figure 3-78. Plot displaying the resistivities by major aquifer material color categories: blue- non-aquifer materials, tan- marginal aquifer materials, yellow- aquifer materials, brown- coarse aquifer materials (Carney et al., 2015b).

3.1.6 Resistivity/Lithology Relationship in the Bedrock

The Cretaceous bedrock in the LPSNRD analyzed in this study includes the ***Kgg, Kd,*** and ***IP.*** These were included to demonstrate the overall distribution in resistivity of bedrock materials across the entire LPSNRD. The median resistivity values for each unit are 16 ohm-m for the ***Kc*** and the ***Kgg*** lumped together, 35 ohm-m for the ***Kd,*** and 25 ohm-m for the ***IP*** (Carney et al., 2015a). For the ENWRA study, the ***Kc*** and the ***Kgg*** were interpreted together. For this study, the proximity of the ***Kgg*** to the surface allows for a more accurate interpretation. The ***Kgg*** showed a more resistive character on the order of 15 ohm-m when the Greenhorn Limestone was present and a lower resistivity of 7 ohm-m when only the Graneros Shale was present. The ***Kd*** within the LPSNRD displayed some low resistivities on the order of 2 to 20 ohm-m indicating either clay/shale dominant lithology or the presence of saline waters, mostly in the western portions of the LPSNRD. Above 20 ohm-m the ***Kd*** displays characteristics of sand and sandstone dominant materials. (Carney et al., 2015b). Resistivities less than or equal to 4 ohm-m have been correlated with the presence of saline waters within the model depth of this investigation (Table 2-4).

3.1.7 Create 3D Interpretative Voxel Grids

A voxel grids were completed for the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcolm. The voxel grids were made using a 100 feet grid cell size and the model layer thickness (Table 2-4 in the previous section). A minimum curvature method was used within Datamine Discover PA (Datamine Discover, 2019). All layers were referenced to their depth from the surface and then projected on the area DEM. After the grid was calculated, the grid was split at the top of the Bedrock, Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***); Cretaceous Dakota Group (***Kd***); and the undifferentiated Pennsylvanian (***IP***). The units were also split at the 1995 CSD water table. These resulting voxel grids can be used to explore the distribution of the aquifer materials within the area in 3D. Specifically, these grids can allow for visual inspection of the volume of materials above the bedrock as well as the ***Kd***, and the ***Q*** materials. The ***Q*** and materials can be separated by the thresholds developed above for the four lithology classes. Utilizing the voxel grids of the ***Q*** analysis can be made of the volume of the different materials within the section. Additionally, the ***Kd*** can be divided into the Sandstone/Sand dominant versus the Shale/Clay or saline water dominant portions. Within the ***Kd*** Sandstone/Sand dominant a higher resistive zone can be illustrated that is greater than 40 ohm-m. Figure 3-79 is a plot of the exploded diagram of the solid model for the ***Q*** material separated from the ***Kd*** above the ***IP*** bedrock looking to the north for the Garland Malcolm Block as an example. The images of the voxel grids can be found in Appendix 2-3D Images, the voxel grids can be found in *Appendix 3-Deliverables\Voxel* as *.xyz files.

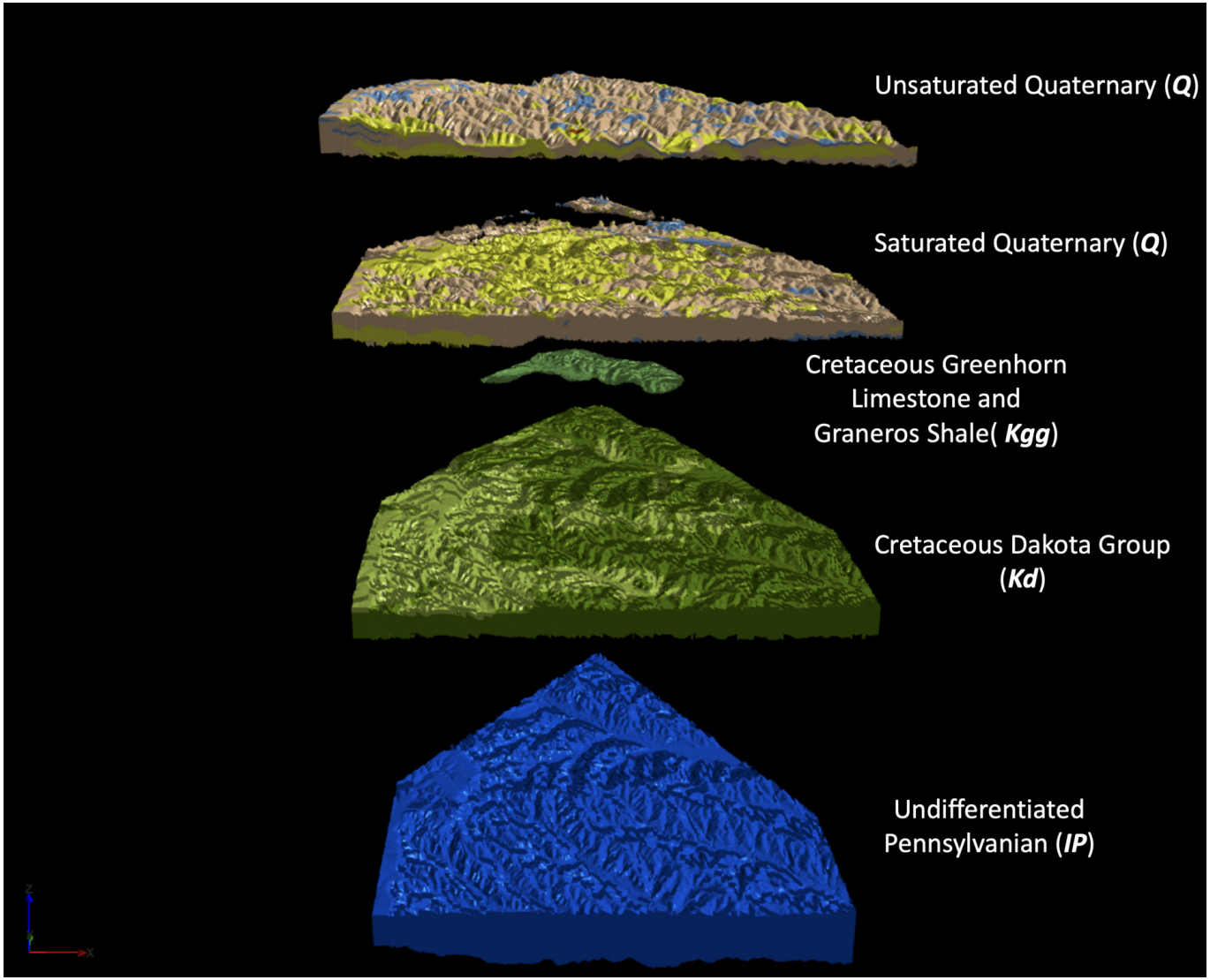


Figure 3-79. Exploded solid model of the aquifer material types for the Garland Malcolm Block of the Quaternary (*Q*) both unsaturated and saturated, Cretaceous Greenhorn Limestone and Graneros Shale (Kgg), and the two types of Cretaceous Dakota Group (*Kd*) separated from the undifferentiated Pennsylvanian (*IP*). Not to scale.

3.1.8 Comparison of Borehole Resistivity Logs to Inverted AEM Resistivity Soundings

Two recent CSD borehole geophysical resistivity logs were selected from the LPSNRD AEM survey area for comparison with the AEM inversions: CSD test holes *01-LPS-19,* and *02-LPS-19*.

Figure 3-80 is a plot of the *01-LPN-19* 16-inch short and the 64-in long normal resistivity logs plotted with the inverted AEM resistivities for flight line L403000, which is approximately 340 feet away. The AEM sounding selected is from the closest points to the location of the borehole geophysical log. The 16-inch and the 64-inch track each other relatively but there is variation away from the borehole. The 64-inch log is also indicating calibration and scale issues in the areas of very low resistivity with the sensor not working in the range of ~ 480-630 feet. The agreement in the resistivity is generally good with the AEM between the two E-logs. All of the logs. Indicate a very low resistivity at the bottom of the ***Kd*** which would indicate saltwater.

Figure 3-81 presents borehole *02-LPN-19* 16-inch short and the 64-in long normal resistivity logs plotted with the inverted AEM resistivity for flight line L411901 which is located 180 feet from *01-LPS-19* at its closest point. The 64-inch long normal resistivity log for this hole indicated very high resistivity values in the thin ***Q*** sand that is encountered just before the ***Kd*** contact. These elevated values are suspect in this environment. In-fact much of the 64-inch normal log is elevated above the 16-inch and the AEM resistivity indicates a possible questionable calibration with the logging tool. The AEM matches the 16-inch relatively well with the exception of the zone in the ***Kd*** where the AEM's wider averaging window and footprint is indicating a lower resistivity suggesting variability away from the test hole.

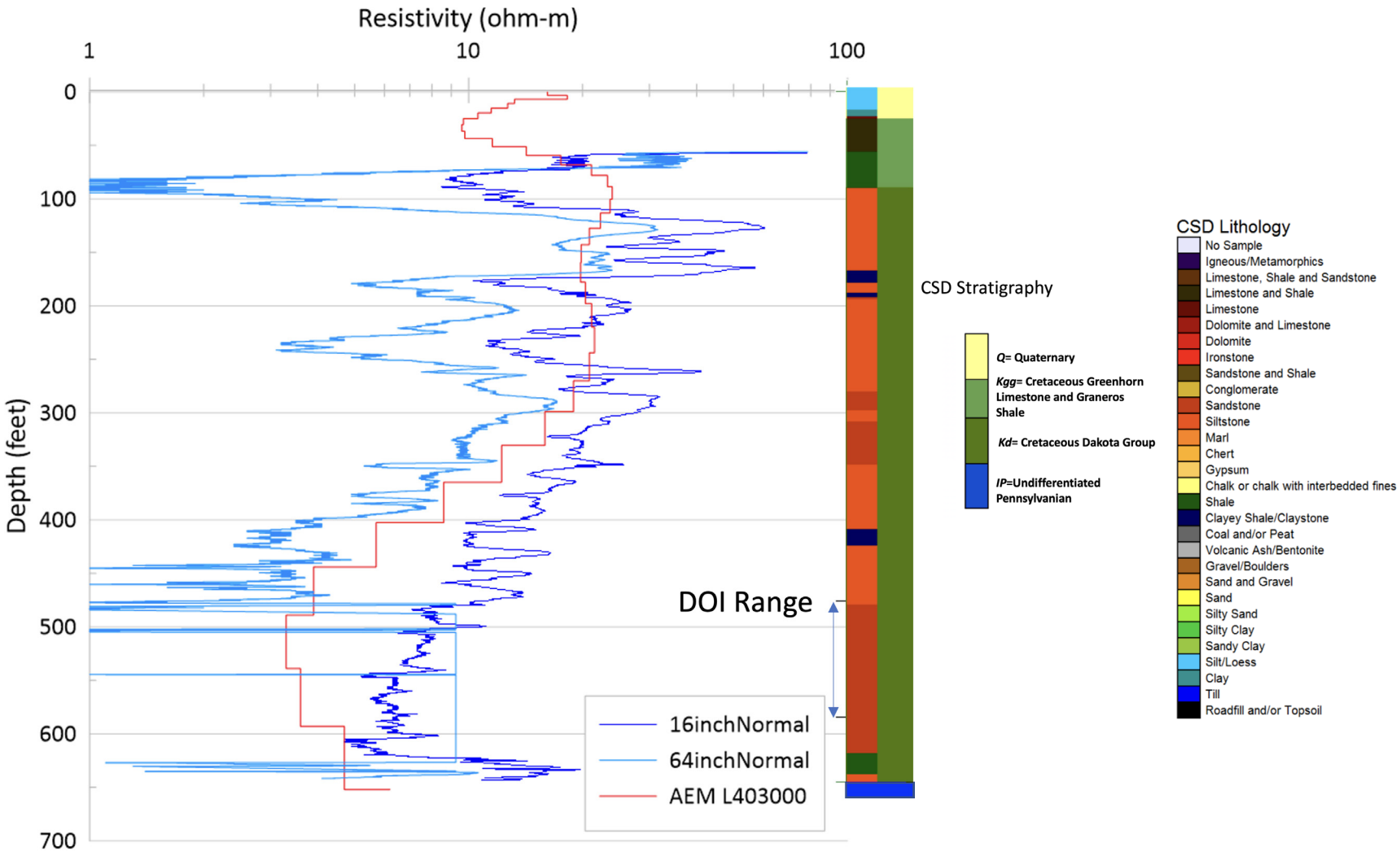


Figure 3-80. Graph of the *02-LPN-15* 16-inch short normal (dark blue line) and 64-inch long normal (light blue line) resistivity logs values and the inverted airborne electromagnetic resistivity values for flight line L504800 (red line). CSD lithology and Stratigraphy are indicated.

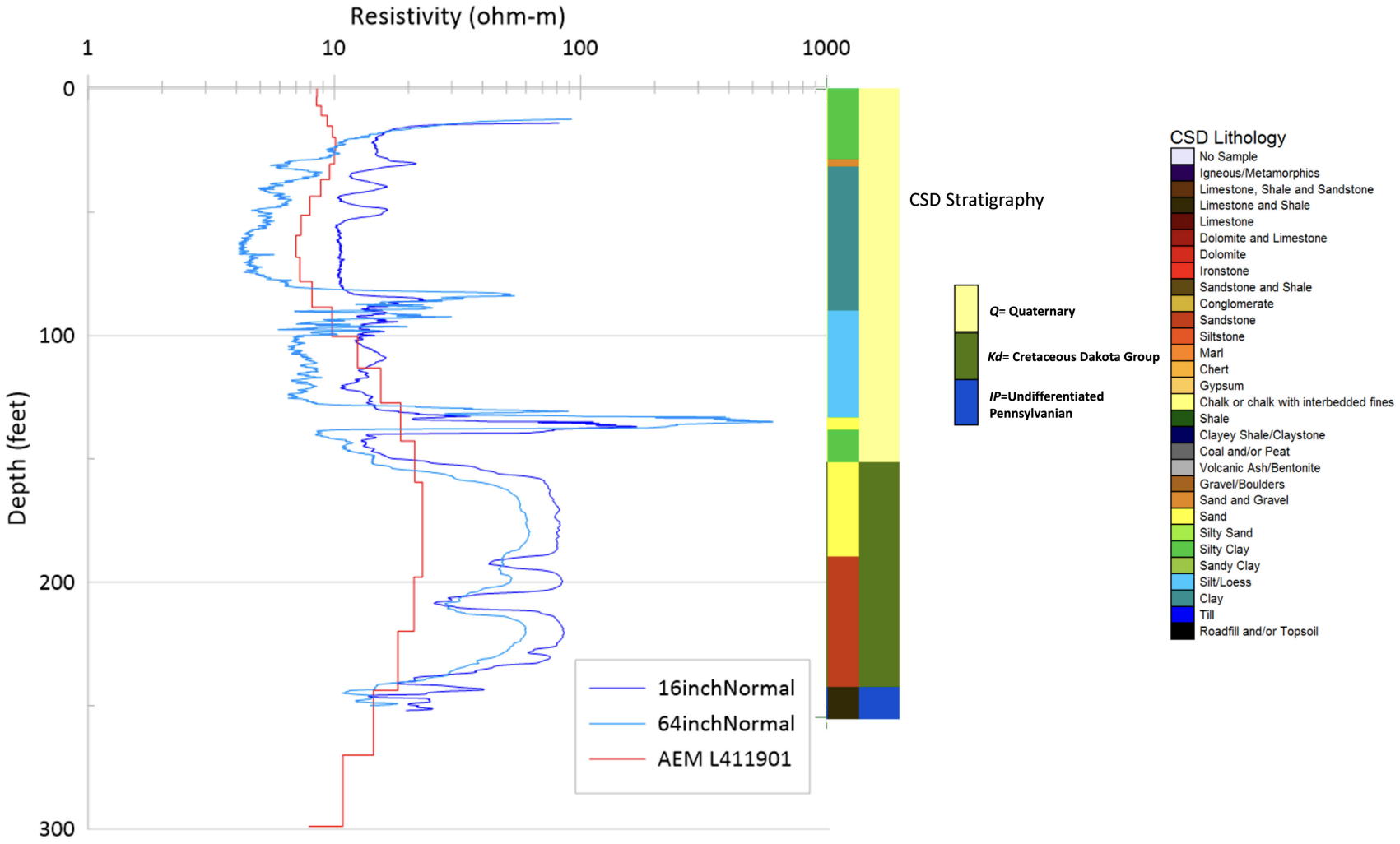


Figure 3-81. Graph of the *03-LPN-15* 16-inch short normal (dark blue line) resistivity log values and the inverted airborne electromagnetic resistivity values for flight line L502900 (red line). CSD lithology and Stratigraphy are indicated.

3.2 Hydrogeological Framework of the LPSNRD 2018 AEM Survey Area

The 2018 survey continues to build upon the previous AEM survey efforts within the LPSNRD. In 2016 AGF flew an AEM survey over areas of interest for well head protection and groundwater availability in LPSNRD (AGF, 2017). Through the previous work and the current work presented in this report much of the area of the LPSNRD has been mapped with AEM technology.

3.2.1 The Hydrogeologic Framework of the LPSNRD Reconnaissance Survey Area

The hydrogeologic framework for LPSNRD survey area based on the reconnaissance flight lines will be described first, then the Block areas in the following order: Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale and Garland Malcolm. The AEM reveals the variability in the Quaternary and Cretaceous deposits which make up the aquifers across the AEM survey area. Figure 3-82 shows the CSD bedrock geology map of the area. For purposes of this section the ***Q*** and ***Kd*** contain the aquifer units in the survey area. The ***Q*** contains aquifer materials composed of non-aquifer (blue color in figures), marginal aquifer (tan color in figures), aquifer (yellow color in figures), and coarse aquifer (brown color in figures) materials. These materials are composed predominantly of glacial, pre-glacial alluvial (paleochannel deposits that include some outwash), and alluvial deposits related to the current drainages.

The dominant hydrogeologic features that are in the LPSNRD Reconnaissance survey area are ***Q*** alluvial deposits found in the modern drainages and paleochannels filled with both pre-glacial and outwash sediments and the till deposits which are a mix of all aquifer materials types. The ***Kd*** Sandstone/ Sand Dominant deposits are found throughout the project area and are considered bedrock aquifers which can be hydrologically connected to streams where the overlying units have been eroded. Figure 3-83 is a 3D image of the AEM interpretation as a fence diagram, looking to the north, showing the geologic formations across the survey area. Figure 3-84 is a 3D image of the AEM interpretation as a fence diagram, looking to the southwest, showing the geologic formations across the survey area and highlights the ***Kd*** Sandstone/Sand dominant areas including where they are hydrologically connected and not hydrologically connected to surface water. Figure 3-85 is the total ***Q*** thickness containing all interpreted non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. The thick areas of ***Q*** are found in the uplands of the project area and the thin areas are in the drainages. ***Q*** thickness ranges from <50 feet to 575 feet.

Figure 3-86 shows the total ***Kd*** thickness including the Shale/Clay or saltwater Dominant and Sandstone/Sand Dominant materials. The ***Kd*** ranges in thickness from <50 feet to 574 feet on the west side of the area. The ***Kd*** contains both Sandstone/Sand dominant and Shale/Clay or Saltwater dominant materials. The Sandstone/Sand dominant materials are the aquifer materials in the ***Kd***.

The 1995 CSD water table map for the LPSNRD 2018 AEM survey area is shown on Figure 3-57 and is used in all calculations for saturated thickness and hydrologic connection to surface water.

Examining the 3D fence diagrams provides a spatial understanding of the distribution of aquifer materials within the LPSNRD 2018 AEM survey area. Figure 3-87 is a 3D fence diagram looking to the

east. The figure includes the undifferentiated Pennsylvanian (***IP***) as well as some of the major streams. The AEM aquifer material classifications illuminate the areas of the ***Q*** (which covers the survey area) with the yellow and brown colors of the aquifer and coarse aquifer materials. These materials can be in hydrologic connection to streams across the area. In areas where there are no paleochannels, outwash gravels or alluvial channels, the dominate aquifer material type is a mix of marginal (tan areas) and non-aquifer (blue areas) materials which can be identified as till/loess deposits.

It is important to note that the marginal aquifer material areas may have wells that produce, just at a lower rate due to the interlayered nature of the marginal materials that contain large portions of silt and clay but may also contain thin layers of sand and gravel and/or silty sand. Discussion on the materials that were found to be within the marginal aquifer materials resistivity range can be found in Carney et al. (2015a).

The ***Kd*** can be a primary or secondary aquifer made up of ***Kd*** Sandstone/Sand Dominant materials. Whether it is a primary or secondary water source depends on whether the ***Q*** aquifer material can be the main supply providing well capacity to meet the demand. Figure 3-88 is north-south line L413700 and just west of the town of Waverly, Nebraska and shows where the ***Kd*** Sandstone/Sand Dominant materials are hydrologically connected to ***Q*** aquifer material and/or surface water in the Salt Creek Valley. This interaction can quickly become non-hydrologically connected and become confined units where the ***Kd*** Shale/Clay or Saltwater dominant and ***Kgg*** (where present) are on top or next to the ***Kd*** Sandstone/Sand. The ***Kd*** is heavily eroded along the line with several channels filled with ***Q*** materials and does not exist in the south and under Salt Creek. The ***Kd*** is ~250 feet thick at the north end of the line. It also shows the ***IP*** surface which slopes south to north.

In some areas of the survey the paleochannels are discrete and have subtle to very sharp transitions from non-aquifer and marginal aquifer materials to aquifer and coarse aquifer materials and the ***Kd*** surface. North-south line L403801 (Figure 3-89) is oriented north-south across the Garland Malcom and Emerald Pleasant Dale AEM block flight areas, near the towns of Garland, Malcom, Emerald and Pleasant Dale, Nebraska in the west portion of the LPSNRD reconnaissance AEM survey area. The paleochannels that lie under the area made up of 3 channels which contains mostly marginal aquifer and non-aquifer material with minor amounts of aquifer material. The southern 2 channels are filled with till and the northern channel is an outwash channel because it is steep walled and filled with some basal aquifer material. No coarse aquifer material is present along this line. The change within the ***Q*** aquifer materials from non-aquifer, marginal aquifer and aquifer material is not the only source of the interruption of groundwater flow as the aquifer geometry between the ***Q***, ***Kd***, ***Kgg*** and ***IP*** provides for sharp groundwater flow boundaries. Within the ***Kd*** change between Sandstone/Sand dominant and Shale/Clay or Saltwater dominant units provide a boundary to groundwater flow. There is a small deposit of ***Kgg*** near northing 440000. Note the variable land surface elevation change along the line.

North-south line L412100 (Figure 3-90), near Denton, Nebraska, displays the subsurface deposits of geologic units of the uplands area inclusive of Oak Creek Valley and Branched Oak Reservoir at the northern end of the profile which is also in uplands made up of minor amounts of glacial outwash in the northern most paleochannel and mostly till deposits capped by loess. The ***Q*** is thick to the south and

thins to near zero thickness near the town of Denton and then thickens to the north upon a gently sloping ***Kd*** bedrock surface with the exception of the paleochannel at the north end which is steep and is ~120 feet deeper than the ***Kd*** surface to the south. Beneath the upland, near northing 340000, is a paleovalley with an elevation change of ~100 ft cut into the ***Kd*** that includes a very small basal sand deposit of aquifer material that are capped by marginal aquifer and non-aquifer material. There is a second paleochannel between northing 345000 and 440000 with a shallow sloping surface that is eroded into the ***Kd*** ~100 feet and contains minor sand deposits of aquifer material with mostly a marginal and non-aquifer material. The ***Kd*** is the bedrock Cretaceous unit resting upon the ***IP*** and is has a maximum thickness of ~420 feet thick along this line. It is composed of minor amounts of Sandstone/Sand dominant and is mostly Shale/Clay or Saltwater dominant materials that have no hydrologic connection with surface water because there is ***Kd*** Shale/Clay or Saltwater dominant material. There is a small area of ***Kd*** Sandstone/Sand dominant near northing 345000 that has minimal hydrologic connection with surface water and small outwash deposits of the ***Q***. There is a small area of hydrologic connection between the ***Q*** paleovalley fill and ***Kd*** Sandstone/Sand next to it near the north end of the line.

East-west line L307501 (Figure 3-91) lies east of Lincoln, Nebraska and north of Highway 34. This upland area is made up of small hills that are made up of nearly 98 percent of ***Q*** marginal and non-aquifer materials that include till and loess. The ***Q*** sediments, which average ~20-150 feet thick. The ***Q*** materials rest upon the ***Kd*** which in turn lie upon the ***IP***. The ***Kd*** has a no hydrologic connection due to its material make up of Shale/Clay or Saltwater dominant materials surrounding Sandstone/Sand dominant. The ***Q*** material overlying the ***Kd*** has little to no ability to transmit groundwater. Note the missing ***Kd*** on the west end of the line and that the ***Q*** lies directly on the ***IP***.

Using the interpretive surfaces and grids that were produced as described above (in Section 3.1.4), an enhanced understanding of the hydrogeological framework of the LPSNRD AEM survey area can be achieved. Referring back to Figure 3-85 which shows the total thickness of all ***Q*** aquifer materials which ranges from <50 feet to 546 feet thick. The ***Q*** covers the entire project area and the thick areas of ***Q*** are in the west/northwest and are related to the top of bedrock elevation map (Figure 3-92). There are 4 distinct paleochannels cut into the bedrock and are indicated by low elevations trending from west to east. When the 1995 CSD water table is used to separate the total thickness of aquifer materials into saturated and unsaturated materials, calculation of the saturated thickness can be determined and ranges from 0 to 439 feet (Figure 3-93) With an understanding of the saturated thickness of the ***Q*** and a comparison to DNR registered well locations and specific capacity of the wells completed in the ***Q*** sediments it becomes apparent that the majority of ***Q*** wells in LPSNRD are of low yield in gallons per minute (gpm) (Figure 3-94). The higher yield wells are completed in the thicker and more coarse ***Q*** deposits with some exceptions. The specific capacity of these wells range from <5 to >25 gpm/ft.

Across the project area the ***Kgg***, ***Kd*** and ***IP*** make up the bedrock of the area and come in contact with the ***Q*** sediments where they coexist. The youngest Cretaceous unit is in the western part of the project area and is ***Kgg.*** The extent of the top of the ***Kgg*** surface is shown in Figure 3-95 and it varies in elevation from 1,241 to 1,463 feet. The ***Kgg*** deposits are discontinuous in nature and occupy small areas

of the project area. They act as aquicludes in the most part. The ***Kgg*** varies in thickness from <25 feet to 143 feet (Figure 3-96).

Figure 3-97 is the elevation of the upper surface of the ***Kd*** and varies in elevation from 979 feet to 1,416 feet and slopes from west to east. The lower elevations tend to be coincident with the paleochannels present in the area. The ***Kd*** is absent near Salt Creek, Ashland, Nebraska and the southeast corner of the project area. The ***Kd*** is divided into 2 sediment packages which are Sandstone/Sand dominant, Shale/Clay dominant or Saltwater dominant materials. The Sandstone/Sand dominant materials are considered the aquifer material of the ***Kd***. Figure 3-86 above shows the total thickness of the ***Kd*** in the area and is described above. When the 1995 CSD water table is used to separate the total thickness of ***Kd*** into saturated and unsaturated materials, calculation of the saturated thickness can be determined and vary from 0 to 574 feet (Figure 3-98). With an understanding of the saturated thickness of the ***Kd*** and a comparison to DNR registered well locations and specific capacity of the wells completed primarily in the ***Kd*** Sandstone/Sand dominant materials it becomes apparent that the majority of ***Kd*** wells in LPSNRD are of low yield in gallons per minute (gpm) (Figure 3-99). The higher yield wells are completed in the thicker portions of the ***Kd*** and/or have a hydrologic connection between ***Q*** aquifer and coarse aquifer materials and/or with surface water with some exceptions. The specific capacity of these wells range from <5 to >25 gpm/ft.

To better understand the ***Kd*** deposits, an improved understanding of the depositional system of the ***Kd*** needs to be put forward. Witzke and Ludvigson (1994) published a cartoon depicting a prograding deltaic environment during deposition of the ***Kd*** as a way to understand the deposits (Figure 3-100).

The ***IP*** is present throughout the LPSNRD project area and is the basal geologic unit mapped by the AEM survey. Figure 3-101 is a map of the elevation of the ***IP*** top surface. This surface slopes from east to west and changes in elevation from 1,252 to 744.

Saltwater areas were detected, analyzed and mapped within the project area. Figure 3-102 shows the areas that have saltwater in the project area. Figure 3-103 shows a map of groundwater sample results retrieved from the USGS NWIS system (USGS, 2019b) showing the Specific conductance values in microsiemens/centimeter (µs/cm) only values above 2,570 and above are shown because this was elected as the boundary where increasing conductivity indicates impacts of saltwater being present. There is a cluster of wells near Lincoln that show values >15,000 µs/cm and indicates groundwater that is saltwater. Figure 3-103 is similar to Figure 3-104 but is showing Total Dissolved Solids (TDS) as values expressed in mg/l. The values range from 2,090 to >30,000 mg/l which indicate impacts from saltwater water. The wells near Lincoln, Nebraska show the largest values.

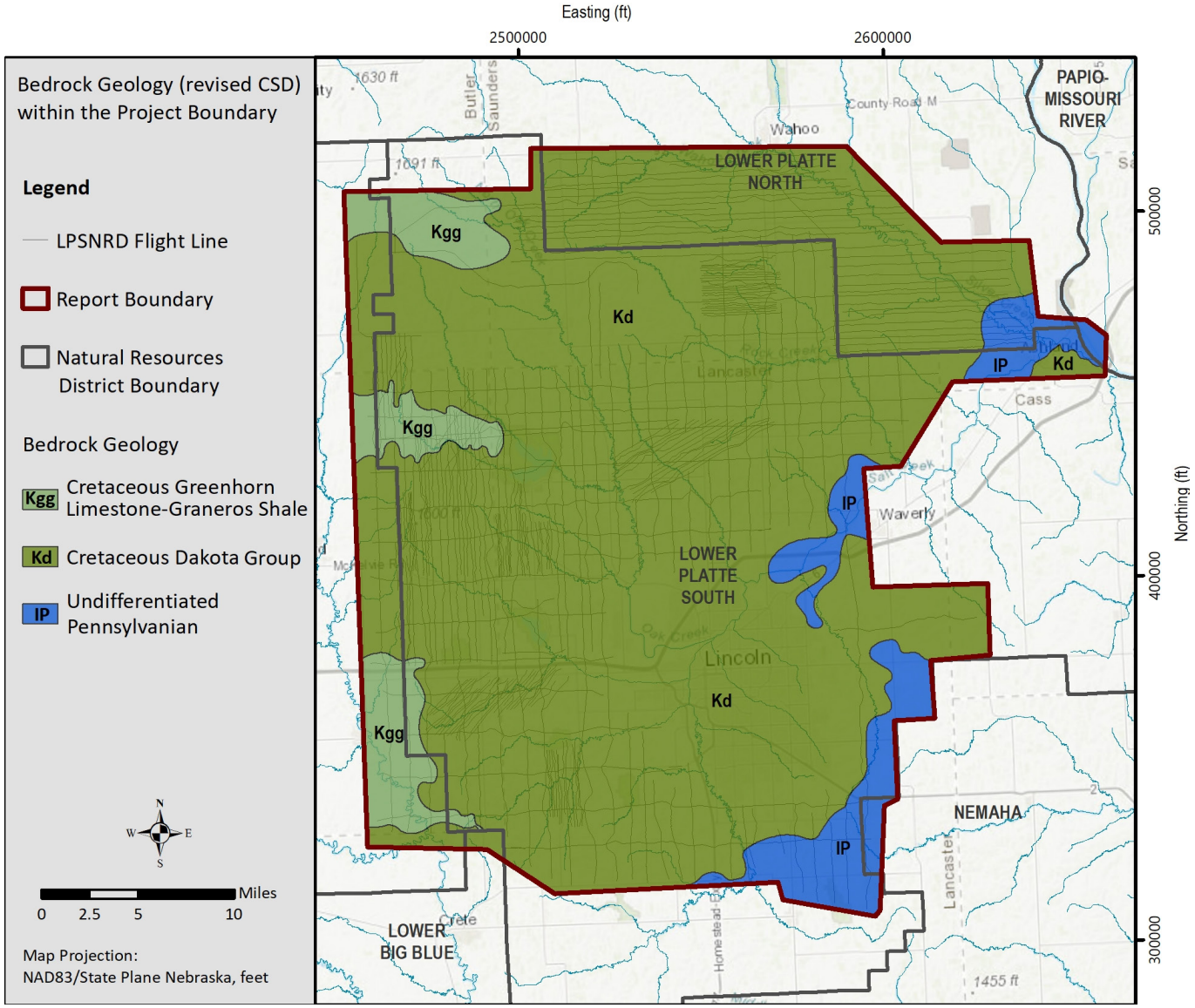


Figure 3-82. Map showing the CSD bedrock geology map for the entire project area, modified from Burchett (1986). Horizontal datum is NAD83 State Plane Nebraska (feet).

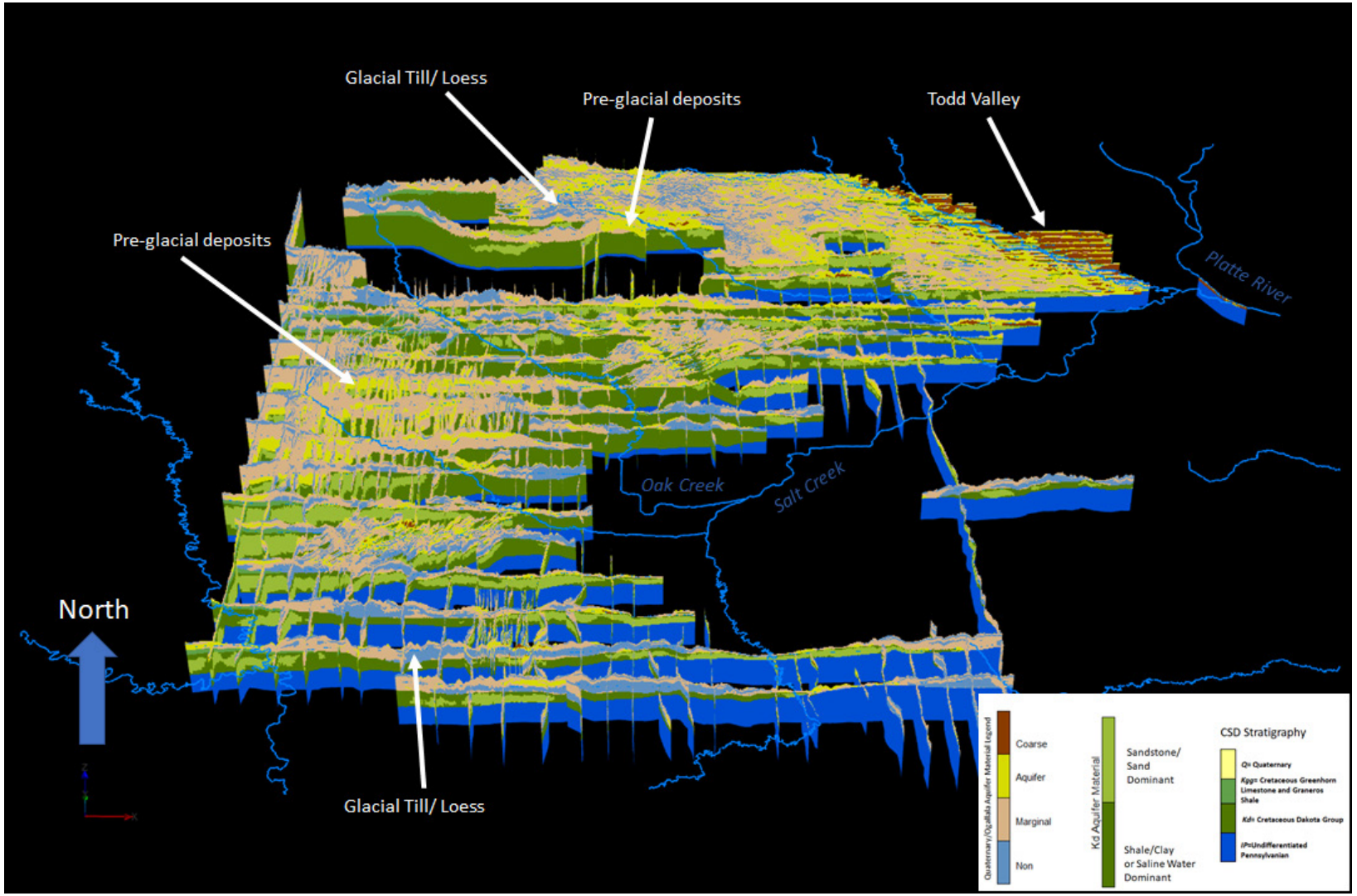


Figure 3-83. 3D fence diagram of the LPSNRD 2018 lines looking north showing *Q* aquifer materials, *Kgg*, *Kd* units are colored in shades of green, dark green is Shale/Clay or Saltwater Dominant and light green is Sandstone/Sand Dominant. The blue area in the fence diagrams is the *IP*. The geologic units present in this survey area include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 15x.

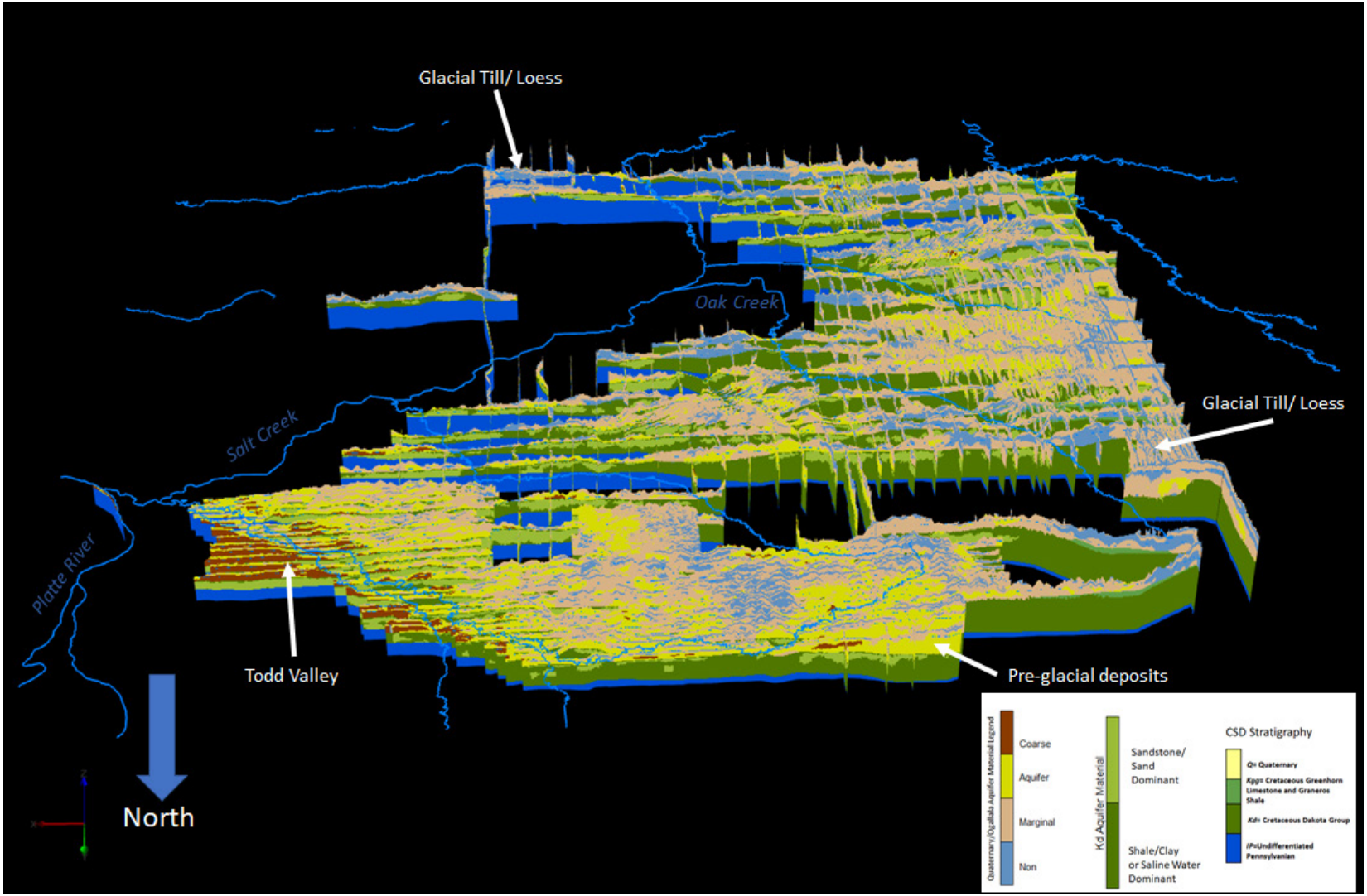


Figure 3-84. 3D fence diagram of the LPSNRD 2018 lines looking south showing *Q* aquifer materials, *Kgg*, *Kd* units are colored in shades of green, dark green is Shale/Clay or Saltwater Dominant and light green is Sandstone/Sand Dominant. The blue area in the fence diagrams is the *IP*. The geologic units present in this survey area include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 15x.

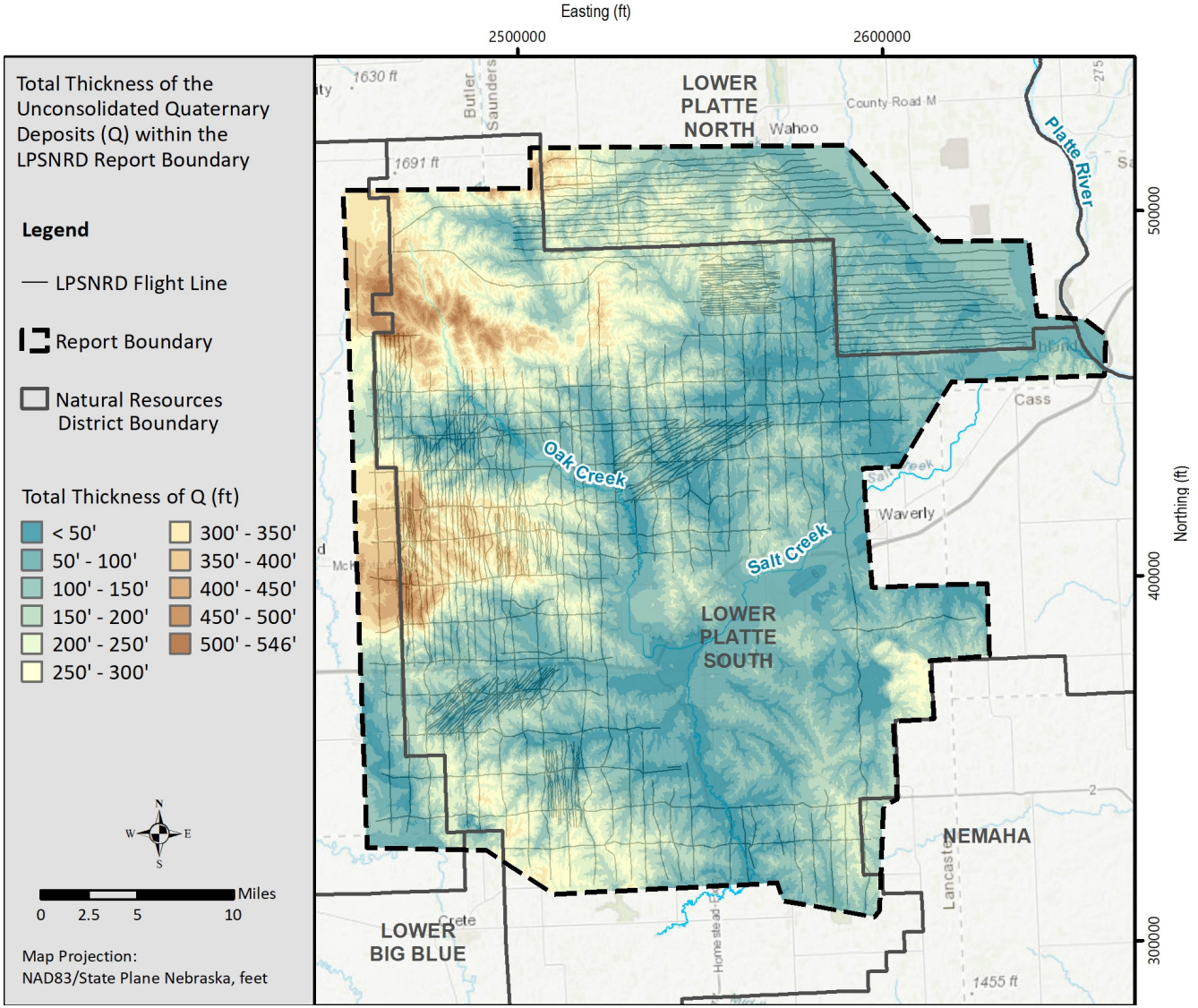


Figure 3-85. Map of the total *Q* aquifer material thickness of the AEM LPSNRD 2018 Reconnaissance survey area. Note the thick areas are generally in the upland and the thin areas are in the stream valleys. The geologic unit present in this figure includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

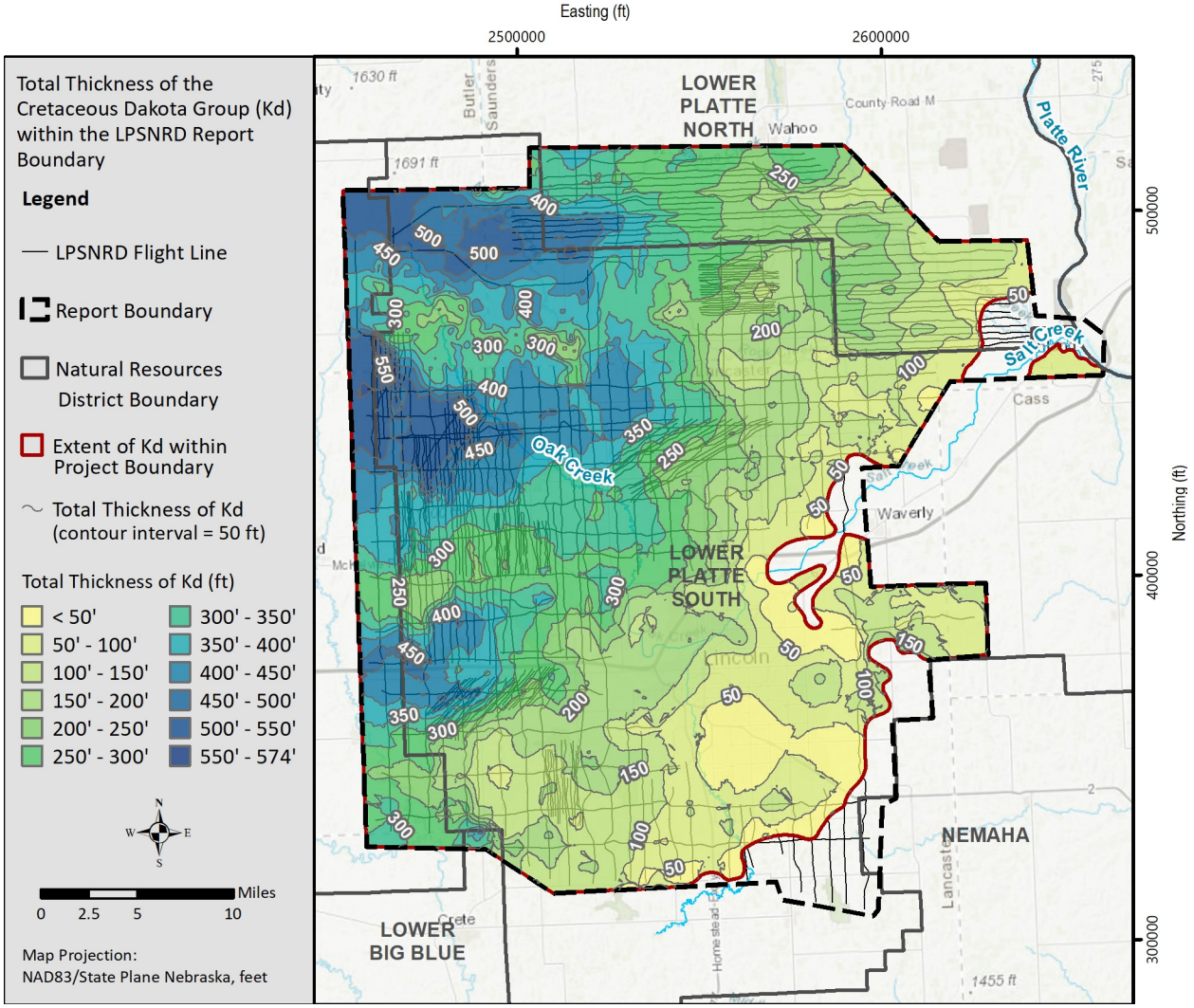


Figure3-86. Map of the total *Kd* thickness of the AEM LPSNRD 2018 Reconnaissance survey area. The thick areas are near west side of the project area. The geologic units present in this figure includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

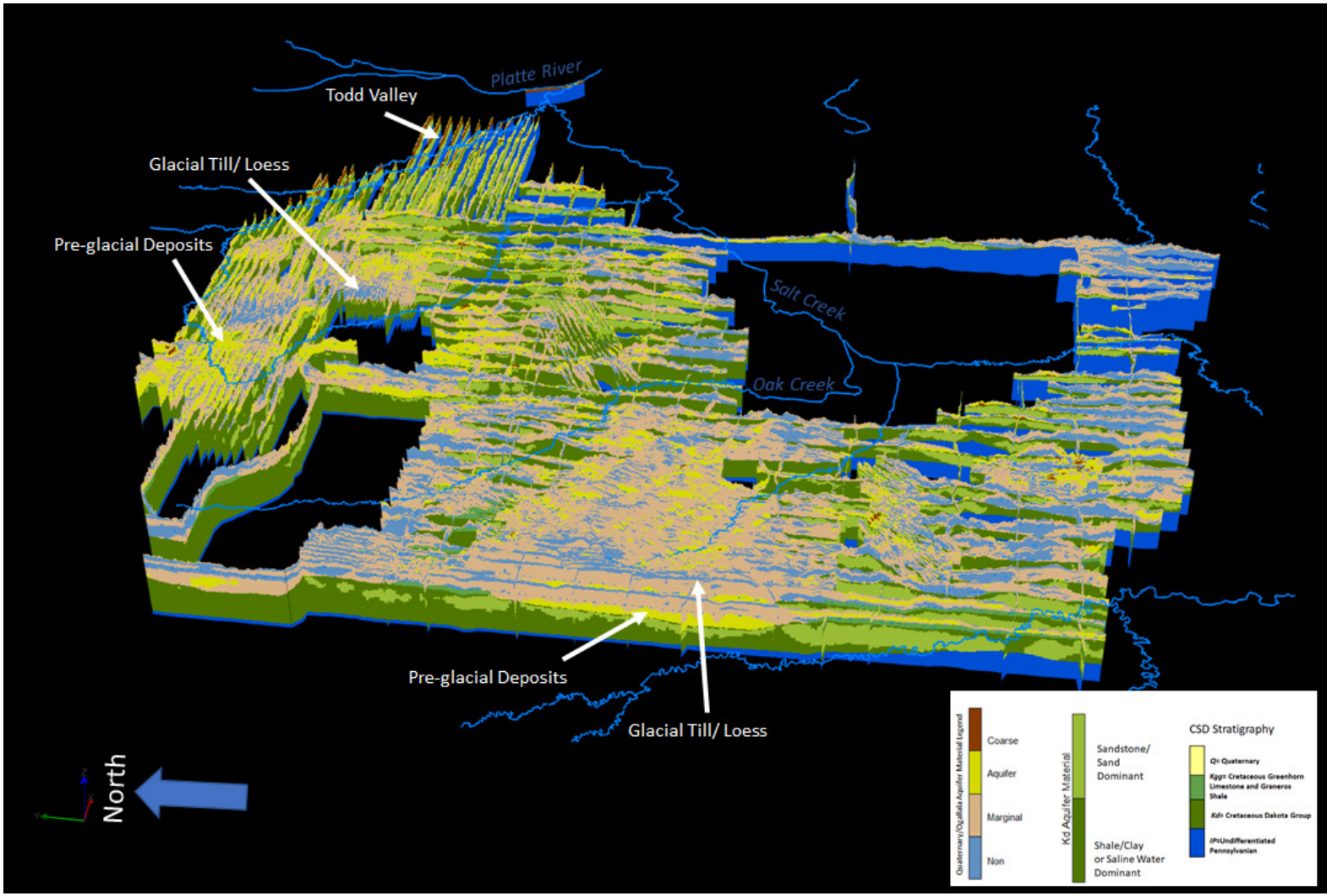


Figure 3-87. 3D fence diagram of the LPSNRD 2018 Reconnaissance lines looking east showing *Q* aquifer materials. *Kgg* units are colored in shades of green. Dark green is *Kd* Shale/Clay or Saltwater Dominant and light green is *Kd* Sandstone/Sand Dominant. Note the abundance of *Kd* Sandstone/Sand dominant materials throughout the area (bottom of image). The blue area in the fence diagrams is the *IP*. The geologic units present in this survey area include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*=Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 15x.

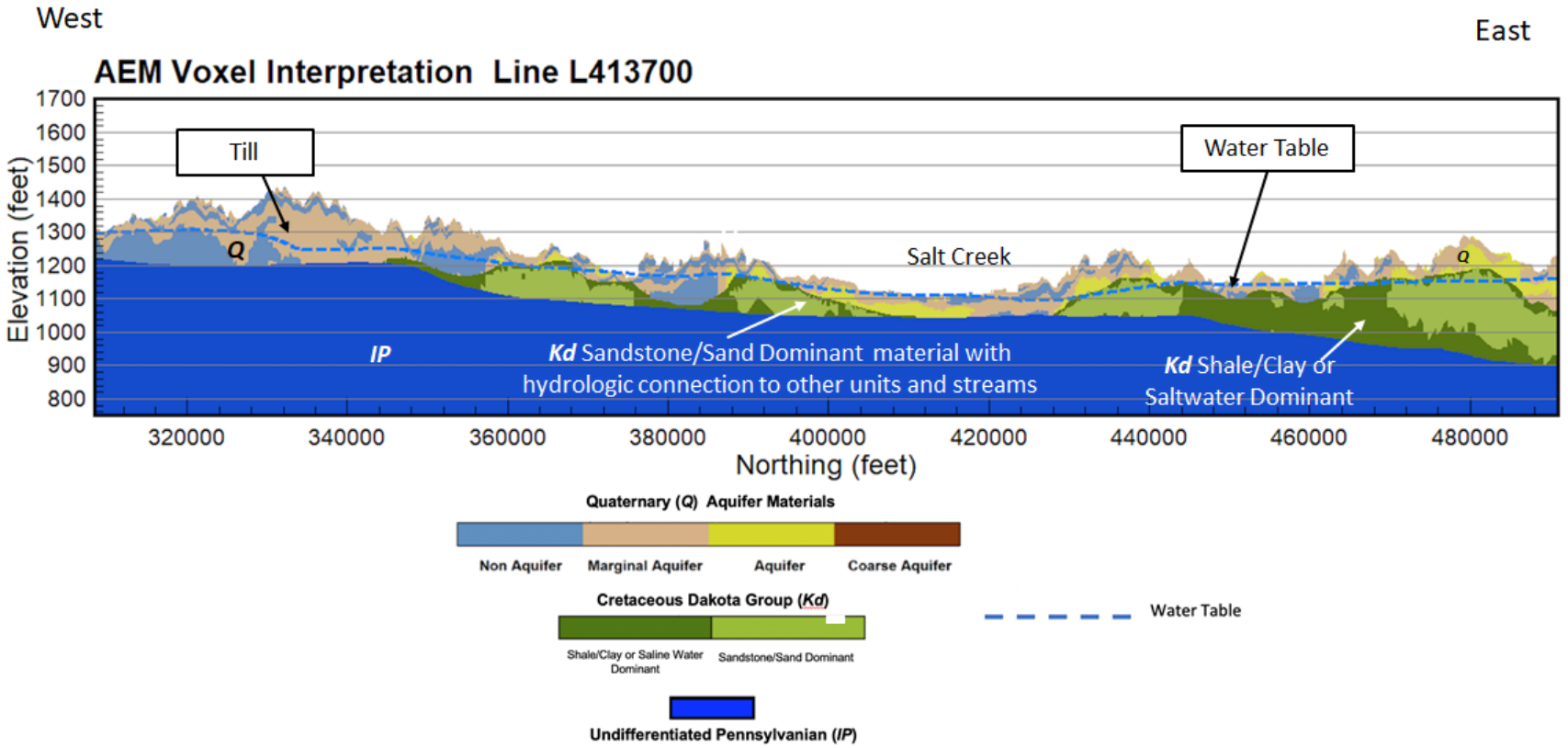


Figure 3-88. Interpreted north-south line, L413700, crosses the Salt Creek just west of the town of Waverly. Salt Creek is a modern channel that cuts through the *Kd* to the *IP*. Note the sharp incision through the *Kd* to the top of the *IP* and the hydrologic connection with the *Q* and surface water. The CSD 1995 water table is indicated with a dashed blue line. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and Undifferentiated Pennsylvanian (*IP*). Horizontal datum is NAD83 State Plane Nebraska (feet).

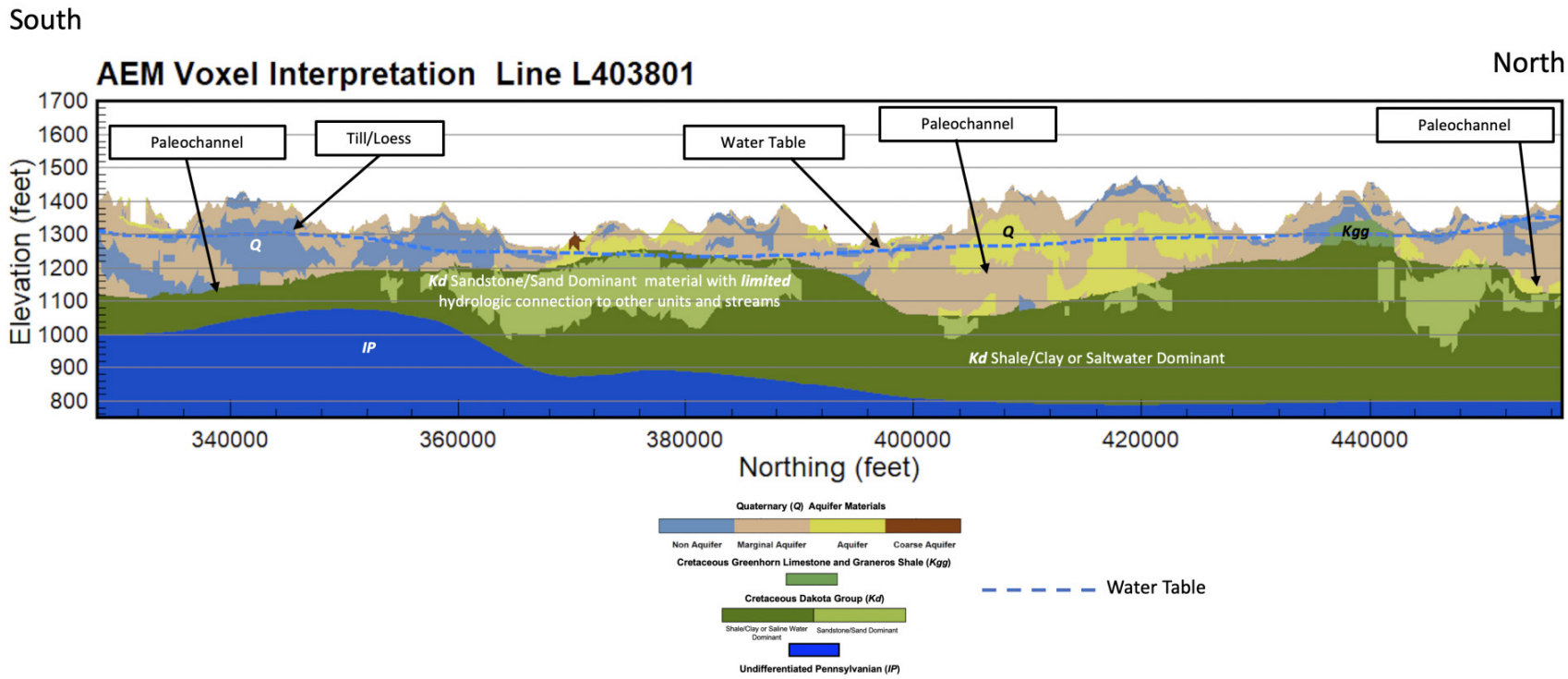


Figure 3-89. Interpreted north-south line, L403801, near the towns of Garland, Malcom, Emerald and Pleasant Dale, Nebraska displays the subsurface deposits of geologic units of the uplands including three paleochannels that appear across the line from south to north. There is a small amount of *Kgg* near northing 440000. The geologic units present in the AEM survey area include the *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*=Undifferentiated Pennsylvanian. Note the small amount of Sandstone/Sand Dominant material in the *Kd*. The CSD 1995 water table is indicated with a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

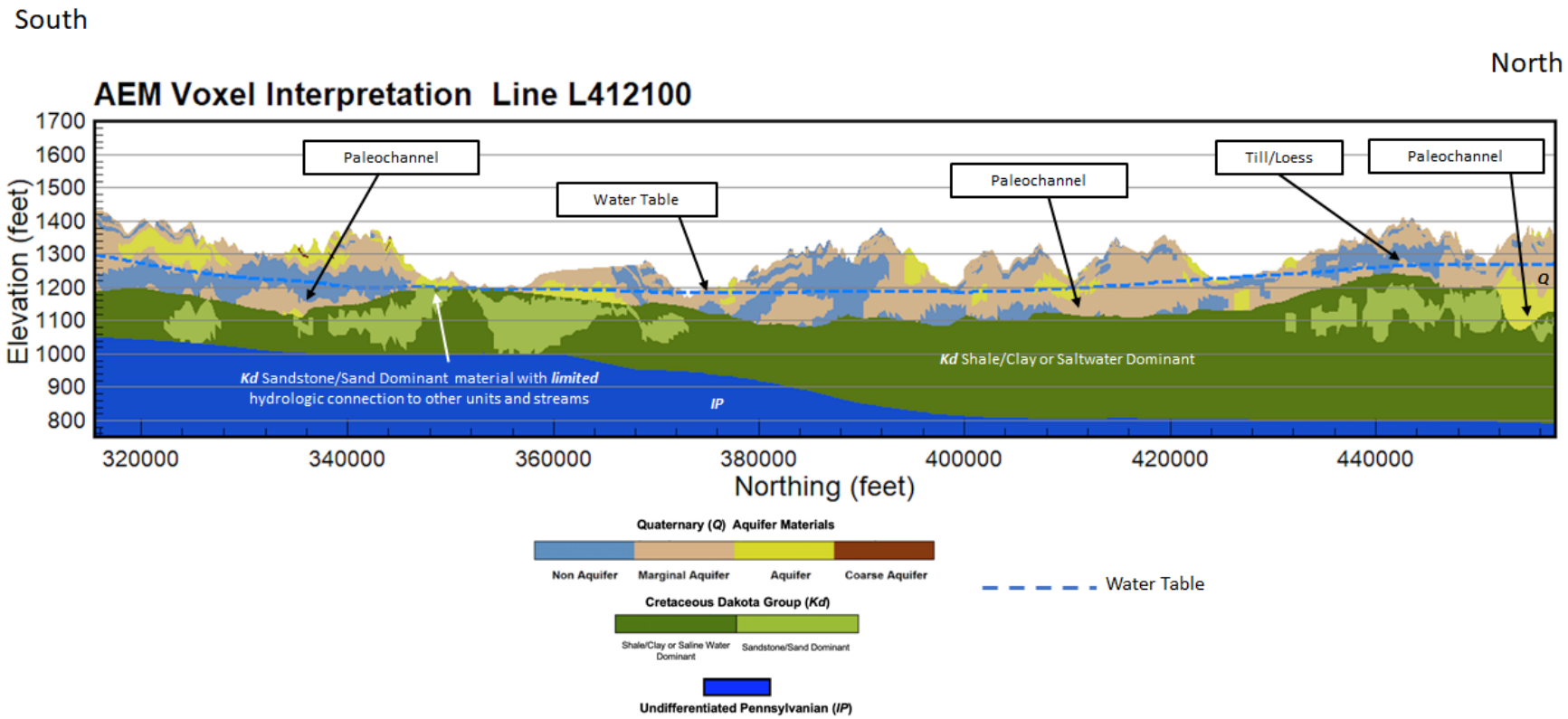


Figure 3-90. Interpreted north-south line L412100 lies ~3 miles west of the Lincoln airport. The *Q* sediments cover the area and are mostly made up of marginal and non-aquifer material with small areas of aquifer material distributed across the line. There is a *Kd* high near northing 345000 and the *Q* is very thin there and is in contact with *Q* aquifer material with a limited hydrologic connection. *Kd* Sandstone/Sand dominant material is limited in along the line. The geologic units present in this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*=Undifferentiated Pennsylvanian. The CSD 1995 water table is indicated with a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

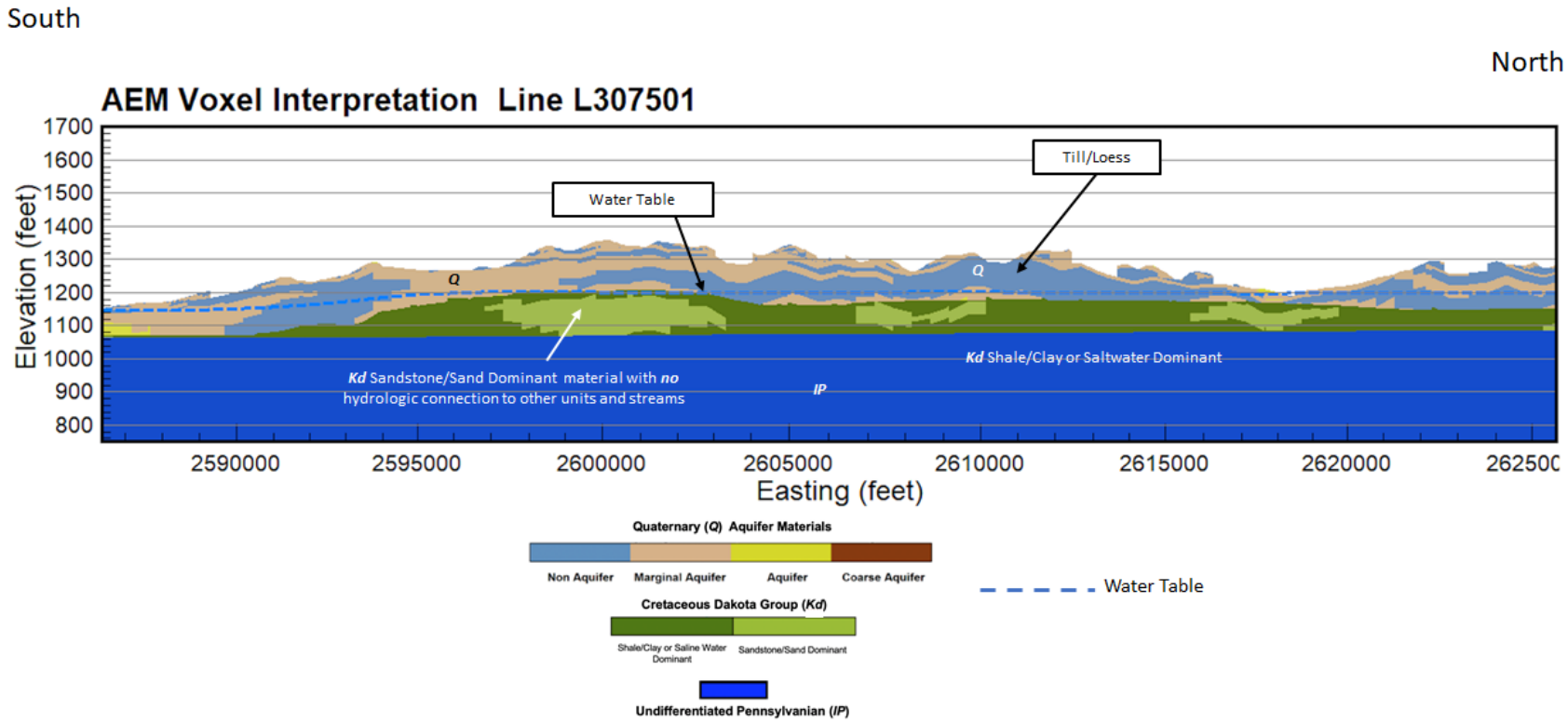


Figure 3-91. Interpreted east-west line, L307501, is approximately one mile east of Lincoln north of Highway 34, Nebraska. The geologic units present in this image include the *Q, Kd* and *IP* units. The *Q* overlies both the *Kd* and *IP* and is in contact with the *IP* in west and the *Kd* in the east. There is no hydrologic connection where the *Kd* Sand/Sandstone Dominant materials with the *Q* materials or surface water. The geologic units present in this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*=Undifferentiated Pennsylvanian. The CSD 1995 water table is indicated with a dashed blue line. Horizontal datum is NAD83 State Plane Nebraska (feet).

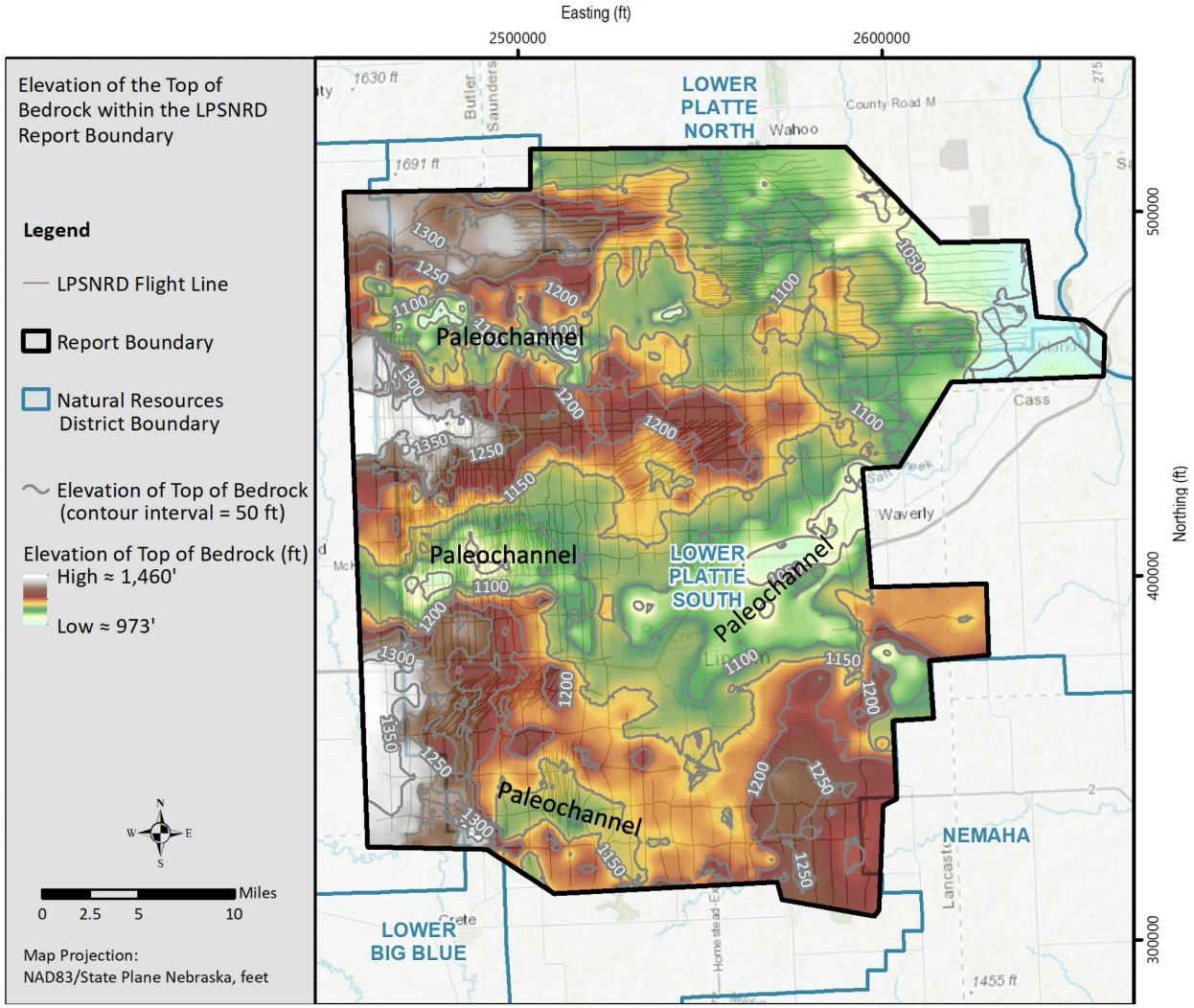


Figure 3-92. Map of the elevation of the top surface of the bedrock composed of *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, and *IP*= undifferentiated Pennsylvanian within the 2018 LPSNRD Reconnaissance AEM survey area. Flight lines are indicated by the grey lines. The elevation varies from 960 to 1,460 feet and generally slopes from west to east. Note the paleochannels that are incised into the bedrock surface along the west side of the project area. Horizontal datum is NAD83 State Plane Nebraska (feet).

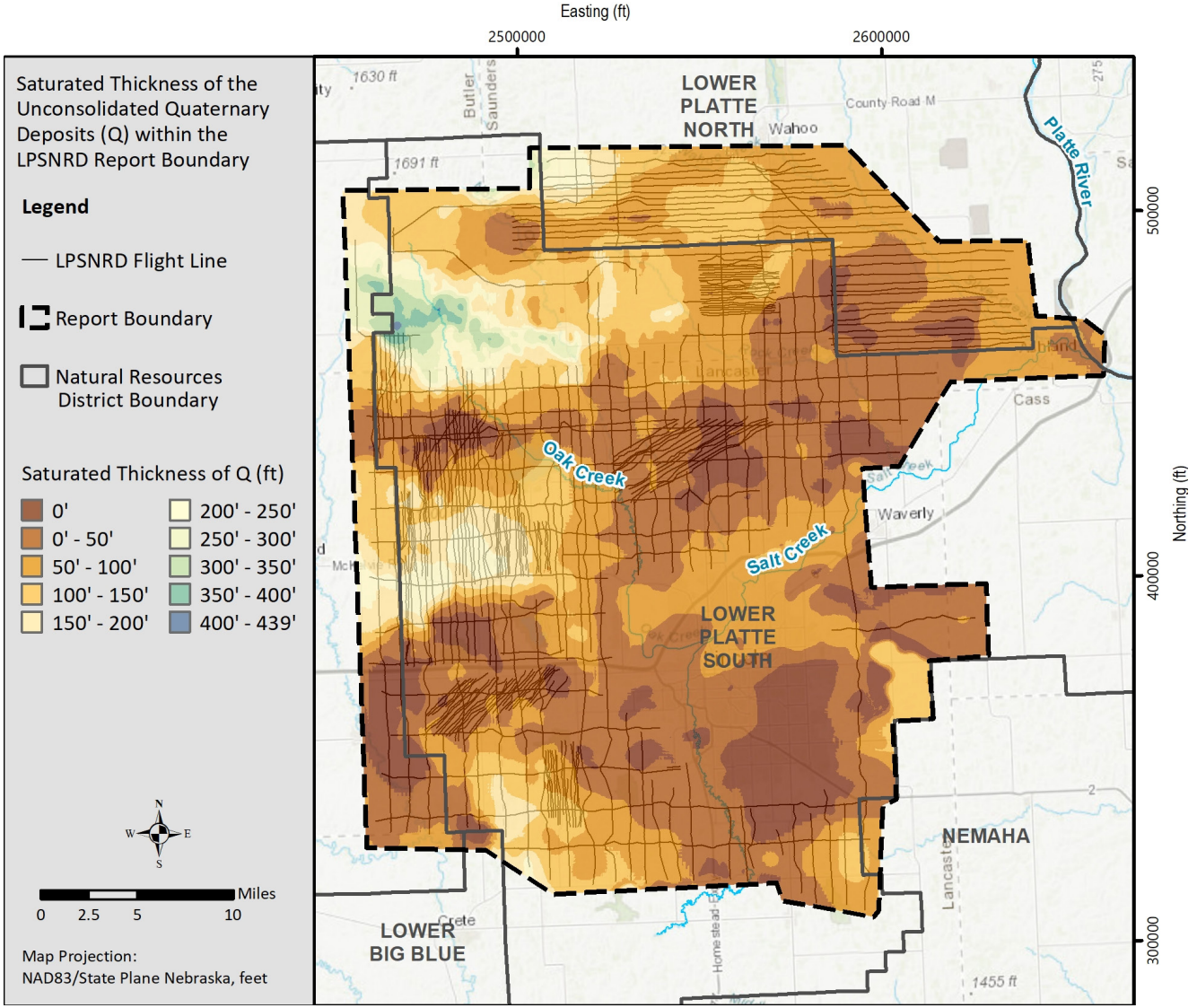


Figure 3-93. Map of the saturated thickness of *Q* aquifer materials within the 2018 LPSNRD Reconnaissance survey area. Saturated thickness varies from 0 to 439 feet. Flight lines are indicated by the grey lines. Note the greater thicknesses are on the west side of the project area. The geologic unit present in this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

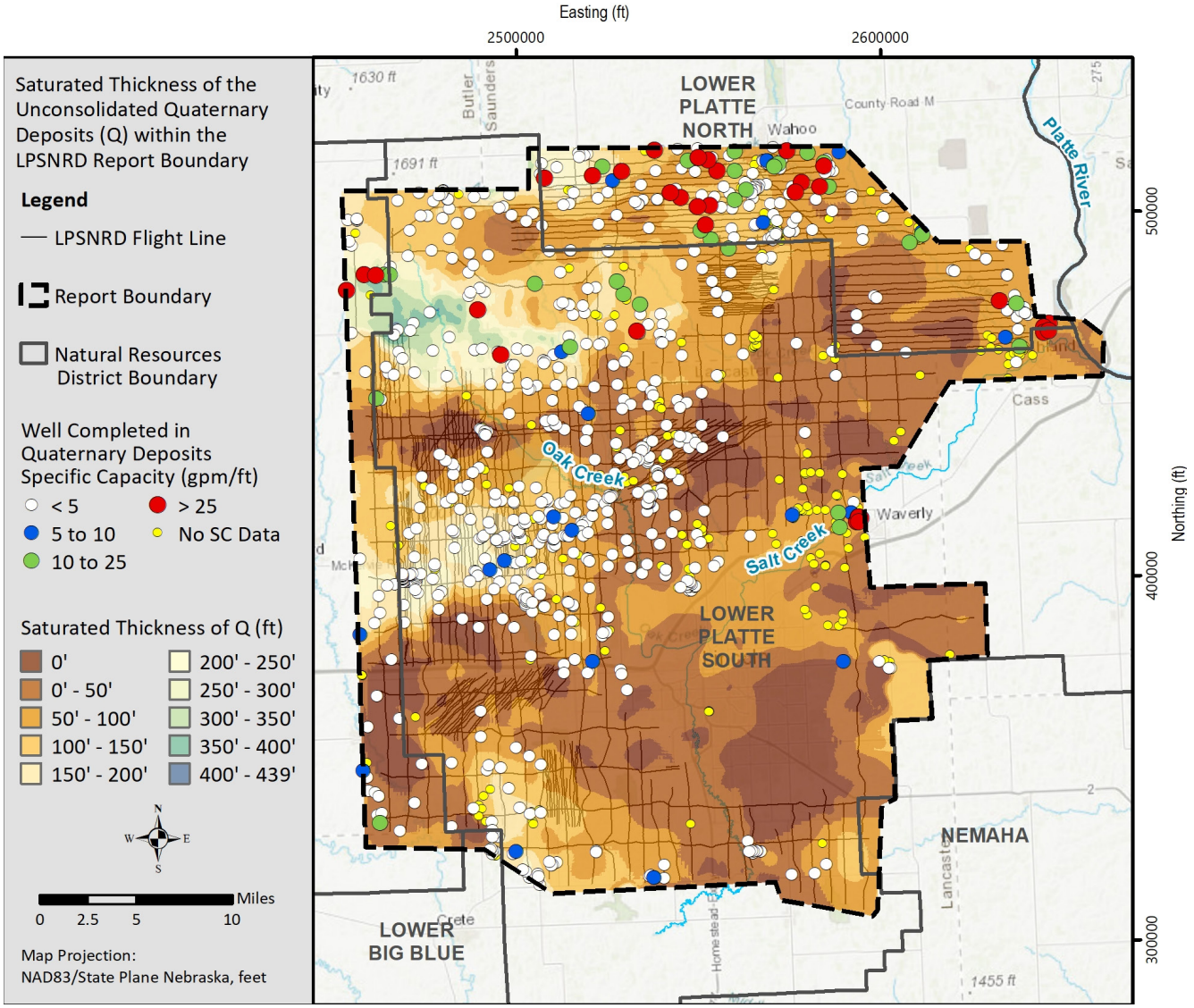


Figure 3-94. Map of the saturated *Q* aquifer thickness for the LPSNRD 2018 Reconnaissance AEM survey area plus the specific capacity of wells screened within the *Q* from the NE-DNR registered well database. The specific capacity of the wells range from <5 to >25 gpm. Overall the <5 gpm wells make up most of the wells in the project area. Horizontal datum is NAD83 State Plane Nebraska (feet).

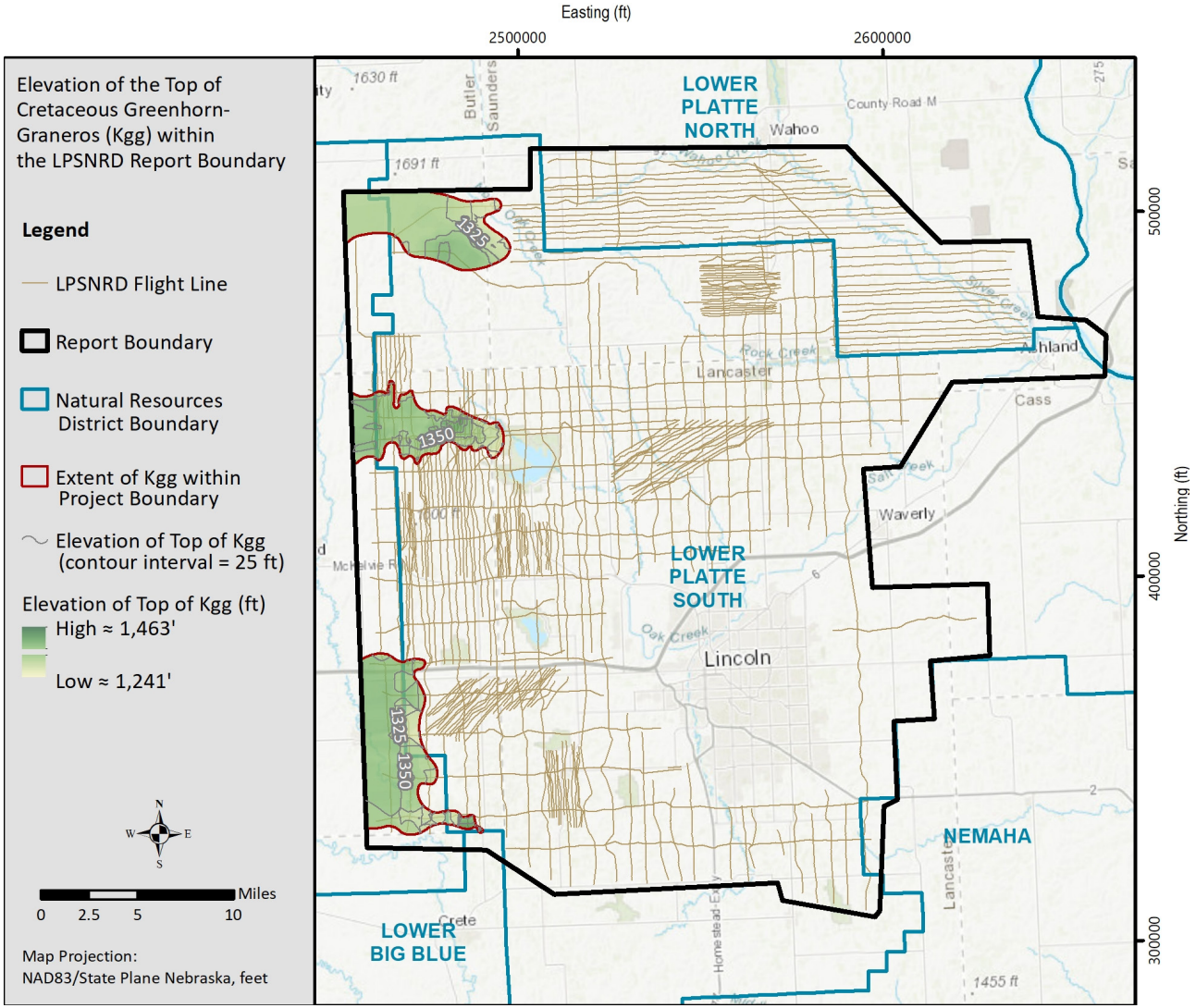


Figure 3-95. Map of the top surface of the *Kgg* within the 2018 LPSNRD Reconnaissance AEM survey area. The *Kgg* is present as small deposits in the west side of the area and varies in elevation from 1,241 to 1,463 feet from west to east. Flight lines are indicated by the grey lines. The geologic units present in this image include *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale. Horizontal datum is NAD83 State Plane Nebraska (feet).

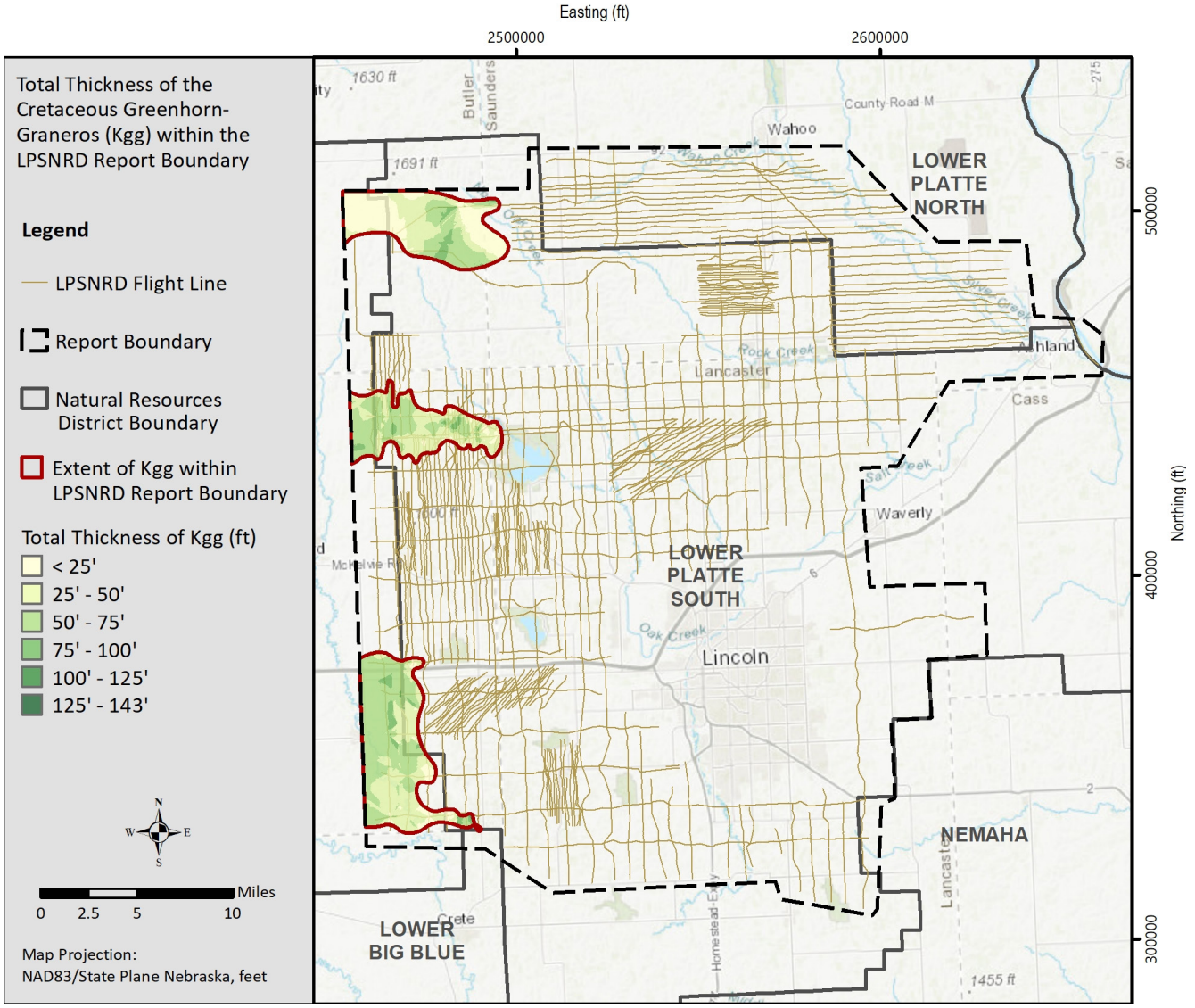


Figure 3-96. Map of the Total Thickness of the *Kgg* within the 2018 LPSNRD Reconnaissance AEM survey area. The *Kgg* (Cretaceous Greenhorn Limestone and Graneros Shale) is present as small deposits in the west side of the area and varies in thickness from <25 to 143 feet. Flight lines are indicated by the grey. Horizontal datum is NAD83 State Plane Nebraska (feet).

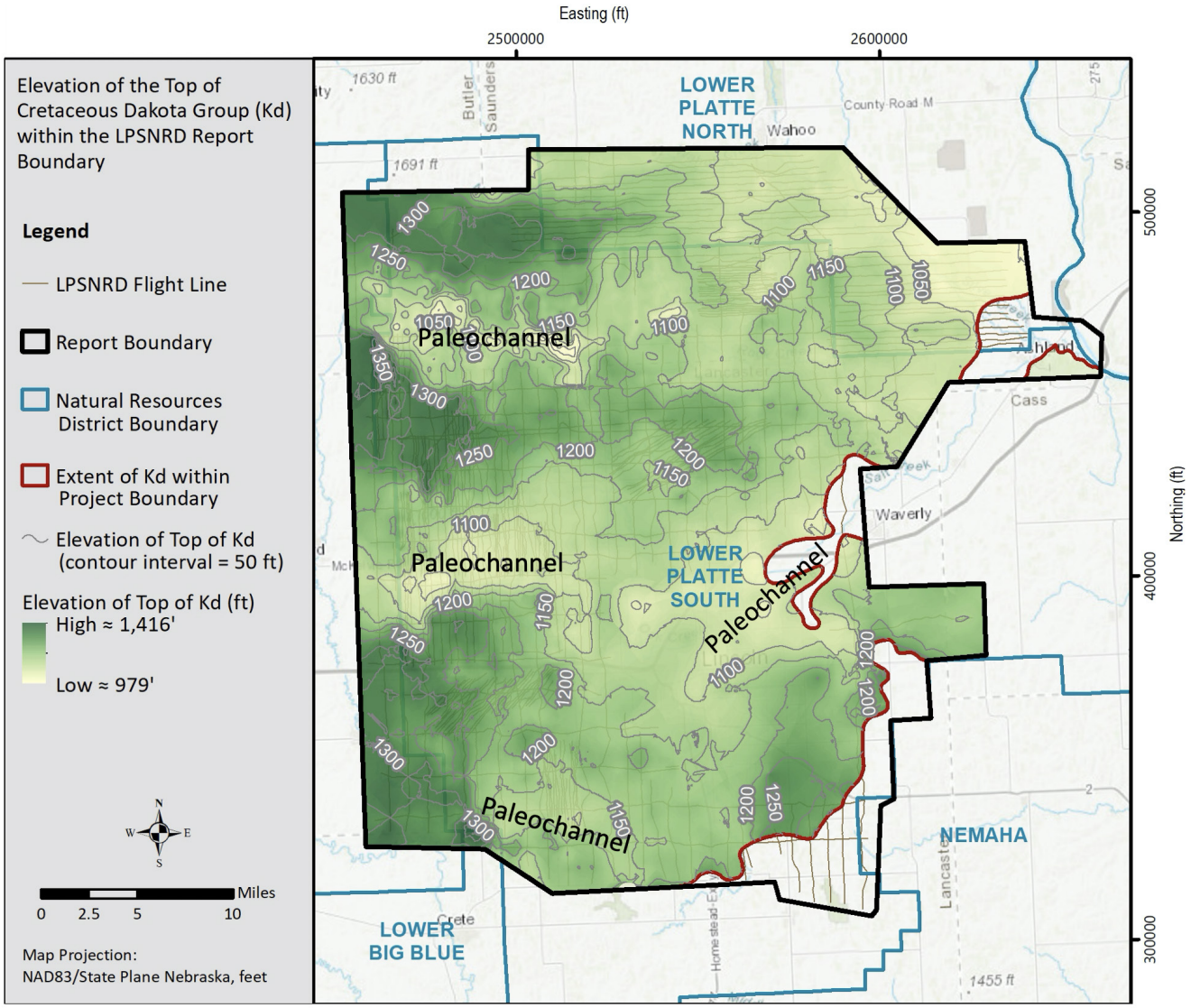


Figure 3-97. Map of the top surface elevation of the of the *Kd* within the 2018 LPSNRD Reconnaissance AEM survey area. The *Kd* (Cretaceous Dakota Group) is present in most of the LPSNRD AEM survey area and varies in elevation 979 to 1,416 feet and slopes from west to east. Flight lines are indicated by the grey lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

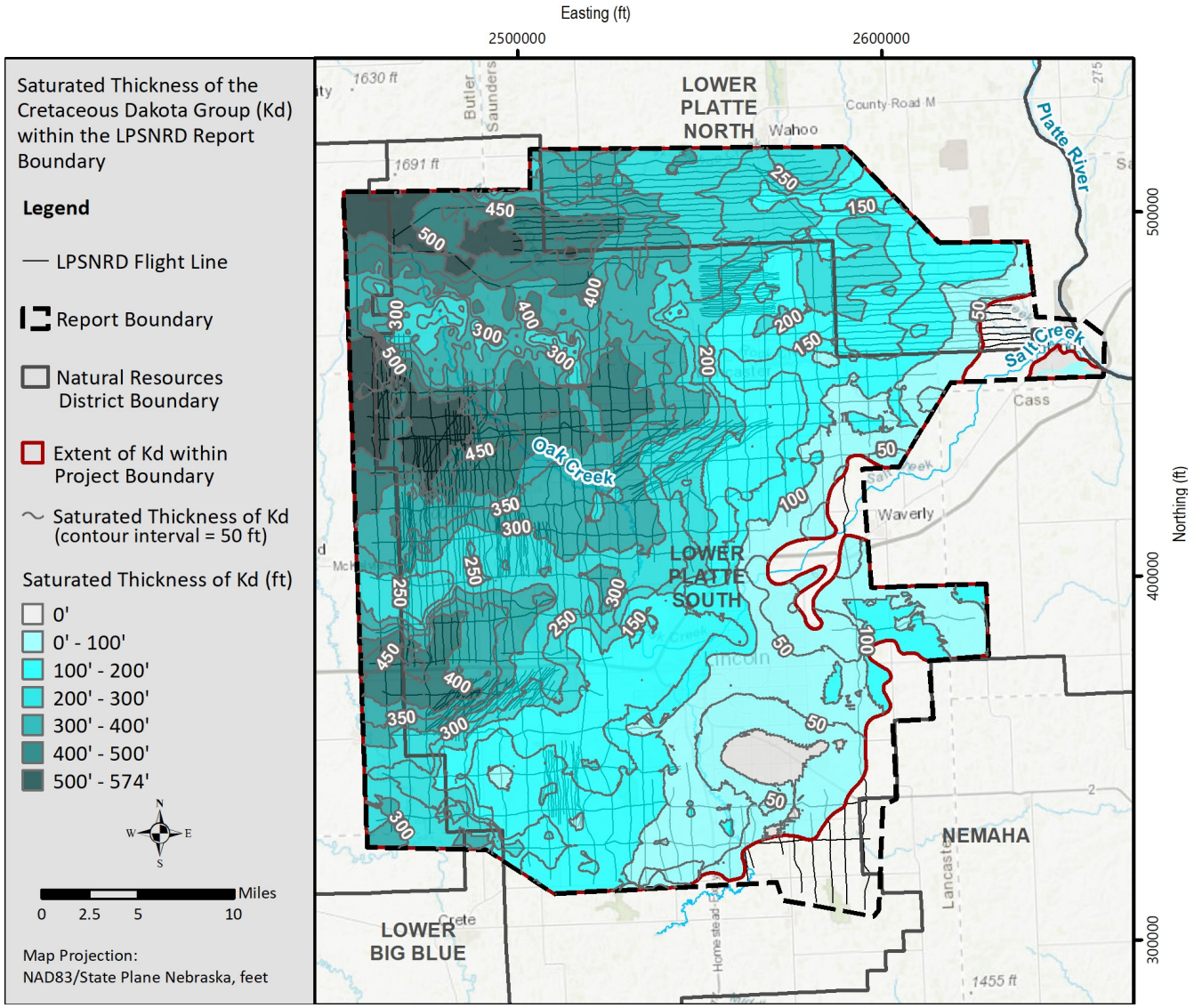


Figure 3-98. Map of the saturated thickness of the *Kd* within the 2018 LPSNRD Reconnaissance AEM survey area. The thickness varies from 0 to 574 feet with the thickest areas along the western line of the project area. Flight lines are indicated by the grey lines. The geologic unit present in this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

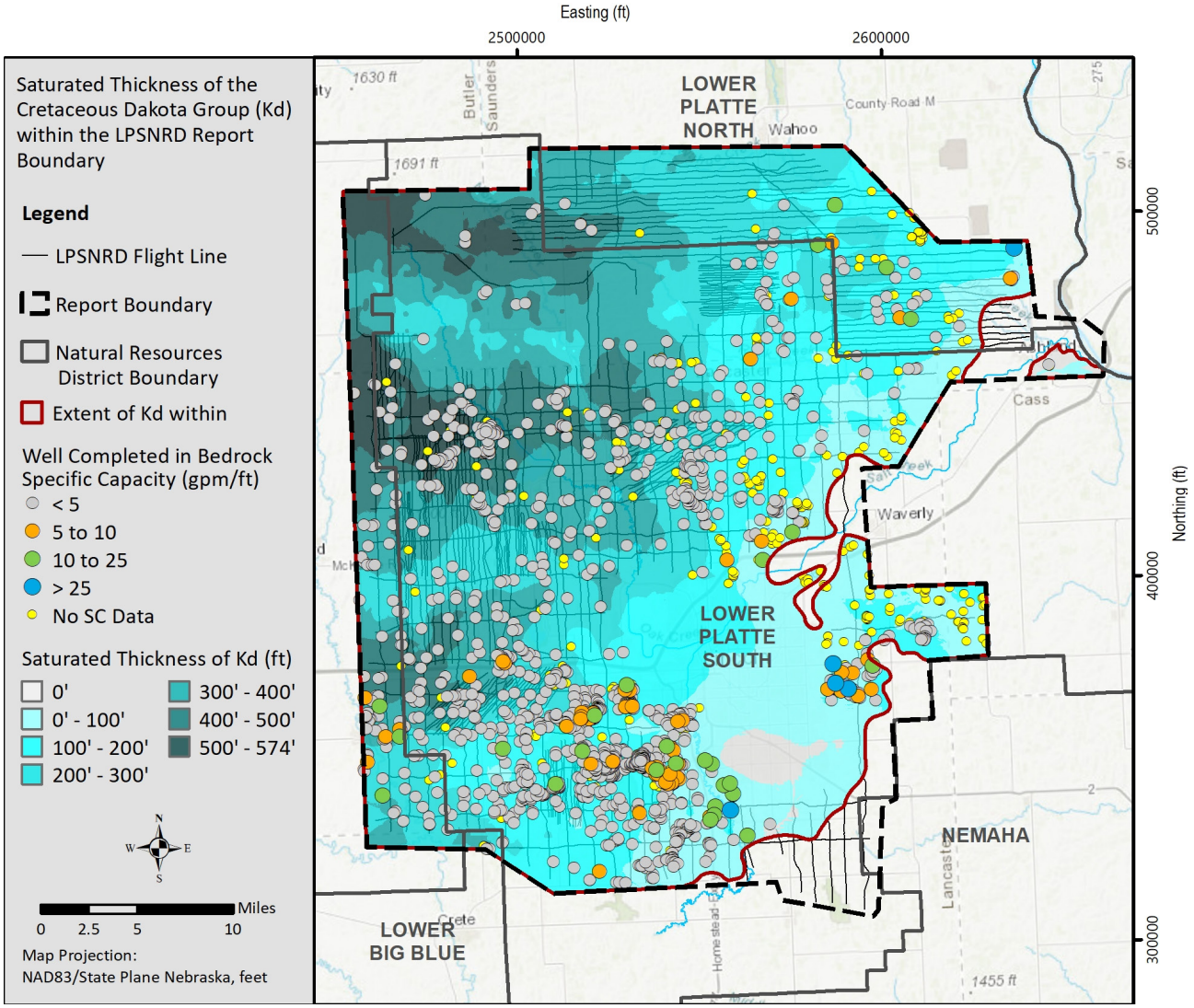


Figure 3-99. Map of the saturated *Kd* aquifer thickness for the LPSNRD 2018 Reconnaissance AEM survey area plus the specific capacity of wells screened within the *Kd* from the NE-DNR registered well database. The specific capacity of the wells varies from <5 to >25 gpm. Overall the <5 gpm wells make up most of the wells in the project area. Flight lines are indicated by the grey lines. The geologic unit present in this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

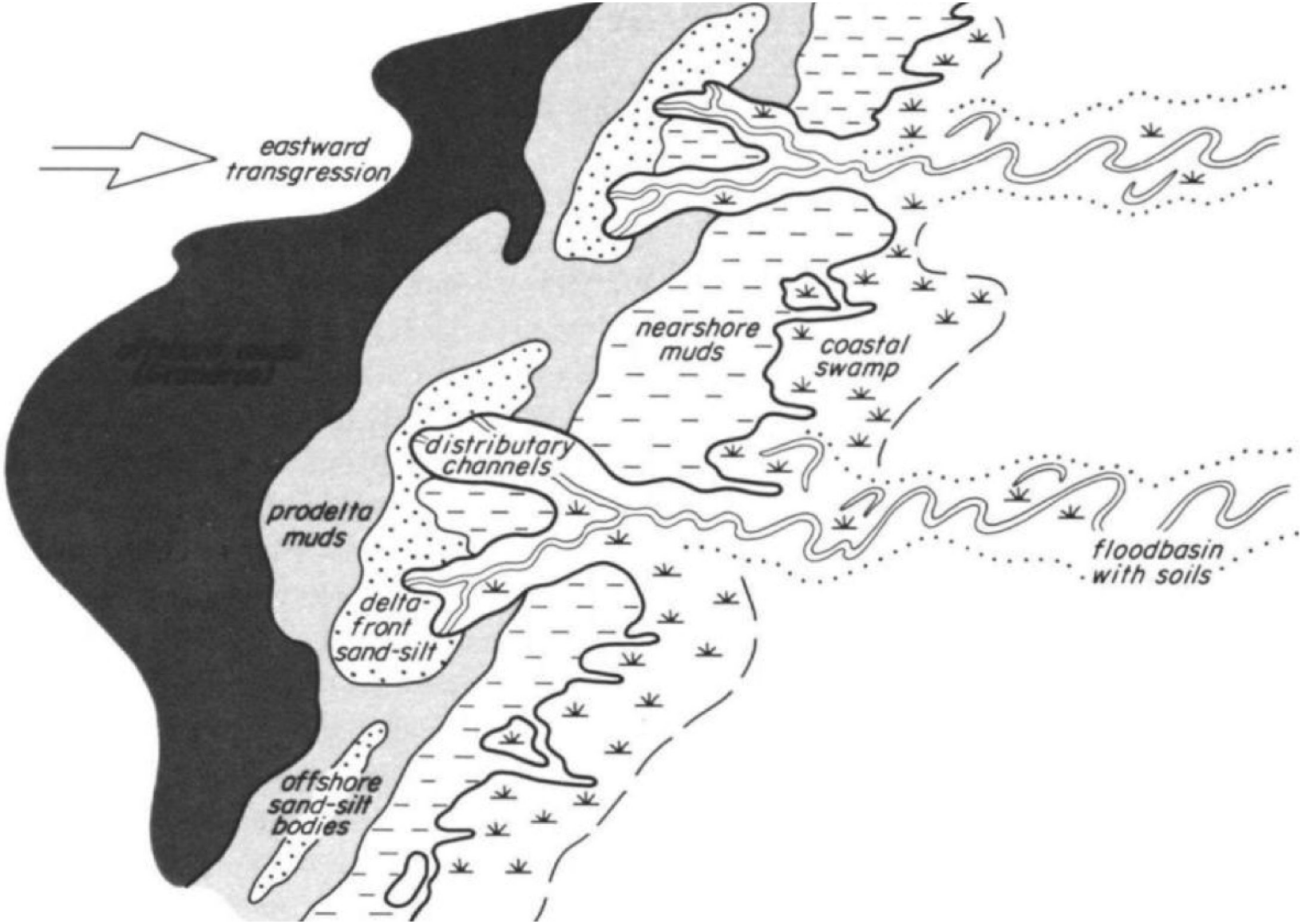


Figure 3-100. Depositional environment of the Cretaceous Dakota Group (*Kd*) sediments in eastern Nebraska and western Iowa (Witzke and Ludvigson, 1994).

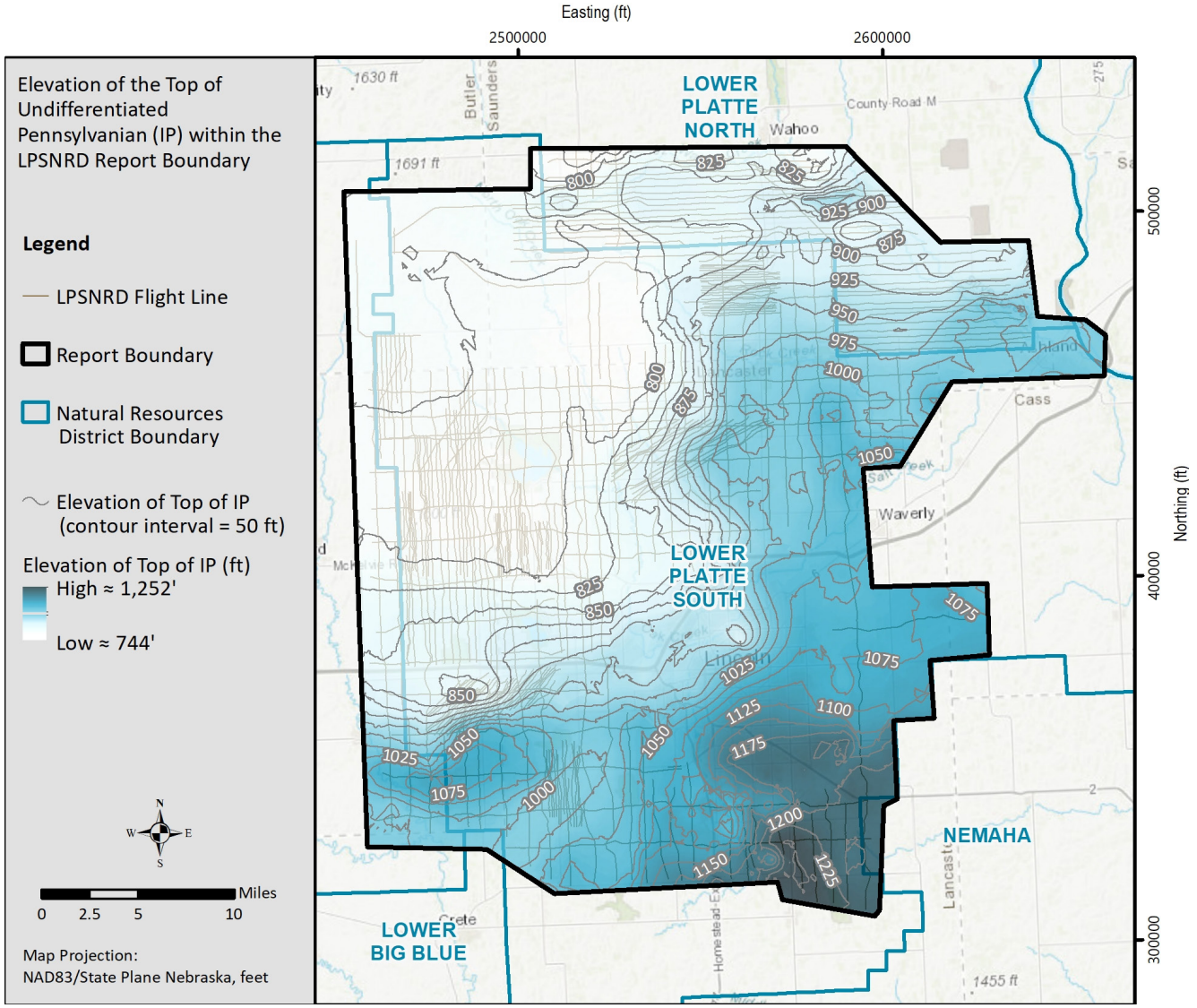


Figure 3-101. Map of the top surface elevation of the of the *IP* within the 2018 LPSNRD Reconnaissance AEM survey area. The *IP* (Undifferentiated Pennsylvanian) is present throughout the LPSNRD AEM survey area and varies in elevation 744 to 1,252 feet and slopes from east to west. Flight lines are indicated by the grey lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

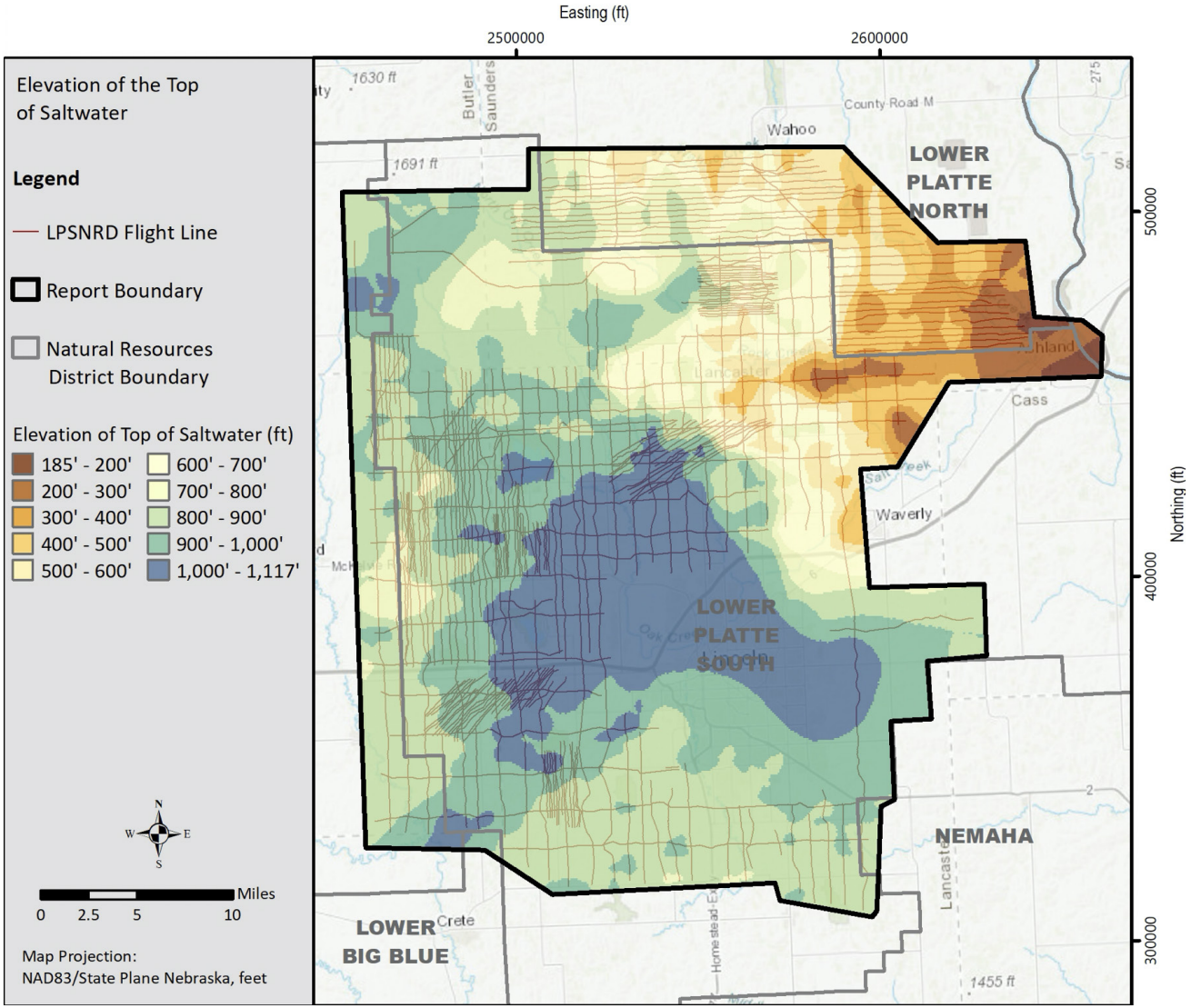


Figure 3-102. Map showing where saltwater is present within the project area and these areas represent where a value of 4 ohm/m which indicates the presence of saltwater. Flight lines are indicated by the grey lines. Horizontal datum is NAD83 State Plane Nebraska (feet). Section 3.1 explains how this determination was made.

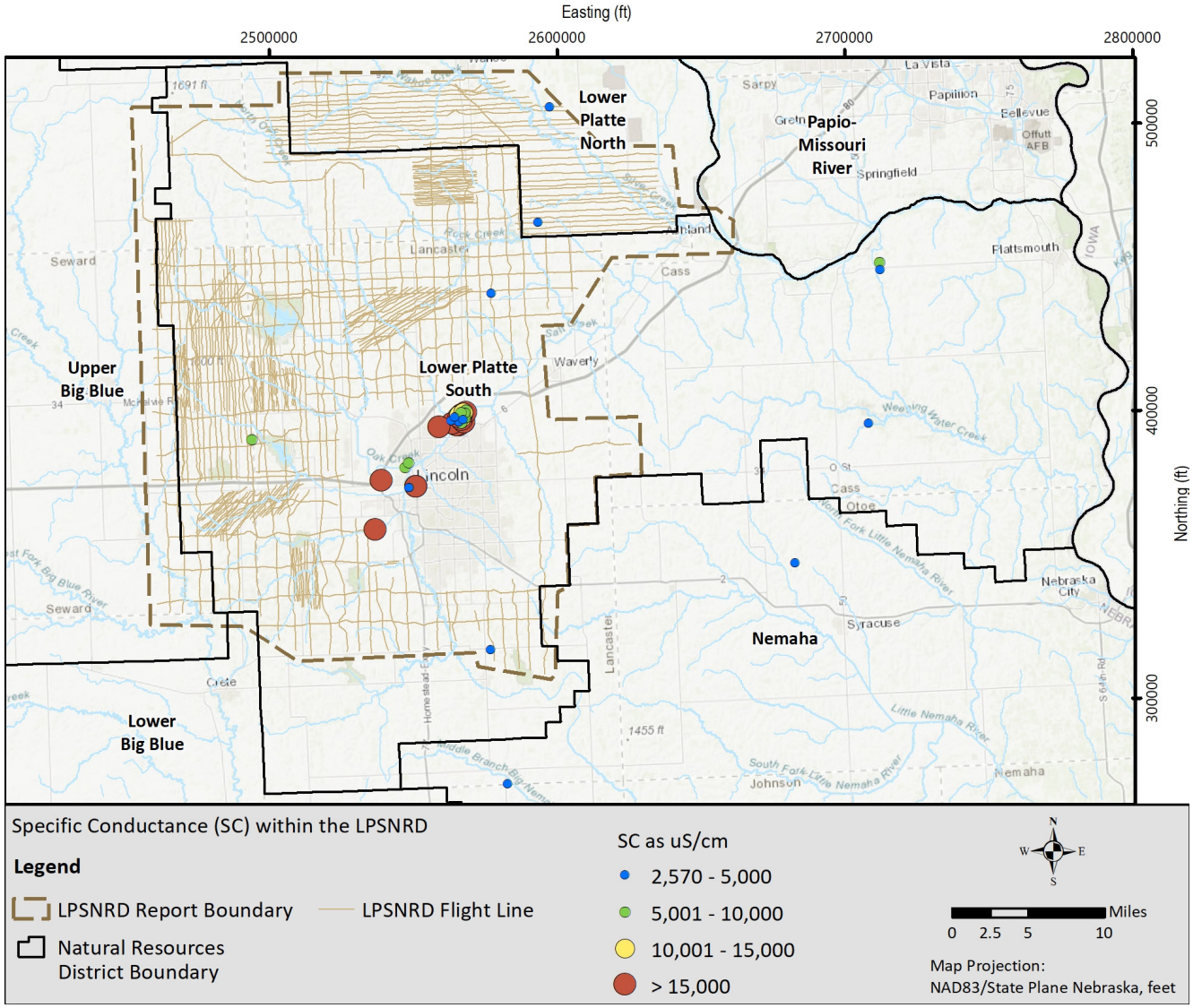


Figure 3-103. Map of wells including the values of specific conductance in µS/cm from groundwater samples taken from wells (USGS, 2019b). The samples taken near Lincoln, Nebraska shows the highest values and indicate the presence of saltwater Flight lines are indicated by the yellow lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

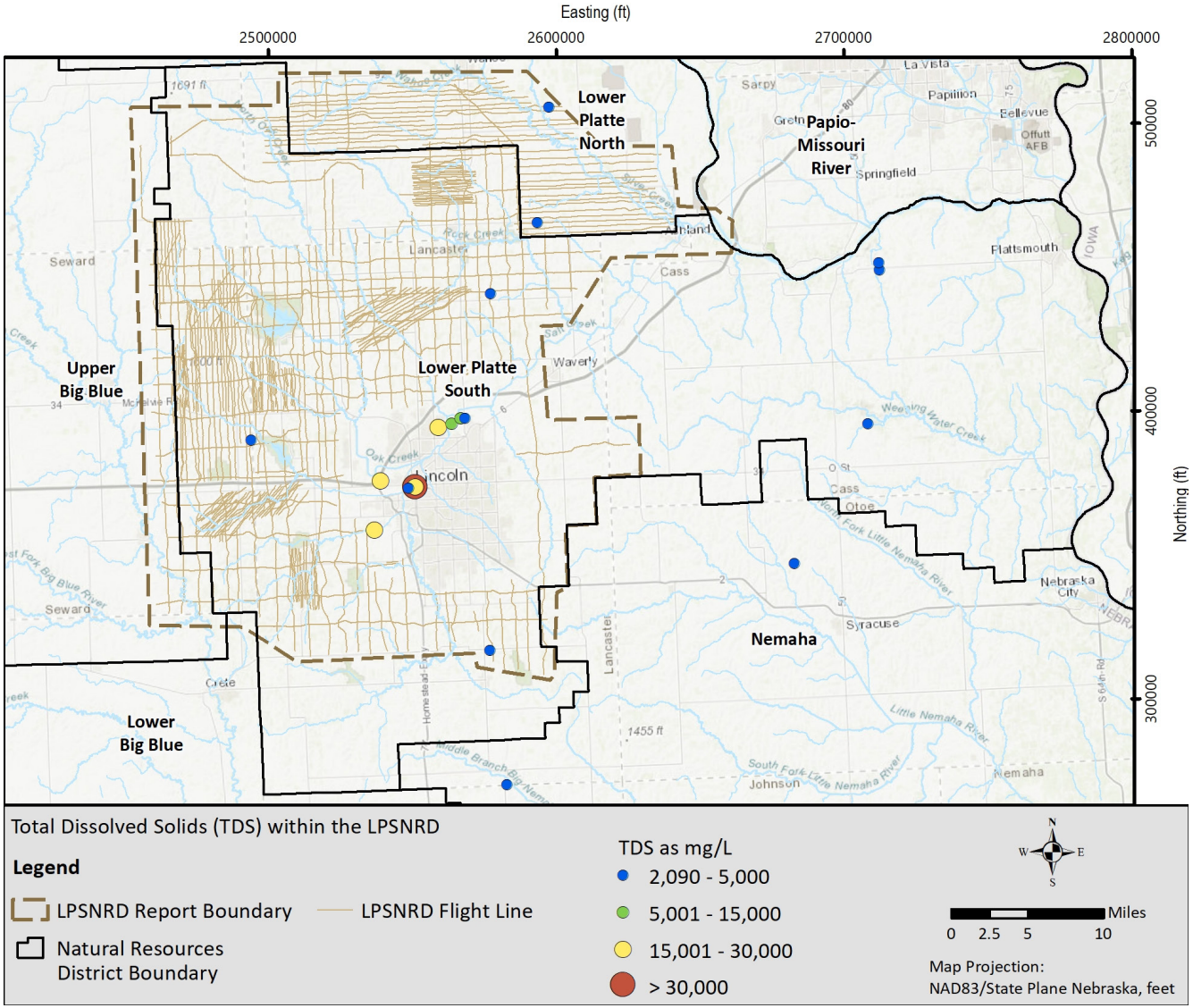


Figure 3-104. Map of wells including the values of Total Dissolved Solids in mg/l from groundwater samples taken from wells (USGS, 2019b). The samples taken near Lincoln, Nebraska shows the highest values and indicate the presence of saltwater. Flight lines are indicated by the yellow lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

3.2.2 Hydrogeologic Framework of the Ceresco Block Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material and the Cretaceous units in the Ceresco Block AEM survey area. The ***Q*** materials within the Ceresco Block are composed of unconsolidated clay, silt, sand and gravel that overlie the consolidated bedrock which is made up of ***Kd*** and ***IP***. The ***Q*** material in the Ceresco Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1. Figure 3-105 is the flight line location map including roads, streams and towns. Generally, the flight block is near Highway 77 where it crosses the North Fork of Rock Creek. The ground surface elevation map shown on Figure 3-106, shows the rolling hills nature of the Ceresco Block. Figure 3-107 displays a 3D fence diagram of the Ceresco Block AEM survey area, looking to the northeast, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** aquifer materials lying upon the ***Kd*** which lies upon the ***IP***. The ***Kd*** contains a mix of Shale/Clay or Saltwater Dominant and Sandstone/Sand Dominant materials.

Figure 3-108 presents 2D profile L409001, located west of Highway 77. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line and the ***Kd*** materials. Note that the ***Q*** aquifer materials and the ***Kd*** sandstone/sand materials are in contact and have a hydrologic connection. The CSD 1995 water table is also on the profile and shows the water table for the area.

The total thickness of the ***Q*** material in the Ceresco Block AEM survey area Figure 3-109 was gridded by subtracting the bedrock elevation (Figure 3-110) from the ground surface elevation (Figure 3-106). The greatest thickness is in the central part of the Ceresco Block AEM survey area. The ***Q*** material varies in thickness from <50 to 283 feet. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to the hydrologic connection of those materials to the surface water of the area. The aquifer and coarse aquifer materials which make up the bulk of ***Q*** aquifer materials present provide the greatest connection for water movement through all of the ***Q*** aquifer materials. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995) (Figure 3-111)to obtain the total saturated thickness of ***Q*** material. Note that the water table slopes from northwest to southeast. The saturated thickness for all aquifer material is shown for the Ceresco Block is on Figure 3-112. The thickness of these materials varies between 0 to 185 feet. The saturated thickness mostly 50-100 feet across the area with the thickest area in the southeast and the thinnest are in the southeast.

Figure 3-113 Is a map of the ***Kd*** surface elevation which ranges in elevation from 1,027 to 1,196 feet. There are low areas in the southeast corner and near Highway 77 but overall the ***Kd*** is a relatively flat lying surface sloping from west to east with a depression in the southeast corner of the area. The thickness map of the ***Kd*** is shown in Figure 3-114. The thickness of the ***Kd*** varies from 125 to 345 feet with the thickest are in the northwest corner and is thin near an area near Highway 77 which correlates with the lowest elevation of the top surface of the ***Kd***.

Figure 3-115 shows the interpreted 2D profile L302001 is an east-west line near the south-center of the block area. Near easting 2555000 there is a ***Kd*** Sandstone/Sand dominant material which has a direct hydrologic connection with the overlying ***Q*** aquifer material. It should be noted that the presence of ***Q*** aquifer material near northing 2560000 extends from the ***Kd*** surface to the land surface over a long distance and is a possible glaciotectonic feature resulting from aquifer material that is pushed up on the end of a Figure 3-116 moraine.

shows the interpreted 2D profile L303001 which is an east-west profile in the along the southern end of the Ceresco area. Near easting 2565000 there is a ***Kd*** Sandstone/Sand dominant material which has a direct hydrologic connection with the overlying ***Q*** aquifer material. Near easting 2570000 there is a ***Kd*** Sandstone/Sand dominant material which has a direct hydrologic connection with the overlying ***Q*** coarse aquifer material. This is also an area the extends from the ***Kd*** surface to the land surface over a long distance and is a possible glaciotectonic feature resulting from aquifer material that is pushed up on the end of a moraine.

An exploded view of the voxel model showing the ***Q***, both saturated and unsaturated, the ***Kd***, and the ***IP*** formations is presented in Figure 3-117. The ***Q*** materials show mostly aquifer and some coarse aquifer materials mixed with marginal and non-aquifer materials. Nearly all of the materials shown are saturated because of the water table being in close proximity to the land surface in places. Because of the near land-surface water table conditions in the Ceresco block there is limited ability for managed aquifer recharge (MAR) sites to be located within. Figure 3-118 shows the saturated thickness of the ***Q*** aquifer and coarse aquifer materials. The saturated aquifer and coarse aquifer materials range in thickness from <25 feet near the edges of the flood plain to 148 feet in the paleochannels.

The map of saturated thickness for ***Q*** deposits and specific capacity of wells completed in the ***Q*** (Figure3-119) shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with only 1 well with a specific capacity of 10 to 25 gpm/ft.

A view of 3D voxel model looking northwest showing the ***Q***, ***Kd*** and ***IP*** of the Ceresco Block AEM survey area is presented in Figure 3-120. The western area of the block shows more marginal and non-aquifer material at the land surface and the east end shows more aquifer and coarse aquifer material at the land surface. This may be indicative of a possible glaciotectonic feature present in the east. Figure 3-121 presents a view to the west of the Ceresco Block showing a 3D voxel of both ***Q*** aquifer material and the coarse aquifer material and the underlying bedrock units with the unsaturated ***Q*** materials shown as a fence diagram on the Voxel. The nearly continuous nature of the ***Q*** aquifer and coarse aquifer material in the east to the center of the block may be indicative of a possible glaciotectonic feature present on the east side of the block. Figure 3-122 is a view to the northwest of a 3D voxel of the ***Q*** aquifer and coarse aquifer material overlying a surface depicting the topography/elevation of the top of the ***Kd*** Sandstone/Sand Dominant material which is in close contact or near contact to the ***Q***. Figure 3-123 presents the same 3D voxel as in Figure 3-122 from another view with CSD and NE-DNR lithology logs.

Figure 3-124 presents a map of the saturated thickness for ***Kd*** Sandstone/Sand Dominant deposits. The deposits vary in thickness from 14 to 211 feet and is discontinuous from south to north with a shale zone that goes through the middle of the block. The ***Kd*** sandstone/sand dominant material is an aquifer in this area. Figure 3-125 shows the relationship between the thickness of ***Kd*** and the specific capacity, in gpm/ft, for wells completed in the ***Kd***. Careful evaluation of the wells in Figure 3-125 shows only one well in the Ceresco block with a specific capacity of 5-10 gpm/ft the rest are <5 gpm/ft. The 5 to 10 gpm/ft well is located in the 150-200 feet thick saturated ***Kd*** Sandstone/Sand Dominant deposits. The best locations for well development are in the thick Sandstone/Sand Dominant zones of the ***Kd***.

lies underneath the Ceresco Block in the ***IP***. Figure 3-126 is a voxel model looking north and shows the affected area from saltwater in the ***IP***. Remember that saltwater is defined as resistivities less than or equal to 4 ohm-m. As seen in Figure 3-126, all of the Ceresco block is underlain by saltwater. Also remember to note that the material containing saltwater is only imaged to the depth of the model (Table 2-4) and so may be thicker than what is shown in the figures illustrating the presence of saline waters.

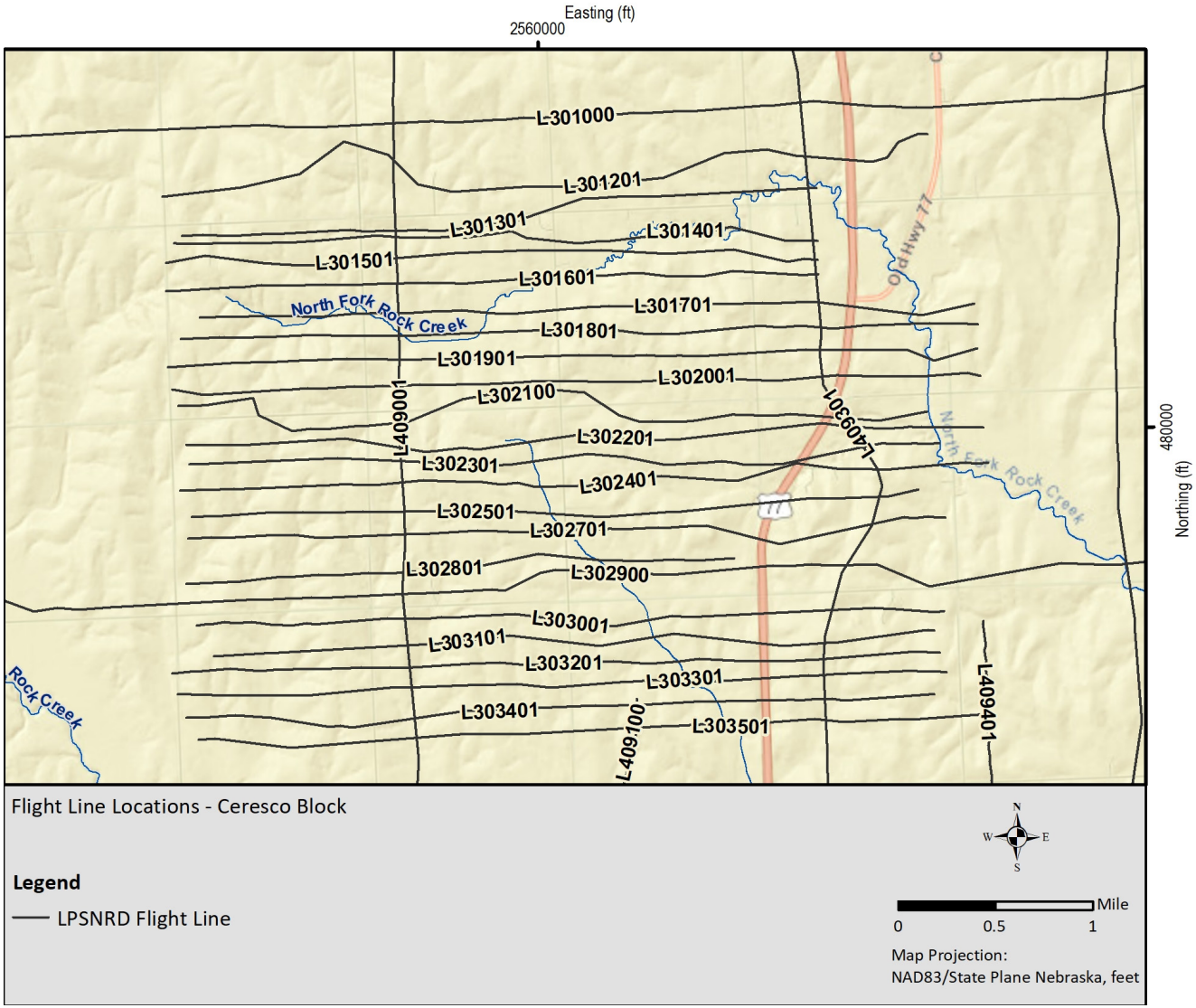


Figure 3-105. Location map of the Ceresco Block indicating numbered AEM flight lines, local roads, and streams. Generally, the flight block is near Highway 77 where it crosses the North Fork of Rock Creek. Block flight lines are indicated by black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

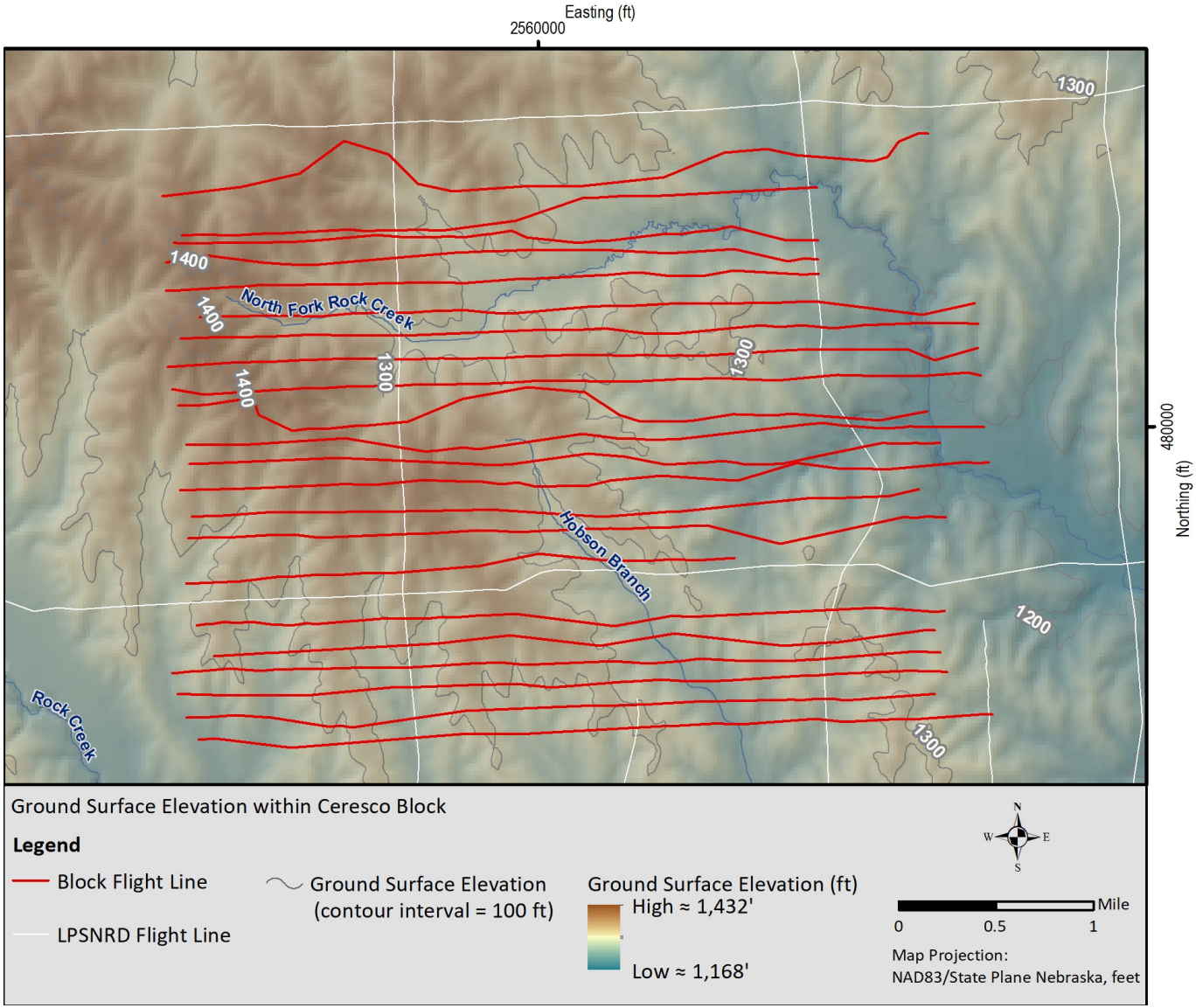


Figure 3-106. Map showing the ground surface elevation with flight lines in the Ceresco Block. Note the rolling hills nature of the ground surface. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

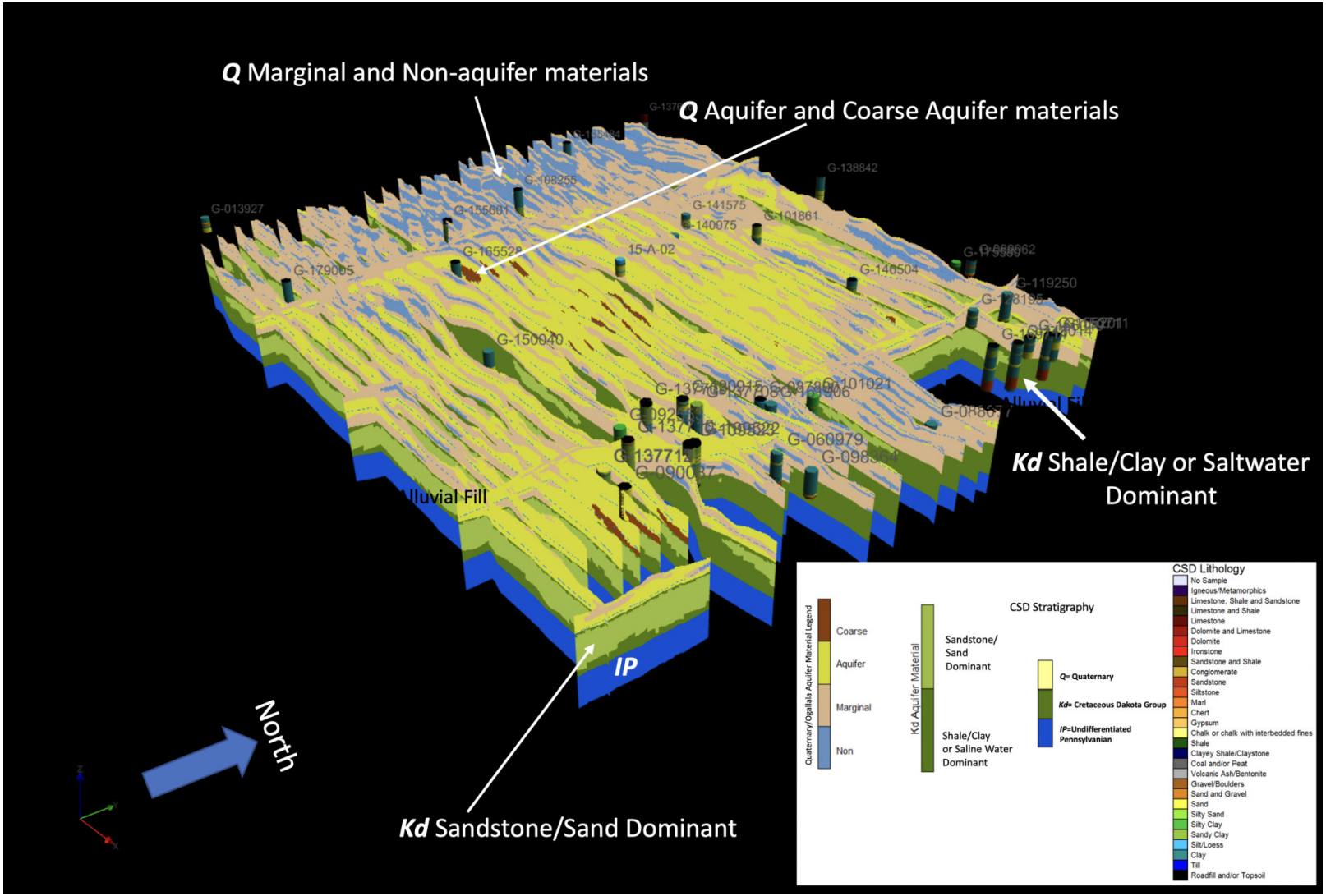


Figure 3-107. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Ceresco Block AEM survey area. CSD and NE-DNR wells are labeled. The area generally contains a mix of all *Q*= Quaternary aquifer materials lying upon the *Kd*= Cretaceous Dakota Group which lies upon the *IP*= Undifferentiated Pennsylvanian. The *Kd* contains a mix of Shale/Clay or Saltwater Dominant and Sandstone/Sand Dominant materials. Vertical exaggeration (VE) = 5x.

South North

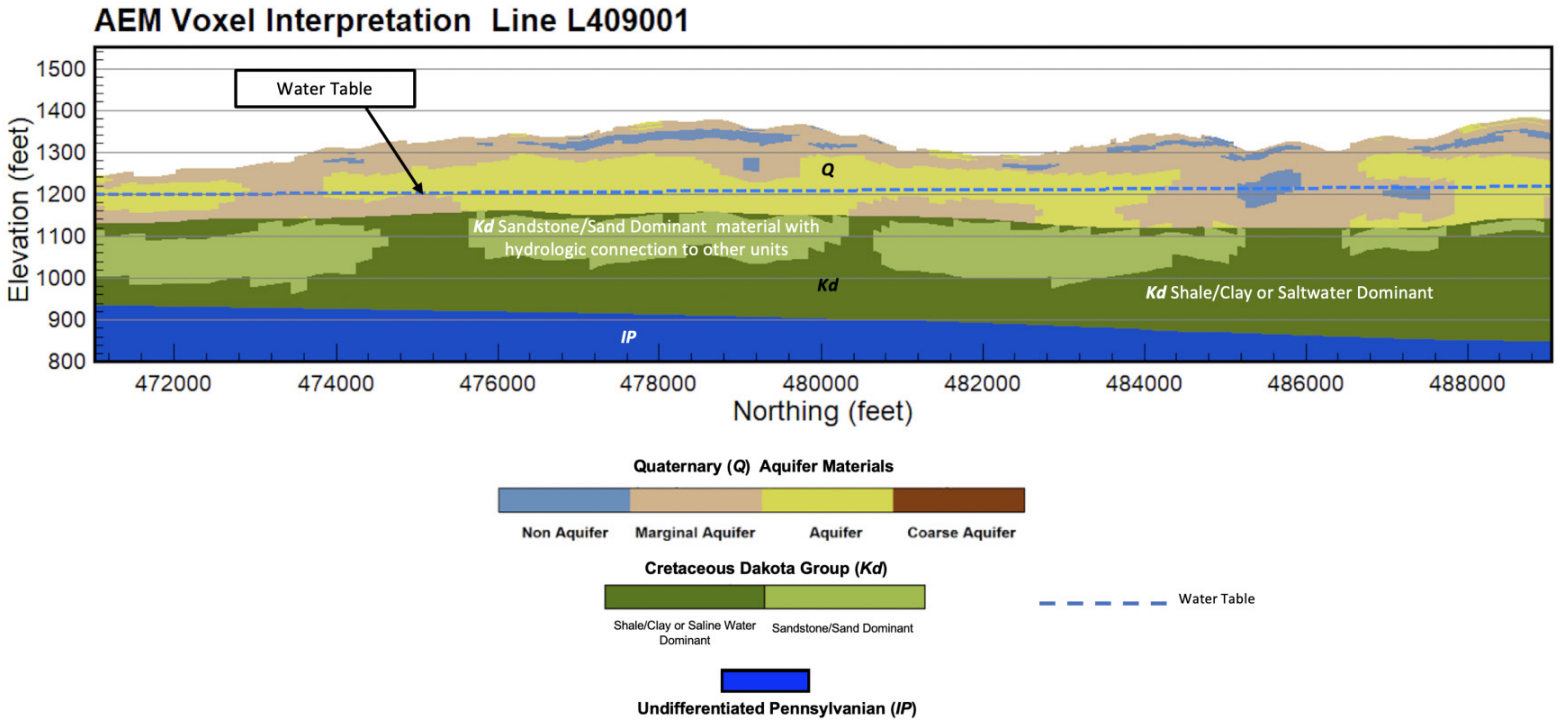


Figure 3-108. Profile of the east-west line L409001 showing Q. Note that the *Q* aquifer materials and the *Kd* sandstone/sand materials are in contact and have a hydrologic connection. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

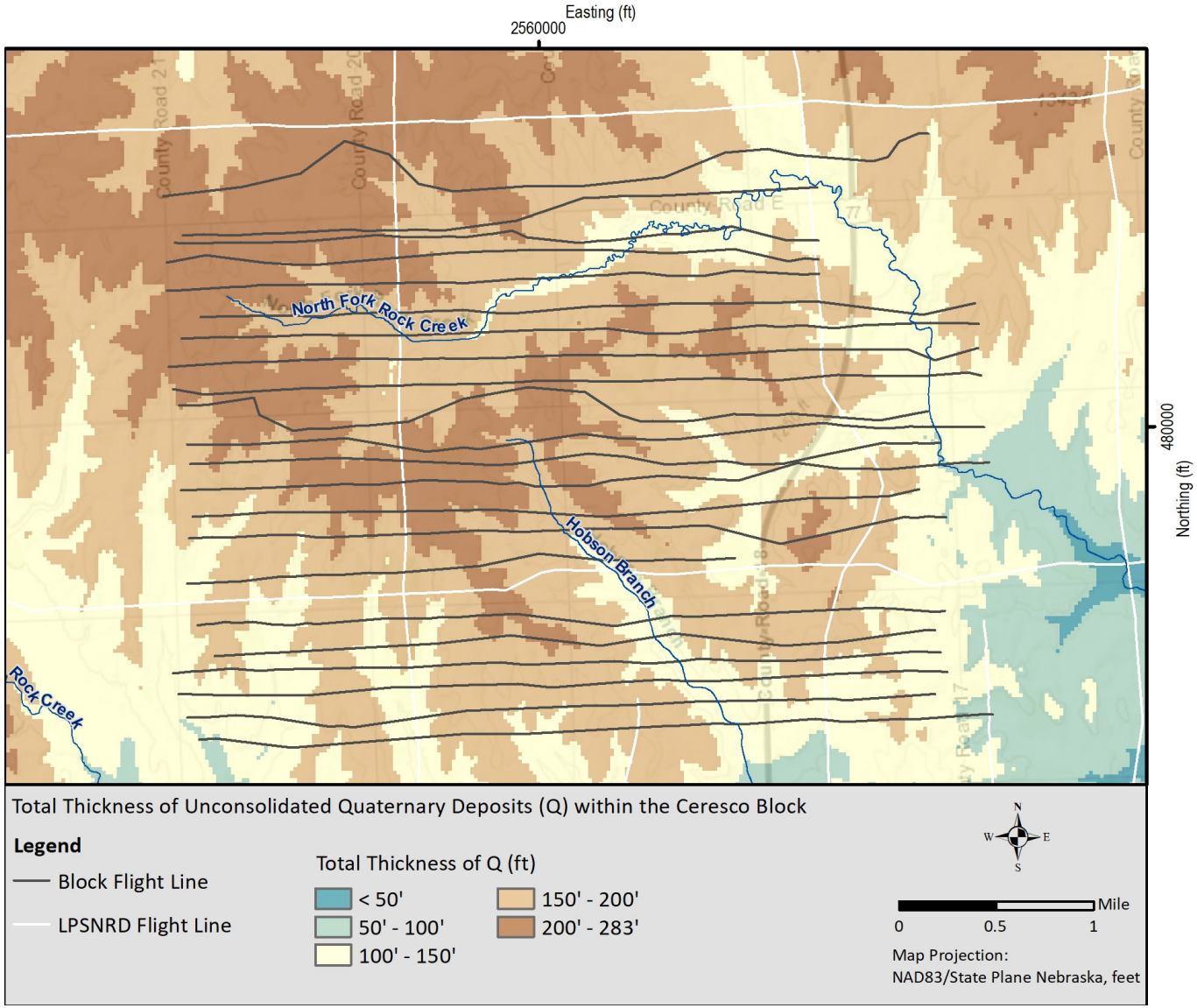


Figure 3-109. Map of the total thickness of the *Q* (Quaternary) deposits within the 2018 Ceresco Block AEM survey area. The thickest areas are near the center of the block. Block flight lines are indicated by white lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

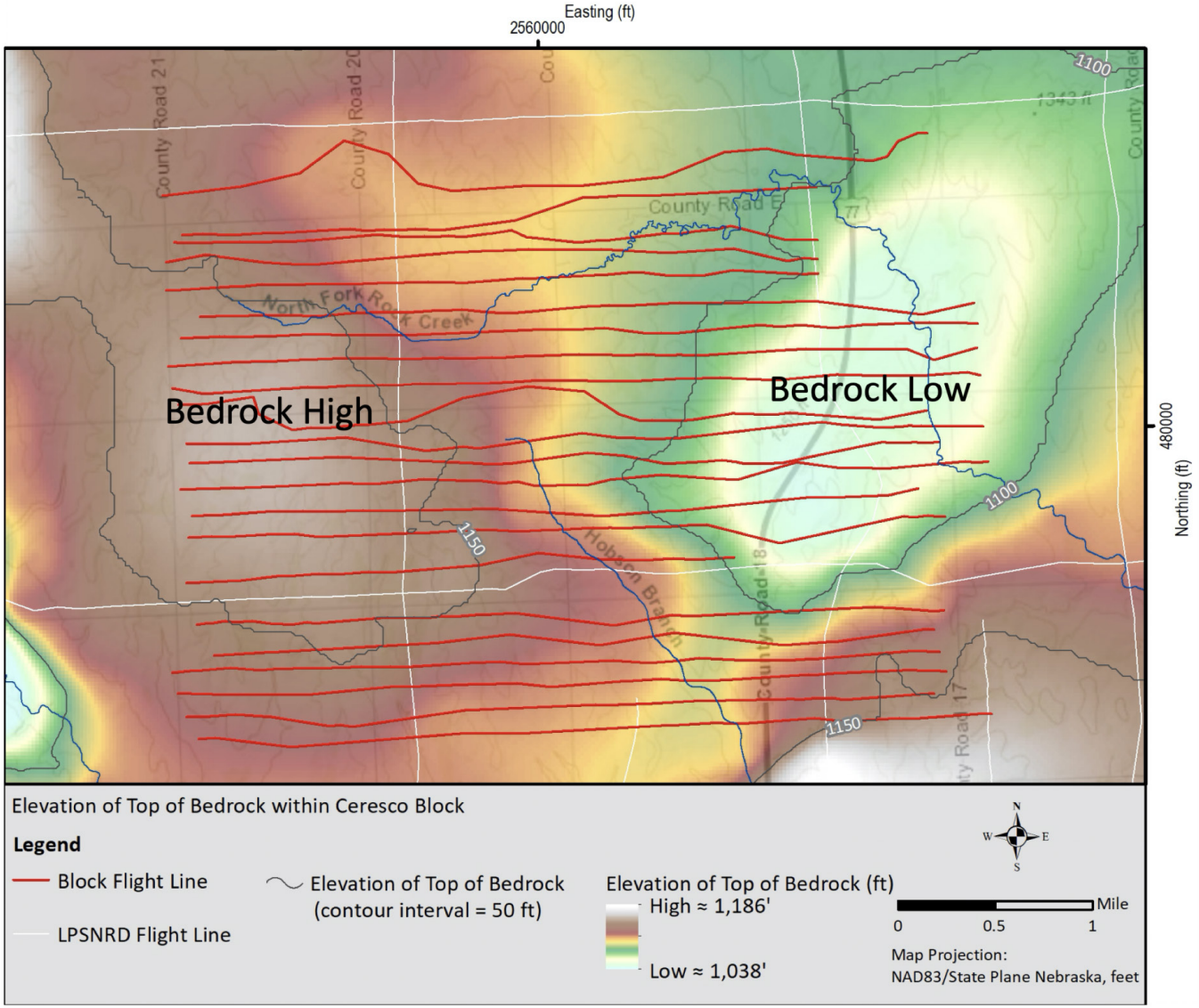


Figure 3-110. Map of the elevation of the top of bedrock within the 2018 Ceresco Block AEM survey area. The bedrock surface slopes in general from west to northeast. Block flight lines are indicated by white lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

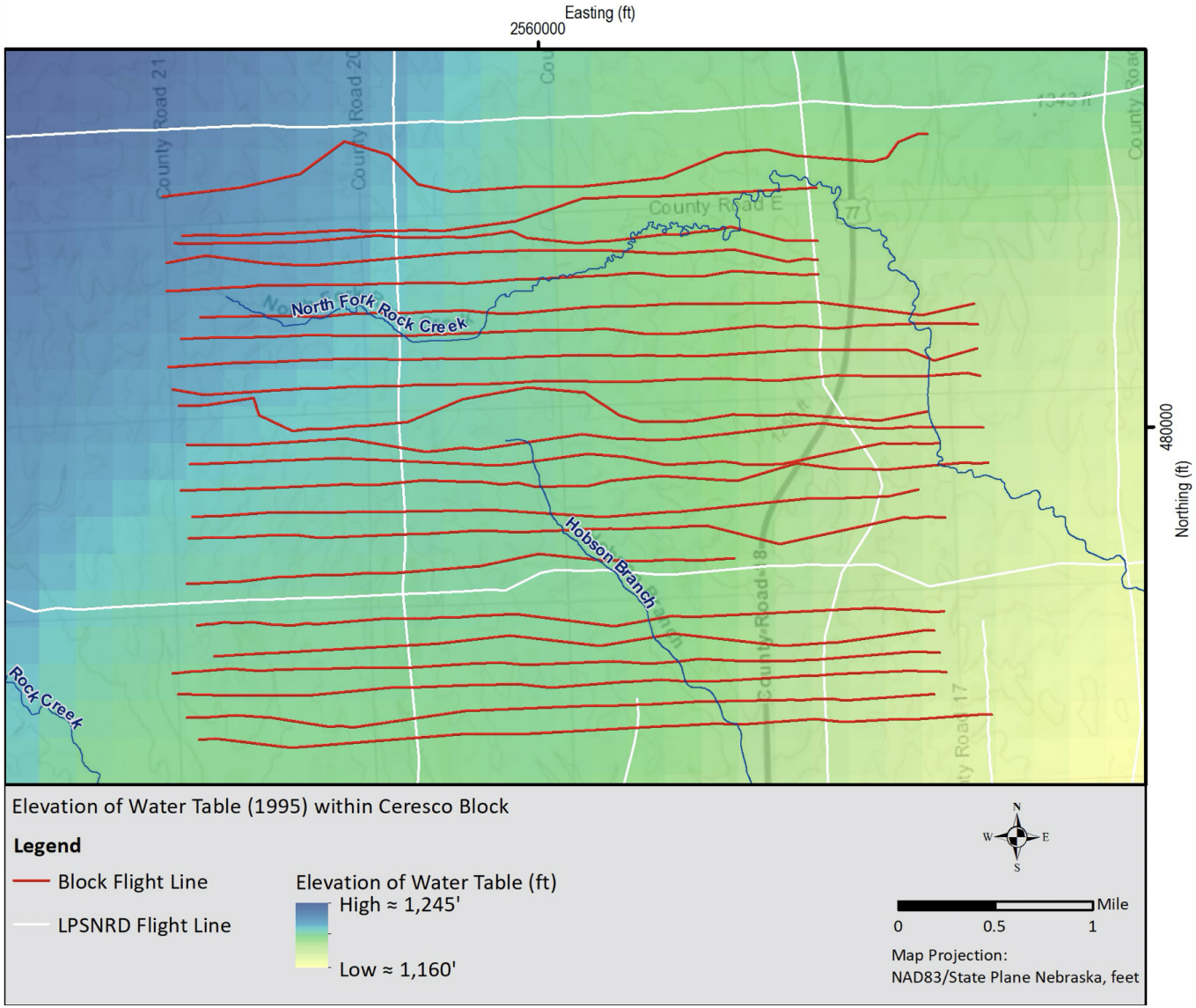


Figure 3-111. Map of the 1995 CSD water table (NE-CSD, 1995) in the Ceresco Block. Flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

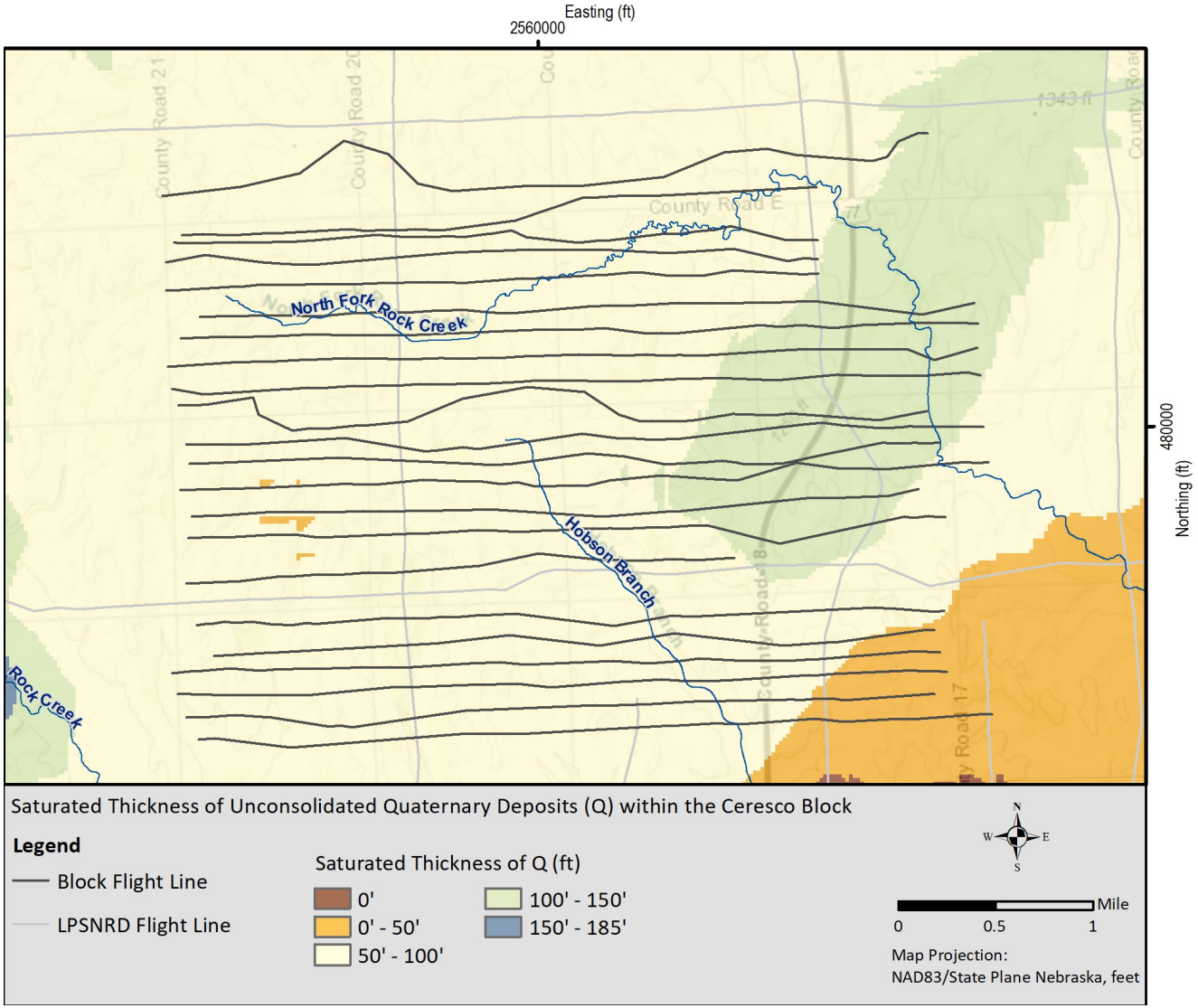


Figure 3-112. Map of saturated thickness of the *Q* saturated aquifer and coarse aquifer materials within the 2018 Ceresco Block AEM survey area. The thickest areas are on the northeast and southwest of the block. Block flight lines are indicated by white lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

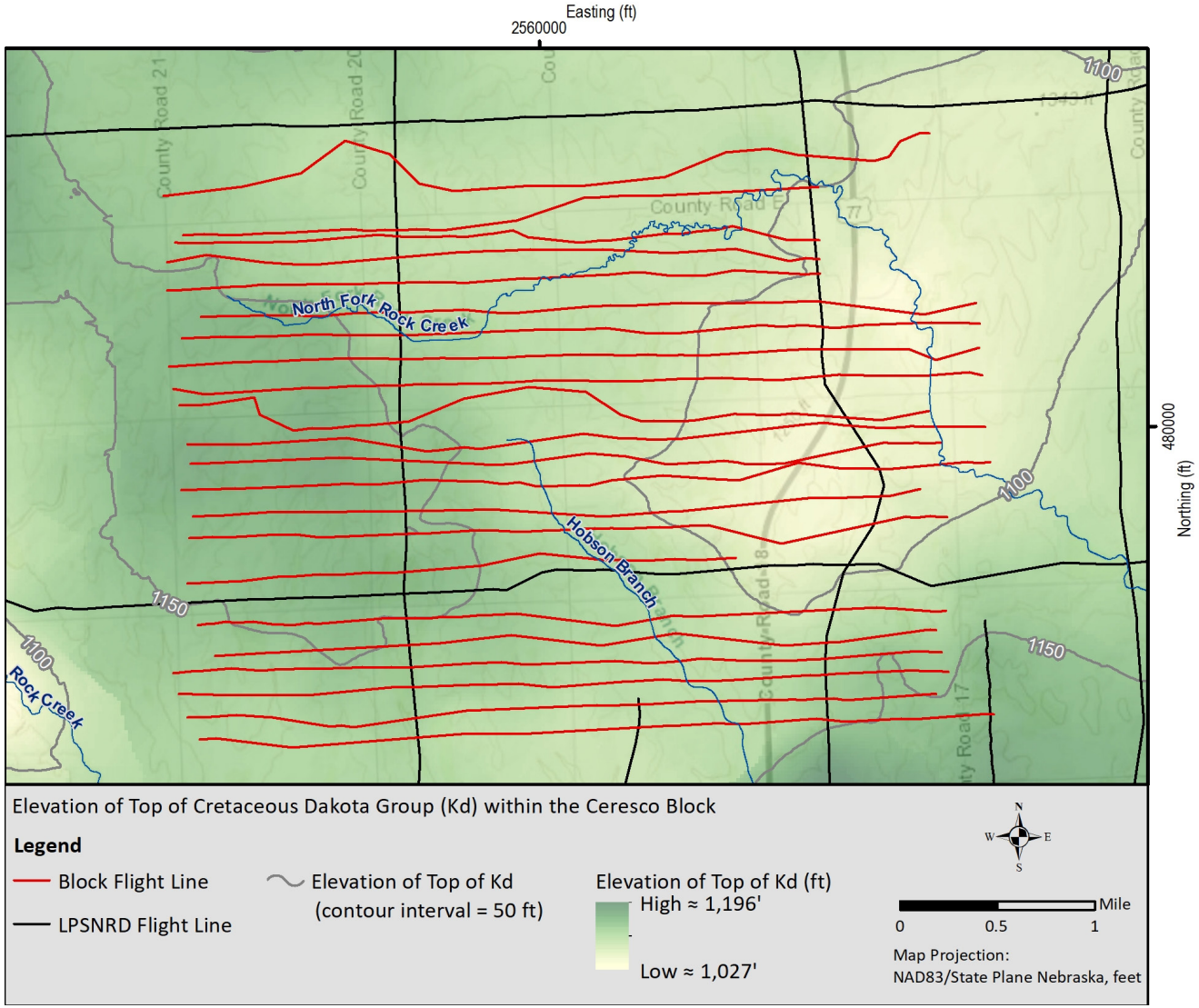


Figure 3-113. Map of the elevation of the top of the *Kd* within the 2018 Ceresco Block AEM survey area. There are low areas in the southwest and near highway 77. Block flight lines are indicated by the white lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

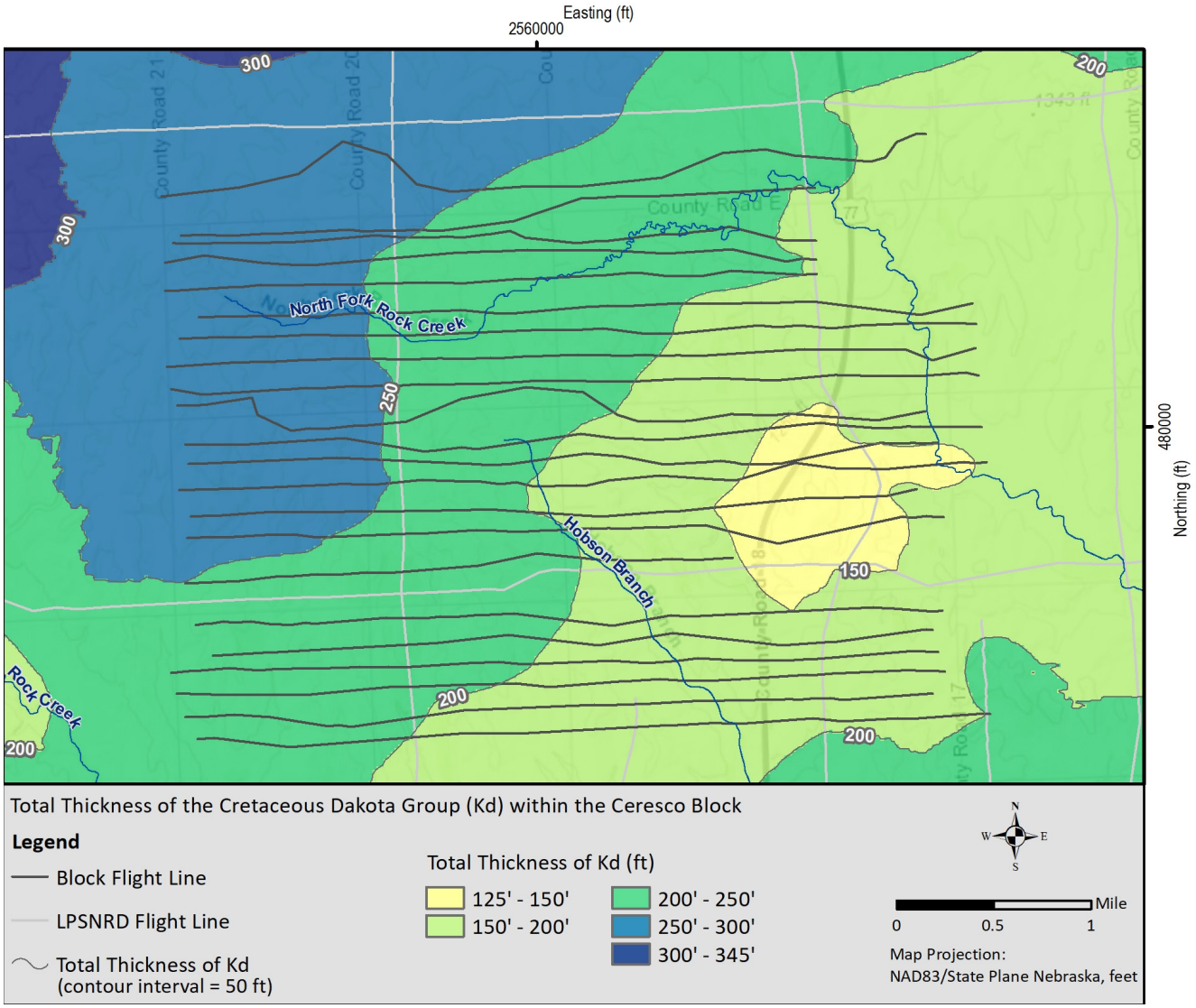


Figure 3-114. Map of the total thickness of the *Kd* within the 2018 Ceresco Block AEM survey area. The thickest areas are in the northwest corner of the area. Block flight lines are indicated by the white lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

West East

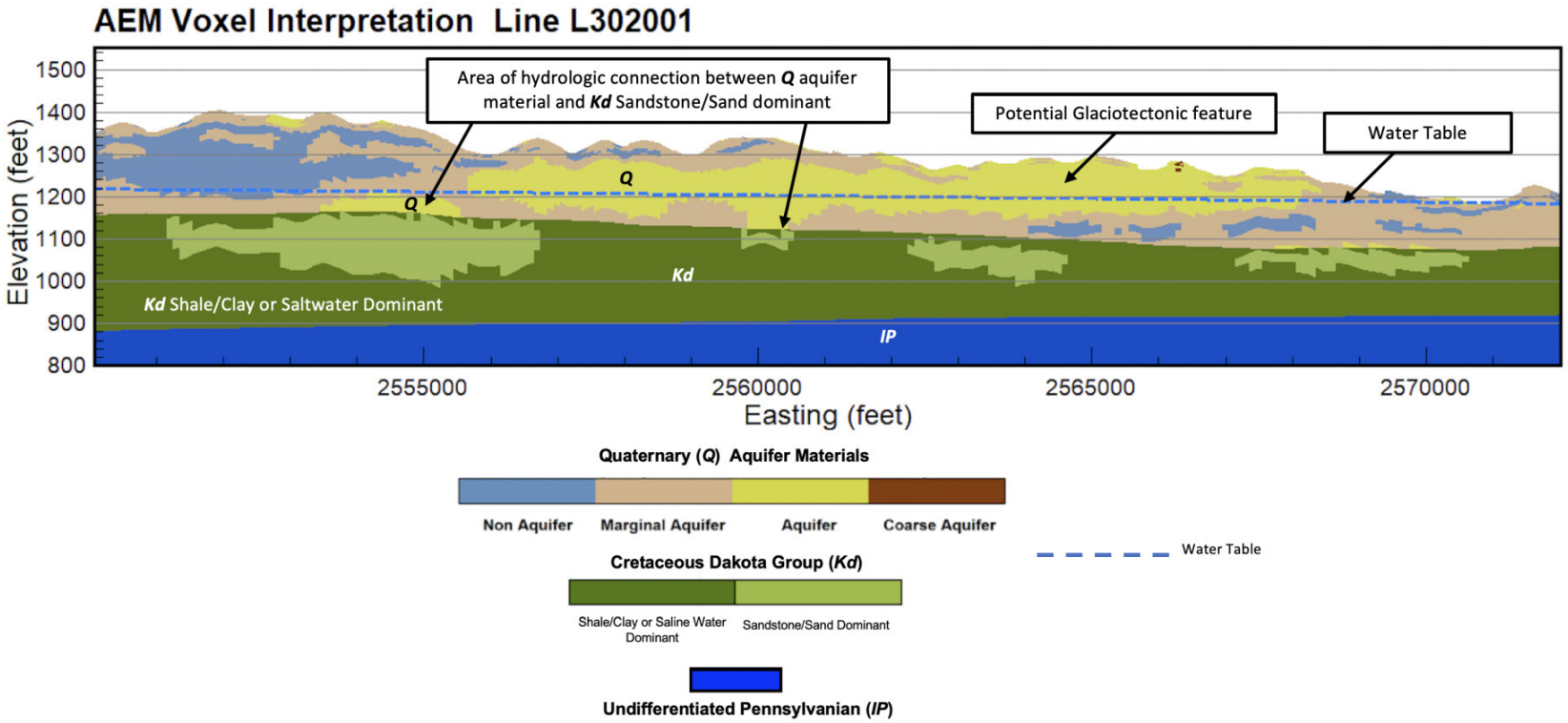


Figure 3-115. Interpreted profile of the north-south line L302001 showing the relationship the *Q*, *Kd* and *IP* of the AEM interpretations across the area. Note the presence of a potential glaciotectonic feature. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

West East

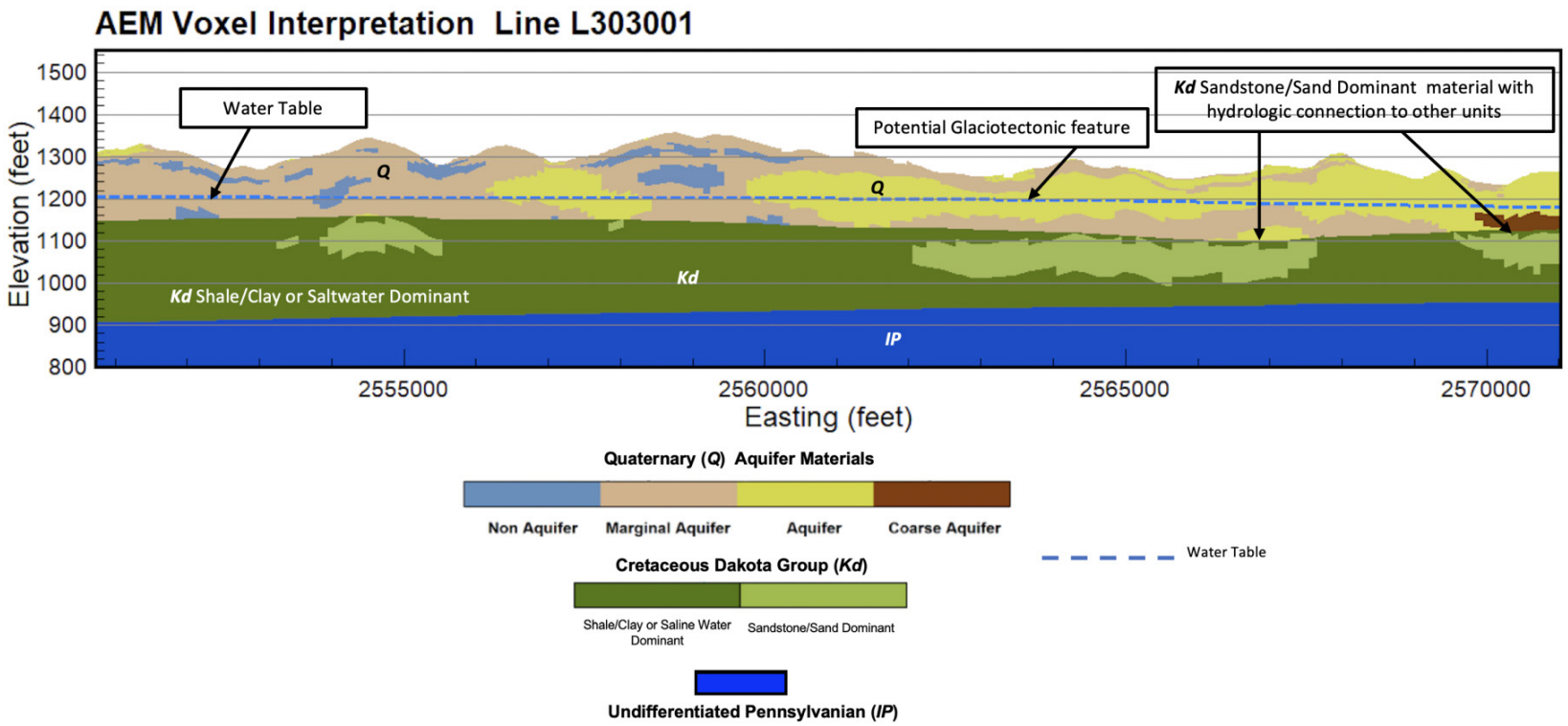


Figure 3-116. Interpreted profile of the north-south line L303001 showing the relationship the *Q*, *Kd* and *IP* of the AEM interpretations across the area. Note the presence of a potential glaciotectonic feature. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

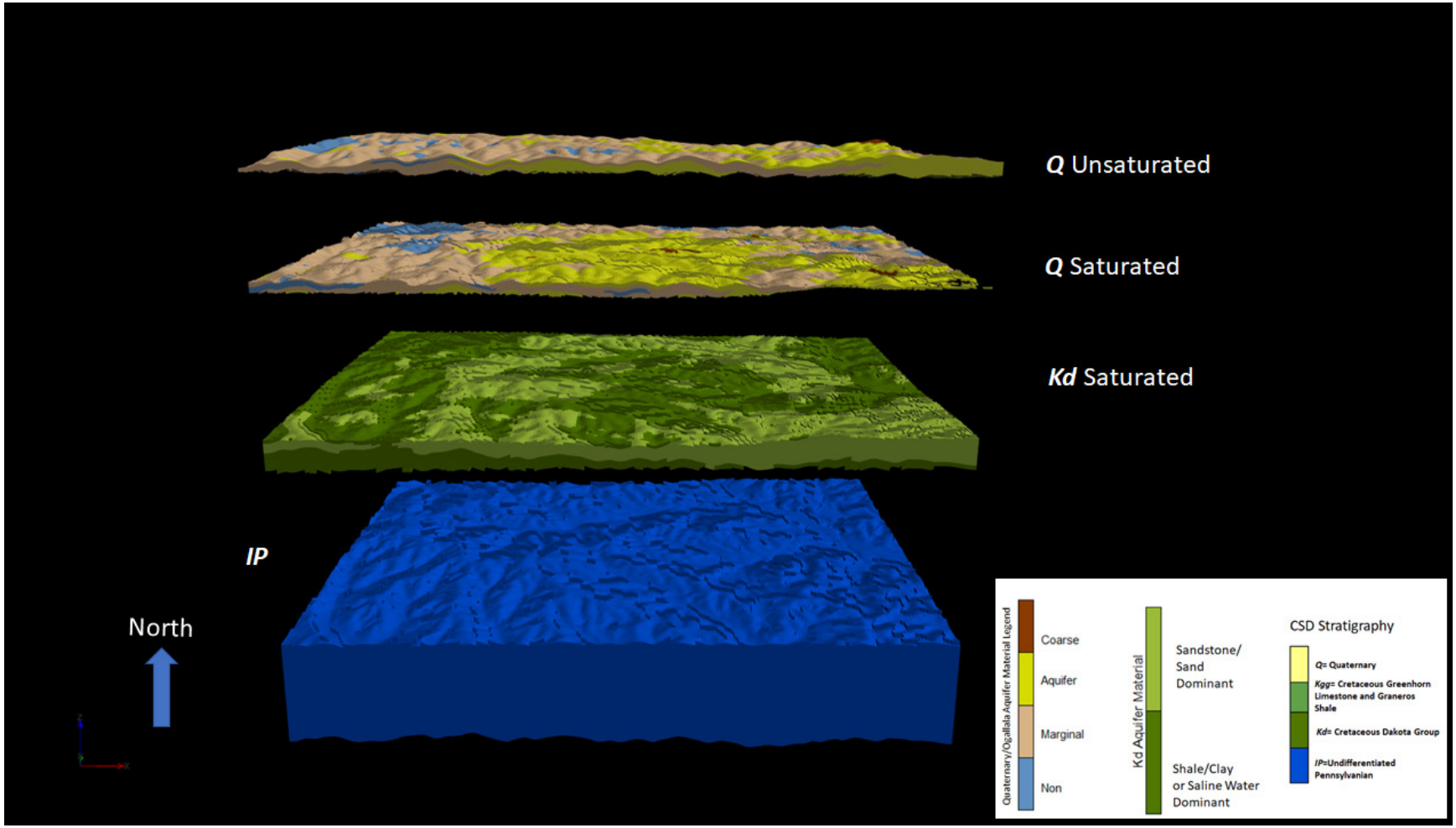


Figure 3-117. 3D exploded voxel model of the Ceresco Block showing *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian. The *Q* is separated into unsaturated and saturated. Vertical exaggeration (VE) = 5x. The figure is not to scale.

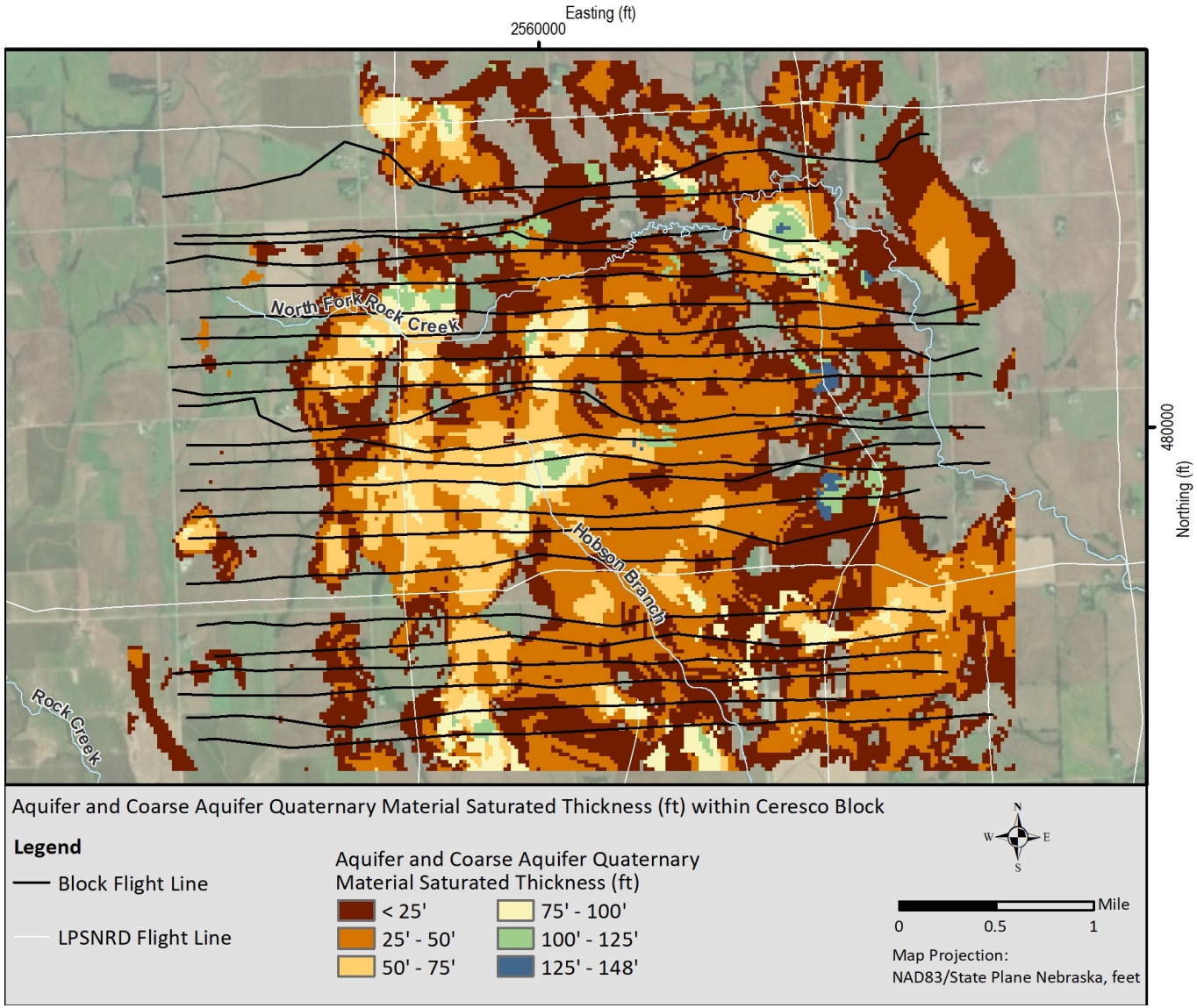


Figure 3-118. Map of saturated Quaternary (*Q*) Aquifer and Coarse Aquifer Materials for the Ceresco Block. Thickest areas are in the center parts of the block. Horizontal datum is NAD83 State Plane Nebraska (feet). Horizontal datum is NAD83 State Plane Nebraska (feet).

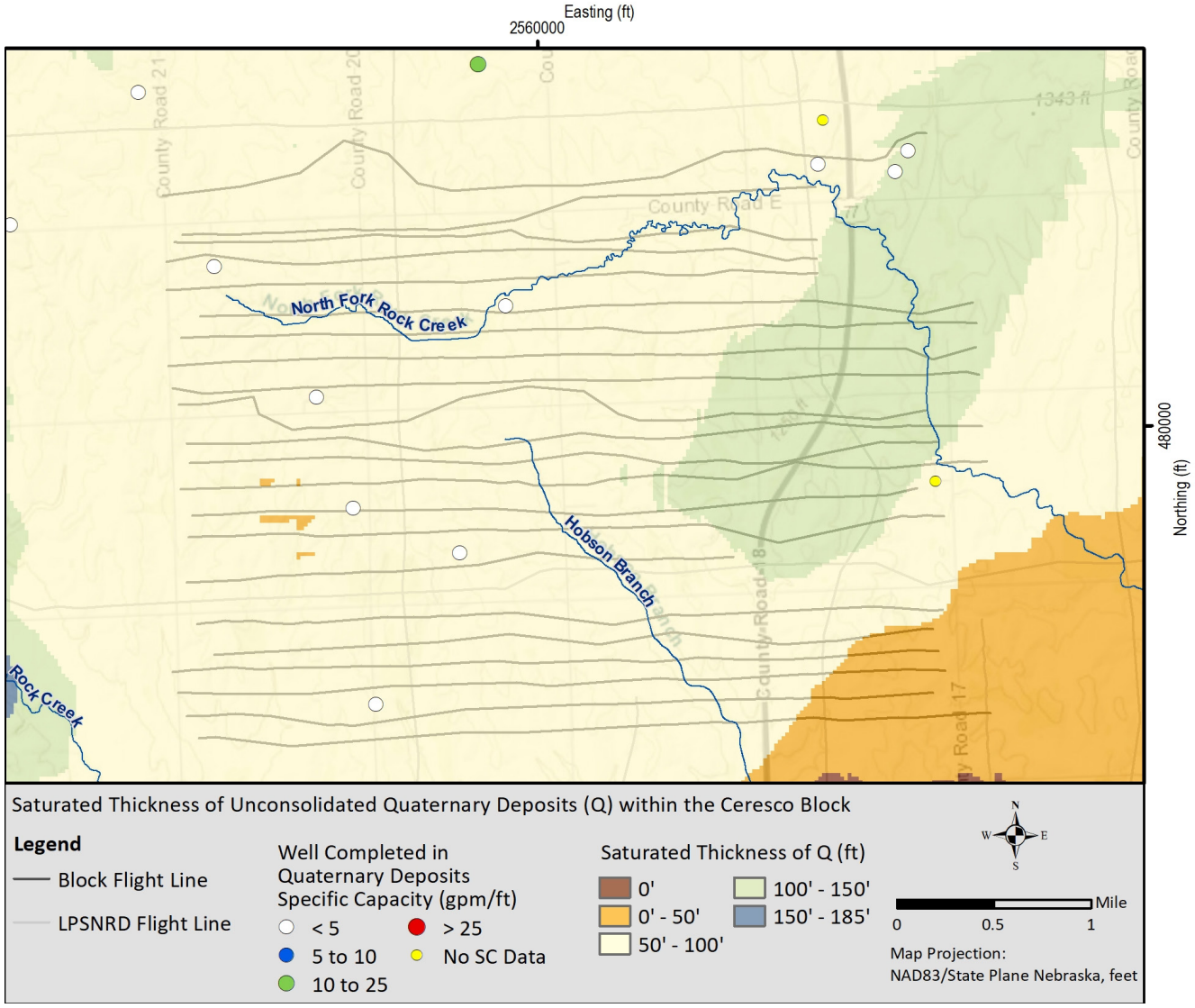


Figure 3-119. Map of saturated thickness of Quaternary (*Q*) deposits and the Specific Capacity measured in wells completed in the *Q* deposits. There is a well with a specific capacity of greater than 5 gpm/ft in the north-center pf the area. Horizontal datum is NAD83 State Plane Nebraska (feet).

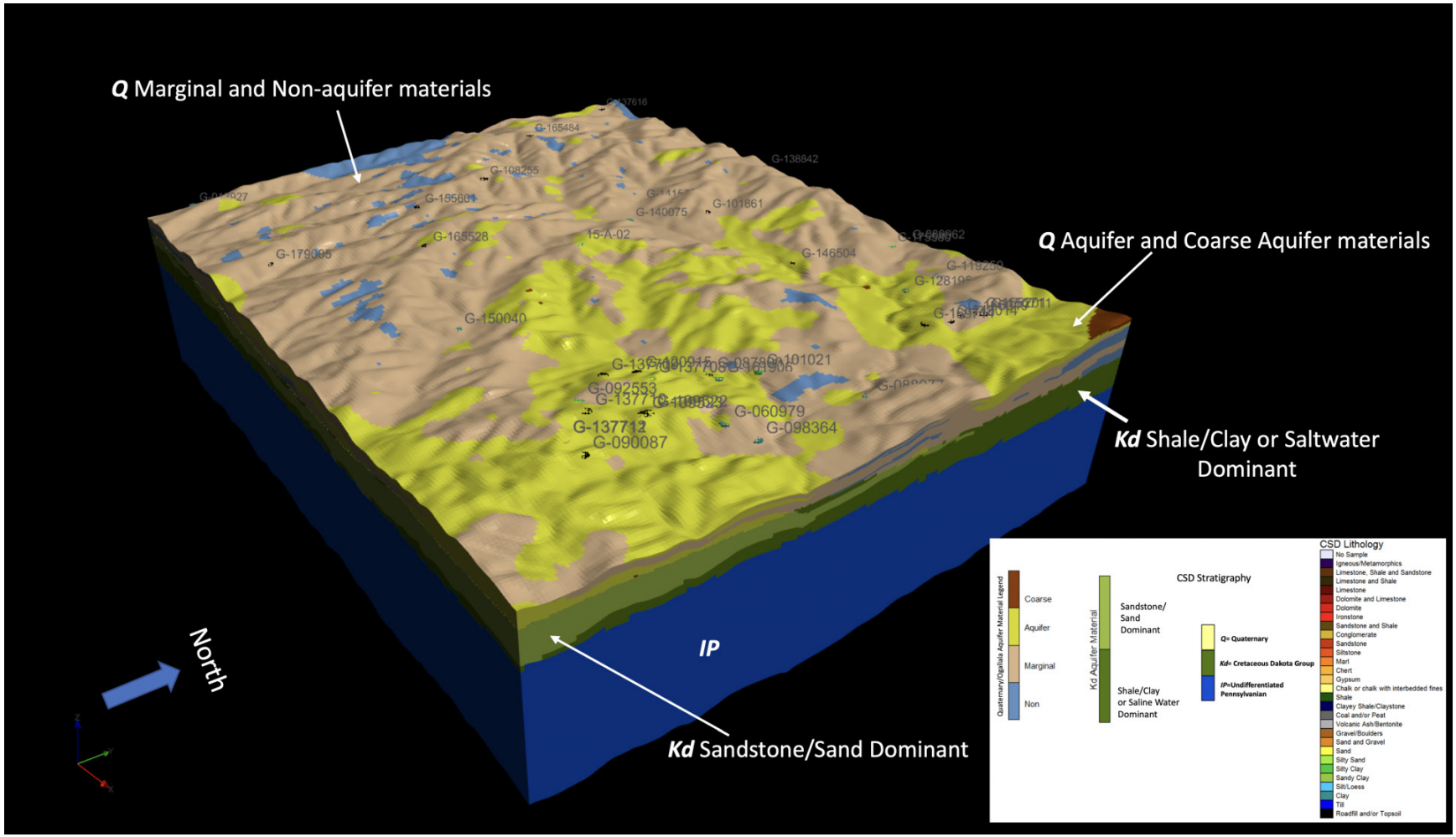


Figure 3-120. View of 3D voxel model looking northwest showing the *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, *IP*=Undifferentiated Pennsylvanian of the Ceresco Block AEM survey area showing all geologic formations in relationship with each other. The western area of the block shows more marginal and non-aquifer material at the land surface and the east end shows more aquifer and coarse aquifer material at the land surface. Vertical exaggeration (VE) = 5x.

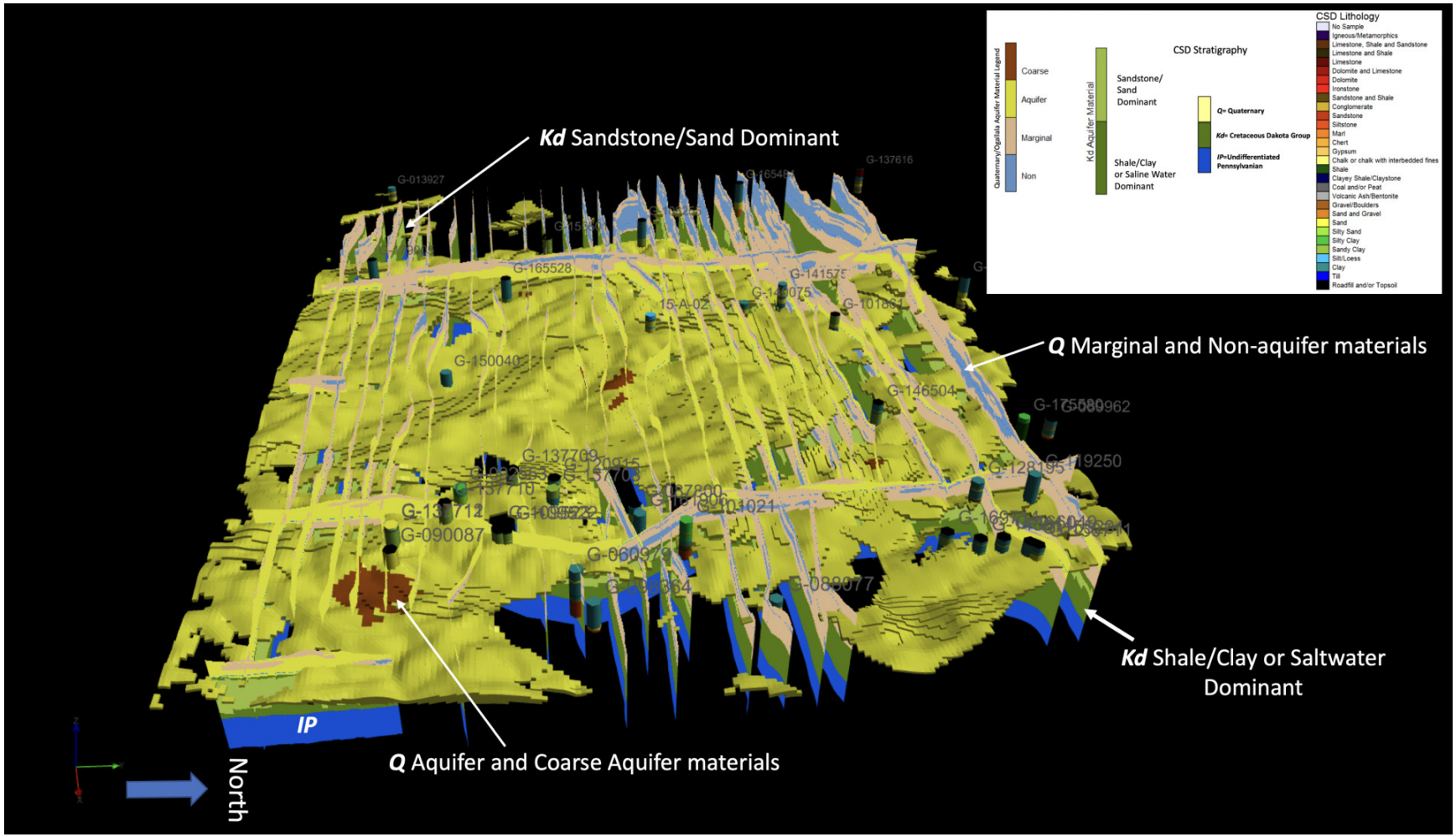


Figure 3-121. View to the west showing a 3D voxel of both *Q*= Quaternary aquifer and the coarse aquifer material and the underlying bedrock units with the unsaturated *Q* materials shown as a fence diagram on the voxel. The *Q* aquifer and coarse aquifer material in the east to the center of the block shows by its shape a possible glaciotectonic feature present on the east side of the block. Vertical exaggeration (VE) = 5x.

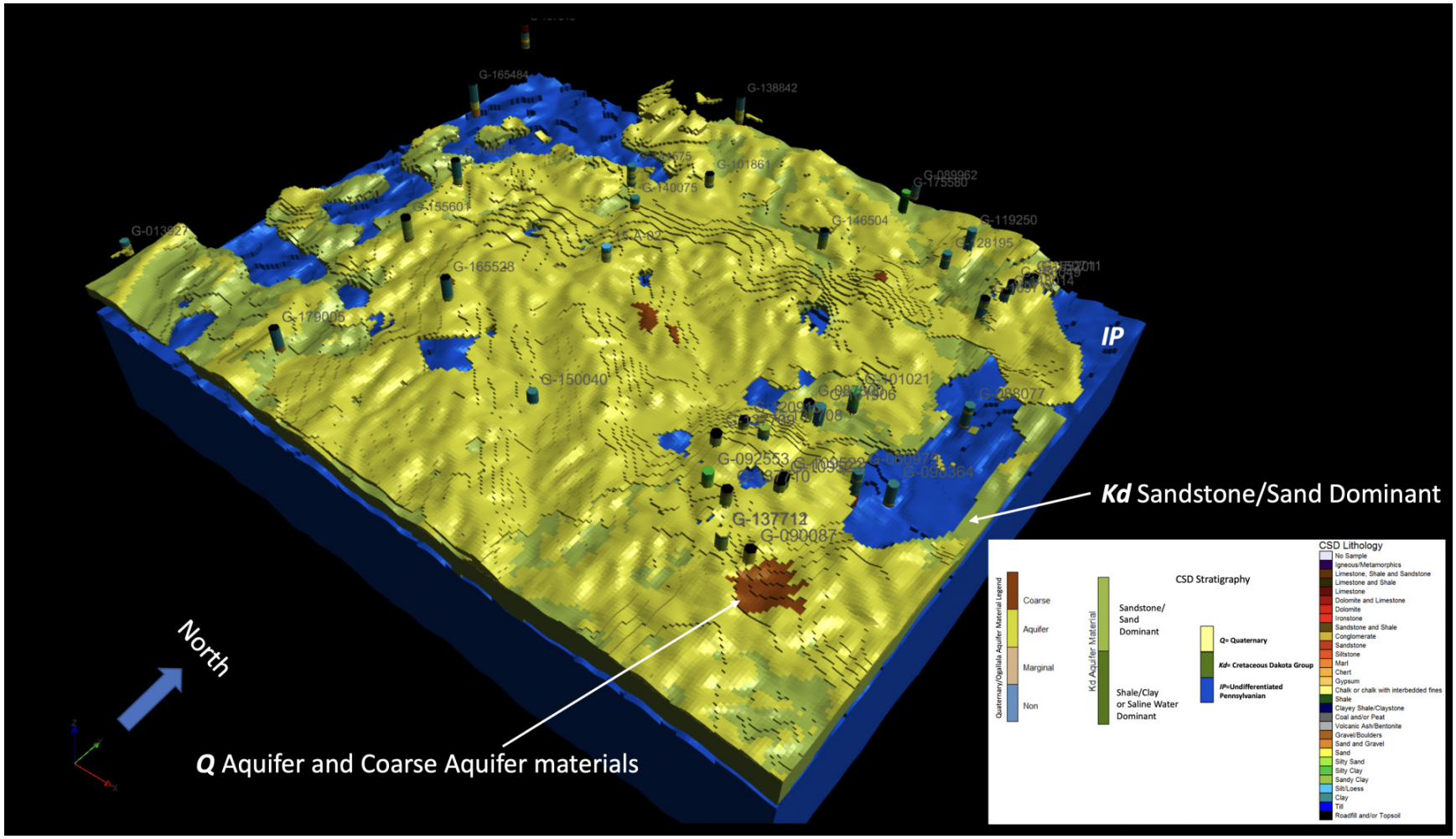


Figure 3-122. A view to the northwest of a 3D voxel of the *Q*= Quaternary aquifer and coarse aquifer material overlying a surface depicting the topography/elevation of the top of the *Kd*= Cretaceous Dakota Group Sandstone/Sand Dominant material which is in close contact or near contact to the *Q*. Vertical exaggeration (VE) = 5x.

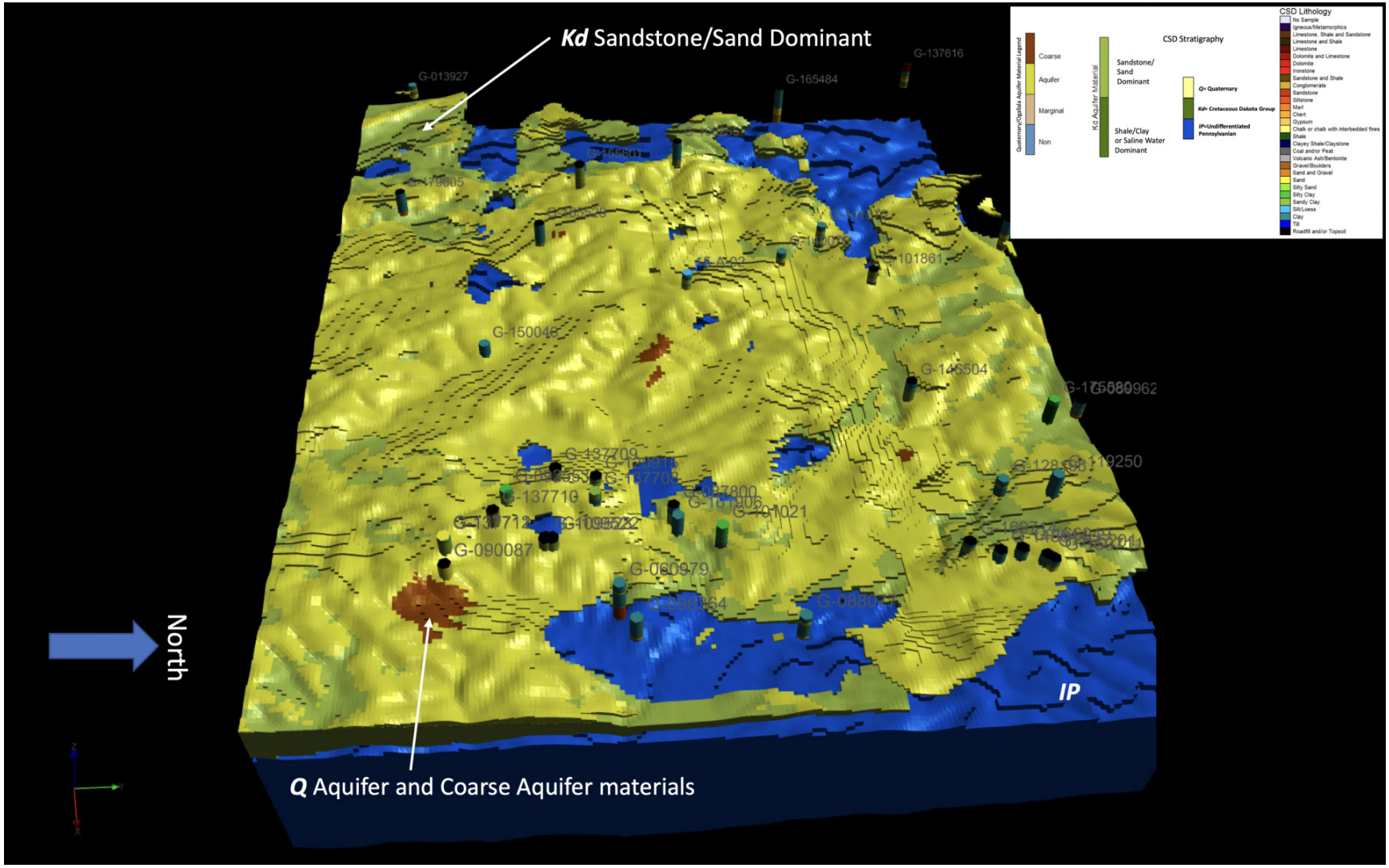


Figure 3-123. A view to the west of a 3D voxel of the *Q*= Quaternary aquifer and coarse aquifer material overlying a surface depicting the topography/elevation of the top of the *Kd*= Cretaceous Dakota Group Sandstone/Sand Dominant material which is in close contact or near contact to the *Q*. Vertical exaggeration (VE) = 5x.

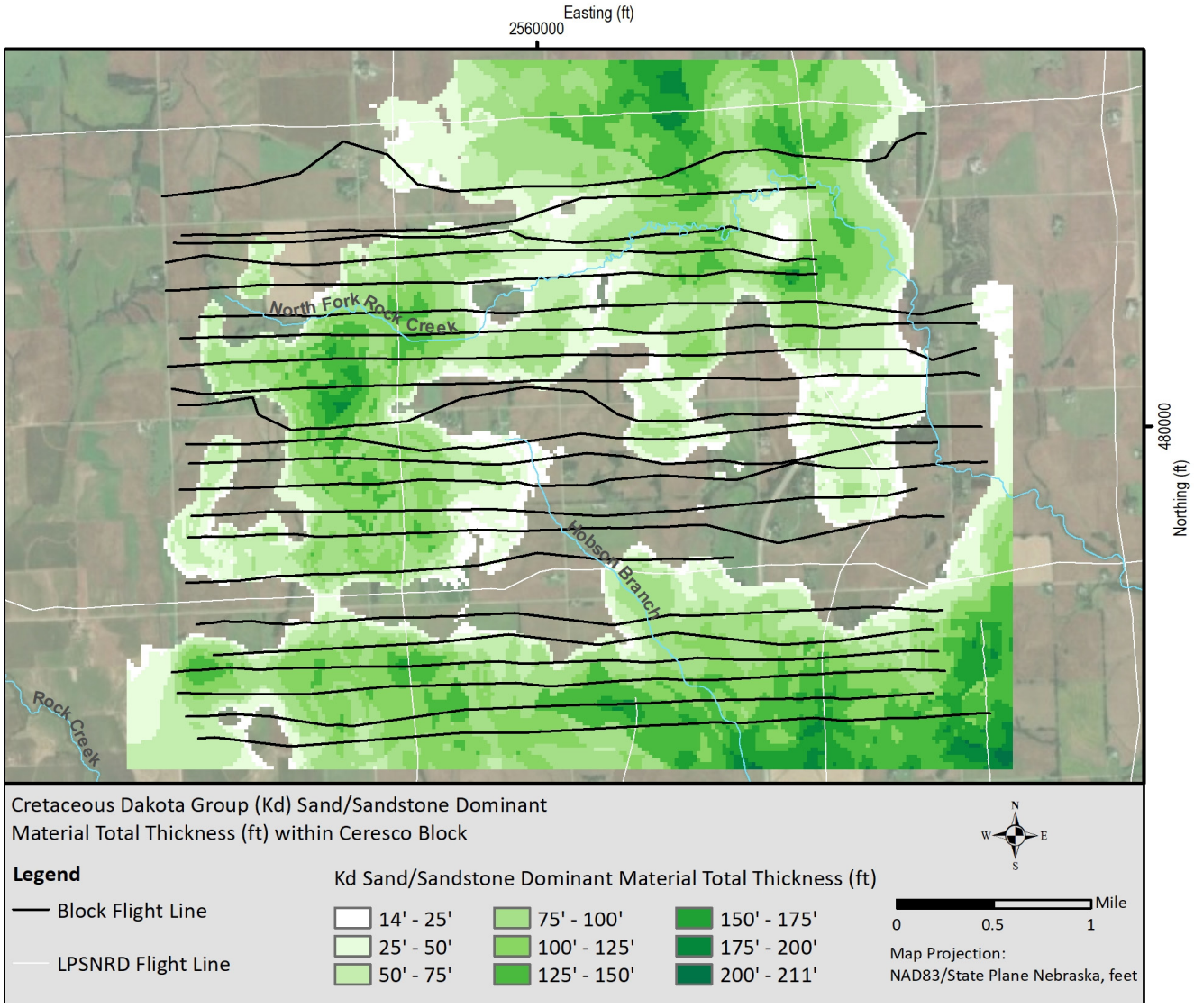


Figure 3-124. Map of the saturated thickness of the *Kd* Sandstone/Sand Dominant in the 2018 Ceresco Block AEM survey area. Note the *Kd* Shale/Clay or Saltwater Dominant zone that separates the north and south Sandstone/Sand dominant deposits. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

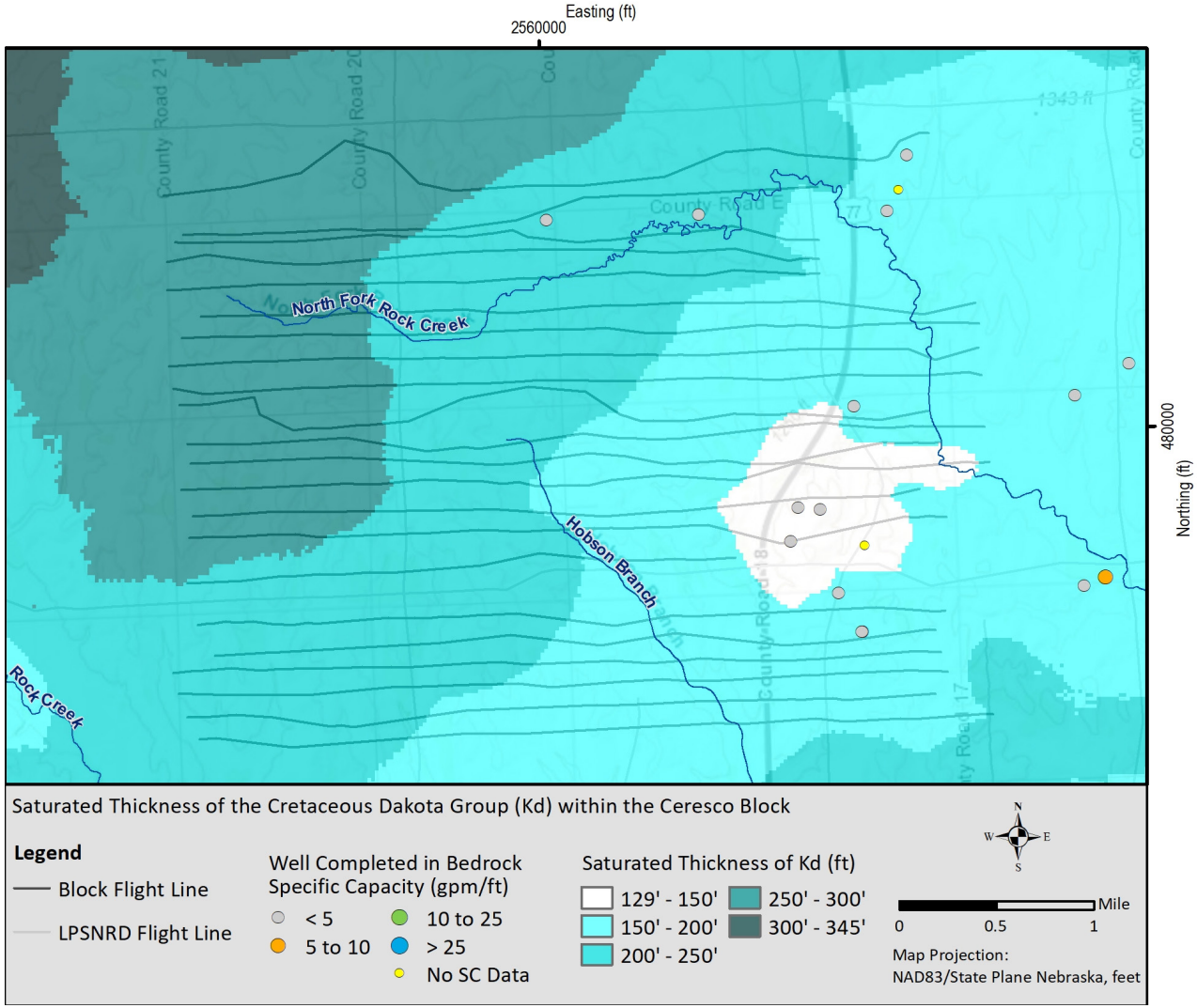


Figure 3-125. Map of the saturated thickness of the *Kd* Sandstone/Sand Dominant material in the 2018 Ceresco Block AEM survey area with specific capacity indicated in wells completed in them. A single well yielding 10-25 gpm/ft follow is located on the eastern side of the Ceresco Block AEM survey area and the rest of the wells produce <5 gpm/ft. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

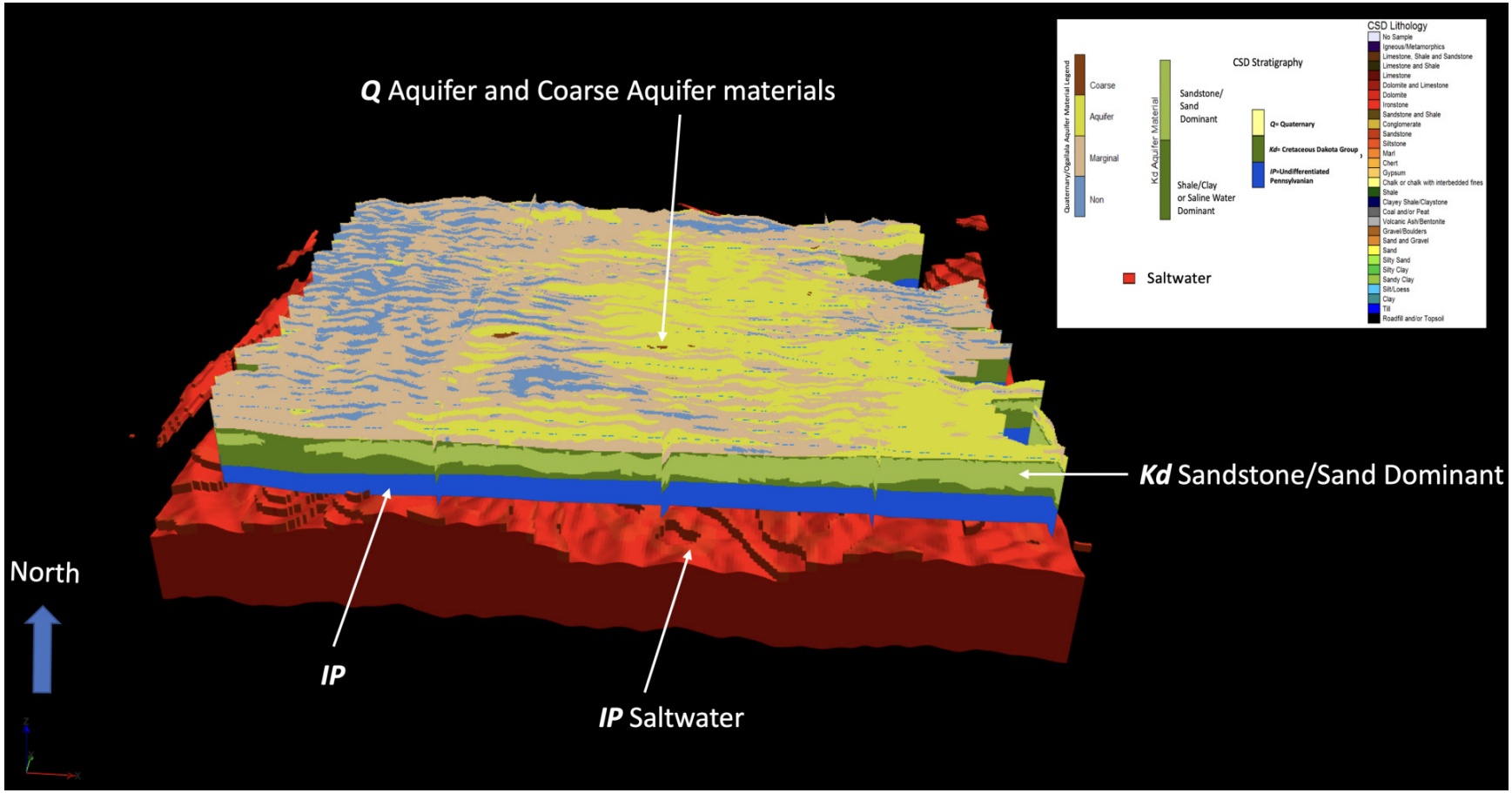


Figure 3-126. View of 3D voxel model looking north showing the saltwater water areas in the block colored red. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

3.2.3 Hydrogeologic Framework of the Davey Raymond Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material and the Cretaceous units in the Davey Raymond Block AEM survey area. The ***Q*** materials within the Davey Raymond Block are composed of unconsolidated clay, silt, sand and gravel that overlie the consolidated bedrock which is made up of ***Kd*** and ***IP***. The ***Q*** material in the Davey Raymond Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1. Figure 3-127 is the flight line location map including roads, streams and towns. Generally, the flight block is east of Raymond, Nebraska and includes North Oak Creek, Little Salt Creek and Ash Hollow Creek within the block. The ground surface elevation map shown on Figure 3-128, shows the rolling hills nature of the ground surface with a ridge between North Oak Creek and Little Salt Creek and an upland near Davey, Nebraska. Figure 3-129 displays a 3D fence diagram of the Davey Raymond Block AEM survey area, looking to the north, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** aquifer materials lying upon the ***Kd*** which lies upon the ***IP***. The ***Kd*** contains a mix of Shale/Clay or Saltwater Dominant and Sandstone/Sand Dominant materials.

Figure 3-130 presents 2D profile L305701, located east of the town of Raymond, Nebraska and parallels Ash Hollow Creek on the east end. The figure shows the subsurface of the area along the line and ***Q*** materials that are present along the line. They are mostly till and loess. These materials have minimal to no saturation. The ***Q*** aquifer materials and the ***Kd*** Sandstone/Sand materials are not in contact and have little hydrologic connection. The ***Kd*** is mostly Shale/Clay or Saltwater dominant except for an area near easting 2555000 which is Sandstone/Sand dominant which has the upper ~10-15 feet unsaturated. The surface of the ***Kd*** and ***IP*** slopes from northeast to southeast. The CSD 1995 water table is also on the profile and shows the water table for the area.

The total thickness of the ***Q*** material in the Davey Raymond Block AEM survey area (Figure 3-131) was gridded by subtracting the bedrock elevation (Figure 3-132) from the ground surface elevation (Figure 3-128). The Total Thickness ***Q*** materials is shown on Figure 3-133, the greatest thickness is on ridges and uplands within the Davey Raymond Block AEM survey area. The ***Q*** material varies in thickness from <50 to 257 feet. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to the hydrologic connection of those materials to the surface water of the area. The aquifer and coarse aquifer materials which make up the bulk of ***Q*** aquifer materials present provide the greatest connection for water movement through all of the ***Q*** aquifer materials. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995)(Figure 3-134) to obtain the saturated thickness of ***Q*** material. Note that the water table slopes from northwest to southeast. The saturated thickness for all aquifer material is shown for the Davey Raymond Block on Figure 3-135. The thickness of these materials varies between 0 to 166 feet. The saturated thickness averages 0-100 feet across the area with the thickest area in the southeast and the thinnest are in the center of the block. The minimal saturation in the ***Q*** and the high elevation of the ***Kd*** leads to this condition.

The map of saturated thickness for ***Q*** deposits and specific capacity of wells completed in the ***Q*** (Figure3-136) shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with all wells having an specific capacity of<5 gpm/ft. The aquifer in the ***Q*** is poor and would not be good for siting MAR.

Figure 3-137 Is a map of the elevation of top of ***Kd*** which ranges in elevation from 1,058 to 1,243 feet. There are low areas in the north and rise in elevation to the south-southeast. The ***Kd*** is a gently rolling surface sloping from north to south and the low areas follow the surface water drainages.

The total thickness map of the ***Kd*** is shown in Figure 3-138. The thickness of the ***Kd*** varies from <50 to 442 feet with the thickest area in the northwest corner and the thin area southeast which correlates with the lowest elevation of the top surface of the ***Kd***.

The **Kd** saturated thickness map is shown on Figure 3-139. it varies in thickness from <50 to 442 feet and slopes from northwest to southeast.

The map of saturated thickness for ***Kd*** deposits and specific capacity of wells completed in the ***Kd*** (Figure 3-140) shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with all wells having an specific capacity of<5 gpm/ft. The aquifer in the ***Kd*** is poor and would not be good for siting MAR.

Figure 3-141 shows the interpreted 2D profile L306400 is an east-west line near the east side and passes near Davey, Nebraska. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly till and loess. These materials have minimal to no saturation. The ***Q*** is very thin ~10 feet thick in the Little Salt Creek valley. The ***Q*** aquifer materials and the ***Kd*** Sandstone/Sand materials are not in contact and have little hydrologic connection. The ***Kd*** is mostly Shale/Clay or Saltwater dominant except for the west end to easting ~2545000 which is Saltwater dominant. The ***Kd*** and ***IP*** dip from northeast to southeast. The CSD 1995 water table is also on the profile.

Figure 3-142 shows the interpreted 2D profile L304603 which is an east-west profile in the along the northern end of the Davey Raymond area. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly till and loess. These materials have minimal to no saturation. Just west of Easting 2535000 is Little Salt Creek which has a minimal hydrologic connection to the ***Q*** aquifer material below it and no connection to the ***Q*** covered hills flanking the stream. Near easting 2540000 there is a ***Kd*** Sandstone/Sand dominant material which has a minor hydrologic connection with the overlying ***Q*** aquifer material. The CSD 1995 water table is also on the profile.

An exploded view of the voxel model showing the ***Q***, both saturated and unsaturated, the ***Kd***, both saturated and unsaturated and the ***IP*** formations is presented in Figure 3-143. The ***Q*** materials show mostly marginal aquifer and non-aquifer materials mixed with aquifer and coarse aquifer materials. Nearly all of the ***Q*** materials shown are unsaturated because of the water table being in close proximity

to the top of the ***Kd*** surface. There is some ***Kd*** that is unsaturated near the center of the block. Because of the amount of ***Q*** marginal and non- aquifer materials and their distribution across the Davey Raymond area there is limited ability for managed aquifer recharge (MAR) sites to be located within the block. Figure 3-144 shows the distribution of ***Q*** marginal and non-aquifer materials thickness in the area illustrating that when compared to Figure 3-145 which shows the thickness of the ***Q*** aquifer and coarse aquifer materials there is complexity in the aquifer materials mix leading minimal opportunity for MAR. The ***Q*** saturated aquifer and coarse aquifer materials (Figure 3-146) range in thickness from <25 feet to 57 feet and show that the ***Q*** has minimal groundwater storage that can yield to wells.

Figure 3-147 shows a 3D voxel model of ***Q*** saturated aquifer and coarse material with a fence diagram of unsaturated ***Q*** marginal and non-aquifer material looking northwest. The ***Kd*** and ***IP*** are also shown. The hill tops generally show more marginal and non-aquifer material near the land surface while the drainages show thin marginal and non-aquifer material deposits. Figure 3-148 presents a view to the north of the Davey Raymond Block showing a 3D voxel of total ***Q*** aquifer material. The intermittent nature of the ***Q*** aquifer and coarse aquifer material shows the discontinuous nature of these deposits. Figure 3-149 is a view to the north of a 3D voxel of the saturated ***Q*** aquifer and coarse aquifer material further illustrating the minimal amount of water bearing ***Q*** materials in the area.

Figure 3-150 presents a map of the thickness for ***Kd*** Sandstone/Sand Dominant deposits. These deposits vary in thickness from <25 to 210 feet and are discontinuous across the block. The ***Kd*** Sandstone/Sand dominant material is an aquifer in this area with the thickest portion in the northeast. Figure 3-151 presents a map of the saturated thickness for ***Kd*** Sandstone/Sand Dominant deposits which range in thickness from <25 to 193 feet. The greatest saturated thickness is in the northwest part of the block in a band approximately 1 mile wide extending from north to south. Figure 3-152 is a voxel model looking northwest showing total ***Kd*** thickness lying on the ***IP***. There is a mix of ***Kd*** Sandstone/Sand Dominant and Shale/Clay or Saltwater Dominant materials across the area. There are wells completed in the ***Kd*** Sandstone/Sand Dominant in this area. Figure 3-153 is a voxel model looking west showing the ***Kd*** Sandstone/Sand dominant materials above the ***IP***. Note the wells completed in this unit versus the wells completed in the ***Q*** aquifer materials.

During the analysis of the AEM data it was apparent that there was saltwater present in some areas in LPSNRD project area. There is a substantial presence of saltwater in the south-southwest part of the Davey Raymond Block AEM survey area. Figure 3-154 is a voxel model looking north that shows these saltwater areas. There are no water quality samples from wells in the area and this determination of saltwater is based on the comparison of resistivity from the AEM versus the lithology from the wells. Figure 3-155 is a close-up view of the voxel showing the sandstone in the borehole and the saltwater.

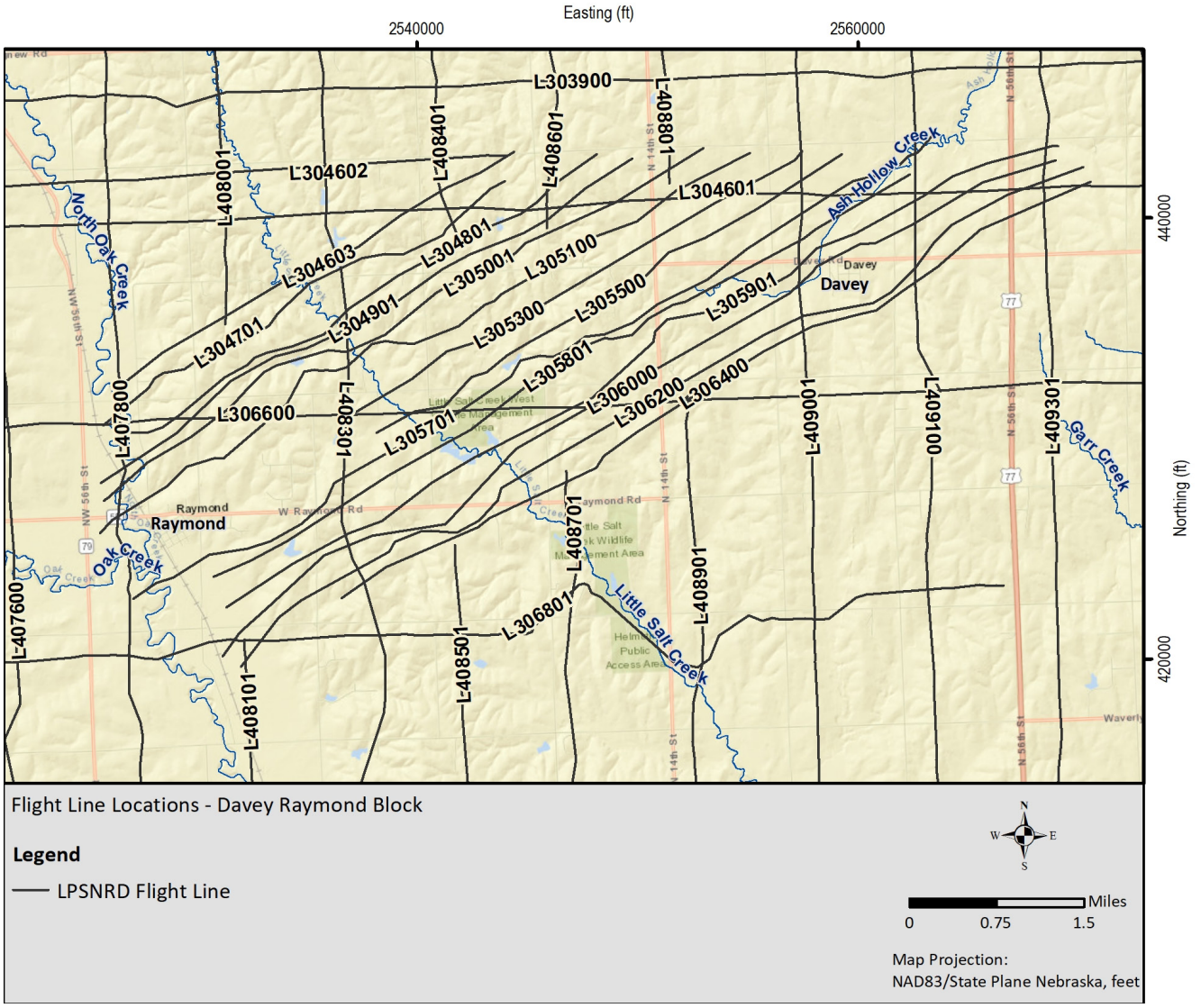


Figure 3-127. Location map of the Davey Raymond Block indicating numbered AEM flight lines, local roads, and streams. Generally, the flight block is east of Raymond, Nebraska and includes North Oak Creek, Little Salt Creek and Ash Hollow Creek within the block. Block flight lines are indicated by the black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

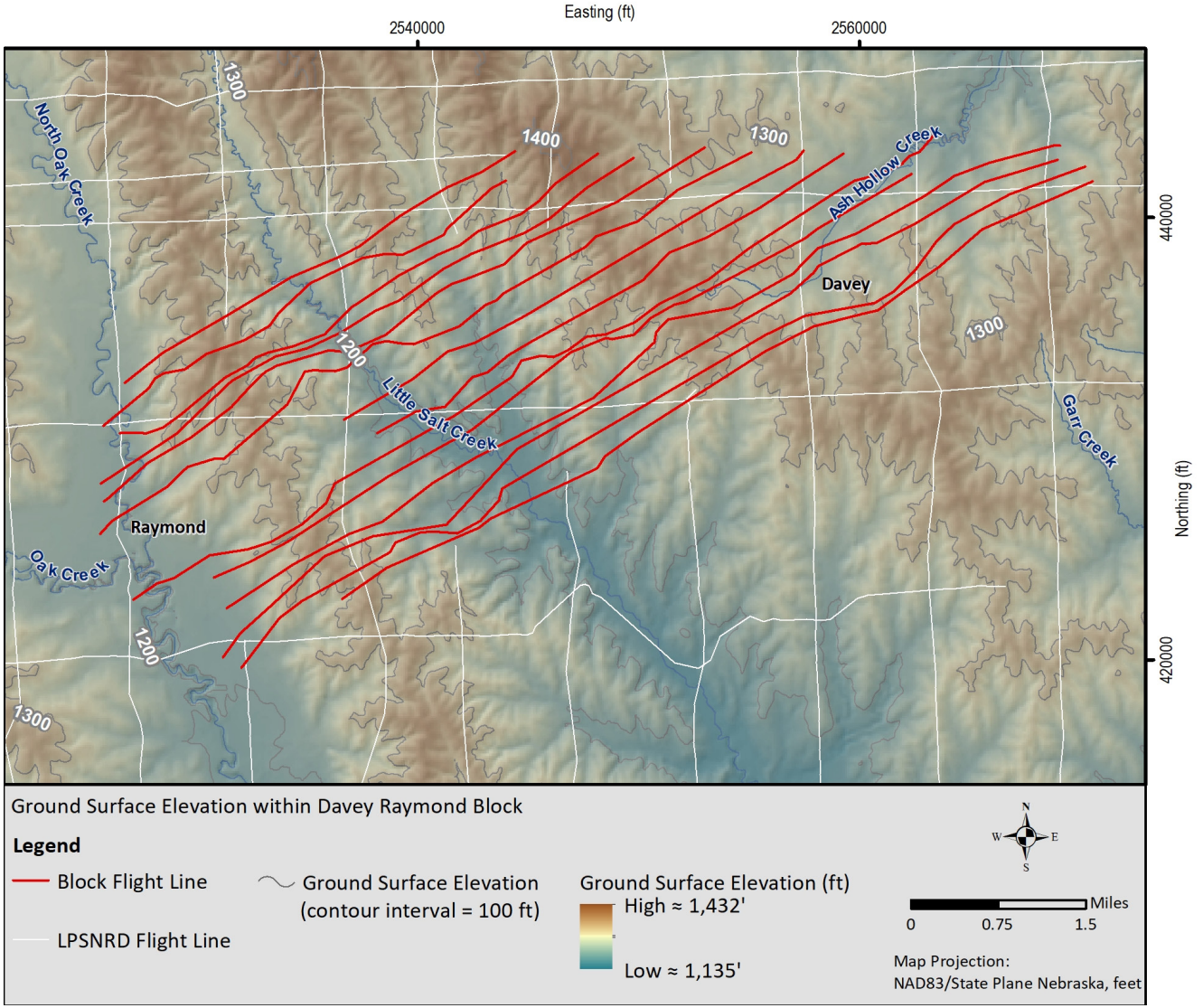


Figure 3-128. Map showing the ground surface elevation with flight lines in the Davey Raymond Block. Note the rolling hills nature of the ground surface. There are rolling hills with a ridge between North Oak Creek and Little Salt Creek and an upland near Davey, Nebraska. Block flight lines are indicated by the red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

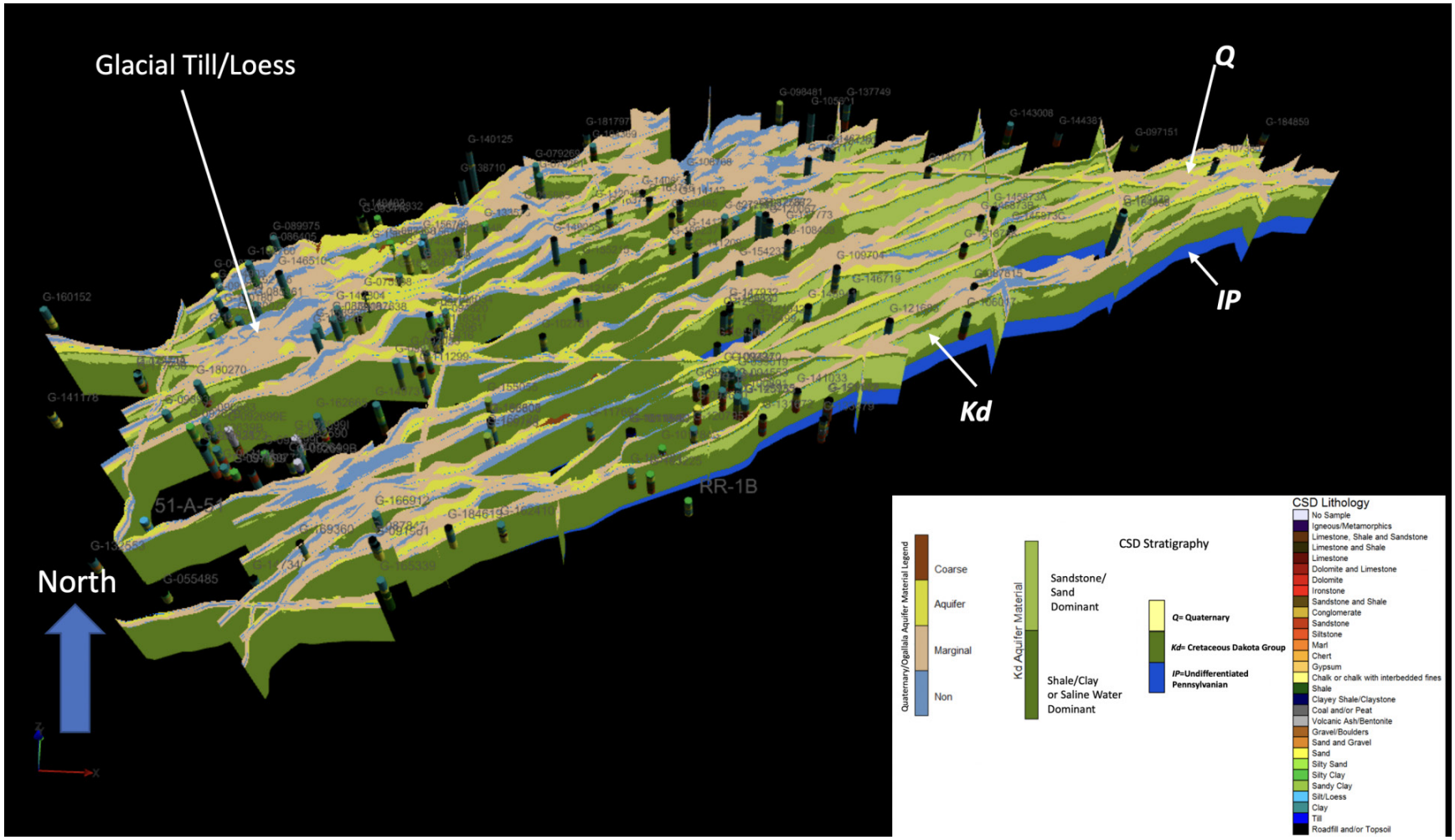


Figure 3-129. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Davey Raymond Block AEM survey area. CSD and NE-DNR wells are labeled. The area generally contains a mix of all *Q* aquifer materials lying upon the *Kd* which lies upon the *IP*. The *Kd* contains a mix of Shale/Clay or Saltwater Dominant and Sandstone/Sand Dominant materials. Geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

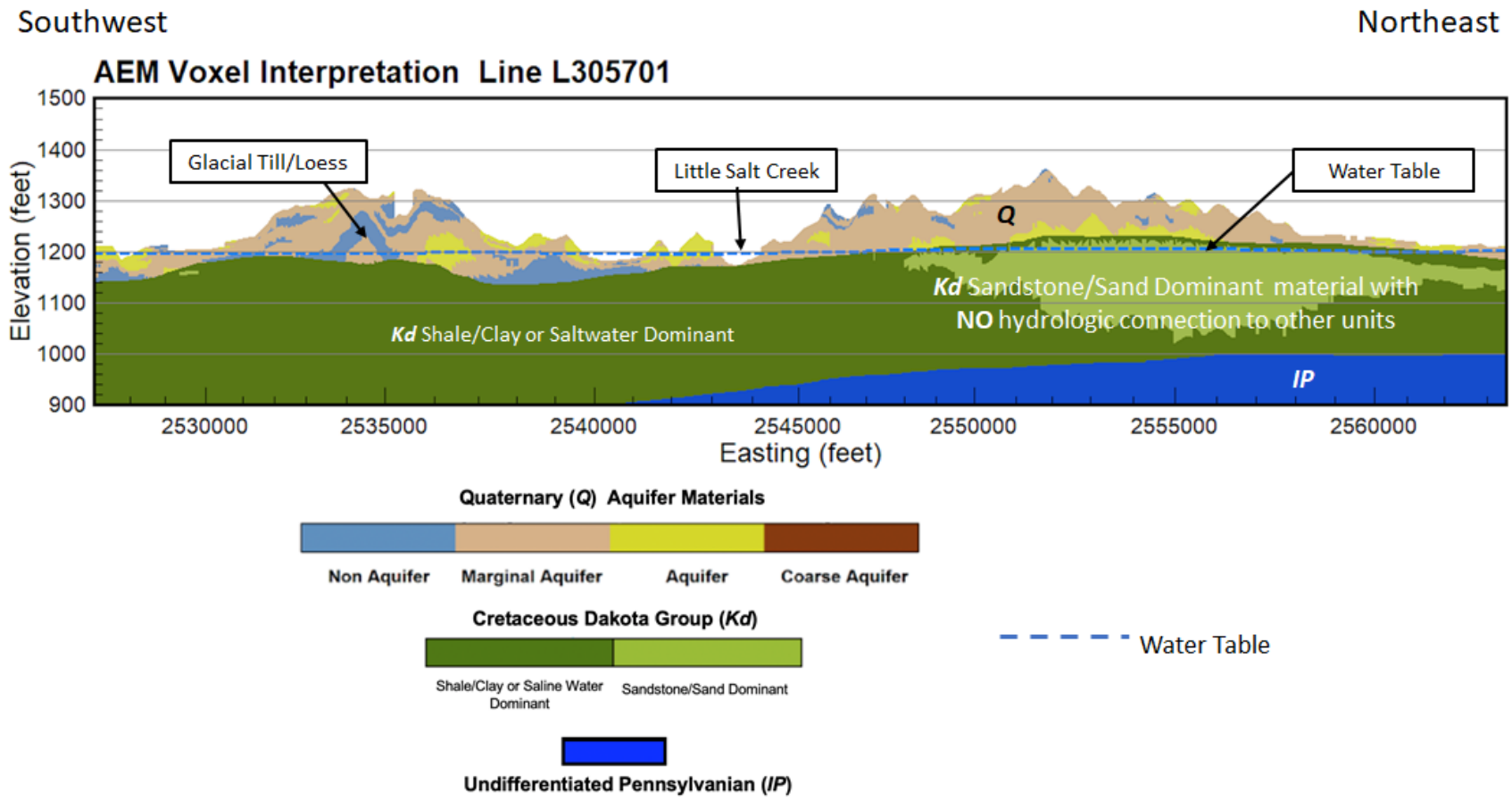


Figure 3-130. Profile of the east-west line L305701 showing the *Q* aquifer materials and the *Kd* sandstone/sand materials are in contact and have a minimal hydrologic connection. They are mostly till and loess. These materials have minimal to no saturation. The *Q* aquifer materials and the *Kd* Sandstone/Sand materials are not in contact and have little hydrologic connection. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

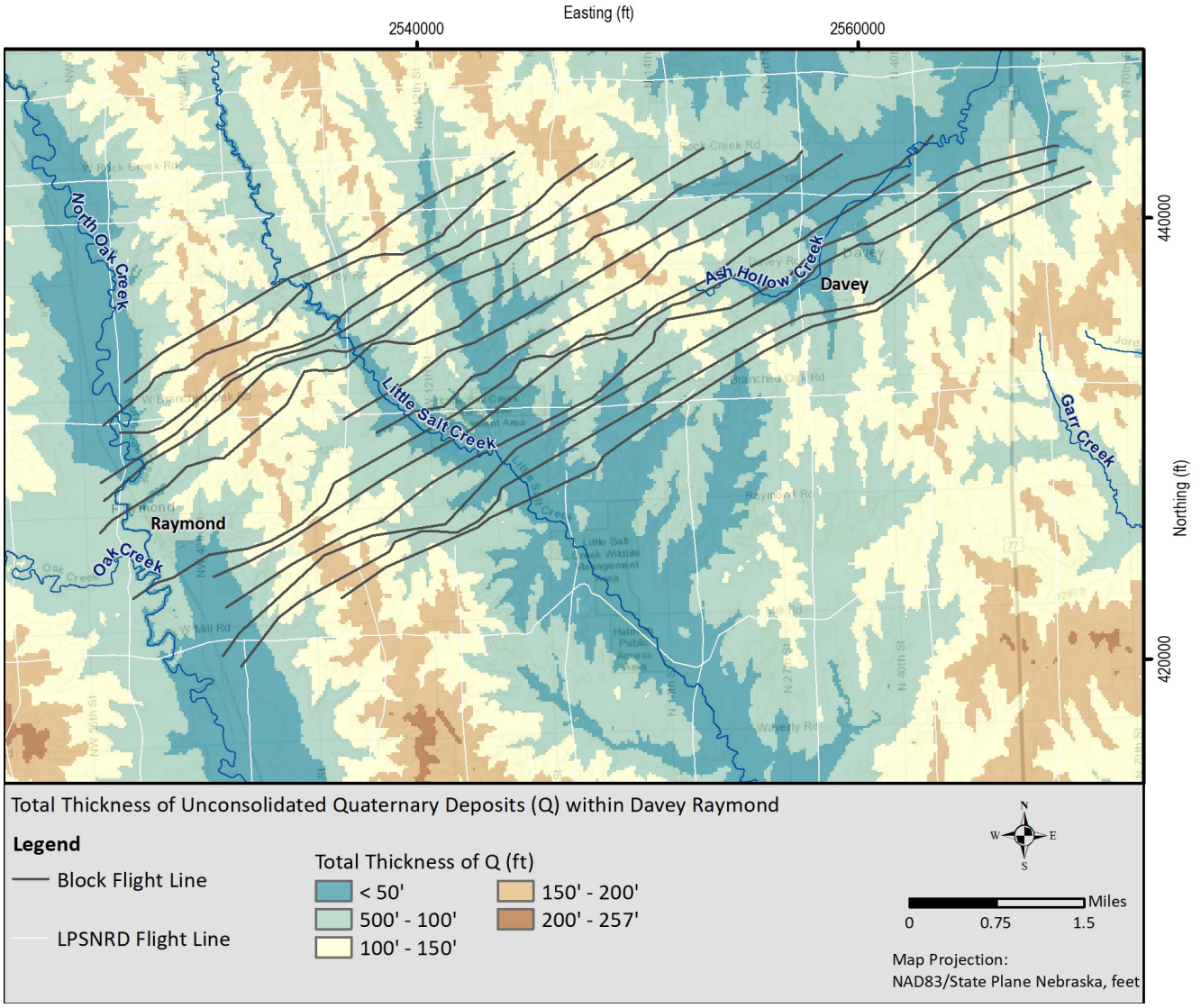


Figure 3-131. Map of the total thickness of the *Q* deposits within the 2018 Davey Raymond Block AEM survey area. The thickest areas are near the tops of ridges and hills in the block. Block flight lines are indicated by grey lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

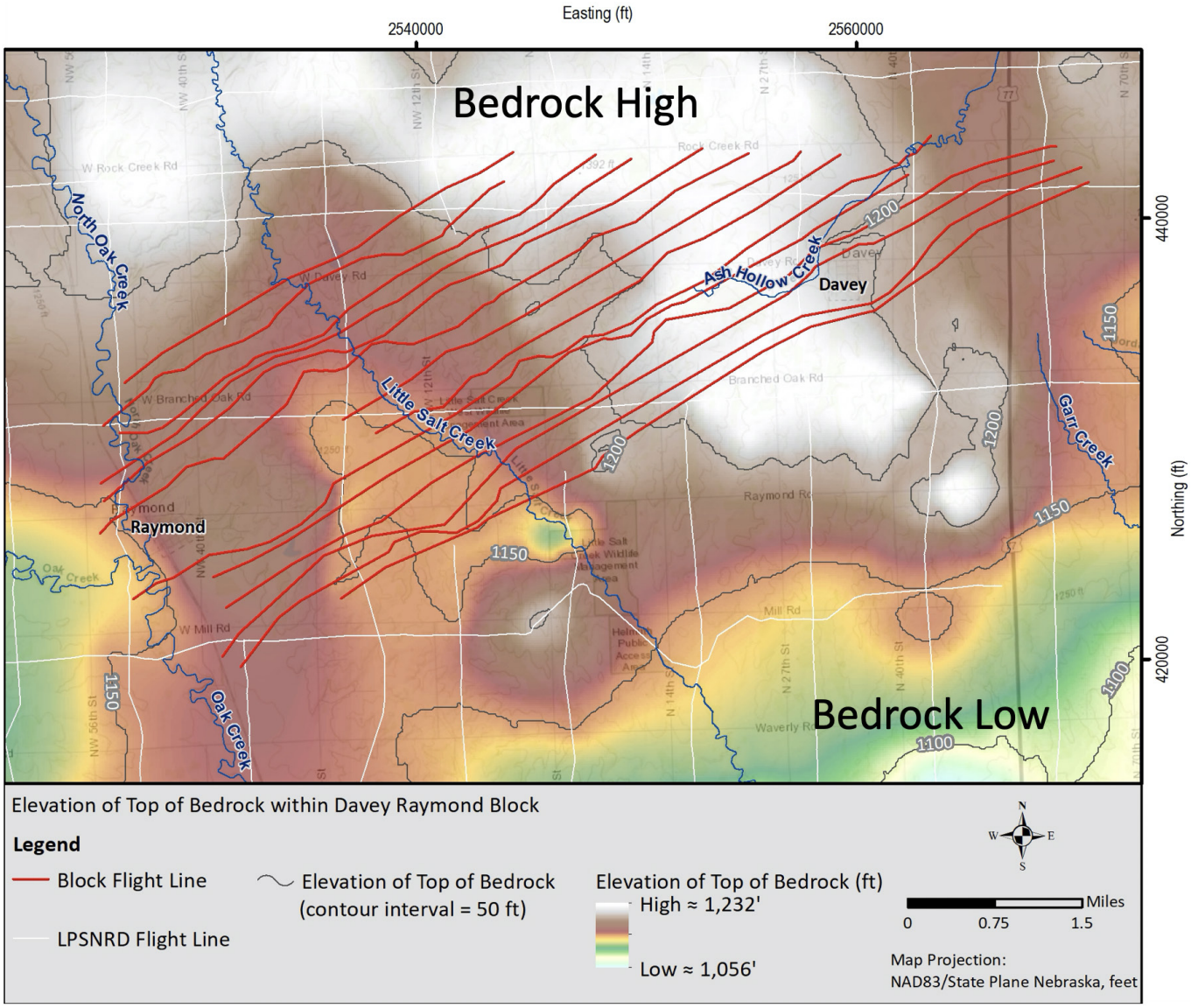


Figure 3-132. Map of the elevation of the top of bedrock within the 2018 Davey Raymond Block AEM survey area. The bedrock surface slopes in general from north to south. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

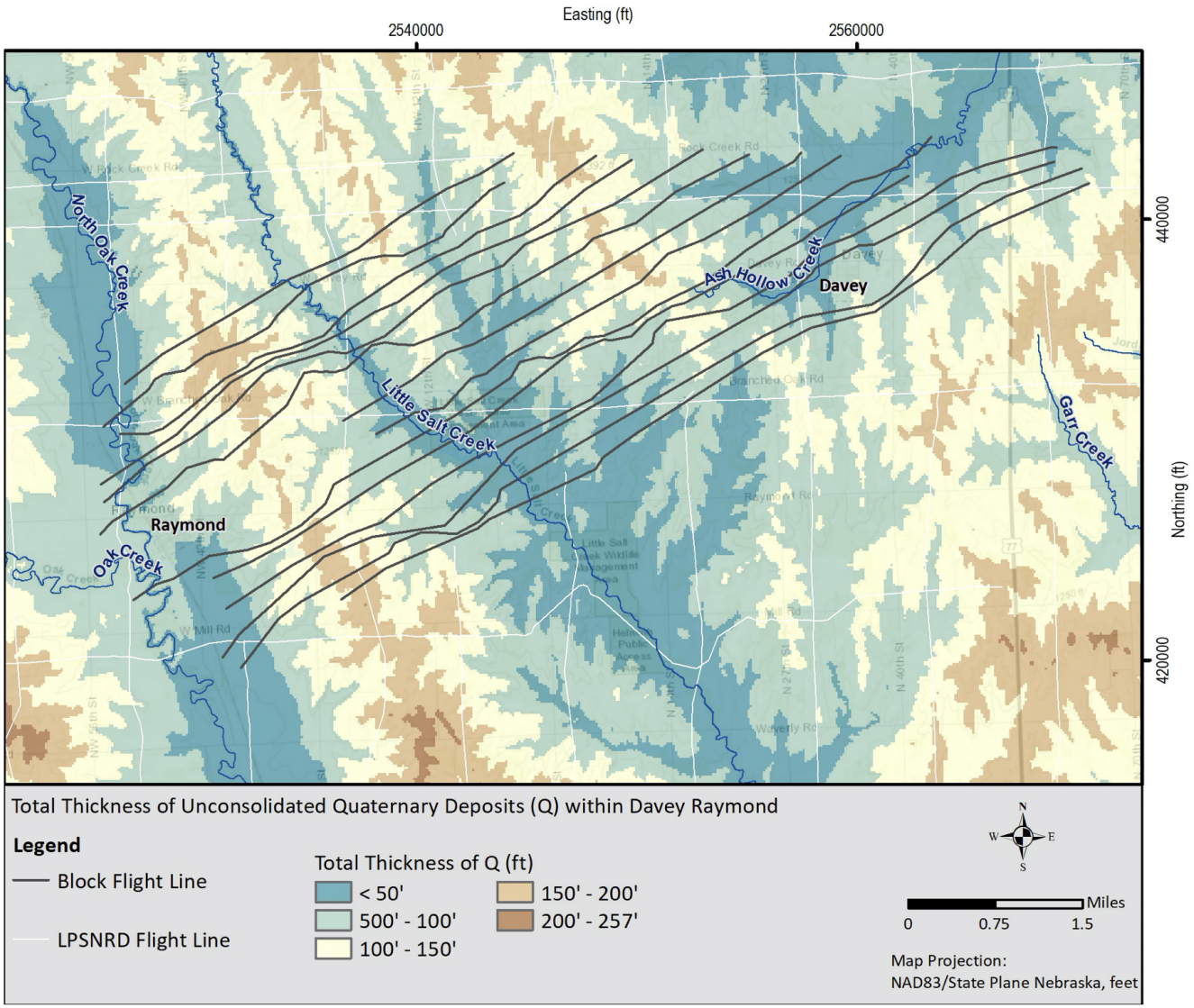


Figure 3-133. Map of total thickness of the Quaternary (*Q*) within the 2018 Davey Raymond Block AEM survey area. The thickest areas are on the southeast and southwest of the block. Block flight lines are indicated by black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

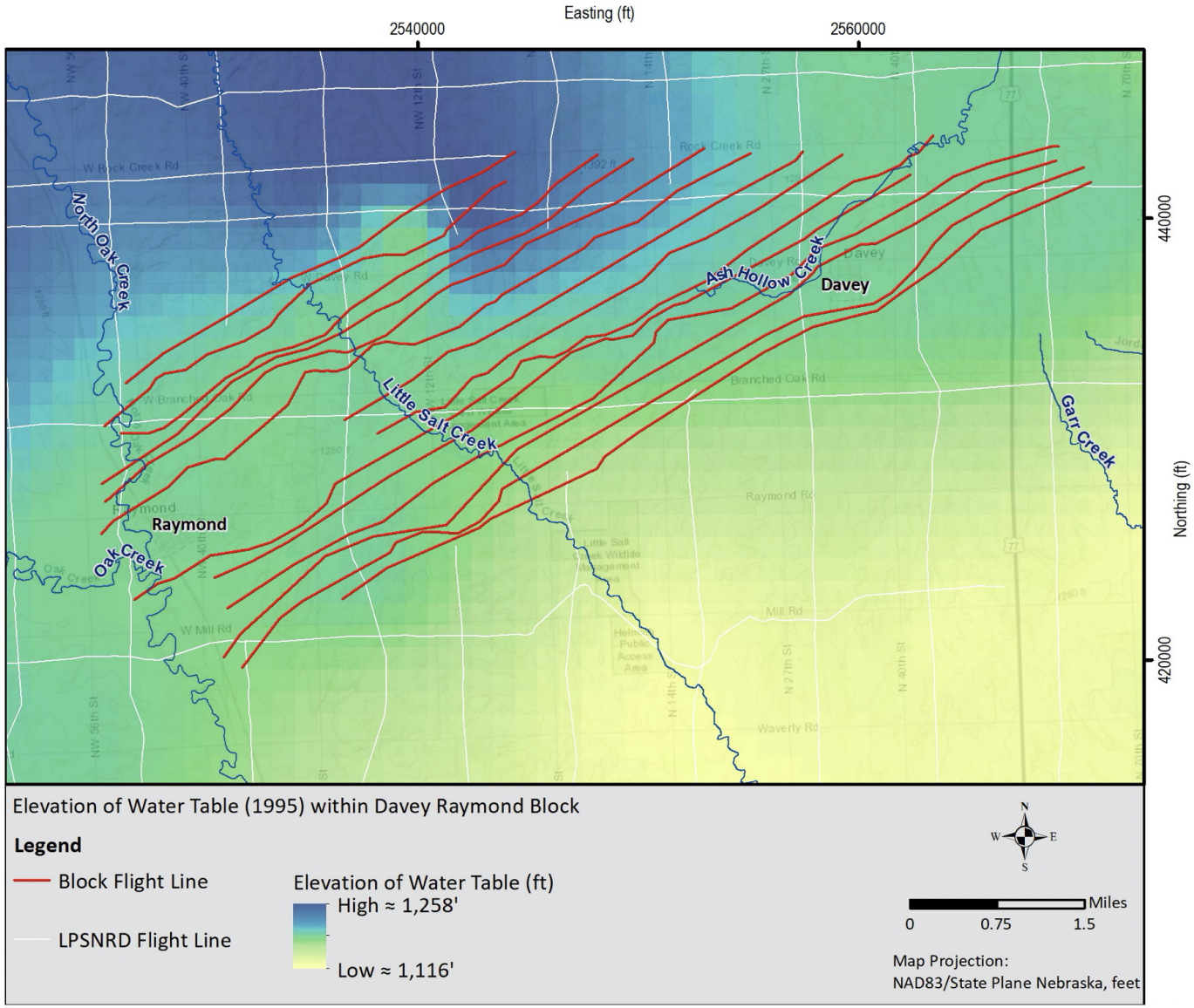


Figure 3-134. Map of the elevation of the 1995 CSD water table (NE-CSD, 1995) for the Davey Raymond Block. Horizontal datum is NAD83 State Plane Nebraska (feet).

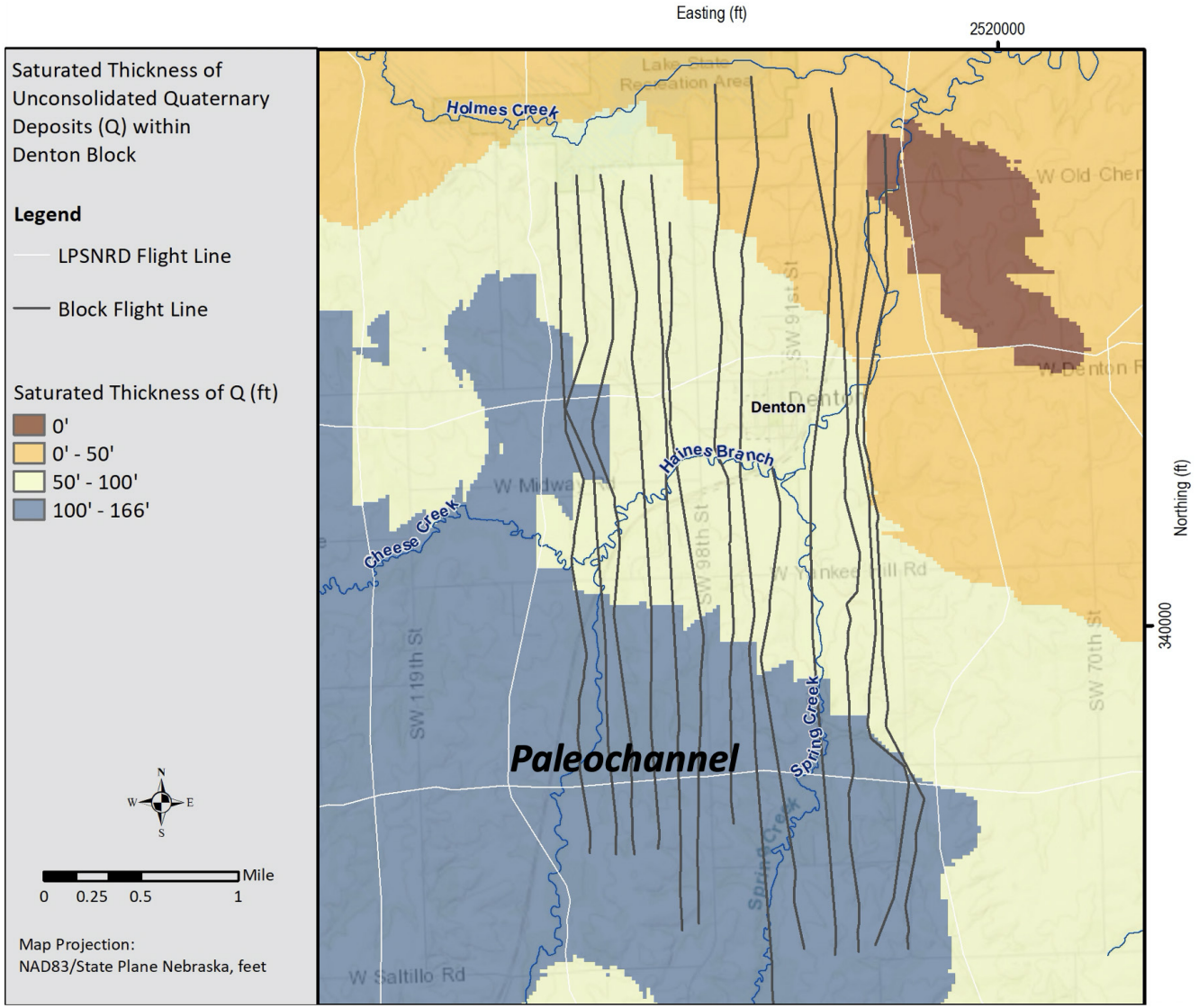


Figure 3-135. Map of saturated thickness of the Quaternary (*Q*) within the 2018 Davey Raymond Block AEM survey area. The thickest areas are on the southeast and southwest of the block. Block flight lines are indicated by black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

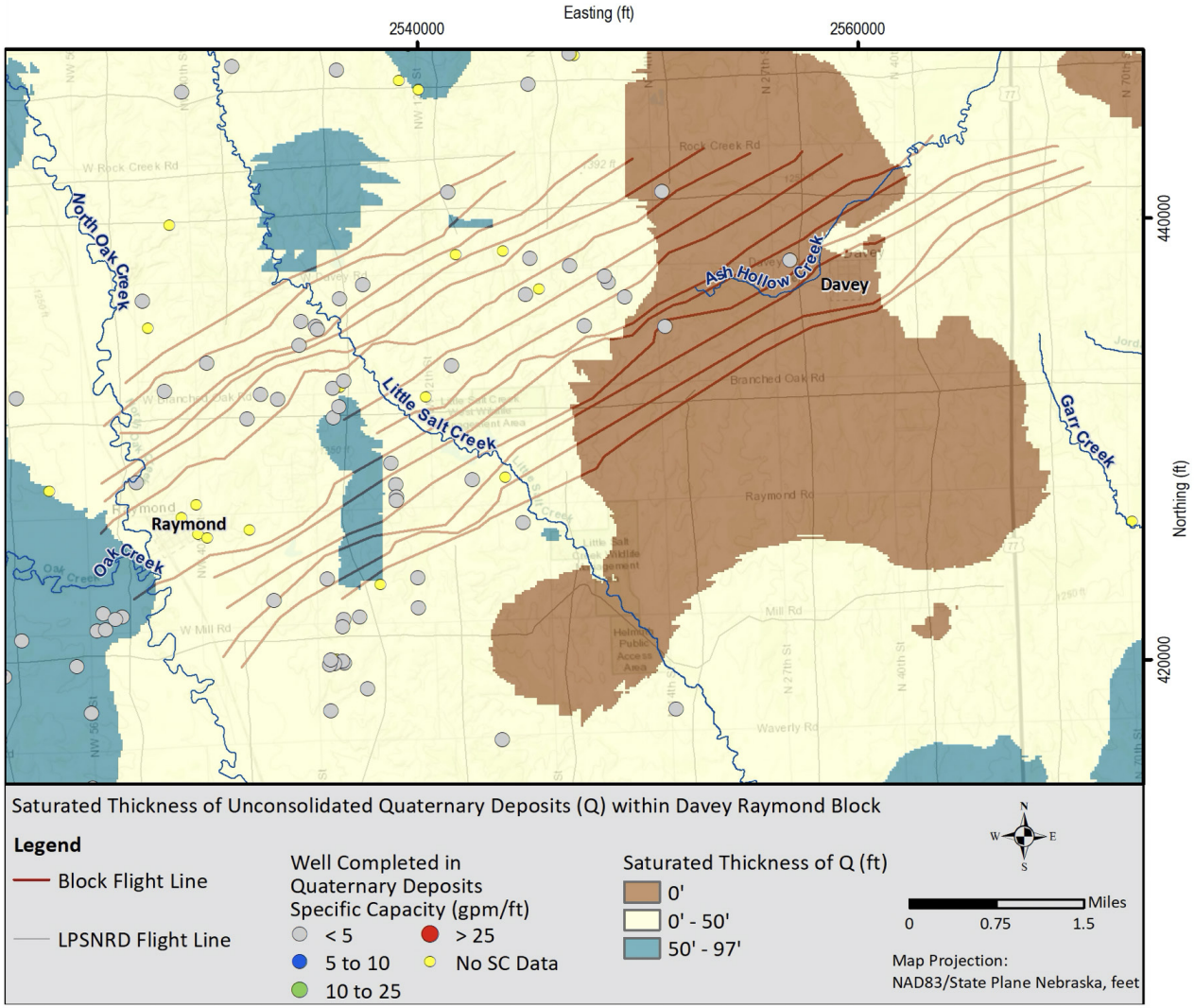


Figure 3-136. Map of saturated thickness for *Q* deposits and specific capacity of wells completed in the *Q* shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with all wells having an specific capacity of<5 gpm/ft. Block flight lines are indicated by red lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

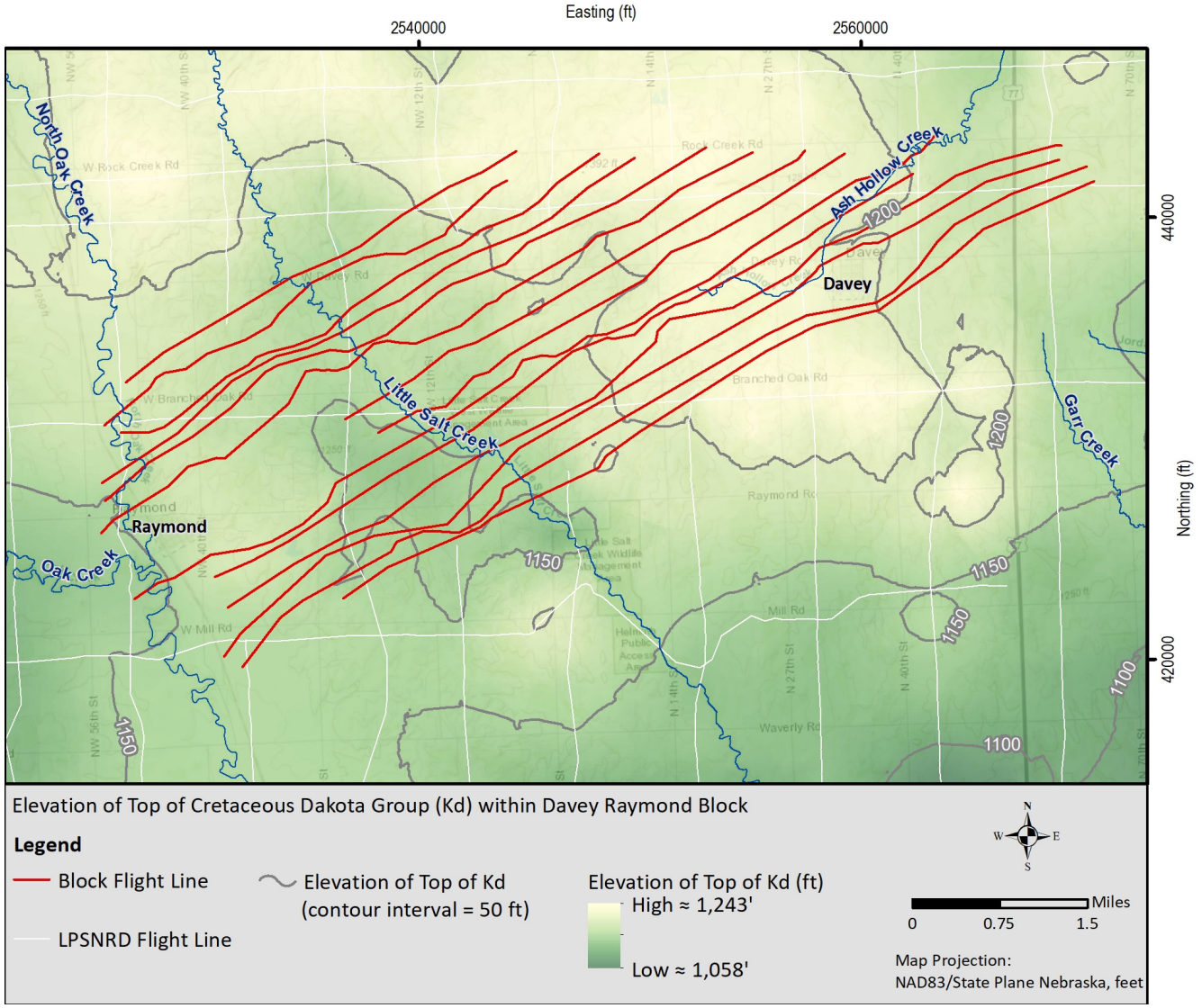


Figure 3-137. Map of the elevation of the top of the *Kd* within the 2018 Davey Raymond Block AEM survey area. The surface slopes generally from north to south. Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

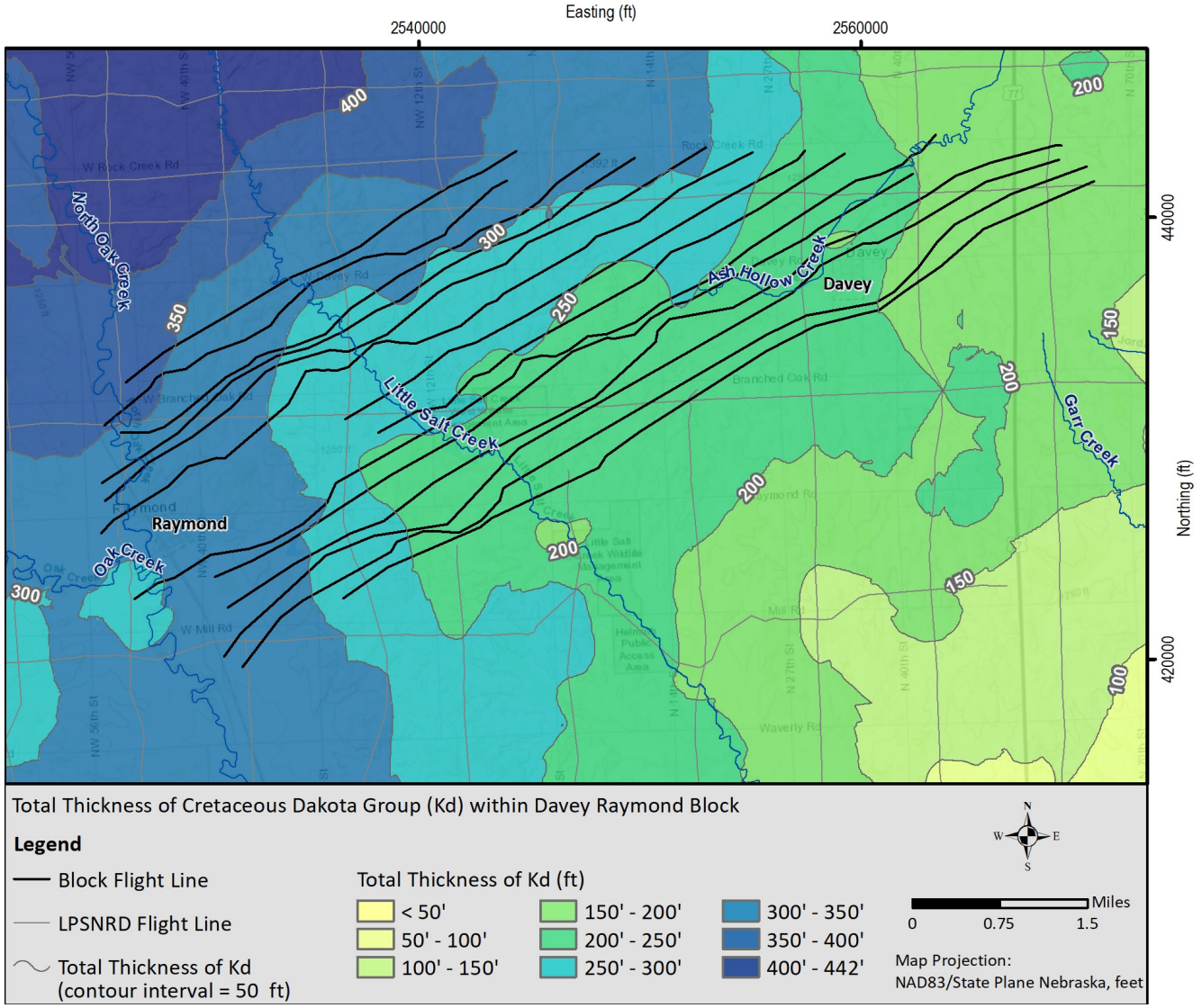


Figure 3-138. Map of the total thickness of the *Kd* within the 2018 Davey Raymond Block AEM survey area. The thickest areas are in the northwest corner of the area. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

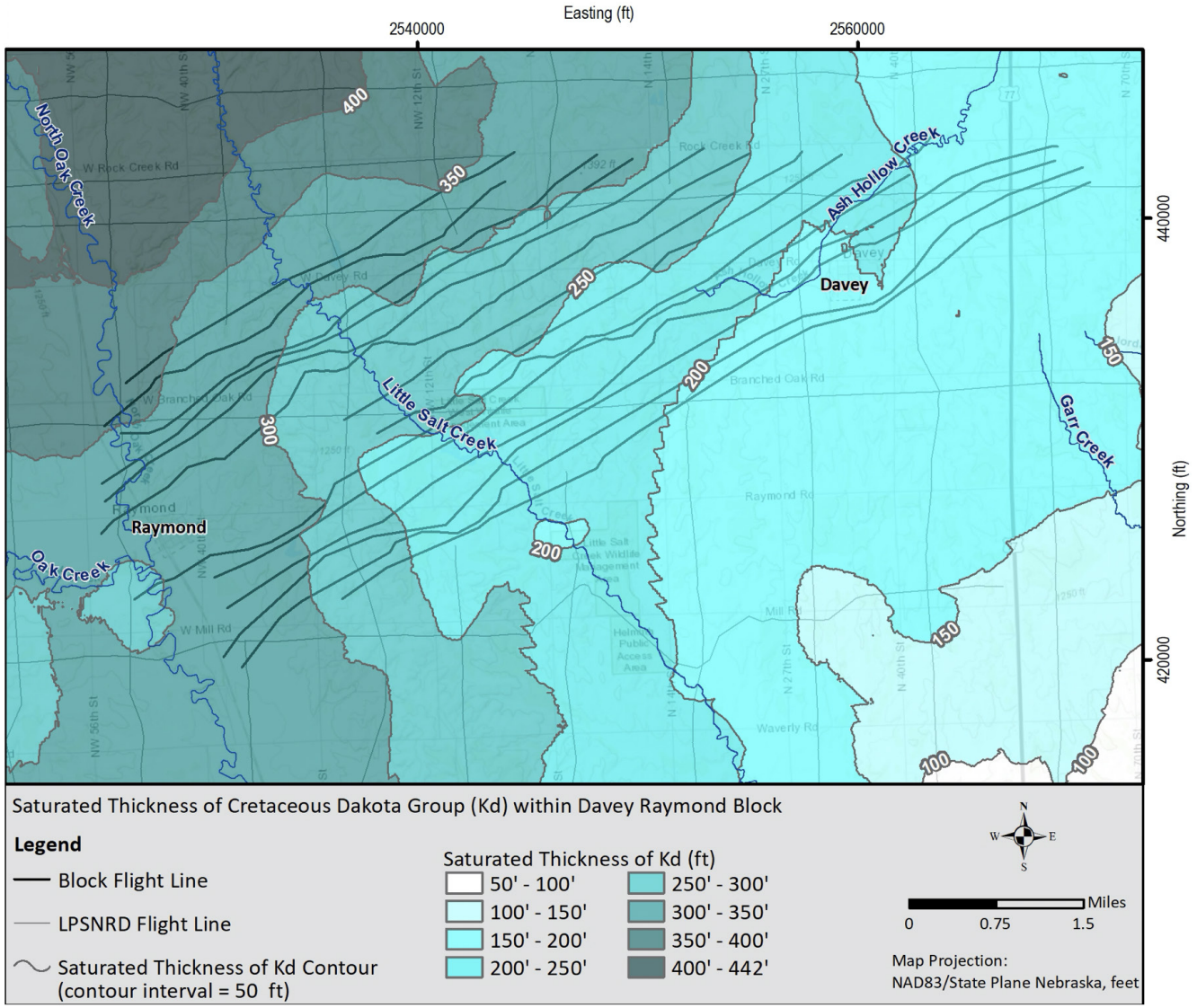


Figure 3-139. Map of the saturated thickness of the *Kd* within the 2018 Davey Raymond Block AEM survey area. The thickest areas are in the northwest corner of the area. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

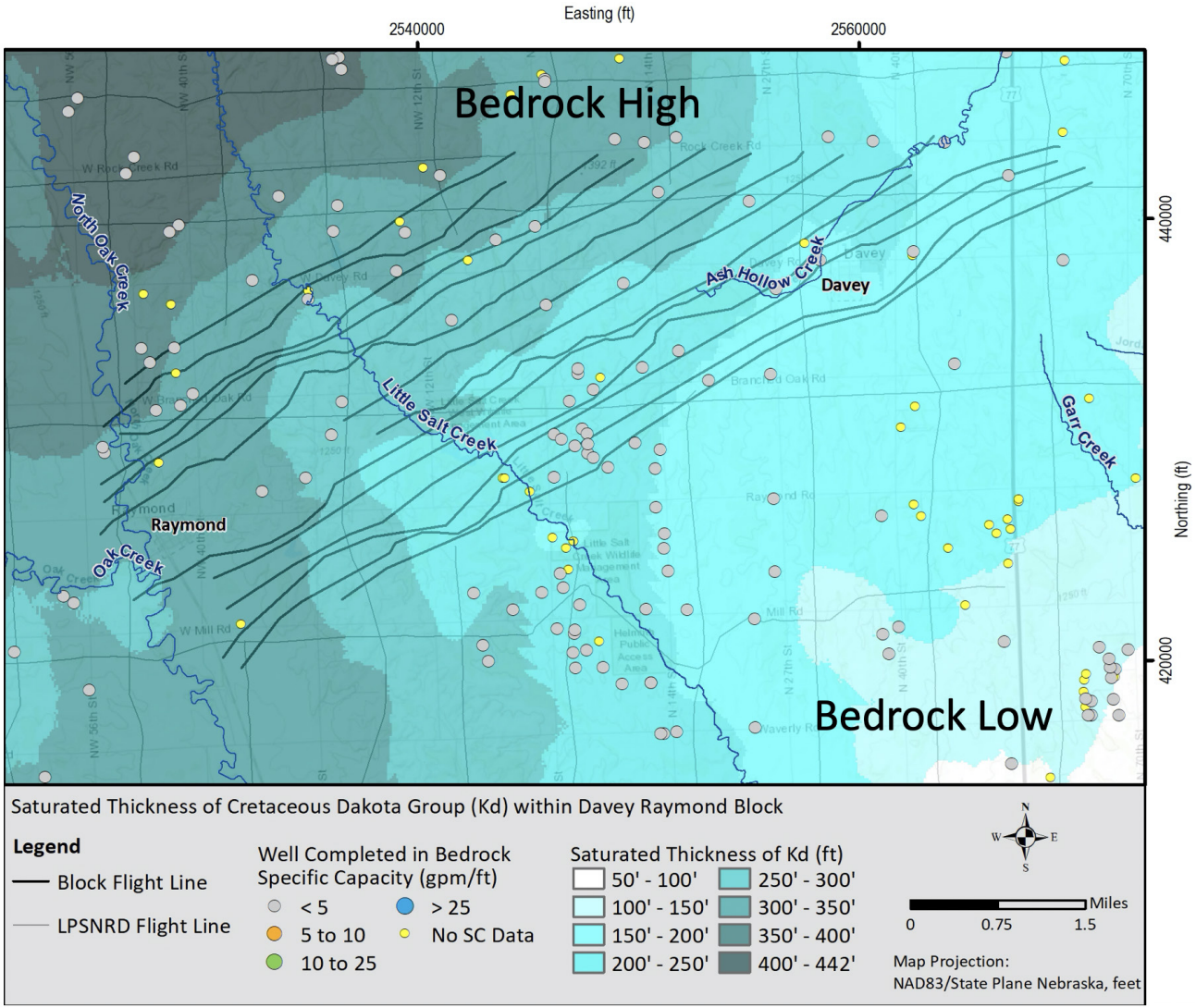


Figure 3-140. Map of saturated thickness for *Kd* deposits and specific capacity of wells completed in the *Kd* shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with all wells having an specific capacity of<5 gpm/ft. Block flight lines are indicated by the green lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

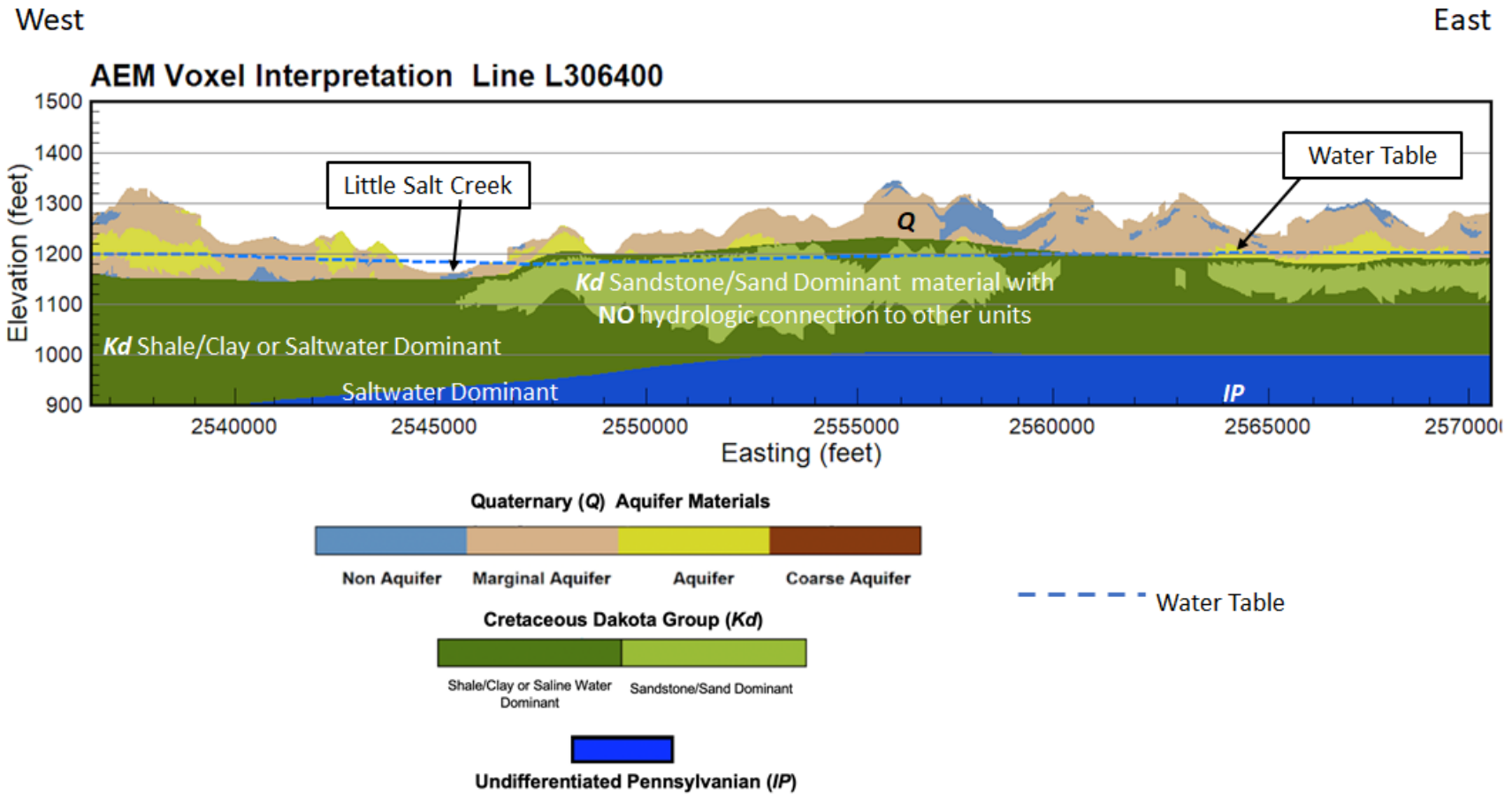


Figure 3-141. Interpreted profile of the north-south line L306400 showing the relationship the *Q*, *Kd* and *IP* of the AEM interpretations across the area. Note the water table is near the top of the *Kd*. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Block flight lines are indicated by the black lines. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

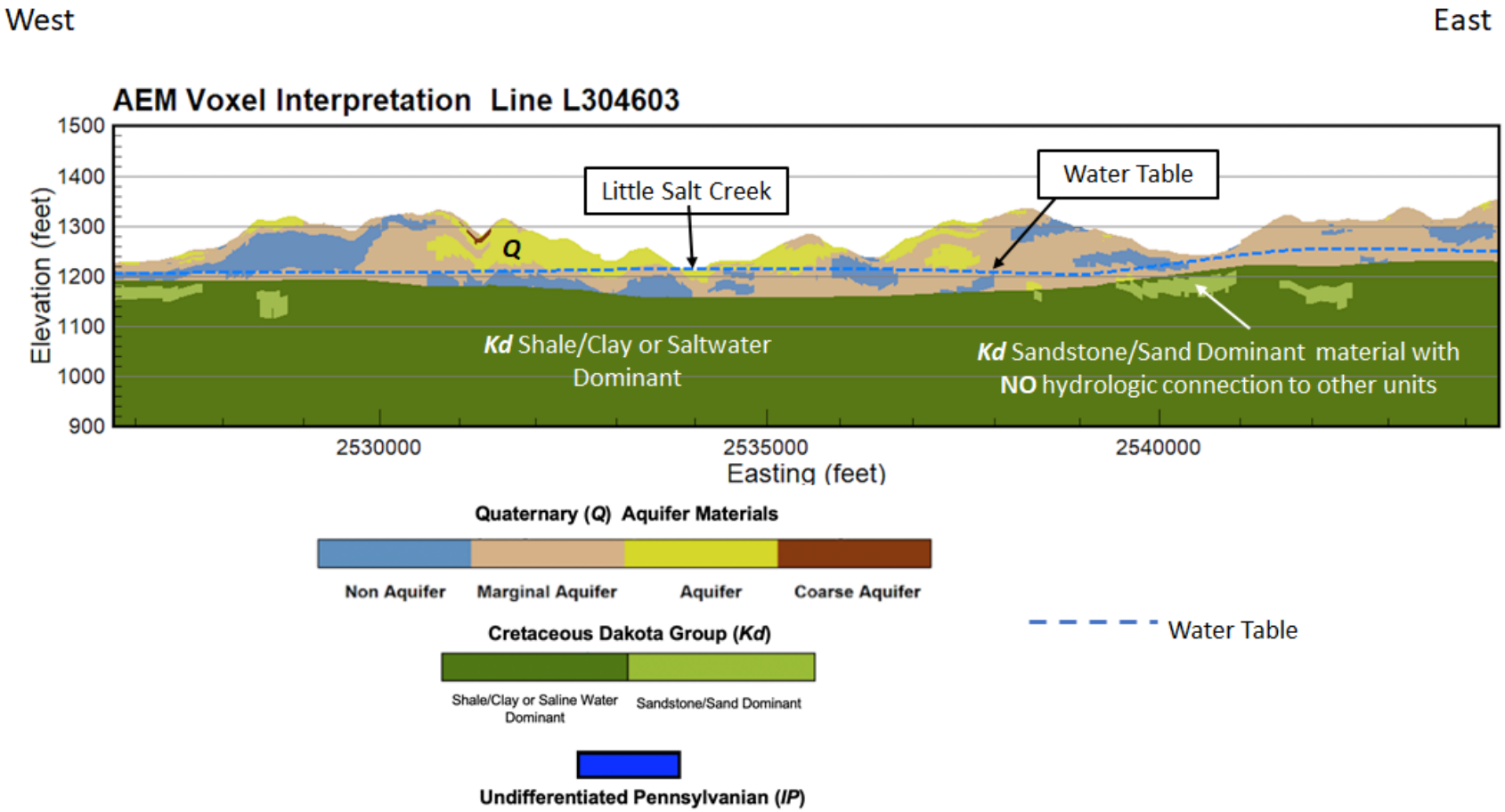


Figure 3-142. Interpreted profile of the north-south line L304603 showing the relationship the *Q*, *Kd* and *IP* of the AEM interpretations across the area. Note the there is little saturated *Q* aquifer material because the water table near the *Kd* top surface. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Block flight lines are indicated by the black lines. The geologic units present on this image include *Q*= Quaternary and *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

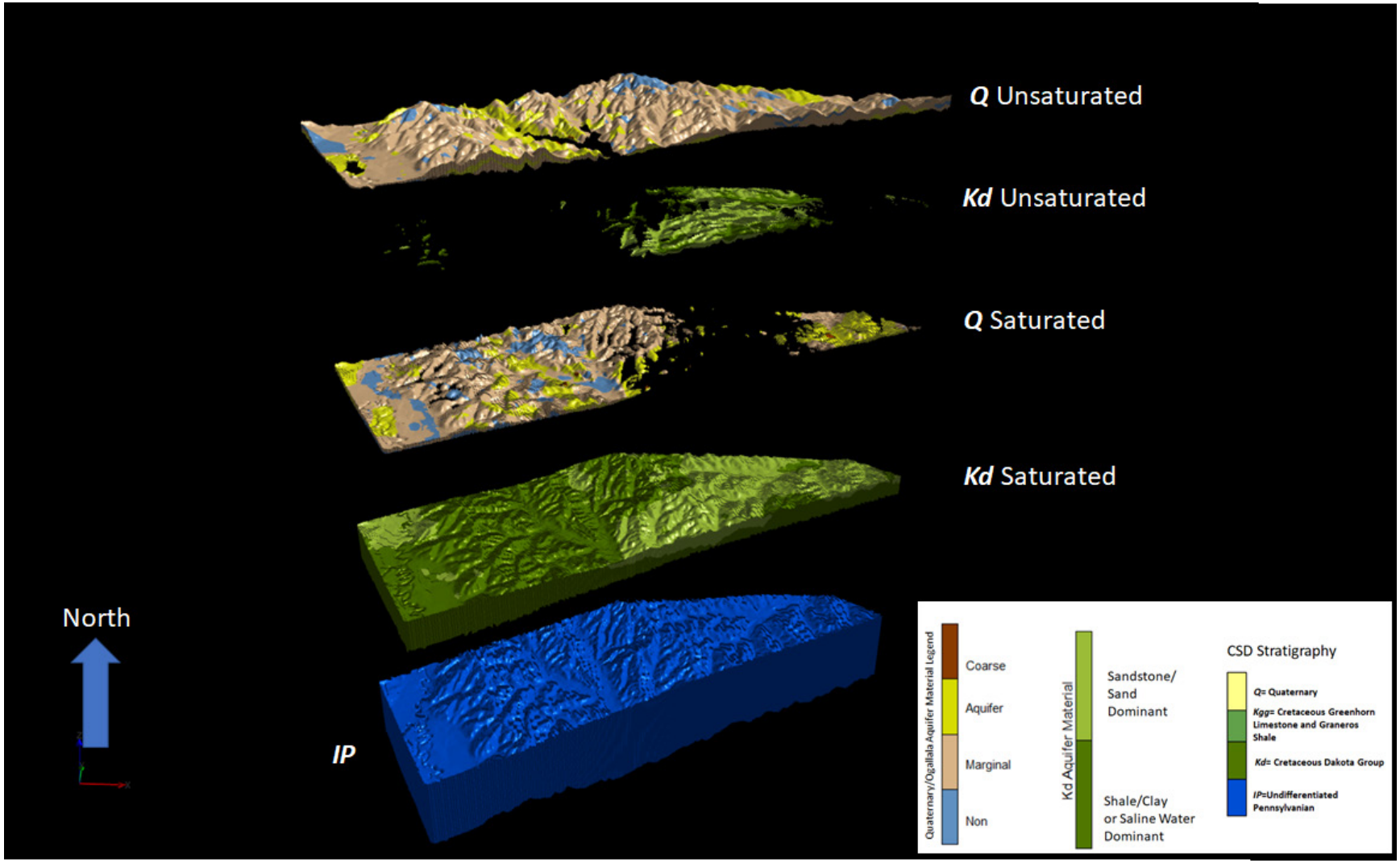


Figure 3-143. 3D exploded voxel model of the Davey Raymond Block showing Unsaturated *Q*, Saturated *Q,* Unsaturated *Kd*, Saturated *Kd* and *IP*. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Not to scale. Vertical exaggeration (VE) = 10x.

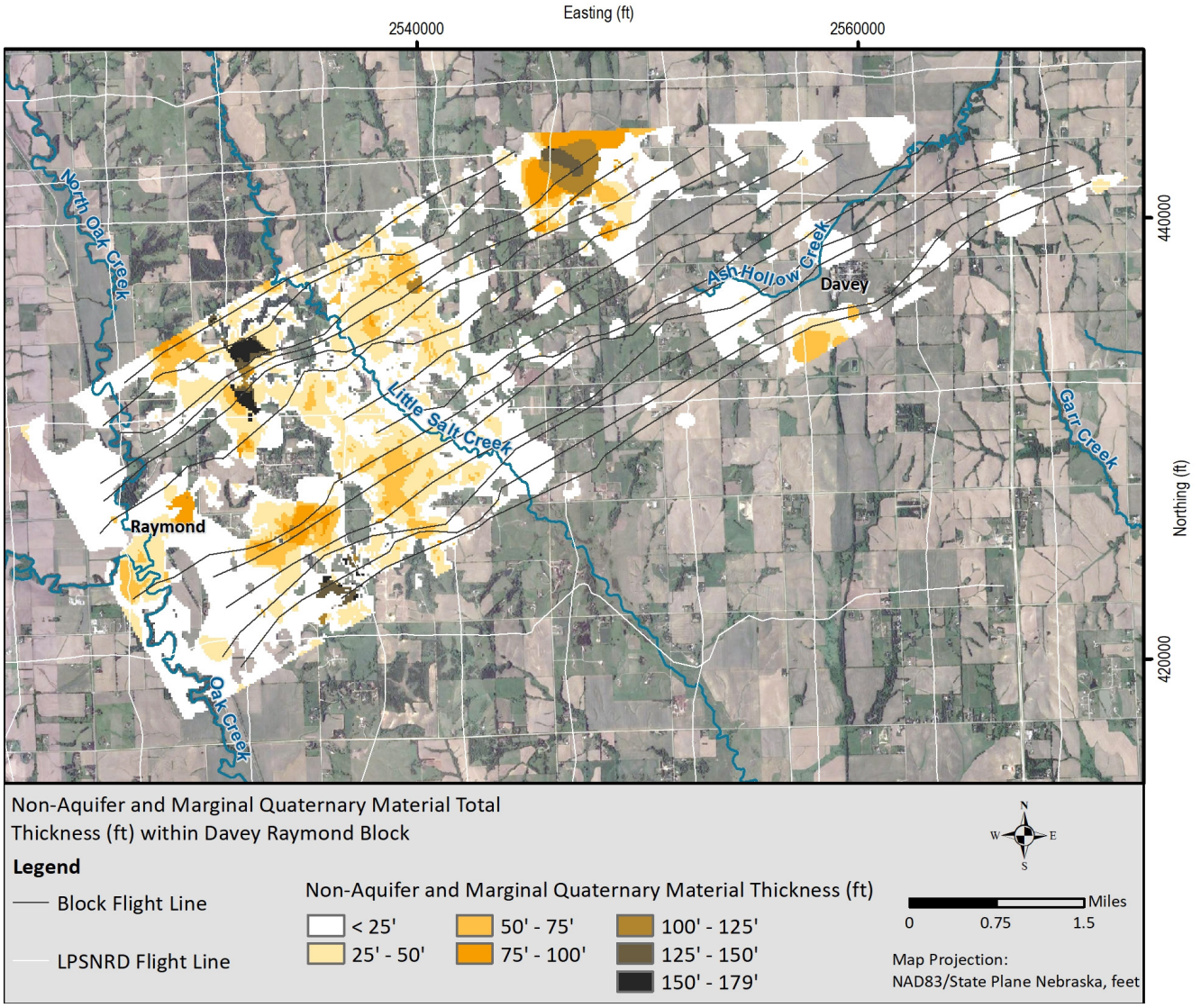


Figure 3-144. Map of *Q* Non-Aquifer and Marginal Aquifer materials total thickness for the Davey Raymond Block. Thickest areas are in the center part of the block. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet). Horizontal datum is NAD83 State Plane Nebraska (feet).

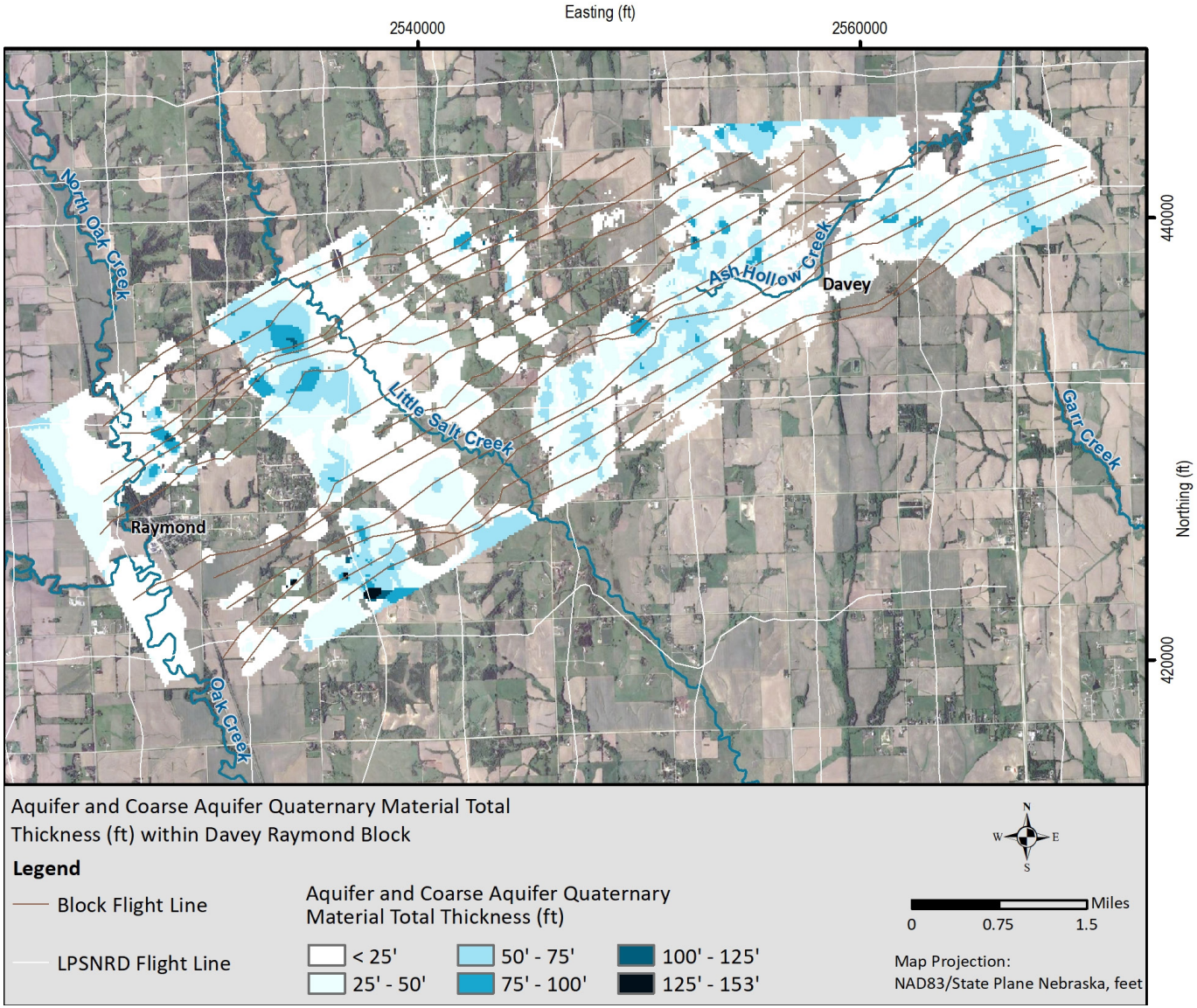


Figure 3-145. Map of total thickness of *Q* deposits of Aquifer and Coarse Aquifer materials. Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

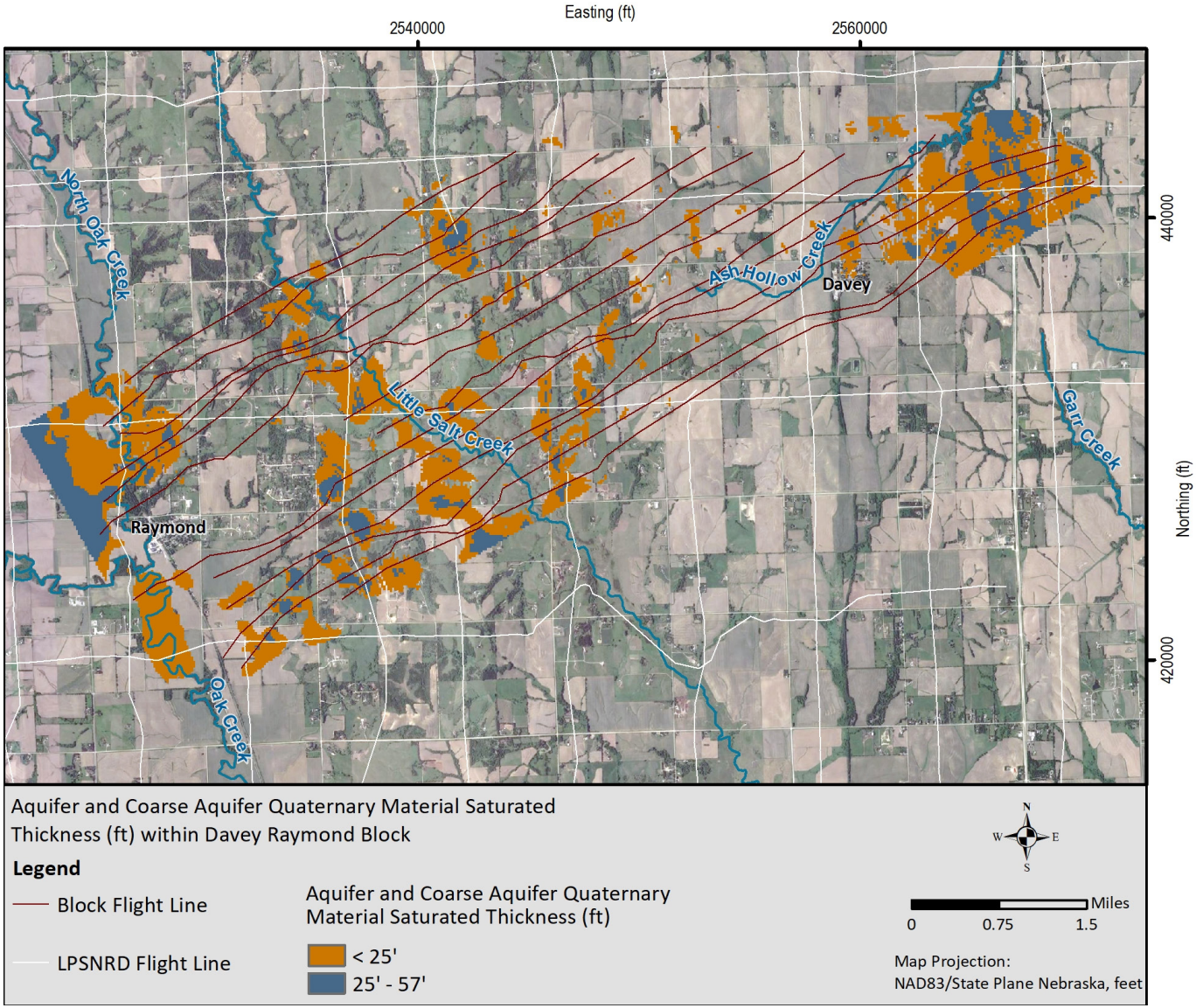


Figure 3-146. Map of total saturated thickness of *Q* deposits of Aquifer and Coarse Aquifer materials. Block flight lines are indicated by the redlines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

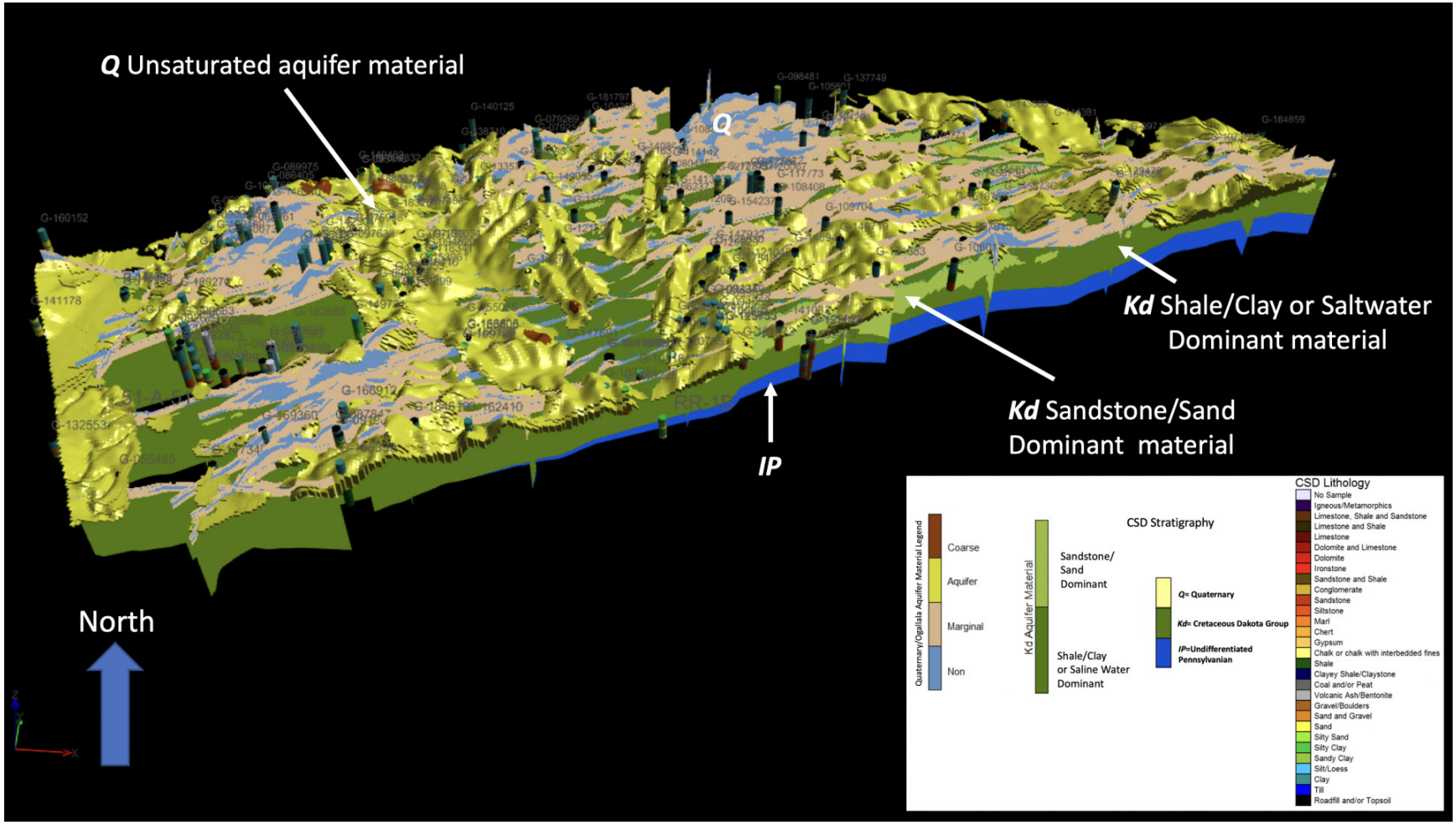


Figure 3-147. View of 3D voxel model of *Q* saturated Aquifer and Coarse Aquifer Material with a fence diagram of unsaturated *Q* Marginal and Non-Aquifer material looking north. The *Kd* and *IP* are also shown. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

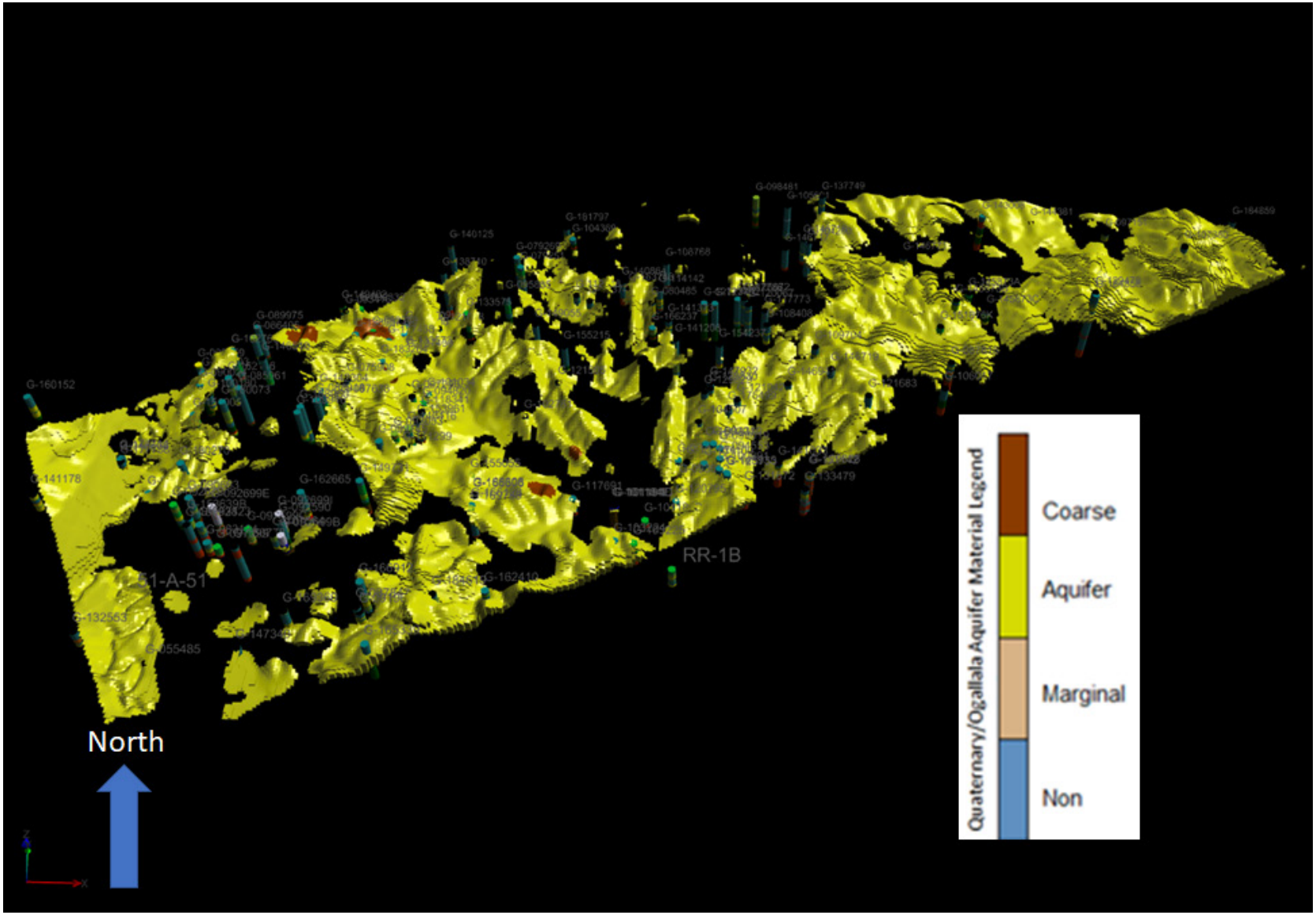


Figure 3-148. View to the north showing a 3D voxel of saturated and unsaturated *Q* Aquifer and Coarse Aquifer Material. The geologic units present on this image include *Q*= Quaternary. Vertical exaggeration (VE) = 10x.

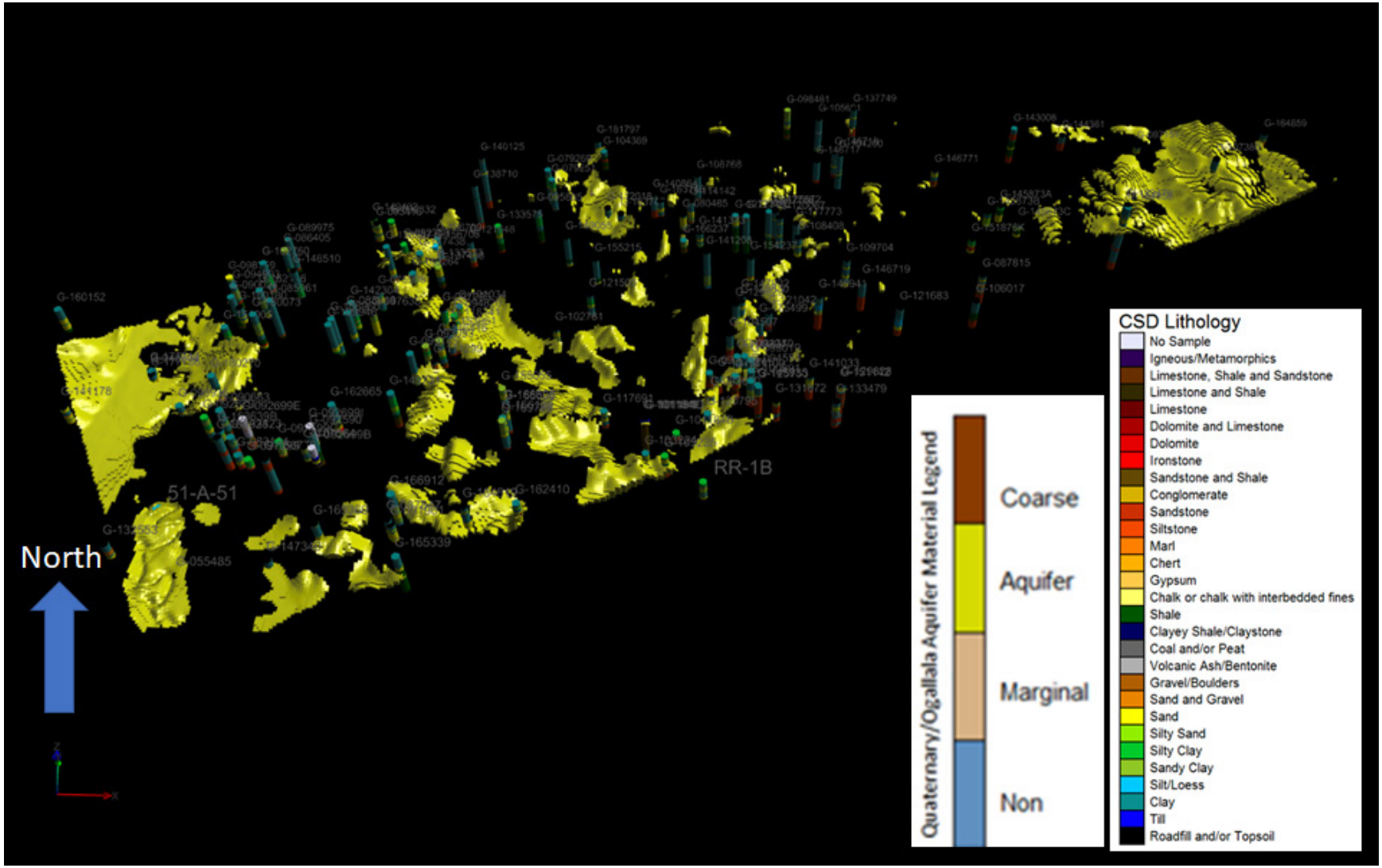


Figure 3-149. View to the north of a 3D voxel of the saturated *Q* Aquifer and Coarse Aquifer Material. The geologic unit present on this image includes the *Q*= Quaternary. Vertical exaggeration (VE) = 10x.

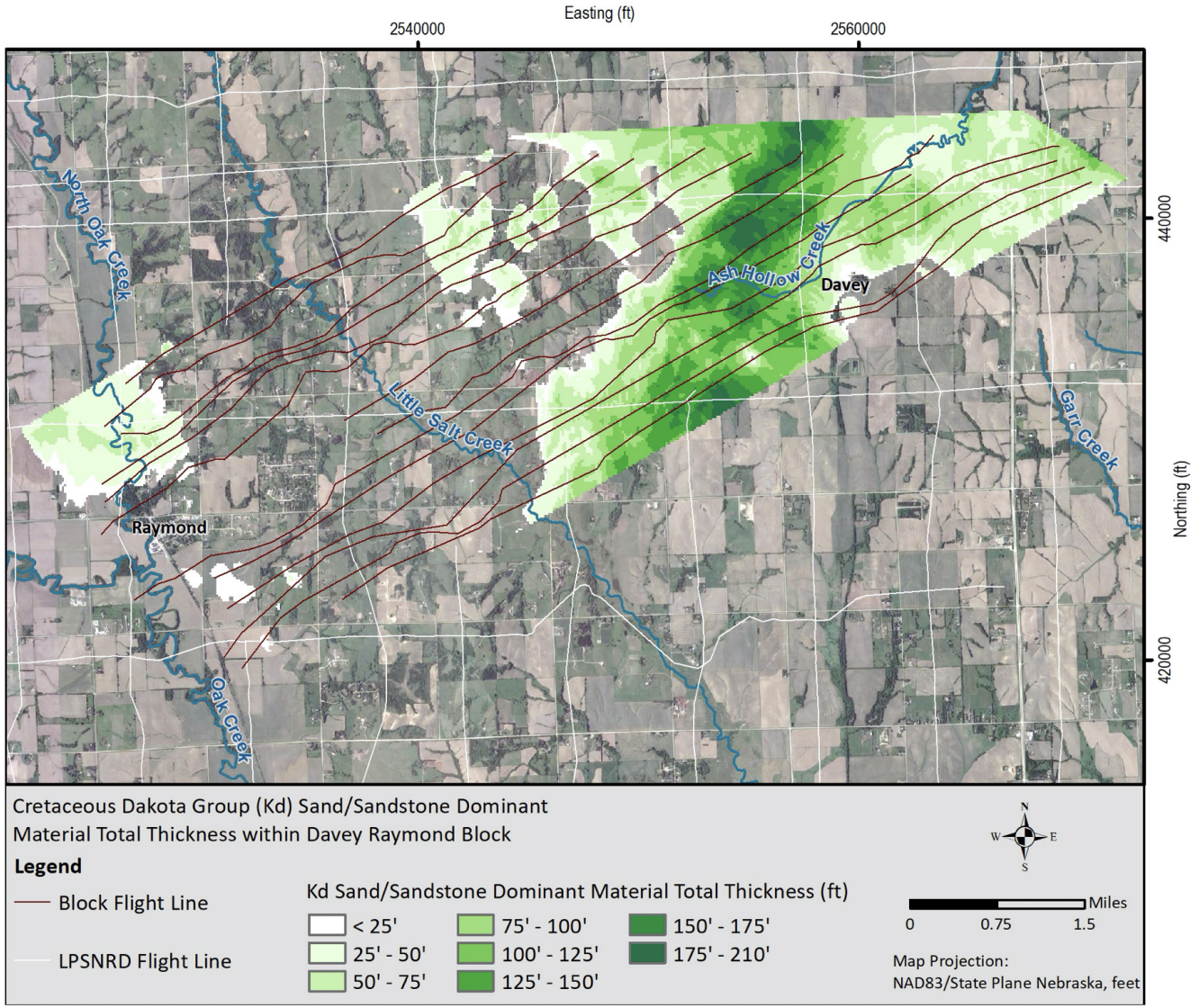


Figure 3-150. Map of the total thickness of the Sandstone/Sand Dominant portion of the *Kd* in the 2018 Davey Raymond Block AEM survey area. Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

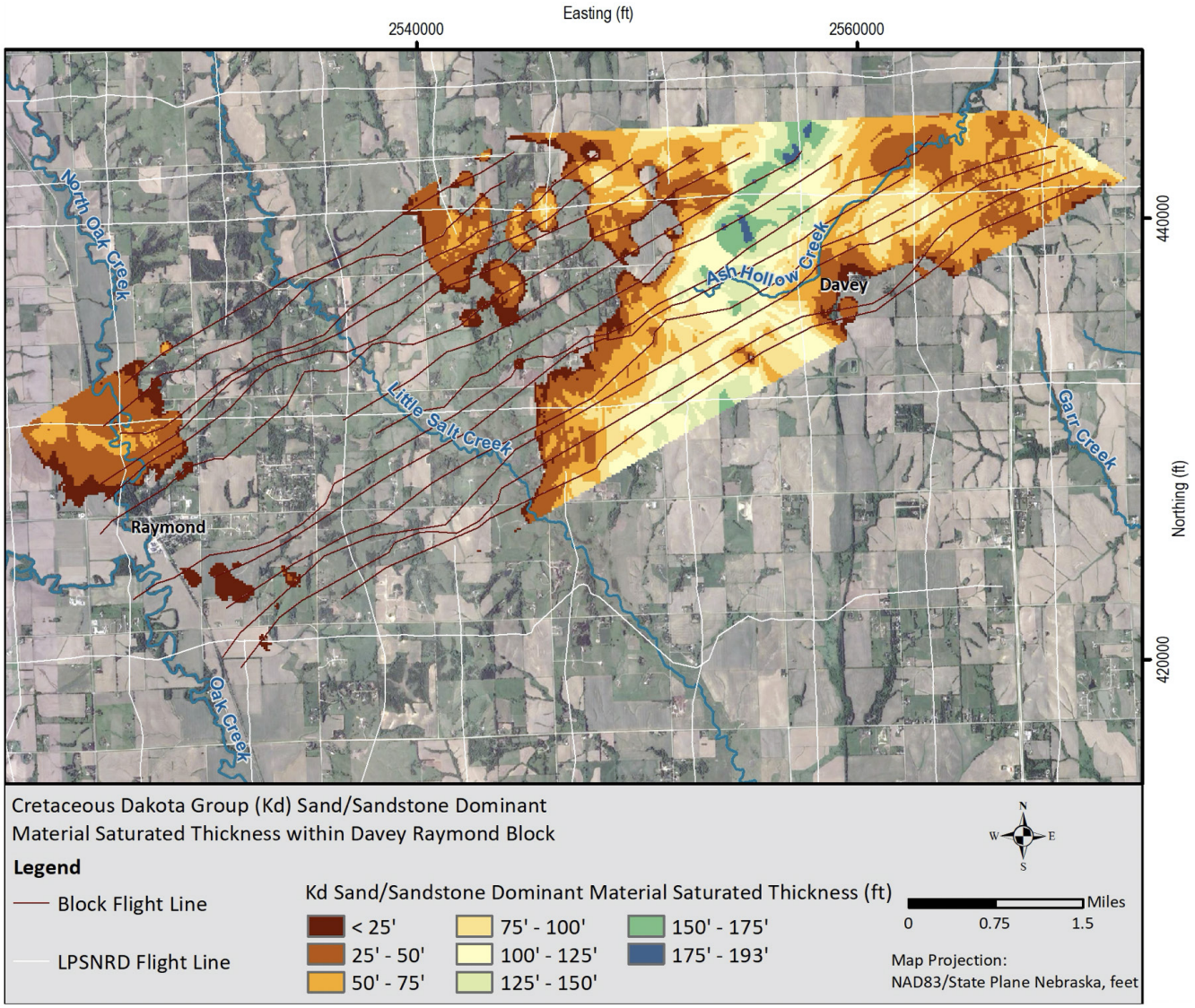


Figure 3-151. Map of the saturated thickness of the Cretaceous Dakota Group (*Kd*) Sandstone/Sand Dominant material in the 2018 Davey Raymond Block AEM survey area. Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

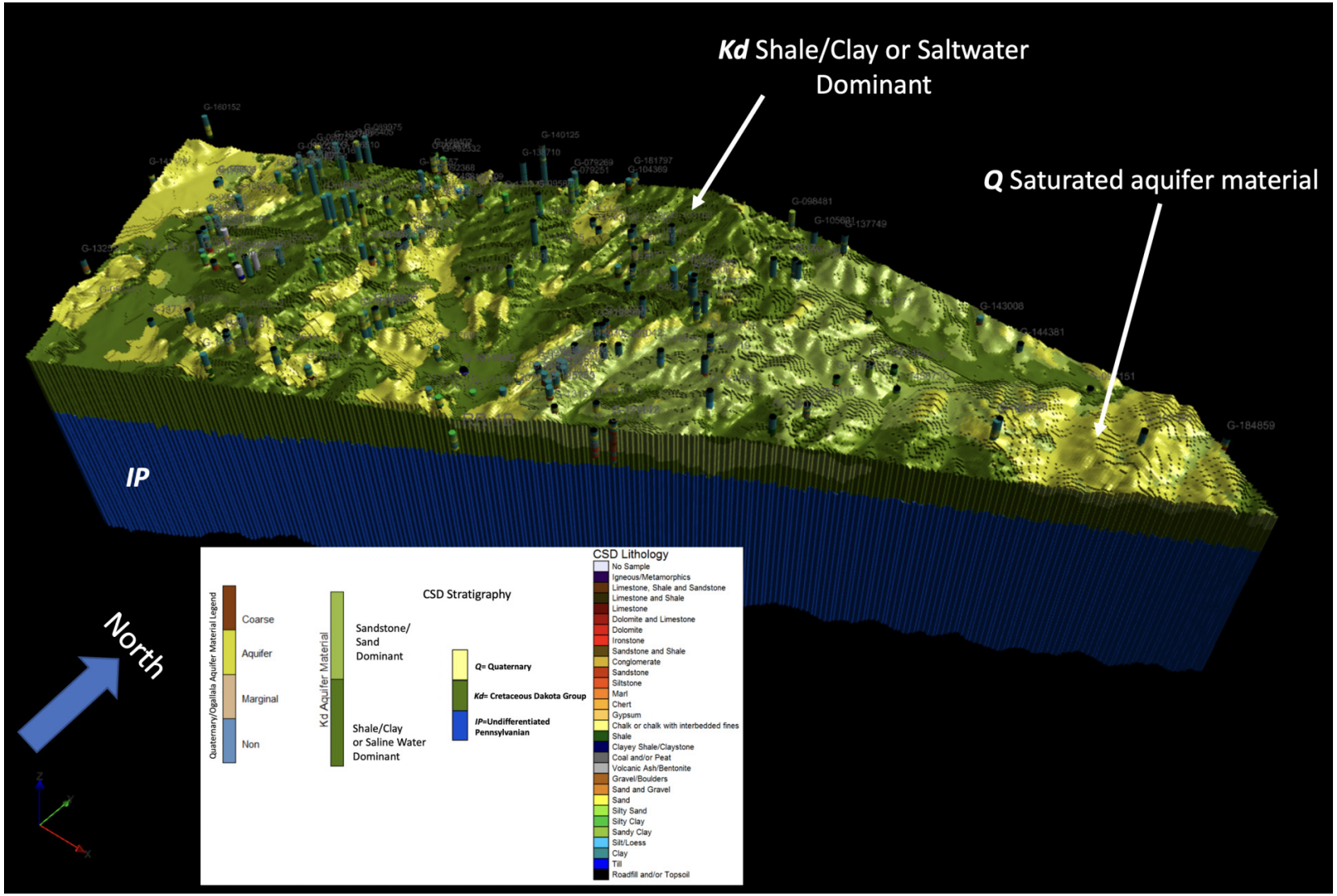


Figure 3-152. View of 3D voxel model of *Kd* Sandstone/Sand dominant and Shale/Clay or Saltwater Dominant materials looking northwest. Saturated Q Aquifer Material and *IP* are also shown. The geologic units present on this image include *Q*=Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 15x.

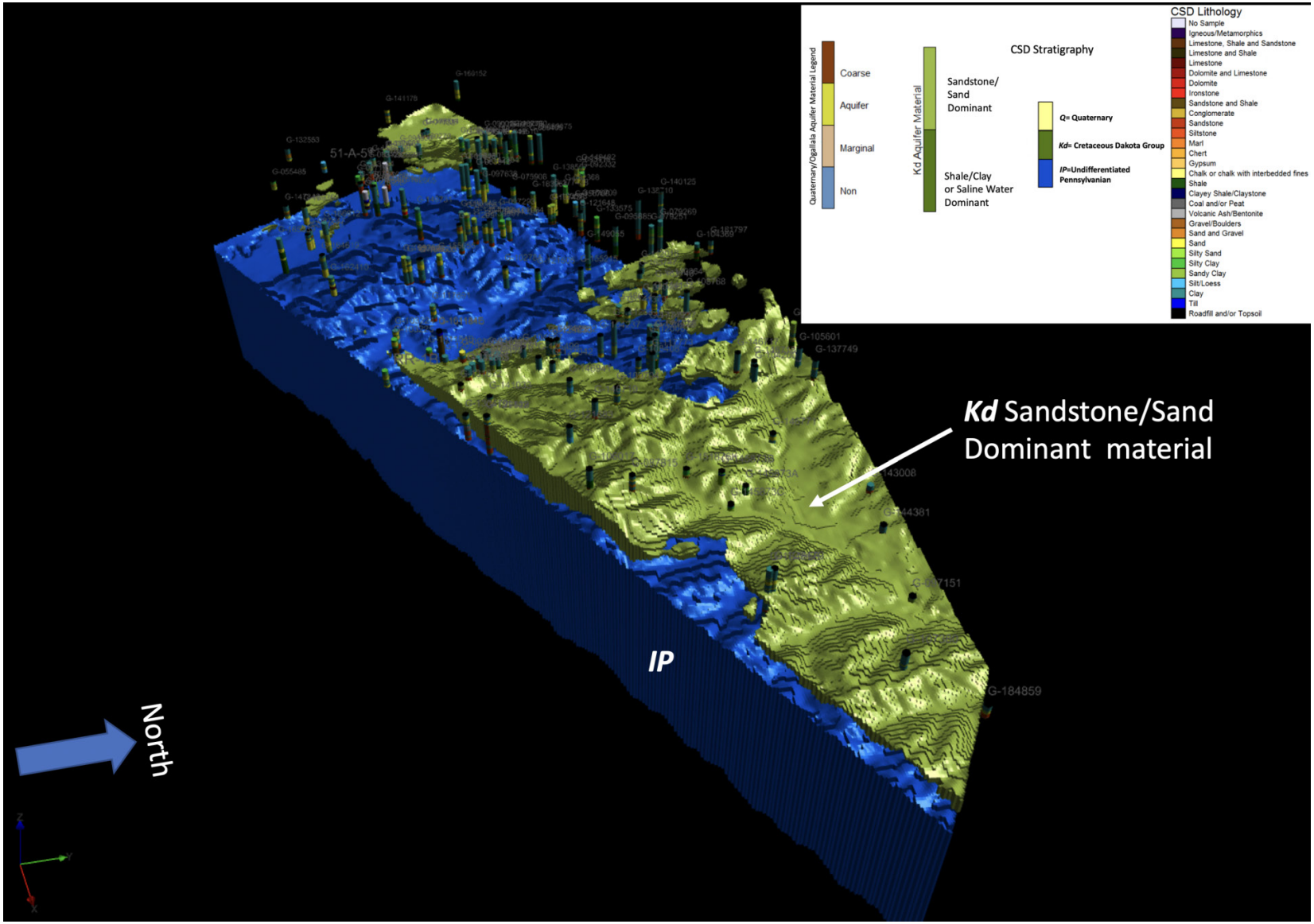


Figure 3-153. View of 3D voxel model of *Kd* Sandstone/Sand dominant looking west. The *IP* is also shown. The geologic units present on this image include *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

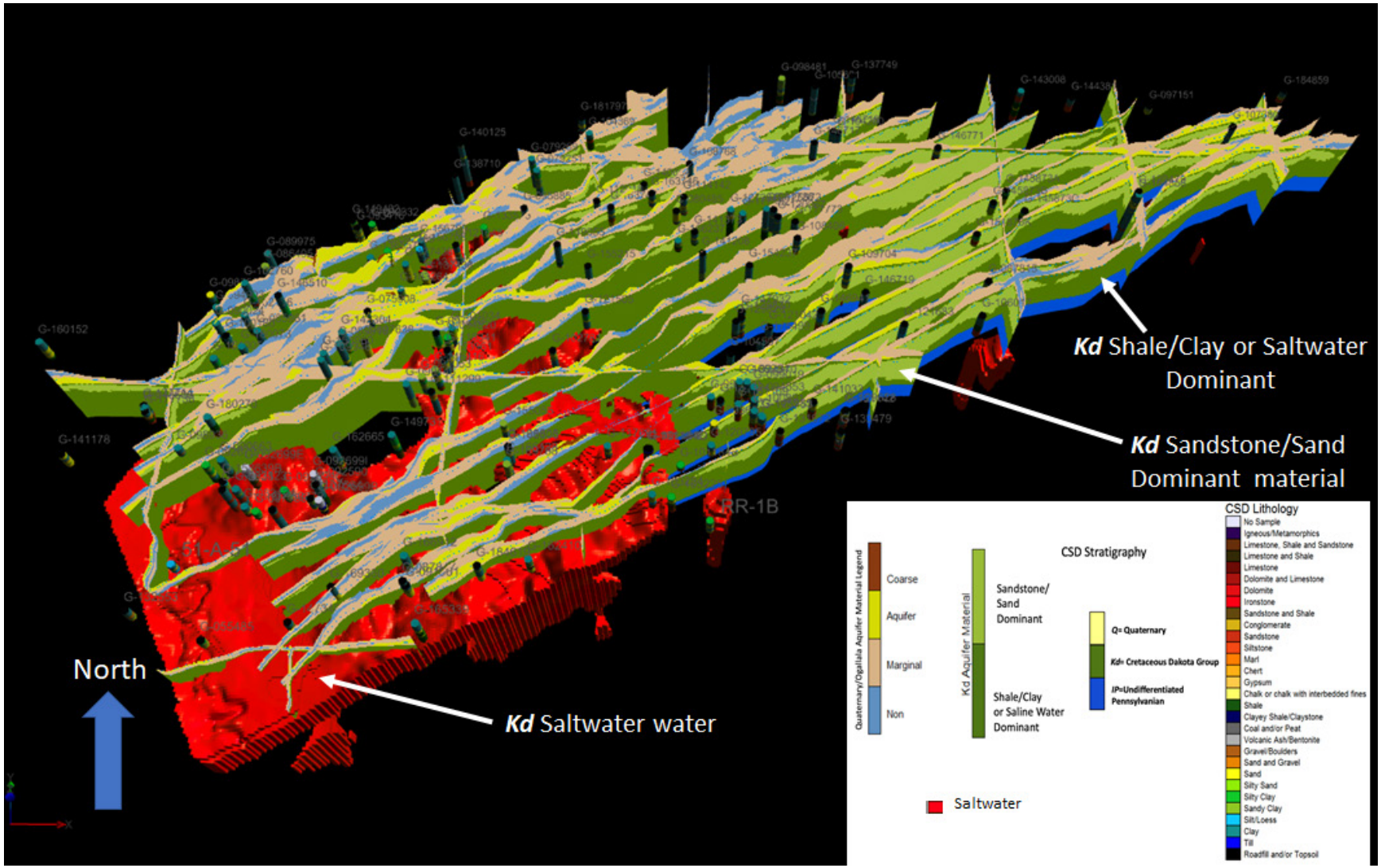


Figure 3-154. View of 3D voxel model looking north showing the saltwater water areas in the Block colored red. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

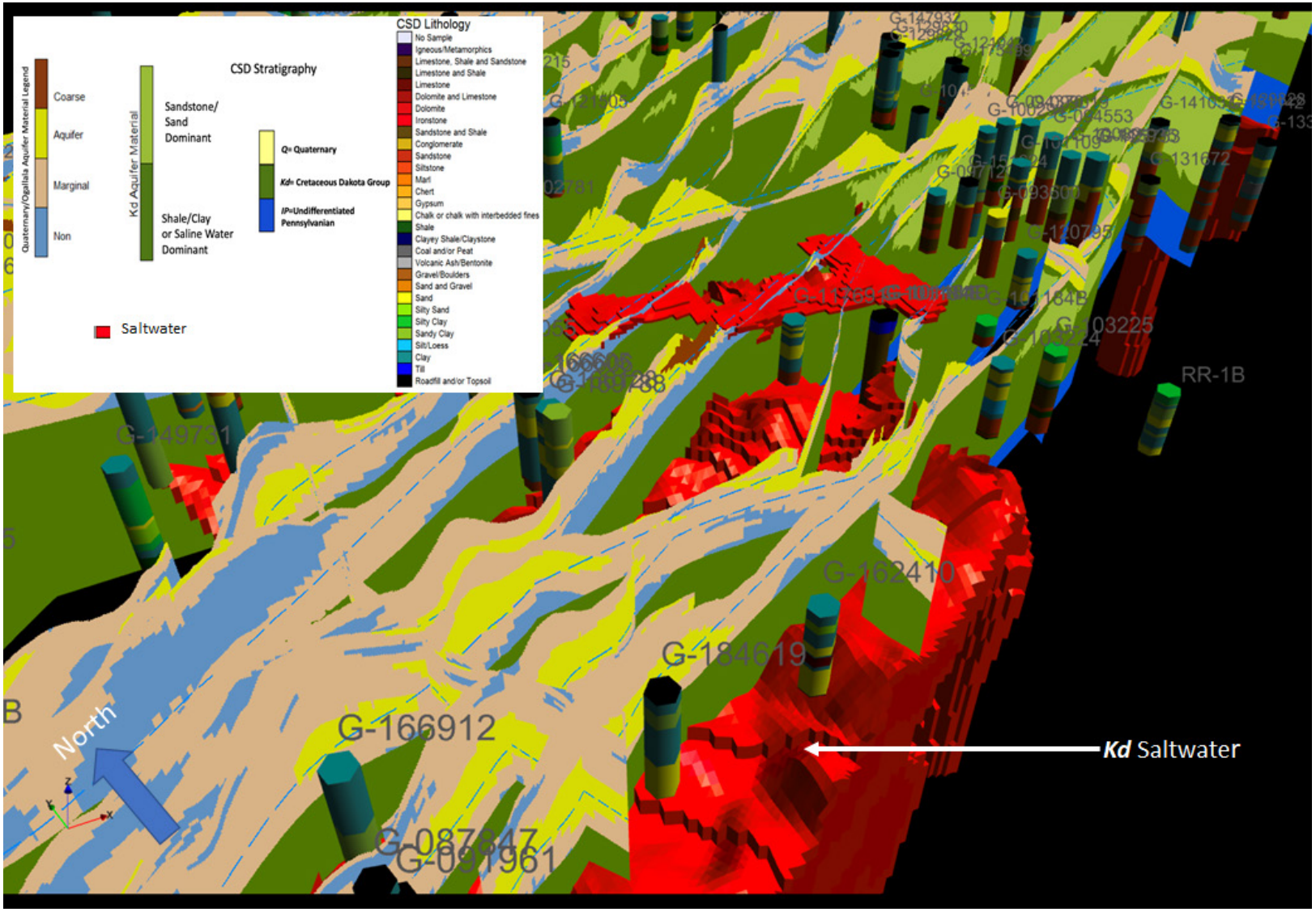


Figure 3-155. Close up view of 3D voxel model looking northeast showing the saltwater water areas in the Block colored red. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

3.2.4 Hydrogeologic Framework of the Denton Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material and the Cretaceous units in the Denton Block AEM survey area. The ***Q*** materials within the Denton Block are composed of unconsolidated clay, silt, sand and gravel that overlie the consolidated bedrock which is made up of ***Kd***. The ***Q*** material in the Denton Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1. Figure 3-156 is the flight line location map including roads, streams and towns. Generally, the flight block is near Denton, Nebraska. The ground surface elevation map shown on Figure 3-157, There are rolling hills with a ridge between Haines Branch, Cheese Creek and Spring Creek. Denton, Nebraska lies near the confluence of Haines Branch and Spring Creek. Figure 3-158 displays a deep 3D fence diagram with a voxel model of the unsaturated ***Q*** aquifer and coarse aquifer material of the Denton Block AEM survey area, looking to the northwest, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** aquifer materials lying upon the ***Kd*** which lies upon the ***IP***. The ***Kd*** contains a mix of Shale/Clay or Saltwater Dominant and Sandstone/Sand Dominant materials.

Figure 3-159 presents 2D profile L411000, located west of the town of Denton, Nebraska and crosses Haines Branch near northing 344000. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly till and loess with a cap of unsaturated aquifer and coarse aquifer material. The ***Q*** aquifer materials and the ***Kd*** sandstone/sand materials are in limited contact and have little hydrologic connection. The ***Kd*** is mostly Shale/Clay or Saltwater dominant except for an area between easting 338000 and 346000 which is Sandstone/Sand dominant which is saturated. The ***Kd*** and ***IP*** are flat lying. The CSD 1995 water table is also on the profile and shows the water table for the area and has little slope (Figure 3-160). Note that the water table slopes from west to east.

The total thickness of the ***Q*** material in the Denton Block AEM survey area Figure 3-161 was gridded by subtracting the bedrock which varies from 1,096 to 1,233 (Figure 3-162), from the ground surface elevation (Figure 3-157). The total thickness varies from 77 to 215feet. The saturated thickness for all aquifer material is shown for the Denton Block on Figure 3-163. The thickness of these saturated ***Q*** materials varies between 0 to 166 feet. The saturated thickness averages ~0-100 feet across the area with the thickest area in the southwest and the thinnest are in the northeast. The minimal saturation in the ***Q*** and the high elevation of the ***Kd*** leads to this condition.

The map of saturated thickness for ***Q*** deposits and specific capacity of wells completed in the ***Q*** (Figure3-164) shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with all 4 wells having an specific capacity of<5 gpm/ft. The aquifer in the ***Q*** is poor and would not be good for siting MAR.

The greatest ***Q*** thickness is on ridges and uplands within the Denton Block AEM survey area. The thin areas (~50-100 feet) of ***Q*** total thickness overlies the paleochannel identified on the bedrock elevation map. The ***Q*** material varies in thickness from <50 to 320 feet. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to the hydrologic connection of those materials to the surface water of the area. The aquifer and coarse aquifer materials which make up the bulk of ***Q*** aquifer materials present provide the greatest connection for water movement through all of the ***Q*** aquifer materials. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995) to obtain the total saturated thickness of ***Q*** material. The saturated thickness for all aquifer material is shown for the Denton Block on Figure 3-163. The thickness of these materials varies between 0 to 166 feet. The saturated thickness averages 50-166 feet across the area with the thickest area in the southwest near the paleochannel and the thinnest are in the northeast of the block.

Figure 3-165 is a map of the elevation of top of ***Kd*** which ranges in elevation from 1,078 to 1,245 feet. The low areas are in the paleochannel in the south-central area with the elevations in the north and south sloping toward it. The total thickness map of the ***Kd*** is shown in Figure 3-166. The total thickness of the ***Kd*** varies from 77 to 215 feet with the thickest area in the northeast corner and the thins in the south-central area near the paleochannel. The map of saturated thickness for ***Kd*** deposits and specific capacity of wells completed in the ***Kd*** (Figure 3-167) shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with most wells having a specific capacity of<5 gpm/ft with 1well 5 to 10 gpm/ft and 2 wells 10 to 25 gpm/ft. The aquifer in the ***Kd*** is poor and would not be good for siting MAR.

Figure 3-168 shows the interpreted 2D profile L311100 is an east-west line near the south side of the area and is approximately 2 miles south of Denton, Nebraska. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly till and loess marginal and non-aquifer material layer that is a ~200-foot thick and continuous across the profile lying upon the ***Kd***. The ***Q*** layer marginal and non-aquifer materials have ~200 feet of saturation but have little ability to transmit water to a well or to a stream. ***Q*** aquifer and coarse aquifer material caps the hills and is discontinuous lying directly on the ***Q*** marginal and non-aquifer material layer. It can be very thin~10 feet to ~100 feet thick, is near the land surface and is a good recharge area but above the water table. The ***Q*** aquifer materials and the ***Kd*** sandstone/sand materials are not in contact and have little hydrologic connection. The ***Kd*** is mostly Shale/Clay or Saltwater water dominant except for the west end to easting ~2512000 which is Sandstone/Sand dominant. The ***IP*** is Saltwater dominant in this a***rea***. The CSD 1995 water table is also on the profile and shows the water table for the area.

Figure 3-169 shows the interpreted 2D profile L407000 which is a north-south profile in the western side of the Denton Block AEM survey area. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly thick till and loess made up of ***Q*** marginal and non-aquifer materials with small amounts of aquifer material that fill a paleochannel. These materials have ~100 to 150 feet of saturation with a high-water table elevation that is relatively flat. All of the creeks have minimal hydrologic connection to the ***Q*** materials due to the abundance of marginal and non-aquifer materials present. Near northing 340000 there is a ***Kd*** Sandstone/Sand dominant

material which has a minor hydrologic connection with the overlying ***Q*** aquifer material. There are Saltwater dominant areas in the ***IP*** on the north end of the profile.

An exploded view of the voxel model showing the ***Q***, both saturated and unsaturated, the ***Kd***, saturated and the ***IP*** formations is presented in Figure 3-170. The ***Q*** materials show mostly marginal aquifer and non-aquifer materials mixed with lesser amounts of aquifer and coarse aquifer materials. Nearly all of the ***Q*** materials shown are saturated because of the water table being in close proximity to the land surface. There is some ***Kd*** that is unsaturated near the center of the block. Because of the amount of ***Q*** marginal and non- aquifer materials and their distribution across the Denton area there is limited ability for managed aquifer recharge (MAR) sites to be located within the block. Figure 3-171 shows the distribution of ***Q*** Marginal and Non-Aquifer Materials thickness near the paleochannel. Figure 3-172 which shows the thickness of the ***Q*** Aquifer and Coarse Aquifer Materials with the thickest deposits near the paleochannel. The ***Q*** saturated Aquifer and Coarse Aquifer Materials (Figure 3-173) range in thickness from <25 feet to 57 feet within the paleochannel and show that the ***Q*** has minimal groundwater storage that can yield to wells or be used as MAR locations.

Figure 3-174 shows a 3D voxel model of ***Q*** saturated Aquifer and Coarse Material with a fence diagram of unsaturated ***Q*** aquifer materials looking northwest. The ***Kd*** and ***IP*** are also shown. The ***Q*** is mostly made up of marginal and non-aquifer material. This limits the transmission of water from the land surface for recharge. Figure 3-175 presents a 3D voxel model with a view to the north of the Denton Block showing a 3D voxel of ***Q*** saturated aquifer and coarse aquifer material along with a fence diagram of all other ***Q*** materials, ***Kd*** materials and ***IP***. The intermittent nature of the saturated ***Q*** aquifer and coarse aquifer material shows the discontinuous nature of these deposits. Figure 3-176 is a 3D voxel model with a view to the north of the Non-Aquifer Material and all other units as a fence diagram. This arrangement further illustrating the near continuous nature of ***Q*** non-aquifer materials in the area which limits recharge from the surface downward.

Figure 3-177 presents a map of the thickness for ***Kd*** Sandstone/Sand Dominant deposits. These deposits are saturated and vary in thickness from 7 to 162 feet and are discontinuous across the block. The ***Kd*** Sandstone/Sand dominant material is an aquifer in this area with the thickest portion in the paleochannel area. Figure 3-178 is a 3D voxel model view to the north showing the saturated thickness for ***Kd*** Sandstone/Sand Dominant deposits which extensive in the area and provide water wells. The greatest saturated thickness is in the paleochannel area. Figure 3-179 is a 3D voxel model looking north and is similar to Figure 3-178.

During the analysis of the AEM data it was apparent that there was saltwater present in some areas in LPSNRD project area. There is a substantial presence of saltwater in the Denton Block AEM survey area. Figure 3-180 is a 3D voxel model looking north that shows these saltwater areas. There are no water quality samples from wells in the area and this determination of saltwater is based on the comparison of resistivity from the AEM versus the lithology from the wells. Figure 3-181 is a view to the northwest of the 3D voxel model that shows these saltwater areas. Figure 3-182 is the thickness map of the saltwater in the block area. It varies in thickness from 5 to 544 feet.

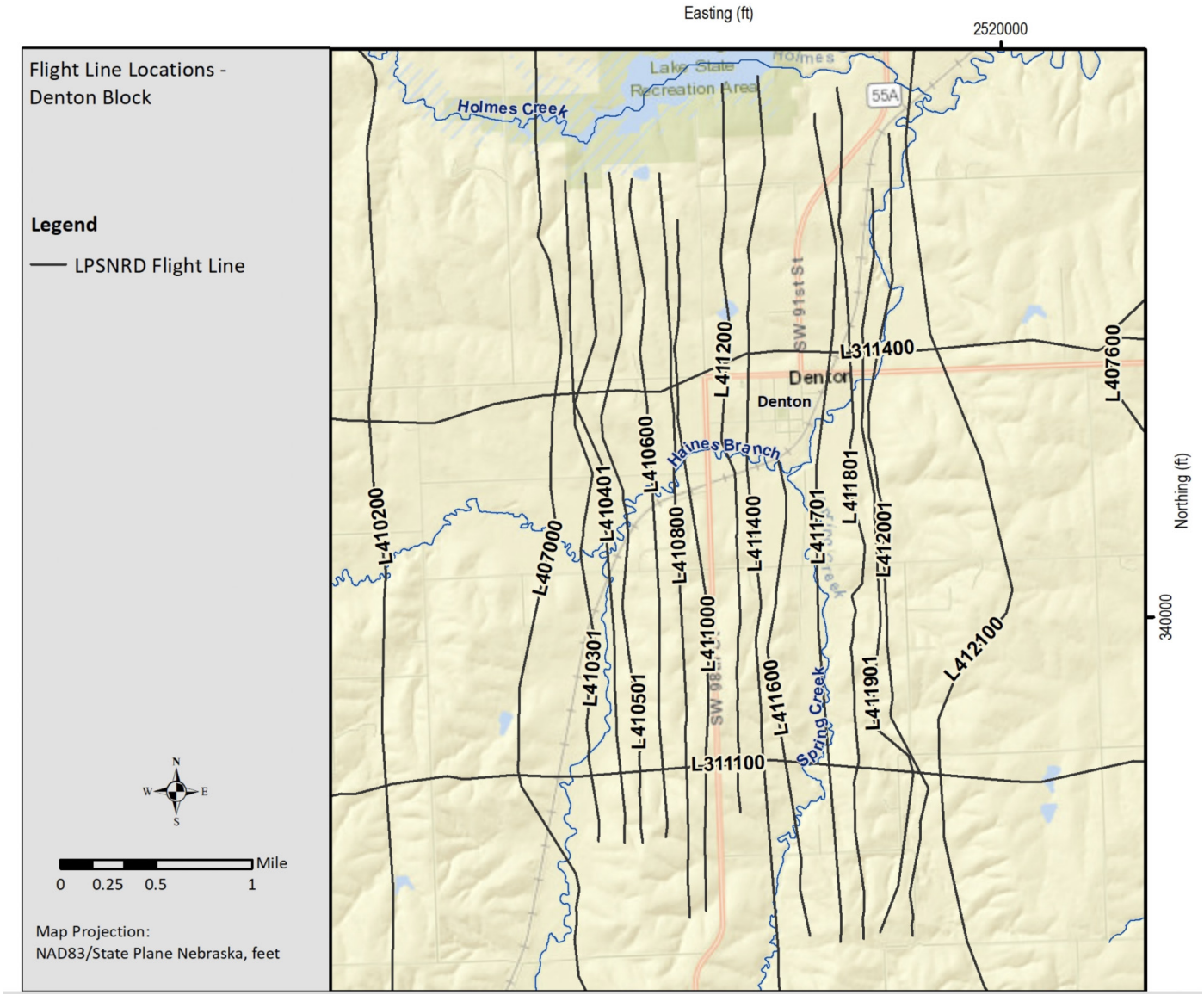


Figure 3-156. Location map of the Denton Block indicating numbered AEM flight lines, local roads, and streams. Generally, the flight block is near Denton, Nebraska. Block flight lines are indicated by black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

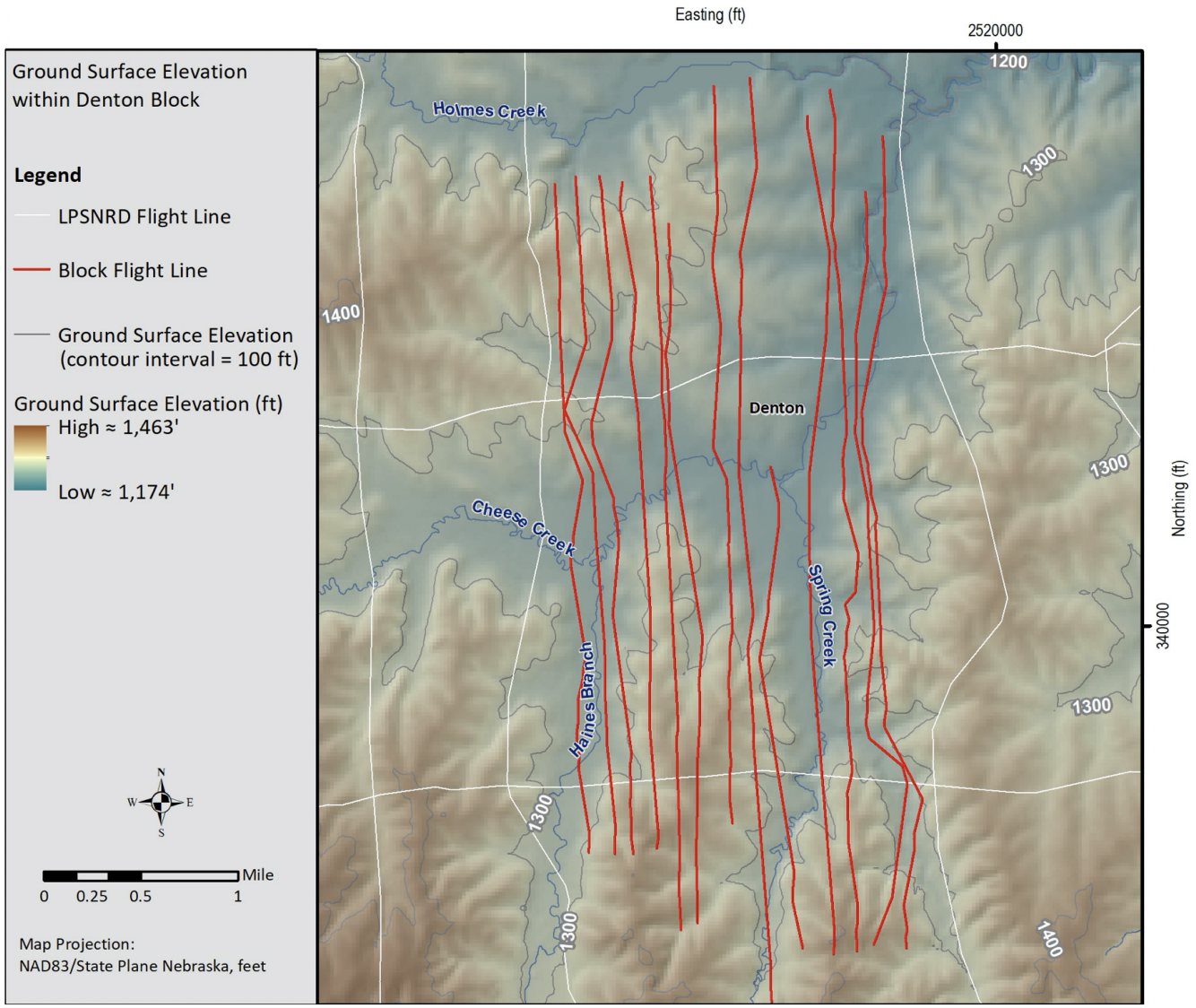


Figure 3-157. Map showing the ground surface elevation with flight lines in the Denton Block. Note the rolling hills nature of the ground surface. There are rolling hills with a ridge between Haines Branch, Cheese Creek and Spring Creek. Denton, Nebraska lies near the confluence of Haines Branch and Spring Creek. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

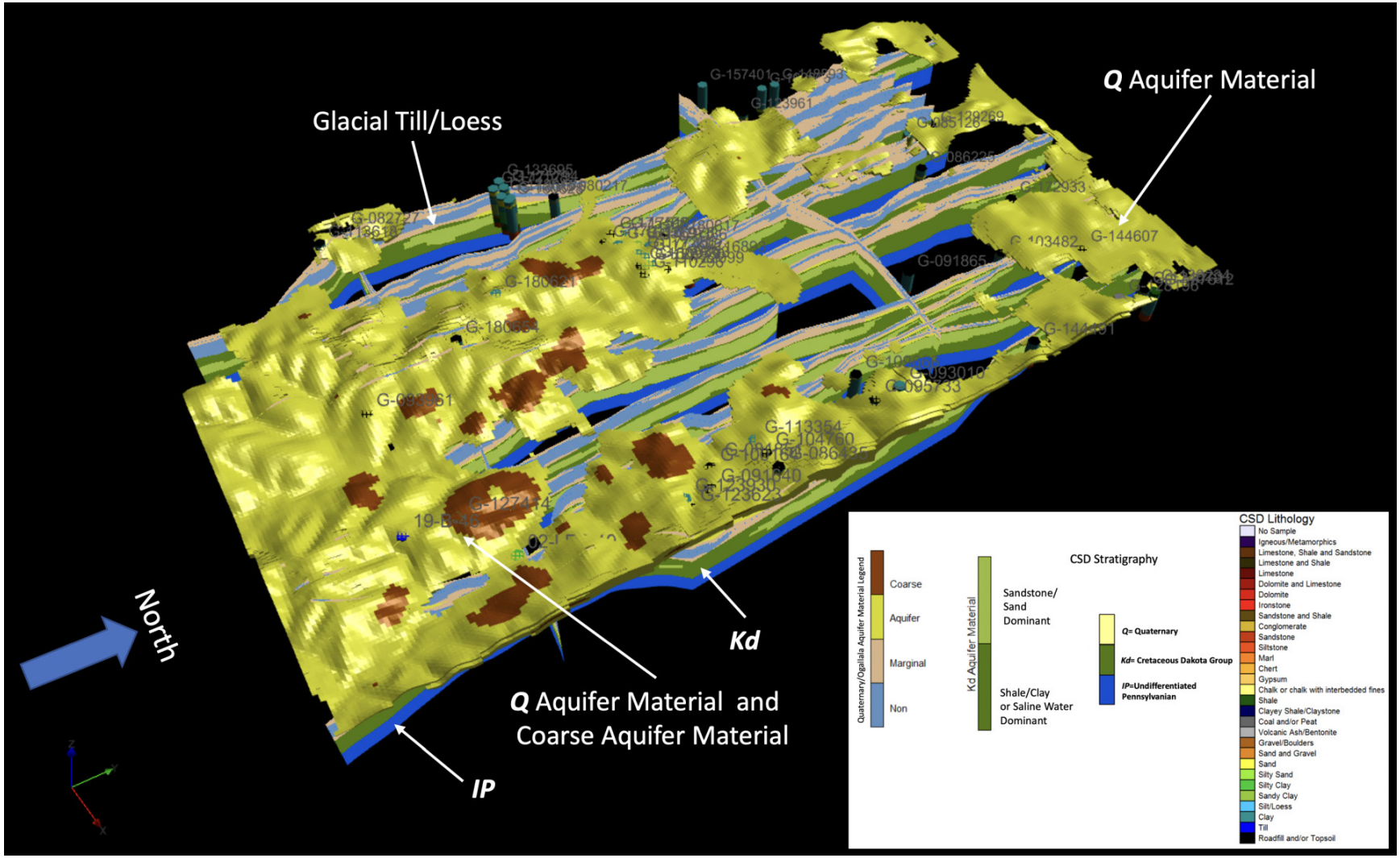


Figure 3-158. 3D fence diagram of interpreted AEM hydrostratigraphic profiles within the 2018 Denton Block AEM survey area. The area generally contains a mix of all *Q* aquifer materials lying upon the *Kd* which lies upon the *IP*. The *Kd* contains a mix of Shale/Clay or Saltwater Dominant and Sandstone/Sand Dominant materials, CSD and NE-DNR wells are labeled. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

South North

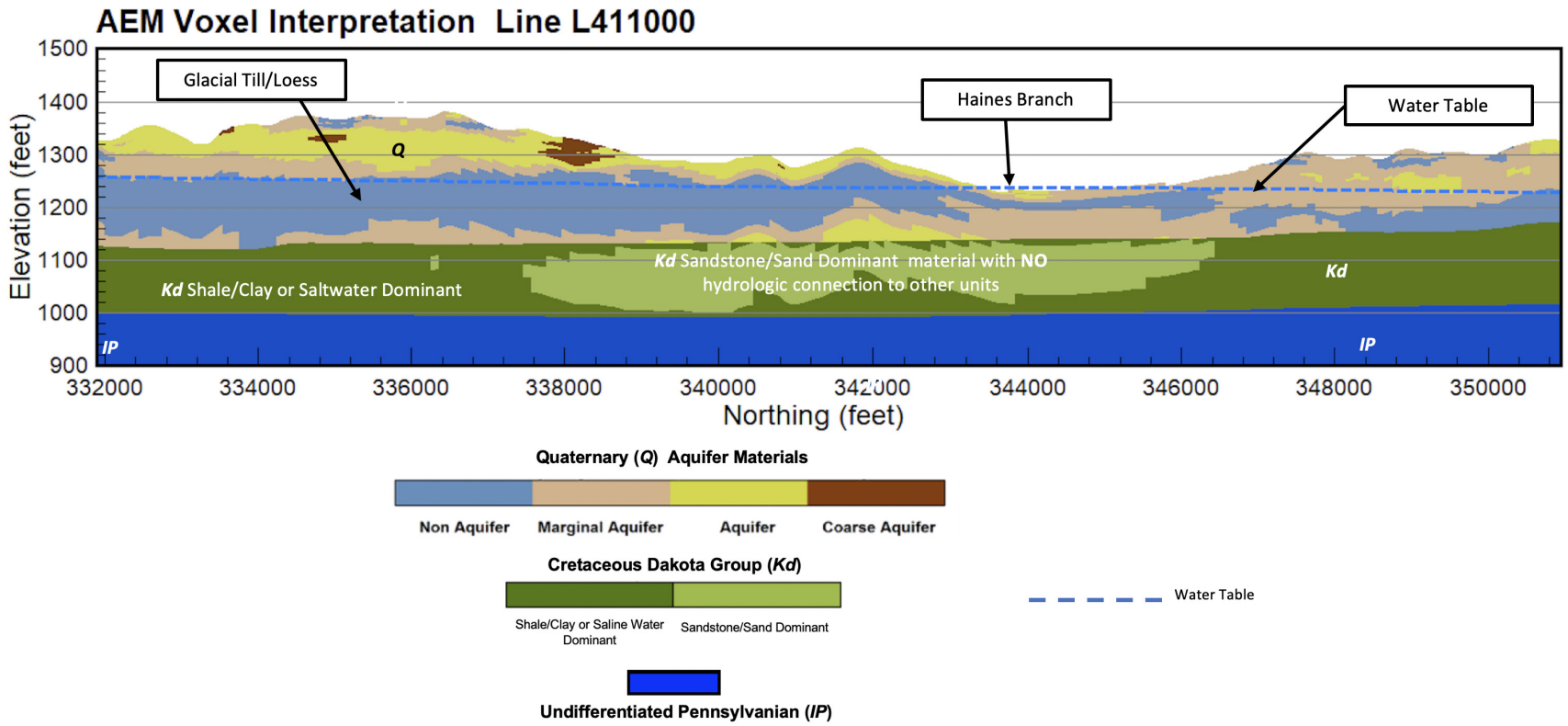


Figure 3-159. Profile presents 2D profile L411000, located west of the town of Denton, Nebraska and crosses Haines Branch near northing 344000. The figure shows the subsurface of the area along the line and the *Q* materials that are present along the line. They are mostly till and loess with a cap of unsaturated aquifer and coarse aquifer material. The *Q* aquifer materials and the *Kd* sandstone/sand materials are in limited contact and have little hydrologic connection. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

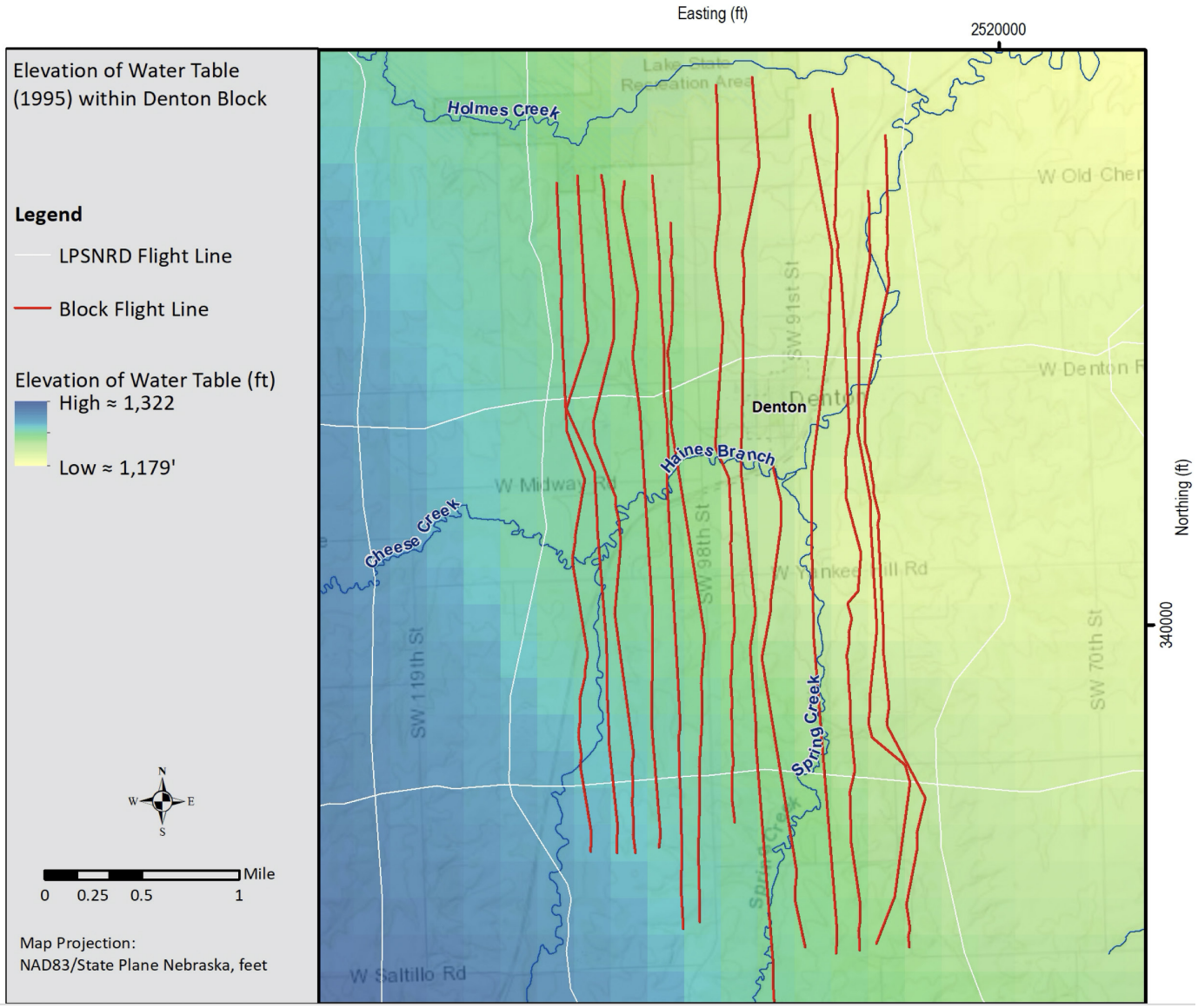


Figure 3-160. Map of the 1995 CSD water table (NE-CSD, 1995) over the Denton Block. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

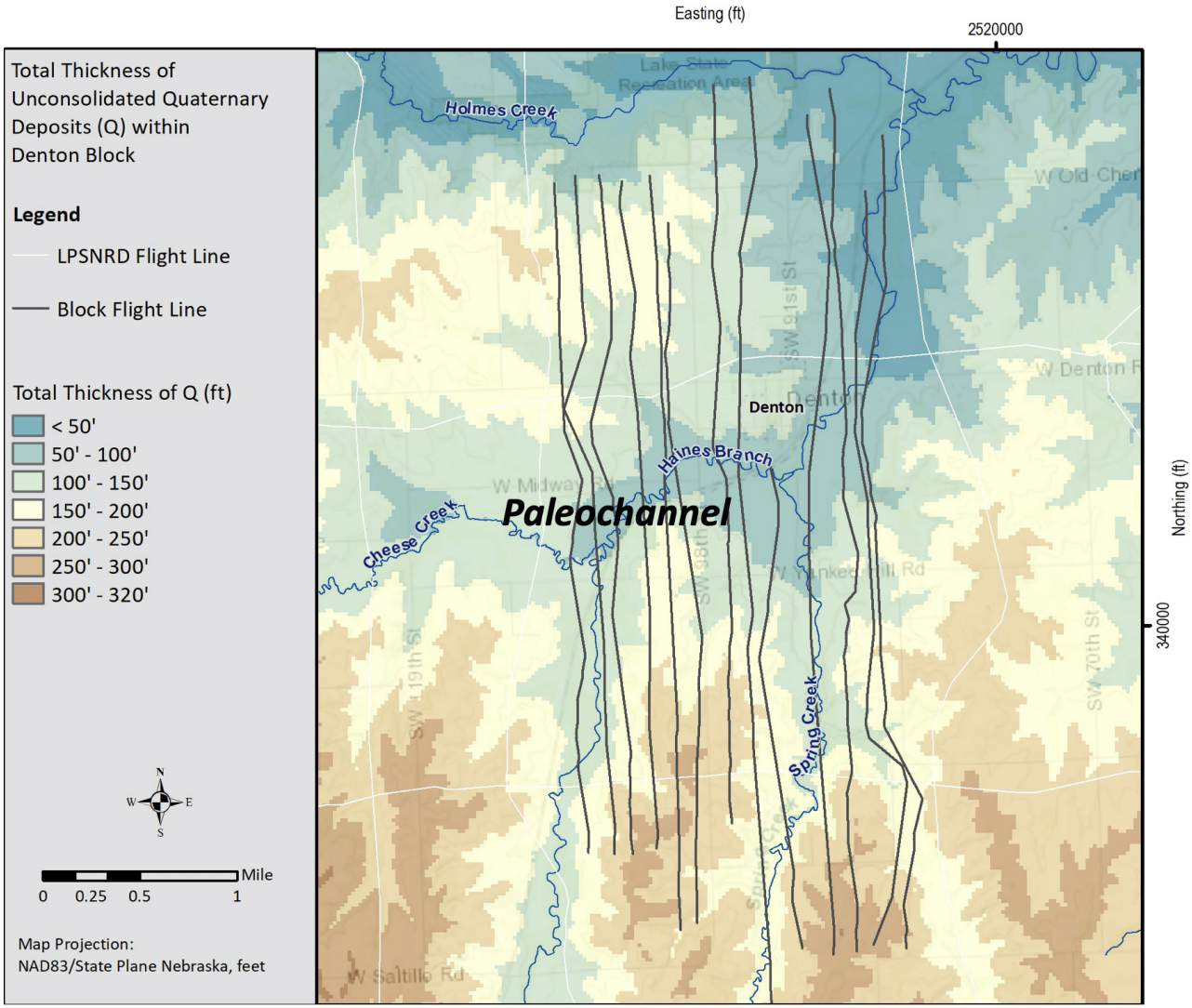


Figure 3-161. Map of the total thickness of the Quaternary (*Q*) deposits within the 2018 Denton Block AEM survey area. The thickest areas are near the tops of ridges and hills in the block. The total thickness varies from <50 to 320 feet. The thin areas overlie the paleochannel. Block flight lines are indicated by black lines. The geologic unit present on this image includes the *Q*= Quaternary. Block flight lines are indicated by black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

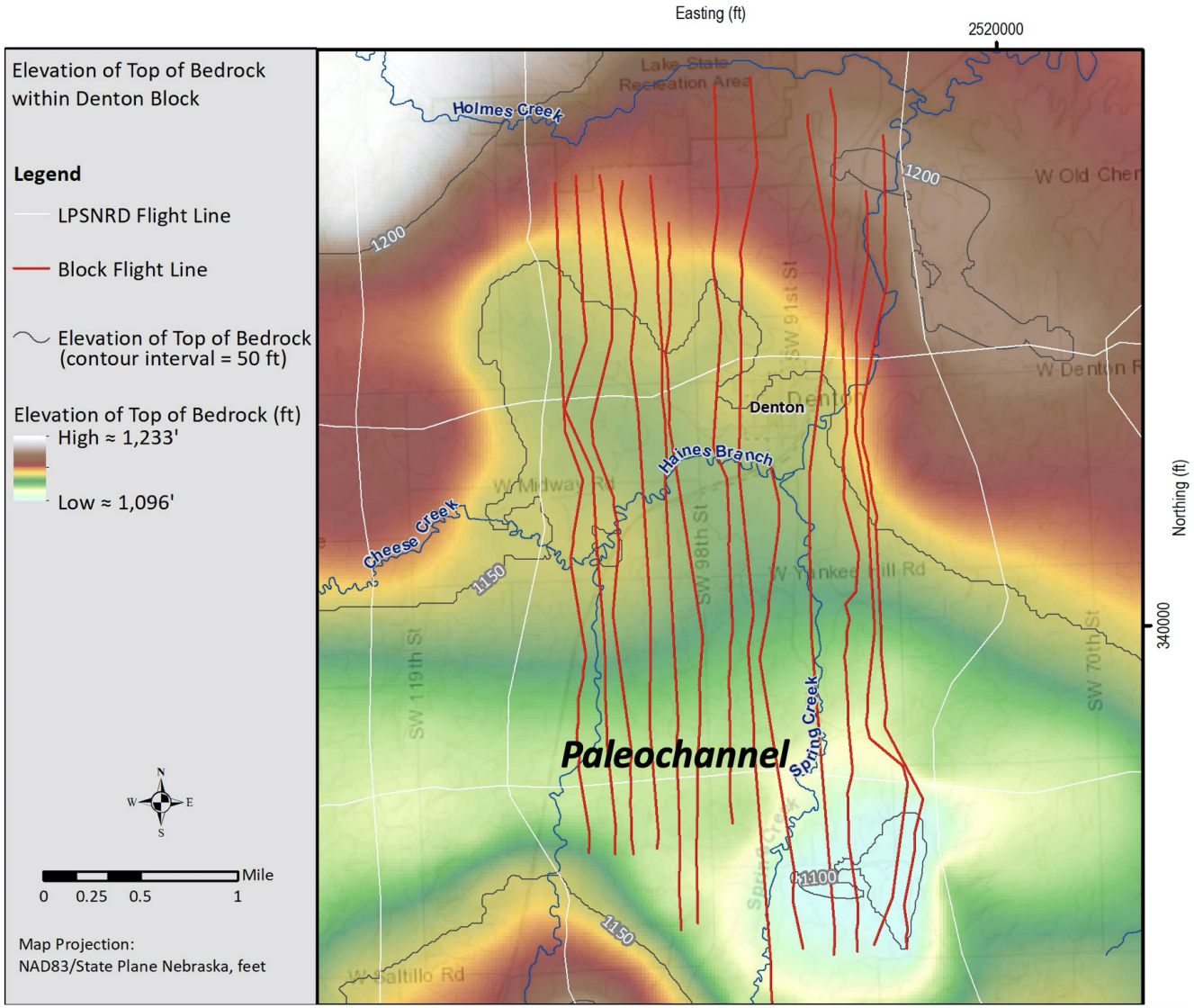


Figure 3-162. Map of the elevation of the top of bedrock within the 2018 Denton Block AEM survey area. The bedrock surface slopes toward the paleochannel from north to south and varies in elevation from 1,096 to 1,233 feet. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

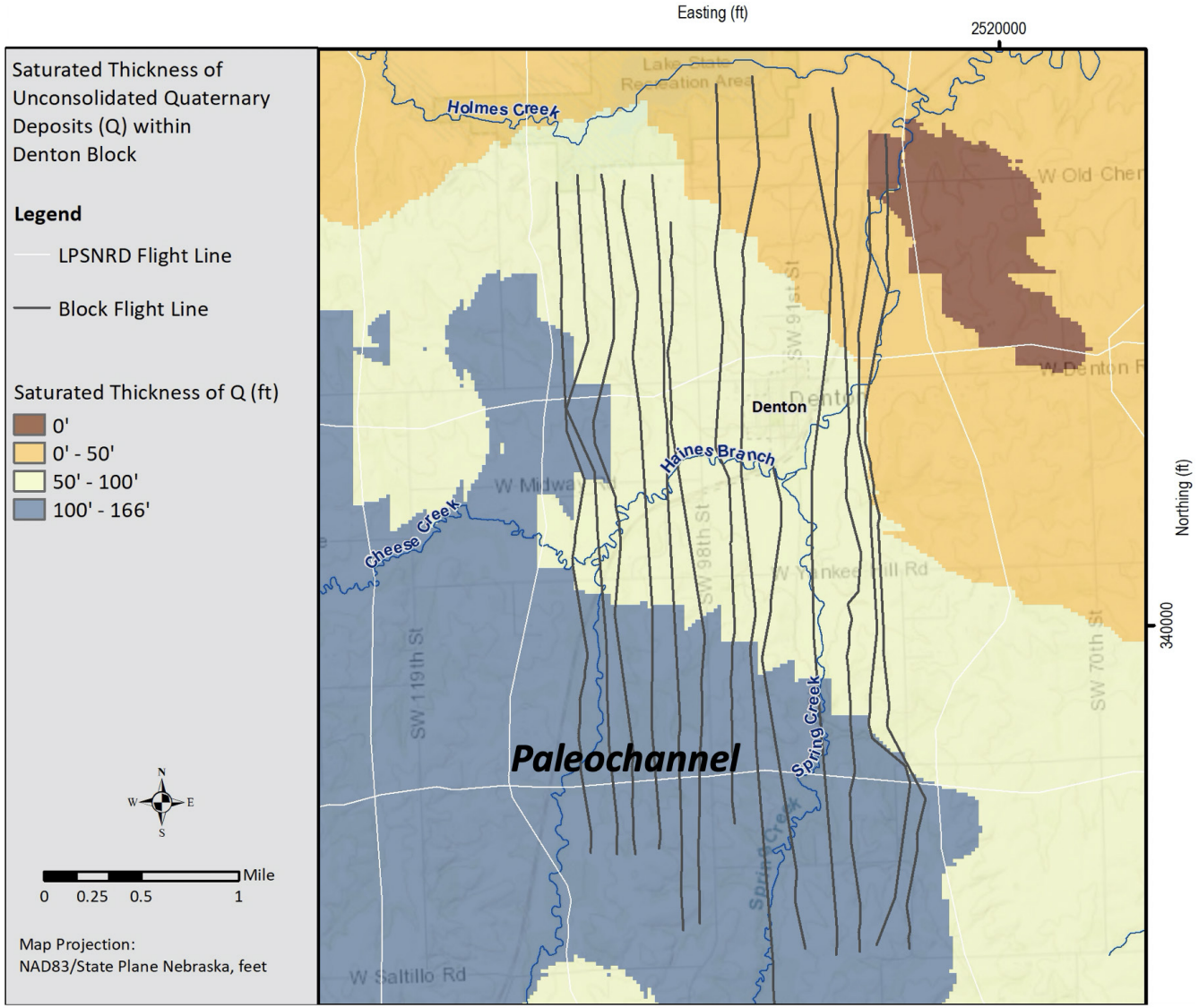


Figure 3-163. Map of saturated thickness of the *Q* within the 2018 Denton Block AEM survey area. The thickest areas are on the southeast and southwest of the block. Thin areas 0 to 50 feet are in the northeast, this includes an area of 0 thickness. Block flight lines are indicated by black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

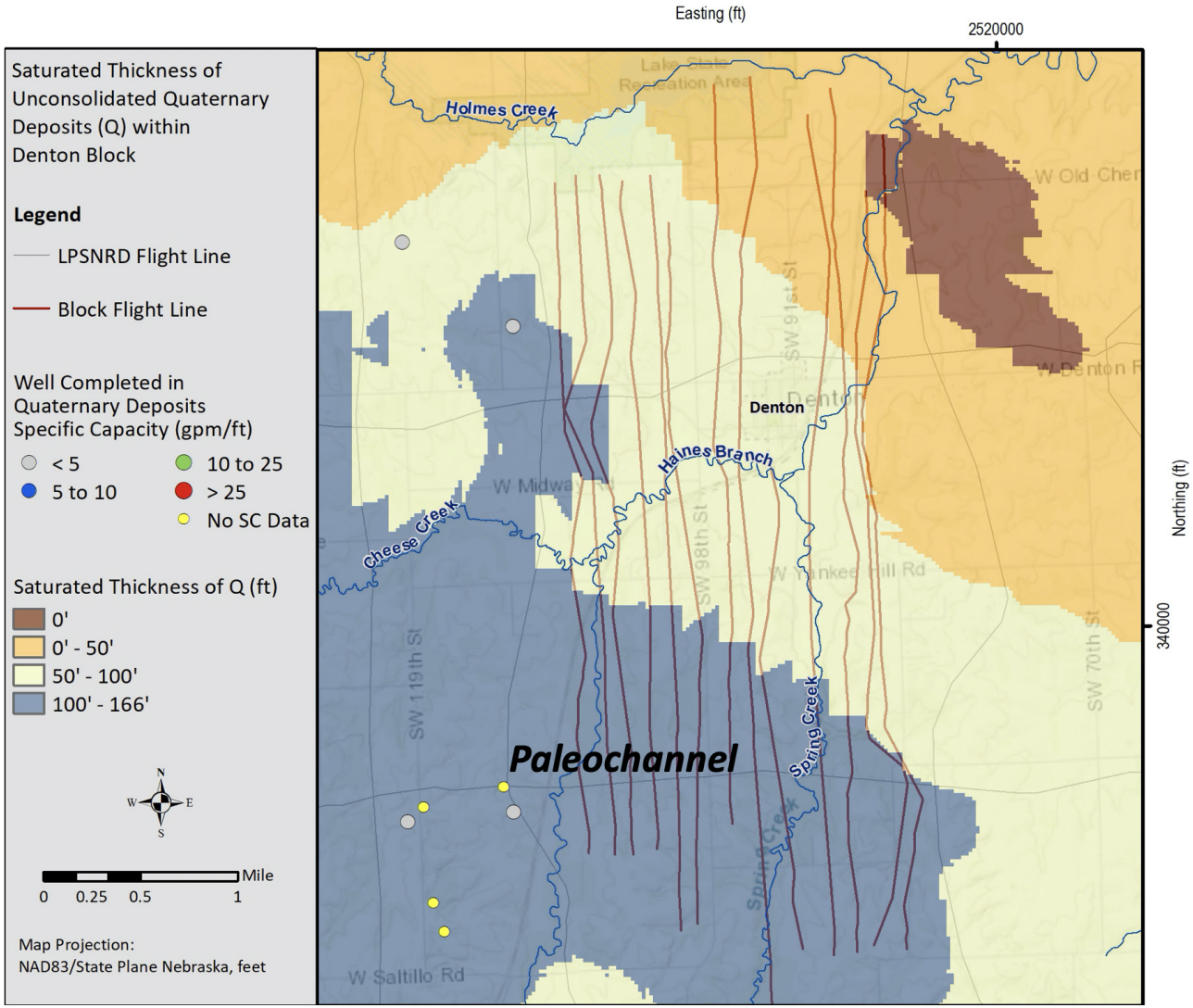


Figure 3-164. Map of saturated thickness for *Q* deposits and specific capacity of wells completed in the *Q* shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with all 4 wells having a specific capacity of<5 gpm/ft. Block flight lines are indicated by orange lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

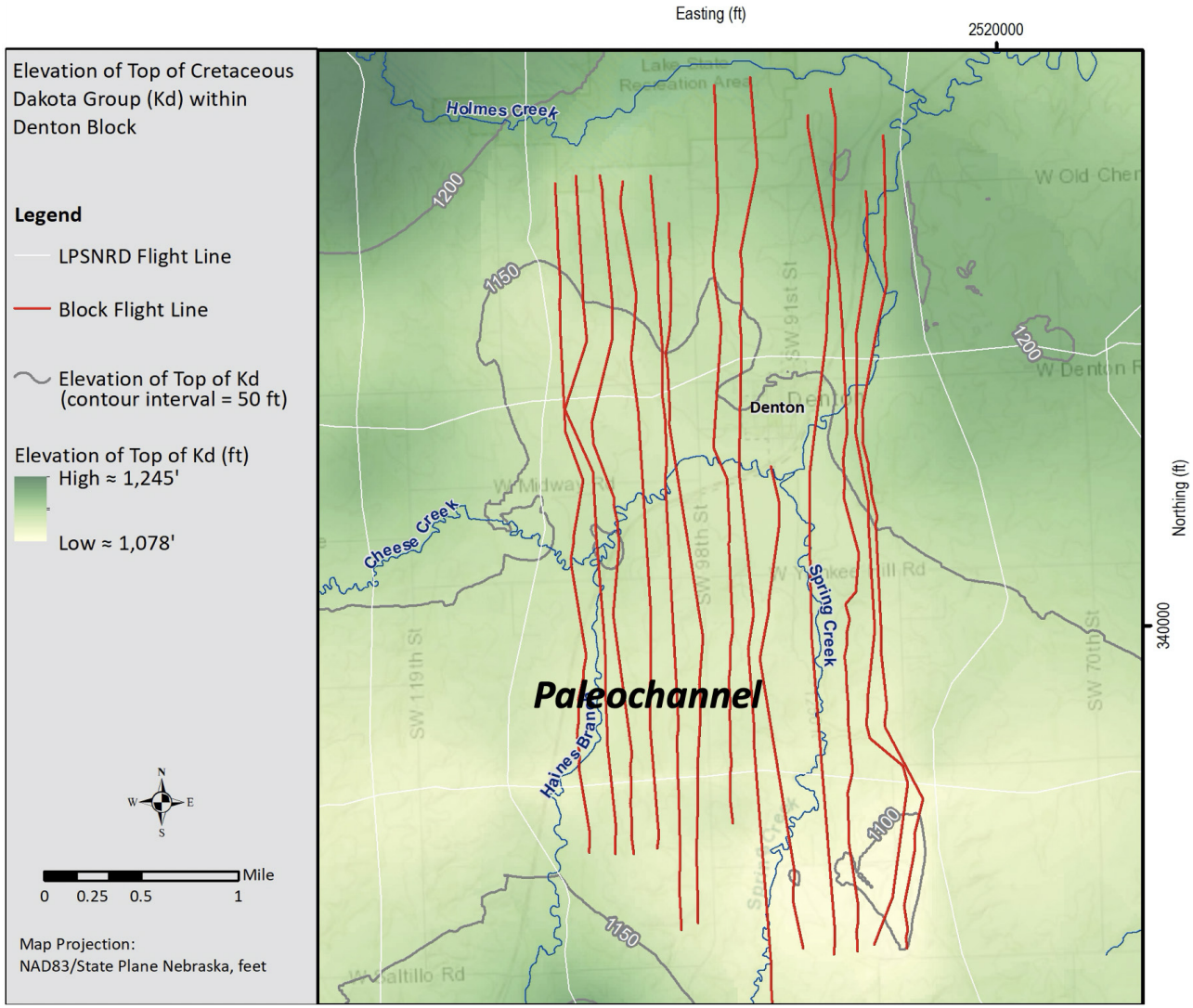


Figure 3-165. Map of the elevation of the top of the *Kd* within the 2018 Denton Block AEM survey area. The elevation of top of *Kd* which ranges in elevation from 1,078 to 1,245 feet. The low areas are in the paleochannel in the south-central area with the elevations in the north and south sloping toward it. Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

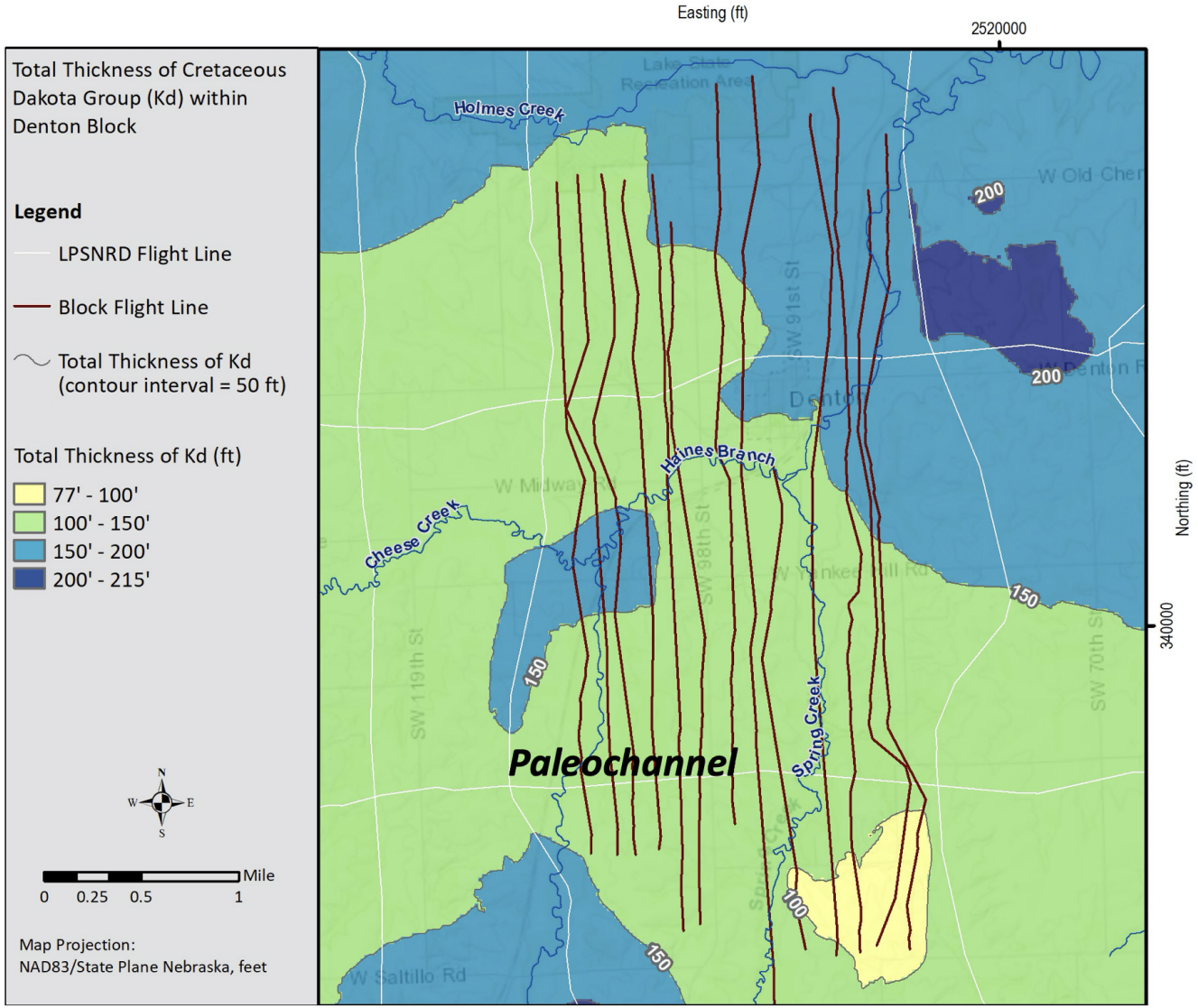


Figure 3-166. Map of the total thickness of the Cretaceous Dakota Group (*Kd*) within the 2018 Denton Block AEM survey area. The thickest areas are in the northeast corner of the area. The thin areas are near the paleochannel. Block flight lines are indicated by the brown lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

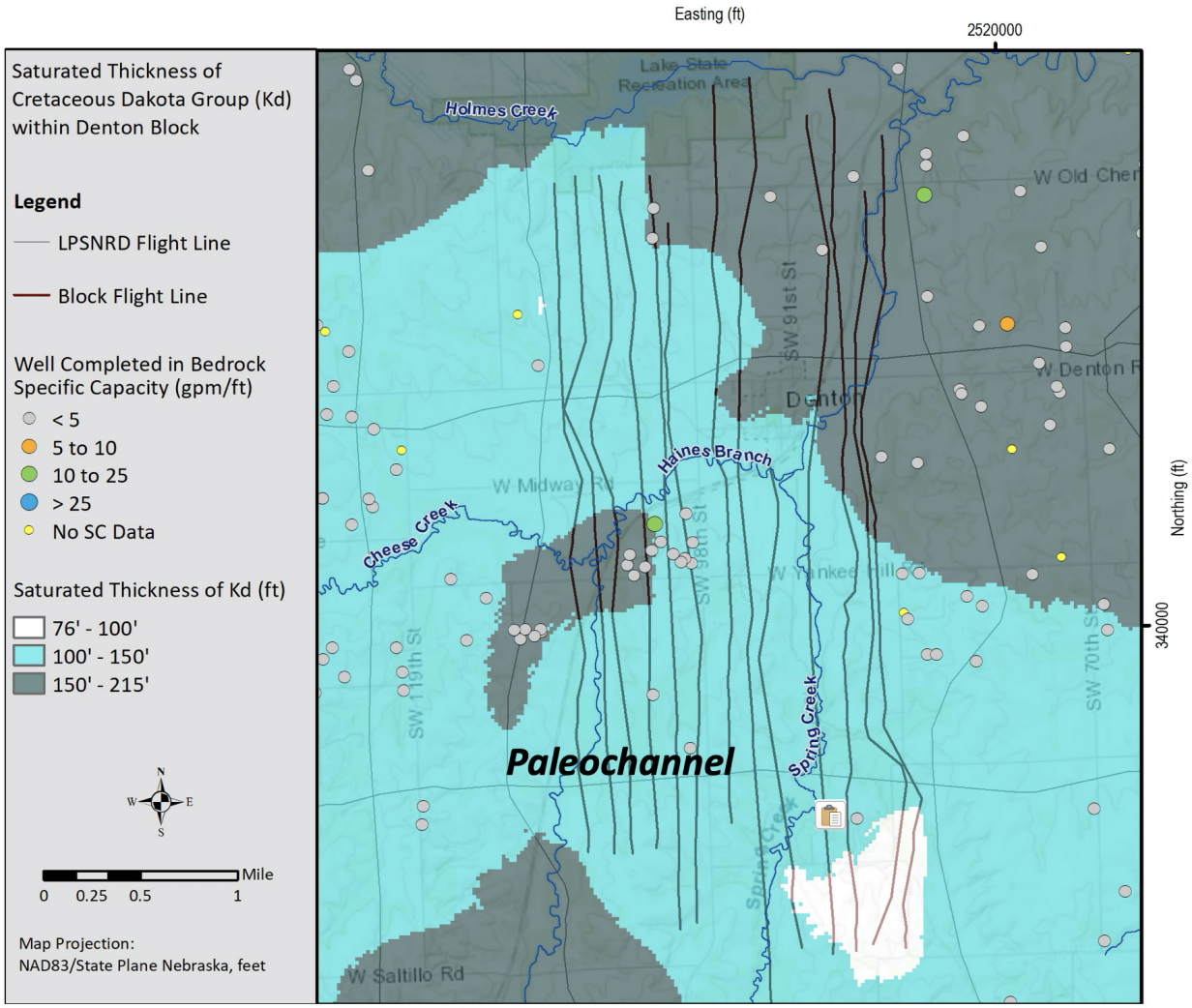


Figure 3-167. Map of saturated thickness for *Kd* deposits and specific capacity of wells completed in the *Kd* shows the relationship between specific capacity in gpm/ft and the saturated thickness. Careful evaluation of the map shows limited development of groundwater wells in the area with all wells having a specific capacity of<5 gpm/ft with 1well 5 to 10 gpm/ft and 2 wells 10 to 25 gpm/ft. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

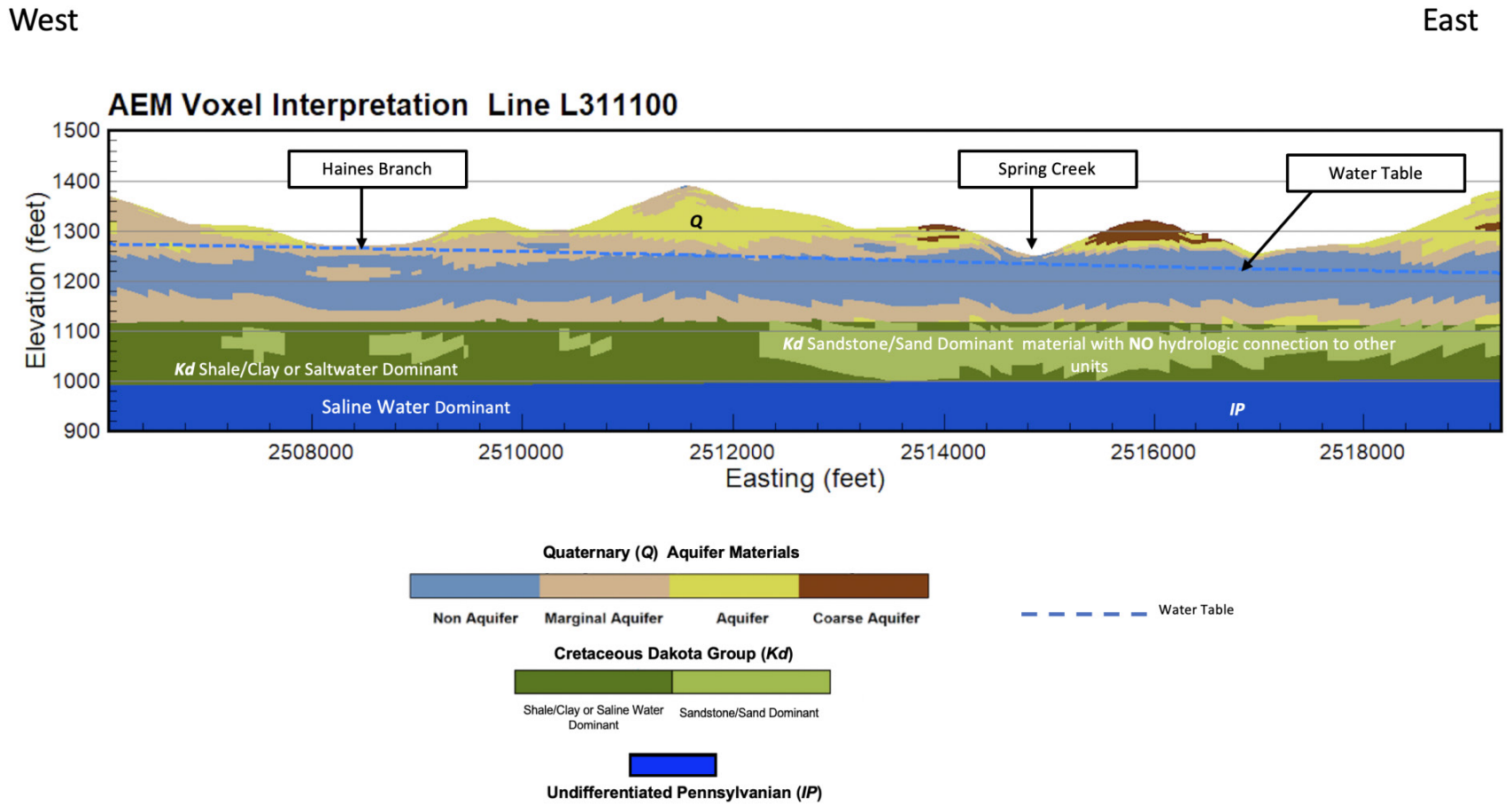


Figure 3-168. Interpreted profile of the north-south line L311100 showing the relationship the *Q*, *Kd*, and *IP* of the AEM interpretations across the area. The *Q* is mostly a till and loess marginal and non-aquifer material layer that is a ~200-foot thick and continuous across the profile lying upon the *Kd*. The CSD 1995 water table is indicated as a dashed blue line it lies at a high elevation and lies near the top of the loess and non-aquifer material. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

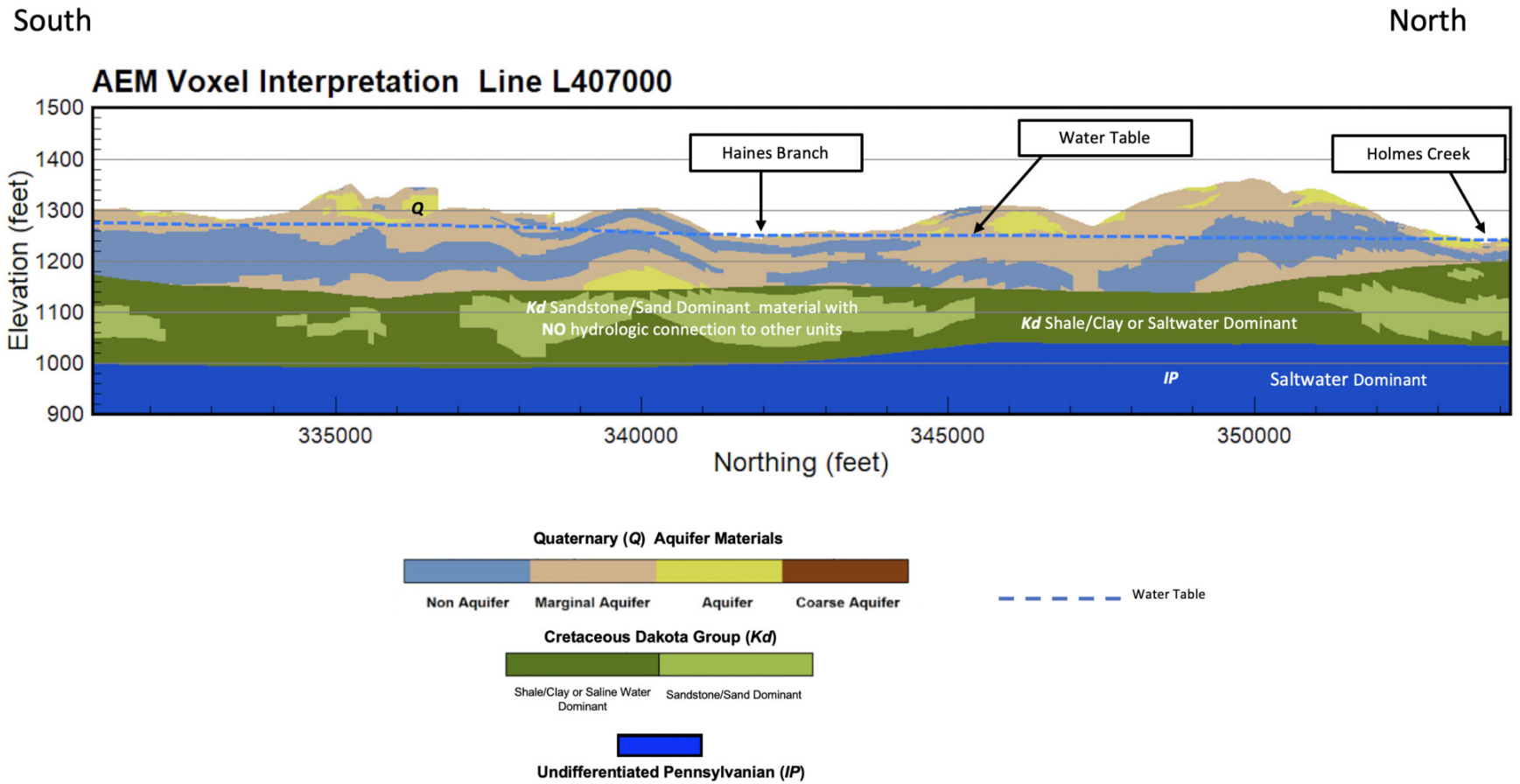


Figure 3-169. Interpreted profile of the north-south line L407000 showing the relationship the *Q*, *Kd* and *IP* of the AEM interpretations across the area. The *Q* materials are mostly thick till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material that fill a paleochannel. These materials have ~100 to 150 feet of saturation with a high-water table elevation that is relatively flat. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Block flight lines are indicated by the red lines. The geologic units present on this image include *Q*= Quaternary and *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

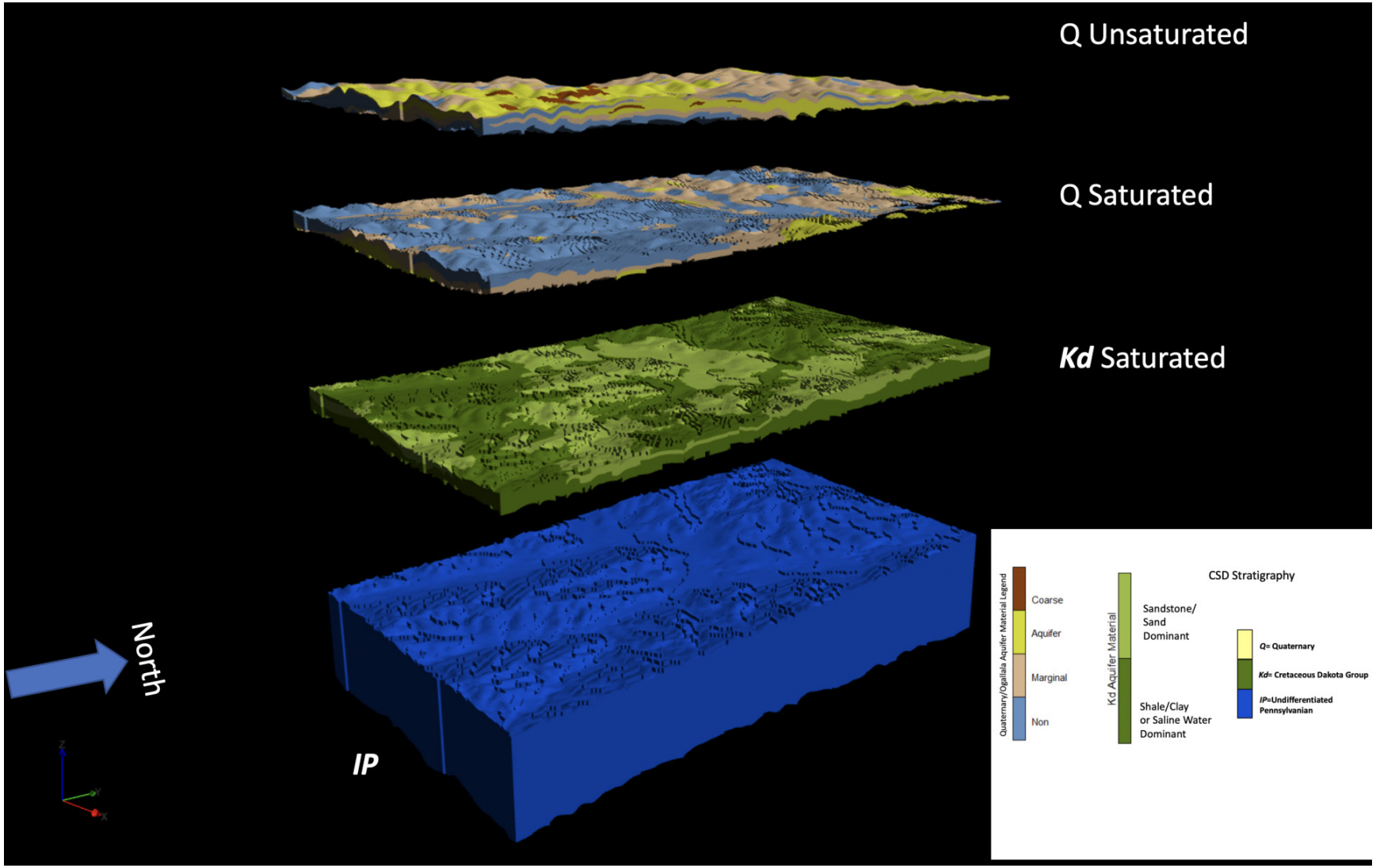


Figure 3-170. 3D exploded voxel model looking northwest of the Denton Block showing Unsaturated *Q*, Saturated *Q, Saturated Kd* and *IP*. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x. The figure is not to scale.

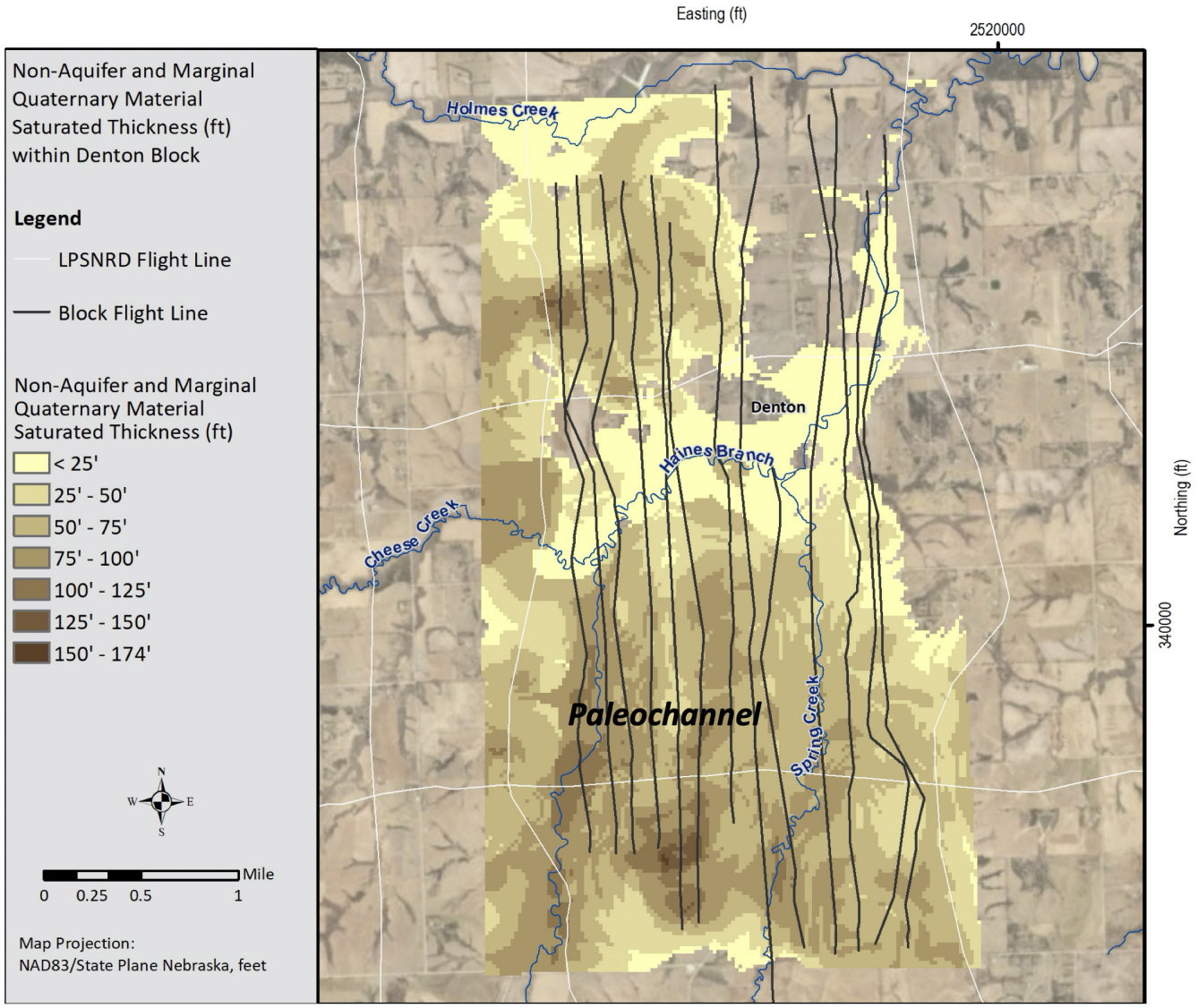


Figure 3-171. Map of Quaternary (*Q*) Non-Aquifer and Marginal Aquifer Materials total thickness for the Denton Block. Thickest areas are in the south-center part of the block. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

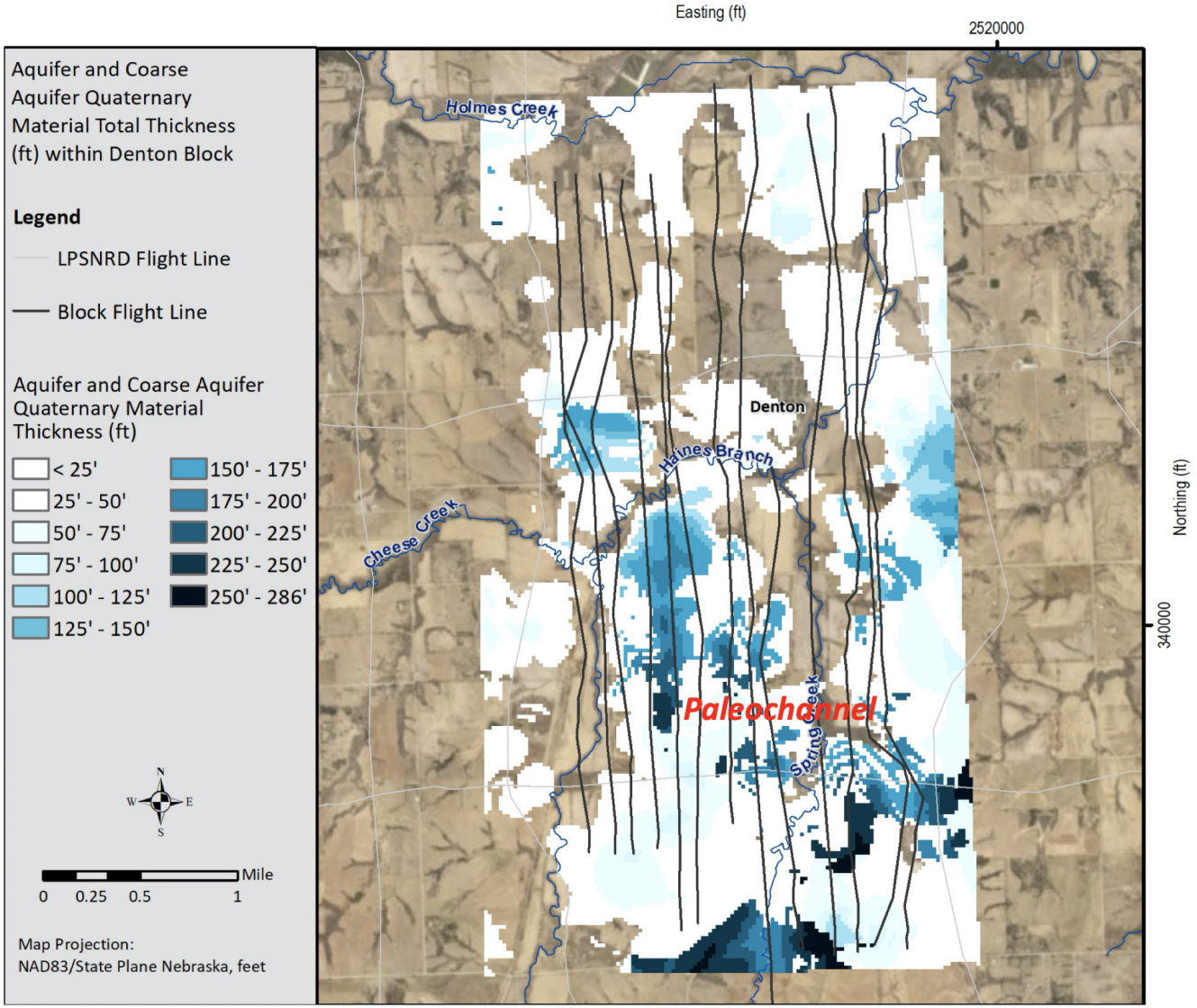


Figure 3-172. Map of total thickness of *Q* deposits of Aquifer and Coarse Aquifer Materials in the Denton Block. The thickest areas are near the paleochannel. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

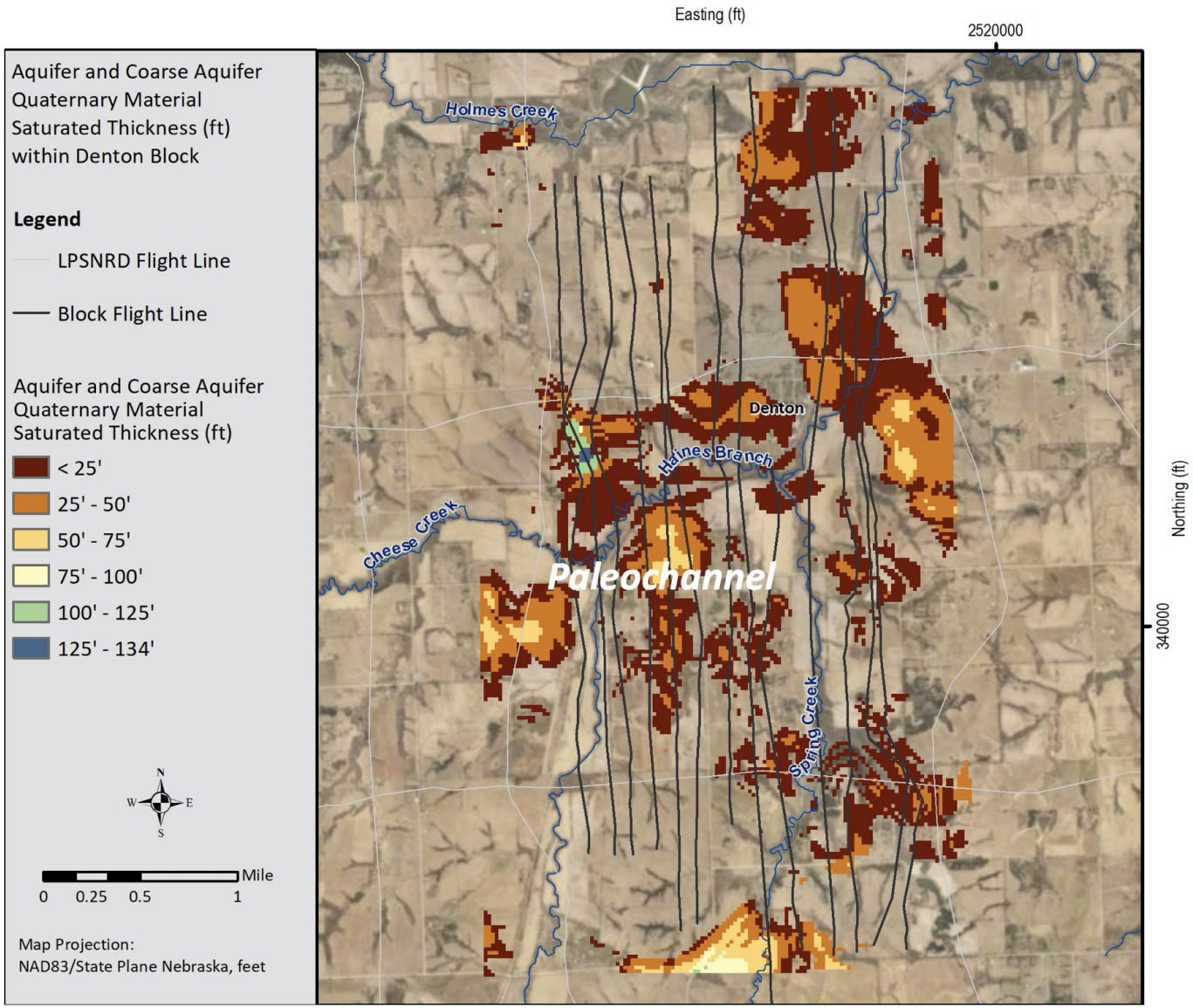


Figure 3-173. Map of total saturated thickness of *Q* deposits of Aquifer and Coarse Aquifer Materials. Block flight lines are indicated by the black lines. The geologic units present on this image include *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

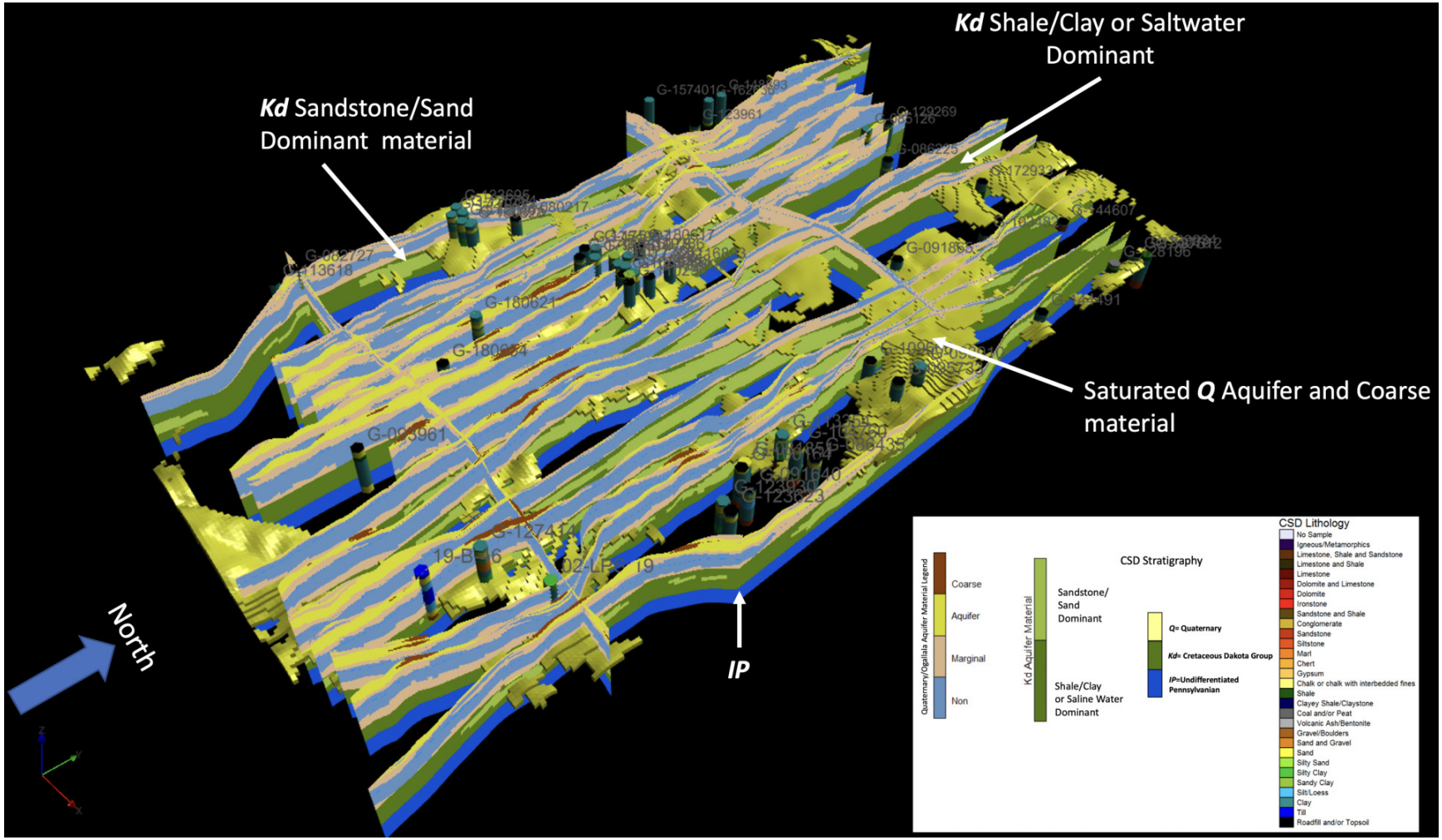


Figure 3-174. View of shows a 3D voxel model of *Q* saturated Aquifer and Coarse Aquifer Material with a fence diagram of unsaturated *Q* aquifer materials looking northwest. The *Kd* and *IP* are also shown. The *Q* mostly made up of marginal and non-aquifer material. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

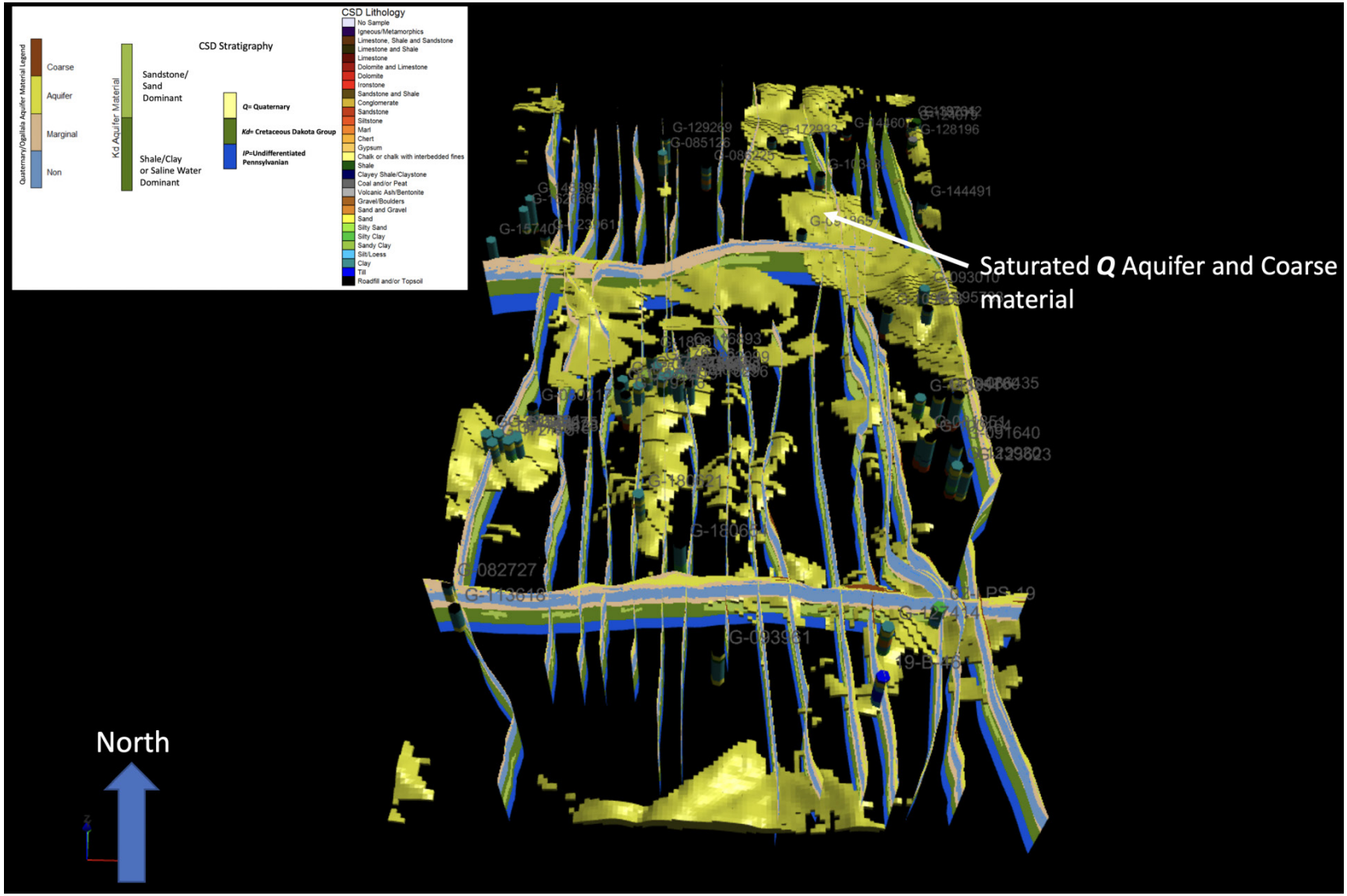


Figure 3-175. View to the north showing a 3D voxel model of saturated *Q* aquifer and the coarse aquifer material with fence diagram of all other materials, *Kd,* and *IP*. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

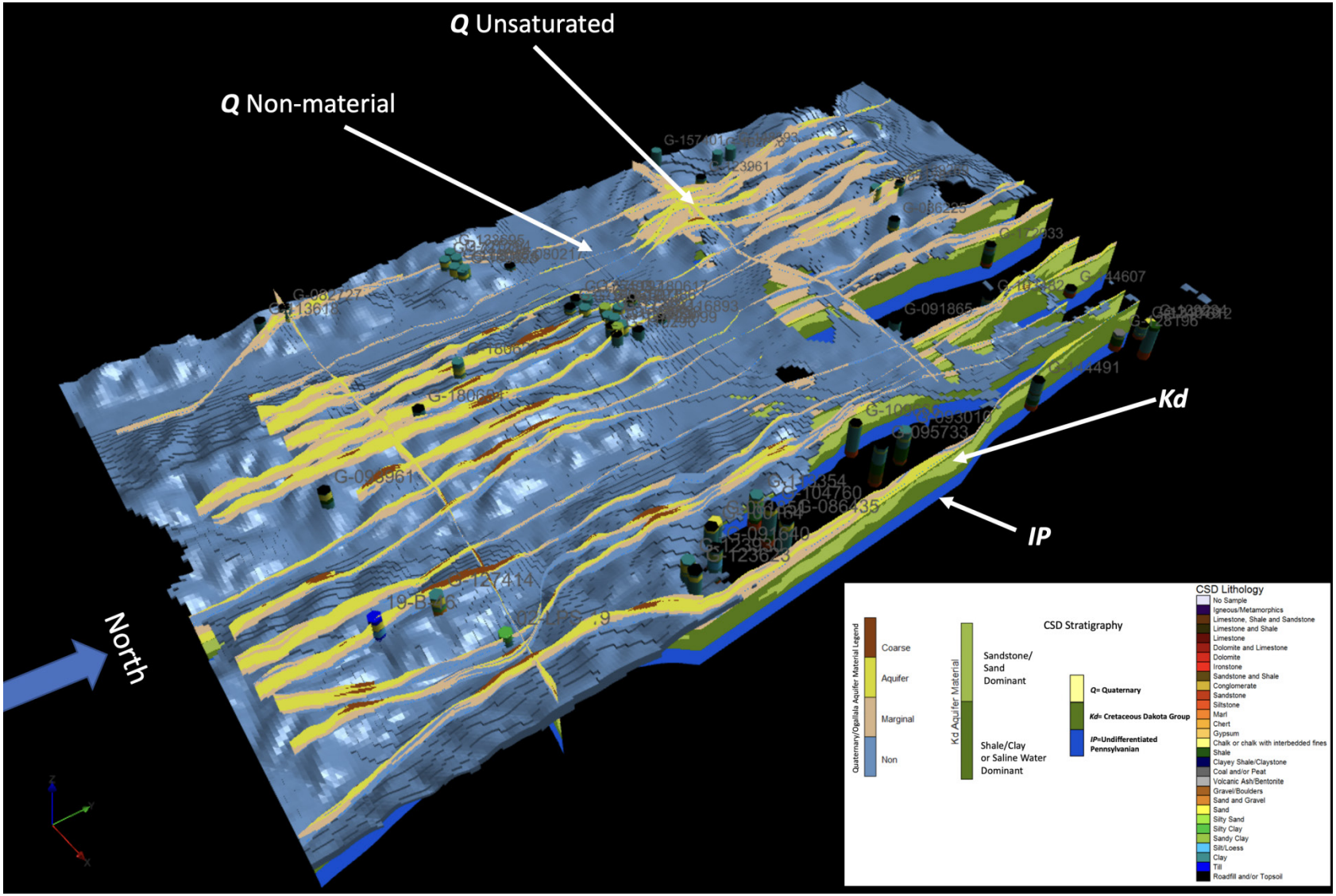


Figure 3-176. View to the northwest of a 3D voxel of the *Q* Non- Aquifer Material and all other units as a 3D Fence Diagram. The Non-Aquifer Material is nearly continuous across the area and limits recharge. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

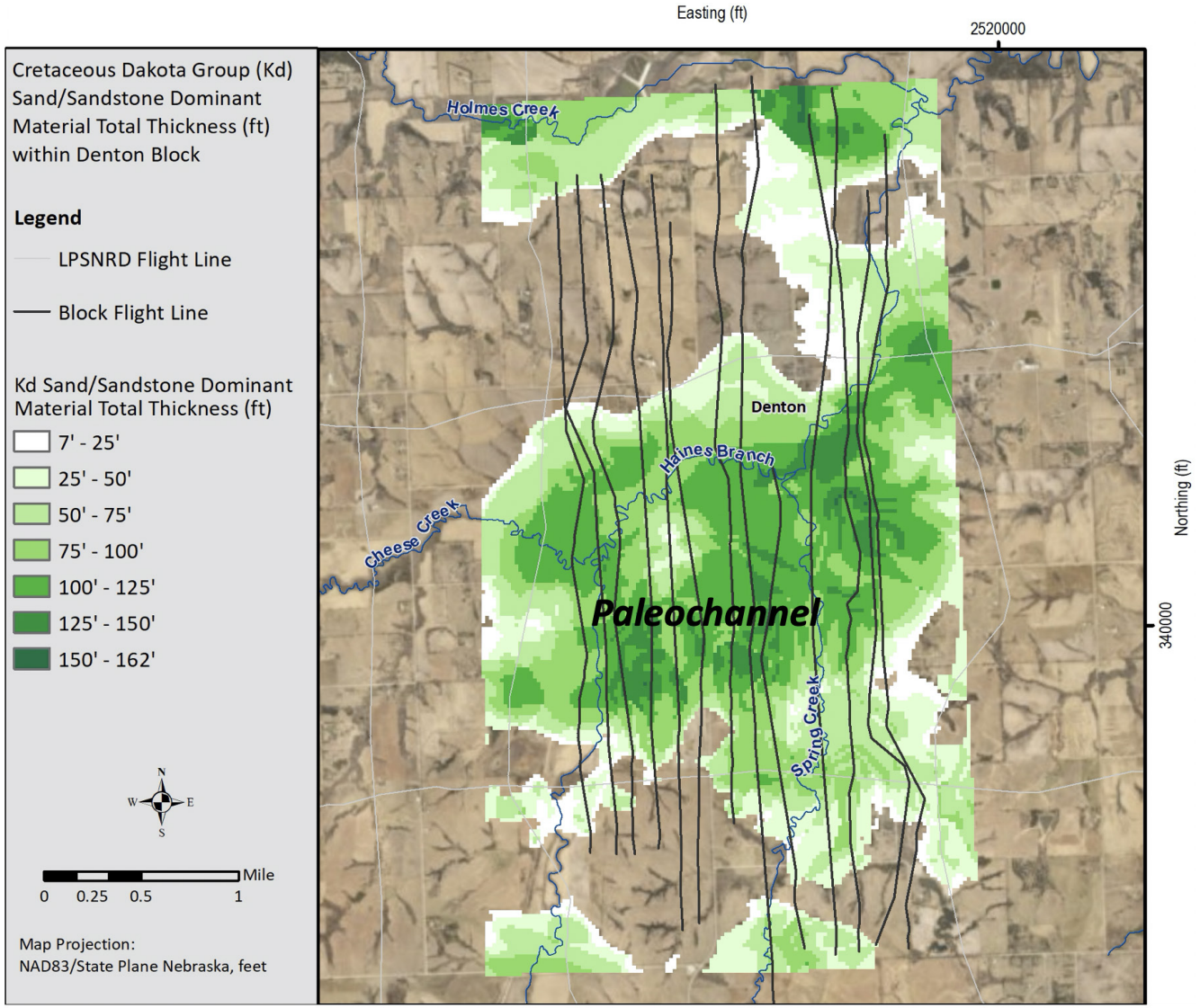


Figure 3-177. Map of the total thickness of the Sandstone/Sand Dominant portion of the *Kd* in the 2018 Denton Block AEM survey area. Block flight lines are indicated by the black lines. The geologic units present on this image include *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

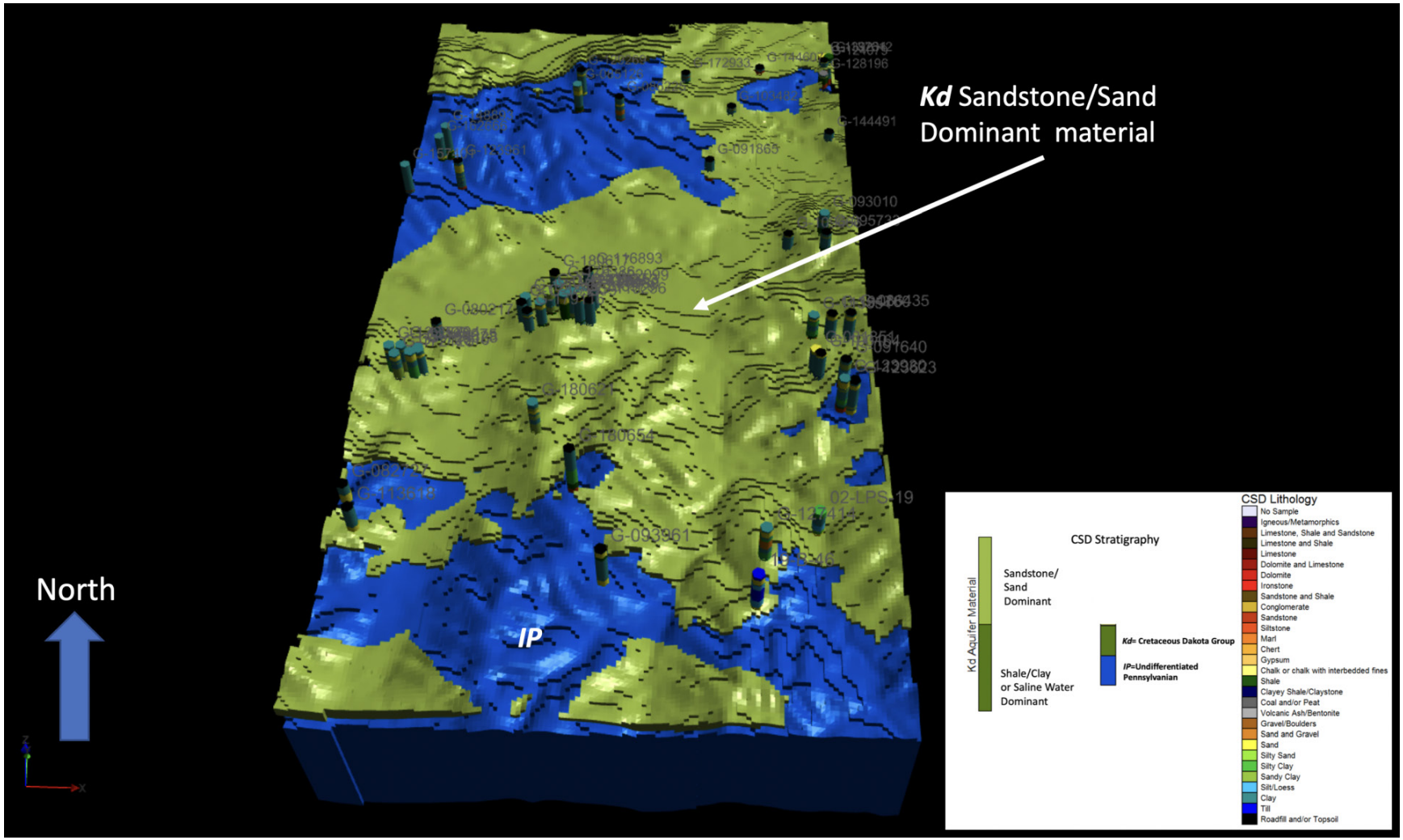


Figure 3-178. View of 3D voxel model of *Kd* Sandstone/Sand dominant materials looking north. The *IP* is also shown. The geologic units present on this image include *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

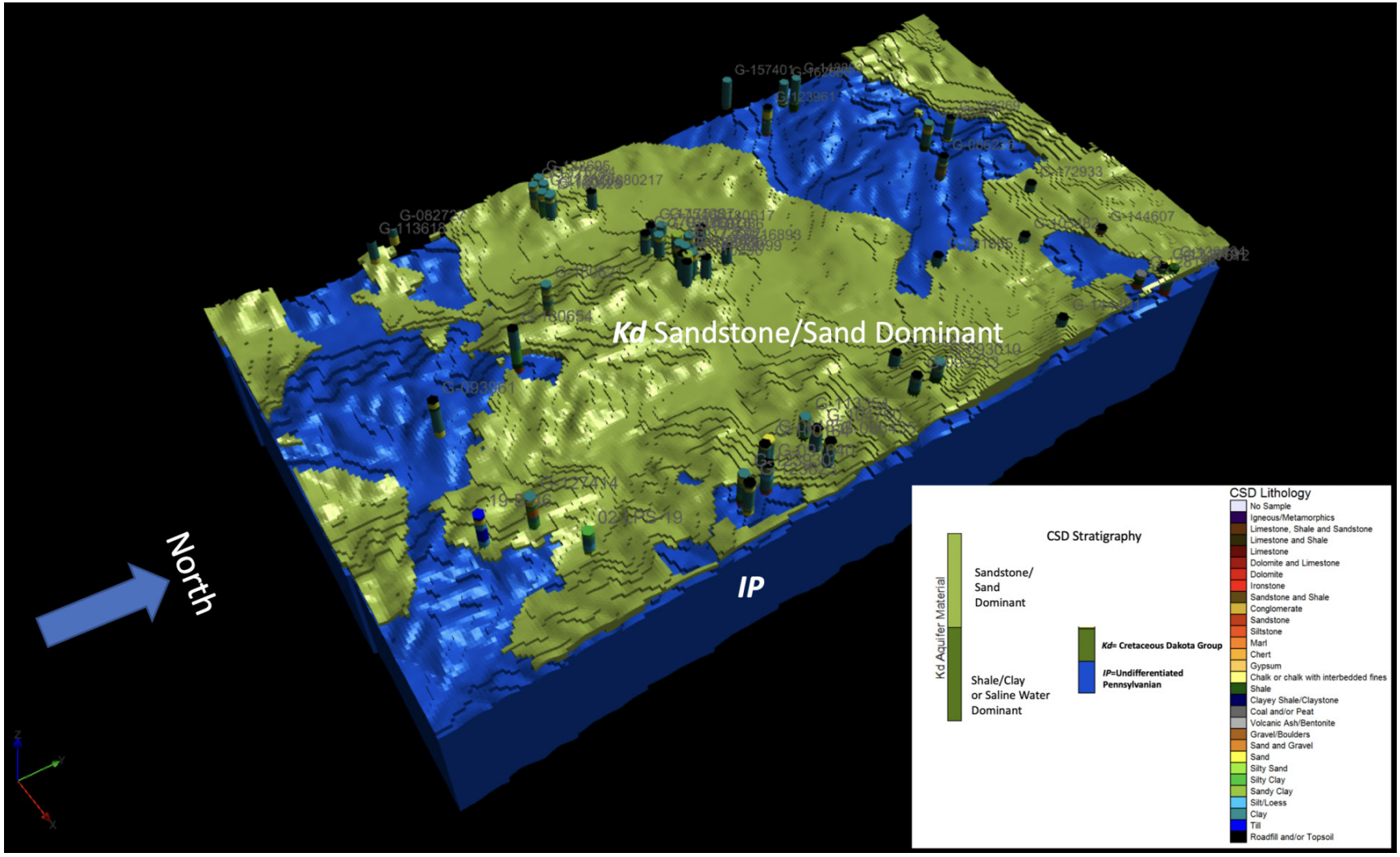


Figure 3-179. View of 3D voxel model of *Kd* Sandstone/Sand dominant to the northwest. The *IP* is also shown. The geologic units present on this image include *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

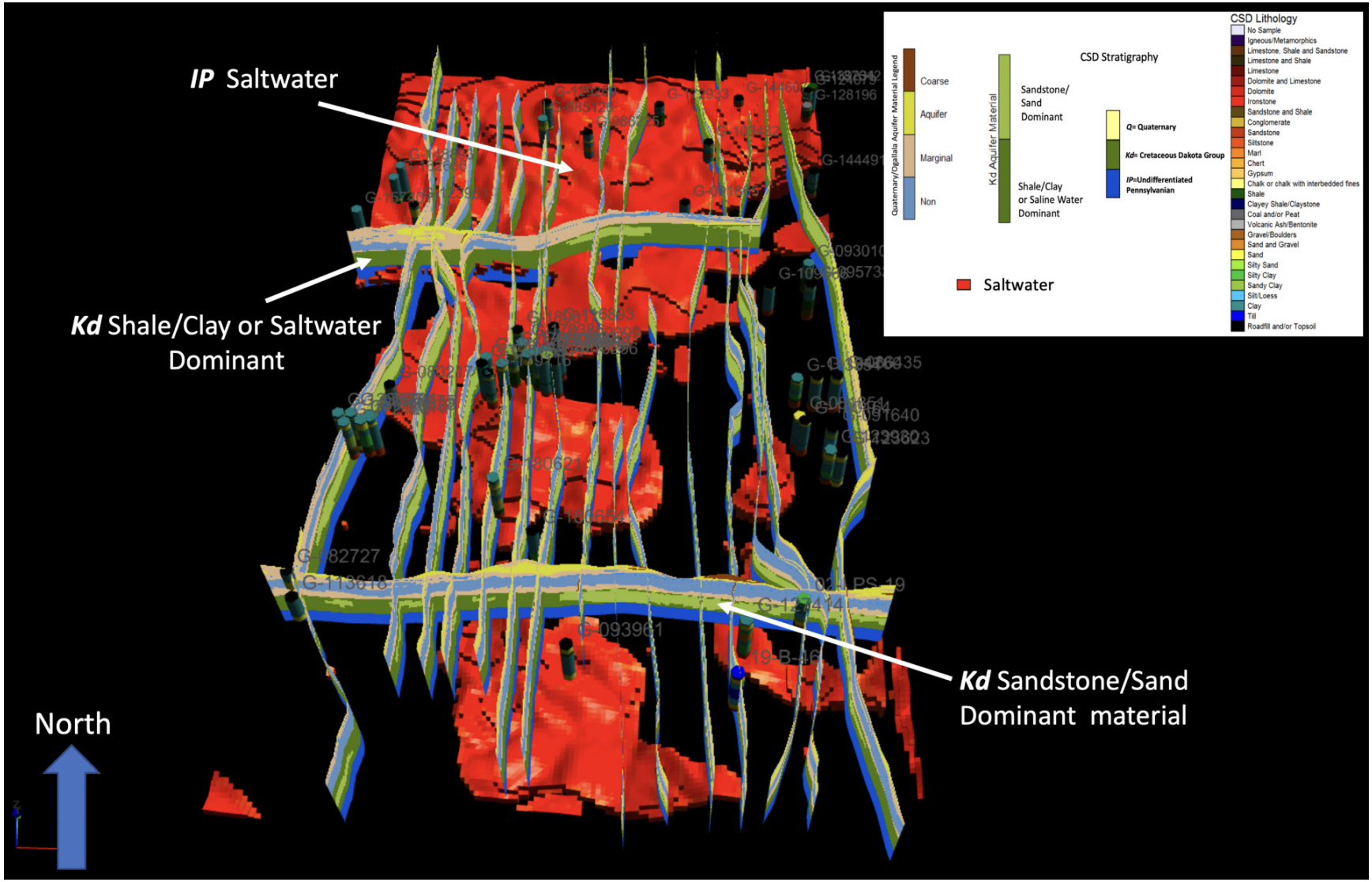


Figure 3-180. View of 3D voxel model looking north showing the saltwater areas in the Denton Block colored red. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

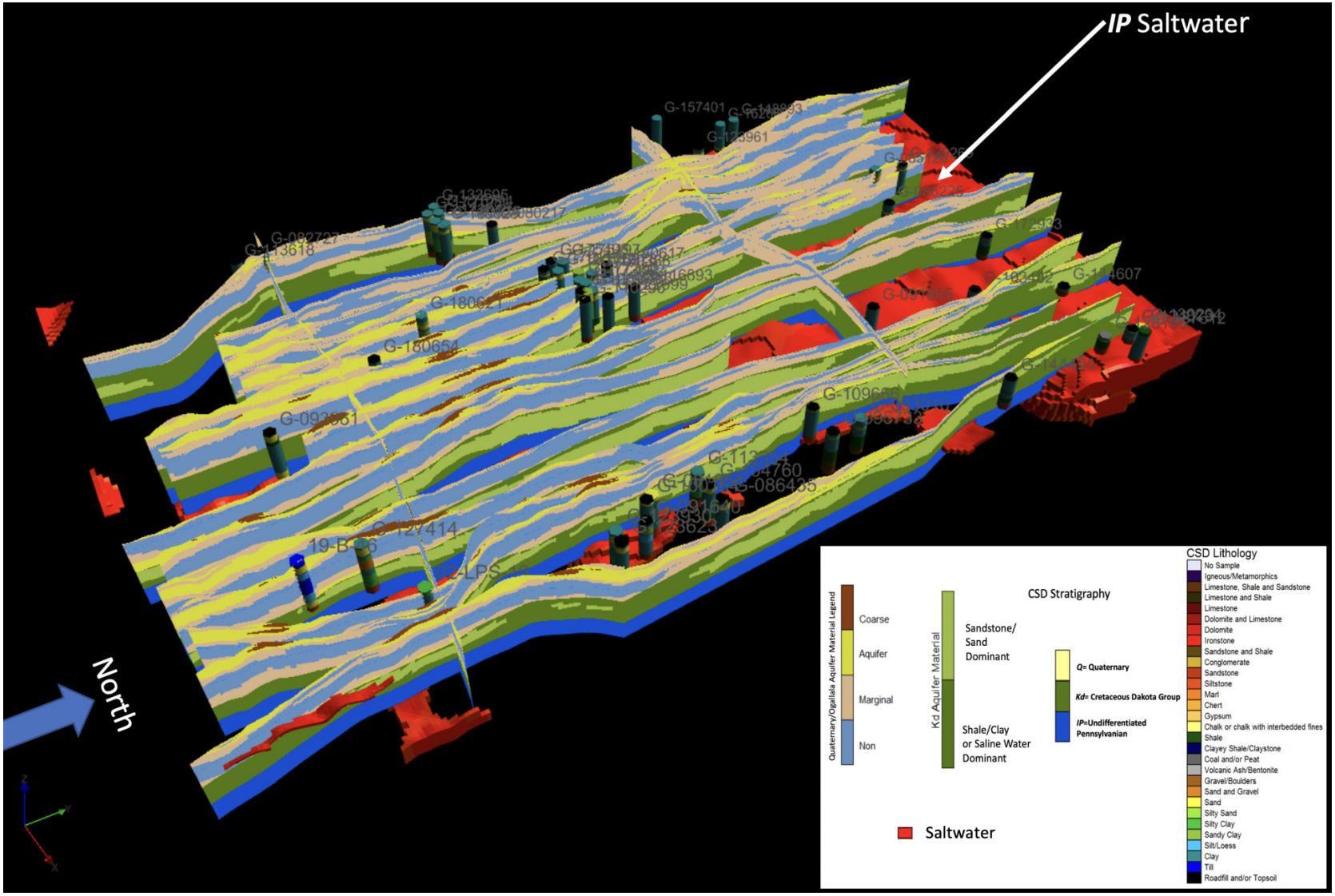


Figure 3-181. View of 3D Fence Diagram of All units and 3D voxel model looking northwest in the Denton Block showing the saltwater water areas colored red. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

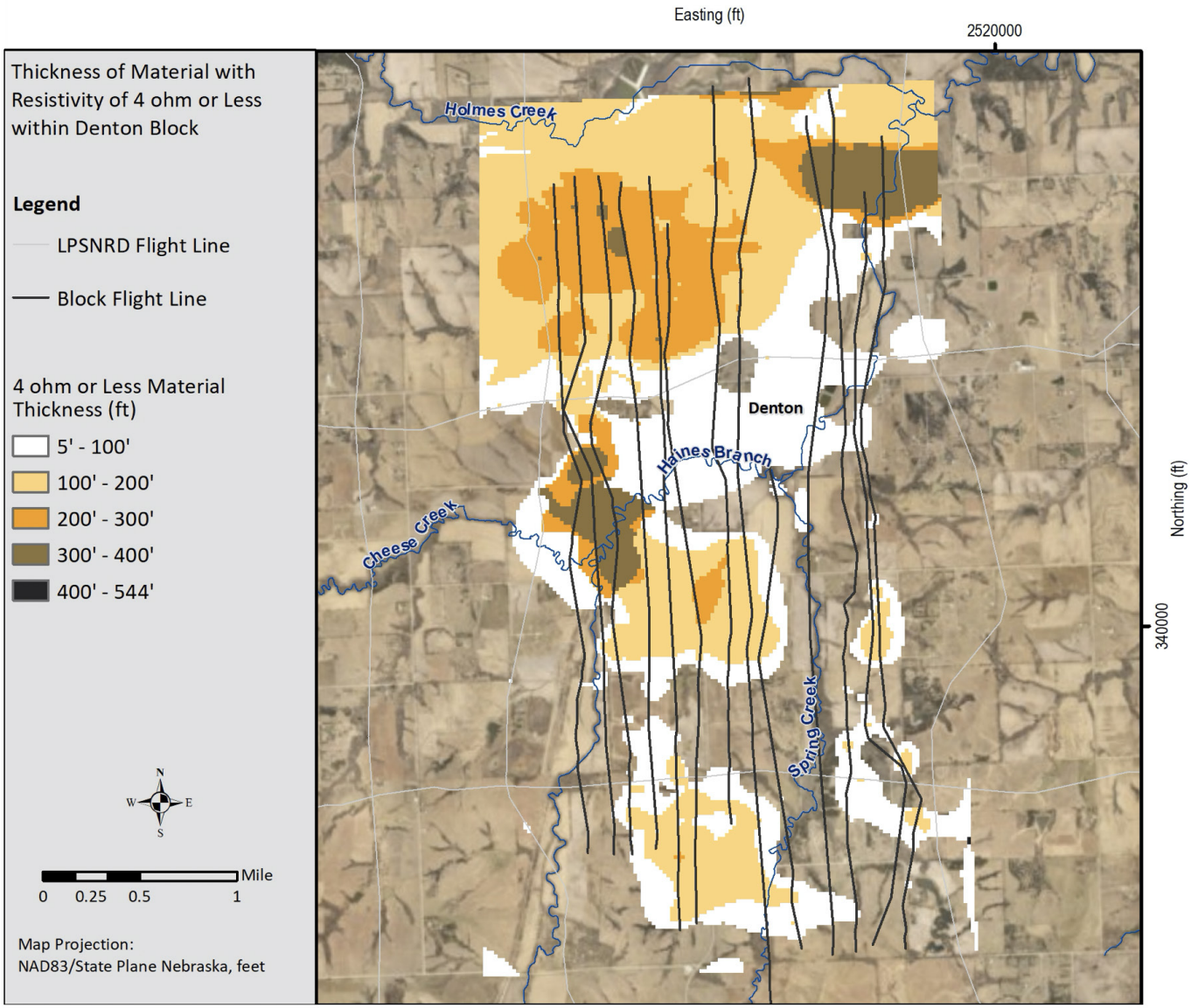


Figure 3-182. Map of the saltwater thickness in the Denton Block area, varying from 5 to 544 feet. Block flight lines are indicated by the black lines. Horizontal datum is NAD83 State Plane Nebraska (feet). The thickness estimate is only to the base of the inversion model.

3.2.5 Hydrogeologic Framework of the Dwight South Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material and the Cretaceous units in the Dwight South Block AEM survey area. The ***Q*** materials within the Dwight South Block are composed of unconsolidated clay, silt, sand and gravel that overlie the consolidated bedrock which is made up of ***Kd***. The ***Q*** material in the Dwight South Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1. Figure 3-183 is the flight line location map including roads, streams and towns. Generally, the area lies south of Dwight, Nebraska and Highway 66. The ground surface elevation map shown on Figure 3-184, shows there are rolling hills surrounding Middle Oak Creek which is the main surface water feature. The ground surface elevation ranges from 1,367 to 1632 feet with highest elevation in the northwest. Figure 3-185 displays a 3D fence diagram with a 3D voxel model of the ***Q*** aquifer materials, ***Kgg***, ***Kd*** and ***IP*** of the Dwight South Block AEM survey area, looking to the southeast, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** with marginal and non-aquifer materials dominating the area and small areas of aquifer material (no coarse aquifer material present). The ***Q*** lies upon lying upon the ***Kgg*** where it exists in the south then ***Kd*** which lies upon the ***IP***. The ***Kd*** contains a mix of Shale/Clay or Saltwater dominant and Sandstone/Sand dominant materials. The bedrock geology map shows the ***Kgg*** lying upon the ***Kd*** in the northwest part of the block. (Figure 3-186). The ***Kd*** contains a mix of Shale/Clay or Saltwater dominant and Sandstone/Sand dominant materials.

Figure 3-187 presents 2D profile L400301is the western most north-south line in the Dwight South Block AEM survey area. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly till and loess. The ***Kd*** Sandstone/Sand materials are not in contact and have little hydrologic connection to ***Q*** aquifer material near northing 465000. The ***Kd*** is mostly Shale/Clay or Saltwater dominant except for an area along the line which are isolated Sandstone/Sand dominant zones which are saturated. The ***Kd*** and ***IP*** are flat lying. The CSD 1995 water table is also on the profile and shows the water table for the area and has little slope (Figure 3-188). Note that the water table generally slopes from west to east.

The total thickness of the ***Q*** material in the Dwight South Block AEM survey area (Figure 3-189) was gridded by subtracting the bedrock elevation (Figure 3-190) from the ground surface elevation (Figure 3-184). The greatest thickness is near the bedrock lows to the northeast and is comparable to bedrock high and low bedrock low within the Dwight South Block AEM survey area. The thin areas (~50-100 feet) of ***Q*** total thickness parallels the drainages of the area. The ***Q*** material varies in thickness from <50 to 525 feet. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to the hydrologic connection of those materials to the surface water of the area. The ***Q*** coarse aquifer and aquifer material which makes up ~50% amount of ***Q*** materials present provide some connection for water movement through all of the ***Q*** aquifer materials. The mix of all ***Q*** materials is complex from profile to profile the hydrologic connection to the streams of the area change. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995)(Figure 3-188) to obtain the total

saturated thickness of ***Q*** material. The saturated thickness for all aquifer material is shown for the Dwight South Block on Figure 3-191. The thickness of these materials varies between 0 to 439 feet. The saturated thickness averages 0-150 feet across the area with the thickest area in the north. Figure 3-192 the relationship between the saturated thickness of ***Q*** and the specific capacity in gpm/ft for wells completed in the ***Q***. Careful evaluation of the wells in Figure 3-192 shows wells in the Dwight South Block AEM survey area have a with a specific capacity of <5 gpm/ft with a single well specific capacity at 10 to 25 gpm/ft. The **Q** is a poor aquifer for well development.

Figure 3-193 Is a map of the elevation of top of ***Kgg*** which ranges in elevation from 1,322 to 1,383 feet. There are low areas in the south-central area and rise in elevation to the north. The ***Kgg*** is a gently shallow undulating surface sloping from high elevation area to the west to east. The thickness map of the ***Kgg*** is shown in Figure 3-194. The thickness of the ***Kgg*** varies from <25 to 82 feet with the thickest area near the bedrock high.

Figure 3-195 Is a map of the elevation of top of ***Kd*** which ranges in elevation from 1,015 to 1,375 feet. There is a low area in the northeast and sharp rise in elevation that is shown by an orange shaded polygon on the map. Past the sharp rise to the south west the ***Kd*** becomes relatively flat. The thickness map of the ***Kd*** is shown in Figure 3-196. The total thickness of the ***Kd*** varies from 213 to 574 feet with the thickest are in the southwest corner and thins in the northeast corner. Figure 3-197 shows the ***Kd*** saturated thickness map the thickness varies from 101 to 464 feet with the thickest area in the northwest. Figure 3-198 shows the relationship between the saturated thickness of ***Kd*** and the specific capacity in gpm/ft for wells completed in the ***Kd***. Careful evaluation of the wells in Figure 3-198 shows only 10 wells in the Dwight South area with a specific capacity of <5 gpm/ft. The best locations for well development are in the thick Sandstone/Sand Dominant zones of the ***Kd***.

The top elevation for the ***IP*** is shown on Figure 3-199 and shows the surface to be a gently sloping surface from the high in the south to the low in the north. The elevation changes from 796 to804 feet showing a nearly flat surface across the block. The ***IP*** has Saltwater dominant areas in the area.

Figure 3-200 shows the interpreted 2D profile L303800 is an east-west line which is the second flight line north from the south side of the block. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are made up entirely of till and loess marginal and non-aquifer material layer that is a ~200-foot thick and continuous across the profile lying upon the ***Kd***. The ***Q*** layer marginal and non-aquifer materials have ~100 to 150 feet of saturation but have little ability to transmit water to a well or to a stream. ***Q*** aquifer and coarse aquifer material provides very small thin caps the hill near easting 2464000. It can be very thin~10 feet at the land surface but above the water table. The ***Kd*** Sandstone/Sand materials do not have hydrologic connection to other geologic units or streams. The ***Kd*** is mostly Shale/Clay or Saltwater dominant except for the continuous band of Sandstone/Sand dominant layer that is ~100-150 feet thick. The ***IP*** has saltwater water dominant areas on the east end. The CSD 1995 water table is also on the profile and shows the water table for the area and it is mostly flat.

Figure 3-201 shows the interpreted 2D profile L304201 which is a north-south profile lies diagonally from southwest to northeast in the Dwight South Block AEM survey area. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly thick till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material. There is a steep rise in the slope of the ***Kd*** top elevation near northing 460000. These materials have ~100 to 300 feet of saturation with a high-water table elevation that is relatively flat. All of the creeks have minimal hydrologic connection to the ***Q*** materials due to the abundance of marginal and non-aquifer materials present. Near northing 448000 there is a ***Kd*** Sandstone/Sand dominant material and there is a deeper saltwater area in the vicinity. The ***Kgg*** is present above the ***Kd*** from the south end to northing 450000. At the far north end of the profile the yellow of the aquifer material can be seen in the paleochannel.

An exploded view of the 3D voxel model showing the ***Q***, both saturated and unsaturated, the ***Kd***, saturated and the ***IP*** formations is presented in Figure 3-202. The ***Q*** materials show mostly marginal aquifer and non-aquifer materials mixed with minor amounts of aquifer and coarse aquifer materials. The ***Q*** aquifer materials are evenly split between saturated and unsaturated along a plane that is relatively flat. There is some ***Kgg*** south end and is saturated. The ***Kd*** saturated material present in the entire block and has a steep slope in the northeast. Because of the amount of ***Q*** marginal and non-aquifer materials and their distribution across the Dwight South area there is no ability for managed aquifer recharge (MAR) sites to be located within the block. Figure 3-203 shows a map of the distribution of ***Q*** marginal and non-aquifer materials thickness which is thickest in north side of the block. These materials range in thickness from <50 to 516 feet. Figure 3-204 is a map which shows the thickness of the ***Q*** aquifer and coarse aquifer materials with the thickest deposits near the north. These materials range in thickness from <50 to 468 feet. A map of ***Q*** saturated aquifer and coarse aquifer materials (Figure 3-205) range in thickness from <25 to 282 feet and show that the ***Q*** has minimal additional groundwater storage that can yield to wells or be used as MAR locations. The paleochannel can be seen in the northern section of the figure.

Figure 3-206 shows a 3D fence diagram of unsaturated and saturated ***Q*** aquifer material looking northwest. The ***Kd*** and ***IP*** are also shown. The ***Q*** mostly made up of marginal and non-aquifer material. This limits the transmission of water from the land surface for recharge. Figure 3-207 presents a view to the east of the Dwight South Block showing a 3D fence diagram of all ***Q*** material, ***Kgg***, ***Kd*** and ***IP***. The intermittent nature of the saturated ***Q*** aquifer material shows the discontinuous nature of these deposits.

Figure 3-208 presents a map of the thickness for ***Kd*** Sandstone/Sand Dominant deposits. These deposits are saturated and vary in thickness from 28 to 282 feet and are discontinuous across the block. The ***Kd*** Sandstone/Sand dominant material is an aquifer in this area with the thickest portion in the south. Figure 3-209 3D voxel model view to the north showing the saturated thickness for ***Q*** aquifer material that is limited to the northern end of the survey area. Figure 3-210 is a 3D voxel model with a view looking west and is similar to Figure 3-209.

During the analysis of the AEM data it was apparent that there was saltwater present in some areas in LPSNRD project area. There is a presence of saltwater in the Dwight South Block AEM survey area. Figure 3-211 is a 3D voxel model with a view looking north that shows these saltwater areas. There are no water quality samples from wells in the area and this determination of saltwater is based on the comparison of resistivity from the AEM versus the lithology from the wells. Figure 3-212 is a 3D voxel model with a view to the northwest of the voxel model that shows these saltwater areas.

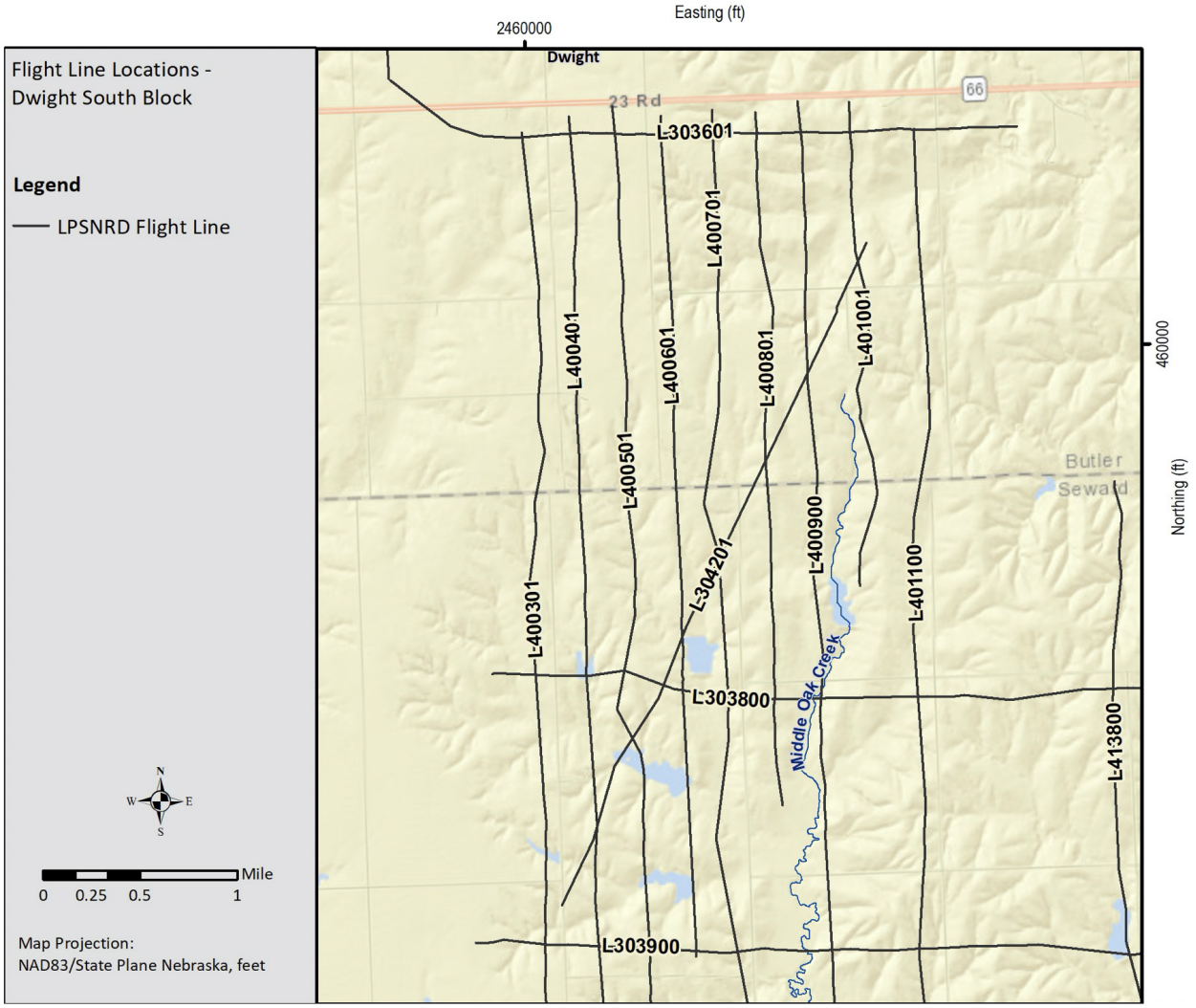


Figure 3-183. Location map of the Dwight South Block AEM survey area showing numbered AEM flight lines, local roads, and streams. The area lies south of Dwight, Nebraska and Highway 66. Block flight lines are indicated by black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

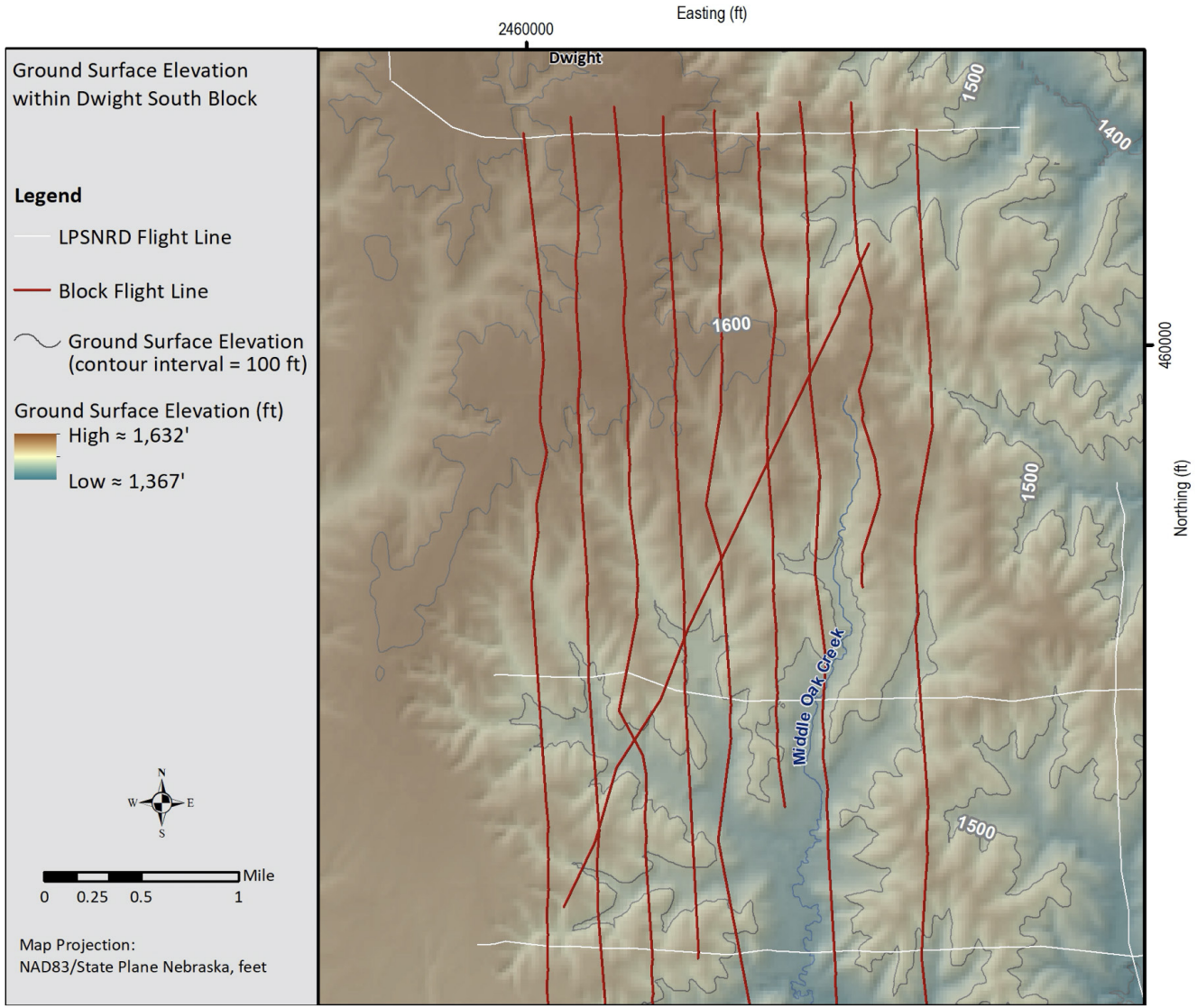


Figure 3-184. Map showing the ground surface elevation with flight lines in the Dwight South Block. Note the rolling hills nature of the ground surface. There are rolling hills in the east and upland in the west the main drainage is Middle Oak Creek. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

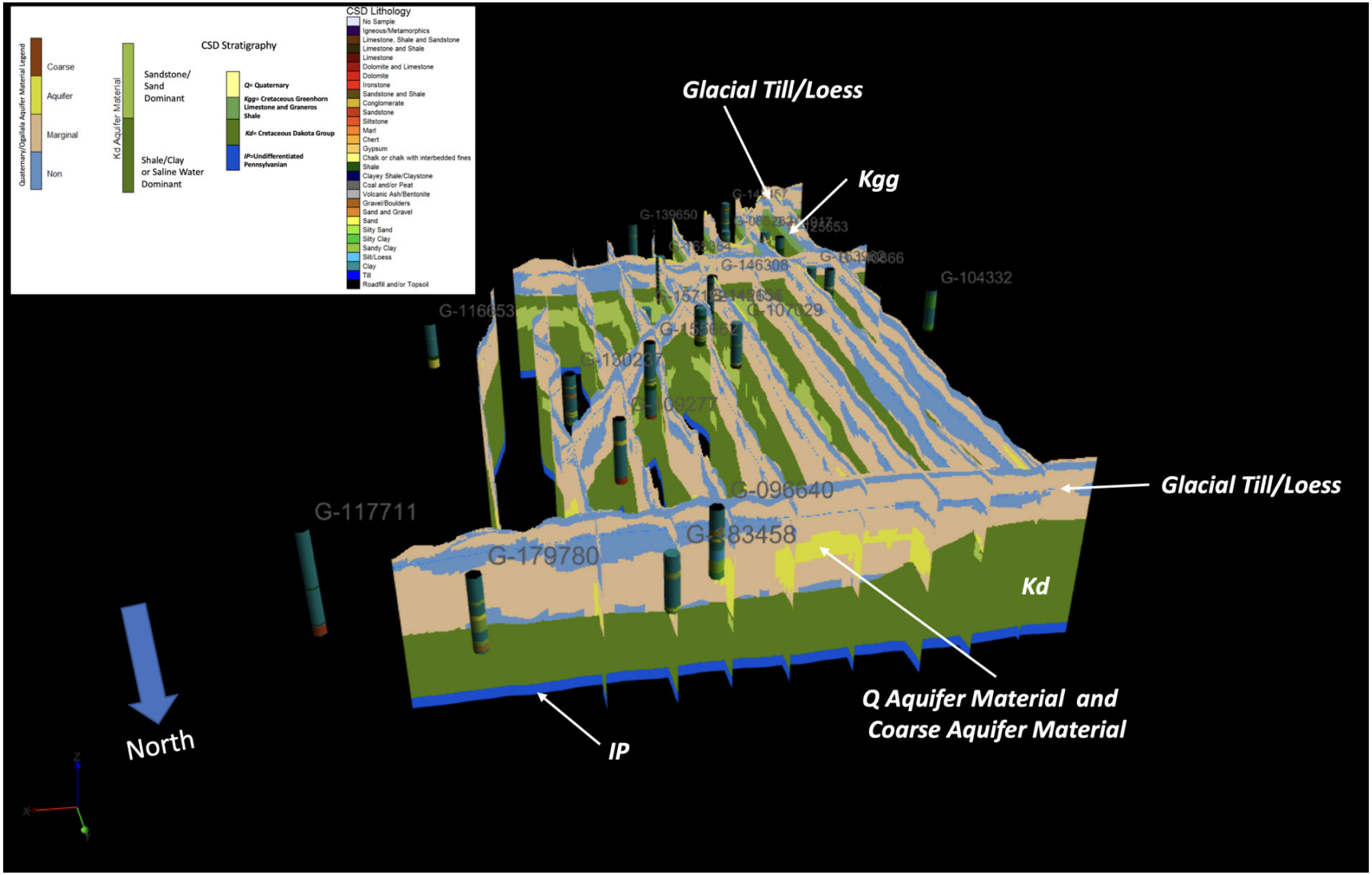


Figure 3-185. 3D fence diagram looking south of interpreted AEM hydrostratigraphic profiles within the 2018 Dwight South Block AEM survey area. The *Q* aquifer materials are mostly marginal and non-aquifer material. There is *Kgg* in the south of block. CSD and NE-DNR wells are labeled. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 5x.

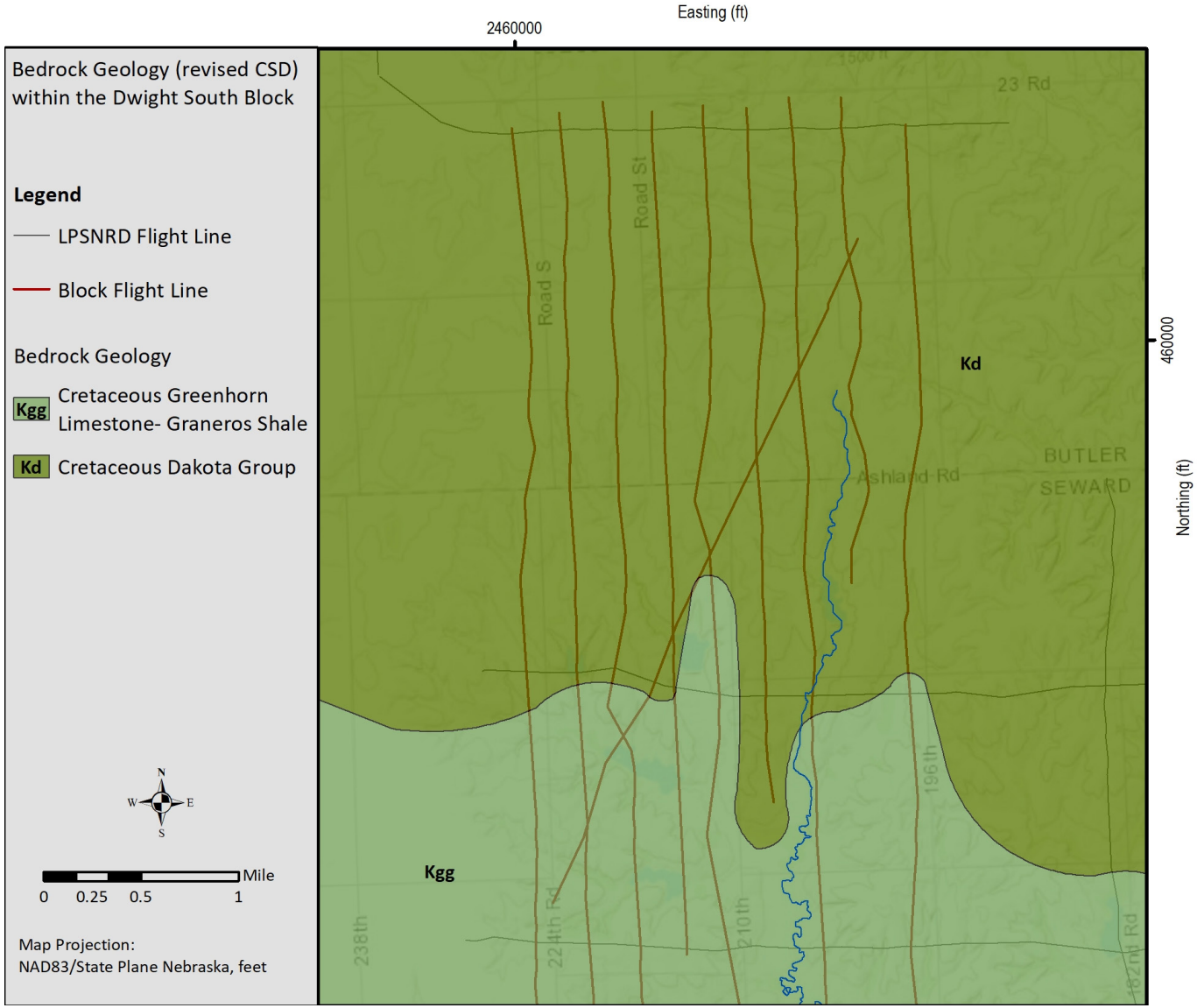


Figure 3-186. The bedrock geology map shows the *Kgg* lying upon the *Kd* in the northwest part of the Block. Block AEM flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

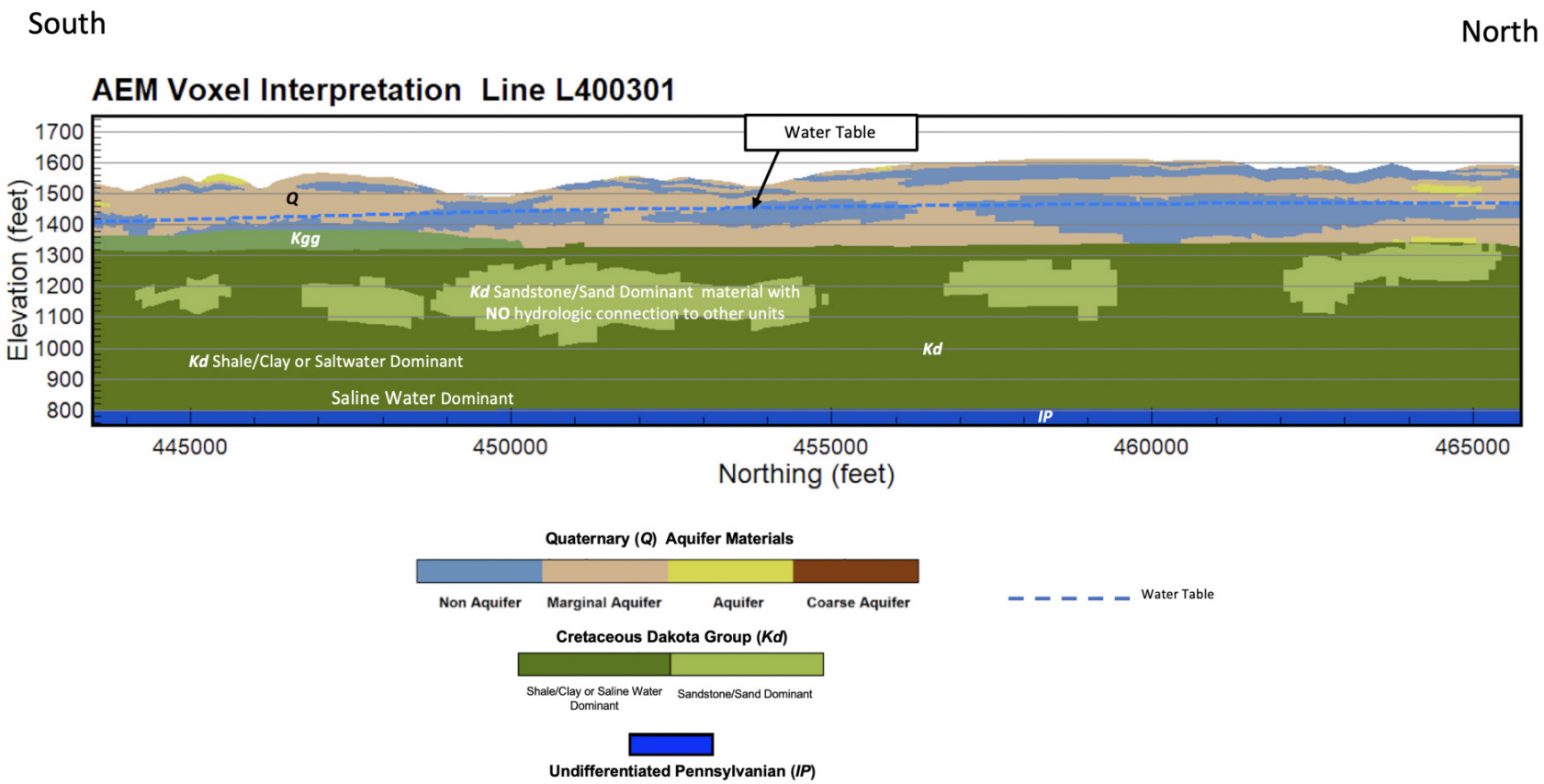


Figure 3-187. Profile of the north-south line L400301 showing the *Q* aquifer materials, *Kgg*, and the *Kd*. The *Q* materials are mostly marginal and non-aquifer materials. The *Kd* Sandstone/Sand materials are in contact with the small amount of *Q* aquifer material neat northing 465000, otherwise have a minimal hydrologic connection to other units and surface water. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Block flight lines are indicated by black lines. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

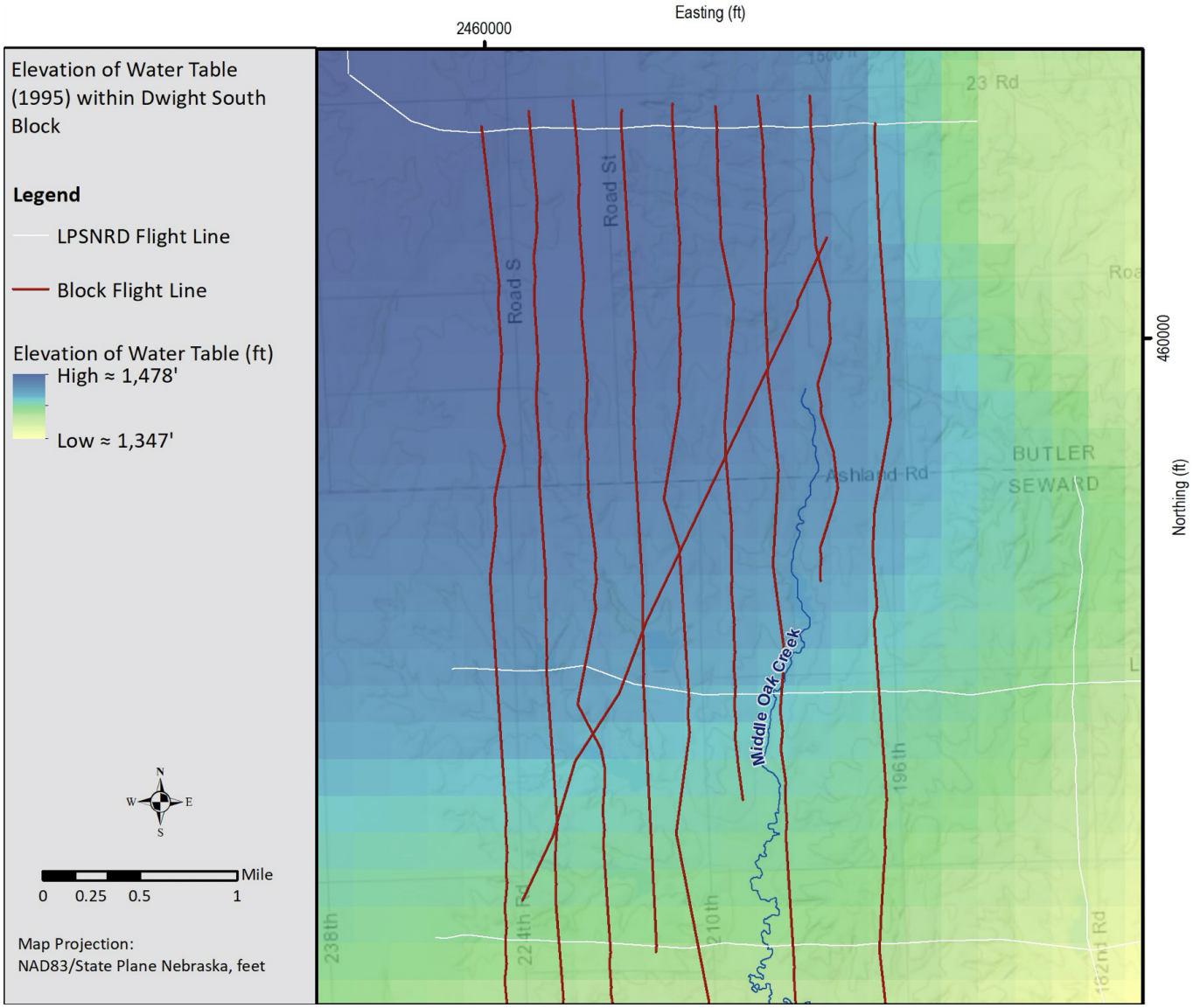


Figure 3-188. Map of the CSD 1995 water table (NE-CSD, 1995) for the area showing that the water table has little slope. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

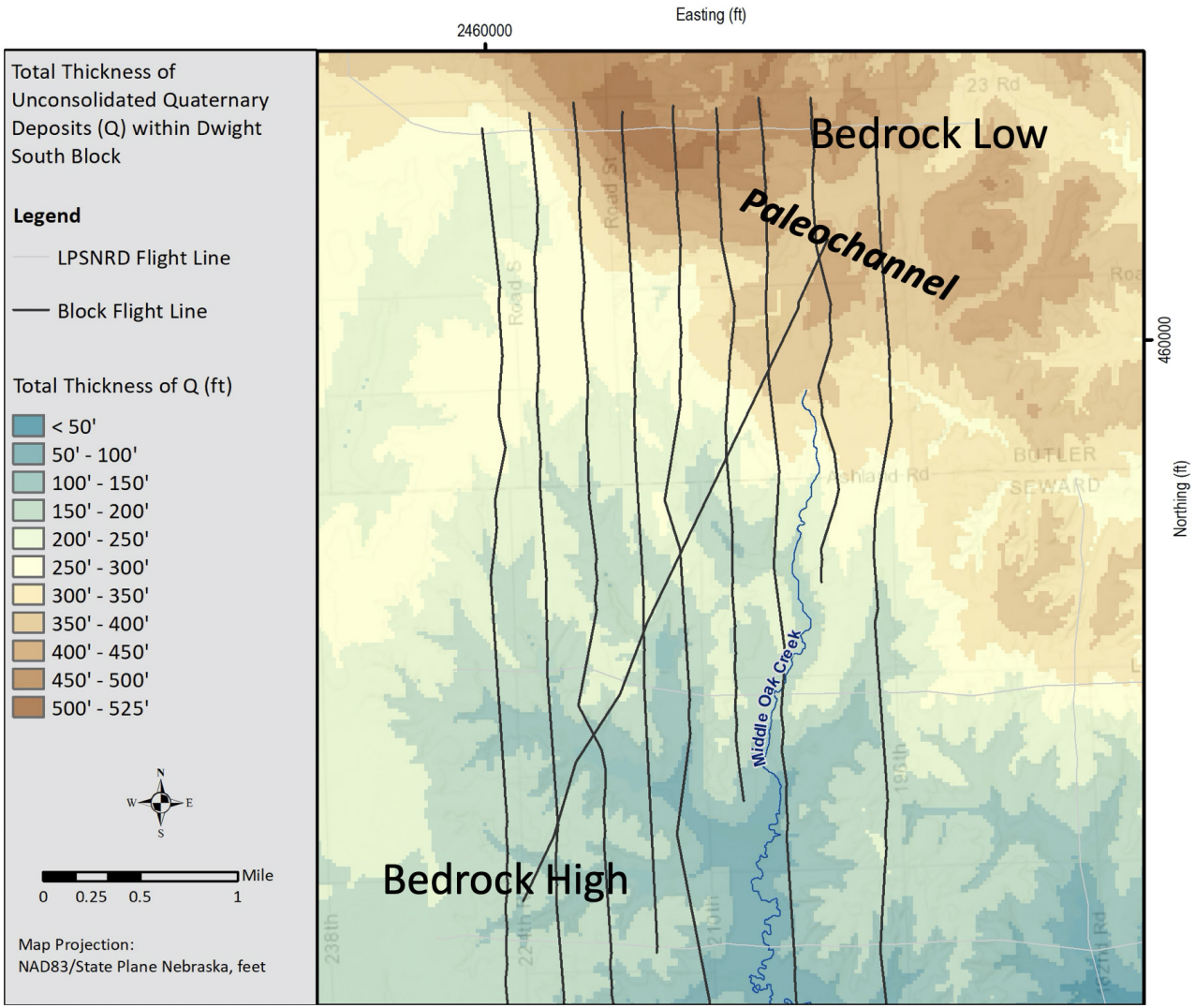


Figure 3-189. Map of the total thickness of the Quaternary (*Q*) deposits within the 2018 Dwight South Block AEM survey area. The thickest areas are in the northeast of the block where a bedrock low exists. The thin areas overlie the bedrock high in the southwest. The geologic unit present on this image includes the *Q*= Quaternary. Block flight lines are indicated by black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

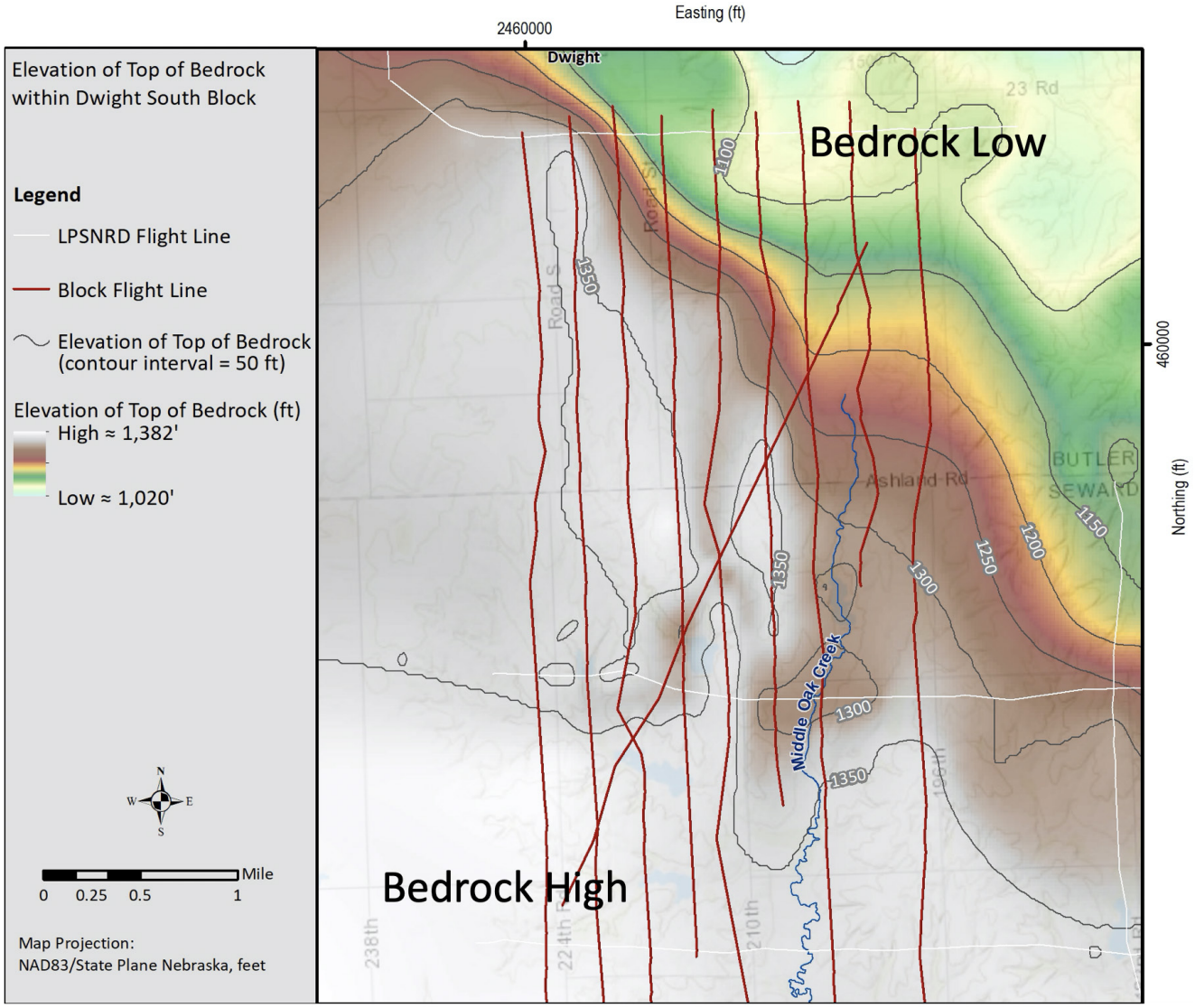


Figure 3-190. Map of the elevation of the top of bedrock within the 2018 Dwight South Block AEM survey area. The bedrock surface slopes in general from a bedrock high to south to a bedrock low in the northeast. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

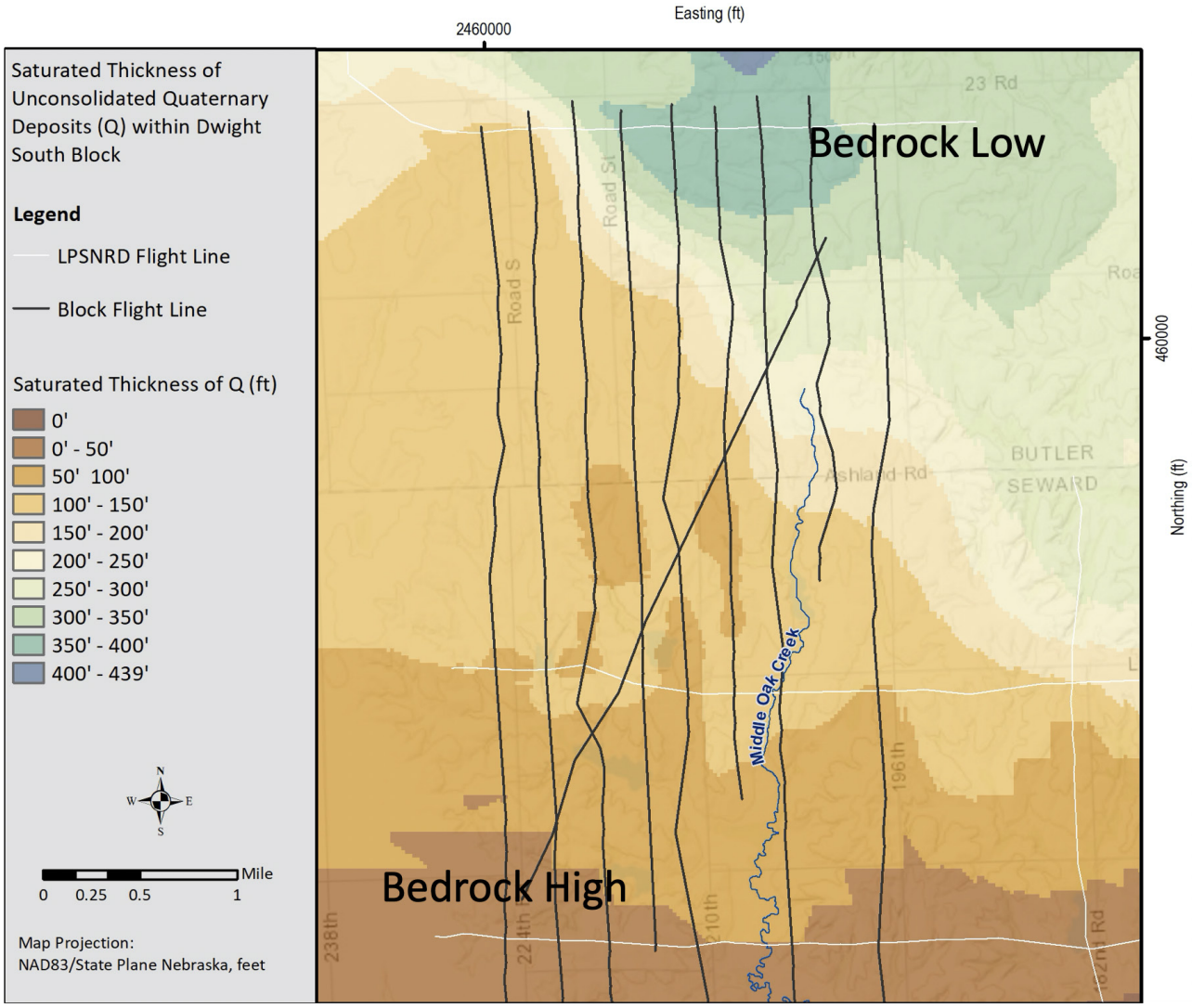


Figure 3-191. Map of saturated thickness of the *Q* within the 2018 Dwight South Block AEM survey area. The thickest areas area is on the northeast over the bedrock low. Thin areas that vary in thickness from 0 to 150 feet are in the uplands to the southwest over the bedrock high. Block flight lines are indicated by black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

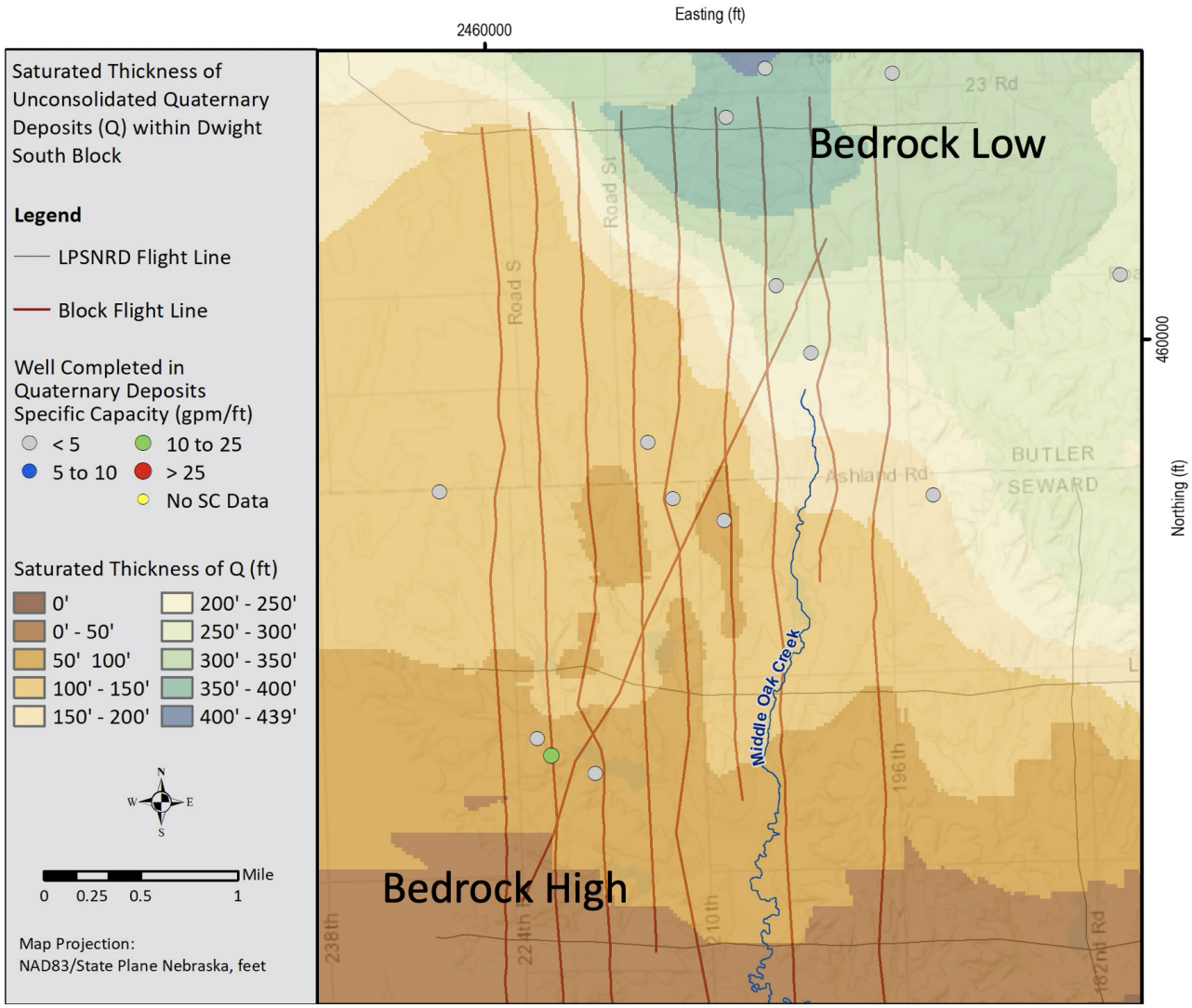


Figure 3-192. Map shows the relationship between the saturated thickness of *Q* and the specific capacity in gpm/ft for wells completed in the *Q*. Careful evaluation of the wells shows they have a specific capacity of <5 gpm/ft with a single well specific capacity at 10 to 25 gpm/ft. Block flight lines are indicated by the brown lines. The geologic unit present on this image include *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

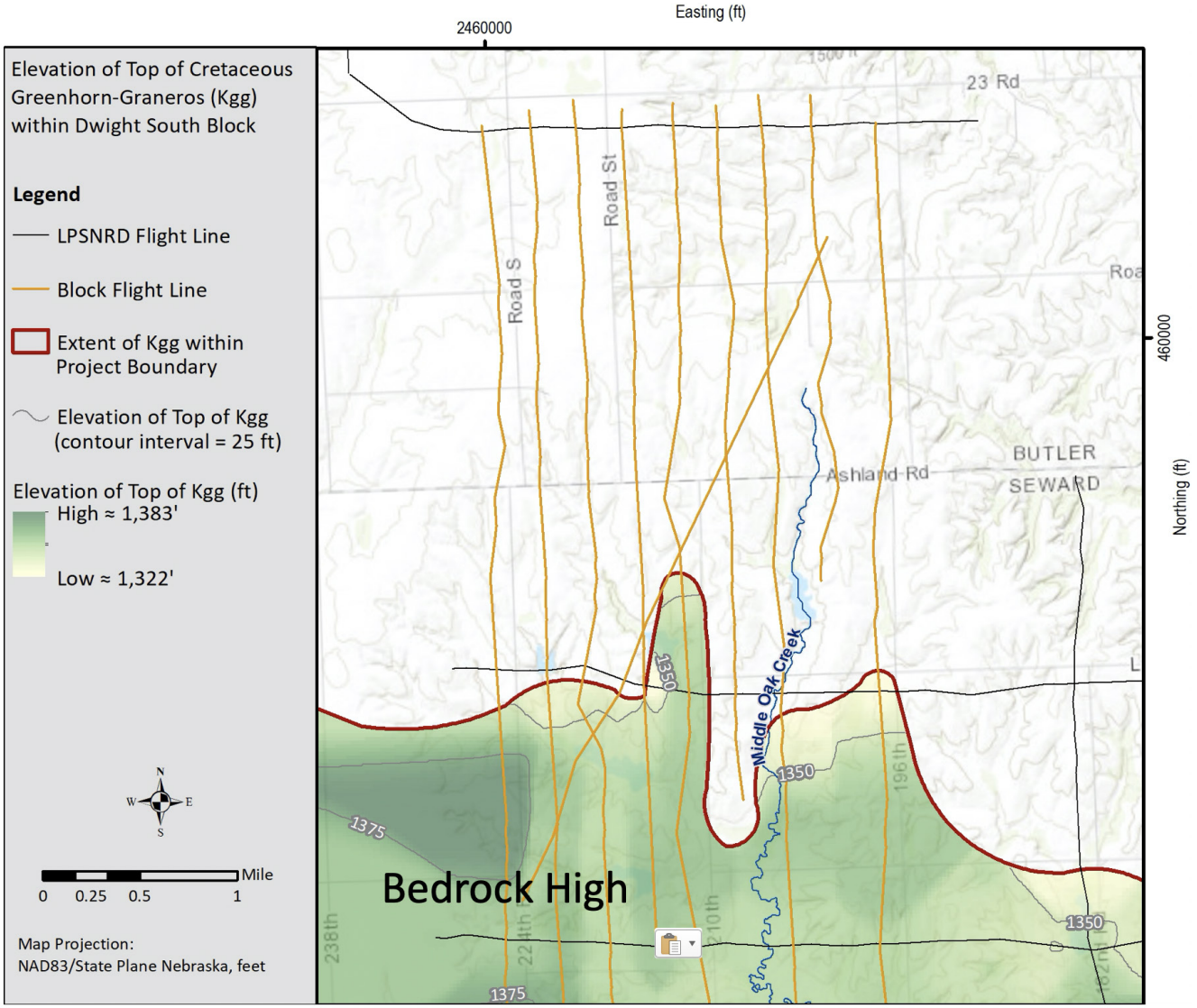


Figure 3-193. Map of the elevation of the top of the *Kgg* within the 2018 Dwight South Block AEM survey area. The surface slopes gently from west to east. Block flight lines are indicated by the orange lines. The geologic unit present on this image includes the *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale. Horizontal datum is NAD83 State Plane Nebraska (feet).

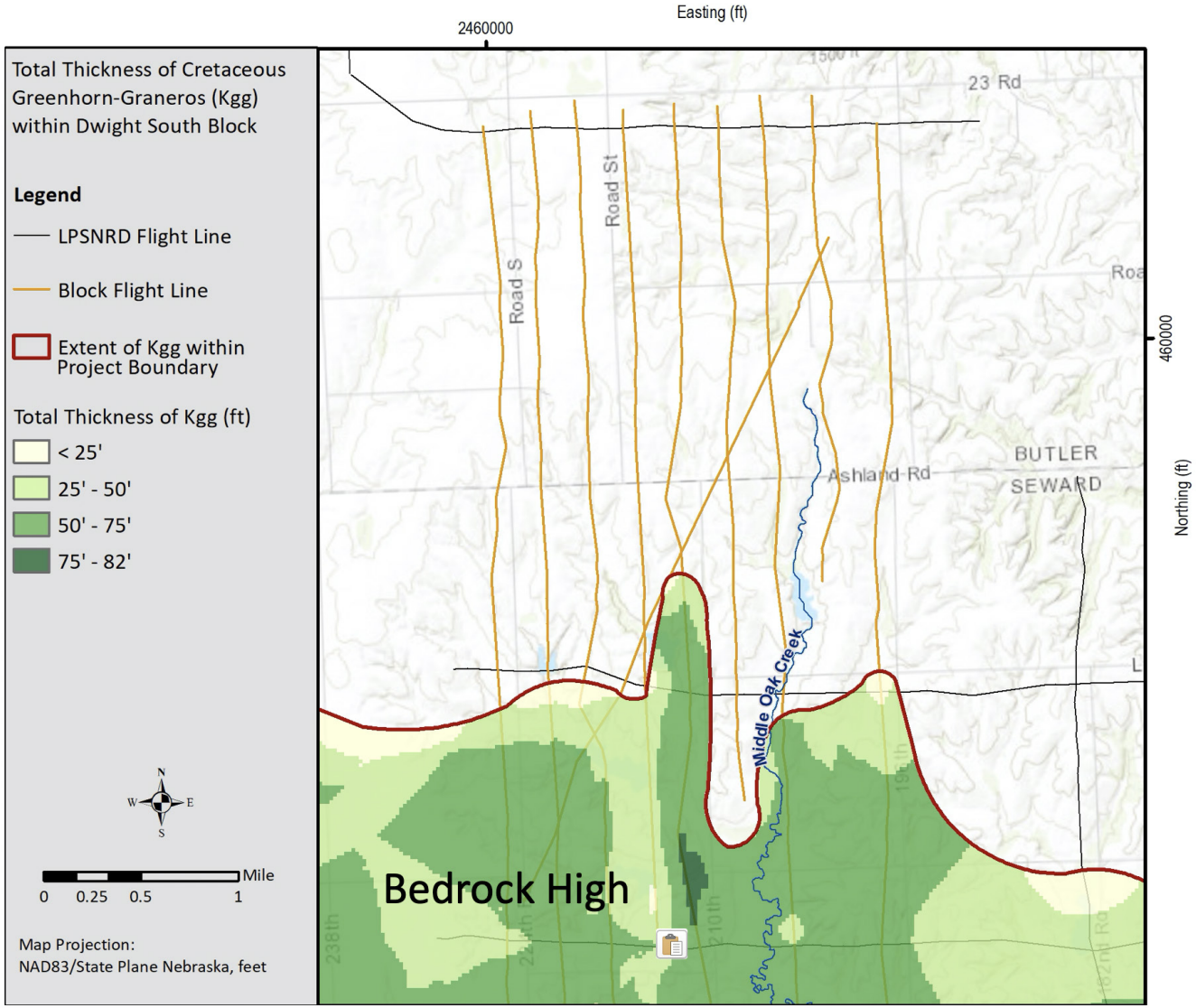


Figure 3-194. Map of the total thickness of the *Kgg* within the 2018 Dwight South Block AEM survey area. The thickest areas are in the center of the south side of the area. Block flight lines are indicated by the orange lines. The geologic unit present on this image includes the *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale. Horizontal datum is NAD83 State Plane Nebraska (feet).

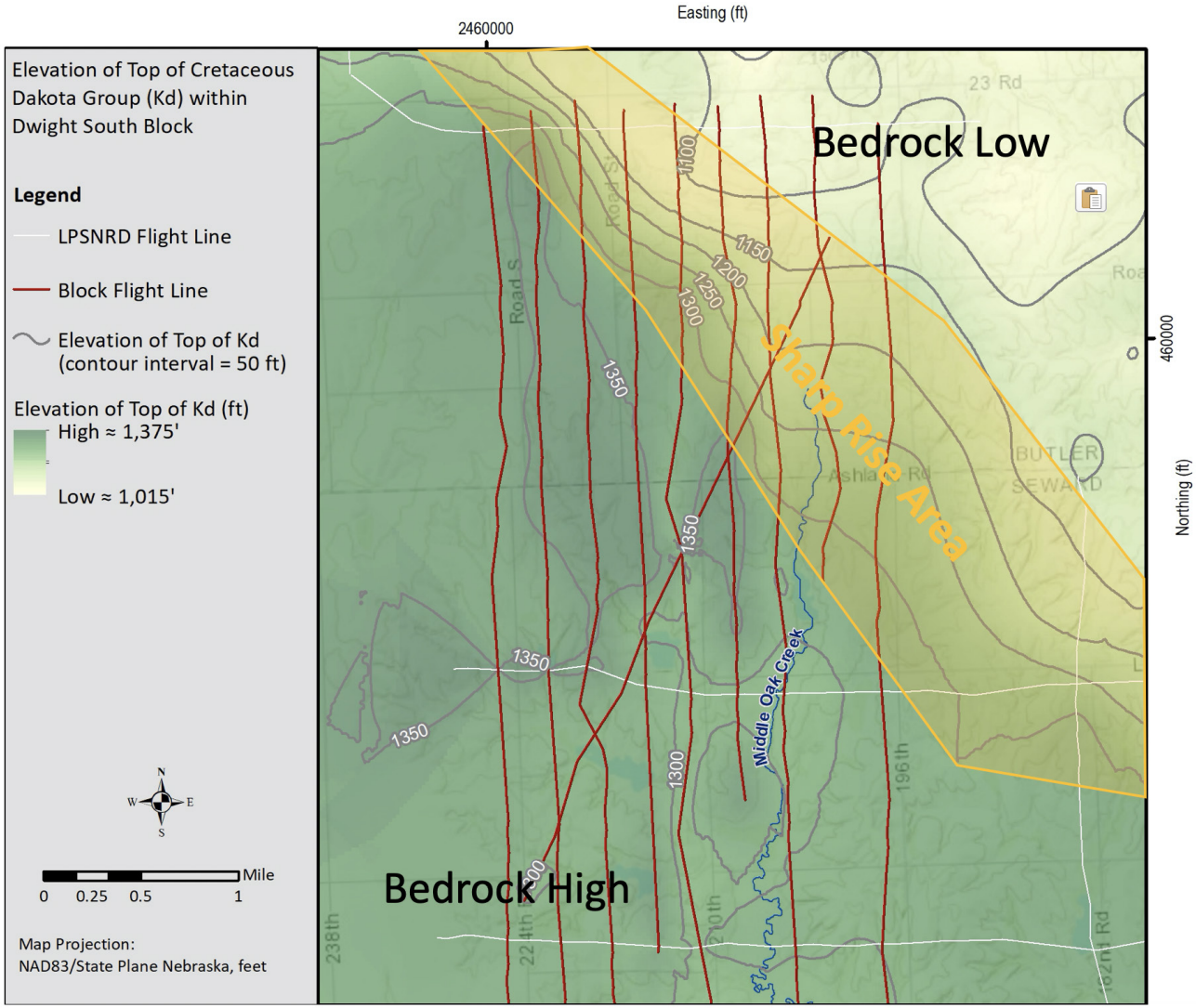


Figure 3-195. Map of the elevation of the top of the *Kd* within the 2018 Dwight South Block AEM survey area. The surface slopes south to north from the bedrock high to the bedrock low. There is a steep slope between the high and low areas. Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

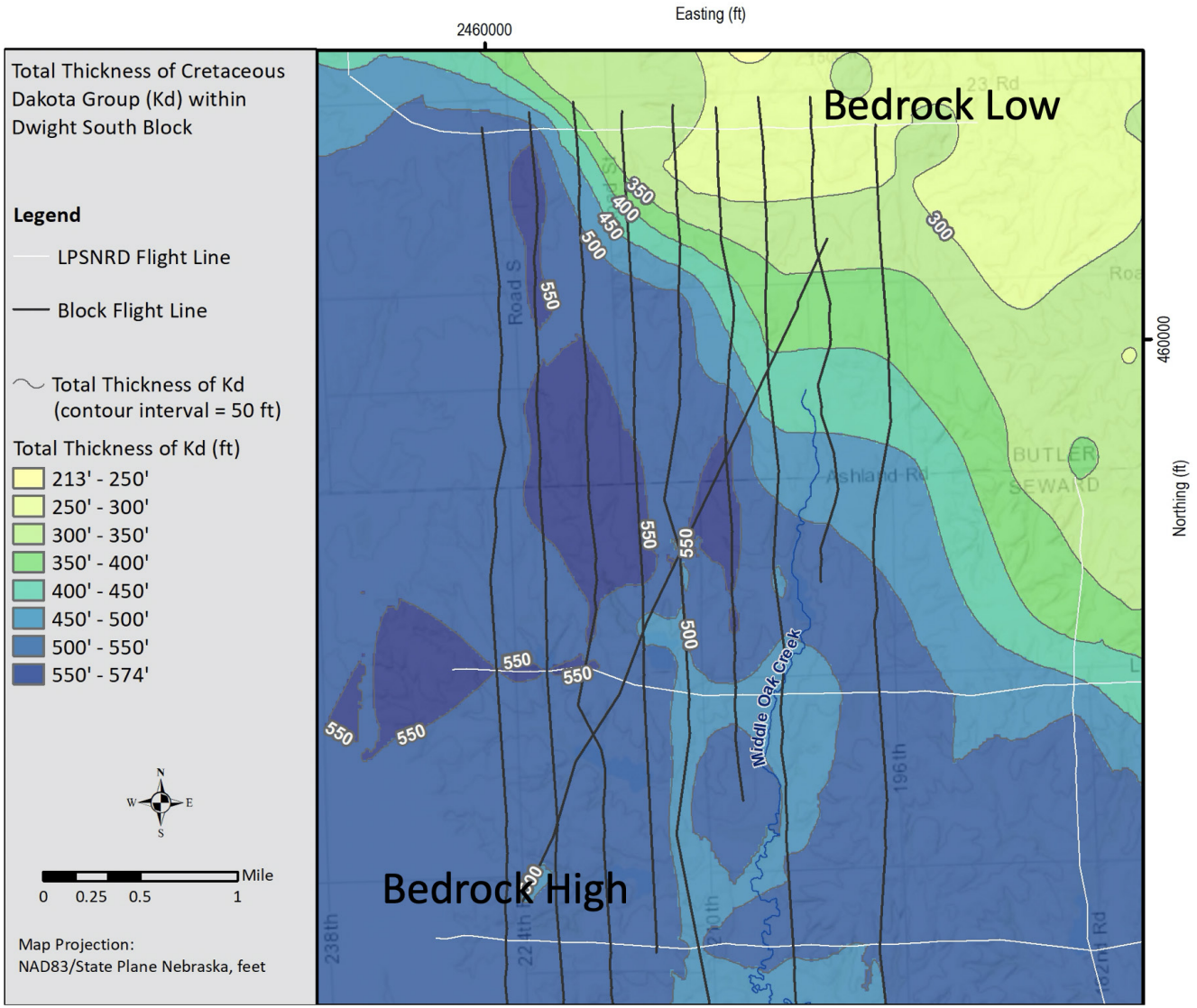


Figure 3-196. Map of the total thickness of the *Kd* within the 2018 Dwight South Block AEM survey area. The thin areas are in the northeast corner of the area near the bedrock low, the thick area is in the south near the bedrock high. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

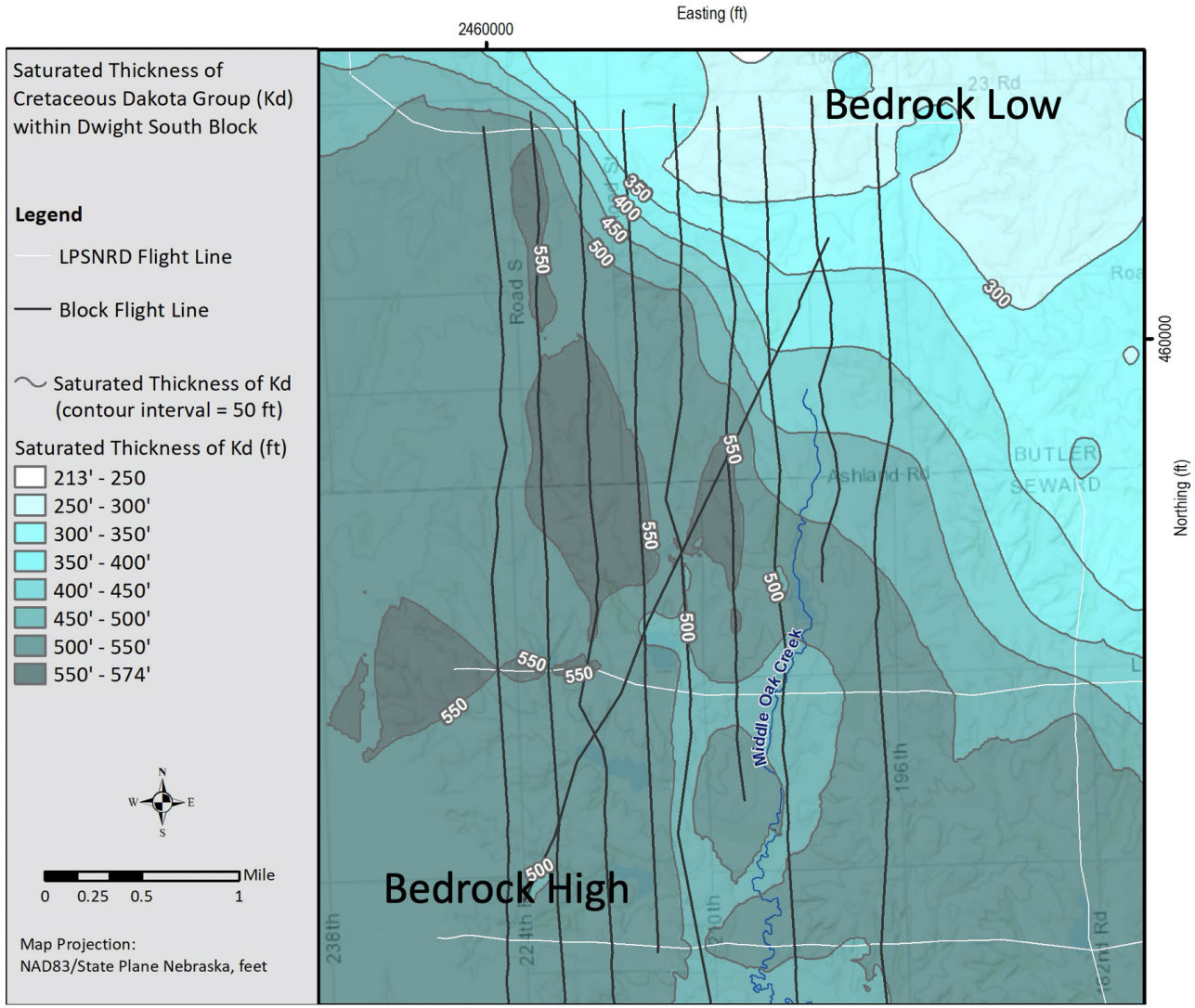


Figure 3-197. Map of the saturated thickness of the *Kd* within the 2018 Dwight South Block AEM survey area. The thin areas are in the northeast corner of the area near the bedrock low, the thick area is in the south near the bedrock high. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

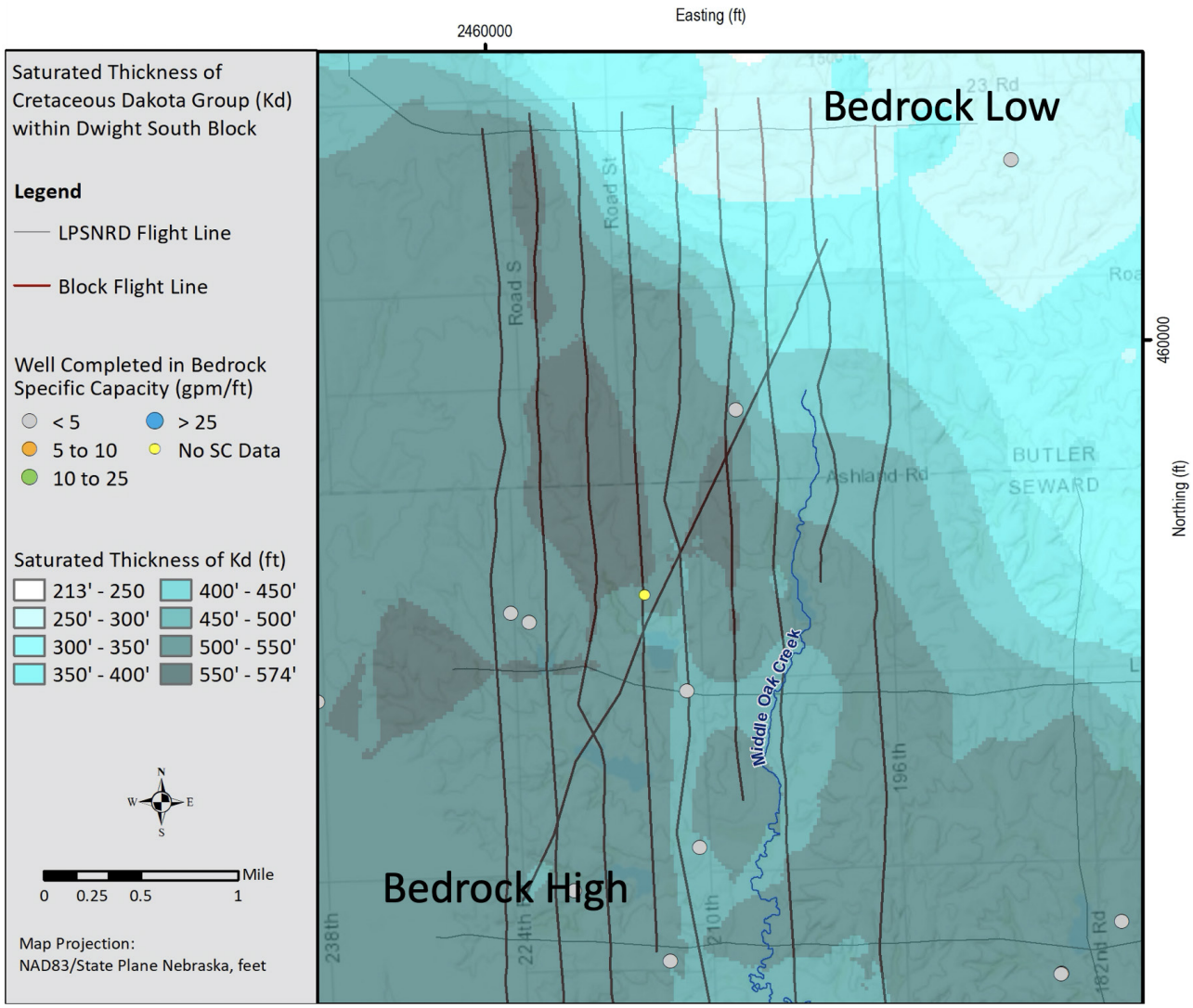


Figure 3-198. Map shows the relationship between the saturated thickness of *Kd* and the specific capacities in gpm/ft for wells completed in the *Kd*. Careful evaluation of the wells shows only 10 wells in the Dwight South area with a specific capacity of <5 gpm/ft m. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

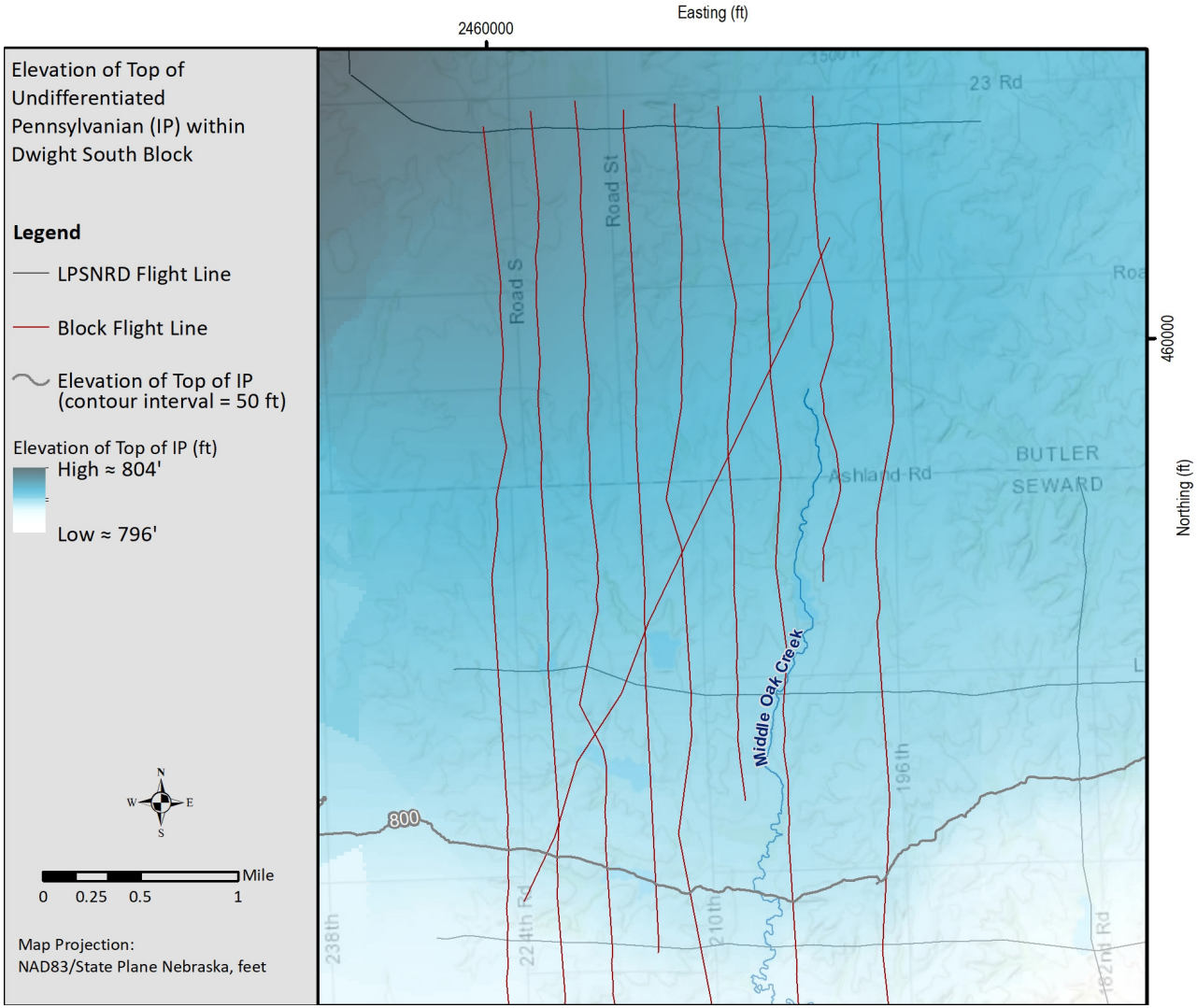


Figure 3-199. Map shows the top elevation for the *IP* shows the surface to be a gently sloping surface from the high in the south to the low in the north. The elevation changes from 796 to 804 feet showing a nearly flat surface across the block. The *IP* has saltwater water dominant areas in the area. Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

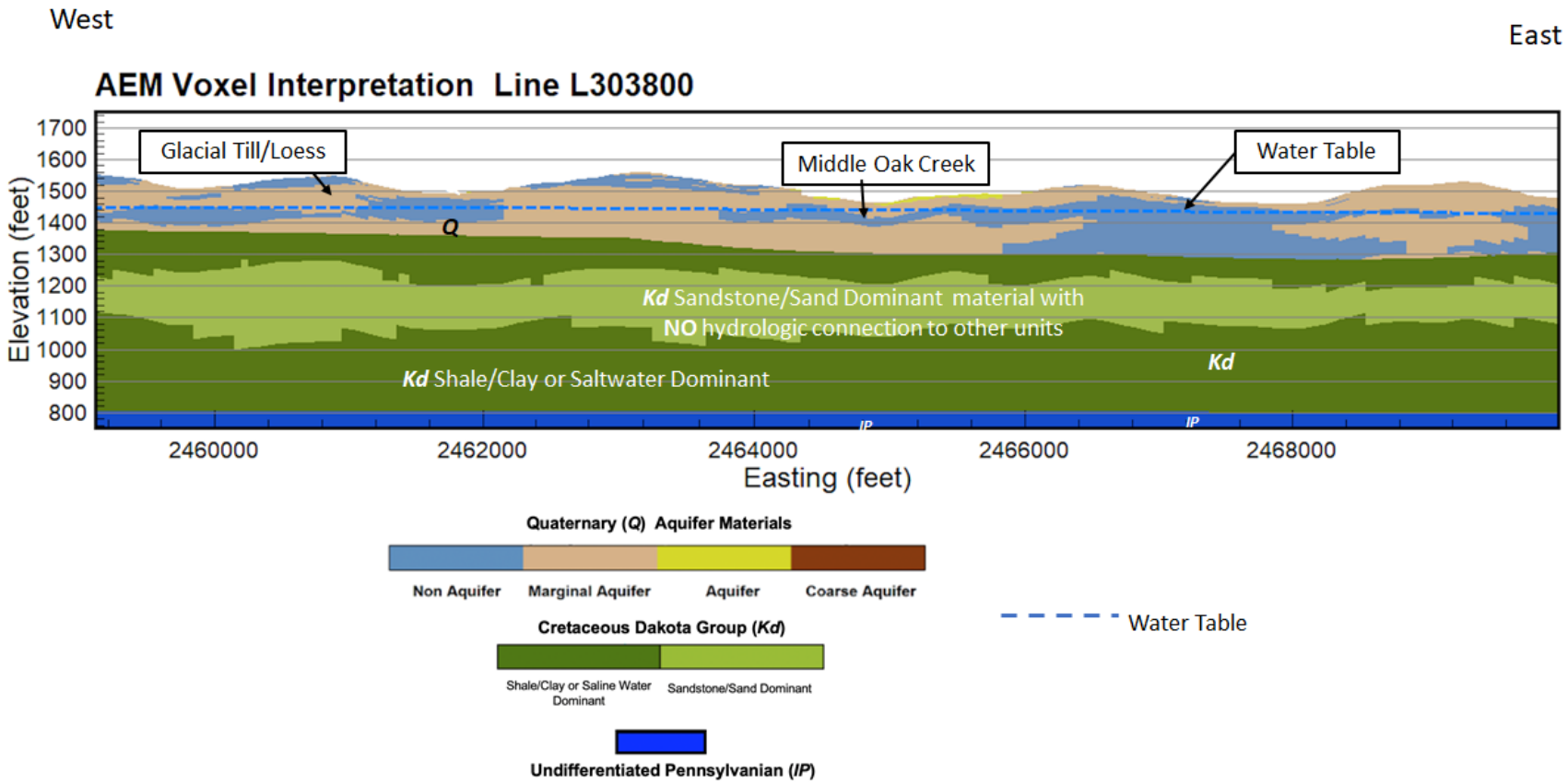


Figure 3-200. Interpreted profile of the north-south line L303800 showing the relationship the *Q*, *Kd* and *IP* of the AEM interpretations across the area. The *Q* is mostly till and loess marginal and non-aquifer material layer that is a ~200-foot thick and continuous across the profile lying upon the *Kd*. The *Kd* has a continuous ~120-foot thick layer of sandstone/sand dominant material across the line from west to east. The CSD 1995 water table is indicated as a dashed blue line it lies at a high elevation and lies near the top of the loess and non-aquifer material. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

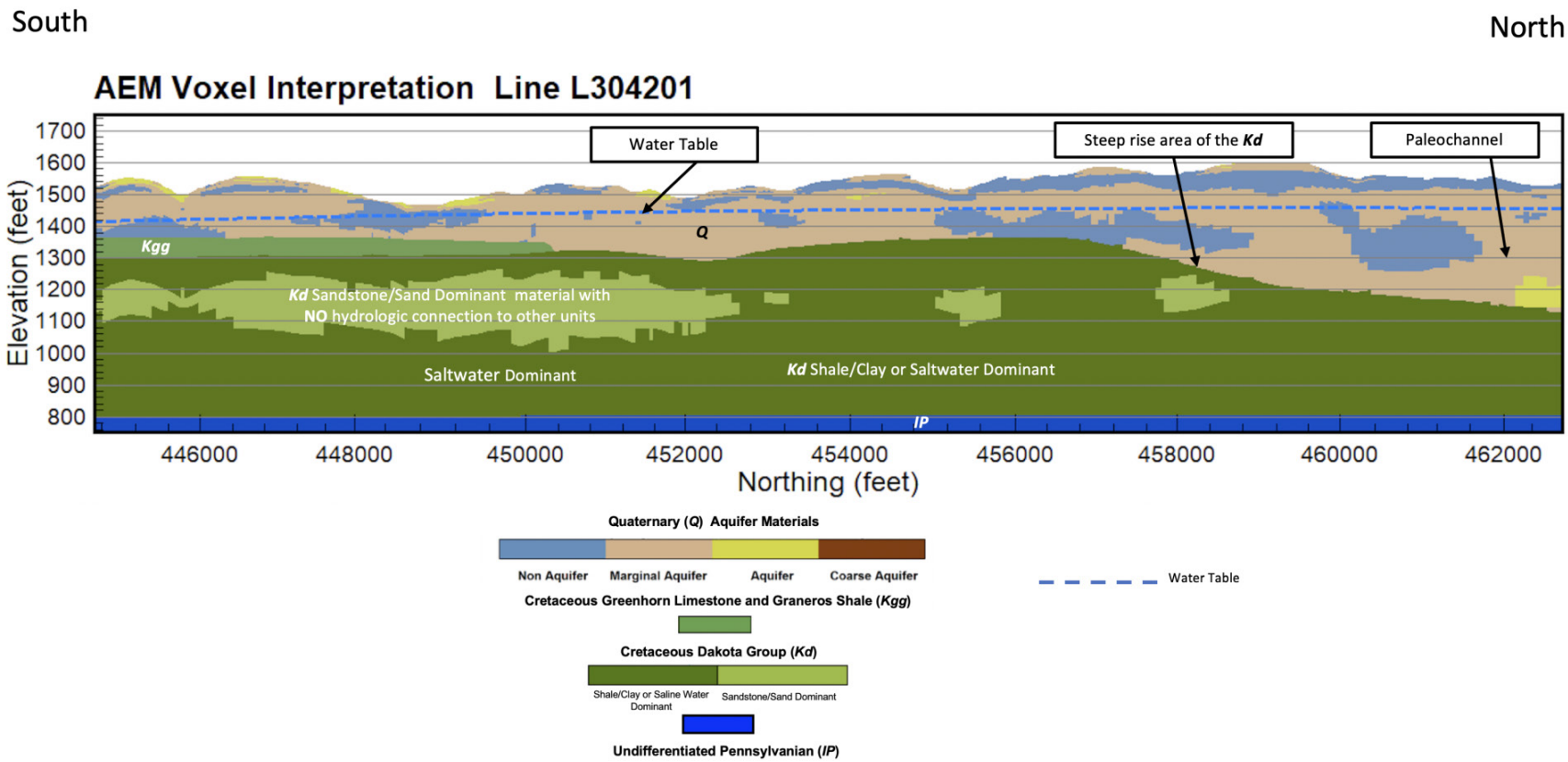


Figure 3-201. Interpreted profile of the north-south line L304201 showing the relationship the *Q*, Kgg, *Kd* and *IP* of the AEM interpretations across the area. The *Q* materials are mostly thick till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material. The Q materials have ~100 to 350 feet of saturation with a high-water table elevation that is relatively flat. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

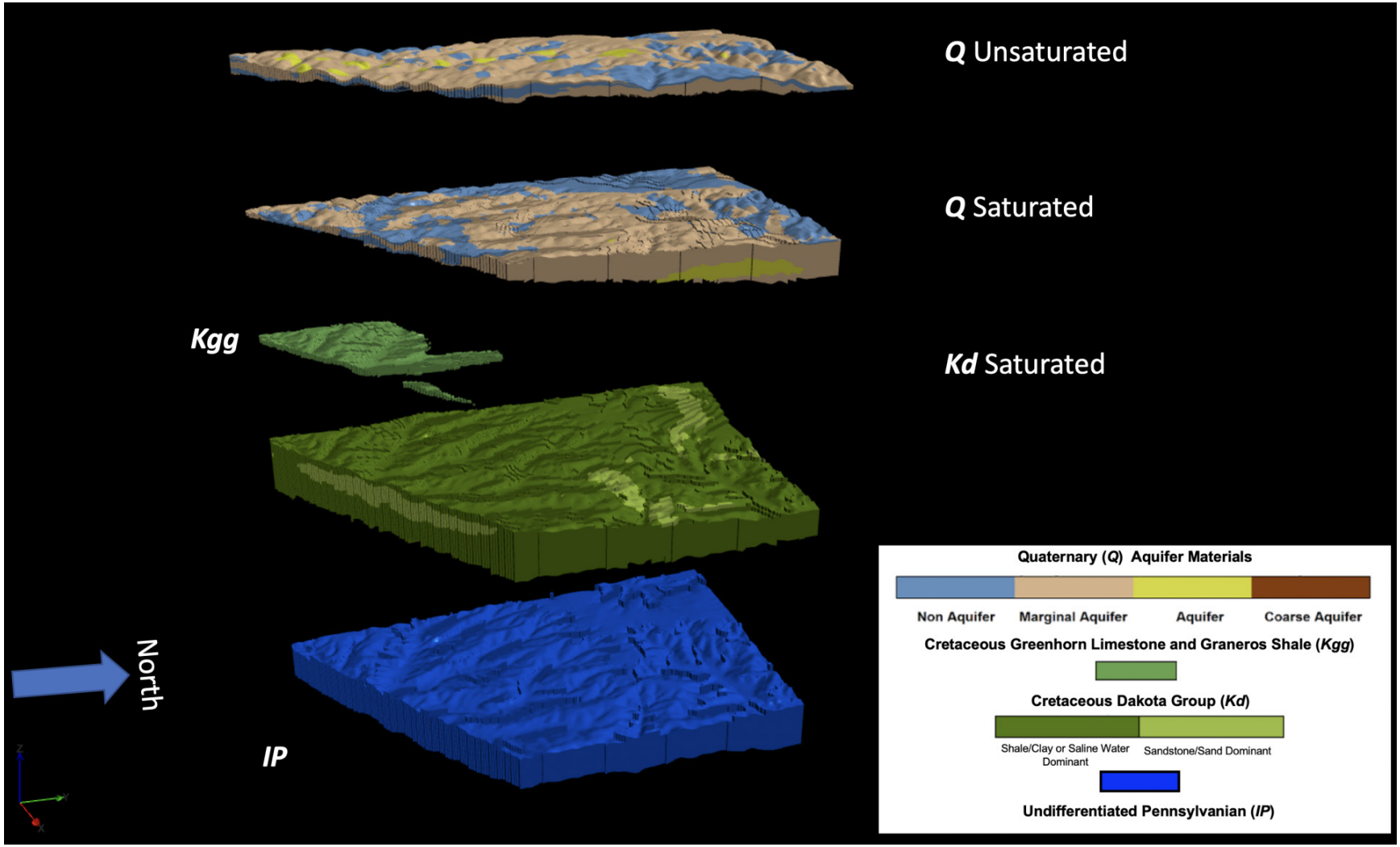


Figure 3-202. 3D exploded voxel model looking northwest of the Dwight South Block showing Unsaturated *Q*, Saturated *Q, Kgg, Saturated Kd* and *IP*. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and Undifferentiated Pennsylvanian (*IP*). Vertical exaggeration (VE) = 5x. The figure is not to scale.

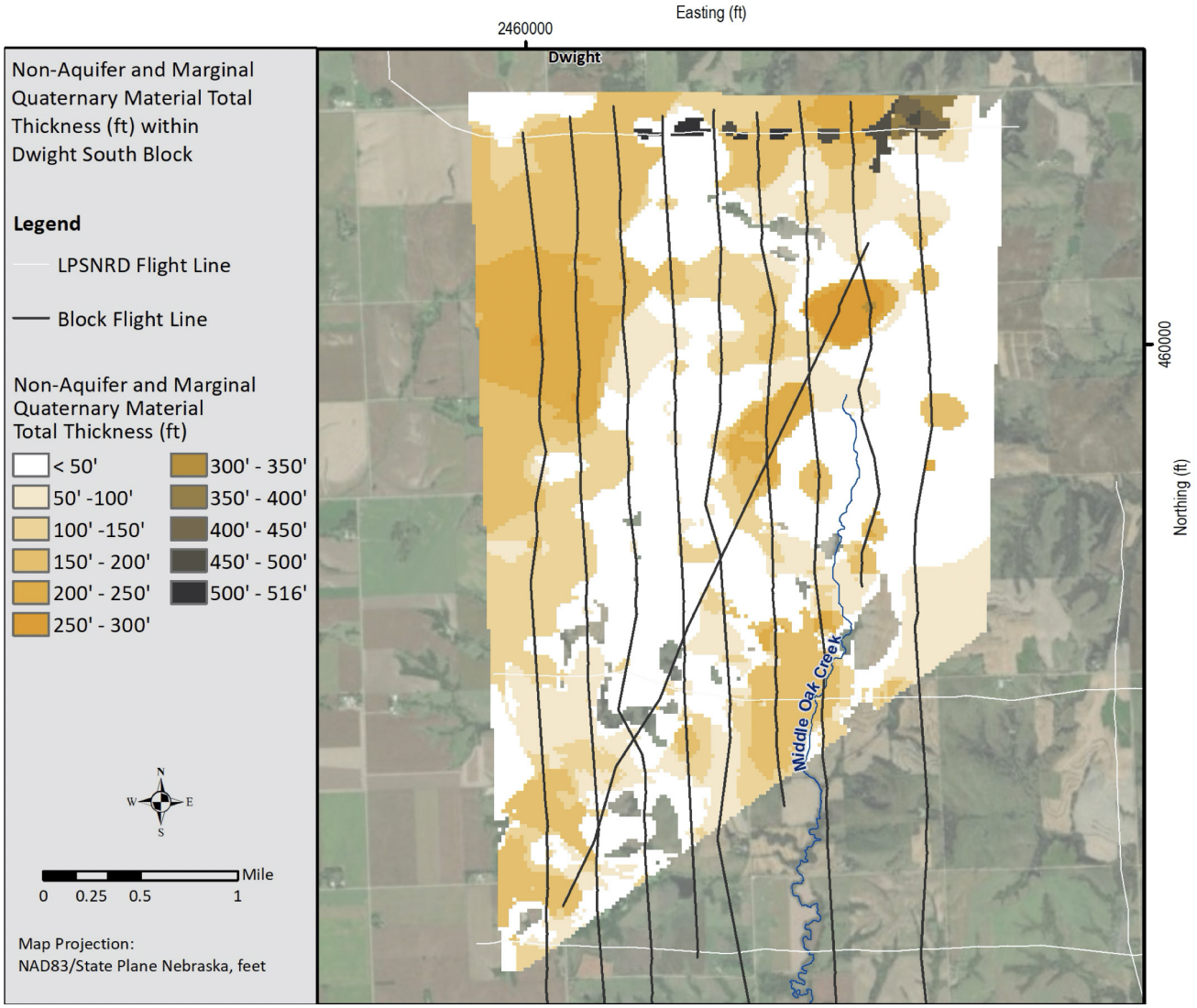


Figure 3-203. Map of Quaternary (*Q*) non-aquifer and marginal aquifer materials total thickness for the Dwight South Block. Thickest areas are in the north edge of the block. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

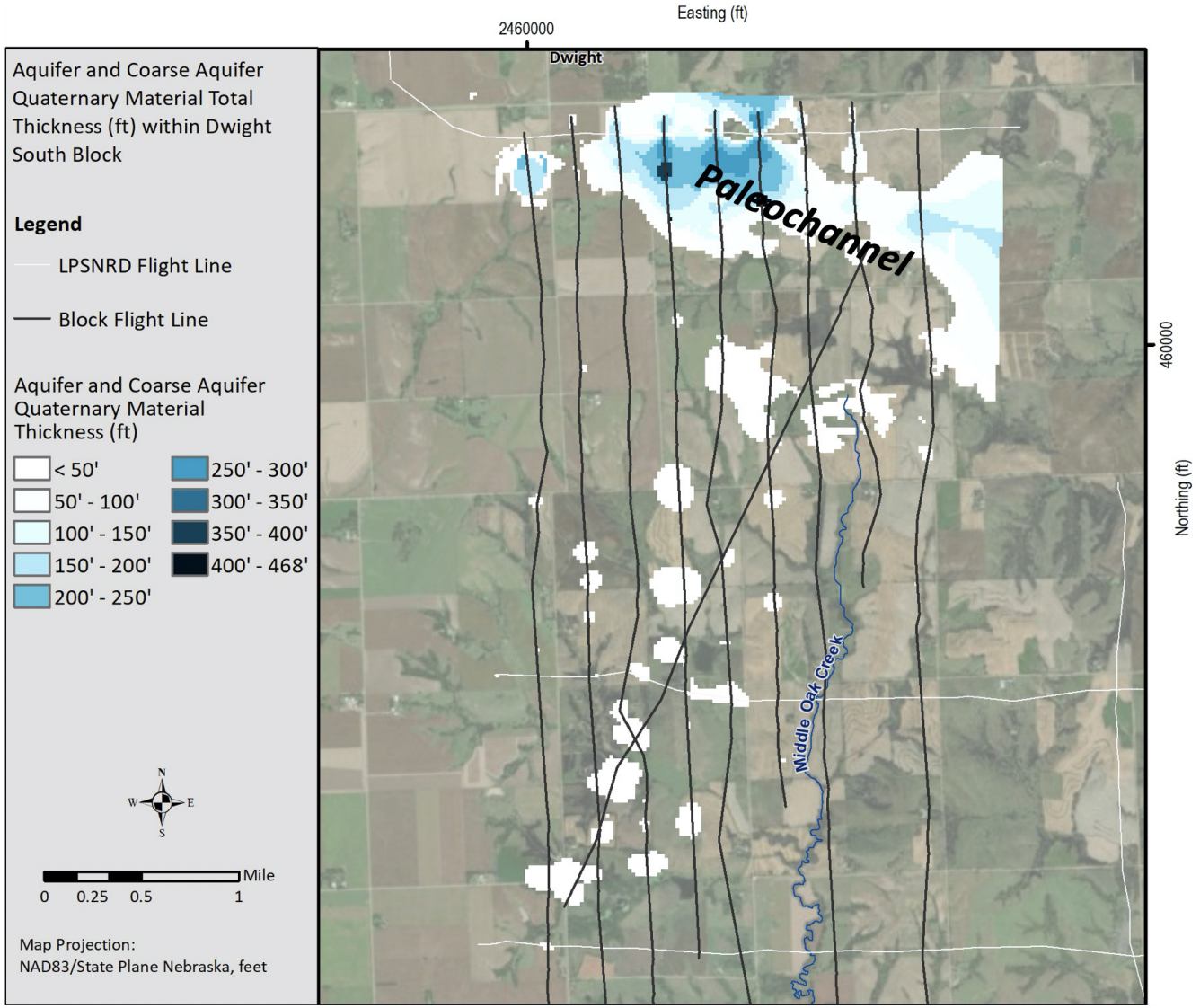


Figure 3-204. Map of total thickness of *Q* deposits of aquifer and coarse aquifer materials in the Dwight South Block. The thickest areas are near the bedrock low in the northeast part of the area in the area of the paleochannel. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

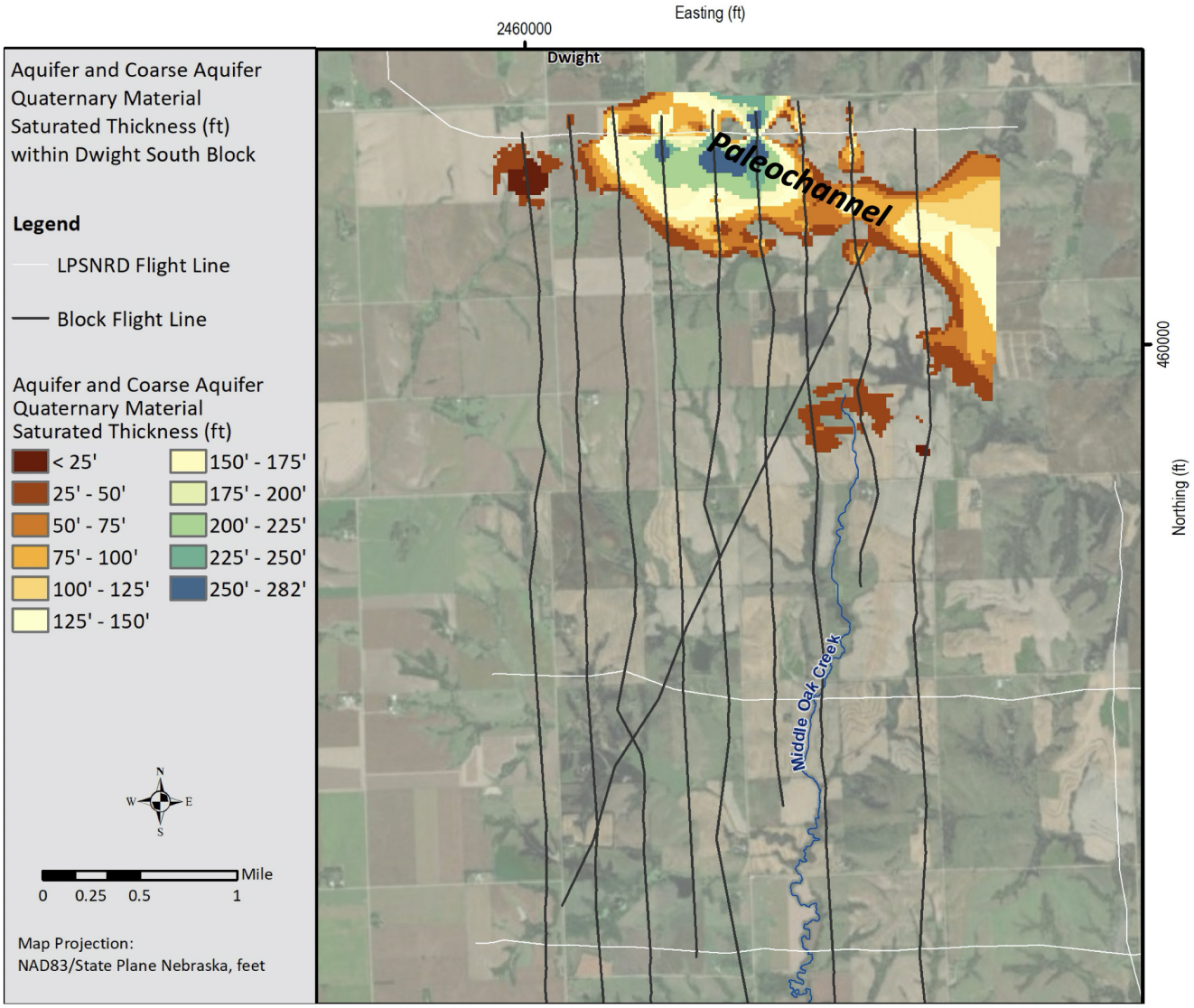


Figure 3-205. Map of total saturated thickness of *Q* deposits of aquifer and coarse aquifer materials in the Dwight South Block. The thickest amount is in the northeast corner of the area. The geologic units present on this image include *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

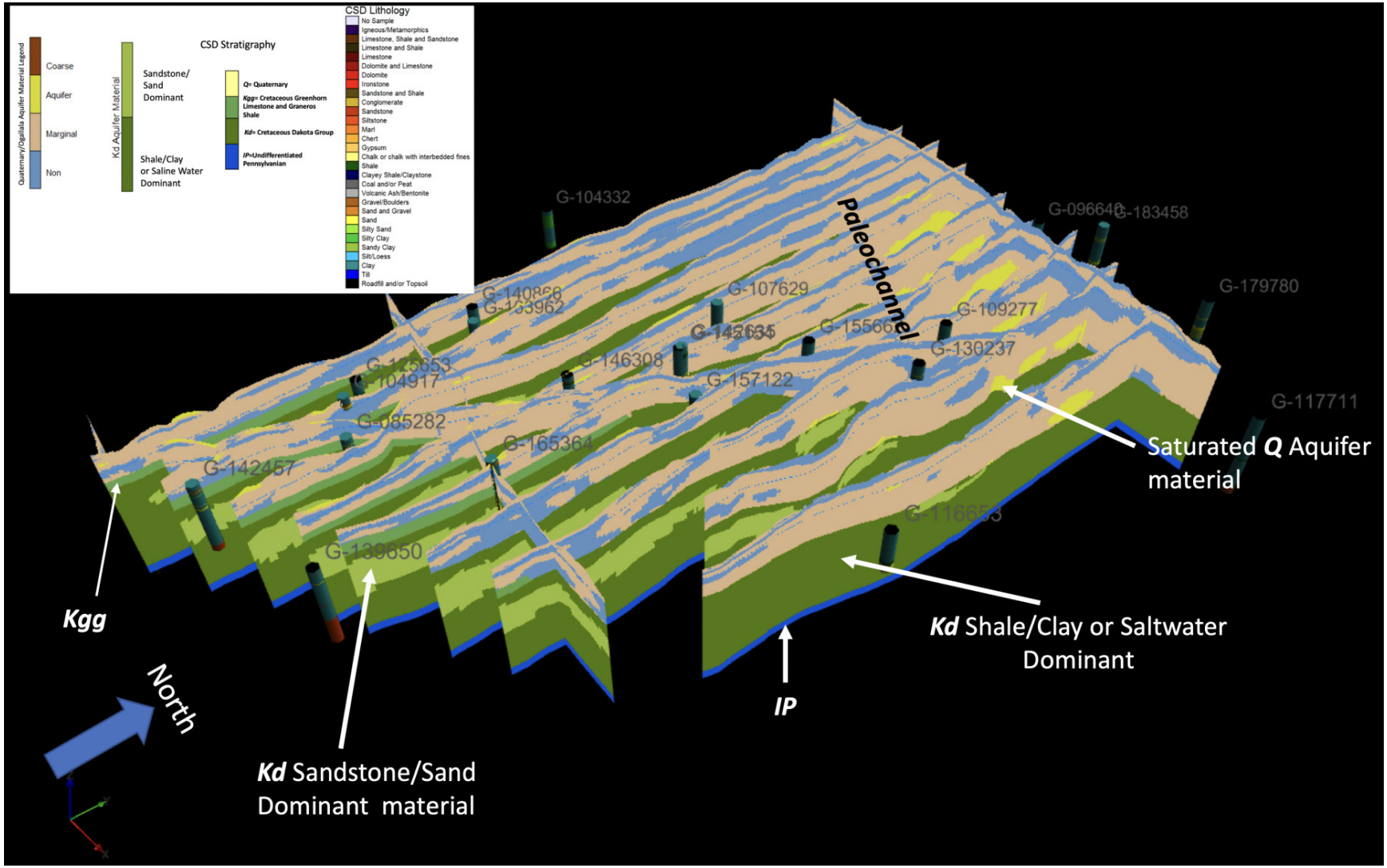


Figure 3-206. View to the northwest that shows a 3D fence diagram of *Q* aquifer materials looking northwest in the Dwight South Block. The *Kgg*, *Kd* and *IP* are also shown. The *Q* mostly made up of marginal and non-aquifer material. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 5x.

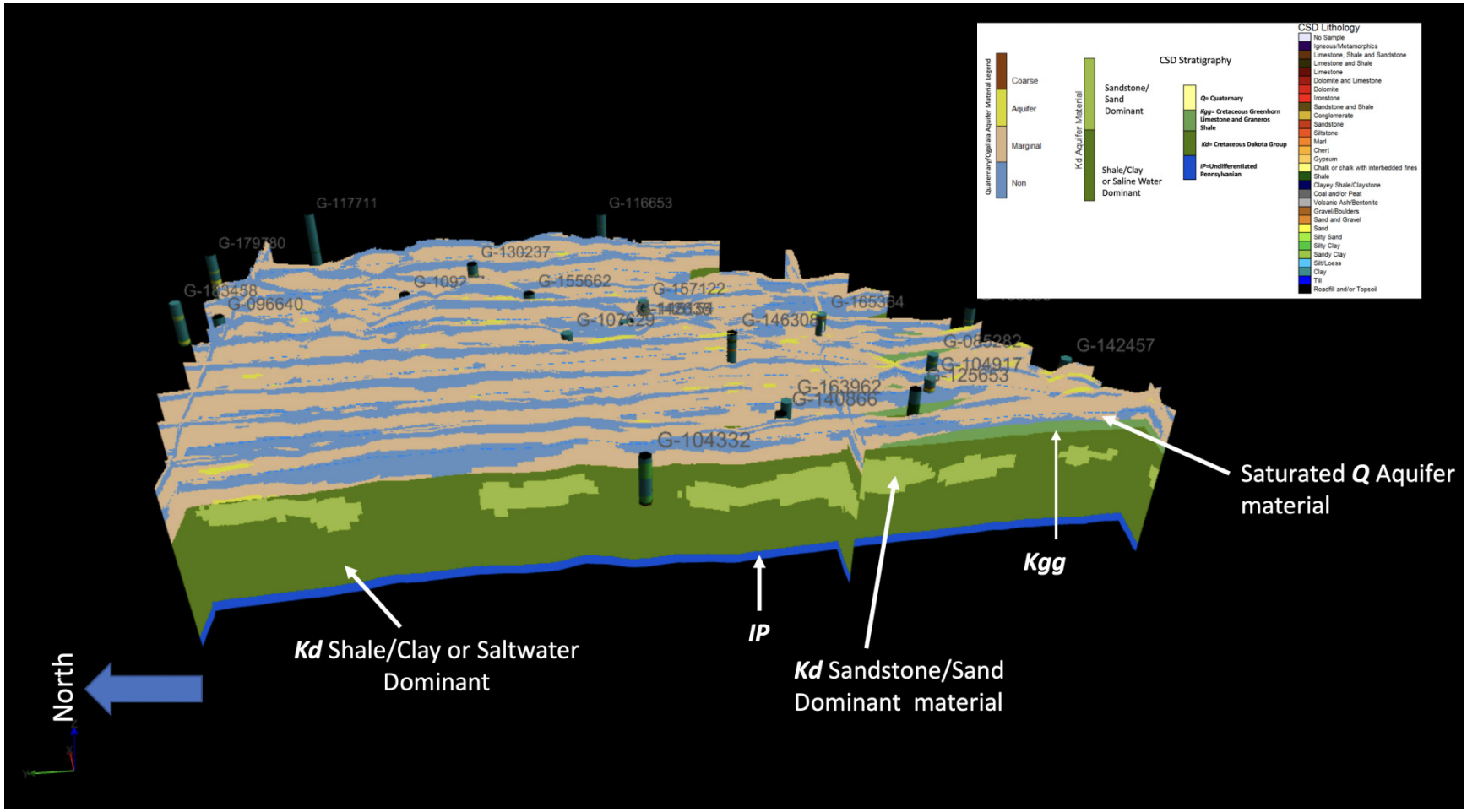


Figure 3-207. View to the east showing a 3D fence diagram of *Q* aquifer materials looking northwest in the Dwight South Block. The *Kgg*, *Kd* and *IP* are also shown. The *Q* mostly made up of marginal and non-aquifer material. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 5x.

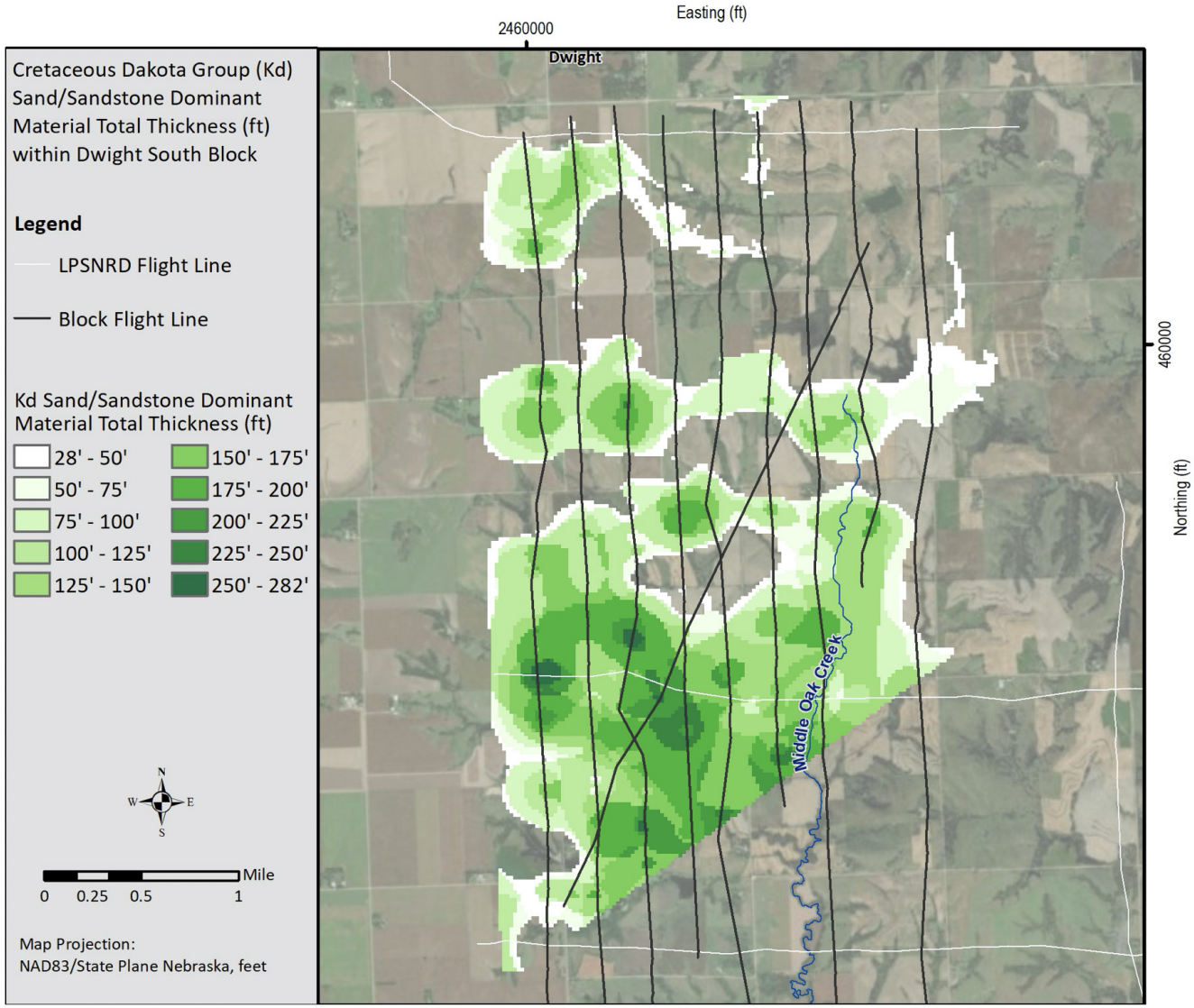


Figure 3-208. Map of the total thickness of the Sandstone/Sand Dominant portion of the *Kd* in the 2018 Dwight South Block AEM survey area. The thick areas are to the south near the bedrock high. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

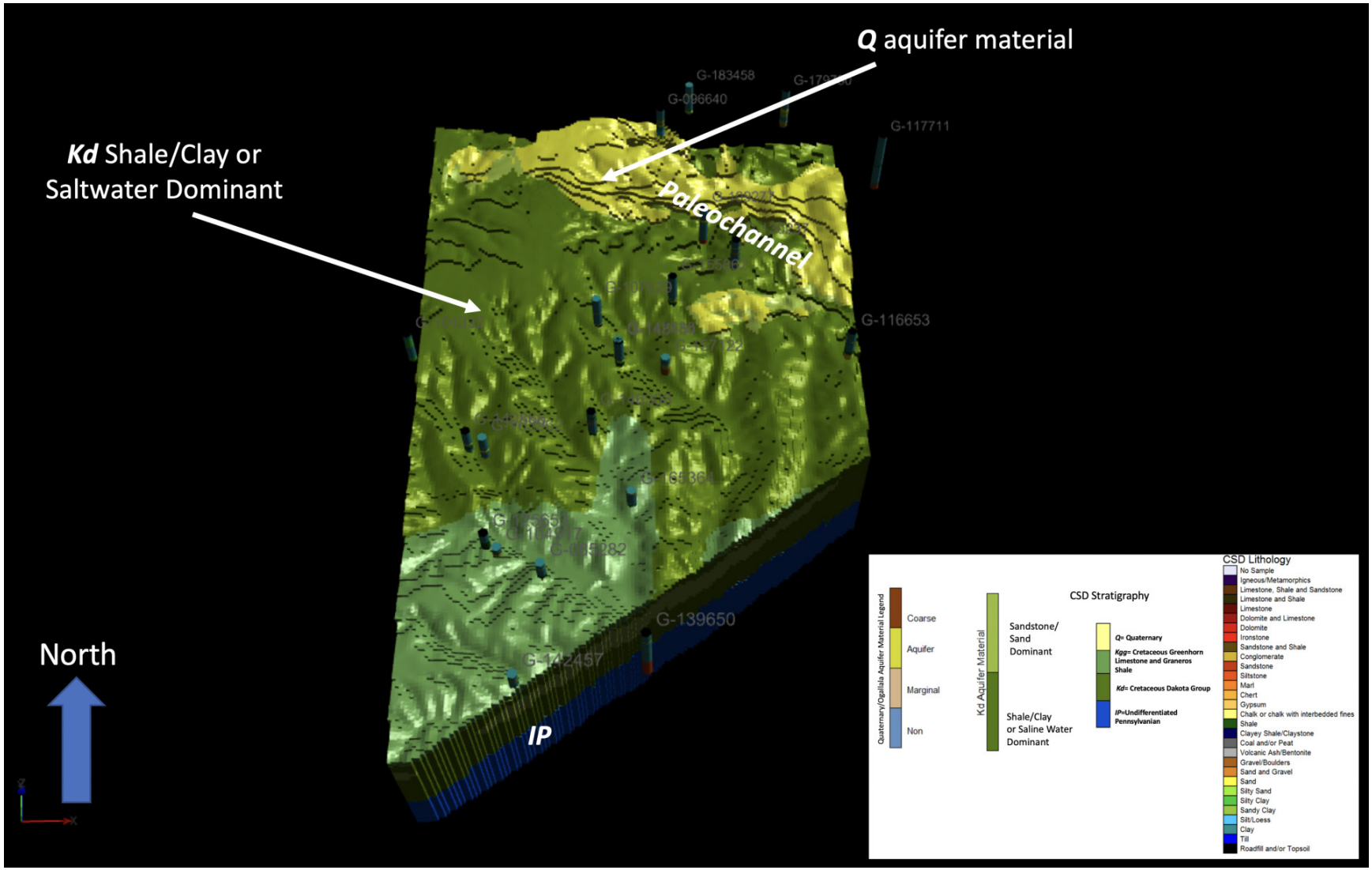


Figure 3-209. View of 3D voxel model looking north of *Q* aquifer material which is a small volume in the north lying on the *Kd* looking north. The *Kgg* and *IP* is also shown. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 5x.

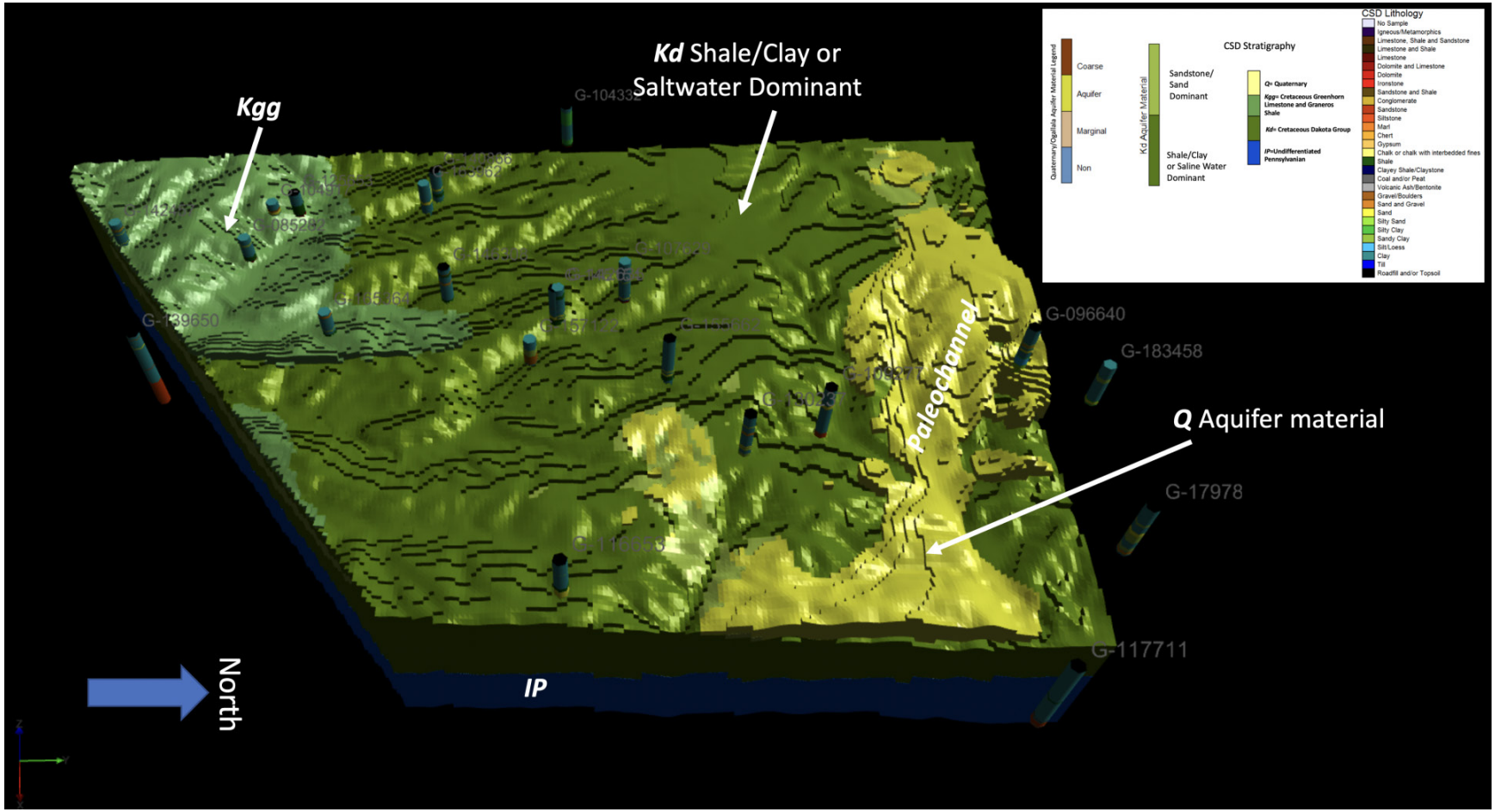


Figure 3-210. View of 3D voxel model similar the Figure 3-209 looking west. The geologic units present on this image include *Q*= Quaternary, Kgg= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 5x.

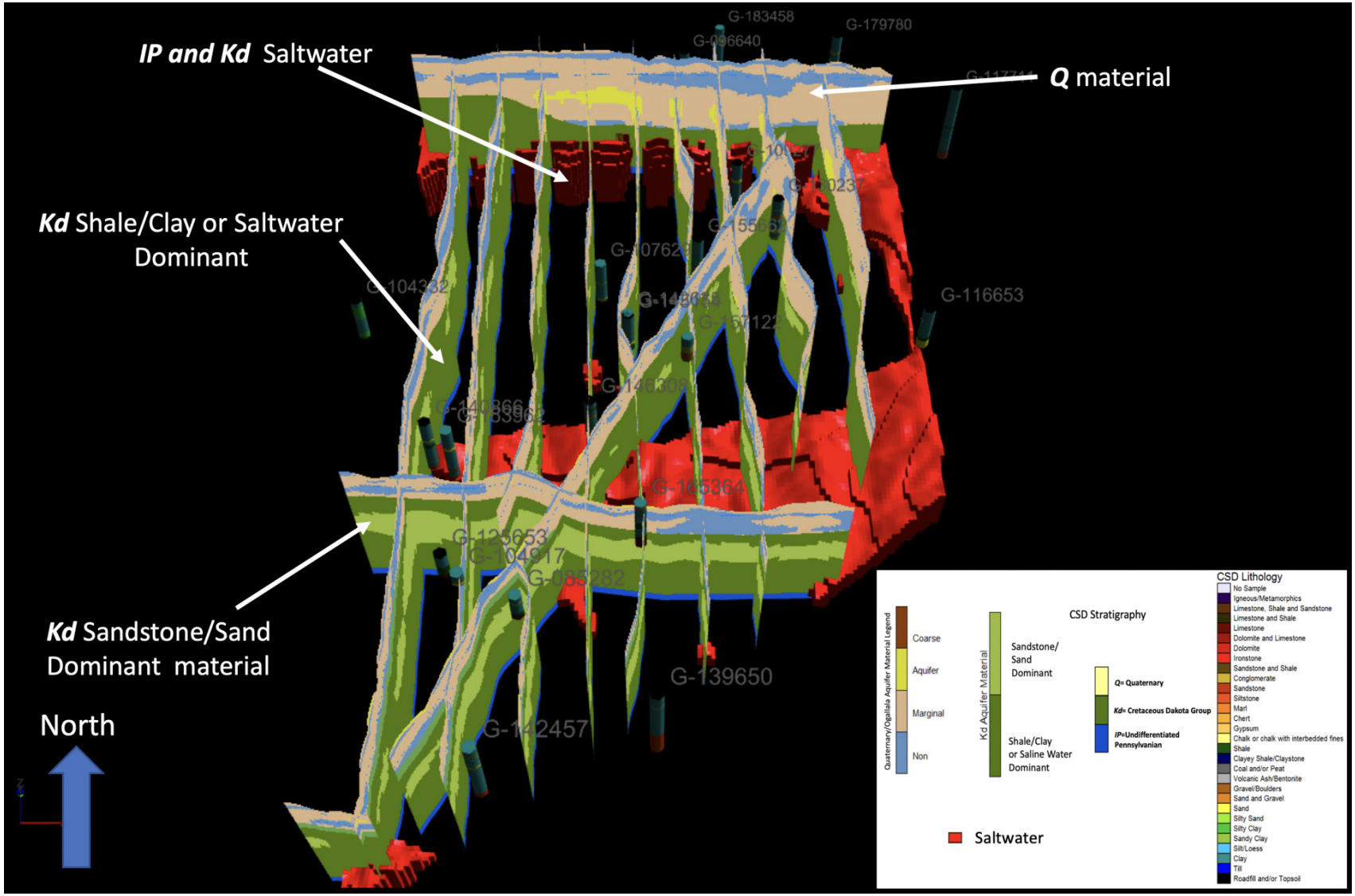


Figure 3-211. View of 3D fence diagram looking north showing the saltwater areas in the Dwight South Block colored red. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 5x.

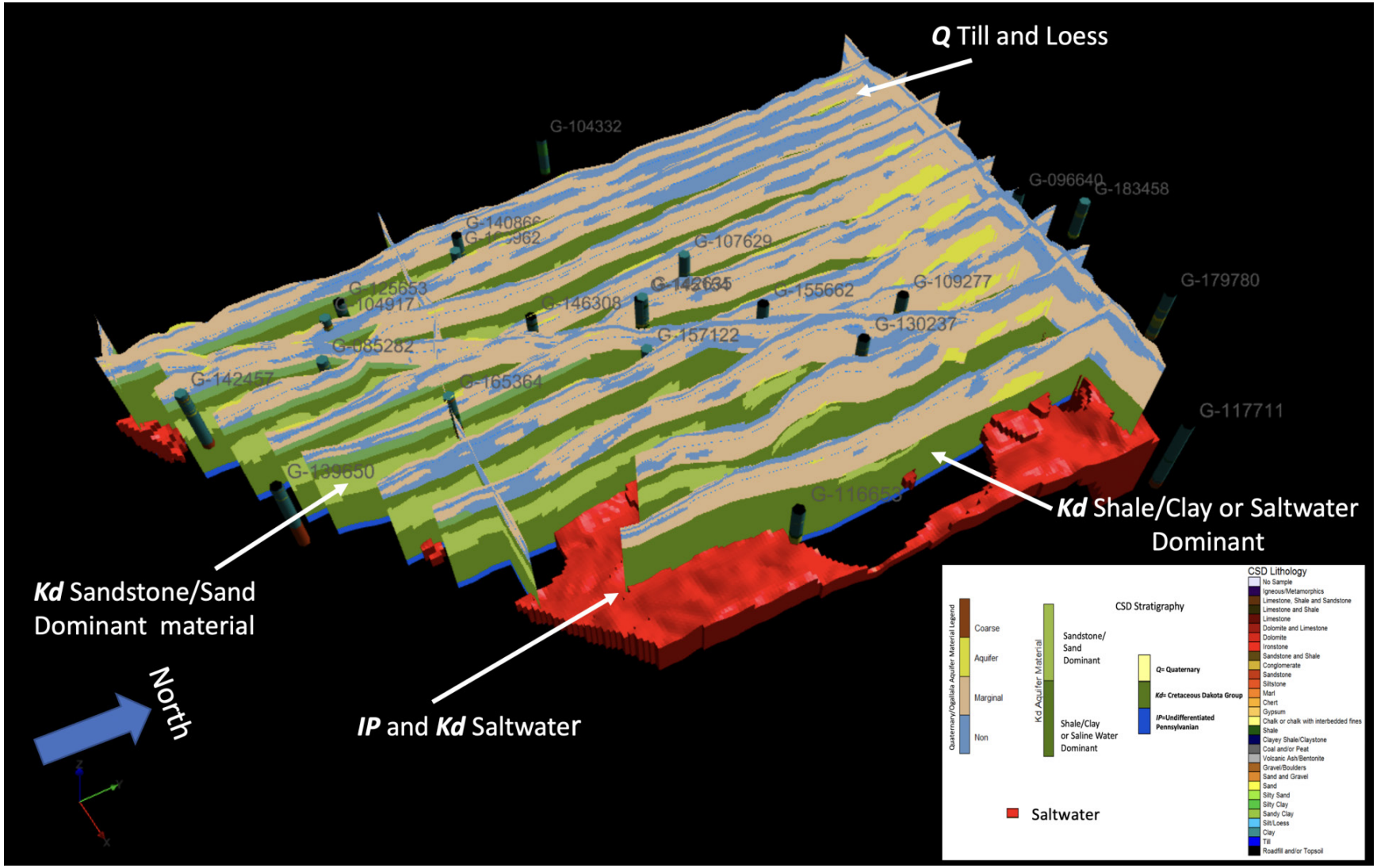


Figure 3-212. View of 3D fence diagram looking northwest showing the saltwater water areas in the Dwight South Block colored red. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 5x.

3.2.6 Hydrogeologic Framework of the Emerald Pleasant Dale Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material and the Cretaceous units in the Emerald Pleasant Dale Block AEM survey area. The ***Q*** materials within the Emerald Pleasant Dale Block are composed of unconsolidated clay, silt, sand and gravel that overlie the consolidated bedrock which is made up of ***Kd***. The ***Q*** material in the Emerald Pleasant Dale Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1. Figure 3-213 is the flight line location map including roads, streams and towns. Generally, the area lies south of intersection of 154th street and Interstate 80 near Pleasant Dale, Nebraska. The ground surface elevation map shown on Figure 3-214, shows there are rolling hills surrounding South Middle Creek which is the main surface water feature. The ground surface elevation ranges from 1,160 to 1,520 feet with highest elevation in the west. Figure 3-215 displays a 3D fence diagram with a 3D voxel model of the ***Q*** aquifer materials, ***Kd*** and ***IP*** of the Emerald Pleasant Dale Block AEM survey area, looking to the north, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** with marginal and non-aquifer materials dominating the area and small areas of aquifer material including coarse aquifer, aquifer, marginal and non-aquifer materials. The ***Q*** lies upon lying upon the ***Kd*** which lies upon the ***IP***. The ***Kd*** contains a mix of Shale/Clay or Saltwater dominant and Sandstone/Sand dominant materials.

Figure 3-216 presents 2D profile L309701 is a north-south line in the center of Emerald Pleasant Dale Block AEM survey area. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly till and loess. The ***Kd*** Sandstone/Sand materials are in minimal contact with the ***Q*** aquifer material near northing 365000 and have minimal hydrologic connection to ***Q*** aquifer material near northing 465000. The ***Kd*** is mostly Sandstone/Sand dominant in a thick continuous layer across the profile with Shale/Clay or Saltwater dominant both above and below the layer. The ***Kd*** is saturated throughout the area. The ***Kd*** is thin ~200 feet in the south and thickens to~300 feet in the north. The ***IP*** top elevation is ~1050 feet in the south and declines to ~900 feet in the north. The CSD 1995 water table is also on the profile and shows the water table for the area and has a gradual slope from south to north.The top elevation for the ***IP*** is shown on Figure 3-217 and shows the surface to gently slope from the high in the south to the low in the north. The ***IP*** has saltwater water dominant areas in the area.

The total thickness of the ***Q*** material in the Emerald Pleasant Dale Block AEM survey area Figure 3-218 was created by subtracting the bedrock elevation (Figure 3-219) from the ground surface elevation (Figure 3-214). The greatest thickness is along the ground elevation highs to the northwest and south and is independent to bedrock high and low bedrock low within the Emerald Pleasant Dale Block AEM survey area. The thin areas (~50-100 feet) of ***Q*** total thickness parallels the drainages of the area. The ***Q*** material varies in thickness from <50 to 268 feet. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to the hydrologic connection of those materials to the surface water of the area. The ***Q*** coarse aquifer and aquifer material which makes up ~50% amount of ***Q*** materials present provide some connection for water movement through all of the ***Q*** aquifer materials. The mix of all ***Q*** materials is complex from profile to profile the hydrologic connection to the streams of

the area change along their length. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995) to obtain the total saturated thickness of ***Q*** material. The saturated thickness for all aquifer material is shown for the Emerald Pleasant Dale Block on Figure 3-220. The thickness of these materials is thin and varies between 0 to 122 feet. The saturated thickness averages 0-50 feet across the area with the thickest area in the south. Figure 221 shows the relationship between the saturated thickness of ***Q*** and the specific capacity in gpm/ft for wells completed in the ***Q***. Careful evaluation of the wells in Figure 3-221 shows wells in the Emerald Pleasant Dale area have a with a specific capacity of <5 gpm/ft. The **Q** is a poor aquifer for well development.

Figure 222 Is a map of the elevation of top of ***Kd*** which is the bedrock in the area which ranges in elevation from 1,088 to 1,336 feet. There is a low area in the northeast which rises to west. The total thickness map of the ***Kd*** is shown in Figure 3-223. The thickness of the ***Kd*** varies from 102 to 486 feet with the thickest are in the northwest corner and thins in the southeast corner and thins in the south. Figure 3-224 shows the ***Kd*** saturated thickness map the thickness varies from 101 to 464 feet with the thickest area in the northwest. Figure 3-225 shows the relationship between the saturated thickness of ***Kd*** and the specific capacity in gpm/ft for wells completed in the ***Kd***. Careful evaluation of the wells in Figure 3-225 shows most wells in the Emerald Pleasant Dale area have a with a specific capacity of <5 gpm/ft with 8 wells having a specific capacity of up to 5 to 10 gpm and 1 well with a specific capacity of 10 to 25 gpm. The best locations for well development are in the thick Sandstone/Sand Dominant zones of the ***Kd***.

Figure 3-226 shows the interpreted 2D profile L307901 is an east-west line which is the second flight line from the west side of the block. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are made up entirely of till and loess marginal and non-aquifer material layer that is ~100 to ~175-foot thick and continuous across the profile lying upon the ***Kd***. The ***Q*** layer marginal and non-aquifer materials have 0 to 50 feet of saturation and have little ability to transmit water to a well or to a stream. ***Q*** aquifer material provides very small thin caps the hills near easting 2476000 and 2482000. It can be very thin~10 to ~25 feet at the land surface but above the water table. The ***Kd*** is mostly sandstone/sand dominant in a thick continuous layer ~200 feet thick across the profile with shale/clay or saltwater water dominant both above and below the layer. The ***Kd*** is saturated throughout the area. The CSD 1995 (NE-CSD, 1995) water table is also on the profile and shows the water table for the area and it is mostly flat.

Figure 3-227 shows the interpreted 2D profile L307701 which is an east-west profile is ~1/2 mile north of Pleasant Dale, Nebraska in the Emerald Pleasant Dale Block AEM survey area. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly thin till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material. These ***Q*** materials have ~10 to ~50 feet of saturation with a high-water table elevation that slopes from west to east. There is a shallow channel in the surface of the ***Kd*** top elevation from easting 2490000 to 2510000. The creeks have minimal hydrologic connection to the ***Q*** materials due to the abundance of marginal and non-aquifer materials present. Saltwater is present in much of the lower part of the ***Kd***.

An exploded view of the 3D voxel model showing the ***Q***, both saturated and unsaturated, the ***Kd***, saturated and the ***IP*** formations is presented in Figure 3-228. The ***Q*** materials show mostly marginal aquifer and non-aquifer materials mixed with minor amounts of aquifer and coarse aquifer materials. The ***Q*** aquifer materials are mostly unsaturated. The ***Kd*** is saturated and present in the entire area and, in some places, it nears the water table. Because of the amount of ***Q*** marginal and non- aquifer materials and their distribution across the Emerald Pleasant Dale area there is no ability for managed aquifer recharge (MAR) sites to be located within the block. Figure 3-229 shows the distribution of ***Q*** marginal and non-aquifer materials thickness which is thick in 3 areas across the block the southwest, northwest and south. These materials range in thickness from <25 to 196 feet. Figure 3-230 shows the distribution of ***Q*** marginal and non-aquifer materials saturated thickness which is thick in 4 areas across the block the southwest, northwest, east and south. These materials range in thickness from <25 to 93 feet. Figure 3-231 which shows the thickness of the ***Q*** aquifer and coarse aquifer materials with the thick deposits spread across the central to east area. These materials range in thickness from <25 to 233 feet. Figure 3-232 shows the ***Q*** saturated aquifer and coarse aquifer materials are thin and range in thickness from <25 to 80 feet and show that the ***Q*** has minimal additional groundwater storage that can yield to wells or be used as MAR locations.

Figure 3-233 shows a 3D fence diagram of the ***Q*** marginal and non-aquifer material with a 3D voxel model of the ***Q*** aquifer and coarse aquifer materials lying upon the ***Kd*** and ***IP*** of the Emerald Pleasant Dale Block AEM survey area, looking to the west, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** with marginal and non-aquifer materials and areas of aquifer material including coarse aquifer and aquifer materials. The ***Kd*** contains a mix of Shale/Clay or Saltwater dominant and Sandstone/Sand dominant materials. There is a saltwater zone in the ***Kd***. Figure 3-234 presents a map of the thickness for ***Kd*** Sandstone/Sand Dominant deposits which is present across nearly the whole area. These deposits are saturated and vary in thickness from 5 to 311 feet and are discontinuous across the block. The ***Kd*** Sandstone/Sand dominant material is an aquifer in this area with the thickest portion in the west. Figure 3-235 presents a 3D voxel model view to the north showing the saturated thickness for ***Kd*** Sandstone/Sand dominant material and Shale/Clay or Saltwater dominant with a fence diagram of all ***Q*** materials. The ***Kd*** Sandstone/Sand dominant material covers nearly all of the survey area. Figure 3-236 is a 3D voxel model looking north showing the thickness for ***Q*** non-aquifer material, with a fence diagram of unsaturated ***Q*** materials ***Kd*** and ***IP***. This shows the extensive near continuous coverage of the non-aquifer material. This limits any recharge coming from the surface downward.

During the analysis of the AEM data it was apparent that there was saltwater present in some areas in LPSNRD project area. There is a presence of saltwater in the Emerald Pleasant Dale Block AEM survey area. Figure 3-237 is a 3D voxel model looking north that shows these saltwater areas to be nearly continuous across the area and affect the ***IP*** and ***Kd***. There are no water quality samples from wells in the area and this determination of saltwater is based on the comparison of resistivity from the AEM versus the lithology from the wells. Figure 3-238 presents a map of the thickness of saltwater affected areas which is present across most of the of the Emerald Pleasant Dale Block AEM survey area based on the voxel. model. These deposits vary in thickness from 36 to 549 feet and affect the ***Kd*** and ***IP***.

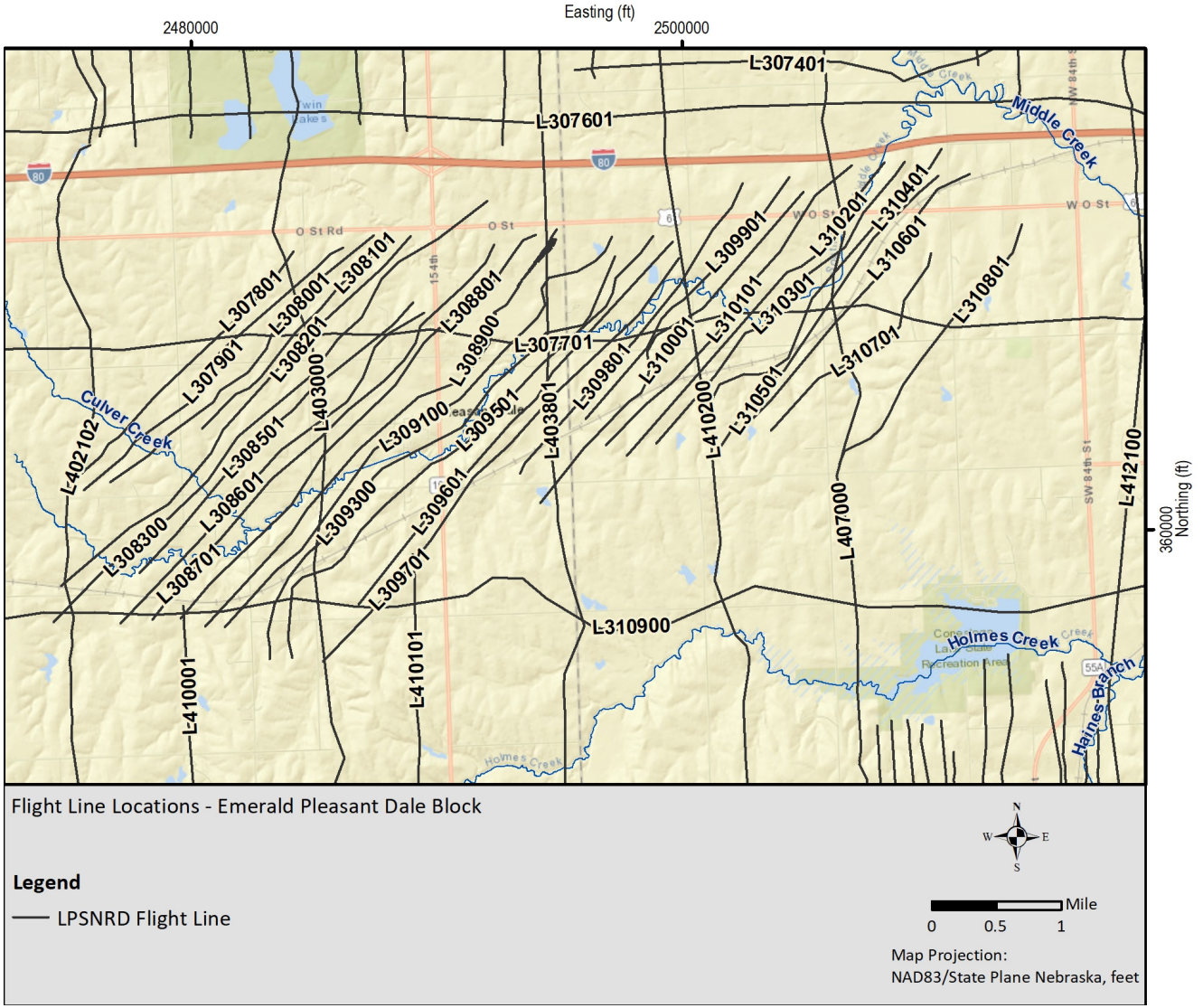


Figure 3-213. Location map of the Emerald Pleasant Dale Block AEM survey area showing numbered AEM flight lines, local roads, and streams. Generally, the area lies south of intersection of 154th street and Interstate 80 near Pleasant Dale, Nebraska. Block flight lines are indicated by black lines. The Horizontal datum is NAD83 State Plane Nebraska (feet).

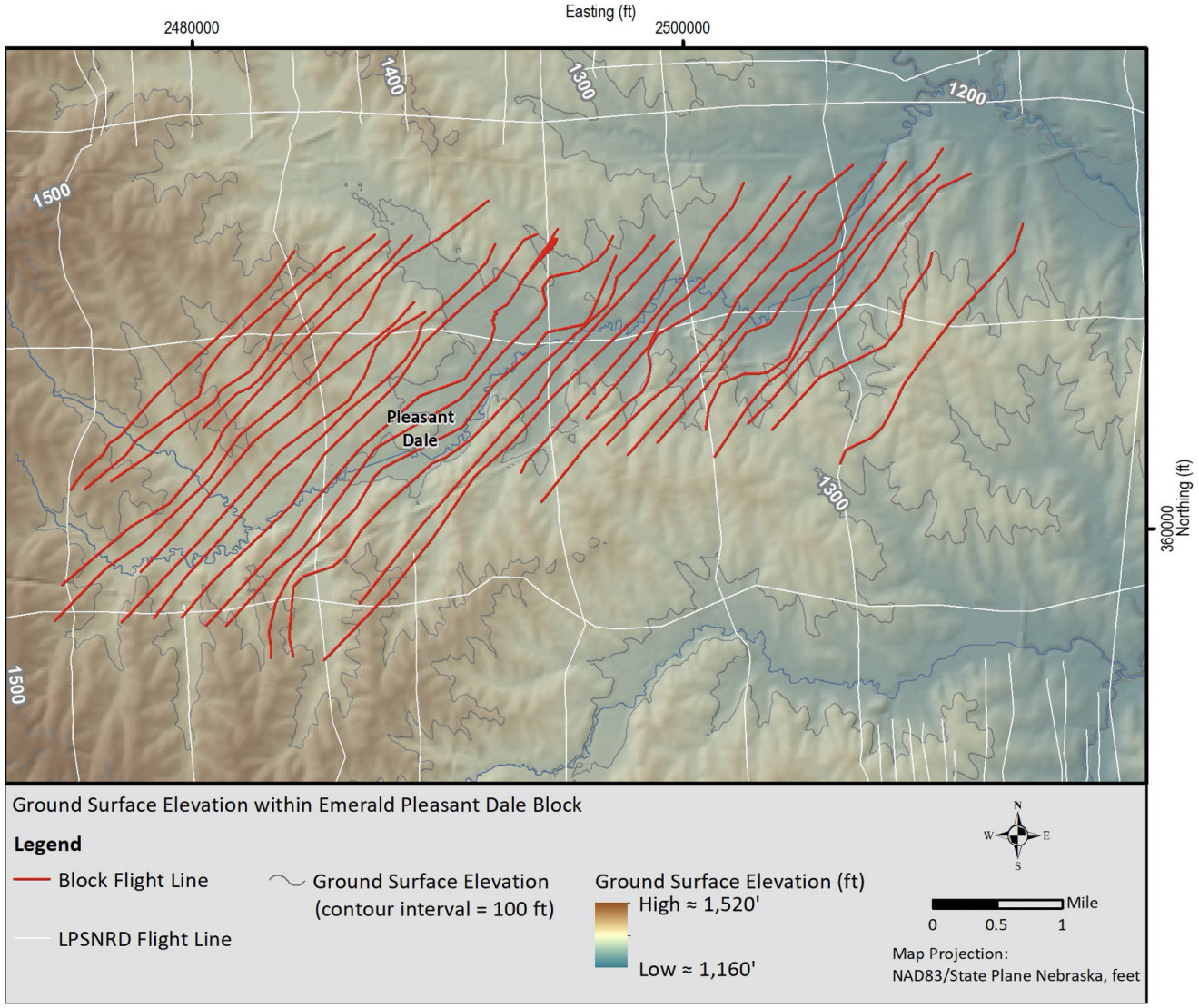


Figure 3-214. Map shows the ground surface elevation map over the Emerald Pleasant Dale Block. There are rolling hills surrounding South Middle Creek which is the main surface water feature. The ground surface elevation ranges from 1,160 to 1,520 feet with highest elevation in the west. Block AEM flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

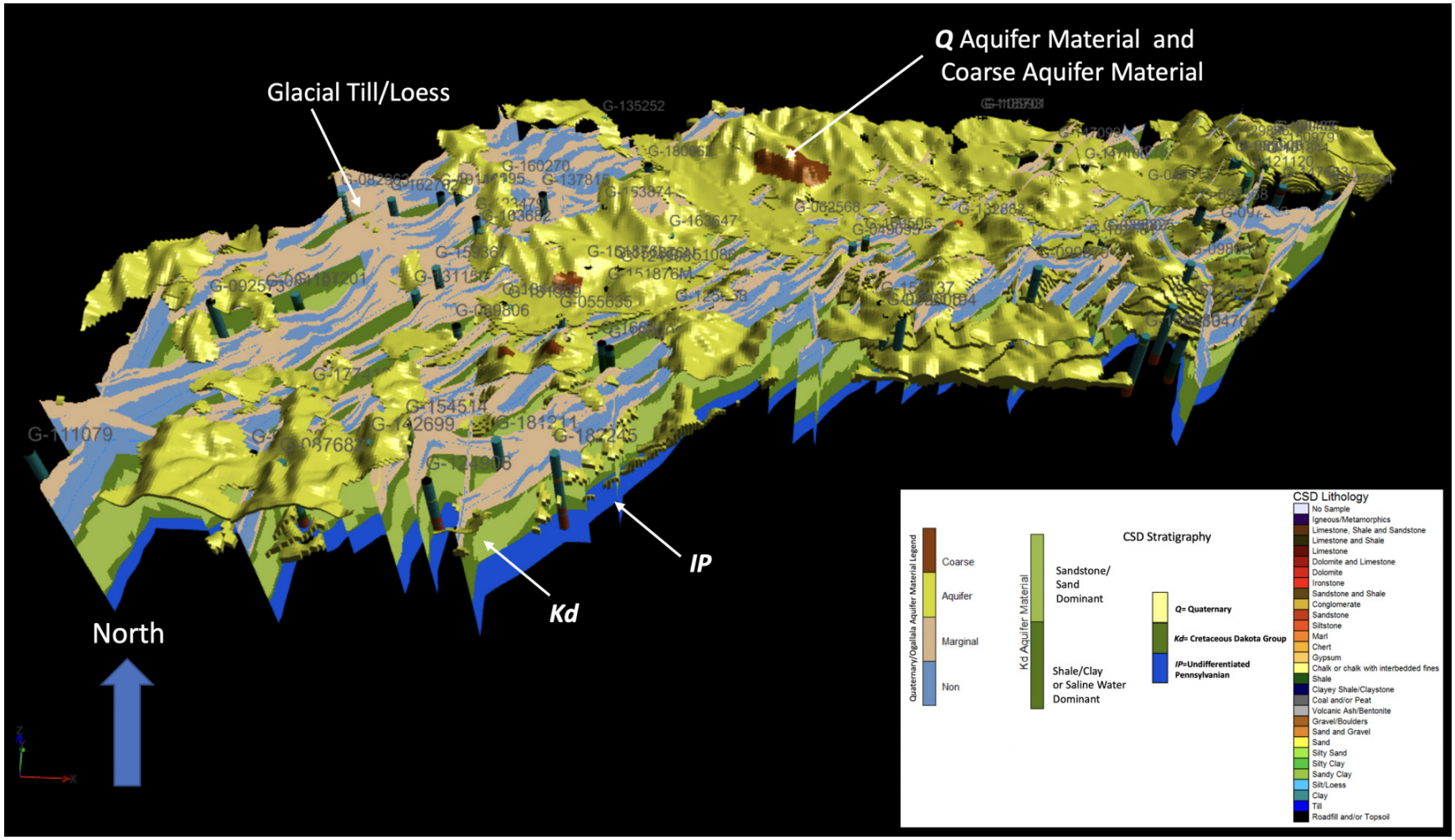


Figure 3-215. 3D Fence Diagram with a 3D voxel model of the *Q* aquifer materials, *Kd* and *IP* of the Emerald Pleasant Dale Block AEM survey area, looking to the north, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all *Q* with marginal and non-aquifer materials dominating the area and small areas of aquifer material including coarse aquifer, aquifer, marginal and non-aquifer materials. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

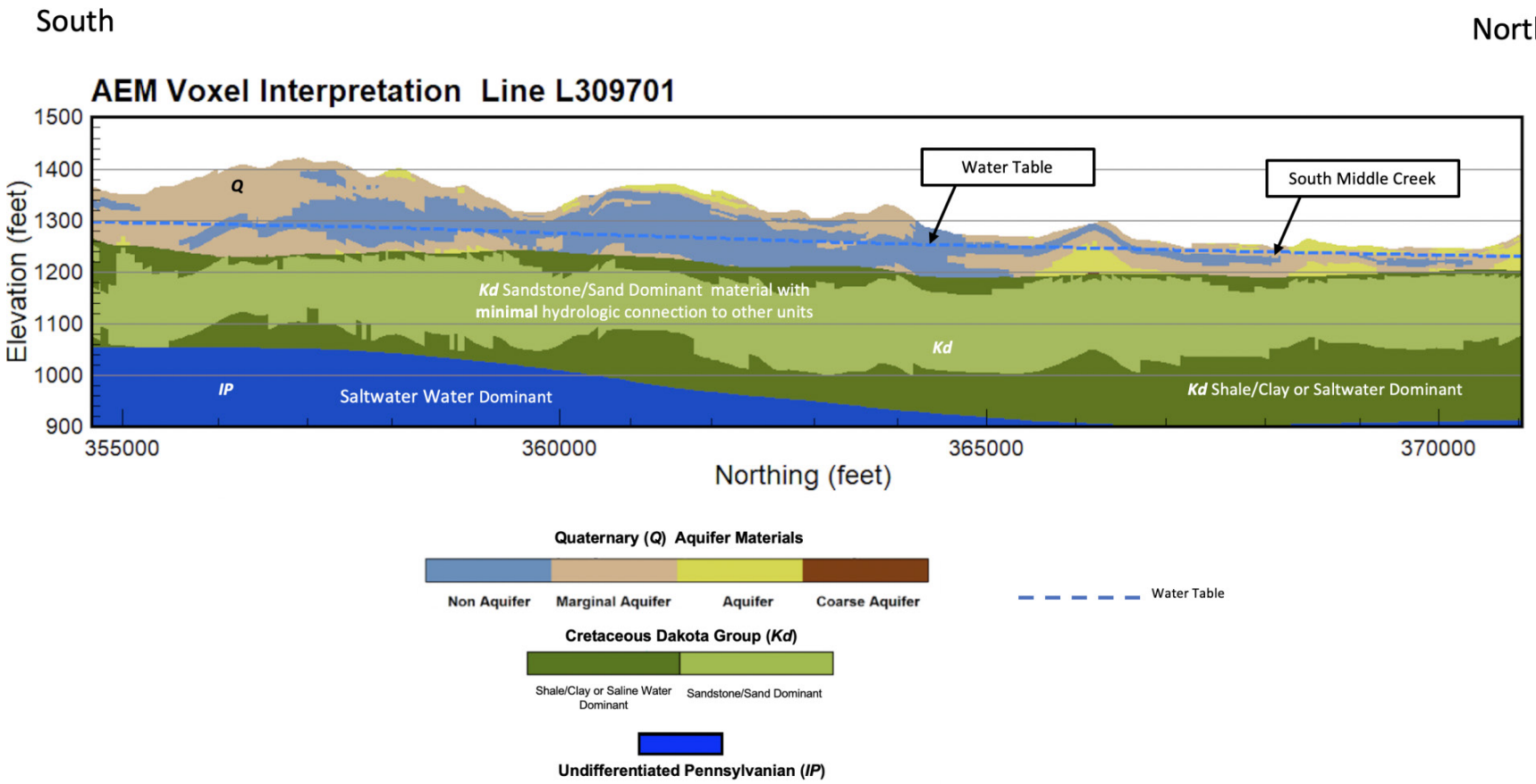


Figure 3-216. 2D profile L309701 is a north-south line in the center of Emerald Pleasant Dale Block AEM survey area. The figure shows the subsurface of the area along the line and the Q materials that are present along the line. They are mostly till and loess. The *Kd* Sandstone/Sand materials are in minimal contact with the Q aquifer material near northing 365000 and have minimal hydrologic connection to Q aquifer material near northing 465000. The CSD 1995 water table is indicated as a dashed blue line on the profiles. Horizontal datum is NAD83 State Plane Nebraska (feet). The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

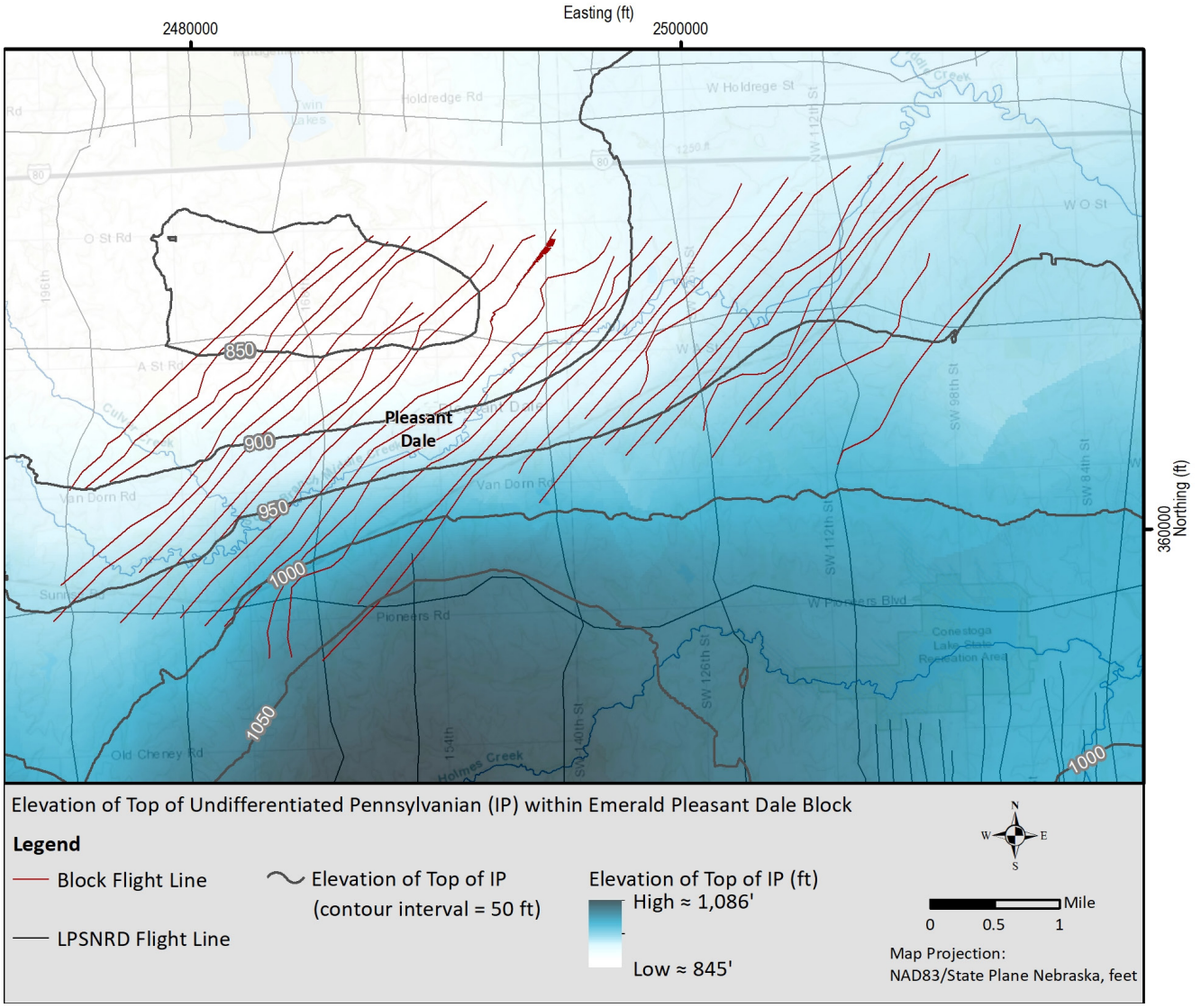


Figure 3-217. Map shows top elevation for the *IP* is shown on and shows the surface to be a gently sloping surface from the high in the south to the low in the north. The *IP* has saltwater water dominant areas in the area. Block flight lines are indicated by red lines. The geologic units present on this image include *IP*= Undifferentiated Pennsylvanian Horizontal datum is NAD83 State Plane Nebraska (feet).

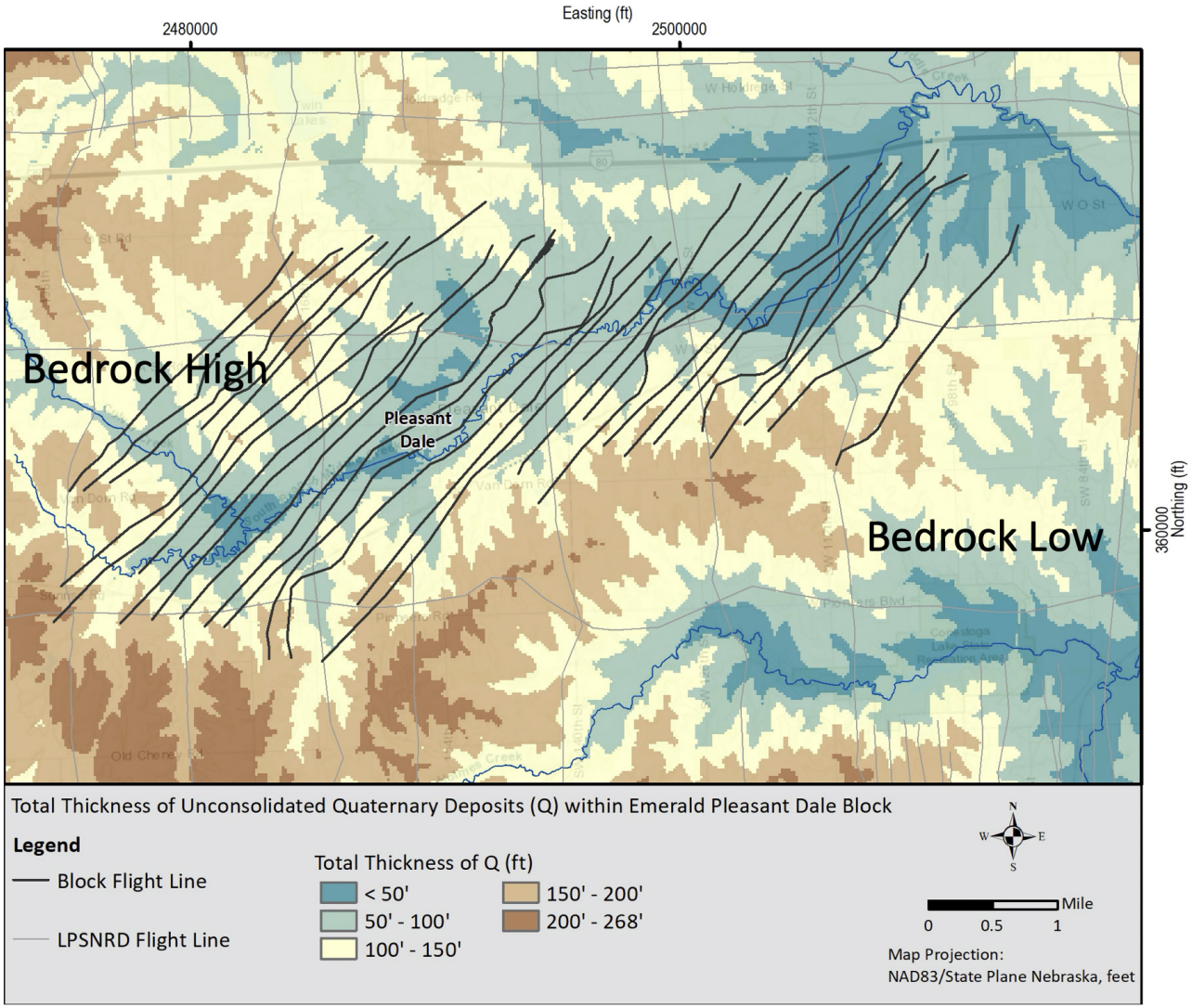


Figure 3-218. Map of the total thickness of the Quaternary (*Q*) deposits within the 2018 Emerald Pleasant Dale Block AEM survey area. The greatest thickness is along the ground elevation highs to the northwest and south and is independent to bedrock high and low bedrock low within the Emerald Pleasant Dale Block AEM survey area. Block flight lines are indicated by black lines. The geologic unit present on this image includes the *Q*= Quaternary. Block flight lines are indicated by black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

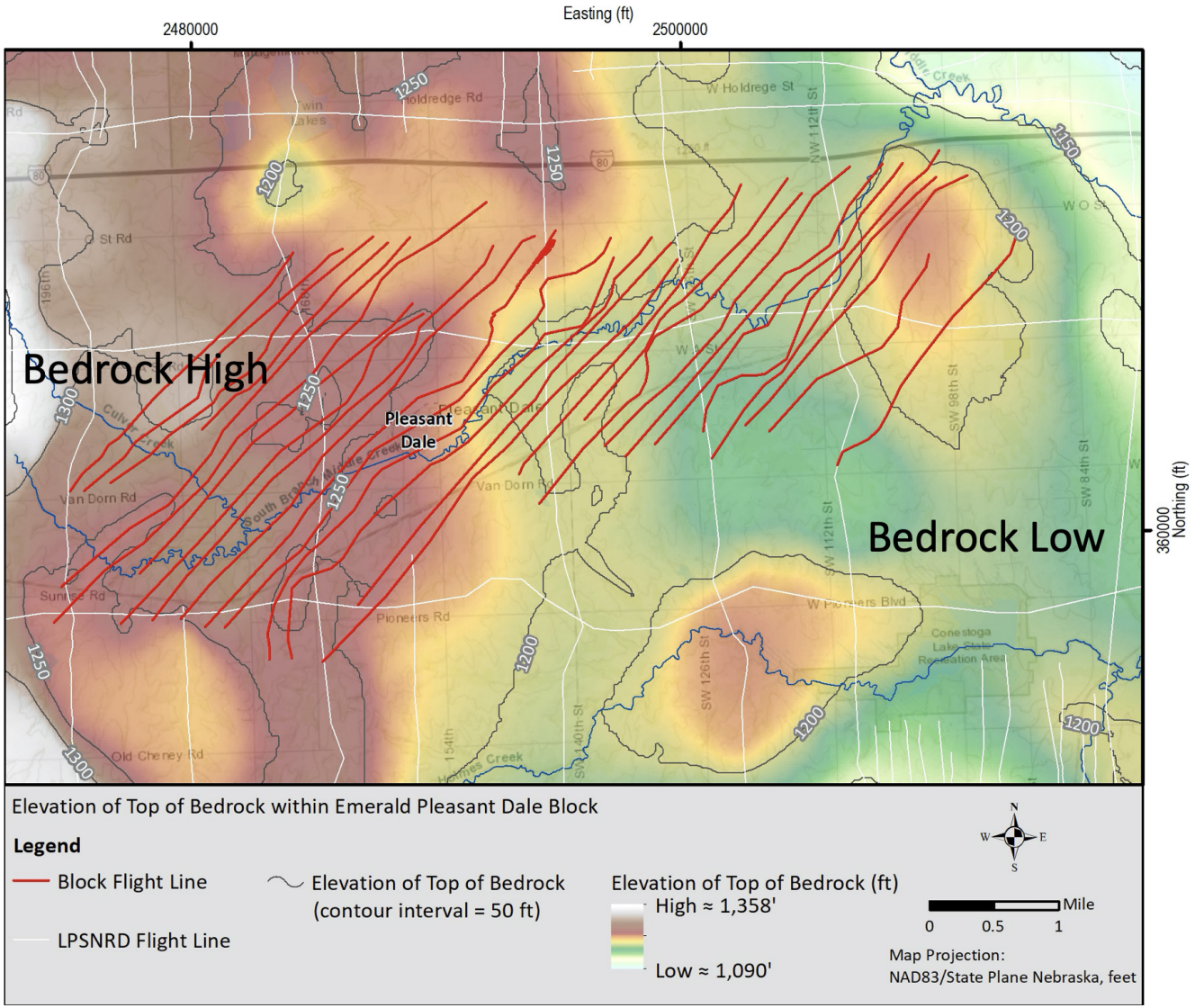


Figure 3-219. Map of the elevation of the top of bedrock within the 2018 Emerald Pleasant Dale Block AEM survey area. The bedrock surface slopes in general from a bedrock high to west to a bedrock low in the east. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

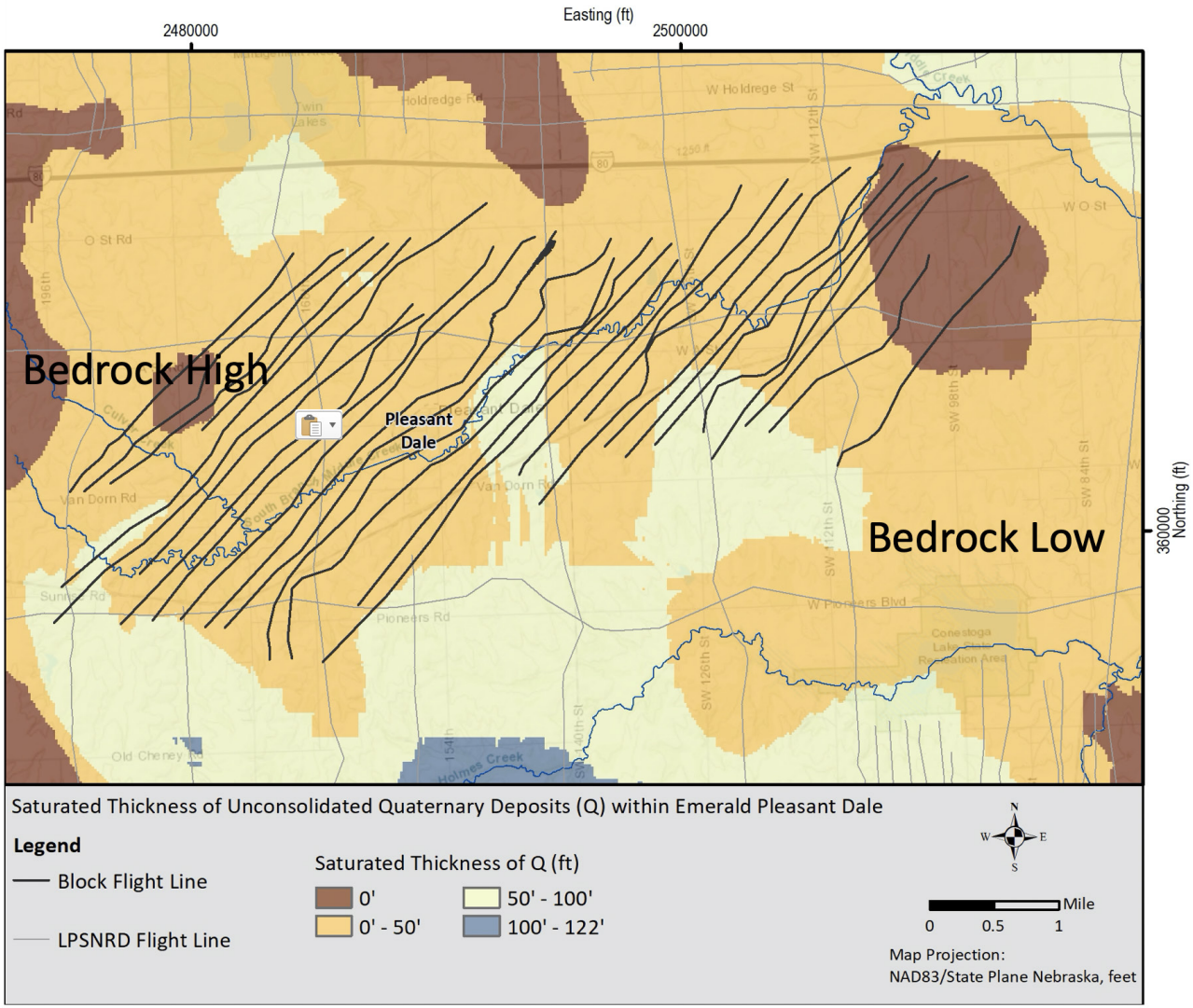


Figure 3-220. Map of saturated thickness of the *Q* within the 2018 Emerald Pleasant Dale Block AEM survey area. The thickness of these materials is thin and varies between 0 to 122 feet. The saturated thickness averages 0-50 feet across the area with the thickest area in the south. Block flight lines are indicated by black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

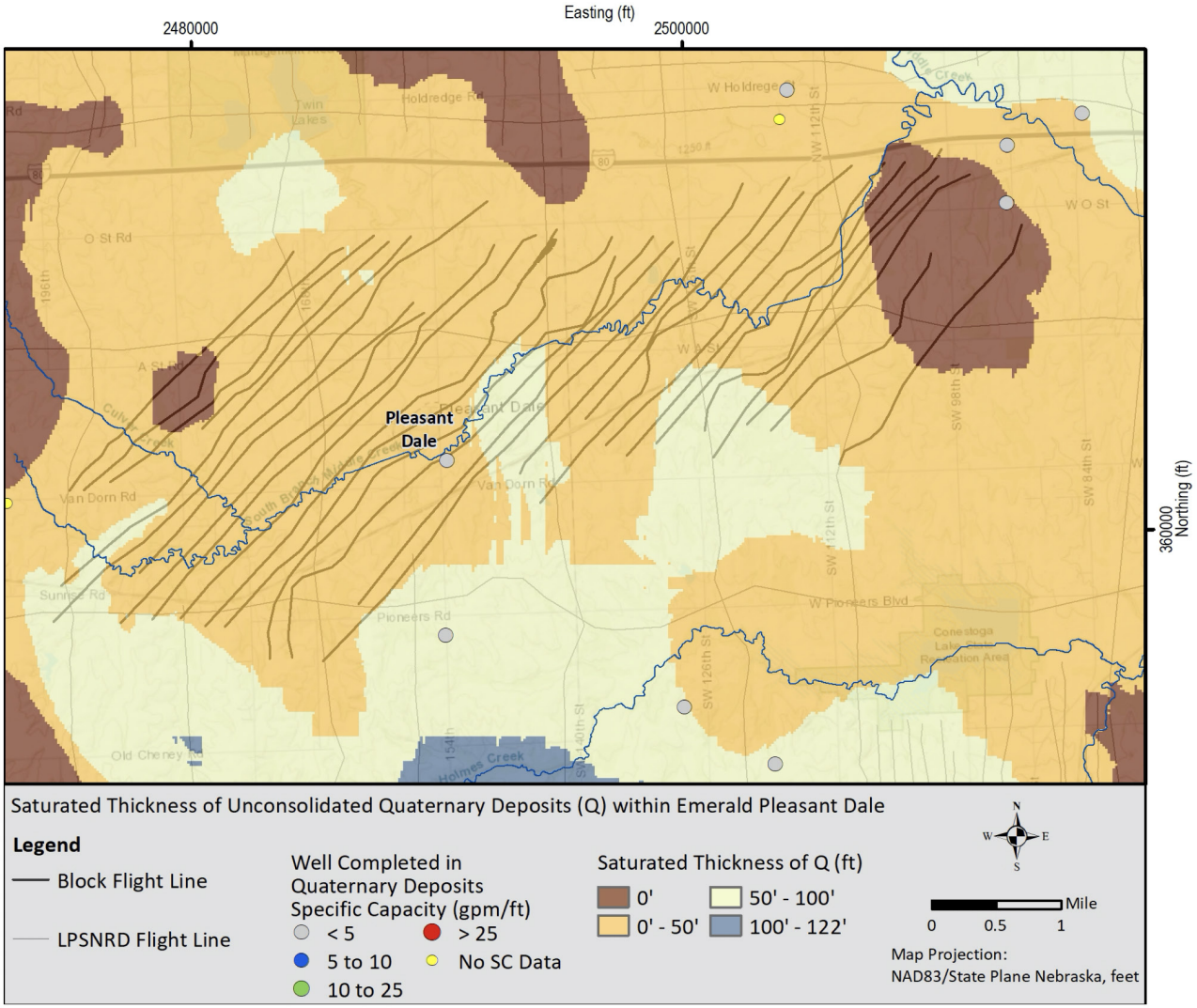


Figure 3-221. Map shows the relationship between the saturated thickness of *Q* and the specific capacity in gpm/ft for wells completed in the *Q* in the Emerald Pleasant Dale Block. Careful evaluation of the wells shows wells in the Emerald Pleasant Dale area have a with a specific capacity of <5 gpm/ft. The *Q* is a poor aquifer for well development. Block flight lines are indicated by grey lines. Geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

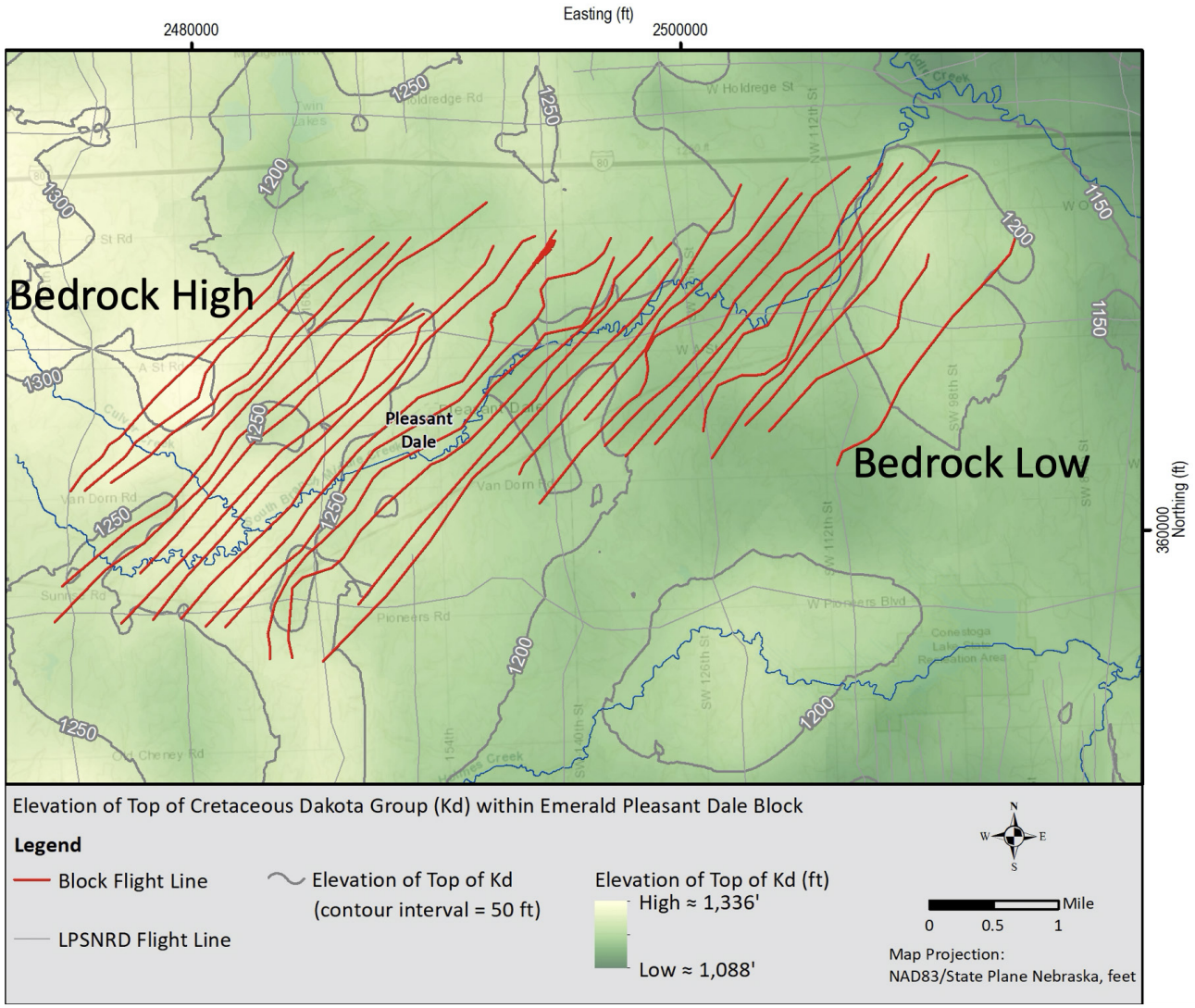


Figure 3-222. Map of the elevation of top of *Kd* in the Emerald Pleasant Dale Block which ranges in elevation from 1,088 to 1,336 feet. There is a low area in the northeast rises to west. AEM Block flight lines are indicated by the red lines. Block flight lines are indicated by red lines. The geologic unit present on this image includes the Kd= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

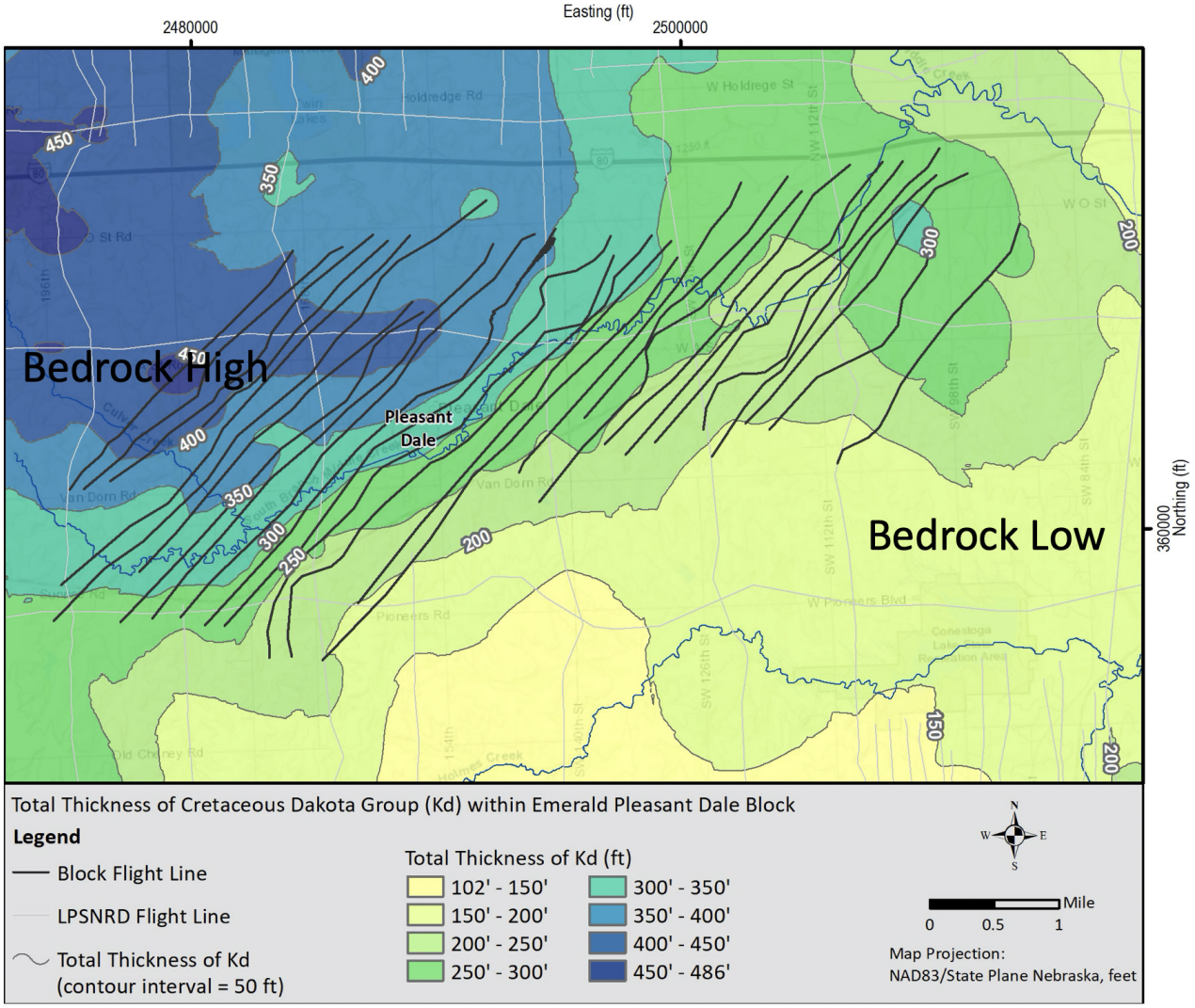


Figure 3-223. Map of the total thickness of the Cretaceous Dakota Group (*Kd*) within the 2018 Emerald Pleasant Dale Block AEM survey area. The thickness of the *Kd* varies from 102 to 486 feet with the thickest are in the northwest corner and thins in the southeast. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

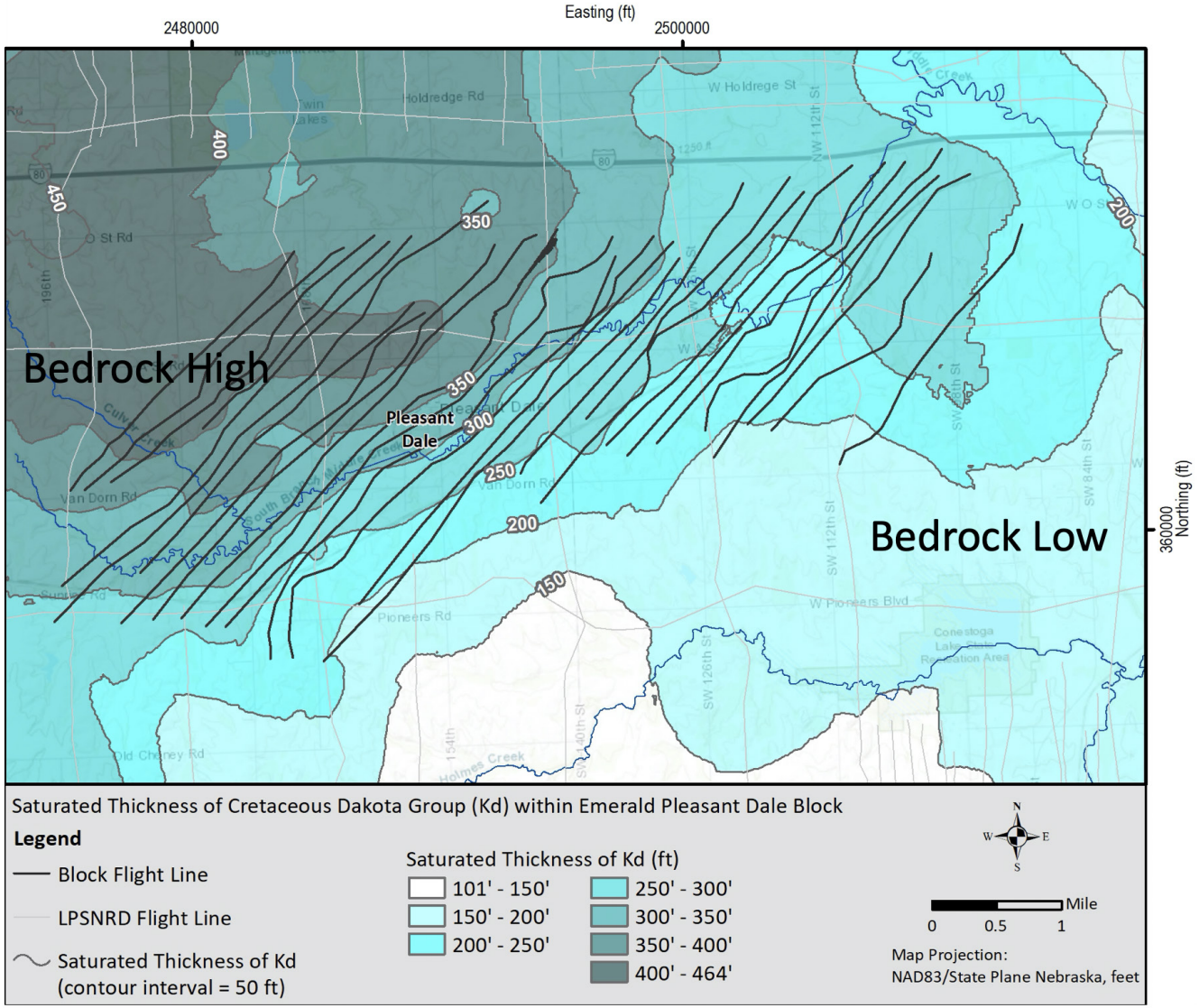


Figure 3-224. Map of the saturated thickness of the *Kd* within the 2018 Emerald Pleasant Dale Block AEM survey area. The map shows the thickness varies from 101 to 464 feet with the thickest area in the northwest Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

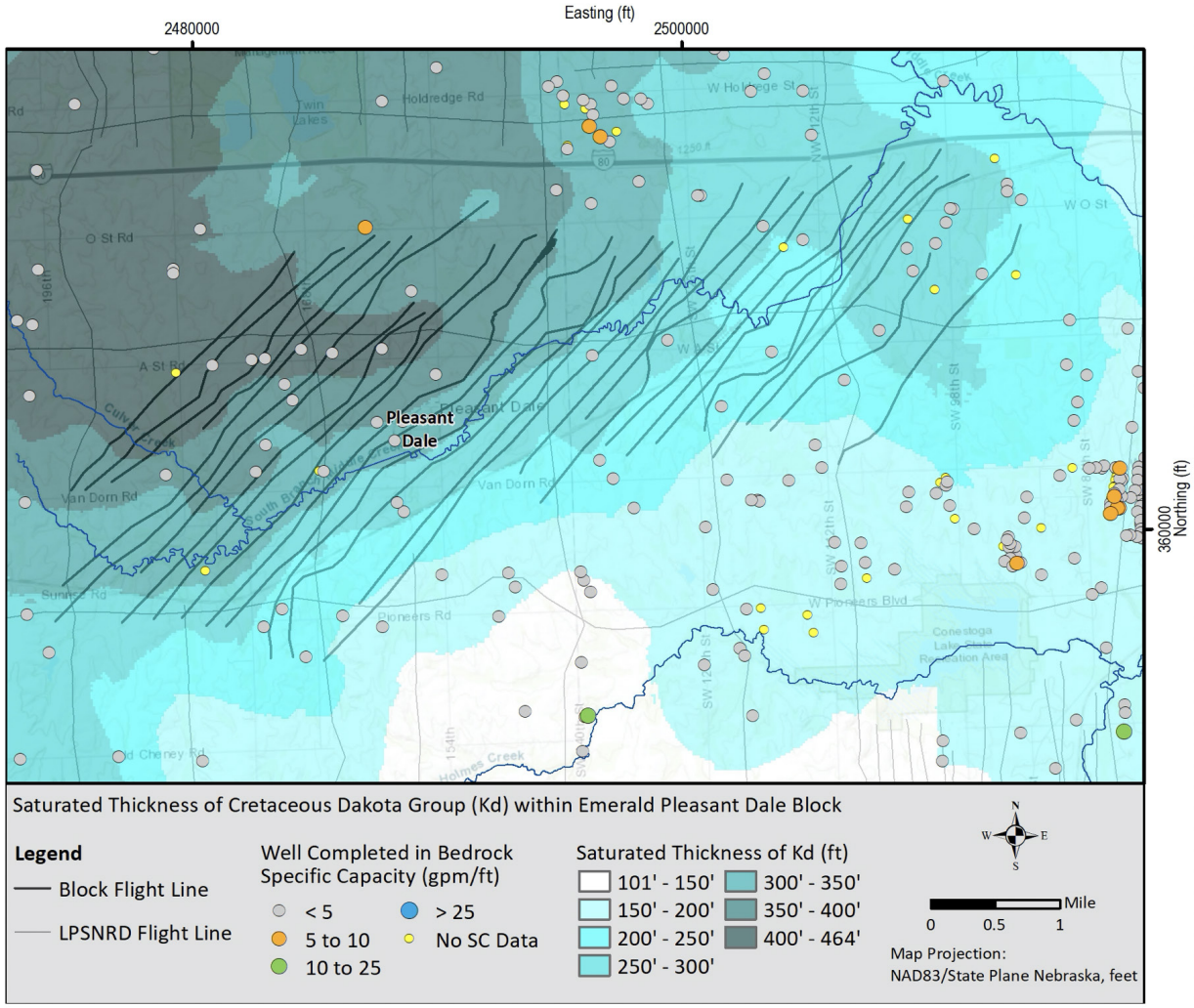


Figure 3-225. Map of the saturated thickness compared to the specific capacity for the *Kd* wells of the area within the 2018 Emerald Pleasant Dale Block AEM survey area. The map shows most wells in the Emerald Pleasant Dale area have a with a specific capacity of <5 gpm/ft with 8 wells having a specific capacity of up to 5 to 10 gpm and 1 well with a specific capacity of 10 to 25 gpm. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

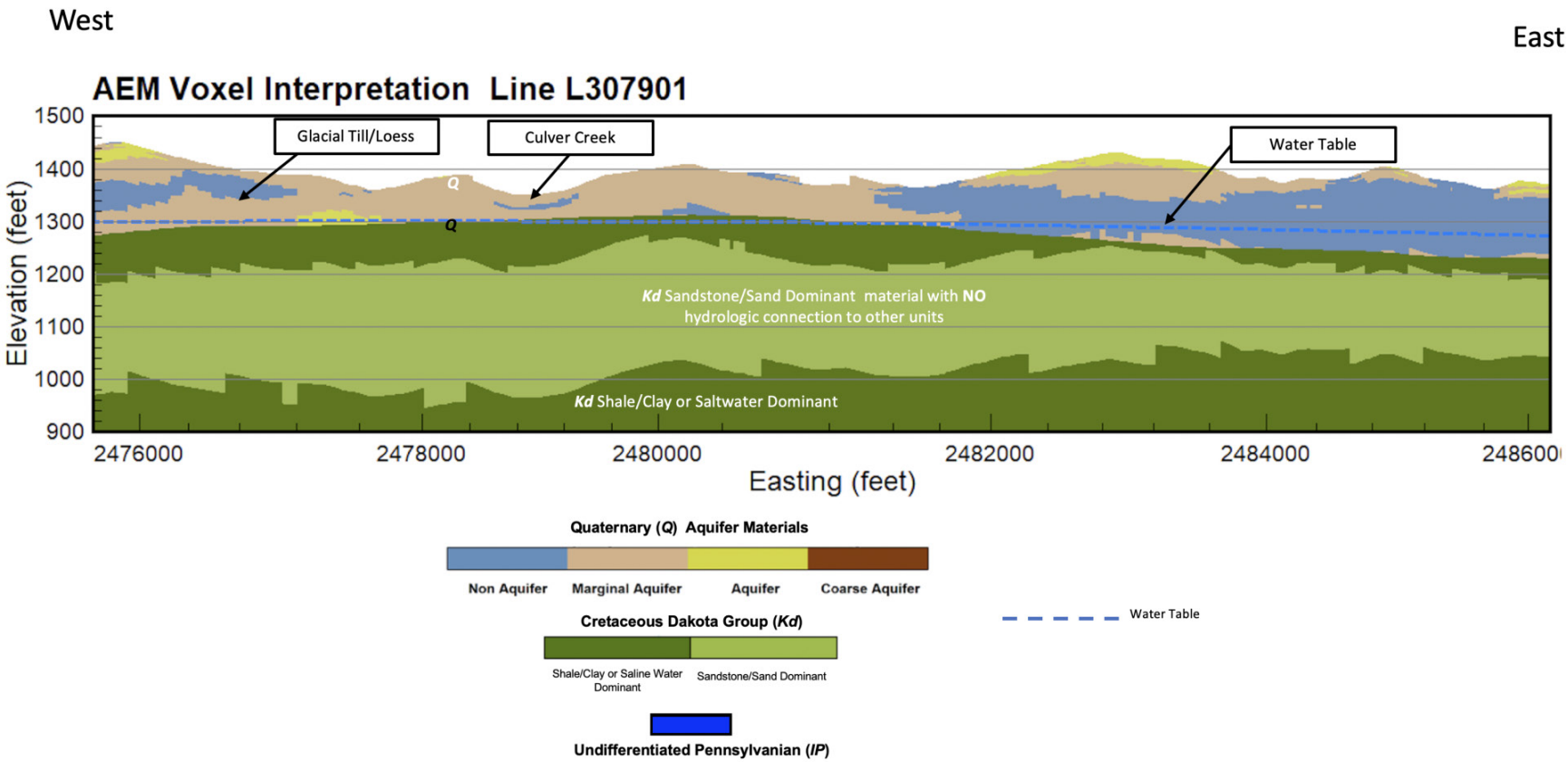


Figure 3-226. Interpreted profile of the north-south line L307901 showing the relationship the *Q* and *Kd* of the AEM interpretations across the Emerald Pleasant Dale survey area. The *Q* is mostly till and loess marginal and non-aquifer material layer that is a ~100 to ~175-foot thick and varies in thickness across the profile and is lying upon the *Kd*. The *Kd* has a continuous is mostly Sandstone/Sand dominant in a thick layer ~200 feet thick across the profile with Shale/Clay or Saltwater water dominant both above and below the layer. The CSD 1995 water table is indicated as a dashed blue line it lies at a high elevation and lies near the top of the loess and non-aquifer material. The geologic units present on this image include *Q*= Quaternary and *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

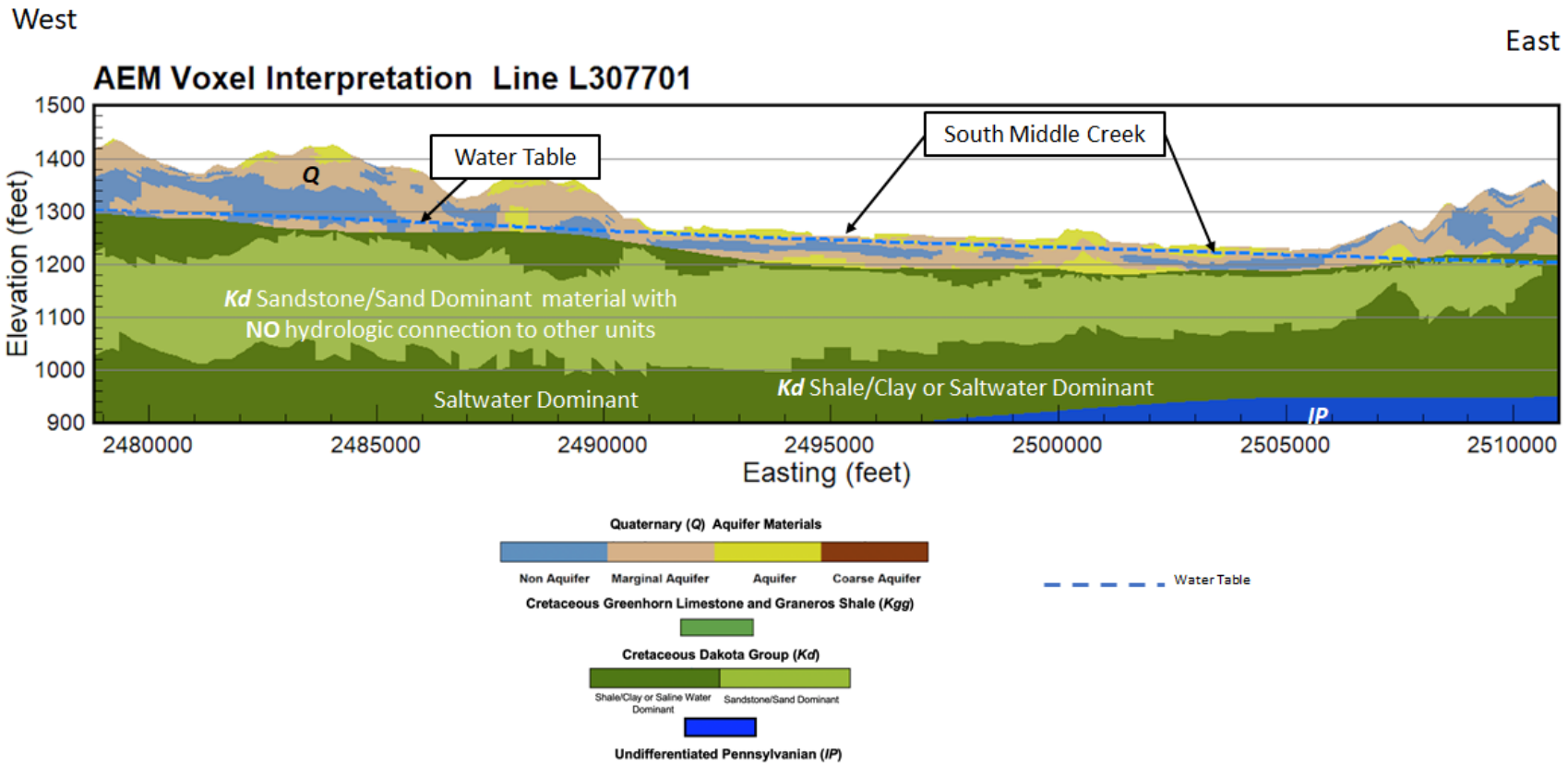


Figure 3-227. Interpreted profile of the north-south line L307701 showing the relationship the *Q*, *Kd* and *IP* of the AEM interpretations across the Emerald Pleasant Dale survey area. The *Q* materials are mostly thick till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material. These *Q* materials have ~10 to ~50 feet of saturation with a high-water table elevation that slopes from west to east. There is a shallow channel in the surface of the *Kd* top elevation from easting 2490000 to 2510000. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q* = Quaternary, *Kd* = Cretaceous Dakota Group, and *IP* = Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

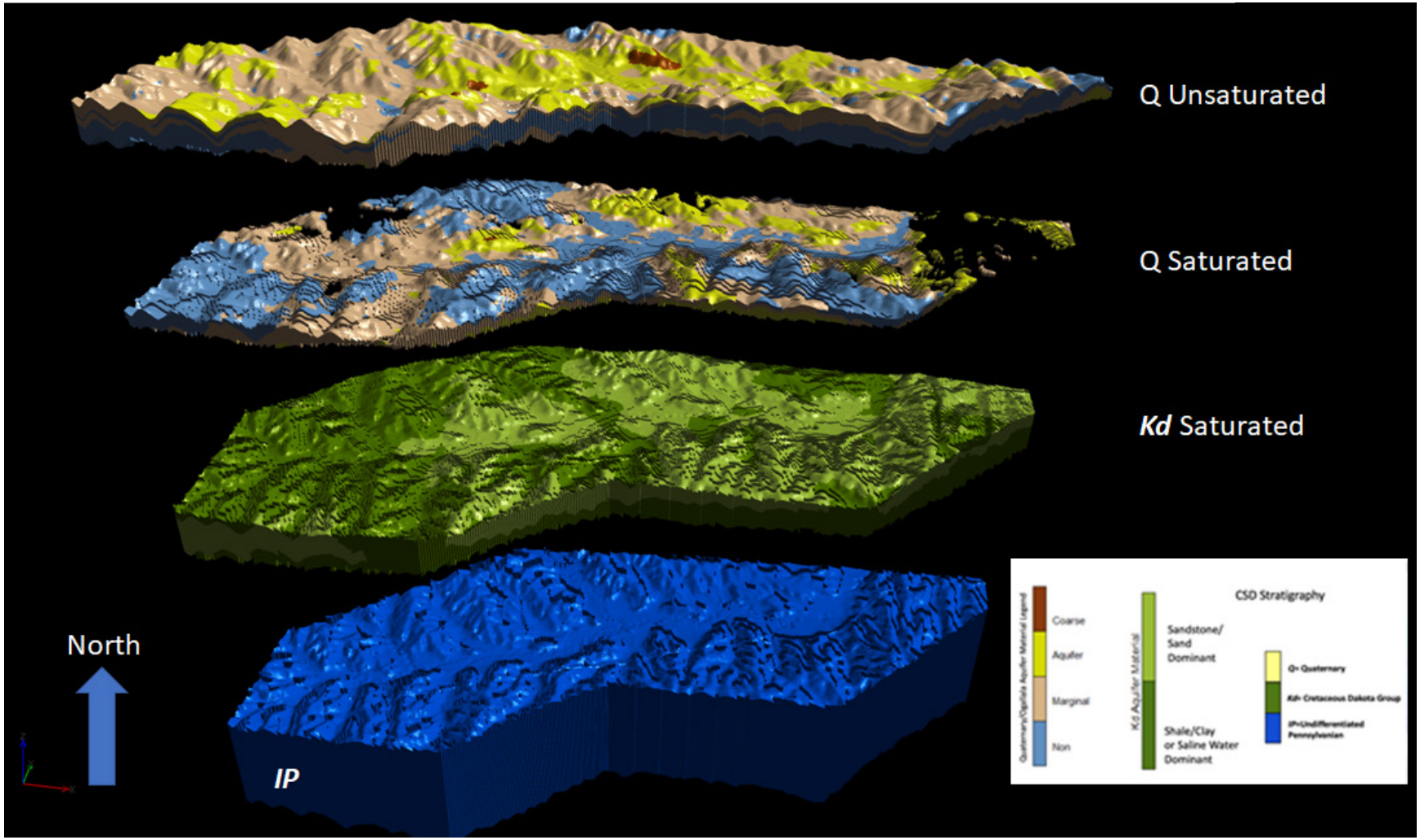


Figure 3-228. 3D exploded voxel model looking northwest of the Emerald Pleasant Dale Block showing Unsaturated *Q*, Saturated *Q*, Saturated *Kd,* and *IP*. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x. The figure is not to scale.

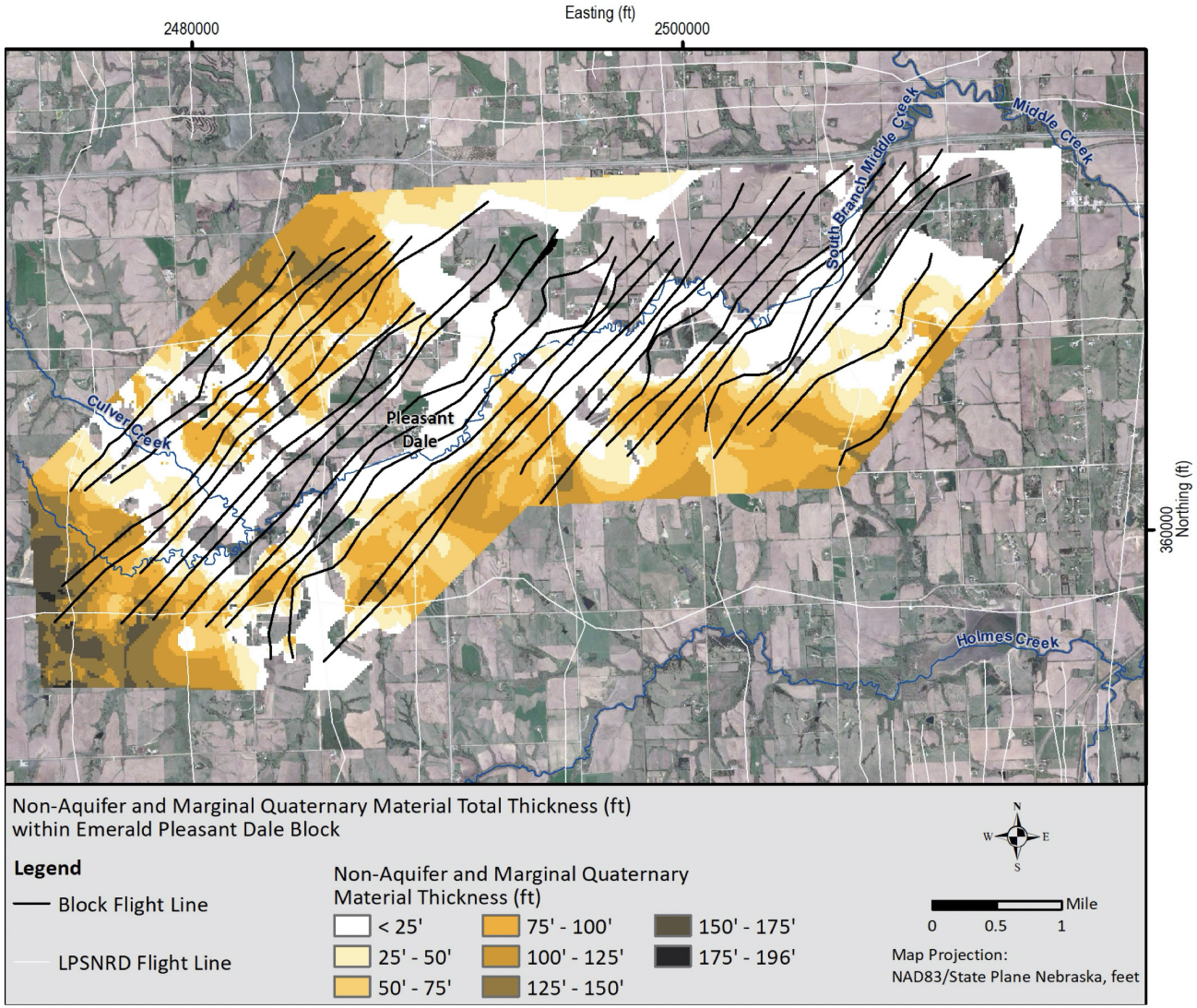


Figure 3-229. Map of *Q* Non-Aquifer and Marginal Aquifer materials total thickness for the Emerald Pleasant Dale Block. Thickest areas are in the north edge of the block. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

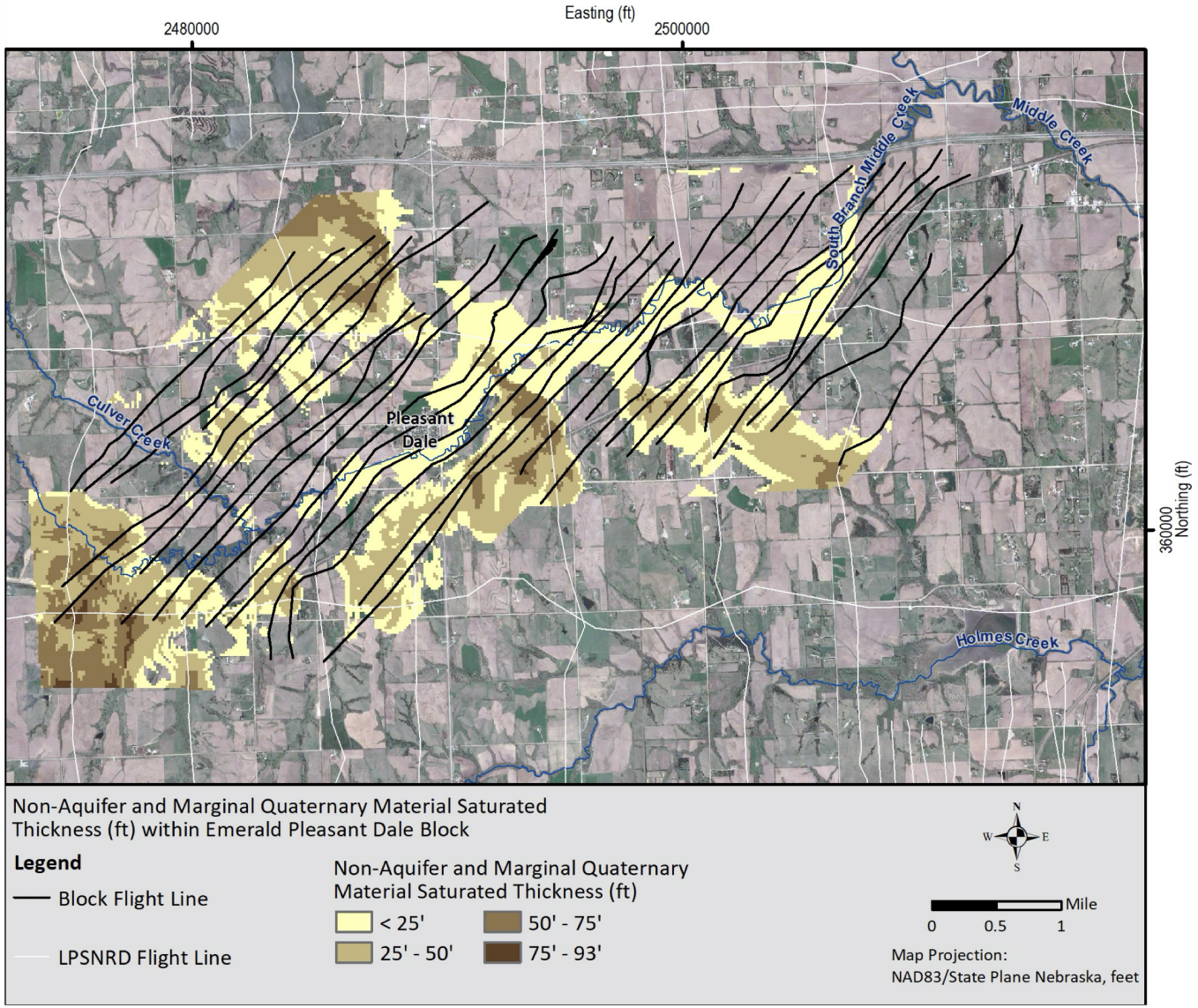


Figure 3-230. Map of thickness of *Q* deposits of saturated Non-Aquifer and Marginal Aquifer materials. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

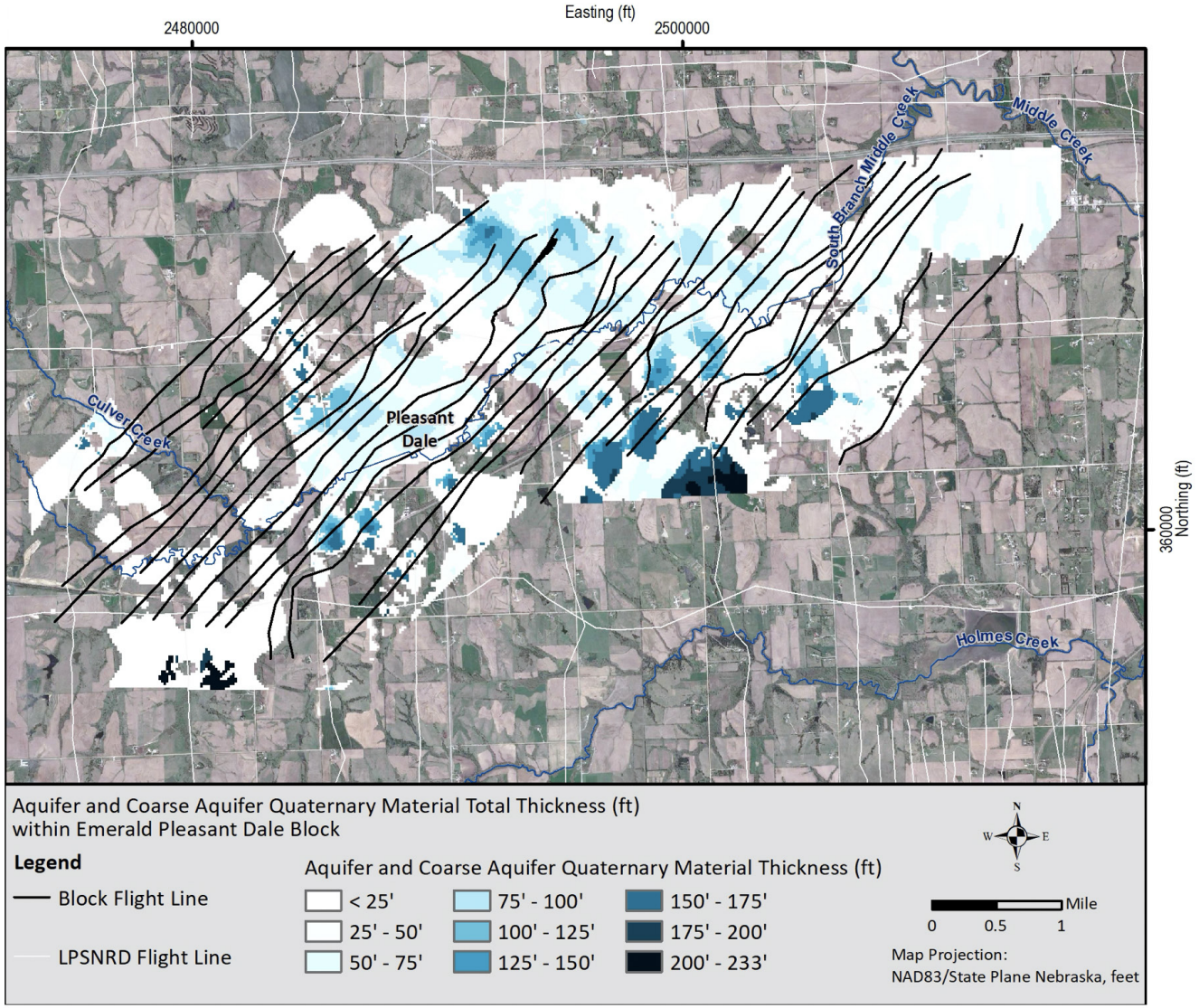


Figure 3-231. Map of total thickness of *Q* deposits of Aquifer and Coarse Aquifer Materials in the Emerald Pleasant Dale Block. The thickest areas are distributed across the area. Block flight lines are indicated by the black lines. Geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

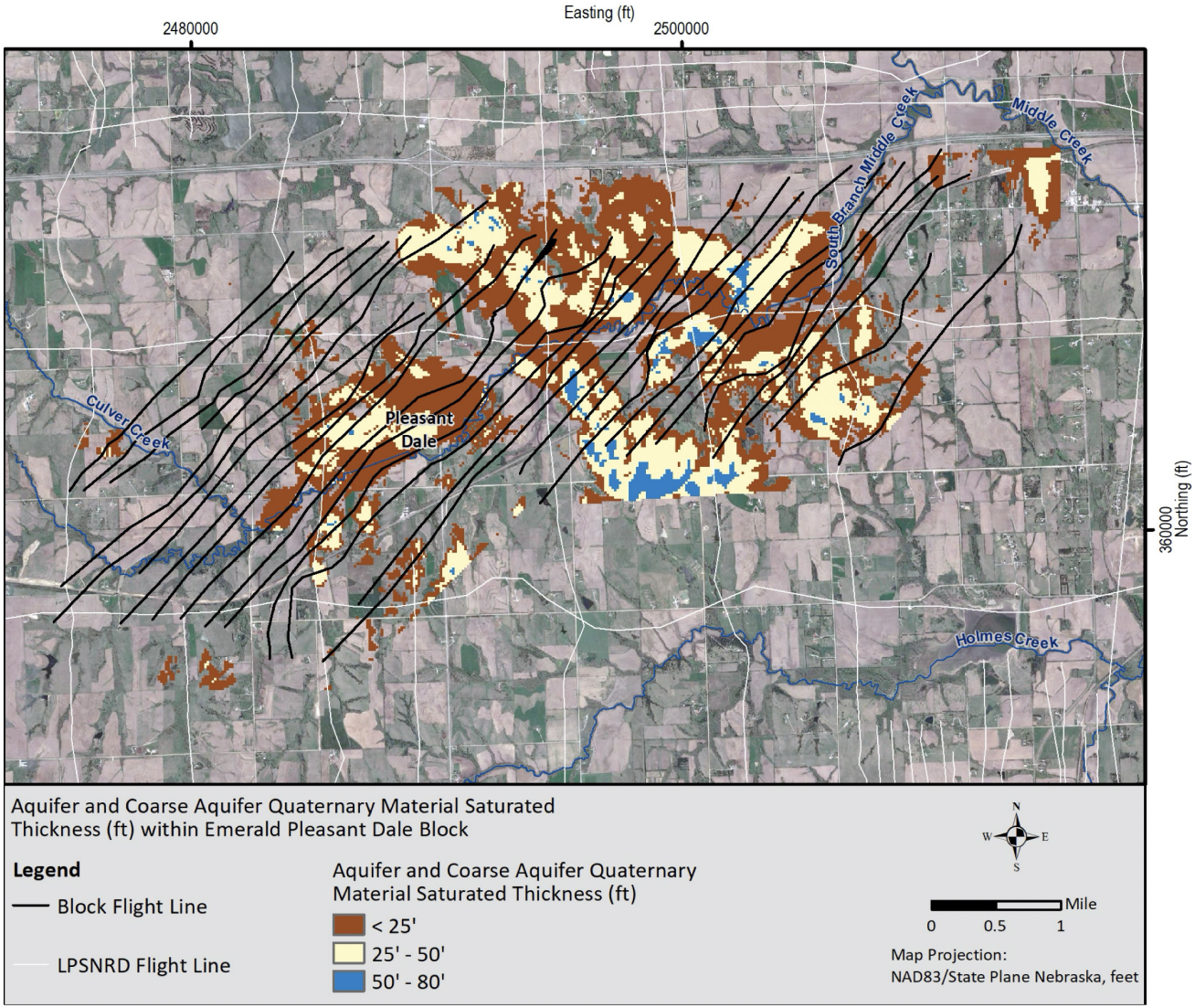


Figure 3-232. Map of saturated thickness of *Q* deposits of Aquifer and Coarse Aquifer Materials in the Emerald Pleasant Dale Block. The thickest areas are across the center of the area. The geologic unit present on this image includes the *Q*= Quaternary. Block flight lines are indicated by the black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

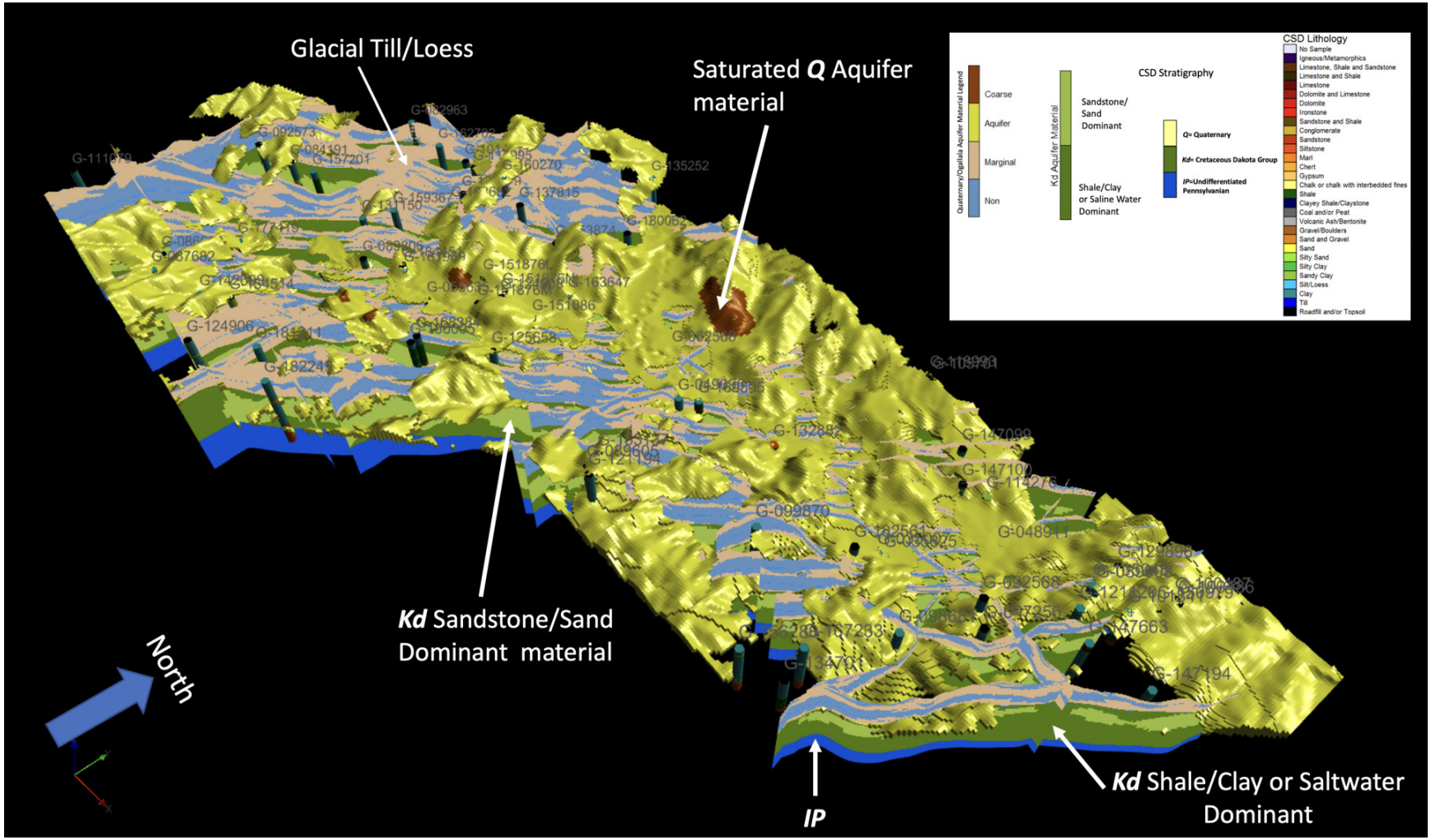


Figure 3-233. View looking west of a 3D voxel model of the *Q* Aquifer and Coarse Aquifer Material lying upon the *Kd* and *IP* with a 3D fence diagram showing *Q* Marginal and Non-Aquifer Material of the Emerald Pleasant Dale Block AEM survey area. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

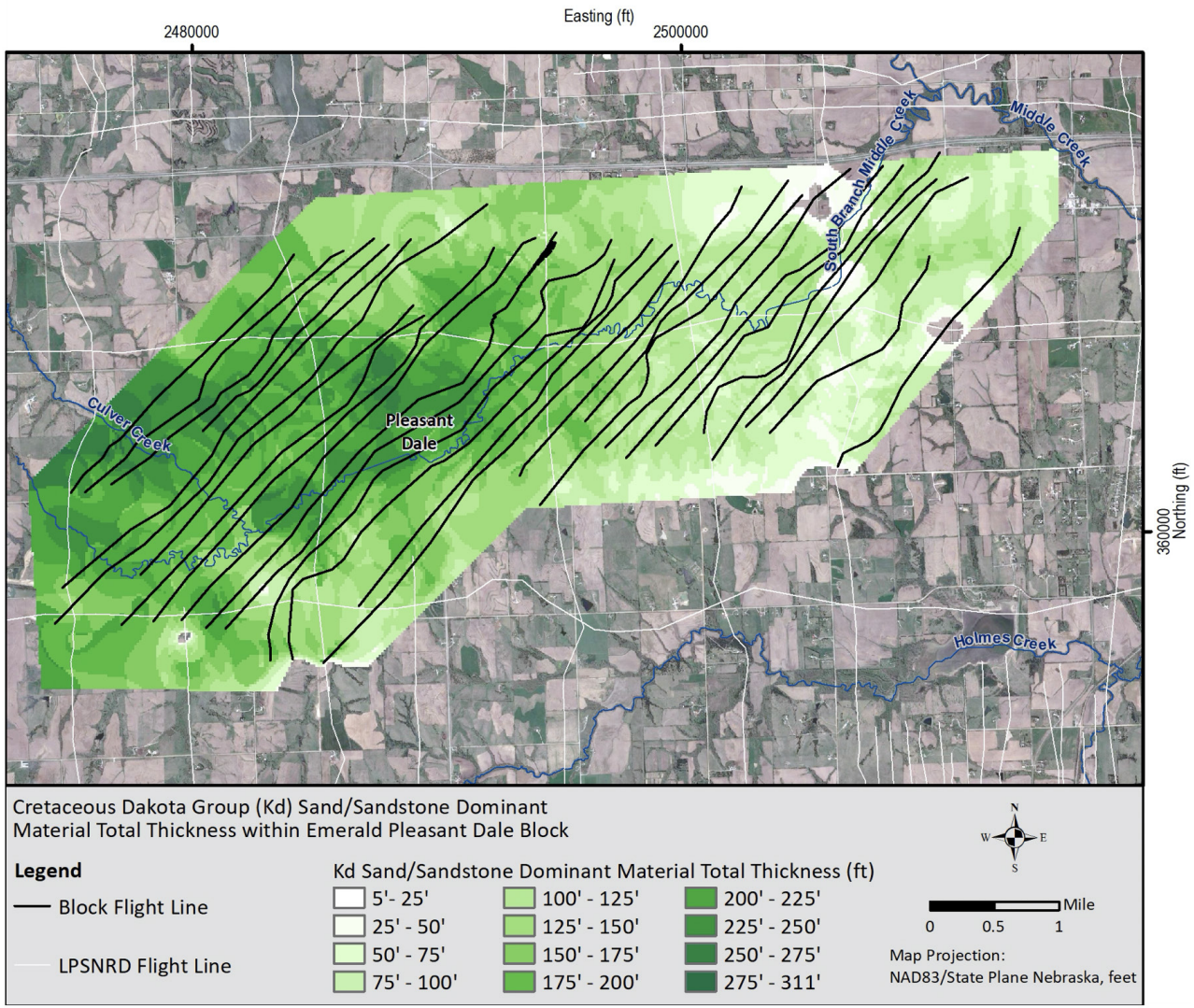


Figure 3-234. Map of the thickness for *Kd* Sandstone/Sand Dominant deposits which is present across nearly the whole of the Emerald Pleasant Dale survey area. These deposits are saturated and vary in thickness from 5 to 311 feet and are continuous across the block. Block flight lines are indicated by the black lines. Horizontal datum is NAD83 State Plane Nebraska (feet). The geologic units present on this image include *Q* = Quaternary, *Kd* = Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian.

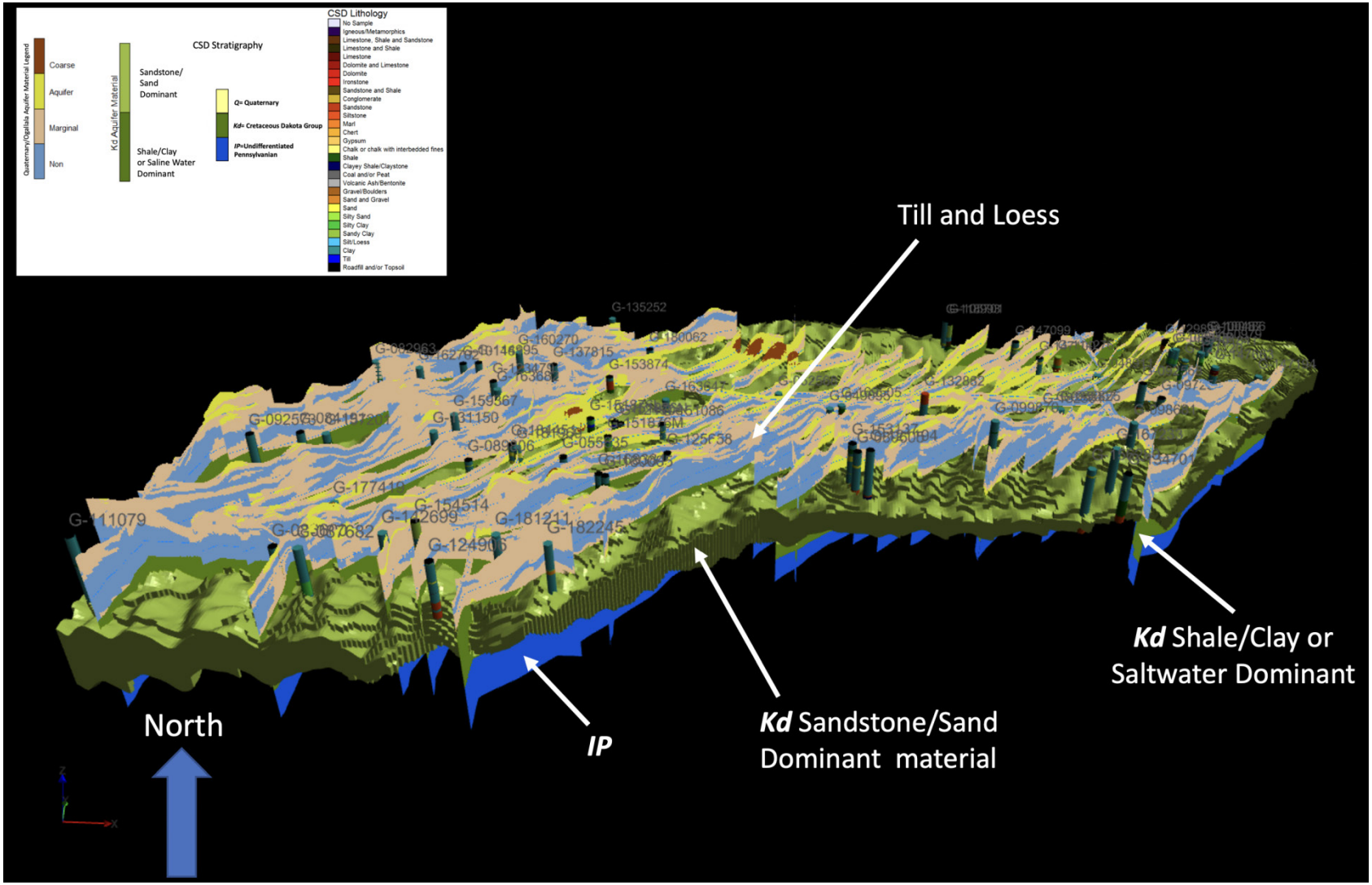


Figure 3-235. View of 3D voxel model looking north showing the saturated thickness for *Kd* Sandstone/Sand Dominant material and Shale/Clay or Saltwater Dominant with a 3D fence diagram of all Q materials in the Emerald Pleasant Dale Block. The *Kd* Sandstone/Sand Dominant material covers nearly all of the survey area. The geologic units present on this image include Q= Quaternary, *Kd*= Cretaceous Dakota Group and IP= Undifferentiated Pennsylvanian. Not to scale. Vertical exaggeration (VE) = 10x.

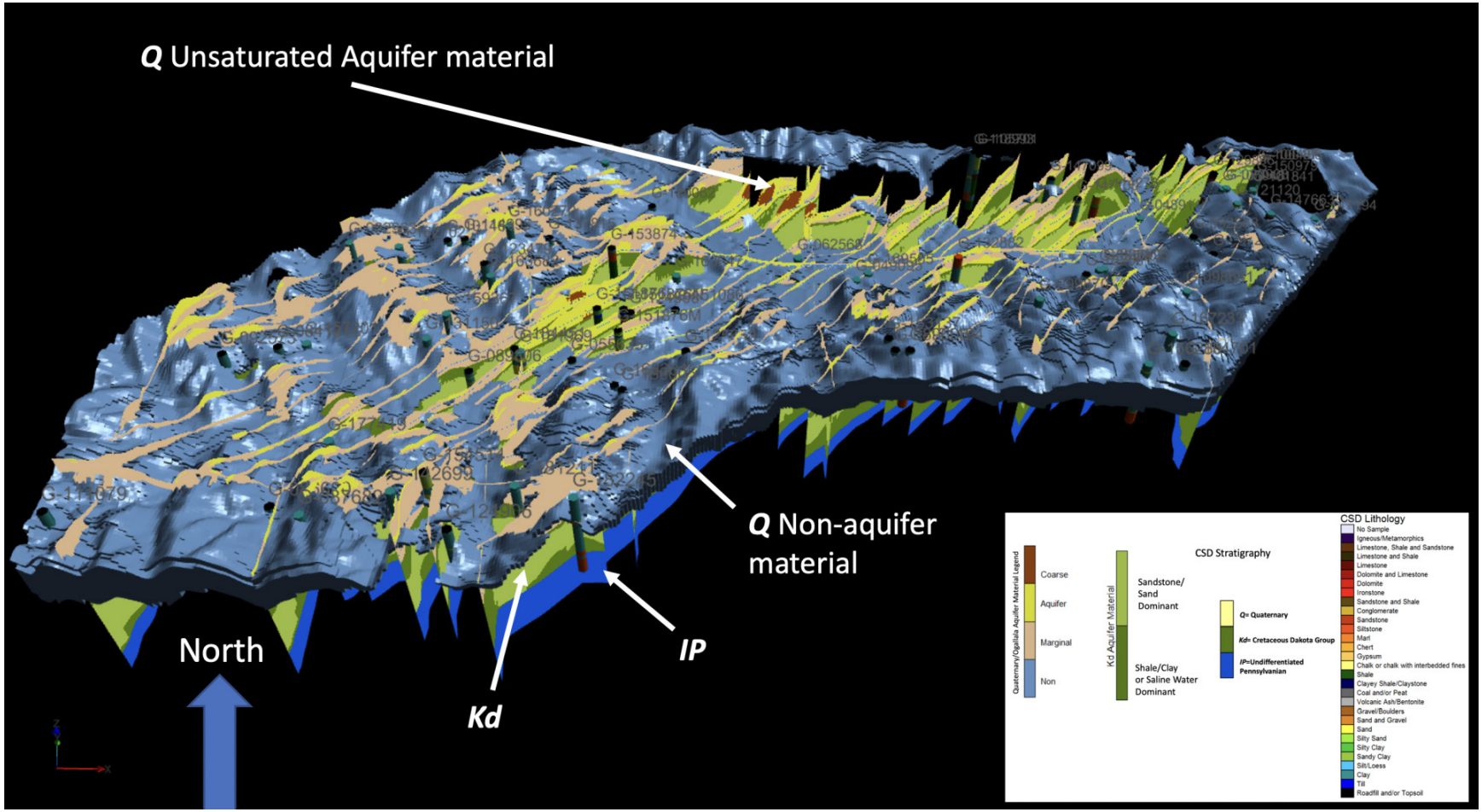


Figure 3-236. 3D voxel model looking north showing the thickness for *Q* Non-Aquifer Material, with a 3D fence diagram of unsaturated *Q* materials, *Kd*, and *IP*. The Q has extensive near continuous coverage of the area with non-aquifer material. The geologic units present on this image include Q= Quaternary, Kd= Cretaceous Dakota Group and IP= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

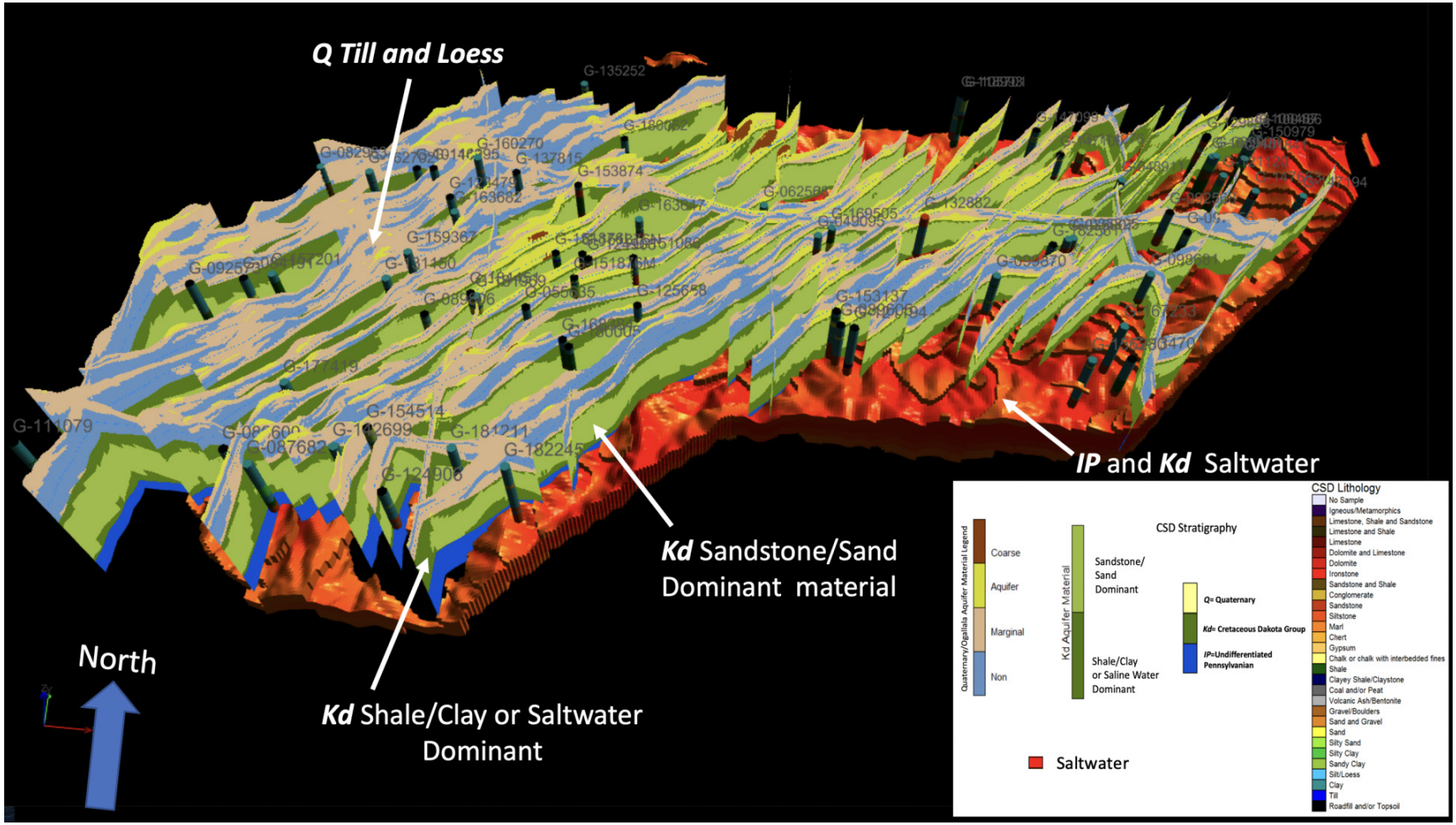


Figure 3-237. 3D voxel model looking north showing the saltwater areas (red) in the Emerald Pleasant Dale Block. A fence diagram of all *Q*, *Kd*, and *IP* materials is shown on top of the voxel model. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. V.E. = x10.

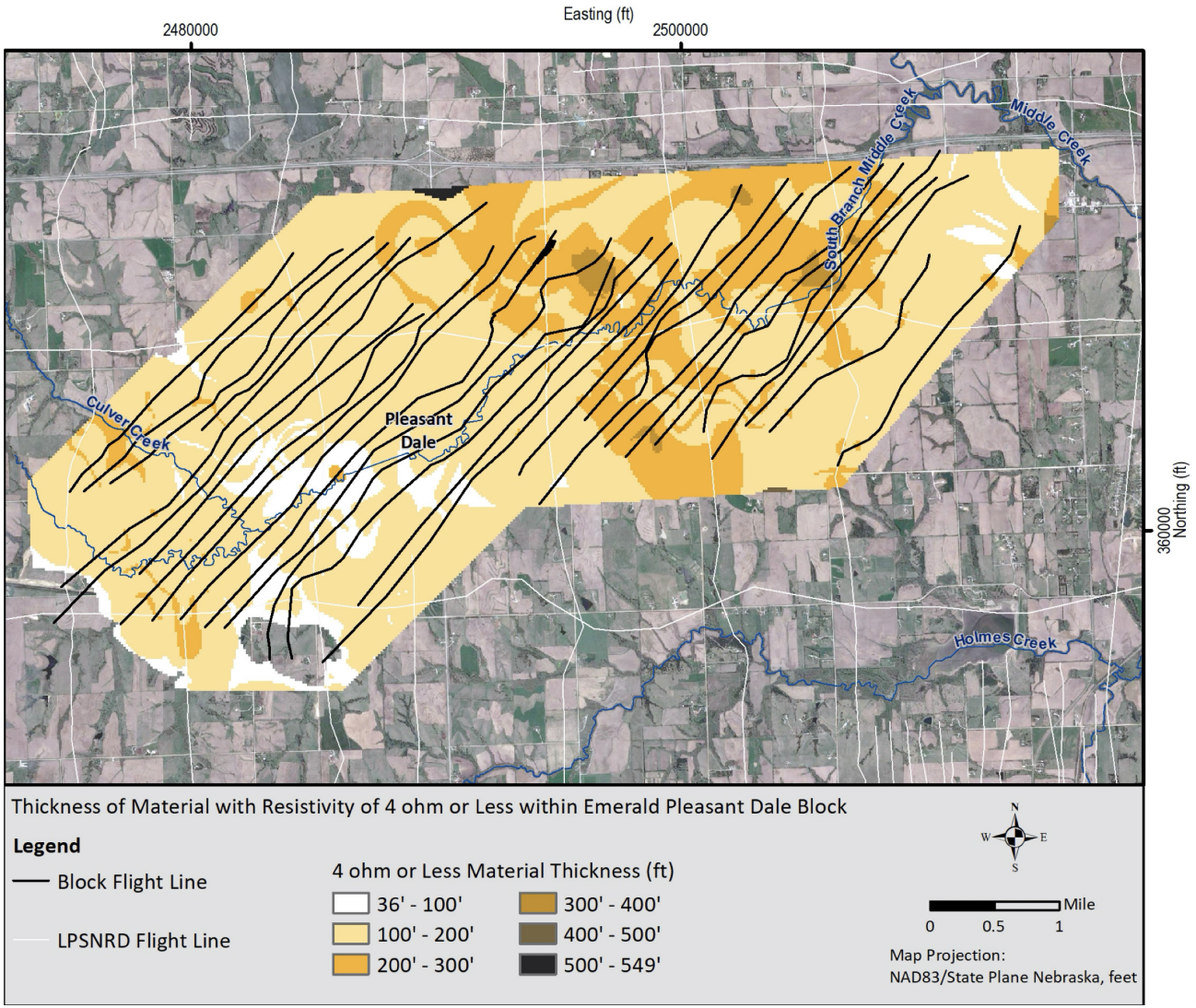


Figure 3-238. Thickness map of saltwater affected areas which is present across nearly the of the Emerald Pleasant Dale Block AEM survey area based on the voxel. model. These deposits vary in thickness from 36 to 549 feet and affect the Kd and IP. Block flight lines are indicated by the black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

3.2.7 Hydrogeologic Framework of the Garland Malcolm Block AEM Survey Area

The AEM provided insight into the geographic distribution and extent of the unconsolidated material and the Cretaceous units in the Garland Malcolm Block AEM survey area. The ***Q*** materials within the Garland Malcolm Block are composed of unconsolidated clay, silt, sand and gravel that overlie the consolidated bedrock which is made up of ***Kd***. The ***Q*** material in the Garland Malcolm Block AEM survey area is identified through interpretation of the AEM data as non-aquifer (blue), marginal aquifer (tan), aquifer material (yellow), and coarse aquifer (brown) material as discussed in Section 3.1. Figure 3-239 is the flight line location map including roads, streams and towns. Generally, the area lies near Branched Oak Lake and Garland, Nebraska. The ground surface elevation map shown on Figure 3-240, shows there are rolling hills surrounding Oak Creek, Middle Oak Creek, West Oak Creek, Elk Creek, Middle Creek and Branched Oak Lake which are the main surface water features. The ground surface elevation ranges from 1,196 to 1,598 feet with highest elevation in the west. Figure 3-241 displays a 3D fence diagram with a voxel model of the ***Q*** aquifer materials, ***Kgg***, ***Kd*** and ***IP*** of the Garland Malcolm Block AEM survey area, looking to the northwest, with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** with marginal and non-aquifer materials making up most of the ***Q*** along with aquifer material and small areas of coarse aquifer material. The ***Q*** lies upon lying upon the ***Kgg*** in the north part of the area and ***Kd*** which lies upon the ***IP.*** The bedrock geology map shows the ***Kgg*** lying upon the ***Kd*** in the northwest part of the block. (Figure 3-242). The ***Kd*** contains a mix of shale/clay or saltwater dominant and sandstone/sand dominant materials.

Figure 3-243 presents 2D profile L414001 is a north-south line in the center of Garland Malcolm Block AEM survey area. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly till and loess with a deposit of ***Q*** aquifer material that extends from the south end to northing 433000 and tapers in thickness from ~150 feet to 0 from south to north. The ***Kd*** Sandstone/Sand materials are in hydrologic contact with the ***Q*** aquifer material near northing 421000 and have minimal hydrologic connection to ***Q*** aquifer material along the rest of the line. The ***Kgg*** is present from Middle Oak Creek, where it outcrops at the surface and continues to the north. The ***Kd*** Shale/Clay or Saltwater dominant is ~350 to 500 feet thick tapering from south to north. The ***Kd*** is saturated throughout the area. The ***IP*** top elevation is 820 feet in the south and declines to 779 feet in the center of the area. The elevation for the ***IP*** is shown on Figure 3-244 and shows the surface to be a gently sloping surface from all sides to the center of the area. The ***IP*** has saltwater water dominant areas in the area. The NE-CSD 1995 (NE-CSD, 1995) water table (Figure3-245) is also on the profile and shows the water table for the area and has a gradual slope from north to south.

The total thickness of the ***Q*** material in the Garland Malcolm Block AEM survey area (Figure 3-246) was gridded by subtracting the bedrock elevation (Figure 3-247) from the ground surface elevation (Figure 3-240). The greatest thickness is along the ground elevation highs to the southwest and south and is independent to bedrock high and low bedrock low within the Garland Malcolm Block AEM survey area. The thin areas (~50-150 feet) of ***Q*** total thickness parallels the drainages of the area. The ***Q*** material varies in thickness from <50 to 508 feet. It is important to understand the distribution of the various ***Q*** aquifer materials in relation to the hydrologic connection of those materials to the surface water of the

area. The ***Q*** coarse aquifer and aquifer material which makes up ~30% amount of ***Q*** materials present provide some connection for water movement through all of the ***Q*** aquifer materials. The mix of all ***Q*** materials is complex and from profile to profile the hydrologic connection to the streams of the area change. Of equal importance is the saturated thickness of the ***Q*** materials calculated by the bedrock elevation subtracted from the gridded 1995 CSD water table surface elevation (NE-CSD, 1995) to obtain the total saturated thickness of ***Q*** material. The saturated thickness for all aquifer material is shown for Garland Malcolm Block on Figure 3-248. The thickness of these materials is thin and varies between 0 to 268 feet. The saturated thickness averages 0-150 feet across the area with the thickest area in the south. Figure 3-249 shows the relationship between the saturated thickness of ***Q*** and the specific capacity in gpm/ft for wells completed in the ***Q***. Careful evaluation of the wells in Figure 3-249 shows the majority of wells in the Garland Malcolm area have a with a specific capacity of <5 gpm/ft with 3 wells having an specific capacity of 5 to 10 gpm/ft. The **Q** is a poor aquifer except where Aquifer material is thick for well development.

The ***Kgg*** exists in a small area in the Northwest corner of the block and is not considered an aquifer. Figure 3-250 Is a map of the elevation of top of ***Kgg*** which is bedrock which ranges in elevation from 1,240 to 1,412 feet. There is outcrops of ***Kgg*** along Middle Oak Creek. The thickness map of the ***Kgg*** is shown in Figure 3-251. The thickness of the ***Kgg*** varies from <25 to 97 feet with the thickest are in the west corner and thins in the east.

Figure 3-252 is a map of the elevation of top of ***Kd*** which is bedrock which ranges in elevation from 1,015 to 1,374 feet. There is a low area in the southeast rises to northwest. The thickness map of the ***Kd*** is shown in Figure 3-253. The thickness of the ***Kd*** varies from 199 to 573 feet with the thickest are in the northwest corner and thins in the southeast corner and thins in the south. Figure 3-254 shows the ***Kd*** saturated thickness map the thickness varies from 199 to 573 feet with the thickest area in the northwest. Figure 3-255 shows the relationship between the saturated thickness of ***Kd*** and the specific capacity in gpm/ft for wells completed in the ***Kd***. Careful evaluation of the wells in Figure 3-255 shows all wells in the Garland Malcolm area have a with a specific capacity of <5 gpm/ft. The best locations for well development are in the thick Sandstone/Sand Dominant zones of the ***Kd***.

Figure 3-256 shows the interpreted 2D profile L306801 is an east-west line which is south of Garland, Nebraska. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are made up ~50/50 split of till and loess marginal and non-aquifer material ~ 200 feet thick and a discontinuous aquifer material layer that is a ~100 to ~175-foot thick across the profile lying upon the ***Kd***. The ***Q*** layer marginal and non-aquifer materials have 0 to 50 feet of saturation on the east end of the line. The ***Q*** aquifer material has ~120 feet of saturation near easting 2470000 to 2485000. The ***Kd*** is mostly Shale/Clay or Saltwater dominant in a thick continuous layer ~300 feet thick across the line. There is a Sandstone/Sand dominant layer in several location just below the ***Q***. The ***Kd*** is saturated throughout the area. The NE-CSD 1995 water table is also on the profile and shows the water table for the area and it is sloping from west to east. There is saltwater along the line.

Figure 3-257 shows the interpreted 2D profile L304300 which is an east-west profile is the northernmost diagonal line north of Garland, Nebraska. The figure shows the subsurface of the area along the line and

the ***Q*** materials that are present along the line. They are mostly thin till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material. These ***Q*** materials have ~10 to ~50 feet of saturation with a high-water table elevation that slopes from west to east. There is a ***Kgg*** outcrop in the center of the line. The ***Kd*** has minimal Sandstone/Sand dominant material with no hydrologic connection to other units or surface water. The creeks have minimal hydrologic connection to the ***Q*** materials due to the abundance of marginal and non-aquifer materials present. Saltwater is present in much of the lower part of the ***Kd***.

Figure 3-258 shows the interpreted 2D profile L402600 which is a north-south profile just west of Garland, Nebraska. The figure shows the subsurface of the area along the line and the ***Q*** materials that are present along the line. They are mostly till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material mixed in and a basal ***Q*** aquifer material layer extending from the south to northing ~424000. The basal ***Q*** materials have up to ~250 feet of saturation. The ***Kd*** has Sandstone/Sand dominant material with hydrologic connection to ***Q*** basal aquifer material. The creeks have minimal hydrologic connection to the ***Q*** materials due to the abundance of marginal and non-aquifer materials present. Saltwater is present in much of the lower part of the ***Kd***.

An exploded view of the 3D voxel model showing the ***Q***, both saturated and unsaturated, ***Kgg***, the ***Kd***, saturated and the ***IP*** formations is presented in Figure 3-259. The ***Q*** materials show mostly marginal aquifer and non-aquifer materials mixed with minor amounts of aquifer and coarse aquifer materials. The ***Q*** aquifer materials are mostly unsaturated. The ***Kgg*** occupies a small area on the north west side of the block. The ***Kd*** is saturated and present in the entire area and some of the Sandstone/Sand dominant material is in hydrologic contact with the ***Q*** aquifer material. Because of the amount of ***Q*** marginal and non- aquifer materials and their distribution across the Garland Malcolm area there is minimal ability for managed aquifer recharge (MAR) sites to be located within the block.

Figure 3-260 shows the distribution of ***Q*** marginal and non-aquifer materials total thickness which is thick Garland, Nebraska, Elk Creek and Middle Creek. These materials are discontinuous and range in thickness from <50 to 425 feet. Figure 3-261 shows the distribution of ***Q*** marginal and non-aquifer materials saturated thickness which is discontinuous and thick Elk Creek. These materials range in thickness from <25 to 227 feet. Figure 3-262 shows the thickness of the ***Q*** aquifer and coarse aquifer materials that are nearly continuous across the area except in the north with the thick deposits spread across the south area. These materials range in thickness from <50 to 468 feet. Figure 3-263 shows the ***Q*** saturated aquifer and coarse aquifer materials are thin and range in thickness from <25 to 277 feet and show that the ***Q*** has minimal additional groundwater storage that can yield to wells or be used as MAR locations.

Figure 3-264Fig3_264 shows a 3D fence diagram looking south of the ***Q*** marginal and non-aquifer material with a voxel model of the ***Q*** aquifer and coarse aquifer materials lying upon the ***Kd*** and ***IP*** of the Garland Malcolm Block AEM survey area with the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The area generally contains a mix of all ***Q*** with marginal and non-aquifer materials and areas of aquifer material including coarse aquifer and

aquifer materials. The ***Kd*** contains a mix of Shale/Clay or Saltwater dominant and Sandstone/Sand dominant materials. There is a saltwater zone in the ***Kd*** and ***IP***.

Figure 3-265 presents a map of the thickness for ***Kd*** Sandstone/Sand Dominant deposits which is discontinuous across area. These deposits are saturated and vary in thickness from 8 to 326 feet and are discontinuous across the block. The ***Kd*** Sandstone/Sand dominant material is an aquifer in this area with the thickest portion in the west. Figure 3-266 3D voxel model view to the north showing the ***Q***, ***Kgg***, ***Kd,*** and ***IP*** as one block. Figure 3-267 is a 3D voxel model looking north showing the thickness for ***Kgg, Kd,*** and ***IP*** materials. This shows the limited coverage of the ***Kgg*** and the ***Kd*** Sandstone/Sand dominant materials. Figure 3-268 is a 3D voxel model looking north showing the ***Q*** saturated thickness and ***Kgg, Kd,*** and ***IP*** materials.

During the analysis of the AEM data it was apparent that there was saltwater present in some areas in LPSNRD project area. There is a presence of saltwater in the Garland Malcolm Block AEM survey area. Figure 3-269 is a 3D voxel model looking west that shows these saltwater areas to be nearly continuous across the area and affect the ***IP*** and ***Kd***. There are no water quality samples from wells in the area and this determination of saltwater is based on the comparison of resistivity from the AEM versus the lithology from the wells. Figure 3-270 is a 3D voxel model which is similar to Figure 171 looking north. Figure 3-271 is a map of the extent of the saltwater in the area and show that it is extensive in the block.

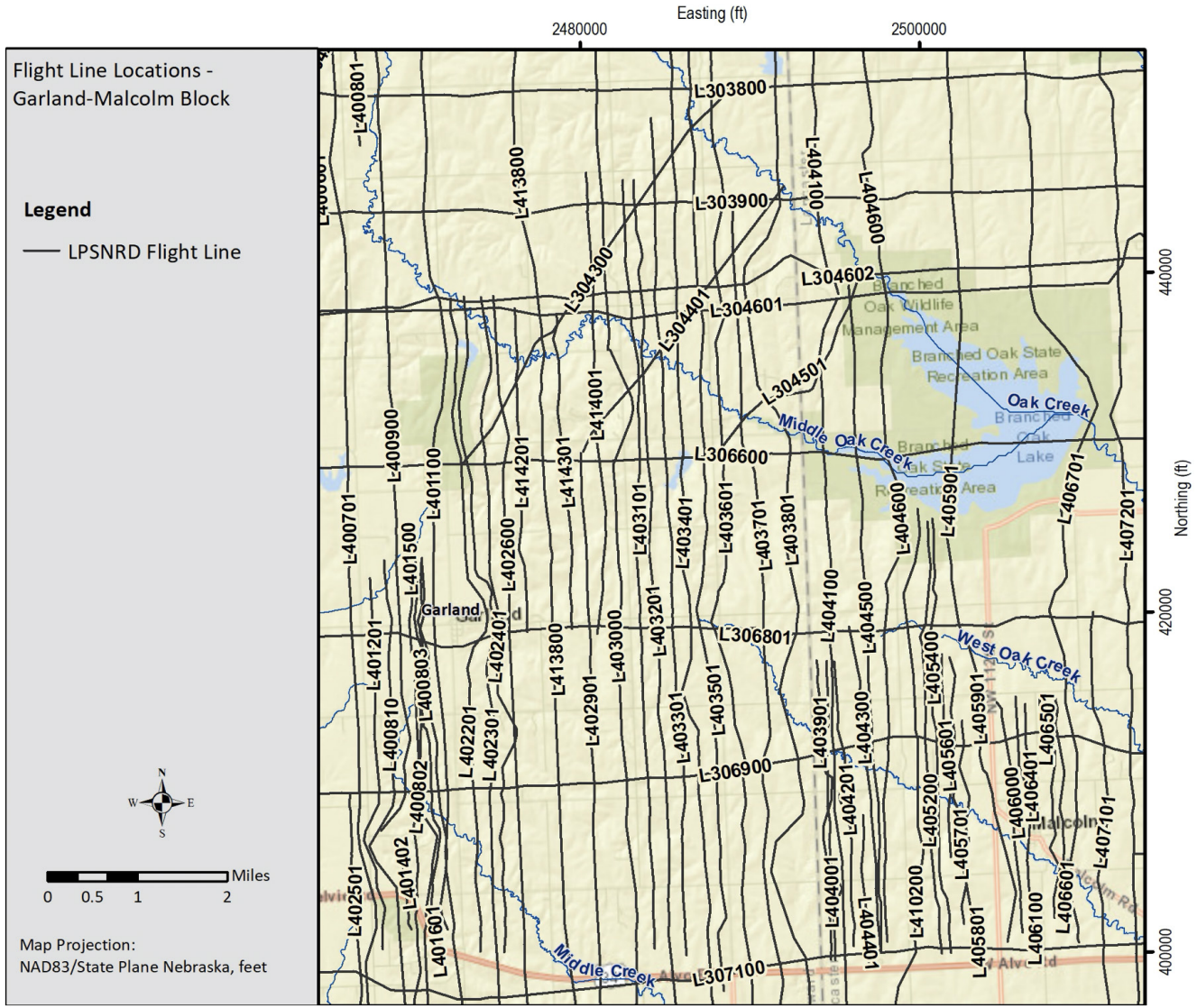


Figure 3-239. Location map of the Garland Malcolm Block AEM survey area showing numbered AEM flight lines, local roads, and streams. Generally, the area lies near Branched Oak Lake and Garland, Nebraska. Block flight lines are indicated by black lines. The Horizontal datum is NAD83 State Plane Nebraska (feet).

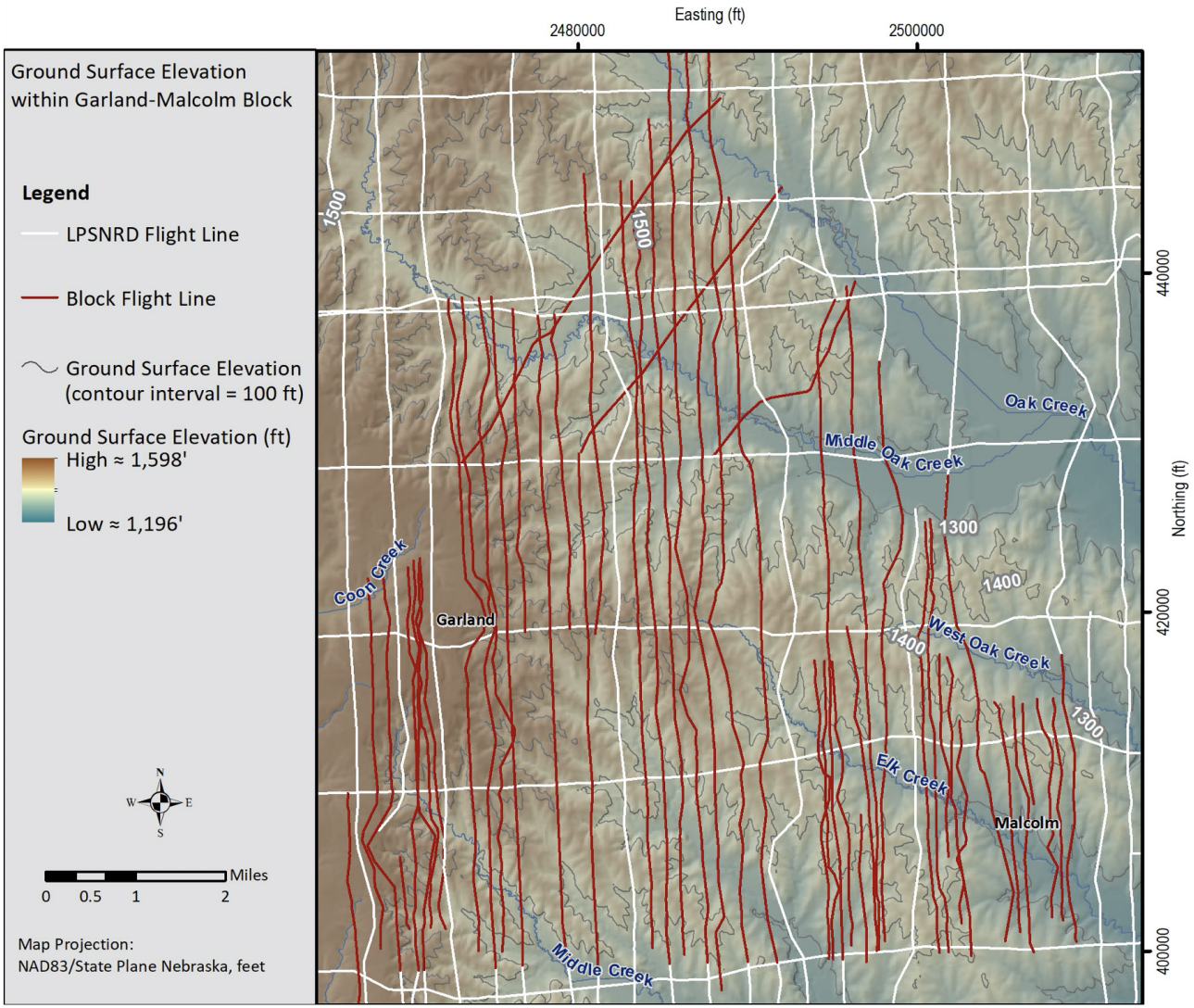


Figure 3-240. Ground surface elevation map shows there are rolling hills surrounding Oak Creek, Middle Oak Creek, West Oak Creek, Elk Creek, Middle Creek, and Branched Oak Lake which are the main surface water features. The ground surface elevation ranges from 1,196 to 1,598 feet with highest elevation in the west. Block AEM flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

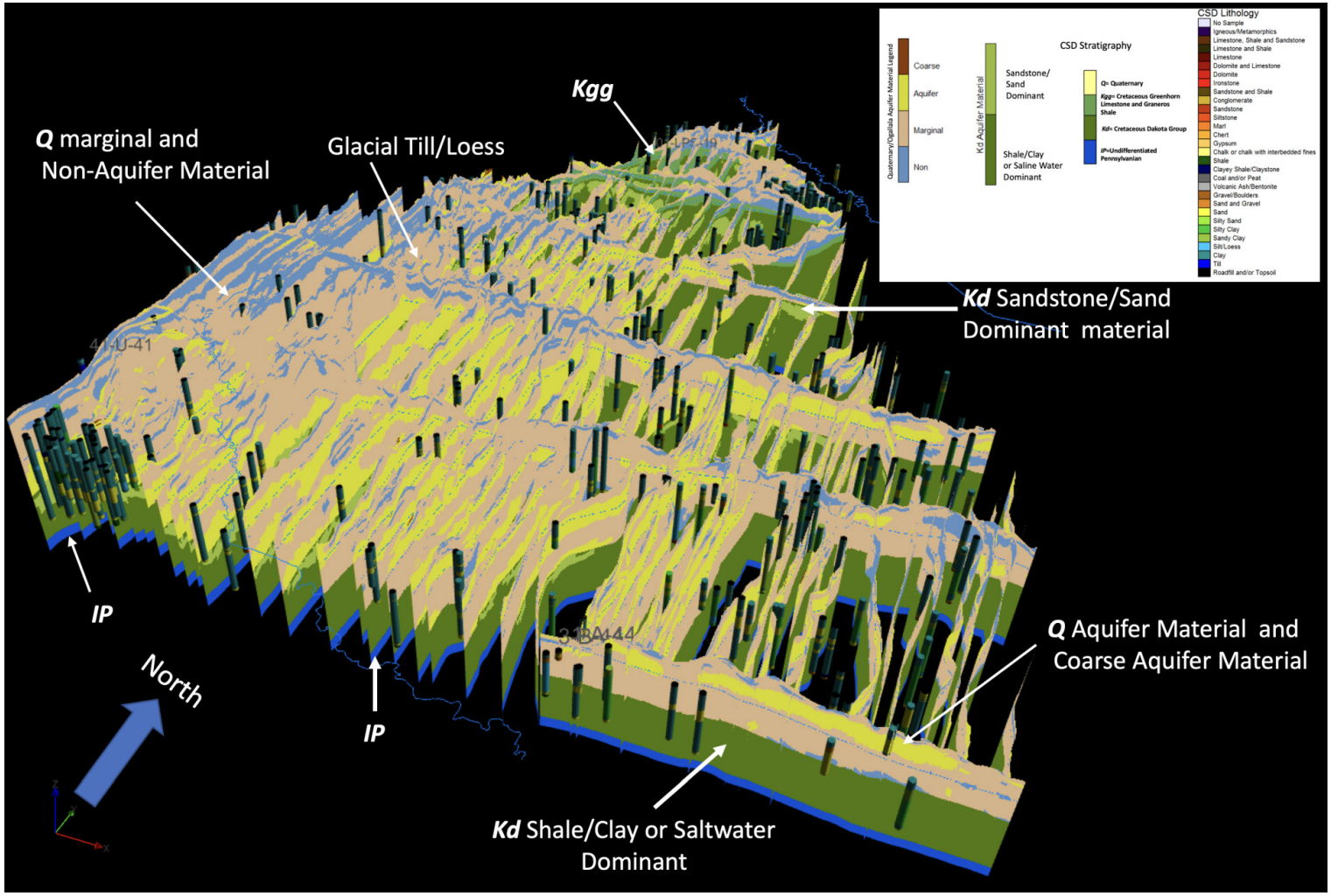


Figure 3-241. 3D fence diagram with a voxel model of the *Q* aquifer materials, *Kgg*, *Kd,* and *IP* of the Garland Malcolm Block AEM survey area, looking to the northwest, with the flight lines and the interpreted hydrostratigraphic profiles along with NE-CSD and NE-DNR borehole lithology data. The area generally contains a mix of all *Q* with marginal and non-aquifer materials making up most of the *Q* along with aquifer material and small areas of coarse aquifer material. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

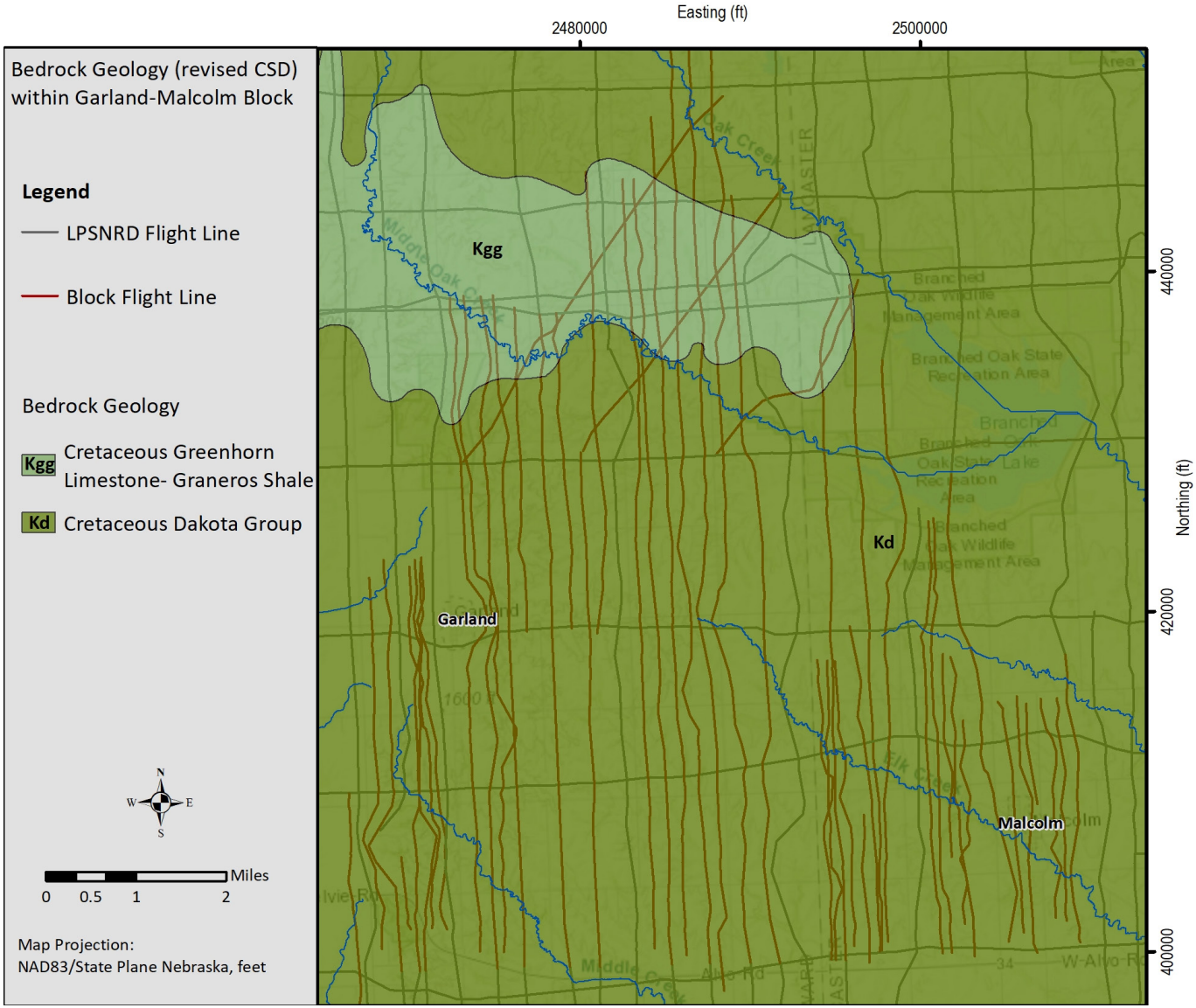


Figure 3-242. The bedrock geology map shows the *Kgg* lying upon the *Kd* in the northwest part of the Garland Malcolm Block. Block AEM flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

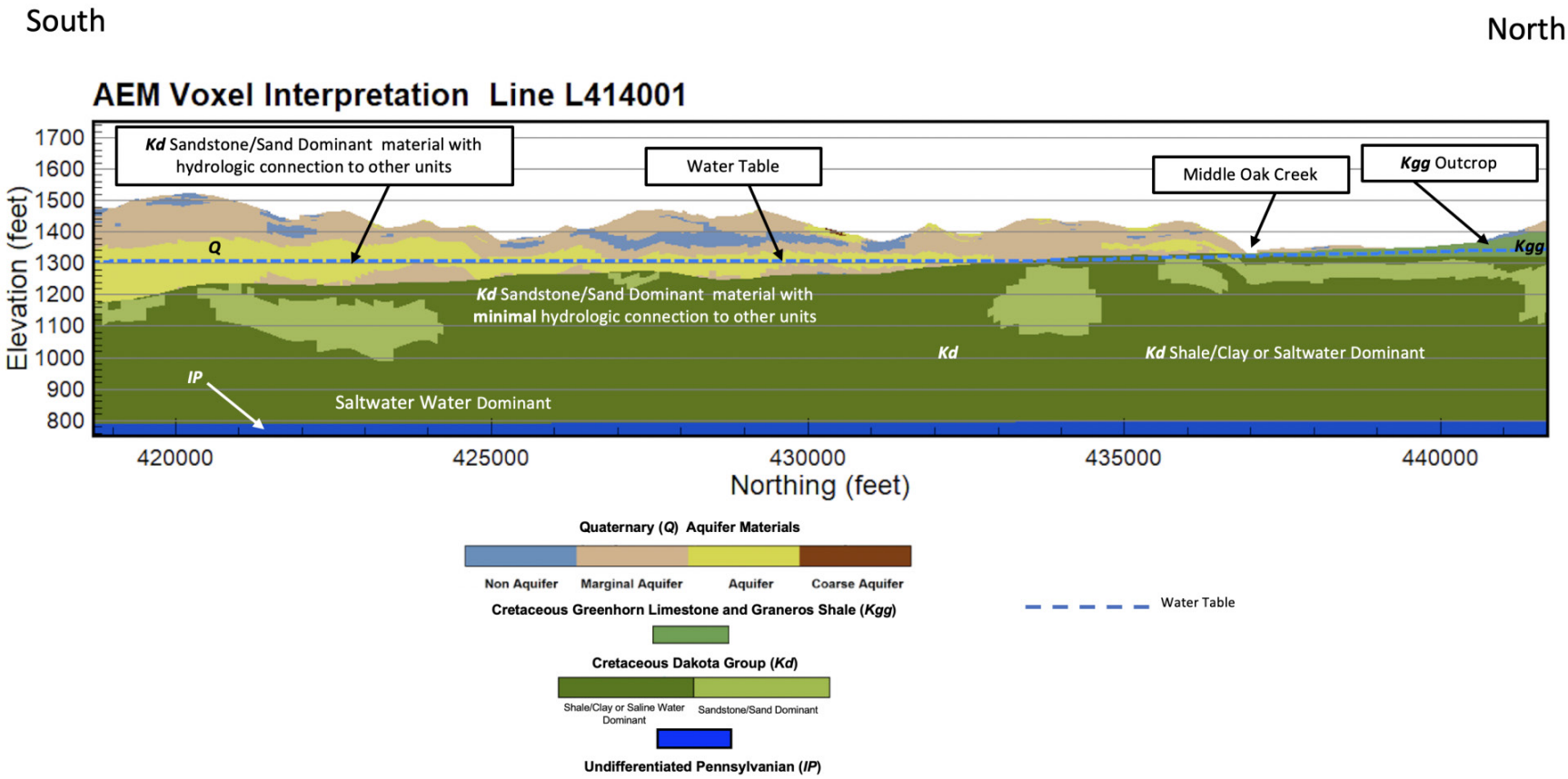


Figure 3-243. 2D profile L414001 is a north-south line in the center of the Garland Malcolm Block AEM survey area. The figure shows the subsurface of the area along the line and the *Q* materials that are present along the line. They are mostly till and loess with a deposit of *Q* aquifer material that extends from the south end to northing 433000 and tapers in thickness from ~150 feet to 0 from south to north. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

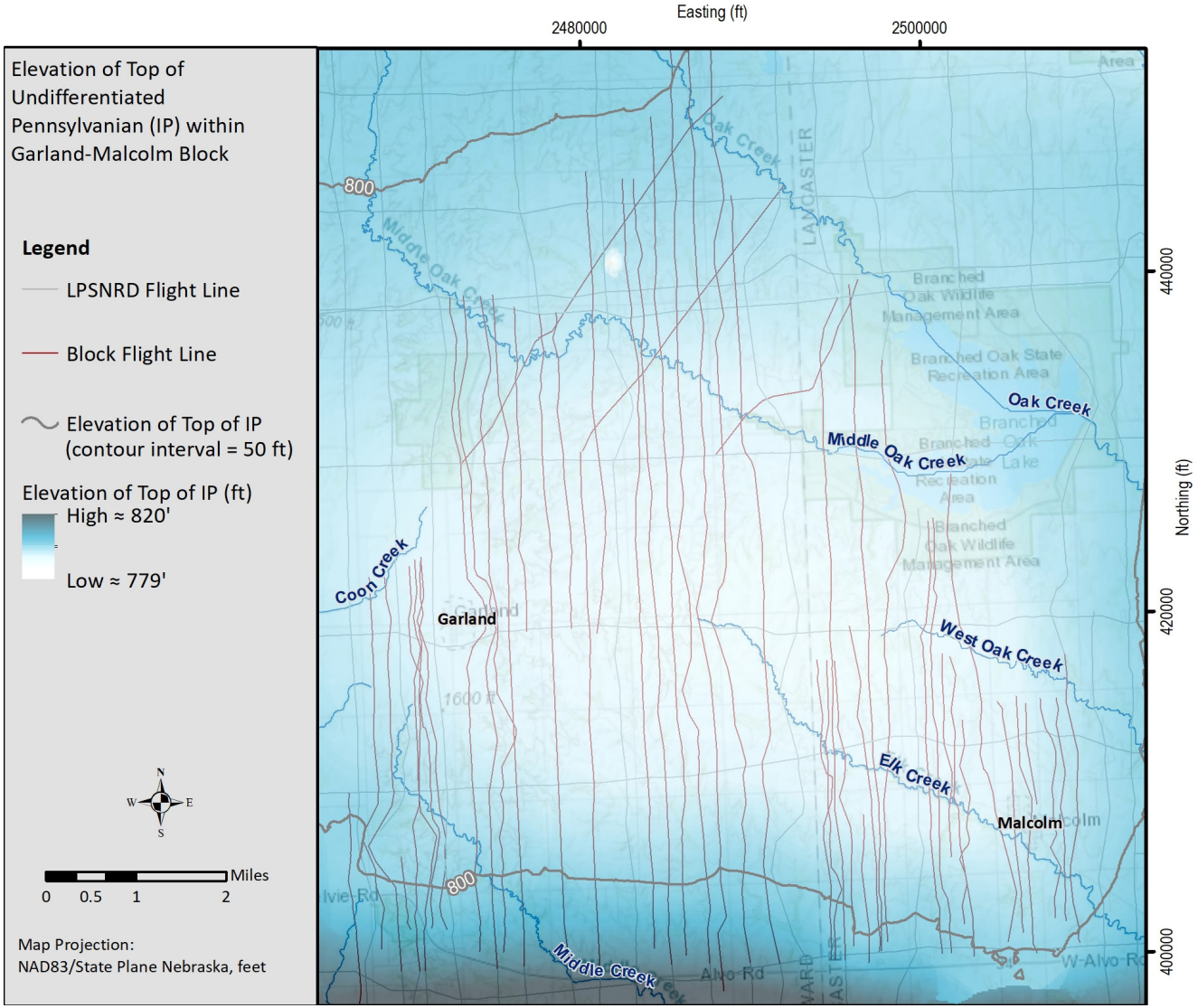


Figure 3-244. Map of the surface elevation for the *IP* as a gently sloping surface from all sides to the center of the Garland Malcolm Block survey area. The *IP* has saltwater water dominant areas in the area. AEM Block flight lines are indicated by the red lines. The geologic units present on this image include *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

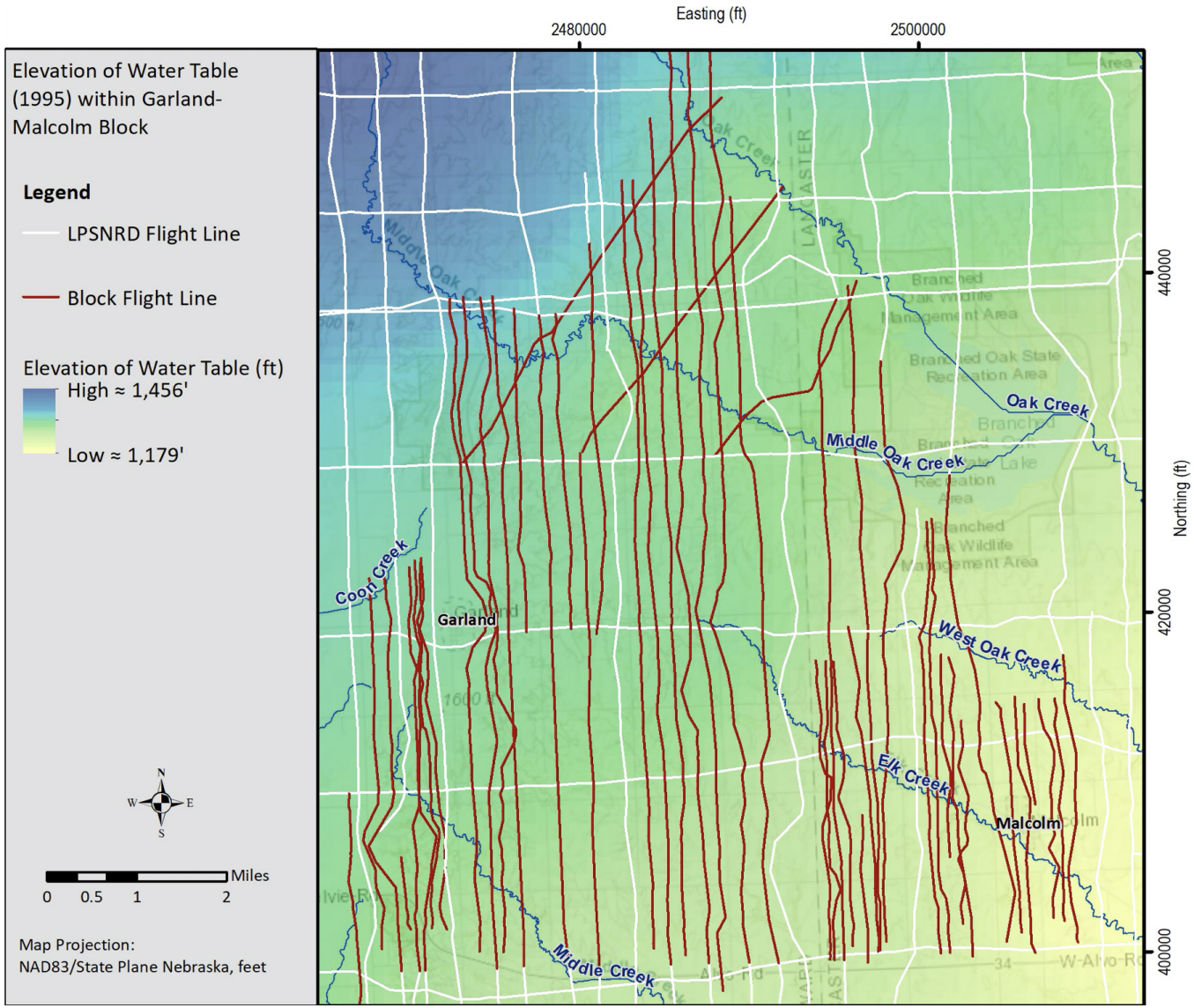


Figure 3-245. Map showing the CSD 1995 (NE-CSD, 1995) water table for the area and has a gradual slope from north to south. AEM Block flight lines are indicated by the red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

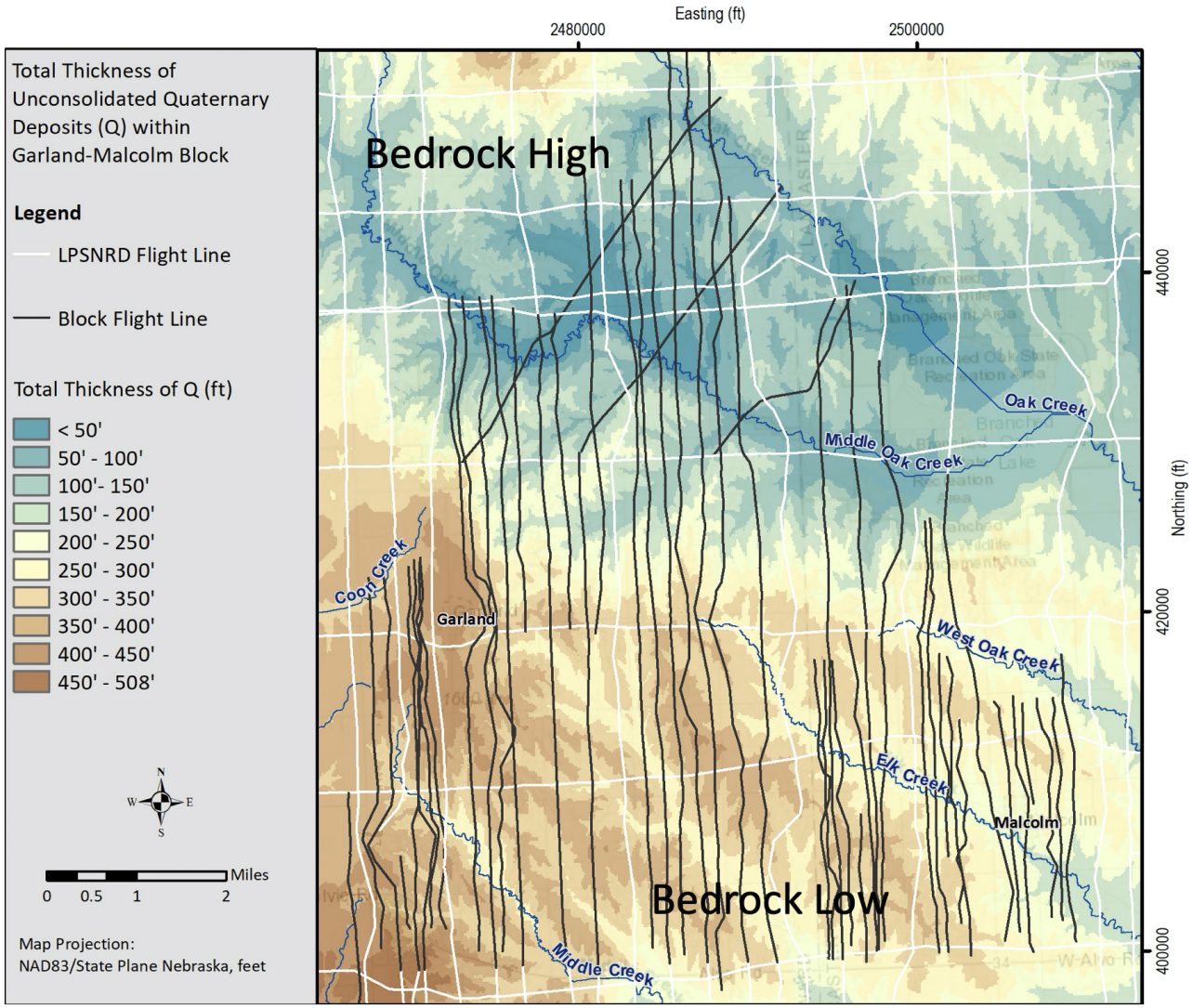


Figure 3-246. Map of the total thickness of the *Q* deposits within the 2018 Garland Malcolm Block AEM survey area. The greatest thickness is along the ground elevation highs to the southwest and south and is independent to bedrock high and low bedrock low within the area. The thin areas (~50-150 feet) of Q total thickness parallels the drainages of the area. Block flight lines are indicated by black lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

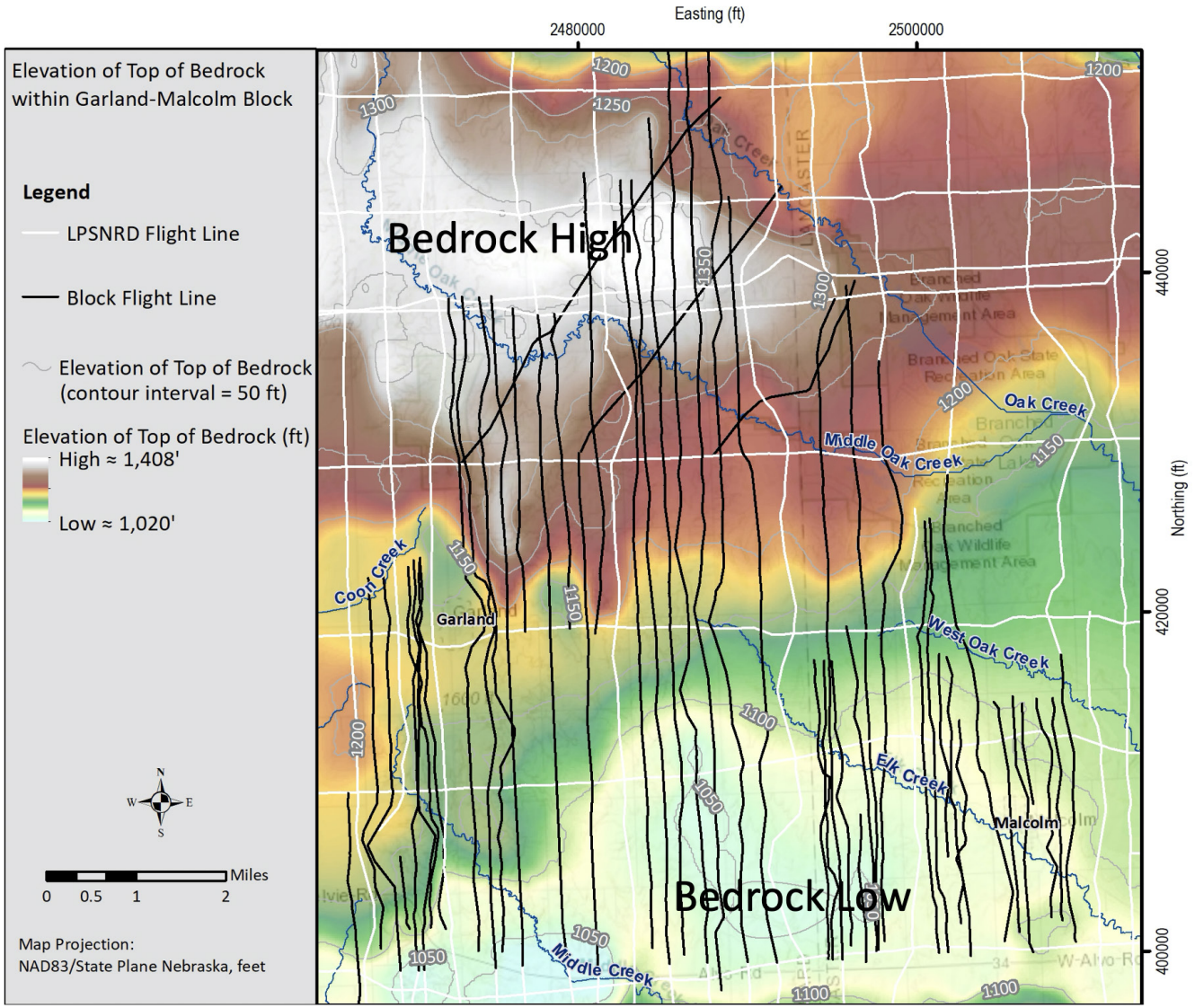


Figure 3-247. Map of the elevation of the top of bedrock within the 2018 Garland Malcolm Block AEM survey area. The bedrock surface slopes in general from a bedrock high to north to a bedrock low in the south. Block flight lines are indicated by red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

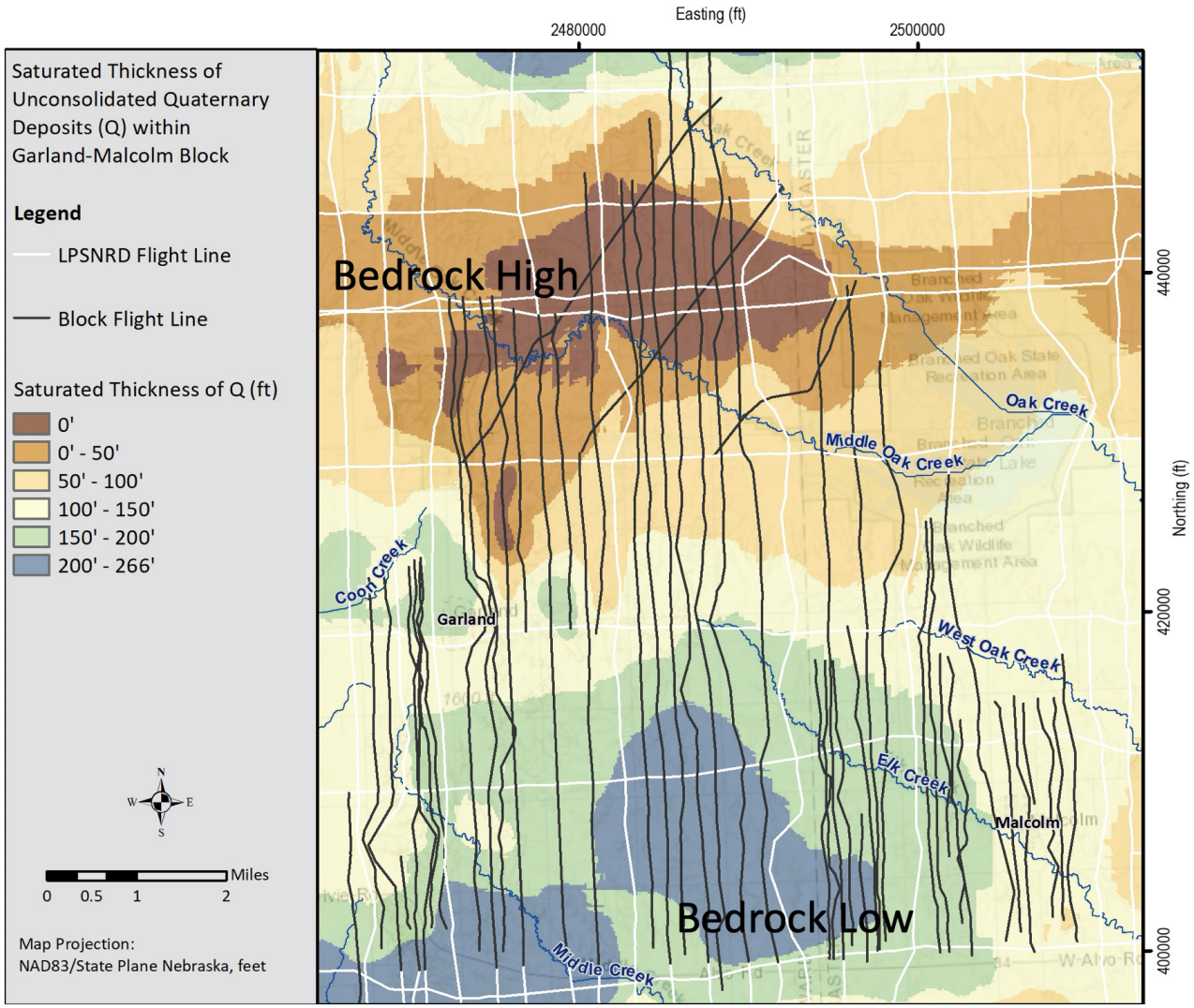


Figure 3-248. Map of the saturated thickness for all *Q* Aquifer Material for the Garland Malcolm Block. The thickness of these materials is thin and varies between 0 to 268 feet. The saturated thickness averages 0-150 feet across the area with the thickest area in the south. AEM Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Q*= Quaternary. AEM Block flight lines are indicated by the black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

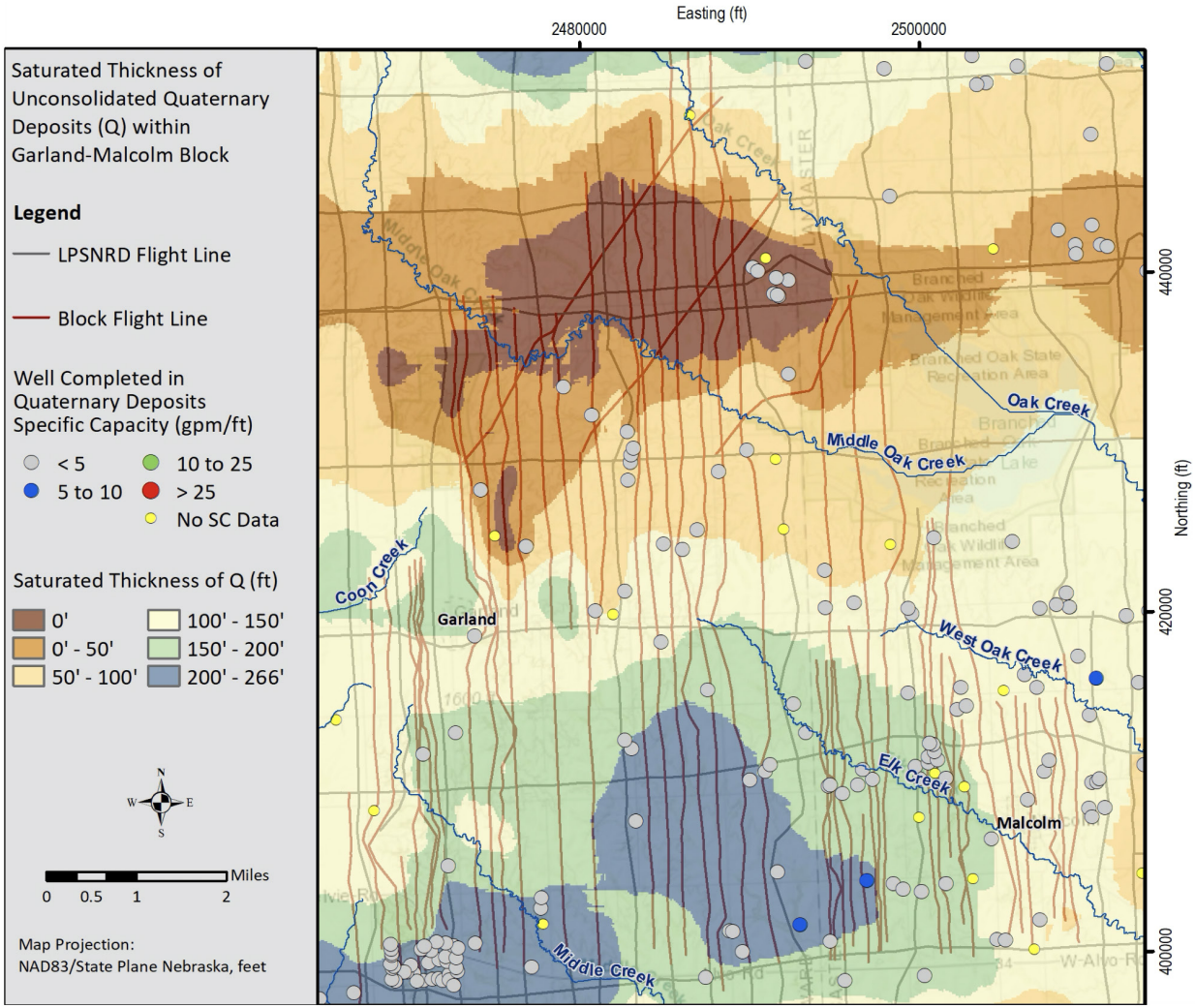


Figure 3-249. Map of the relationship between the saturated thickness of *Q* and the specific capacity in gpm/ft for wells completed in the *Q*. The majority of wells in the Garland Malcolm area have a with a specific capacity of <5 gpm/ft with 3 wells having a specific capacity of 5 to 10 gpm/ft. The *Q* is a poor aquifer for well development. AEM Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *Q*= Quaternary. AEM Block flight lines are indicated by the red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

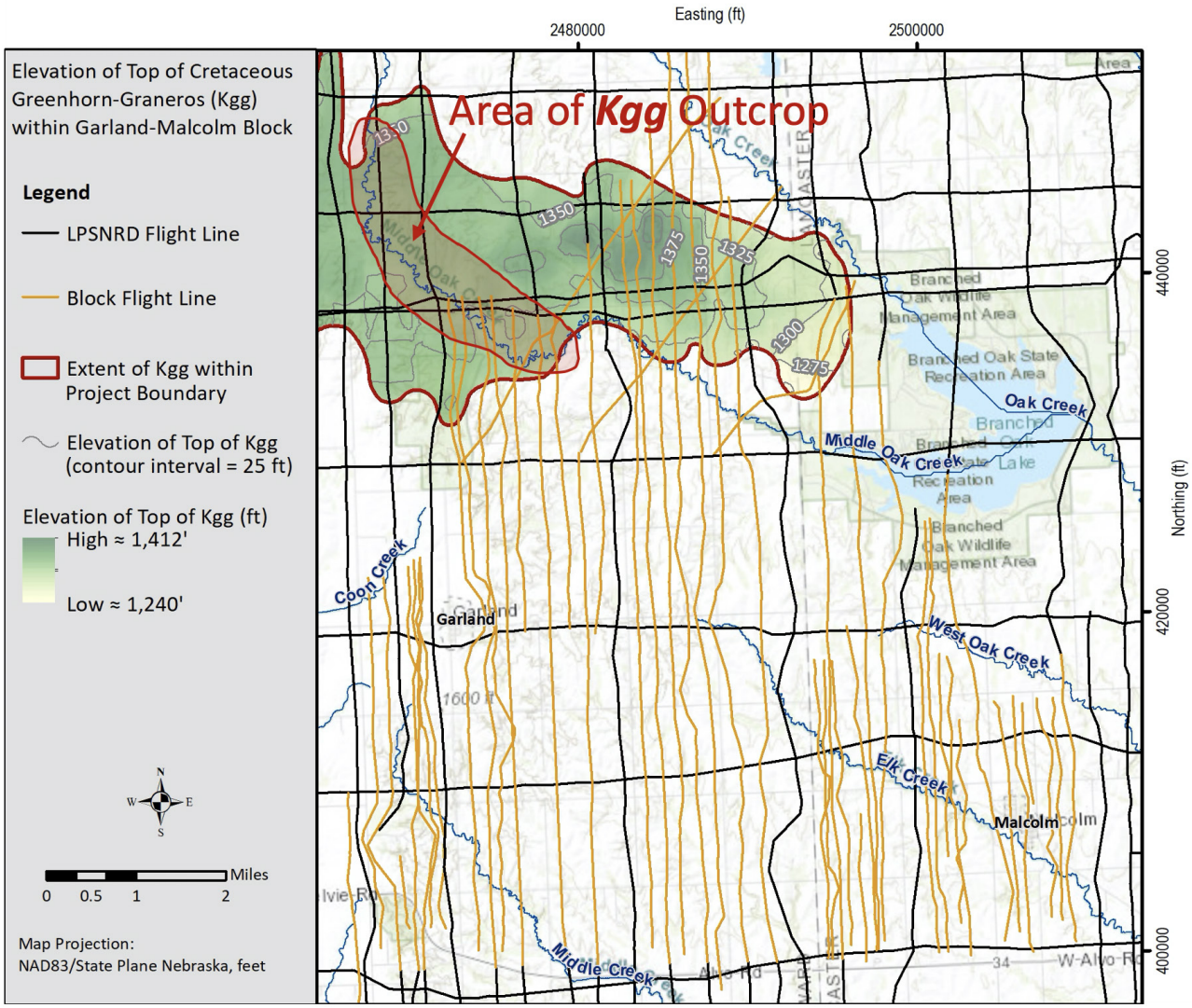


Figure 3-250. Map of the elevation of the top of *Kgg* in the Garland Malcolm Block and ranges in elevation from 1,240 to 1,412 feet. There are outcrops shown by the red shaded polygon of *Kgg* along Middle Oak Creek. AEM Block flight lines are indicated by the orange lines. The geologic unit present on this image includes the *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale. AEM Block flight lines are indicated by the orange lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

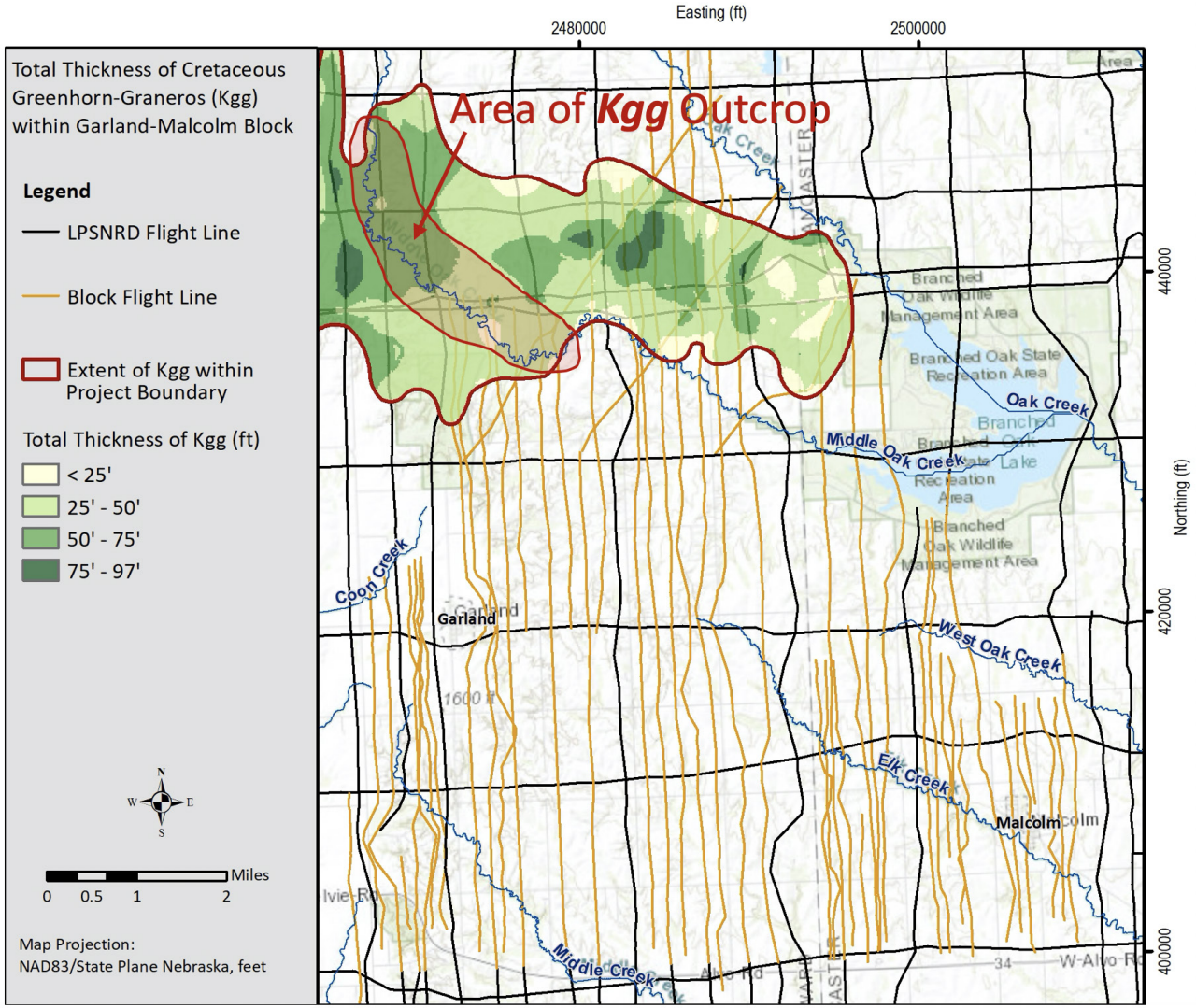


Figure 3-251. Map of the total thickness of the *Kgg* within the 2018 Garland Malcolm Block AEM survey area. The thickness of the *Kgg* varies from <50 to 508 feet with the thickest are in the southwest and thins in the north. Block flight lines are indicated by the orange lines. The geologic unit present on this image includes the *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale. Horizontal datum is NAD83 State Plane Nebraska (feet).

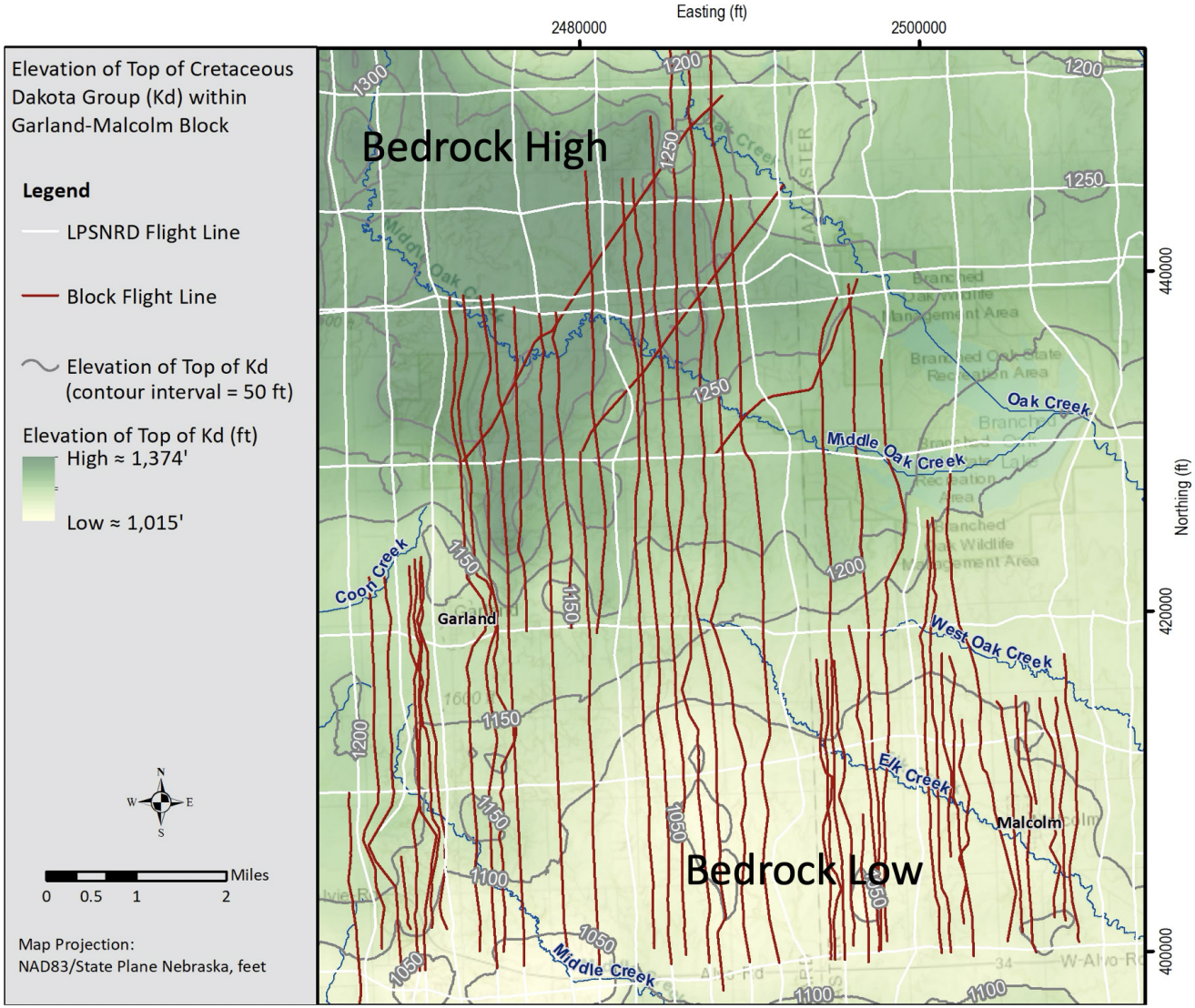


Figure 3-252. Map of the elevation of top of *Kd* in the Garland Malcolm Block which ranges from 1,015 to 1,374 feet. AEM Block flight lines are indicated by the red lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. AEM Block flight lines are indicated by the red lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

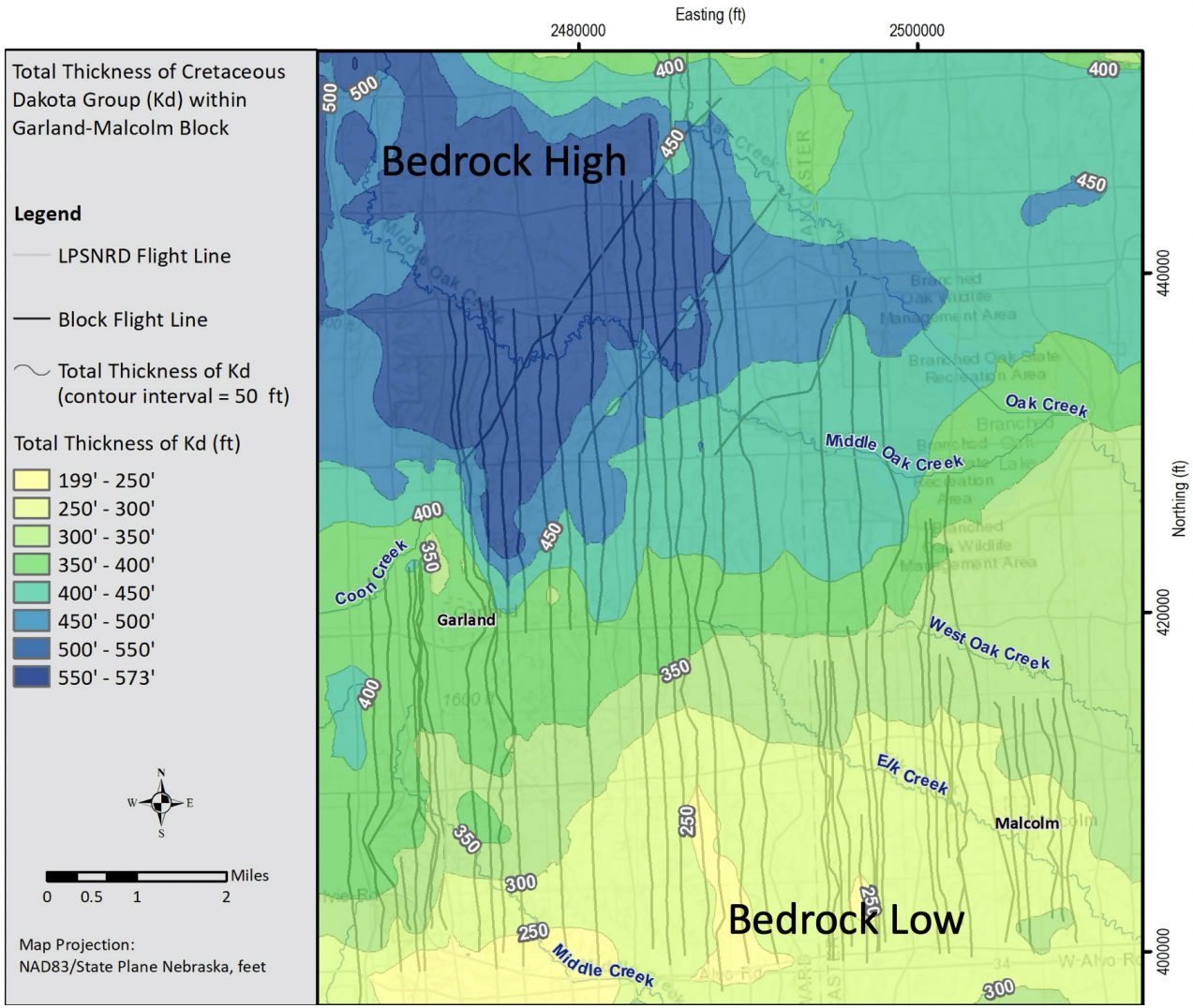


Figure 3-253. Map of the total thickness of the *Kd* within the 2018 Garland Malcolm Block AEM survey area. The thickness of the *Kd* varies from 102 to 486 feet with the thickest are in the northwest corner and thins in the southeast. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

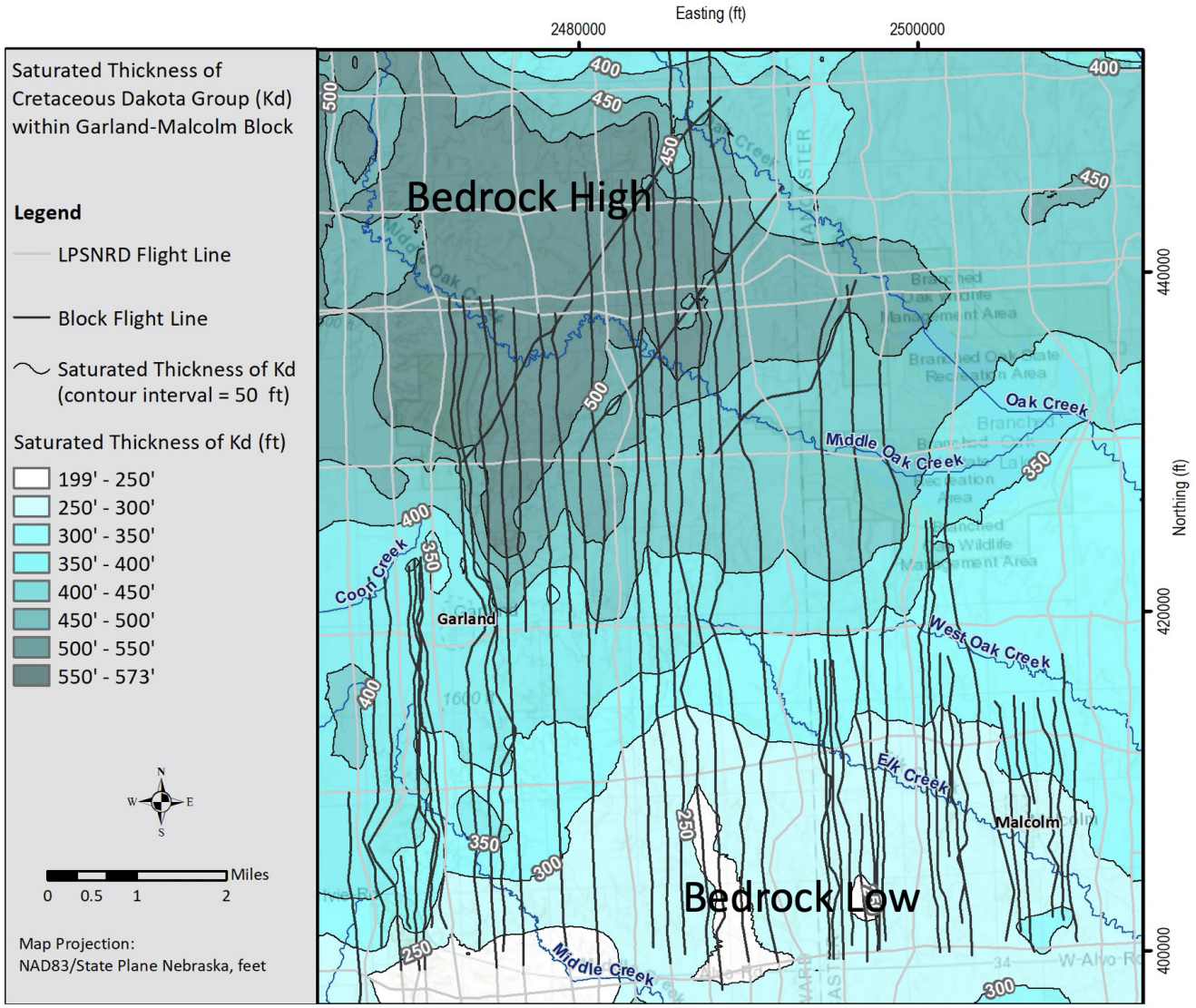


Figure 3-254. Map of saturated *Kd* thickness for the Garland Malcolm Block. The thickness varies from 199 to 573 feet with the thickest area in the northwest. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

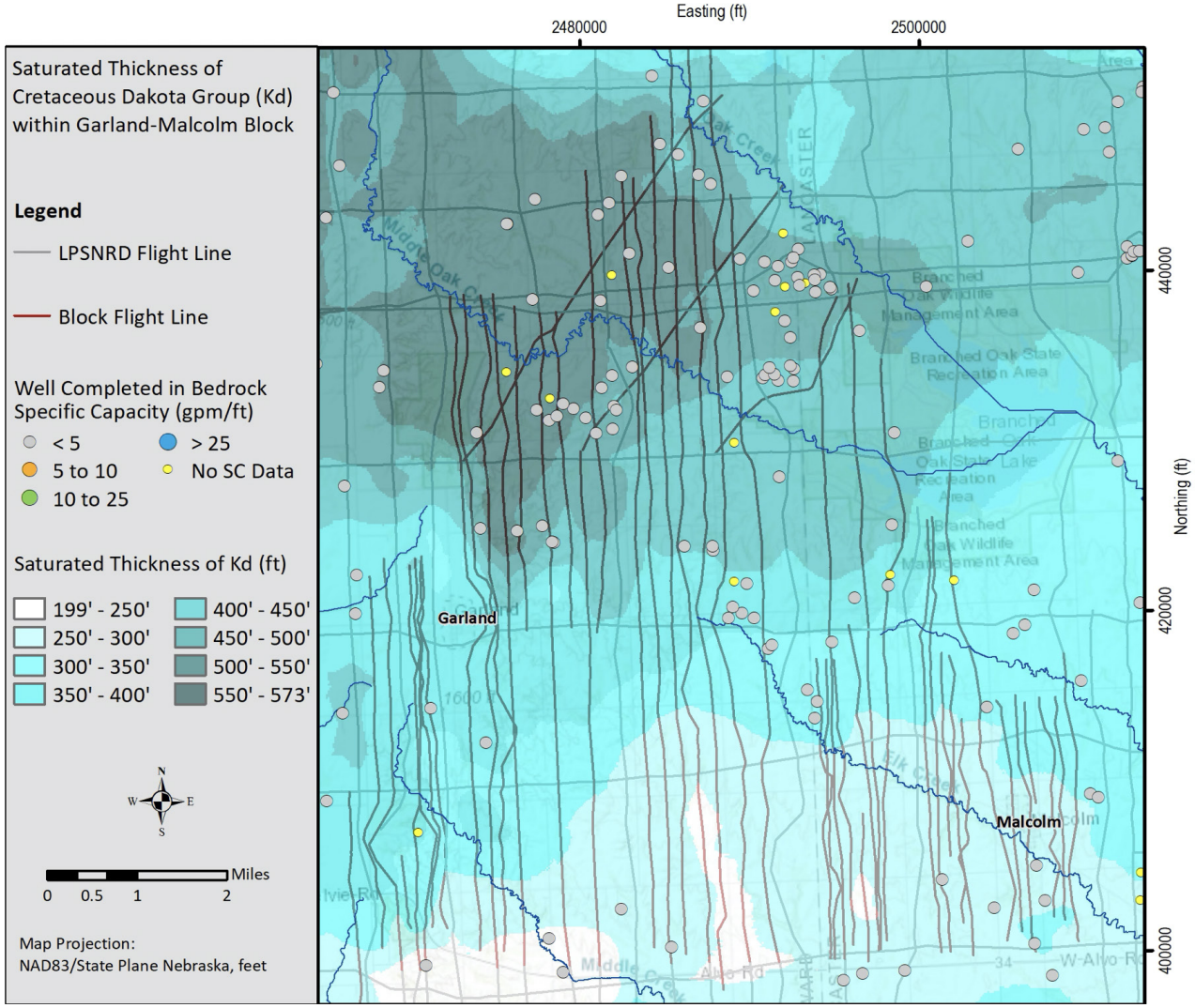


Figure 3-255. Map of the relationship between the saturated thickness of *Kd* and the specific capacity in gpm/ft for wells completed in the *Kd*. Careful evaluation of the wells shows all wells in the Garland Malcolm area have a with a specific capacity of <5 gpm/ft. The best locations for well development are in the thick sandstone/sand dominant zones of the *Kd*. Block flight lines are indicated by the black lines. The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group. Horizontal datum is NAD83 State Plane Nebraska (feet).

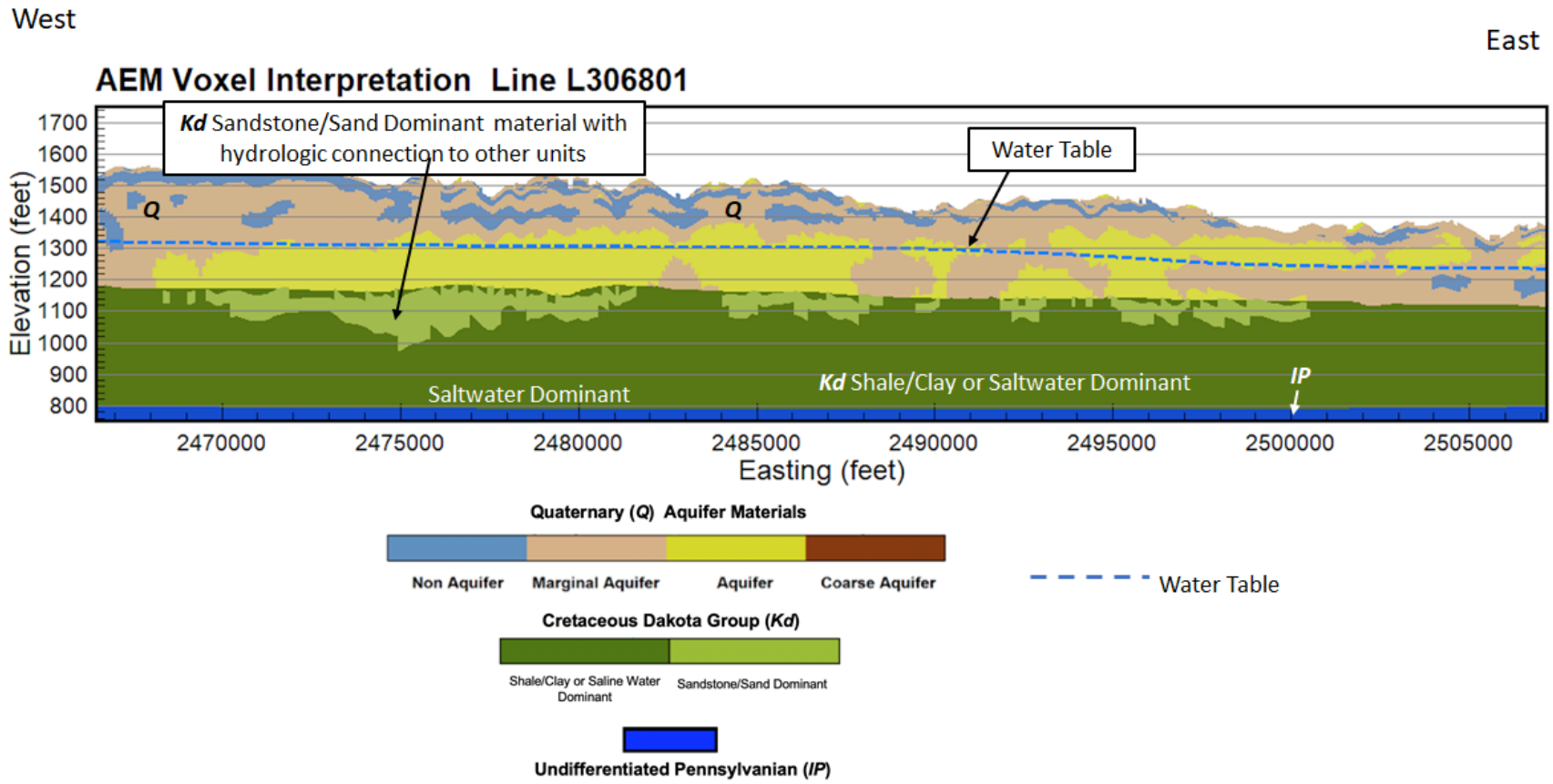


Figure 3-256. Interpreted 2D profile L306801 is an east-west line south of Garland, Nebraska. The figure shows the subsurface of the area along the line and the *Q* materials that are present along the line. They are made up ~50/50 split of till and loess marginal and non-aquifer material ~ 200 feet thick and a discontinuous aquifer material layer that is a ~100 to ~175-foot thick across the profile lying upon the *Kd*. The CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

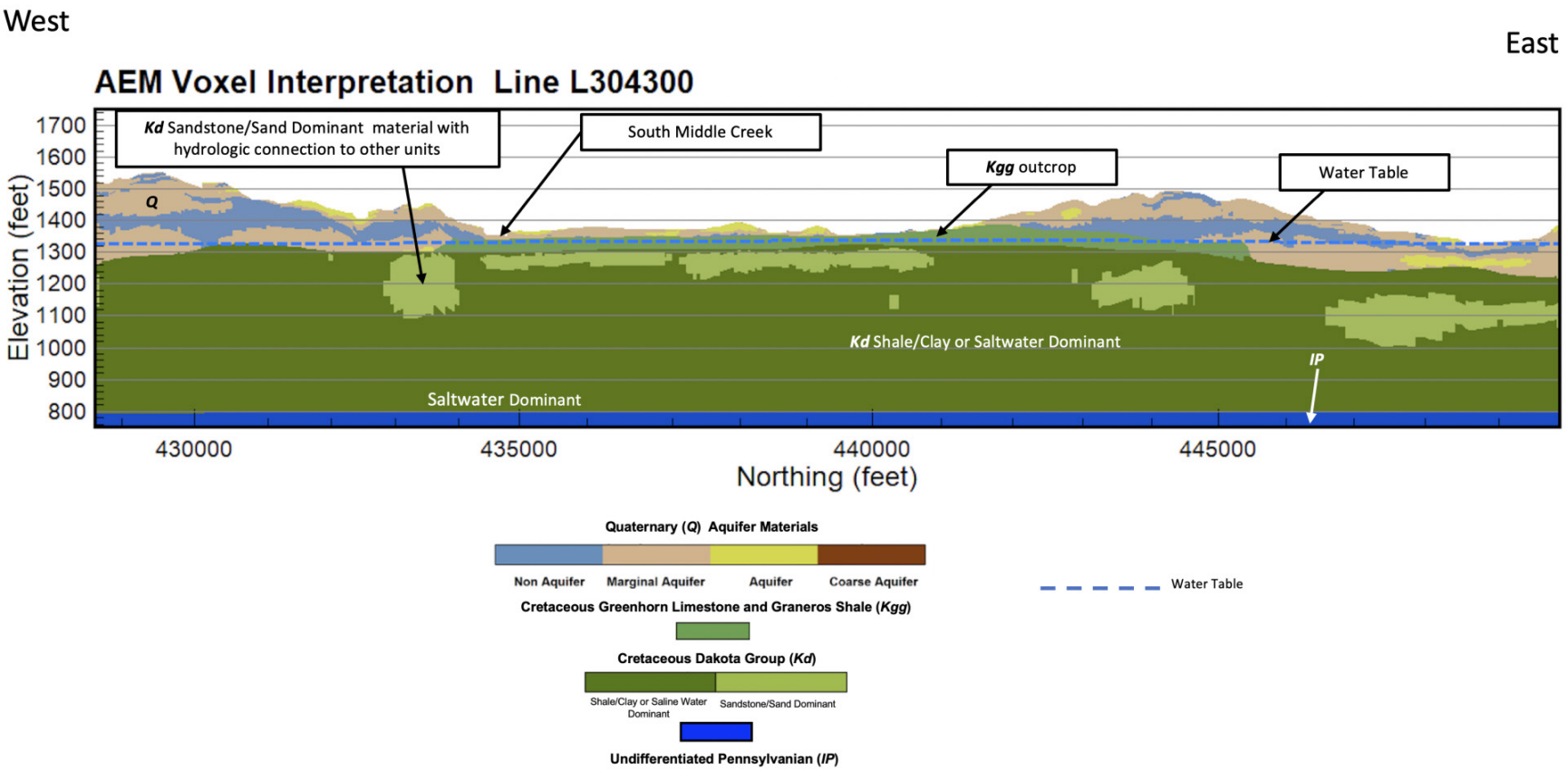


Figure 3-257. Interpreted 2D profile L304300 is an east-west profile in the northernmost diagonal line north of Garland, Nebraska. The figure shows the subsurface of the area along the line and the *Q* materials that are present along the line. They are mostly thin till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material. These Q materials have ~10 to ~50 feet of saturation with a high-water table elevation that slopes from west to east. There is a *Kgg* outcrop in the center of the line. The NE-CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group and IP= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

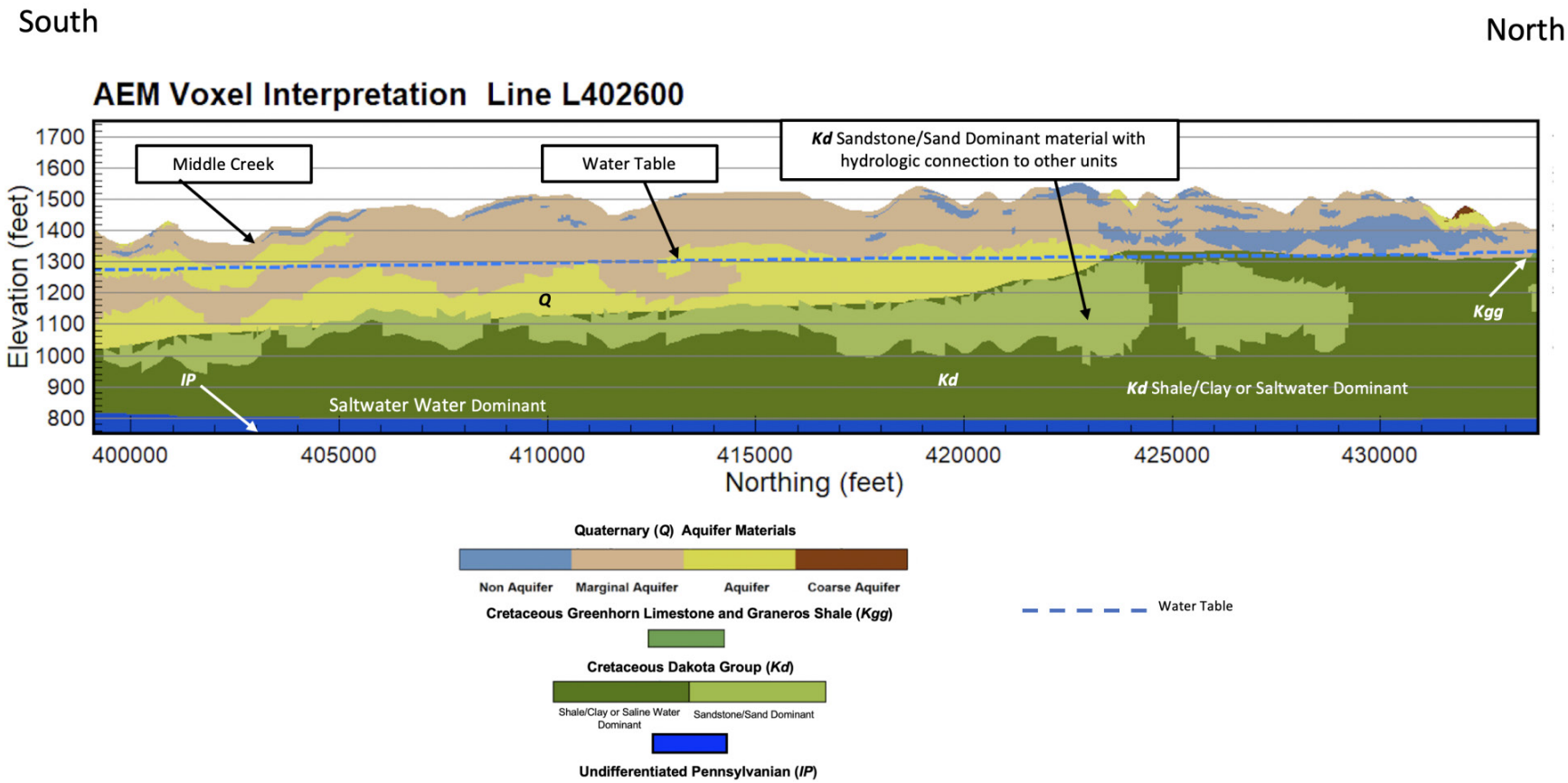


Figure 3-258. Interpreted 2D profile L402600 is a north-south profile just west of Garland, Nebraska. The figure shows the subsurface of the area along the line and the *Q* materials that are present along the line. They are mostly till and loess made up of marginal and non-aquifer materials with small amounts of aquifer material mixed in and a basal *Q* aquifer material layer extending from the south to northing ~424000. The basal *Q* materials have up to ~250 feet of saturation. The NE-CSD 1995 water table is indicated as a dashed blue line on the profiles. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Horizontal datum is NAD83 State Plane Nebraska (feet).

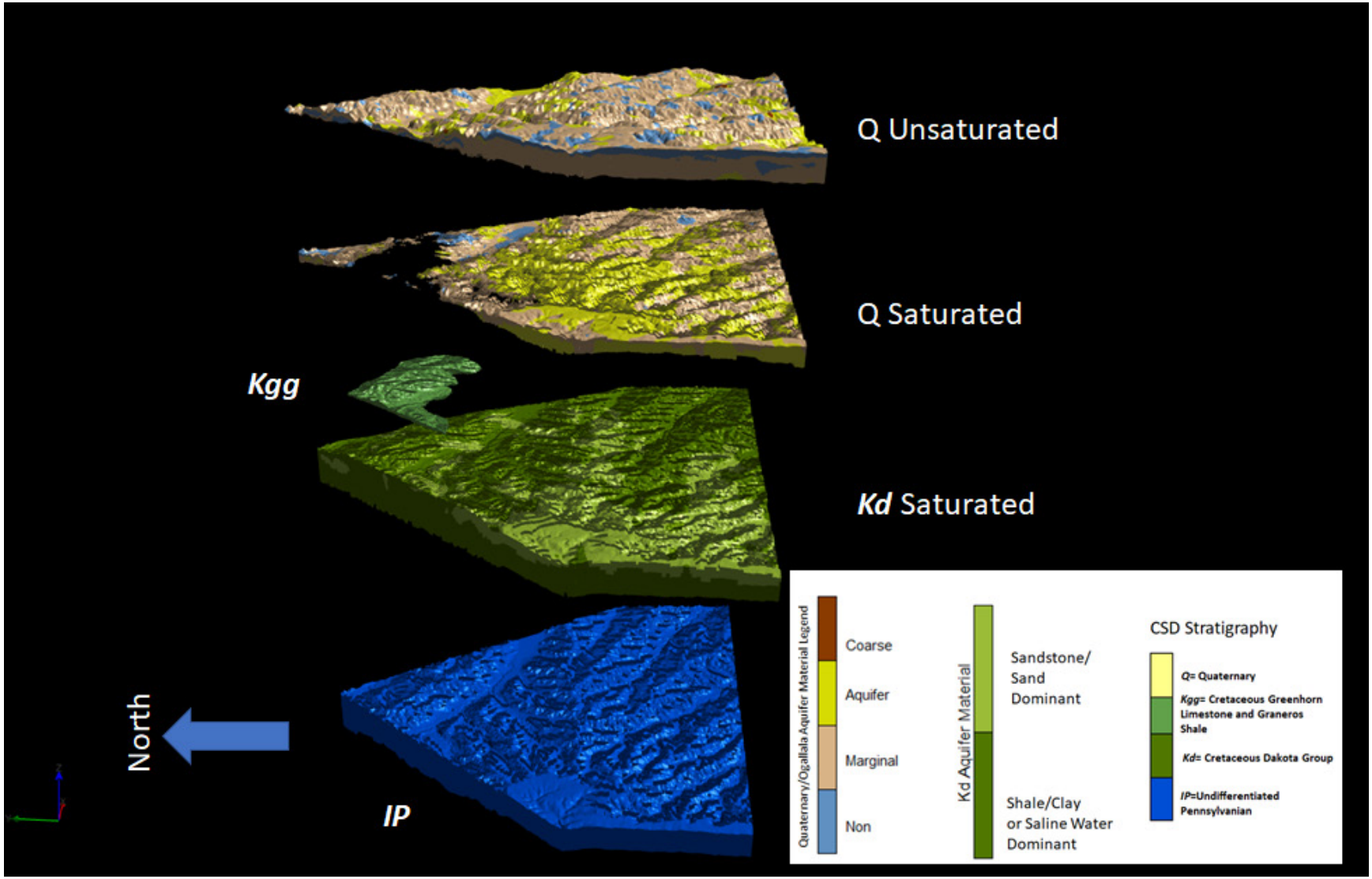


Figure 3-259. 3D exploded voxel model of the Garland Malcolm Block looking northwest showing Unsaturated *Q*, Saturated *Q*, *Kgg*, Saturated *Kd*, and *IP*. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x. The figure is not to scale.

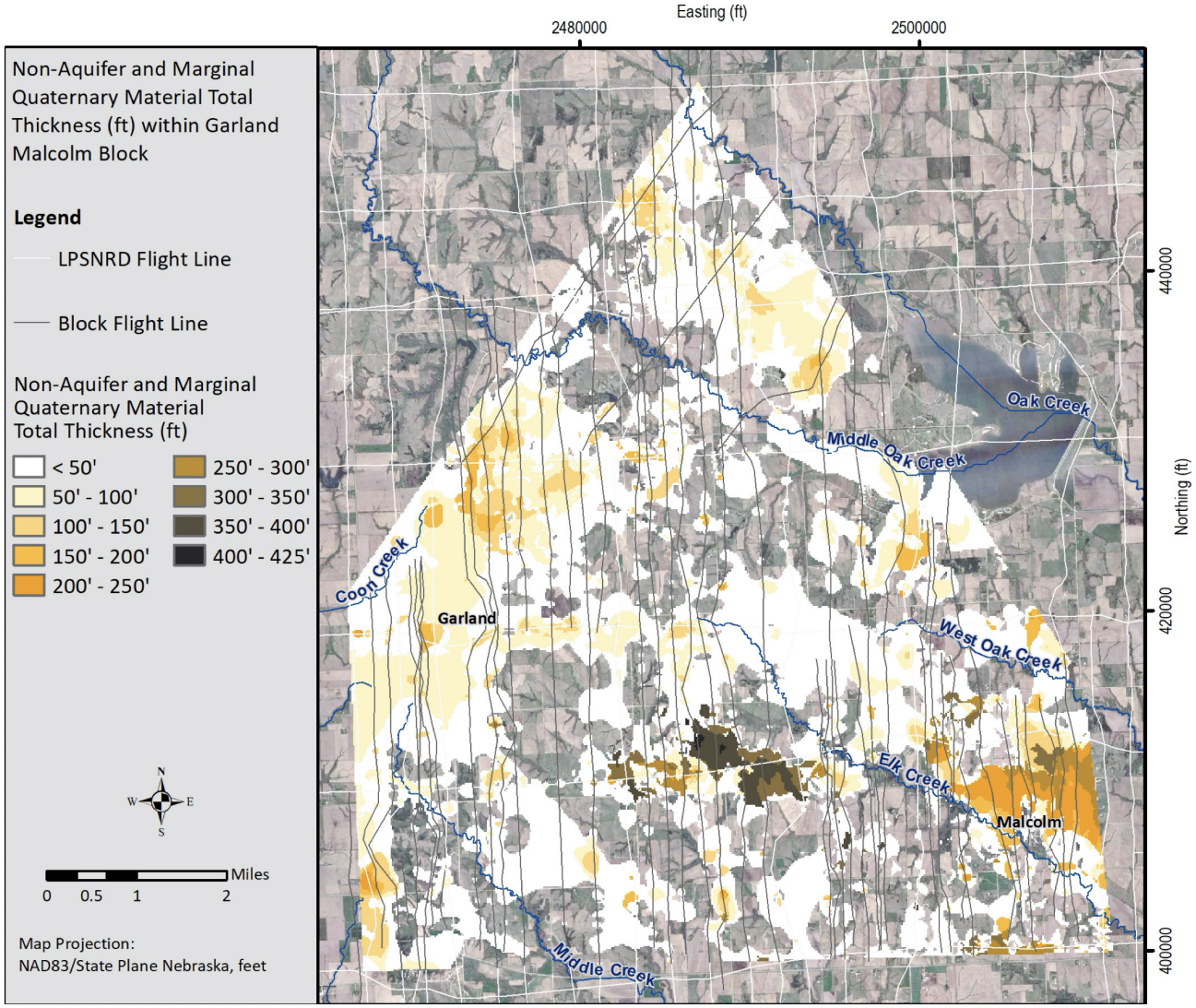


Figure 3-260. Map of the distribution of *Q* Marginal and Non-Aquifer Materials total thickness in the Garland Malcolm Block. These materials are discontinuous and range in thickness from <50 to 425 feet. Block flight lines are indicated by the grey lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

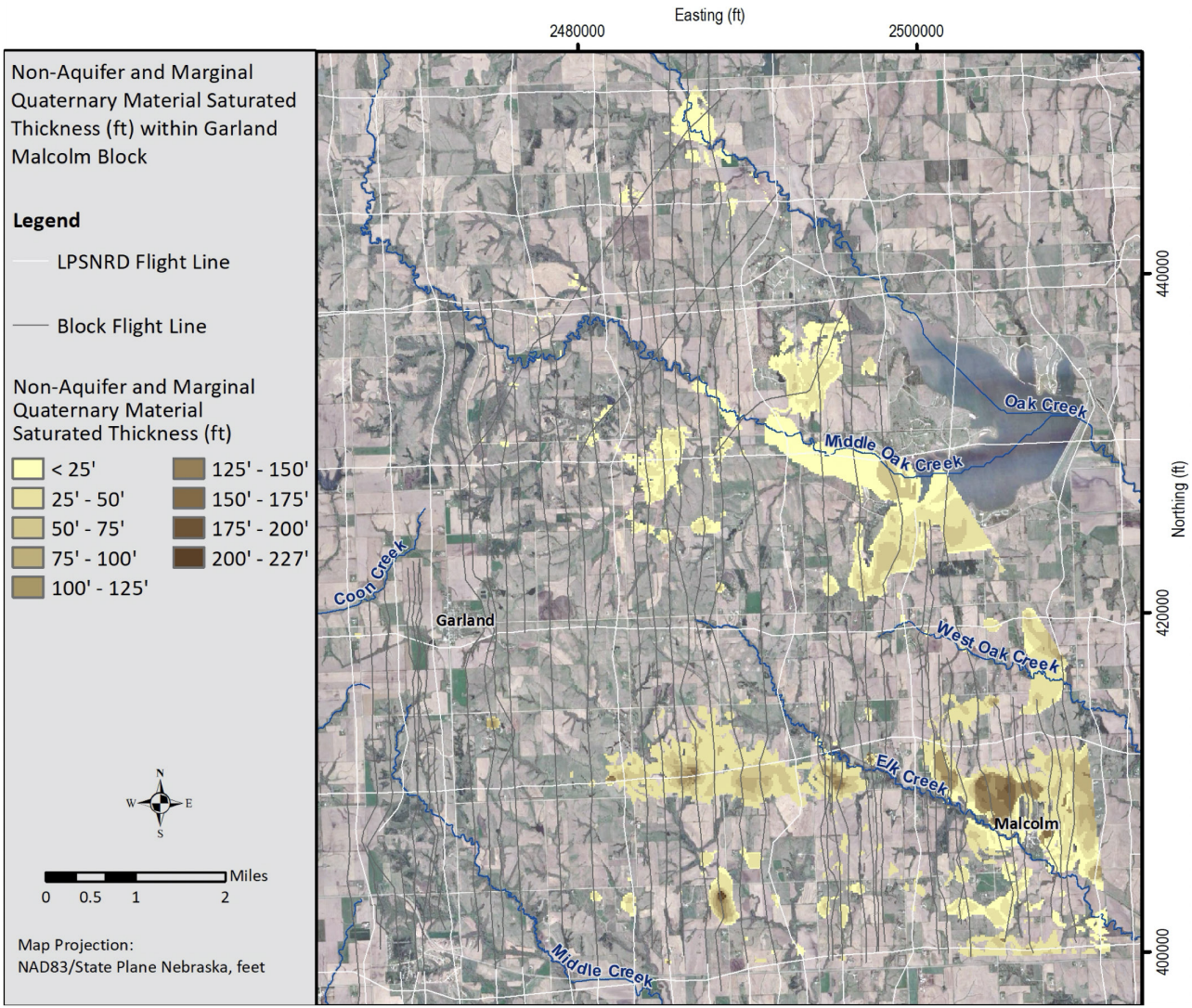


Figure 3-261. Map of the distribution of the saturated thickness of *Q* Marginal and Non-Aquifer materials in the Garland Malcolm Block. The distribution is discontinuous and thick near Elk Creek. These materials range in thickness from <25 to 227 feet. Block flight lines are indicated by the grey lines. The geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

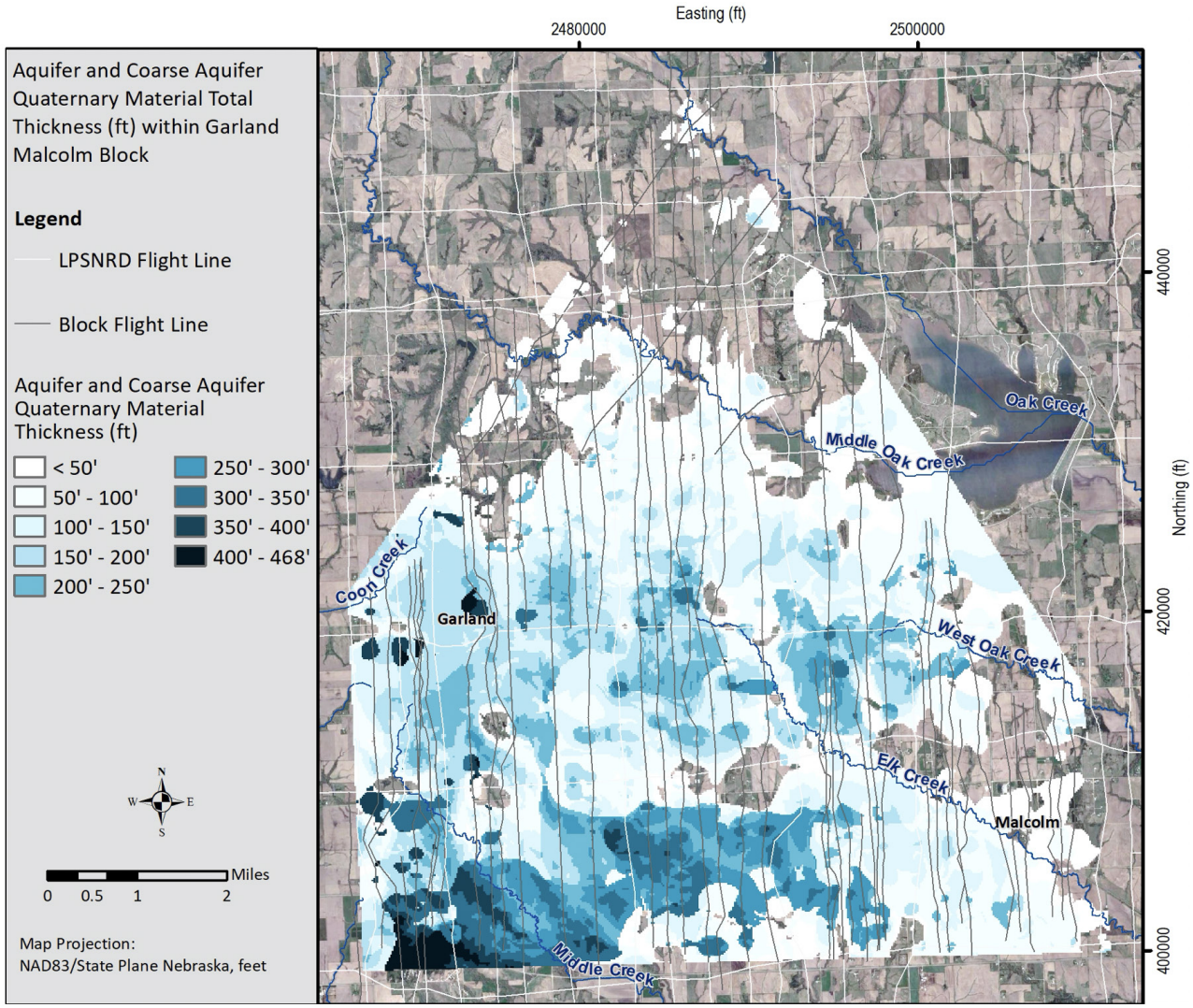


Figure 3-262. Map the thickness of the *Q* Aquifer and Coarse Aquifer Materials which are nearly continuous across the area except in the north with the thickest deposits spread across the south part of the survey area. These materials range in thickness from <50 to 468 feet. Block flight lines are indicated by the grey lines. Geologic unit present on this image includes the *Q*= Quaternary. Horizontal datum is NAD83 State Plane Nebraska (feet).

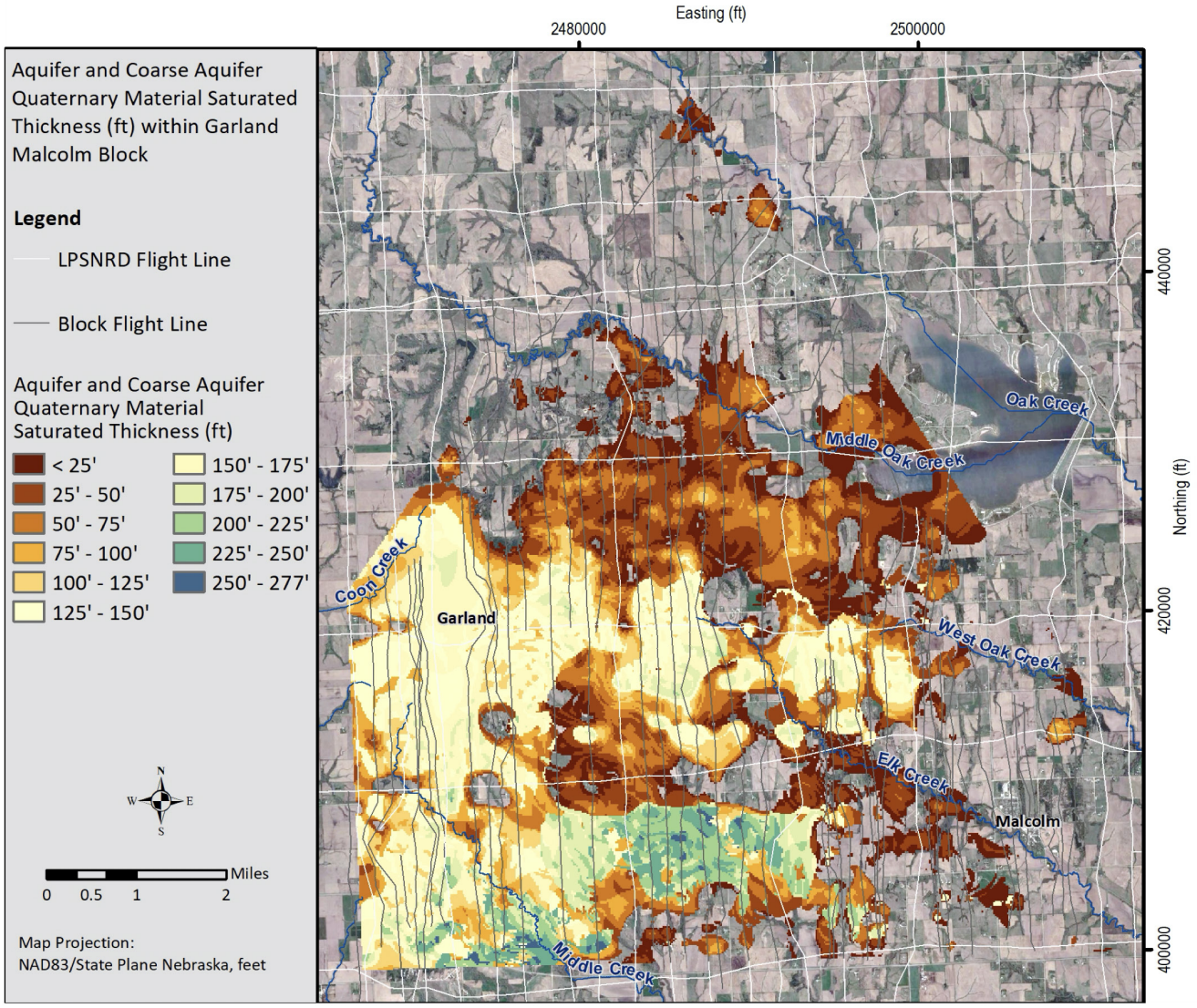


Figure 3-263. Map of the *Q* saturated Aquifer and Coarse Aquifer Materials in the Garland Malcolm Block which are thin and range in thickness from <25 to 277 feet. The geologic unit present on this image includes the *Q*= Quaternary. Block flight lines are indicated by the grey lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

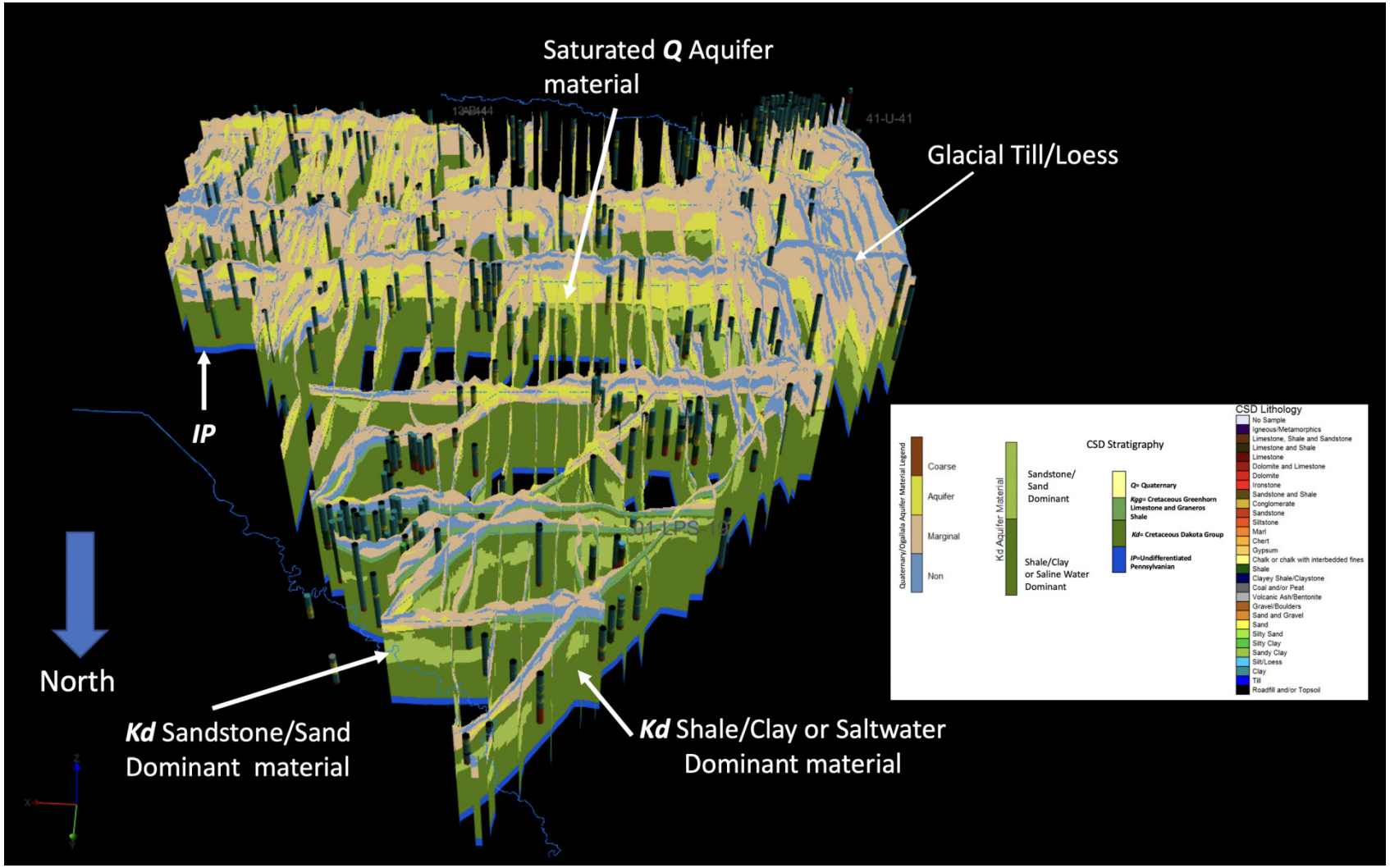


Figure 3-264. 3D fence diagram looking south of the *Q* Marginal and Non-Aquifer Material with a 3D voxel model of the *Q* Aquifer and Coarse Aquifer Materials lying upon the *Kgg*, *Kd,* and *IP* of the Garland Malcolm Block AEM survey area. Includes the flight lines and the interpreted hydrostratigraphic profiles along with CSD and NE-DNR borehole lithology data. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

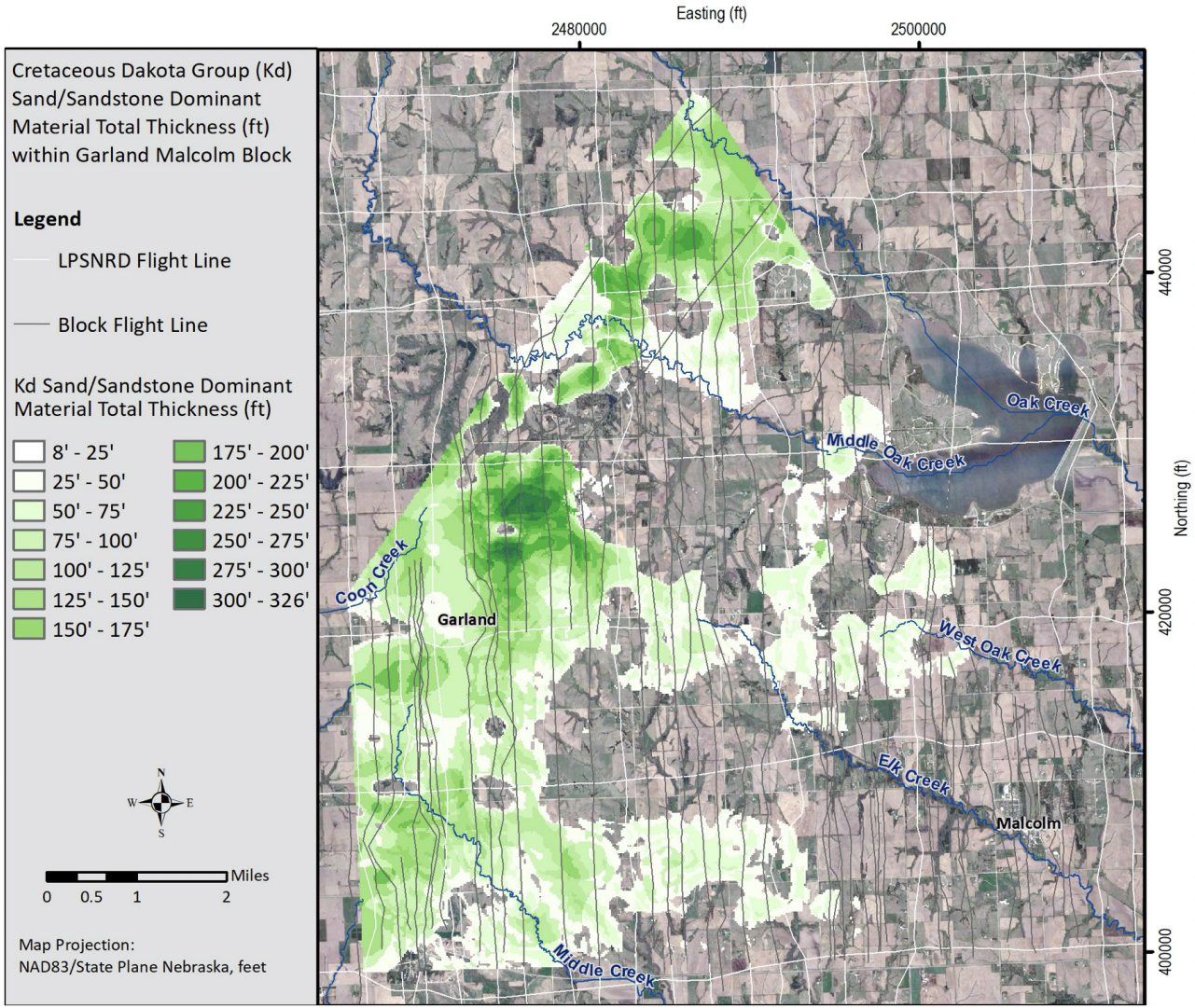


Figure 3-265. Map of the thickness for *Kd* Sandstone/Sand Dominant deposits which is discontinuous across the Garland Malcolm survey area. These deposits are saturated and vary in thickness from 8 to 326 feet and are discontinuous across the block. Block flight lines are indicated by the black lines. Horizontal datum is NAD83 State Plane Nebraska (feet). The geologic unit present on this image includes the *Kd*= Cretaceous Dakota Group.

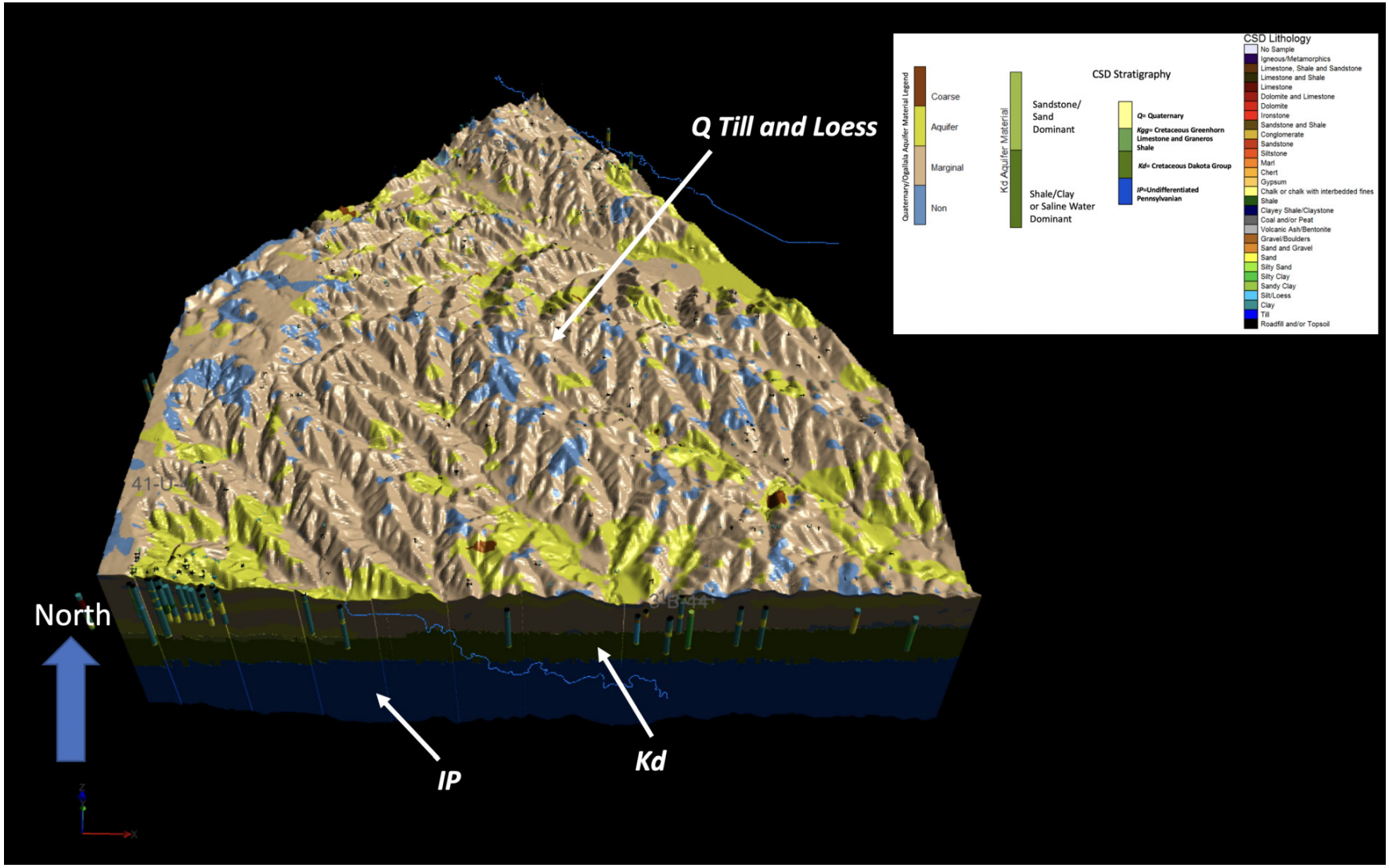


Figure 3-266. 3D voxel model view to the north showing the *Q*, *Kgg*, *Kd* and *IP* in the Garland Malcolm Block. The geologic units present on this image include *Q*= Quaternary, *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

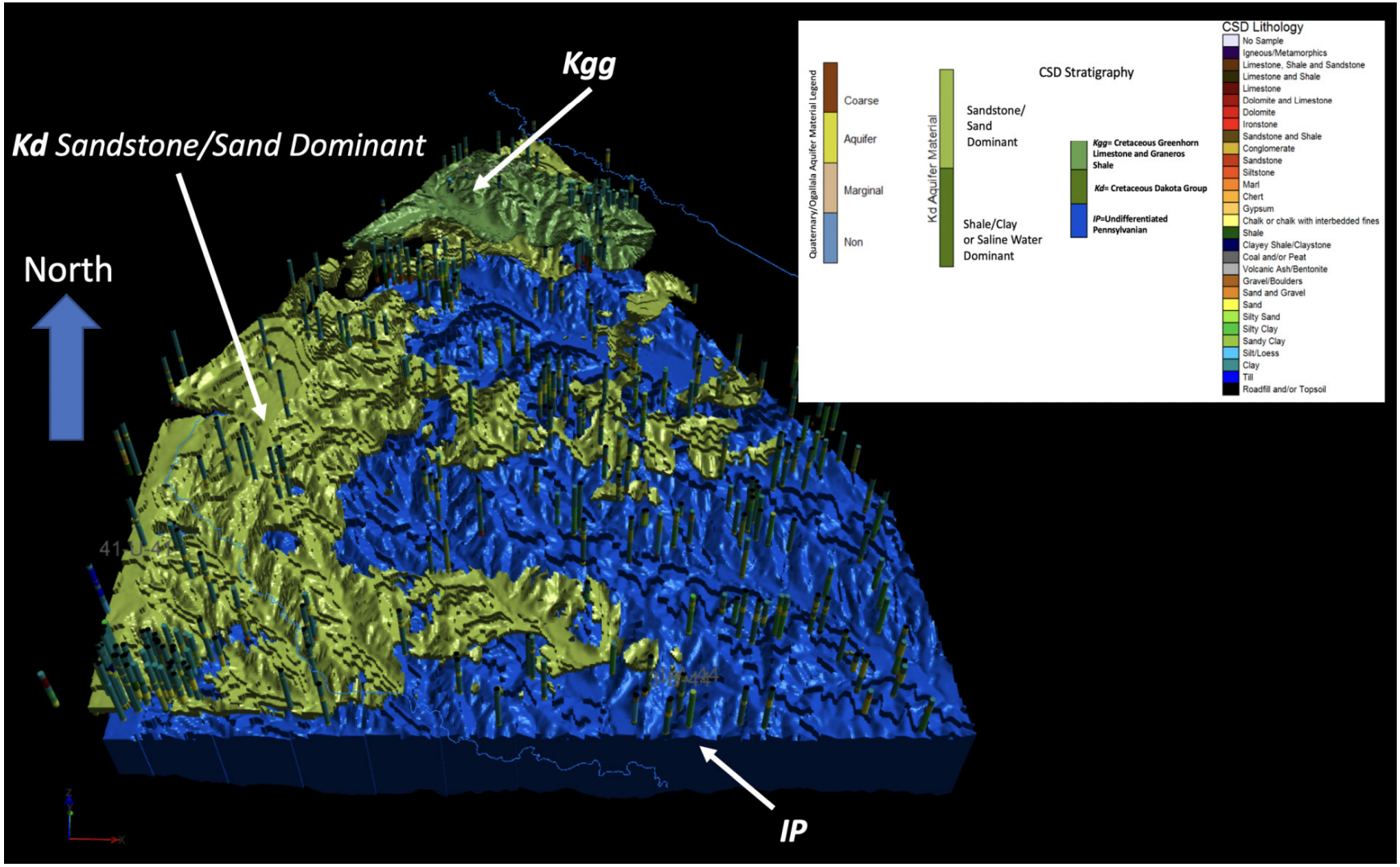


Figure 3-267. 3D voxel model looking north showing the thickness for *Kgg*, *Kd* and *IP* materials in the Garland Malcolm Block. This shows the limited coverage of the *Kgg* and the *Kd* sandstone/sand dominant materials. The geologic units present on this image include *Kgg*= Cretaceous Greenhorn Limestone and Graneros Shale, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

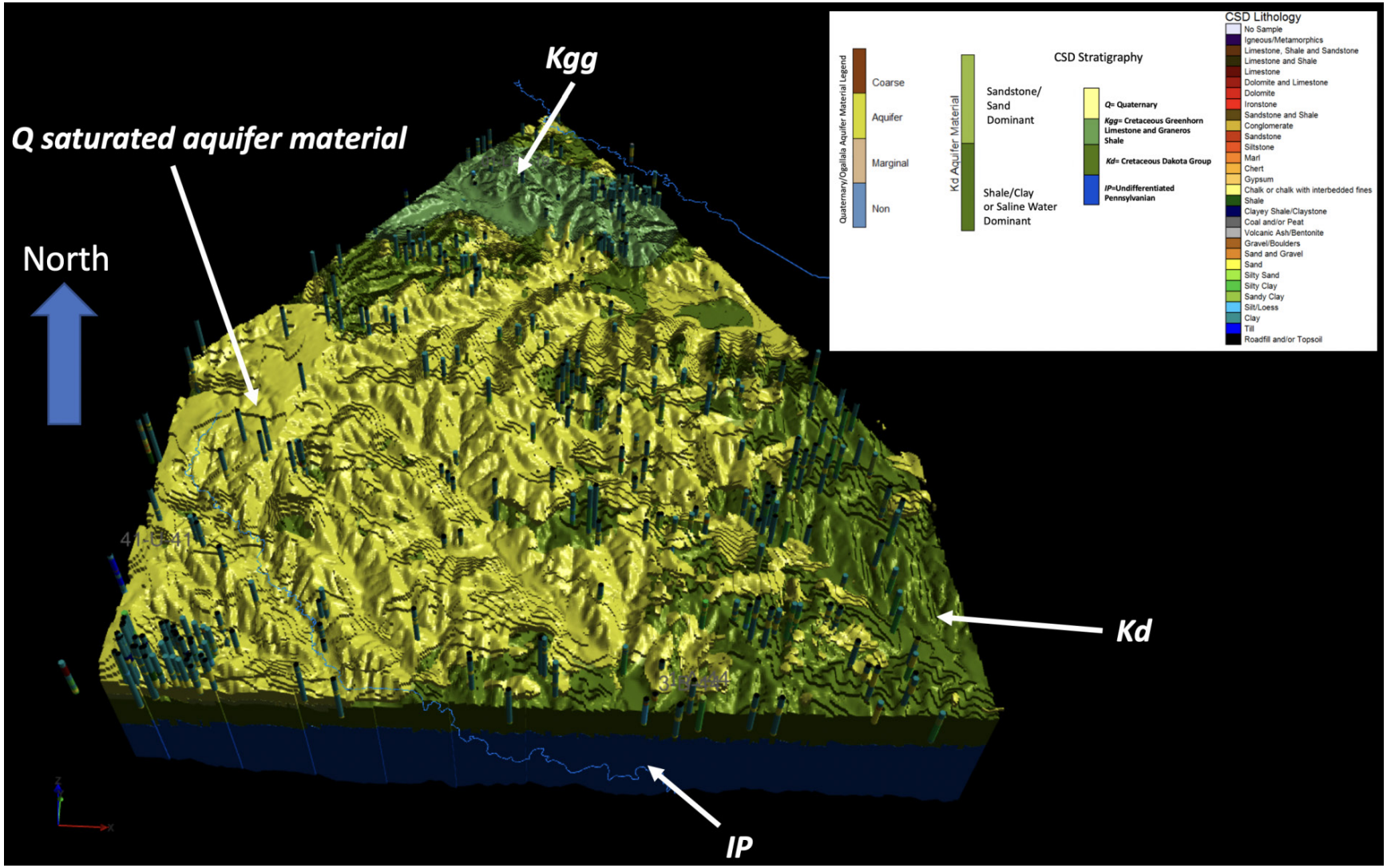


Figure 3-268. 3D voxel model looking north showing the *Q* saturated thickness and *Kgg*, *Kd* and *IP* materials in the Garland Malcolm Block. The geologic units present on this image include *Q*= Quaternary, *Kd*= Cretaceous Dakota Group, and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

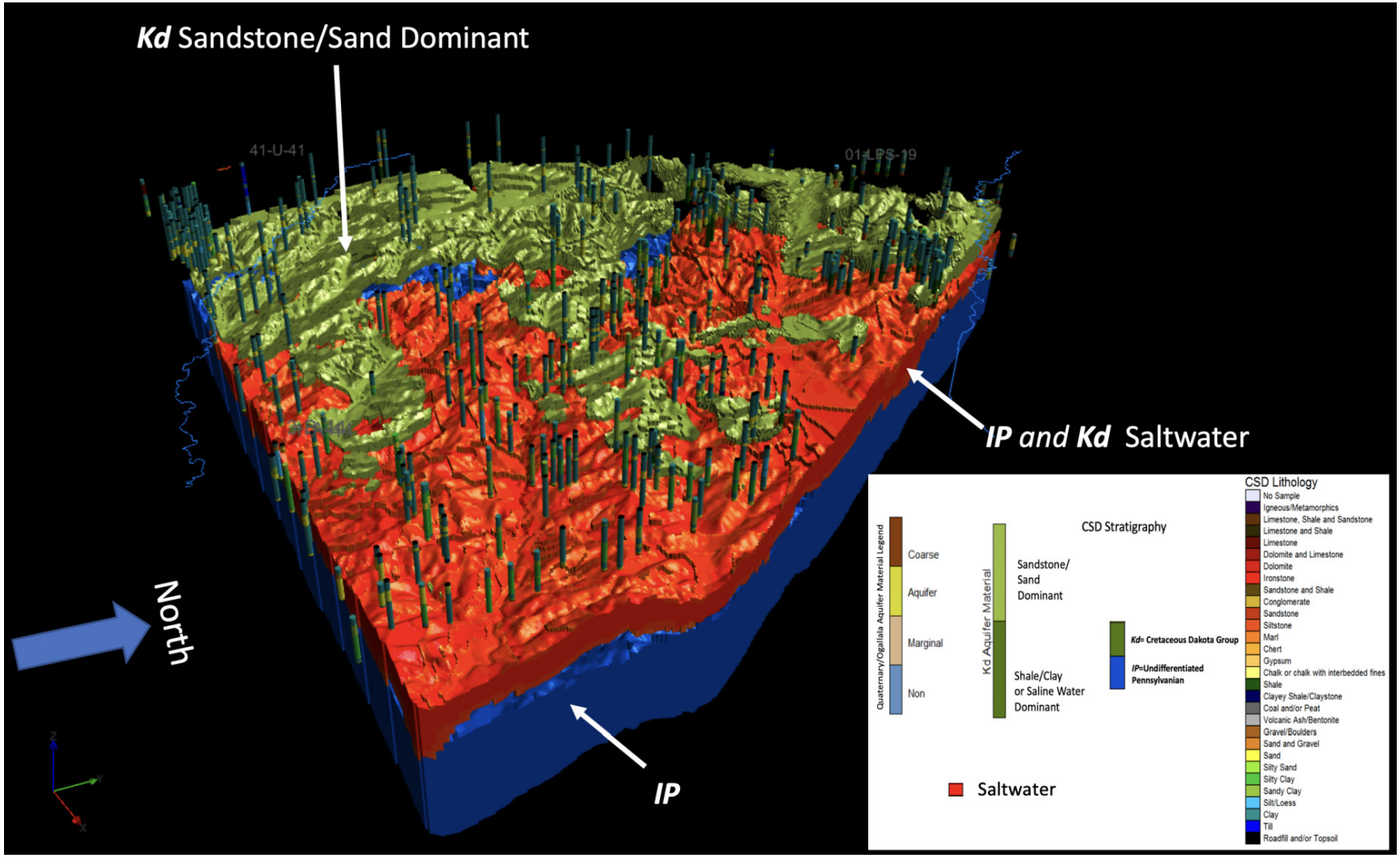


Figure 3-269. 3D voxel model looking northwest showing saltwater areas to be nearly continuous across the Garland Malcolm Block area and affecting the *IP* and *Kd*. The geologic units present on this image include *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x.

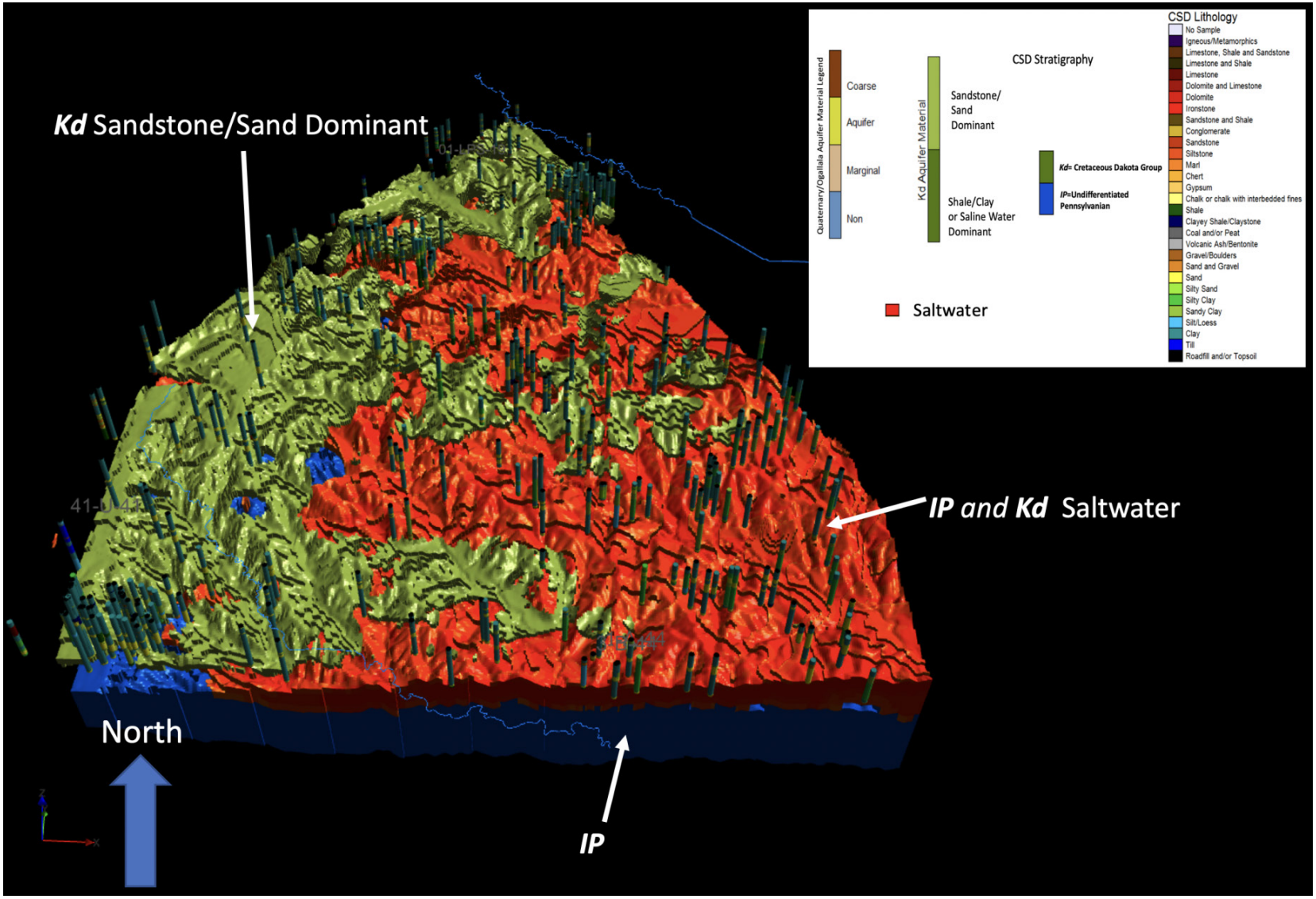


Figure 3-270. 3D voxel model looking north showing saltwater areas to be nearly continuous across the Garland Malcolm Block area and affecting the *IP* and *Kd*. The geologic units present on this image include *Kd*= Cretaceous Dakota Group and *IP*= Undifferentiated Pennsylvanian. Vertical exaggeration (VE) = 10x. T

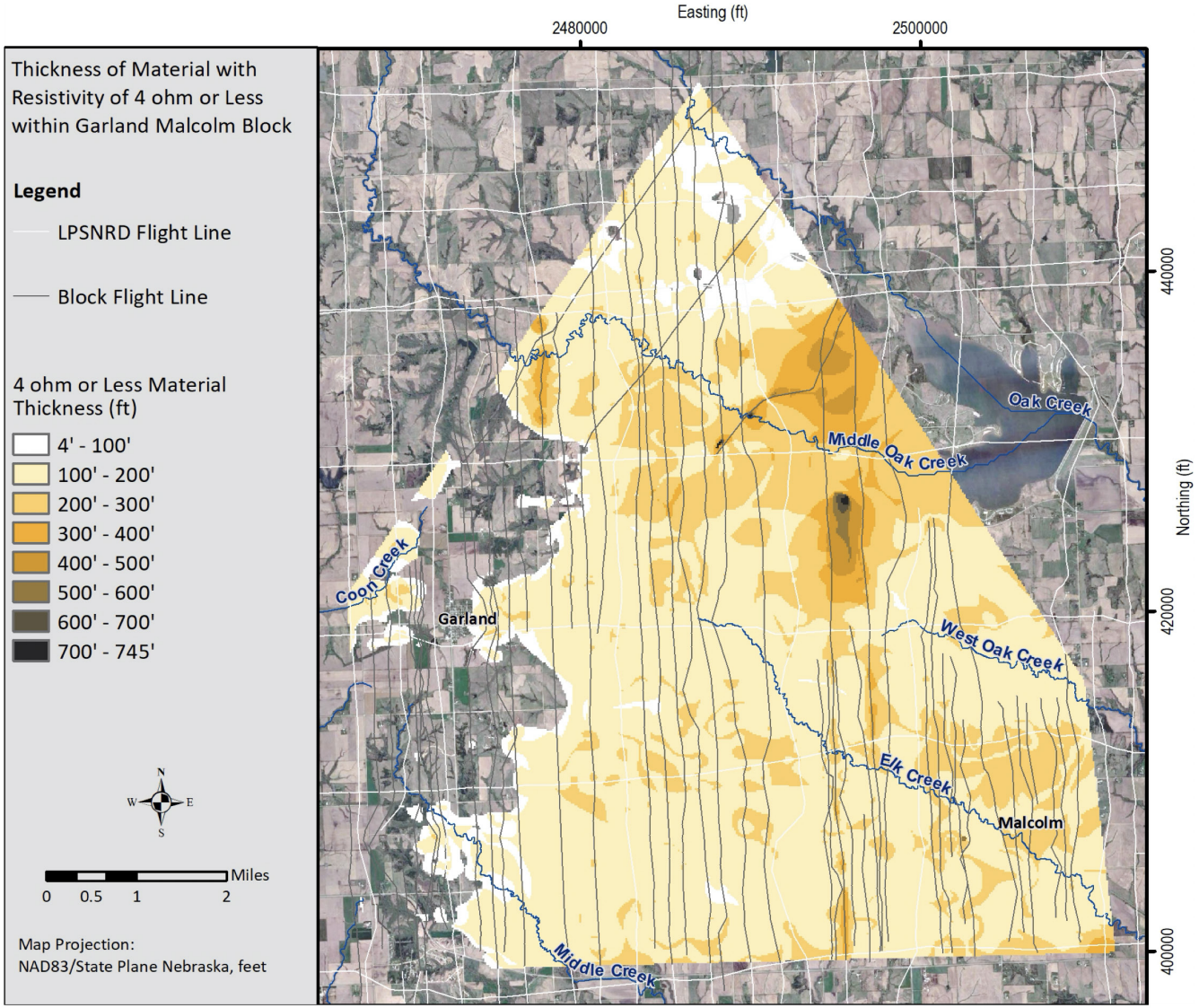


Figure 3-271. Thickness map of voxel model of the saltwater-affected areas present across most of the Garland Malcolm Block AEM survey area. These deposits vary in thickness from 4 to 745 feet and affect the *Kd*= Cretaceous and *IP*= Undifferentiated Pennsylvanian. Block flight lines are indicated by the black lines. Horizontal datum is NAD83 State Plane Nebraska (feet).

3.2.8 Estimation of Aquifer Volume and Water in Storage for the LPSNRD Ceresco, Davey Raymond, Denton, Dwight South and Garland Malcolm AEM Block Areas

The 3D digital representation of the subsurface resulting from the AEM method provides users the ability to more accurately estimate total unsaturated and saturated aquifer volume and the amount of extractable water present. The Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcolm Block AEM survey areas were mapped at high resolution for this purpose. The Ceresco area covers approximately 14.9 mi^2. or 9,533 acres, the Davey Raymond area covers approximately 22.5 mi^2 or 14,304 acres, the Denton area covers approximately 11.1 mi^2 or 7129 acres, the Dwight South approximately 9.7 mi^2 or 6,212 acres, the Emerald Pleasant Dale approximately 20.1 mi^2 or 12,896 acres and the Garland Malcolm approximately 55.2 mi^2 or 35,337 acres (Figure 3-272). The 100 ft grid cell size was used for the block areas and resulting products.

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 3.1, Interpretive Process. Figure 3-273 shows resistivity ranges for interpreted non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials. The ***Kd*** sand/sandstone dominant material has resistivity >20 ohm-m and the shale/clay or saltwater dominant is < 20 ohm-m. This report provides information on unsaturated and saturated volumes of non-aquifer, marginal aquifer, aquifer, and coarse aquifer materials.

A calculation for the volume of saltwater in acre-ft was made for all LPSNRD AEM Block survey areas based on all materials with a resistivity of less than or equal to 4 ohm-m and the AEM model layer structure (Table 2-4). The results of the calculation are:

Ceresco Block	5,783,620 acre-ft
Davey Raymond Block	1,152,917 acre-ft
Denton Block	552,767 acre-ft
Dwight South Block	262,025 acre-ft
Emerald Pleasant Dale Block	2,079,875 acre-ft
Garland Malcolm Block	5,583,276 acre-ft

Voxel models of the individual AEM Block areas showing the distribution of the volumes of all saturated and unsaturated ***Q*** aquifer materials and saturated and unsaturated ***Kd*** sand/sandstone and shale/clay dominant materials are presented in Figure 3-274 for the Ceresco AEM Block area, Figure 3-275 for the Davey Raymond AEM Block area, Figure 3-276 for the Denton AEM Block area, Figure 3-277 for the Dwight South AEM Block area, Figure 3-278 for the Emerald Pleasant Dale Block area, and Figure 3-279 for the Garland Malcolm AEM Block area. These figures show the complex nature of each area. From these voxels only the volumes of ***Q*** and ***Kd*** aquifer materials are calculated for each block and are used in the calculation of aquifer volume in ft^3, aquifer volume in acre-ft, groundwater in storage volume acre-ft, and extractable water volume acre-ft.

All aquifer materials including Non-Aquifer material, Marginal Aquifer Material, Aquifer Material, and Coarse Aquifer material are used for calculating the groundwater in storage volume and the extractable water volumes for the survey area. Reported values of the average porosity for sand, making up the

Aquifer Material, and sand and gravel, making up Coarse Aquifer Material, are based on values from Freeze and Cherry (1979). Clay ranges from 40%-70%, silt ranges from 35%-50%, sand ranges from 25%-50%, and gravel is from 25%-40%. Conservative estimates for the porosity values used in these calculations within the survey area are 40% for non-aquifer material, 35% for marginal aquifer material, 20% for the aquifer material, and 25% for the coarse aquifer material.

Specific yield values for all AEM block areas were selected by estimating values from personal communication (Susan Olafsen Lackey, January 5, 2017). No aquifer test information was available for this report for the AEM block areas. Estimates of specific yield were made for all aquifer materials. Specific yield for Non-Aquifer (<12 ohm-m) materials was chosen at 0.02, for Marginal Aquifer materials (12-20 ohm-m) a value of 0.05 was selected (Heath, 1983). The Aquifer Material (20-50 ohm-m) ranges from 0.1 to 0.2 with an average of 0.15. Estimates of specific yield for the Coarse Aquifer Material (>50 ohm-m) ranges from 0.10 to 0.20 with an average of 0.15.

Porosity and Specific Yield values for the ***Kd*** sandstone/sand dominant and the shale/clay dominant materials were taken from published values by Heath (1983) and O'Connor (1987). The values for sandstone for porosity is 0.11 of volume and specific yield is 0.06. The for the ***Kd*** shale/clay dominant materials have values is 0.40 of volume and specific yield is 0.02 for calculating groundwater storage/yield.

Tables have been created that describe the volumes of ***Q*** aquifer materials including Non-Aquifer, Marginal Aquifer, Aquifer and Coarse Aquifer that are both saturated and unsaturated. Tables describing the volumes of ***Kd*** aquifer materials including shale/clay dominant and sandstone/sand dominant that are both saturated and unsaturated. Total volumes of all materials listed in the table are included in the "**TOTAL**" row at the bottom of each column. The tables are presented in alphabetic order of the AEM Block areas in the following order, ***Q*** unsaturated, ***Q*** saturated, ***Kd*** unsaturated, and ***Kd*** saturated. Note that not all AEM Block areas contain all four classification groups of aquifer materials.

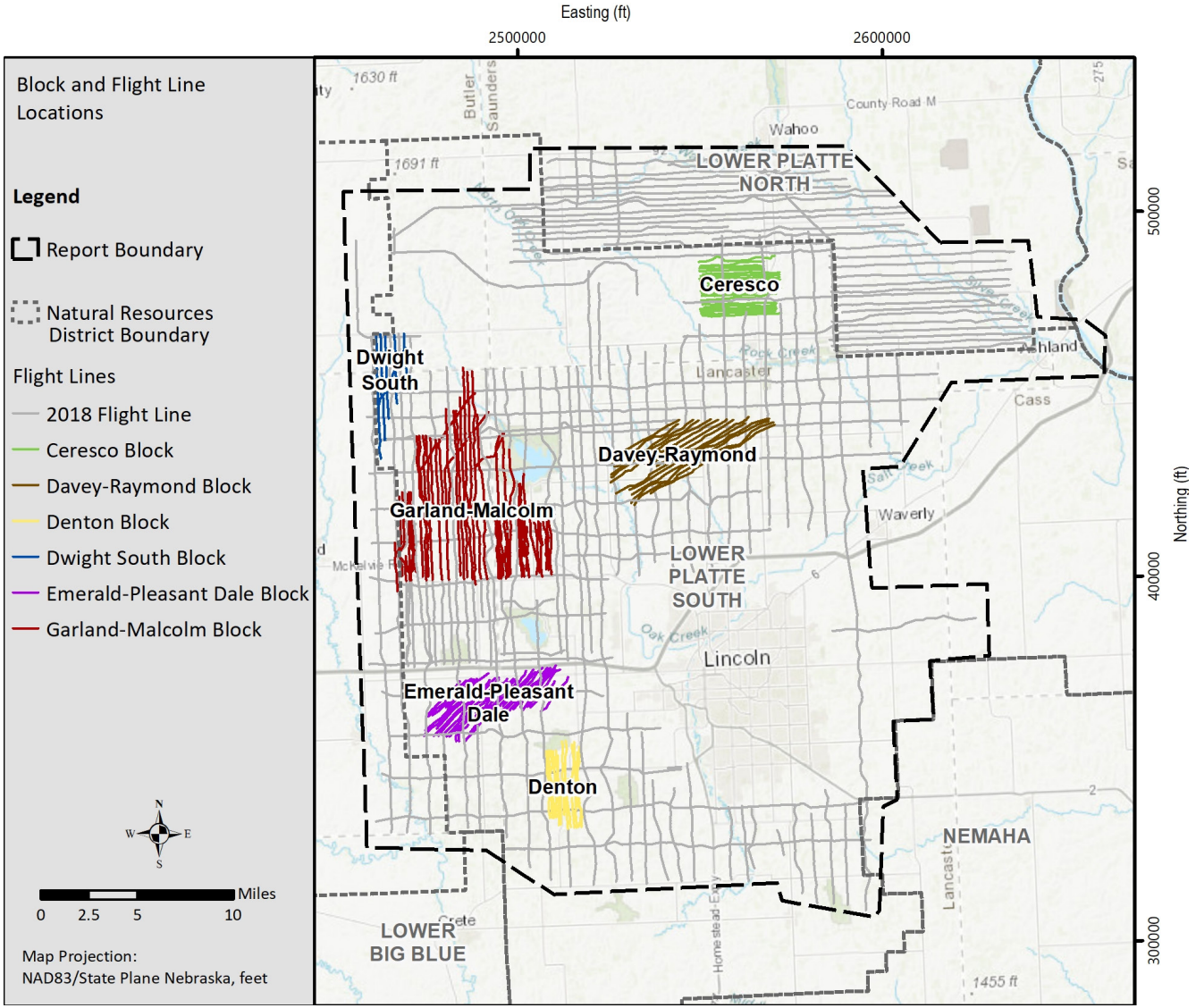


Figure 3-272. Map of the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale and Garland Malcolm block locations. Flight lines are indicated by color for each separate block, Ceresco-green, Davey Raymond-brown, Denton-yellow, Dwight South-blue, Emerald Pleasant Dale-purple, and Garland Malcolm-maroon. The projection is NAD83 State Plane Nebraska (feet).

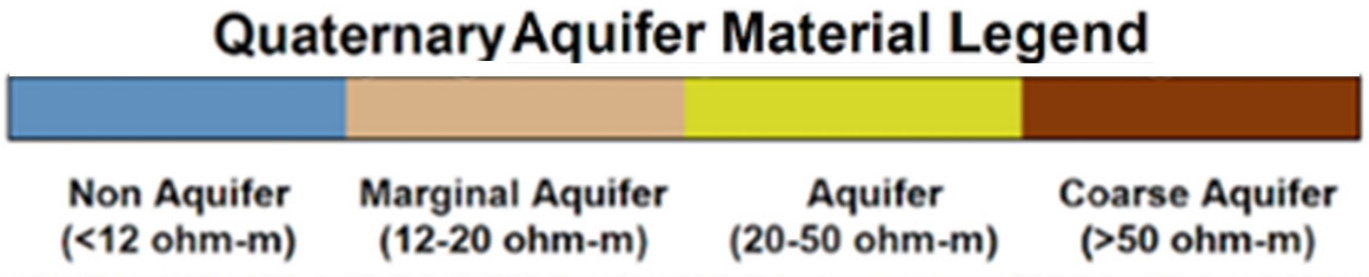


Figure 3-273. Resistivity ranges for interpreted Quaternary (*Q*) Non-Aquifer, Marginal Aquifer, Aquifer, and Coarse Aquifer Materials.

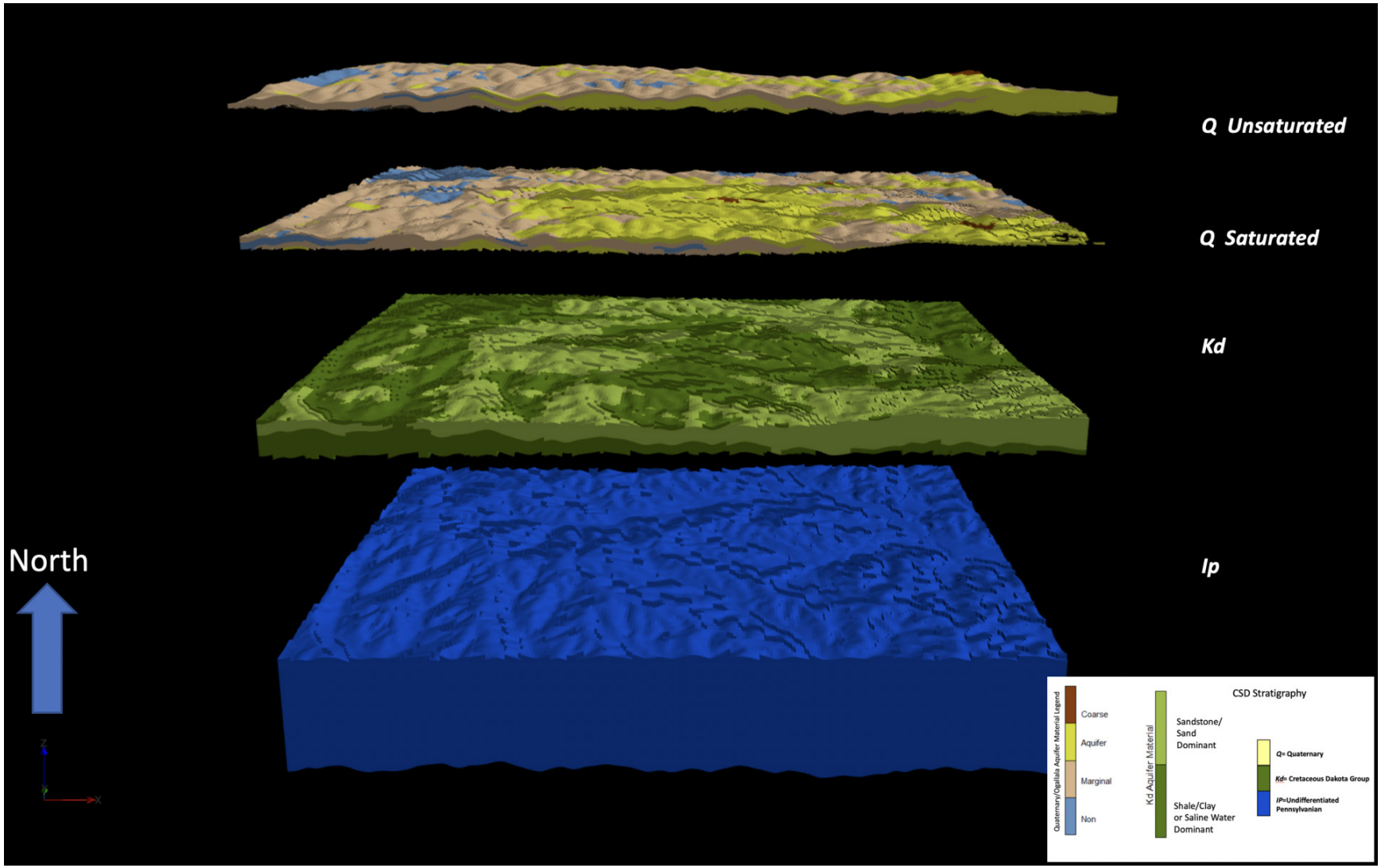


Figure 3-274. 3D voxel model of the Ceresco AEM block area facing north showing Quaternary Unsaturated (*Q*), Quaternary Saturated (*Q*), Cretaceous Dakota Formation (*Kd*) aquifer materials and Undifferentiated Pennsylvanian (*Ip*). Note the complexity of aquifer materials distributed across the area. Not to scale.

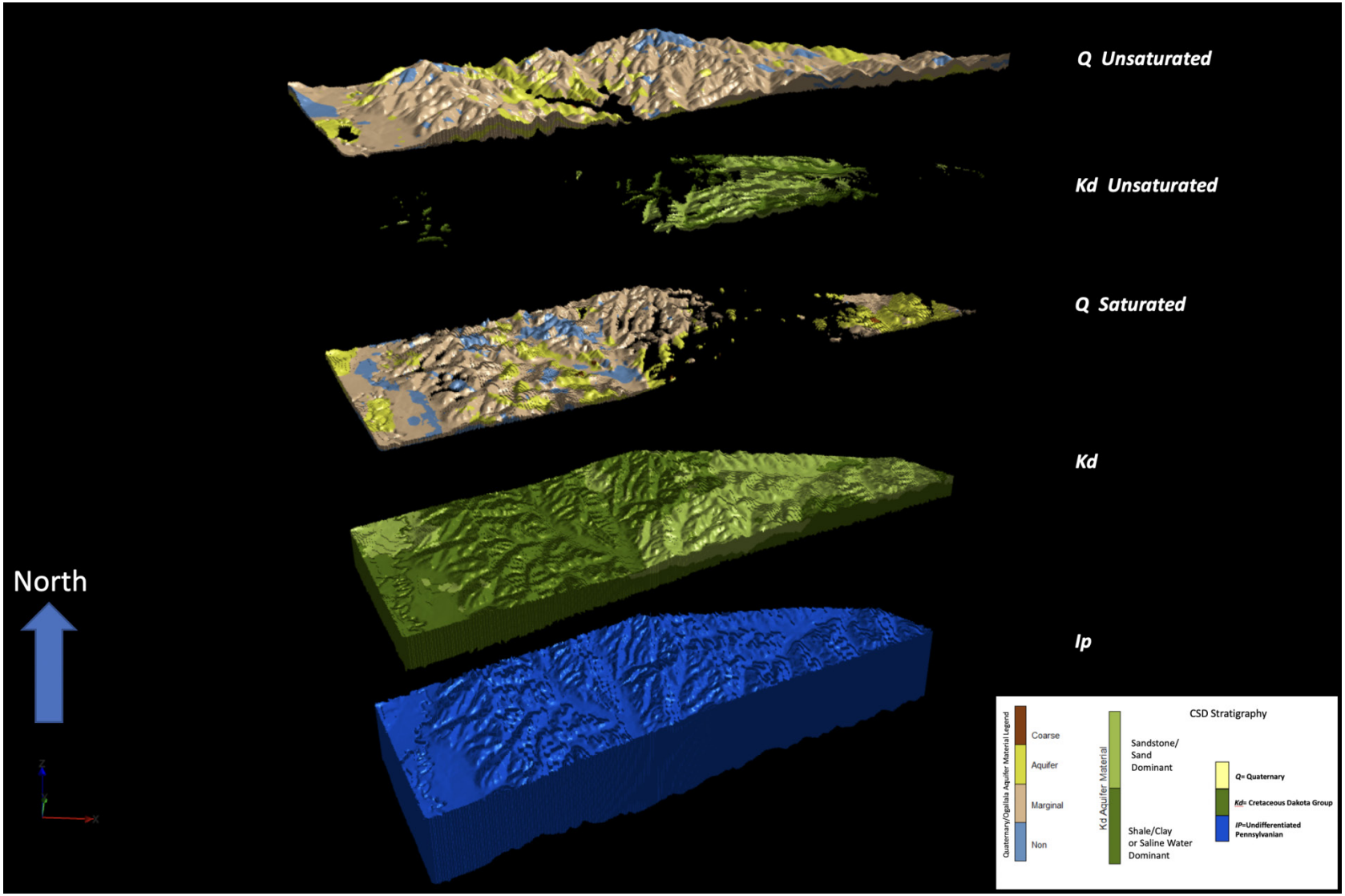


Figure 3-275. Exploded 3D voxel model of the Davey Raymond AEM Block area facing north showing all unsaturated and saturated Quaternary (*Q*), unsaturated and saturated Cretaceous Dakota Formation (*Kd*) aquifer materials, and Undifferentiated Pennsylvanian (*Ip*). Note the complexity of aquifer materials distributed across the area. Not to scale.

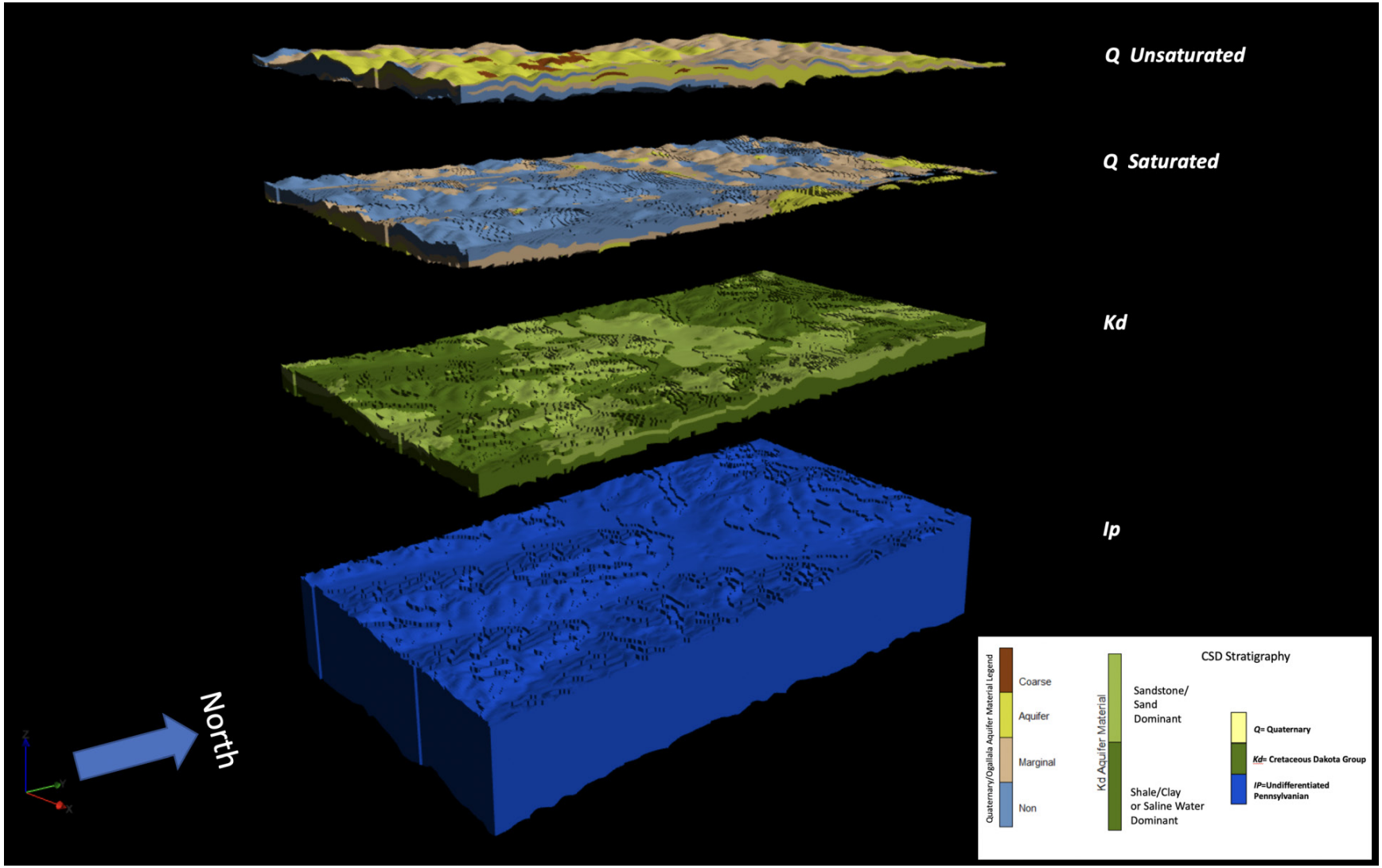


Figure 3-276. 3D voxel model of the Denton AEM Block area facing north showing all unsaturated and saturated Quaternary (*Q*), Cretaceous Dakota Formation (*Kd*) aquifer materials, and Undifferentiated Pennsylvanian (*IP*). Not to scale.

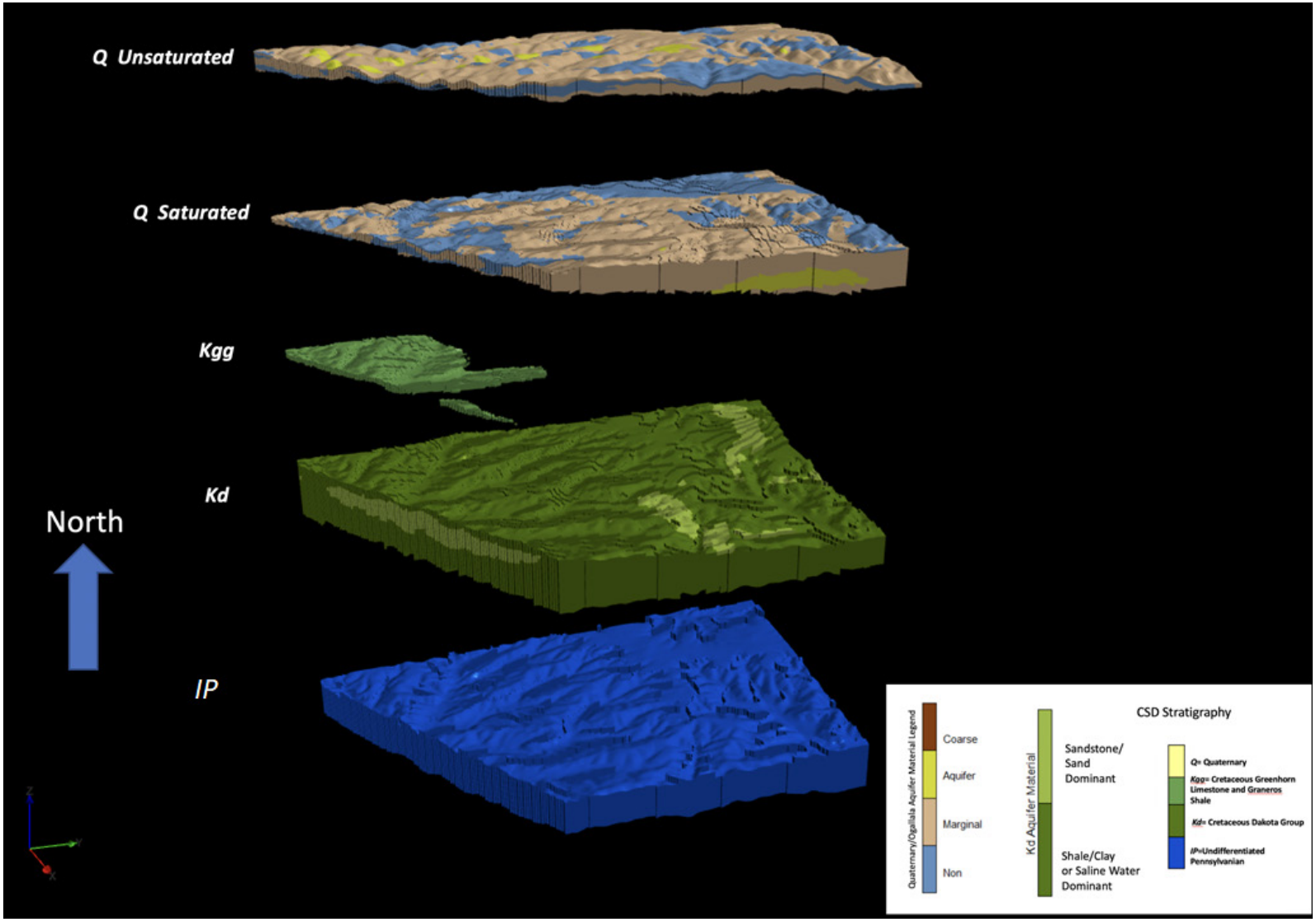


Figure 3-277. 3D voxel model of the Dwight South AEM block area facing north showing all unsaturated and saturated Quaternary (*Q*), Cretaceous Greenhorn-Graneros Formation (*Kgg*), Cretaceous Dakota Formation (*Kd*) aquifer materials, and Undifferentiated Pennsylvanian (*IP*). Note the complexity of aquifer materials distributed across the area. Not to Scale.

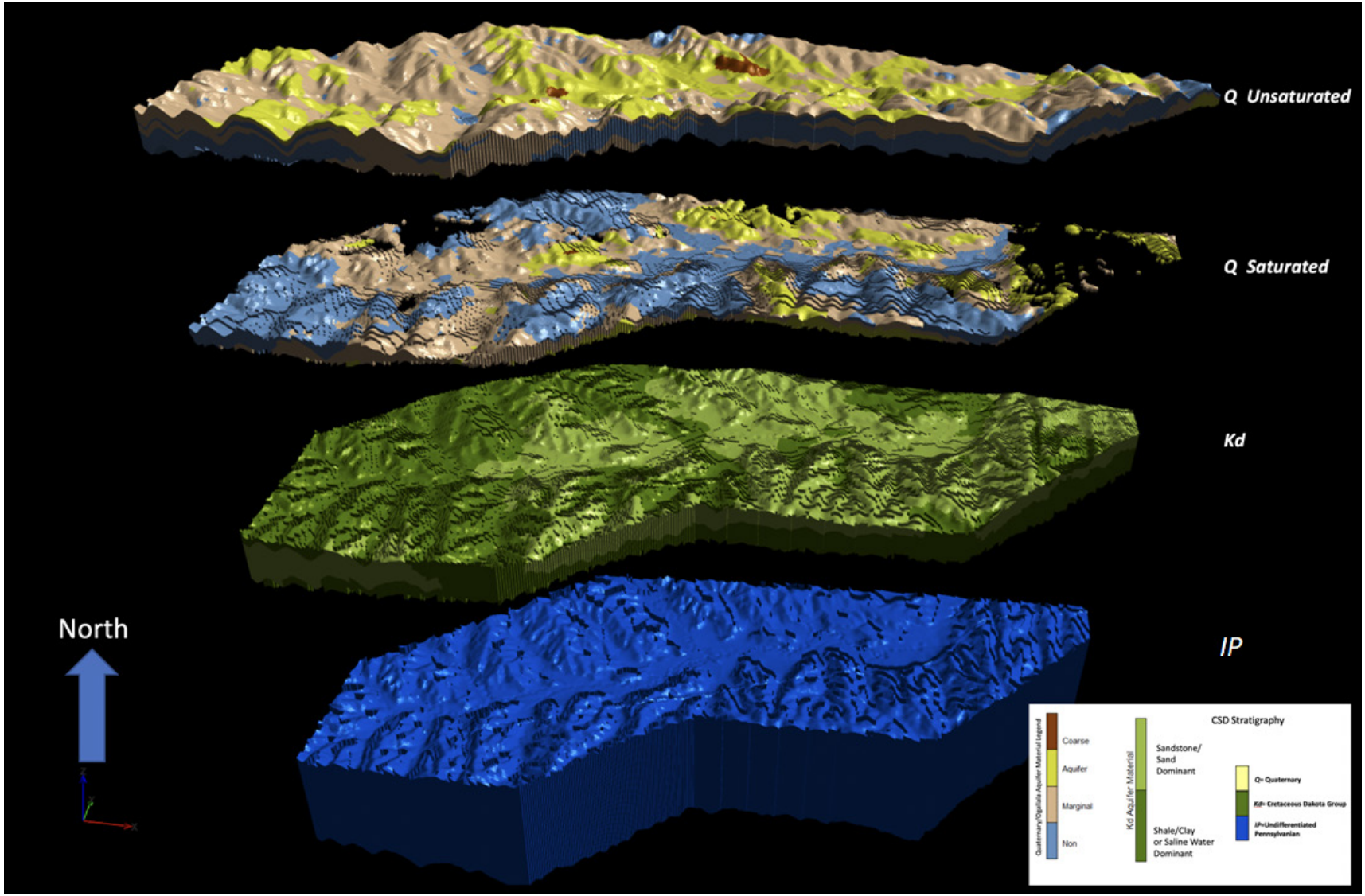


Figure 3-278. 3D voxel model of the Emerald Pleasant Dale AEM block area facing north showing all unsaturated and saturated Quaternary (*Q*), Cretaceous Dakota Formation (*Kd*) aquifer materials, and Undifferentiated Pennsylvanian (*IP*). Note the complexity of aquifer materials distributed across the area. Not to scale.

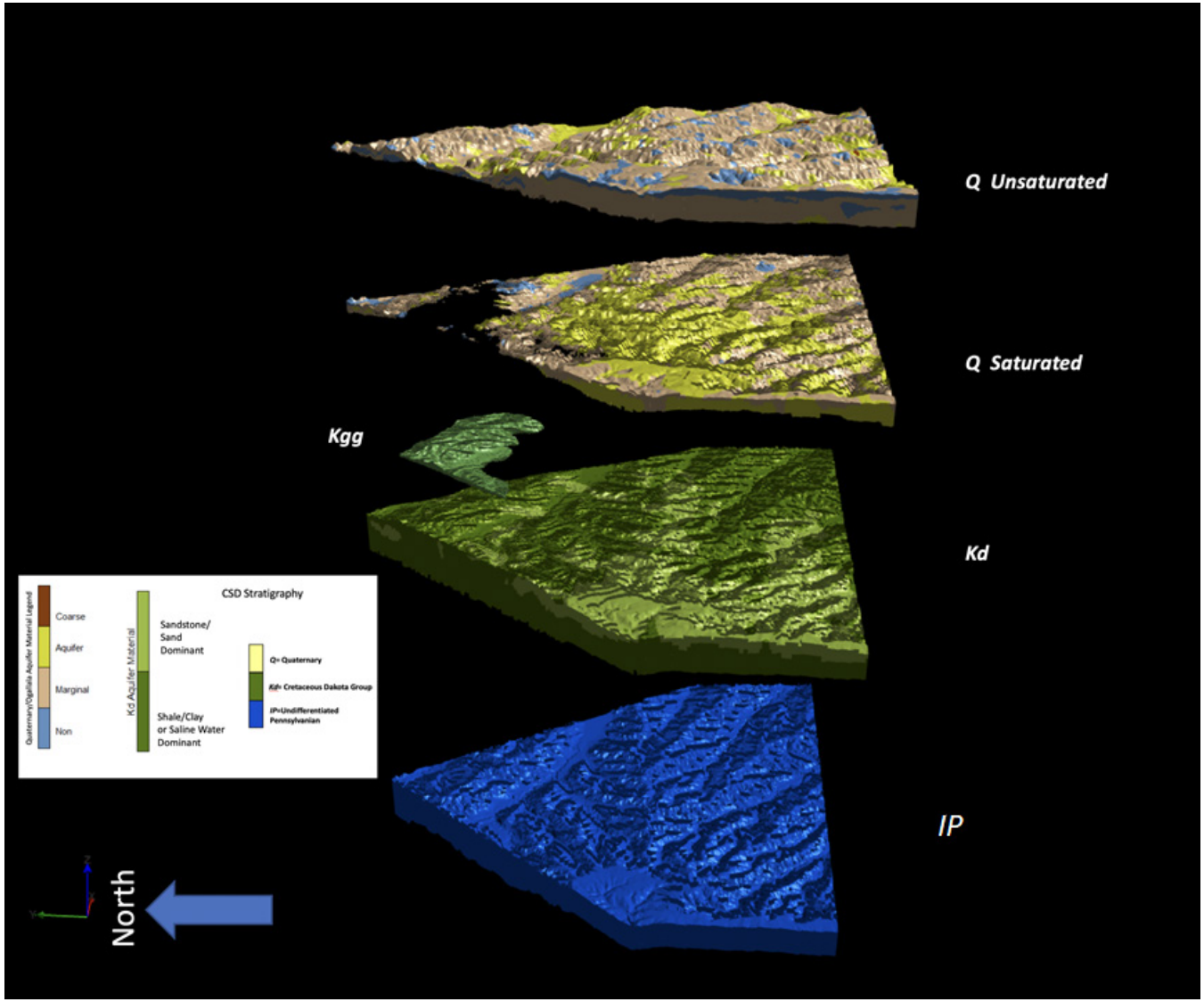


Figure 3-279. 3D voxel model of the Garland Malcolm AEM block area facing north showing all unsaturated and saturated Quaternary (*Q*), Cretaceous Greenhorn Graneros Formation (*Kgg*), Cretaceous Dakota Formation (*Kd*) aquifer materials, and Undifferentiated Pennsylvanian (*IP*). Note the complexity of aquifer materials distributed across the area. Not to scale.

Ceresco AEM Block Area

Table 3-1. *Q* aquifer materials underlying the Ceresco AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre ft)	Average Specific Yield	Extractable Water Volume (acre ft)
Coarse	302,060,581	6,934	0.25	1,773	0.02	34
Aquifer	24,509,677,265	562,666	0.2	112,533	0.05	5,626
Marginal	43,379,775,929	995,864	0.35	348,552	0.1	34,855
Non-Aquifer	11,855,420,622	272,163	0.4	108,865	0.15	16,329
TOTAL	80,046,934,396	1,837,627		571,723		56,844

Table 3-2. Saturated *Q* aquifer materials underlying the Ceresco AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre ft)	Average Specific Yield	Extractable Water Volume (acre ft)
Coarse	1,412,250,938	32,420	0.25	8,105	0.02	162.1
Aquifer	19,454,234,688	446,608	0.2	89,321	0.05	4,466
Marginal	7,054,229,063	161,493	0.35	56,522	0.1	5,652
Non-Aquifer	1,729,965,313	39,741	0.4	15,896	0.15	2,384
TOTAL	29,650,680,000	680,262		169,844		12,664

Table 3-3. Saturated *Kd* aquifer materials underlying the Ceresco AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre ft)	Average Specific Yield	Extractable Water Volume (acre ft)
Sandstone/Sand	19,417,048,125	445,754	0.11	49,032	0.02	980
Shale/Clay	201,479,350,938	4,625,336	0.4	1,850,134	0.06	111,008
TOTAL	220,896,399,063	5,071,091		1,899,166		111,988

Davey Raymond AEM Block Area

Table 3-4. *Q* aquifer materials underlying the Davey Raymond AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre ft)	Average Specific Yield	Extractable Water Volume (acre ft)
Coarse	75,127,957	1,725	0.25	431	0.02	8
Aquifer	9,466,538,118	217,322	0.2	43,464	0.05	2,173
Marginal	33,277,825,883	763,955	0.35	267,384	0.1	26,738
Non-Aquifer	7,401,495,662	169,915	0.4	67,966	0.15	10,194
TOTAL	50,220,987,620	1,152,917		379,245		39,113

Table 3-5. Saturated *Q* aquifer materials underlying the Davey Raymond AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	0	0	0.25	0	0.02	0
Aquifer	2,477,148,500	56,868	0.2	11,373	0.05	568
Marginal	7,860,522,958	180,453	0.35	63,158	0.1	6,315
Non-Aquifer	3,201,351,836	73,493	0.4	29,397	0.15	4,409
TOTAL	13,539,023,294	310,814		103,928		11,292

Table 3-6. Total *Kd* aquifer materials underlying the Davey Raymond AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Sandstone/Sand	21,881,001,417	502,319	0.11	55,255	0.02	1,105
Shale/Clay	144,822,380,644	3,324,669	0.4	1,329,867	0.06	79,792
TOTAL	166,703,382,061	3,826,989		1,385,122		80,897

Table 3-7. Saturated *Kd* aquifer materials underlying the Davey Raymond AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Sandstone/Sand	19,786,872,821	454,245	0.11	49,966	0.02	999
Shale/Clay	144,206,697,789	3,310,535	0.4	1,324,214	0.06	79,452
TOTAL	163,993,570,610	3,764,780		1,374,180		80,451

Denton AEM Block Area

Table 3-8. *Q* aquifer materials underlying the Denton AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	250,807,097	5,758	0.25	1,439	0.02	28
Aquifer	6,092,617,548	139,867	0.2	27,973	0.05	1,398
Marginal	20,030,279,811	459,833	0.35	160,941	0.1	16,094
Non-Aquifer	17,927,195,775	411,552	0.4	164,620	0.15	24,693
TOTAL	44,300,900,231	1,017,010		354,973		42,213

Table 3-9. Saturated *Q* aquifer materials underlying the Denton AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	0	0	0.25	0	0.02	0
Aquifer	1,894,503,551	43,492	0.2	8,698	0.05	246
Marginal	12,205,834,446	280,208	0.35	98,072	0.1	9,807
Non-Aquifer	12,857,064,097	295,158	0.4	118,063	0.15	17,709
TOTAL	26,957,402,095	618,858		224,833		27,762

Table 3-10. Saturated *Kd* aquifer materials underlying the Denton AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Sandstone/Sand	15,495,640,710	355,731	0.11	39,130	0.02	782
Shale/Clay	28,969,524,904	665,050	0.4	266,020	0.06	15,961
TOTAL	44,465,165,614	1,020,781		305,150		16,743

Dwight South AEM Block Area

Table 3-11. *Q* aquifer materials underlying the Dwight South AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	0	0	0.25	0	0.02	0
Aquifer	4,552,978,017	104,522	0.2	20,904	0.05	1,045
Marginal	52,262,866,618	1,199,792	0.35	419,927	0.1	41,992
Non-Aquifer	16,883,485,782	387,592	0.4	155,036	0.15	23,255
TOTAL	73,699,330,417	1,691,906		595,867		66,292

Table 3-12. Saturated *Q* aquifer materials underlying the Dwight South AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	0	0	0.25	0	0.02	0
Aquifer	4,424,962,926	101,583	0.2	20,316	0.05	1,015
Marginal	33,900,027,368	778,239	0.35	272,383	0.1	27,238
Non-Aquifer	7,831,076,313	179,777	0.4	71,910	0.15	10,786
TOTAL	46,156,066,607	1,059,599		364,609		39,039

Table 3-13. Saturated *Kd* aquifer materials underlying the Dwight South AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Sandstone/Sand	16,788,863,492	385,420	0.11	42,396	0.02	847
Shale/Clay	110,838,376,736	2,544,503	0.4	1,017,801	0.06	61,068
TOTAL	127,627,240,228	2,929,923		1,060,197		61,915

Emerald Pleasant Dale AEM Block Area

Table 3-14. *Q* aquifer materials underlying the Emerald Pleasant Dale AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	189,443,919	4,349	0.25	1,087	0.02	21
Aquifer	9,025,112,291	207,188	0.2	41,137	0.05	2,071
Marginal	27,588,752,780	633,352	0.35	221,673	0.1	22,167
Non-Aquifer	21,591,377,459	495,671	0.4	198,268	0.15	29,740
TOTAL	58,394,686,448	1,340,560		462,165		53,999

Table 3-15. Saturated *Q* aquifer materials underlying the Emerald Pleasant Dale AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	0	0	0.25	0	0.02	0
Aquifer	131,358,750	102,966	0.2	20,593	0.05	1,029
Marginal	41,065,625	176,498	0.35	61,774	0.1	6,177
Non-Aquifer	16,940,625	143,575	0.4	57,430	0.15	8,614
TOTAL	189,365,000	423,040		139,797		15,820

Table 3-16. Saturated *Kd* aquifer materials underlying the Emerald Pleasant Dale AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Sandstone/Sand	80,432,991,018	1,846,490	0.11	203,113	0.02	4,062
Shale/Clay	85,761,663,819	1,968,820	0.4	787,528	0.06	47.251
TOTAL	166,194,654,837	3,815,310		990,641		51,313

Garland Malcolm AEM Block Area

Table 3-17. *Q* aquifer materials underlying the Garland Malcolm AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	43,103,676	990	0.25	247	0.02	5
Aquifer	129,117,122,968	2,964,126	0.2	592,825	0.05	29,641
Marginal	229,168,134,280	5,260,984	0.35	1,841,344	0.1	184,134
Non-Aquifer	34,629,937,600	794,995	0.4	317,998	0.15	47,699
TOTAL	392,958,298,524	9,021,095		2,752,414		261,479

Table 3-18. Saturated *Q* aquifer materials underlying the Garland Malcolm AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Coarse	0	0	0.25	0	0.02	0
Aquifer	78,648,618,473	1,805,527	0.2	361,105	0.05	18,055
Marginal	102,435,763,095	2,351,605	0.35	823,061	0.1	82,306
Non-Aquifer	8,454,723,727	194,094	0.4	77,637	0.15	11,645
TOTAL	189,539,105,295	4,351,226		1,261,803		112,006

Table 3-19. Saturated *Kd* aquifer materials underlying the Garland Malcolm AEM Block Area.

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Sandstone/Sand	61,804,391,489	1,418,836	0.11	156,071	0.02	3,121
Shale/Clay	499,822,494,746	11,474,363	0.4	4,589,745	0.06	275,384
TOTAL	561,626,886,235	12,893,198		4,745,816		278,505

3.3 Recharge Areas in the LPSNRD AEM Survey Area

3D representations of the subsurface resulting from AEM investigations illustrate areas of aquifer materials from the bedrock up to the land surface. From these interpretations a new series of near-surface maps have been constructed for the LPSNRD Area incorporating all of the LPSNRD AEM Reconnaissance lines (2014, 2016, and 2018) and the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcom 2018 AEM Block survey areas. The near-surface maps present the results of the resistivity to lithology relationship described in Section 3.1.5 over an average of the first three (3) layers of the AEM inverted earth model, down to a depth of -10.8 feet. From the discussion around Table 2-4 each model layer represents an average of the earth's resistivities within the top and bottom of those layer depths based on the physics of the electromagnetic exploration technique. Maps of the first layers show aquifer materials and indicate the areas at the land surface and just below that can potentially transmit water to the groundwater aquifers in the area. These model layers, near the ground surface, provide a visualization of whether the sediments are made up of Aquifer Material (yellow - "good") to Coarse Aquifer Material (brown - "very good"). The Coarse Aquifer Material can transmit the largest volume of water. By viewing layers at depth an understanding of the heterogeneity of the aquifer materials and their distribution can be achieved. There is not always a direct path downwards to the subsurface aquifer from the land surface and often there is no path available for the water to move through.

Maps of the ***Q*** surface sediments indicating recharge capabilities are represented as aquifer material types for the whole of the LPSNRD AEM survey area (Figure 3-280) and the Block AEM survey areas shown in Figure 3-281. Potential recharge maps of the individual AEM Block locations are presented in Figure 3-282 (Ceresco Block), Figure 3-283 (Davey Raymond Block), Figure 3-284 (Denton Block), Figure 3-285 (Dwight South Block), Figure 3-286 (Emerald Pleasant Dale Block), and Figure 3-287 (Garland Malcolm Block).

Note that since the amount of slope of the land surface plays a large role in the amount of residence time that water will spend in an area, the greater the length of time spent at a location, the greater the amount of infiltration potential. The greatest possibility for recharge in the LPSNRD AEM survey areas are the alluvial valley floors in valleys. In other areas, the best possible locations for recharge would be where there is a combination of Aquifer and Coarse Aquifer Materials at the land surface with little relief in elevation and with a pathway of similar materials down to the saturated aquifer at depth. A more in-depth recharge analysis could be performed using slope and run-off analyses combined with detailed soils maps with the addition of the AEM interpretation.

The recharge layers shown are included as Google Earth kmz's in Appendix 3-Deliverables\KMZ\ Recharge.

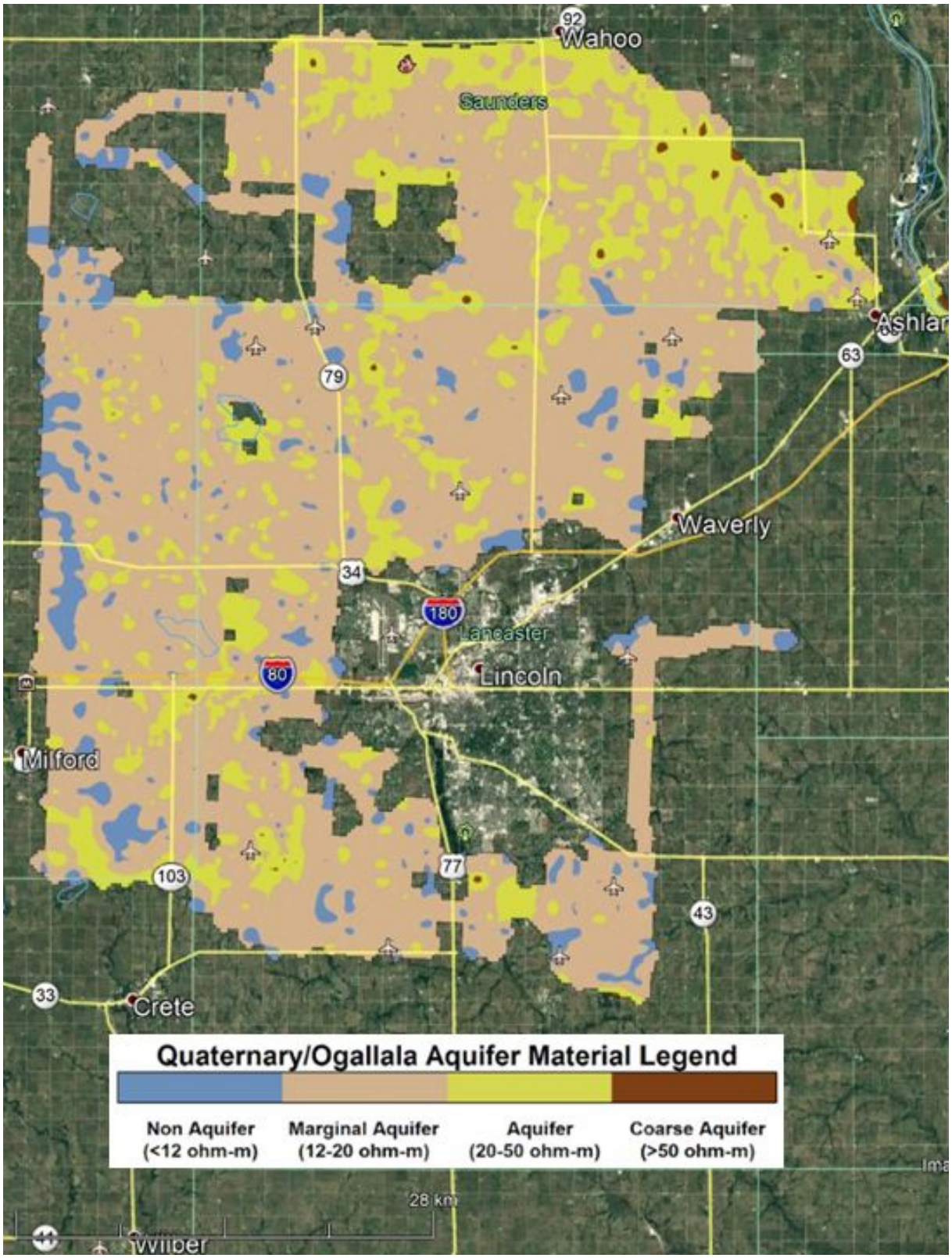


Figure 3-280. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 LPSNRD AEM survey area. This kmz included in Appendix 3-Deliverables\KMZ\ Recharge.

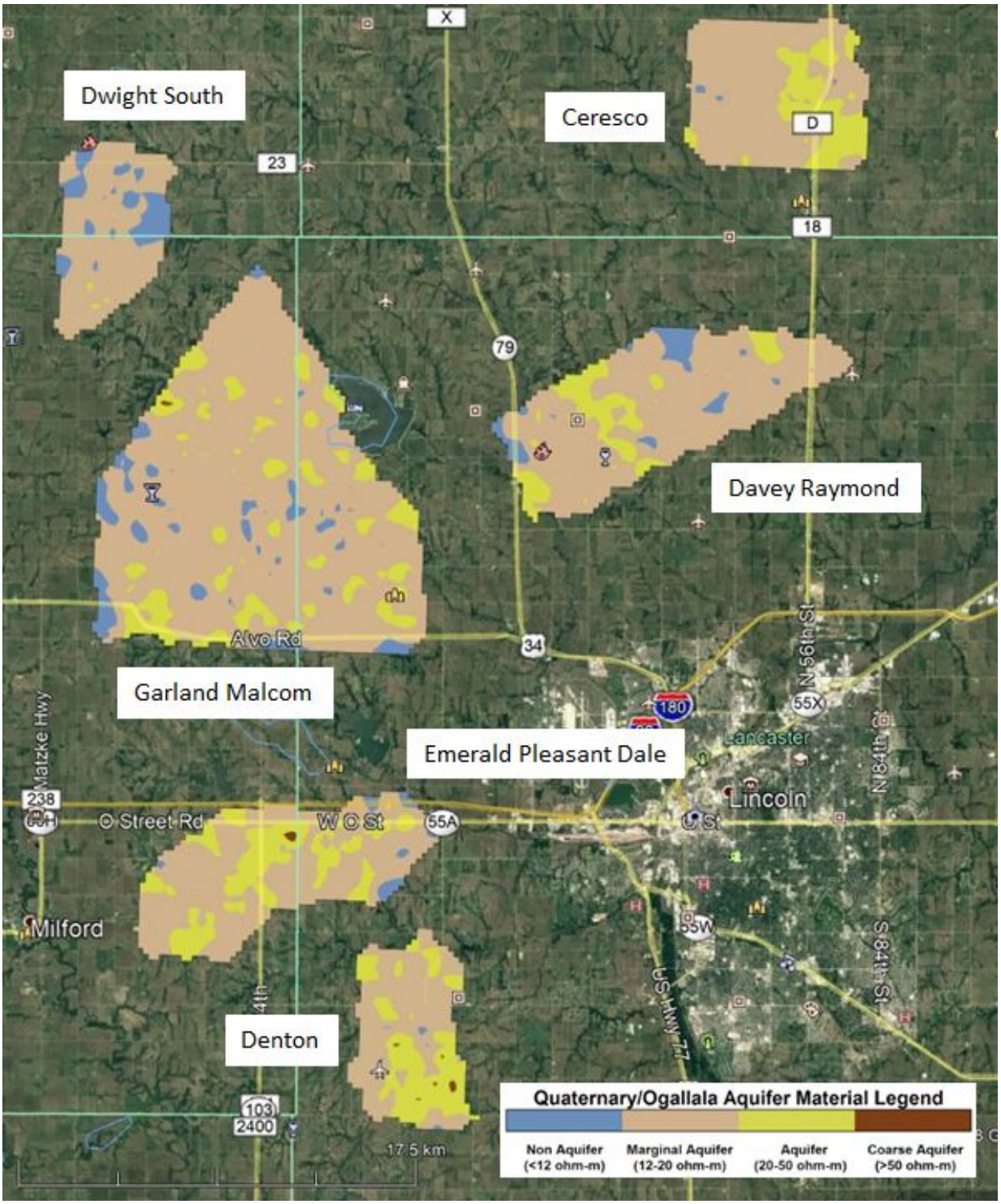


Figure 3-281. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 LPSNRD Block AEM survey areas. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

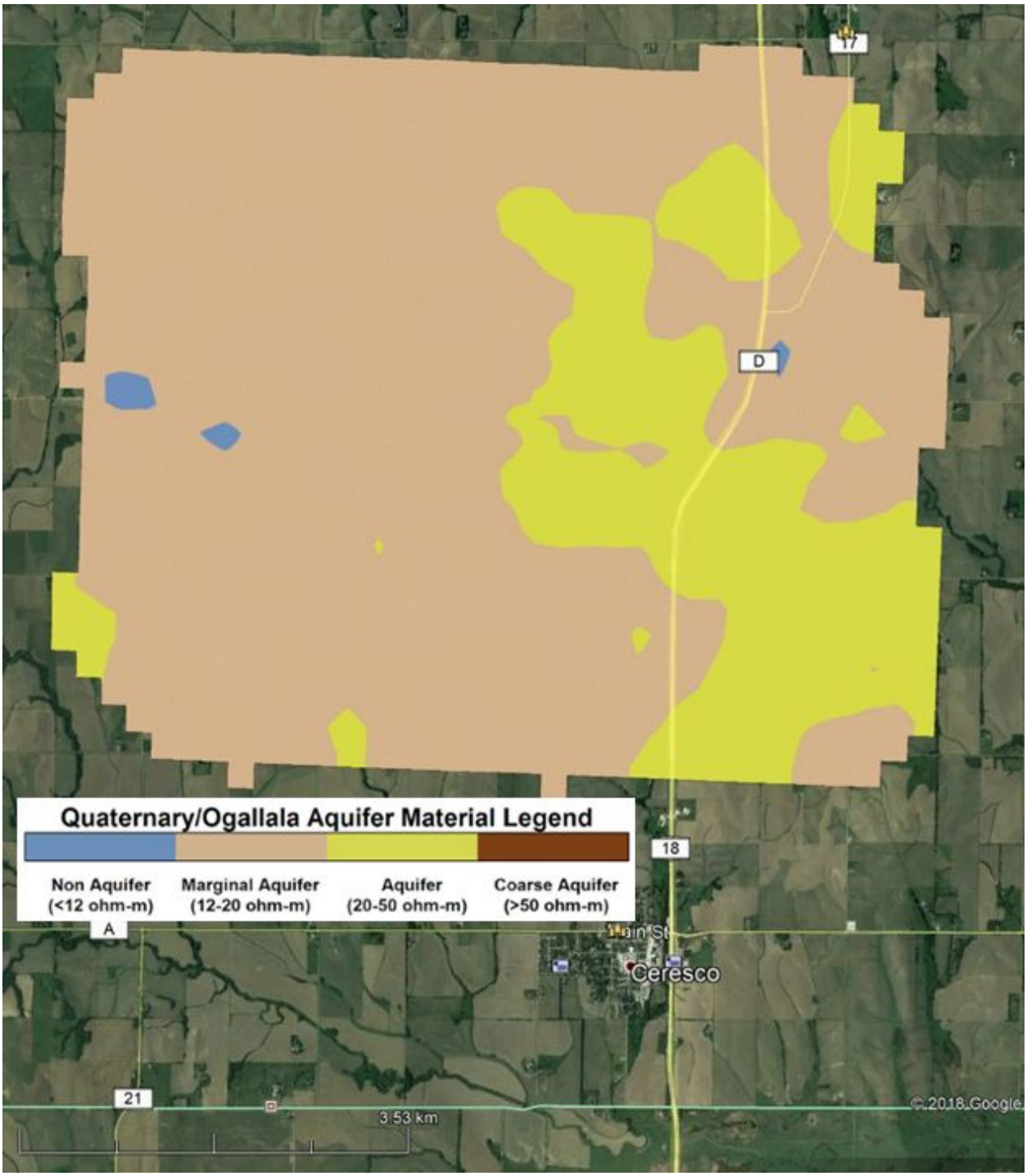


Figure 3-282. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Ceresco Block AEM survey area. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

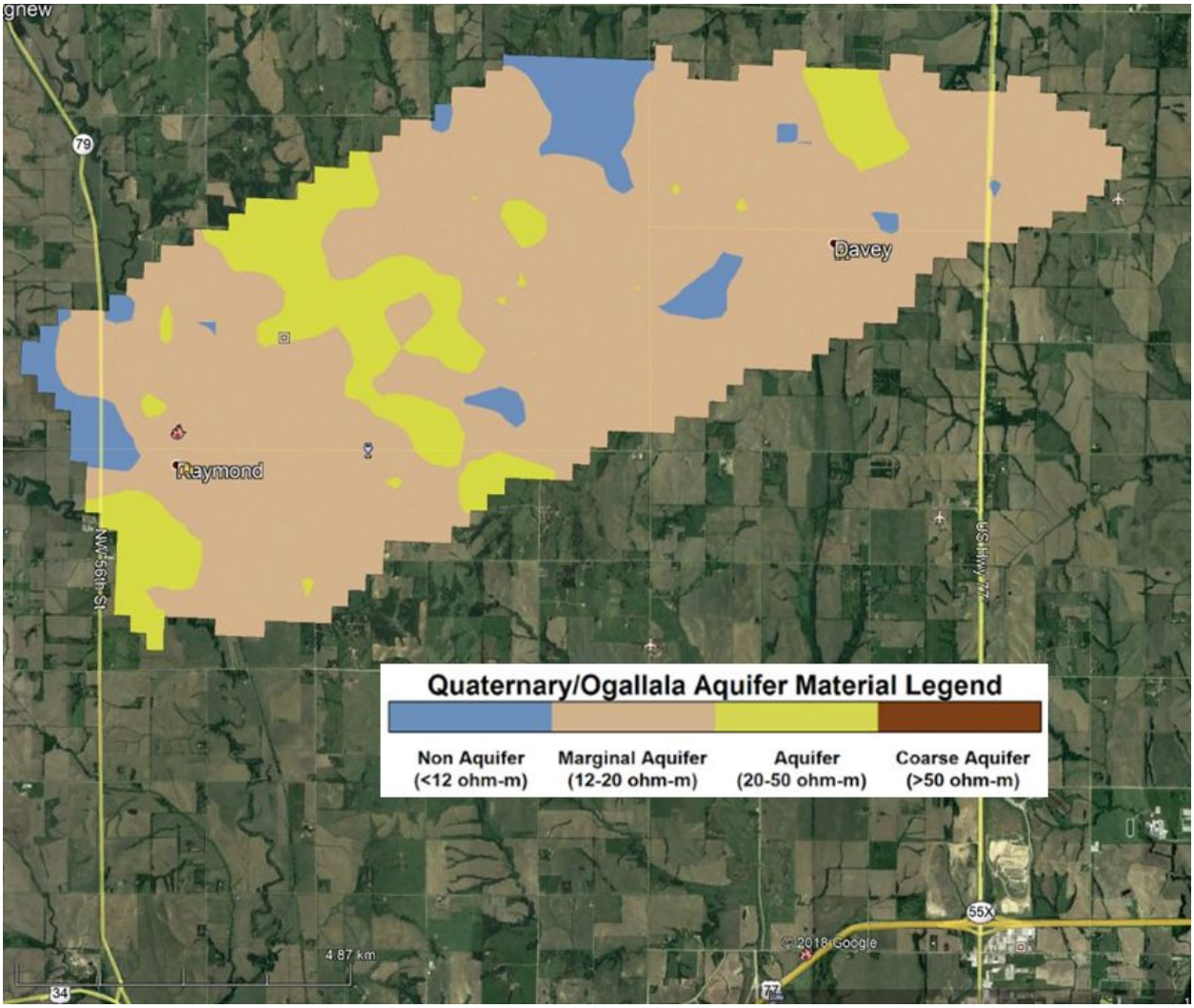


Figure 3-283. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Davey Raymond Block AEM survey area. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

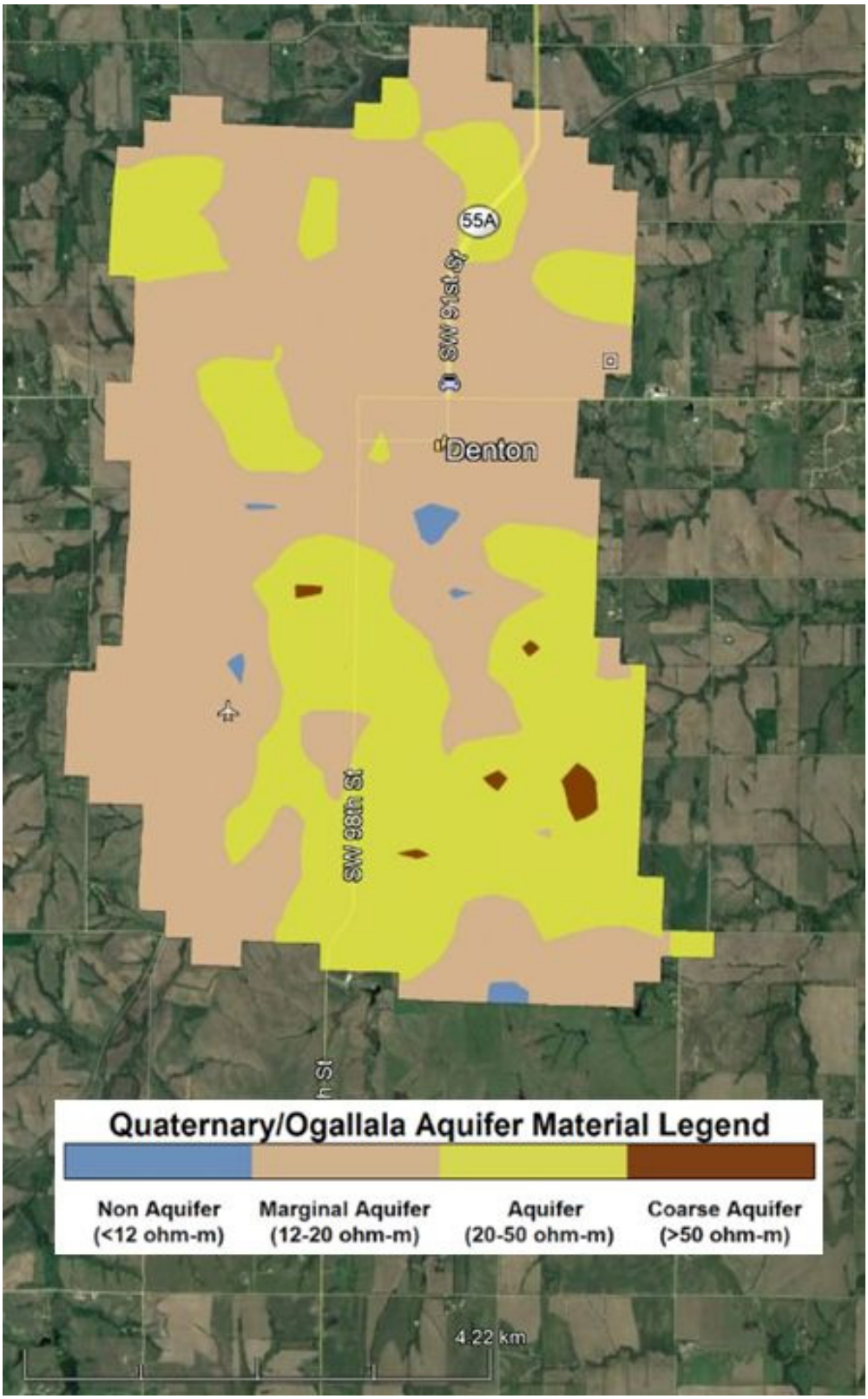


Figure 3-284. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Denton Block AEM survey area. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

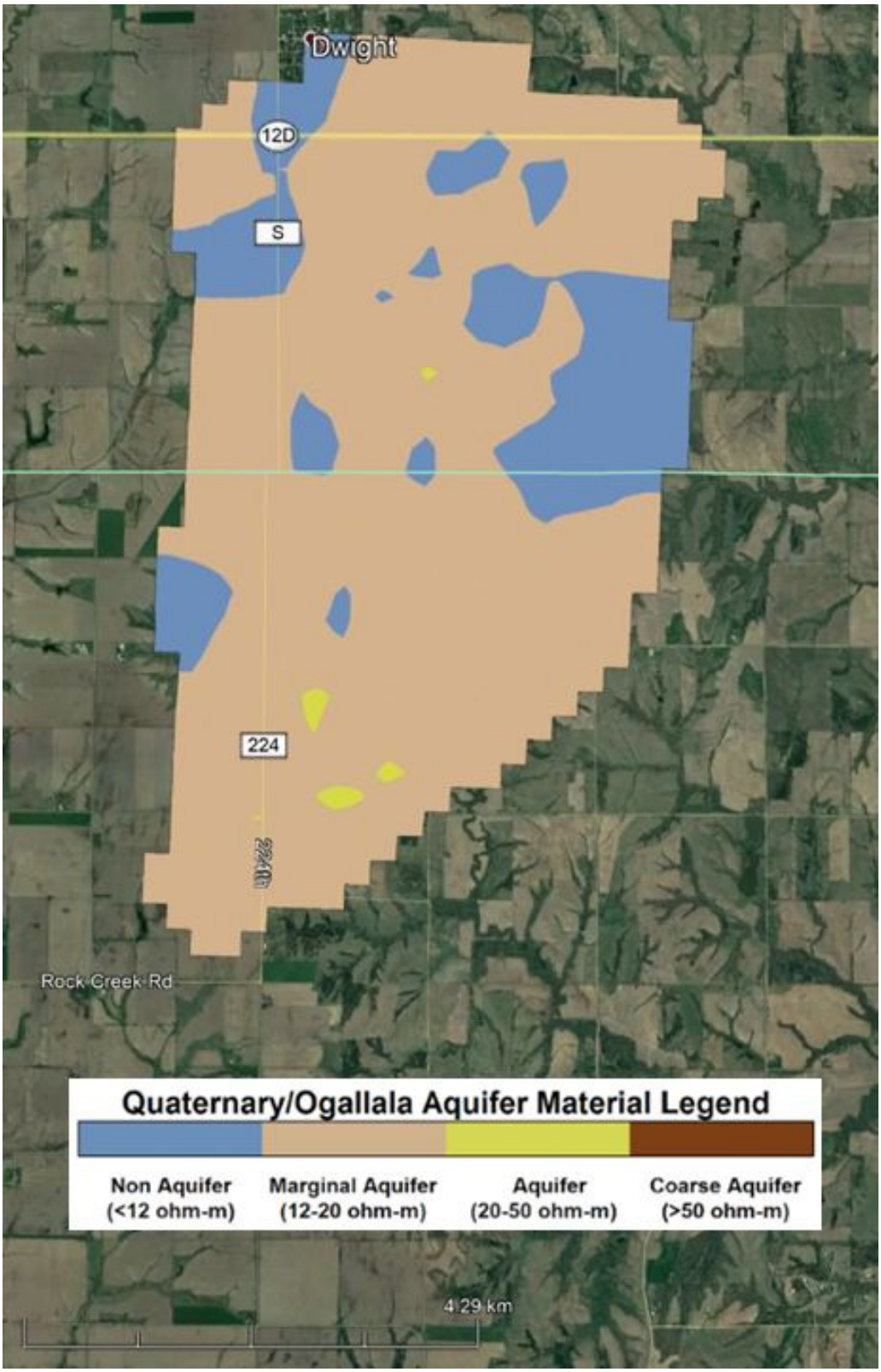


Figure 3-285. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Dwight South Block AEM survey area. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

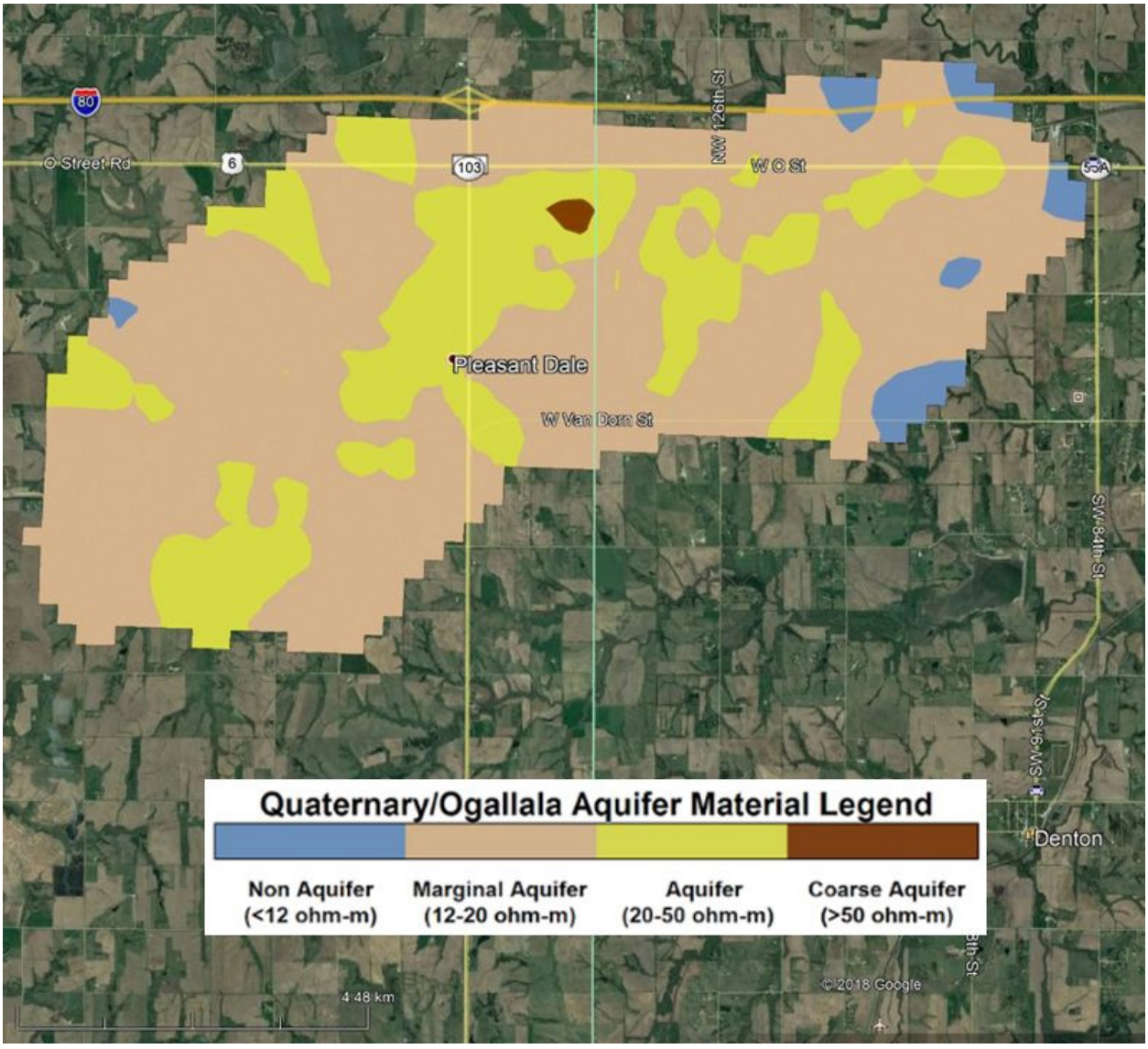


Figure 3-286. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Emerald Pleasant Dale Block AEM survey area. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

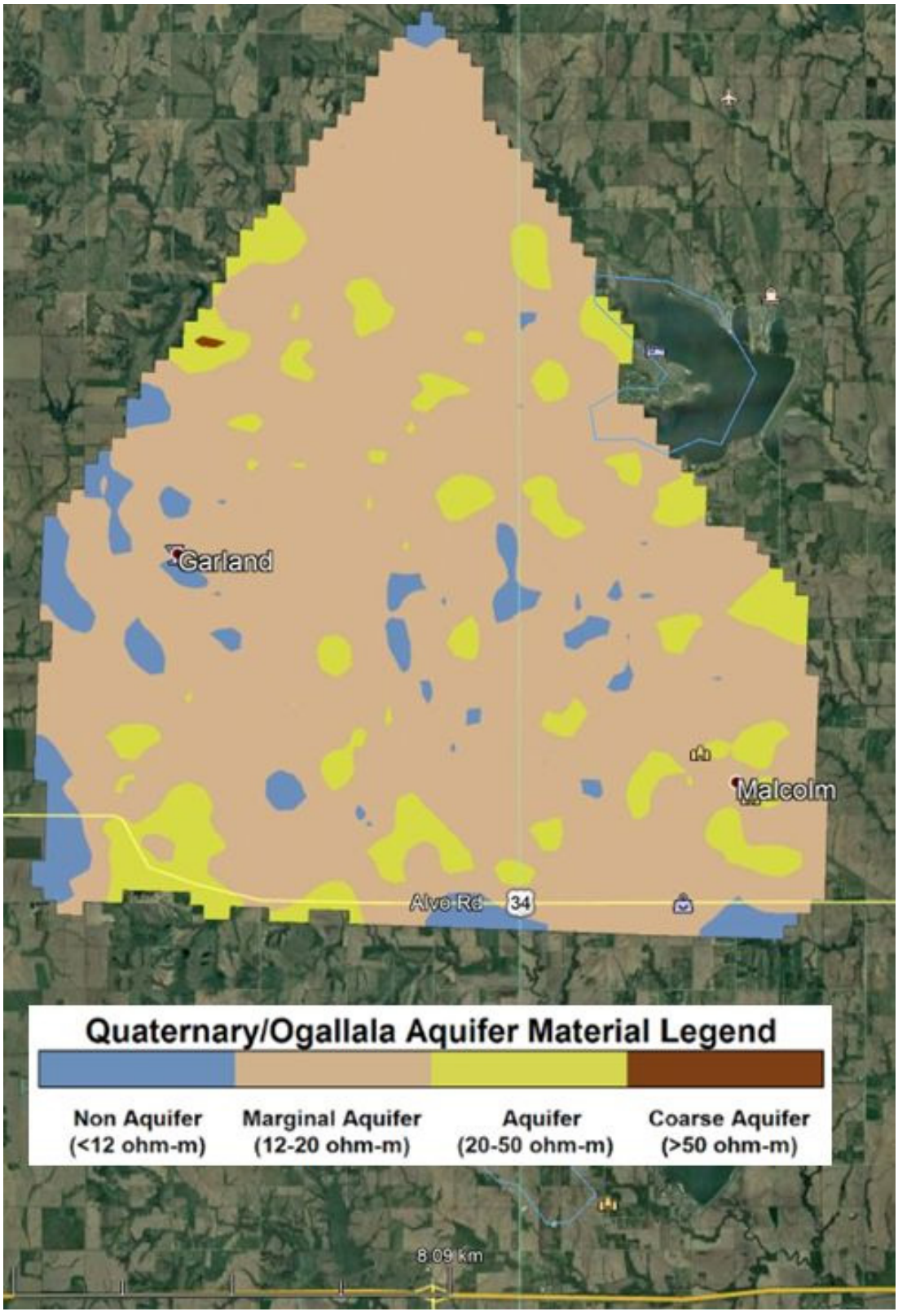


Figure 3-287. Google Earth image of potential soil recharge by aquifer material type in the first 10.8 feet over the 2018 Garland Malcolm Block AEM survey area. This kmz included in Appendix 3-Deliverables\KMZ\Recharge.

3.4 Key AEM Findings

3.4.1 Boreholes

Information from boreholes was used to analyze the AEM inversion results and was critical for all areas in the LPSNRD. The CSD (Nebraska Conservation and Survey Division) and the NE- DNR (Nebraska Department of Natural Resources) registered wells were used extensively in the interpretation of the geological contacts. In many areas the wells encountered saltwater which is characterized by the AEM but is seldom indicated in the CSD or NE-DNR wells. The dependence on just boreholes for geologic interpretation also has its limitations due to errors in the entry of the logs into the database, improperly located or documented wells, and improper stratigraphic/lithology picks, and/or other errors. These errors in the boreholes are usually encountered in the NE-DNR registered wells. Very rarely are inconsistencies encountered in the oldest of the NE- CSD wells. The limited errors in the CSD wells may very well be due to poor positioning from a time before GPS and modern survey methods. As a guide in the interpretation of the AEM***,*** a bedrock surface was prepared using the of CSD and NE-DNR borehole logs and surface maps of the geologic outcrops. As in all surveys of this nature, the use of boreholes with AEM needs to be approached in a thoughtful and considered manner as to the value of information from an individual borehole.

3.4.2 Digitizing Interpreted Geological Contacts

Characterization and interpretation of the subsurface was performed in cross-section and derived surface grid formats. Contacts between the geologic units were digitized in 2D including: Quaternary (***Q),*** Cretaceous Greenhorn Limestone and Graneros Shale (***Kgg***), Cretaceous Dakota Group (***Kd***), and undifferentiated Pennsylvanian (***IP***). The interpretive process benefited from the use of CSD, Nebraska Oil and Gas Conservation Commission (NEOGCC), and NE-DNR borehole logs. Geologic maps of surface outcrops and geologic maps contributed to the understanding of geologic interpretation. Surface grids of the interpreted geologic formations were then produced. Each flight line profile with interpretation including the ***Q*** aquifer material mapping is included in the appendices as well as interpretative surface grids. The surfaces in this study only include the data from 2018; No merging was done with previous studies conducted in the LPSNRD.

3.4.3 Resistivity/Lithology Relationship

Assessment of the sediment character in the Quaternary aquifer system and the bedrock strata was conducted to determine the overall composition of the major categories used to define the aquifer and aquitards in eastern Nebraska. The resistivity relationship that was used in previous studies of Carney et al. (2015a, 2015b) were used in this project. The resistivity thresholds used were <12 ohm-m (Non-Aquifer Materials), 12-20 ohm-m (Marginal), 20-50 ohm-m (Aquifer Materials), and >50 ohm-m (Coarse Aquifer Materials (e.g. sand-rich intervals). This allowed for the aquifer material characterization of the ranges of resistivities present in the major geologic units described in this report.

3.4.4 Hydrogeological Framework of the LPSNRD

The 2018 LPSNRD AEM survey reveals variability in the Quaternary (***Q***) and Cretaceous Dakota Group (***Kd***) deposits across the LPSNRD AEM survey area that make up the aquifer materials. The ***Q*** makes up the aquifer materials overlying the Cretaceous bedrock units of which the ***Kd*** Sandstone/Sand Dominant material is the aquifer material. Across the AEM survey area, the Aquifer Material and Coarse Aquifer Material exist in paleovalleys, glacial outwash and glaciotectonic deposits that are separated by ***Q*** Marginal and Non-Aquifer material deposits. These separating ***Q*** Marginal and Non-Aquifer Material deposits are glacial till and loess that can be more than 500 ft thick. ***Q*** Aquifer and Coarse Aquifer materials are thickest in the paleovalleys located across 2018 survey areas. There are significant amounts of saltwater within the ***Kd*** and ***IP*** as the saltwater can be widespread across some of the Block areas. This can be a future issue as wells get drilled deeper to supply domestic purposes or as groundwater is pumped, there may be upwelling of the saltwater. Areas of glaciotectonic movement of sediment can impact areas of the LPSNRD due to the mixing of aquifer materials causing the development of both water bearing materials as well boundaries to flow in unpredictable areas. These areas are where sands and gravel are thrust up on the top of tills as the glacier moved over previous deposits. They can be observed in areas where isolated sands and gravels are on top of till deposits. Note that a majority of these are above the water table. Many of the Block areas have limited groundwater well development in the ***Q*** due to the lack of water bearing sediments. In these areas the ***Kd*** Sandstone/Sand dominant materials are the primary and/or secondary source of groundwater to the wells. Note that many of the wells in the ***Kd*** have specific capacities of less than 5 gpm/ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Ceresco AEM Block of aquifer material below the 1995 CSD water table elevation is 89,321 acre-ft. The amount of extractable groundwater from Aquifer Material is 4,466 acre-ft and Coarse Aquifer Material is 162.1 acre-ft. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 980 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Davey Raymond AEM Block of Aquifer Material below the 1995 CSD water table elevation is 11,373 acre-ft. The amount of extractable groundwater from Aquifer Material is 568 acre-ft and Coarse Aquifer Material is 0 acre-ft. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 1,1050 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Denton AEM Block of Aquifer Material below the 1995 CSD water table elevation is 8,698 acre-ft. The amount of extractable groundwater from Aquifer Material is 246 acre-ft and coarse aquifer material is 56. While these materials will produce water, the yields and specific capacity will be reduced. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 782 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Dwight South AEM Block of Aquifer Material below the 1995 CSD water table elevation is 20,316 acre-ft. The amount of extractable groundwater from Aquifer Material is 1,015 acre-ft and Coarse Aquifer material is 0. While these materials will produce water, the yields and specific capacity will be reduced. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 847 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Emerald Pleasant Dale AEM Block of Aquifer Material below the 1995 CSD water table elevation is 20,593 acre-ft. The amount of extractable groundwater from Aquifer Material is 1,029 acre-ft and Coarse Aquifer material is 0. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 4,062 acre-ft.

Estimates of the groundwater in storage within the ***Q***-portion of the Garland Malcolm AEM Block of Aquifer Material below the 1995 CSD water table elevation is 361,105 acre-ft. The amount of extractable groundwater from Aquifer Material is 18,055 acre-ft and Coarse Aquifer material is 0. The amount of extractable groundwater from ***Kd*** Sandstone/Sand Dominant material is 3,121 acre-ft.

3.4.5 Potential Recharge Zones within the LPSNRD AEM Survey Area

Within the LPSNRD Reconnaissance AEM flight area, the highest rate of recharge can be expected along the river-stream valleys due to the presence of Aquifer and Coarse Aquifer materials and the uplands having deposits of Aquifer and Coarse Aquifer materials from the land surface down to the water table and beyond. Areas with Aquifer and Coarse Aquifer materials at the surface can also become conduits for infiltration of nitrates into the groundwater system. These areas exist in the river and stream areas and uplands of the AEM survey area where the reconnaissance lines are the basis for this determination. It should be noted that in these areas, the results shown in the interpreted recharge maps are based on actual AEM data. A potential solution for any nonpoint source water quality contamination is adding additional fresh surface water as recharge to select areas of rangeland that can dilute any potential nitrate contaminant problem occurring from cropland. Additional work can be done to identify where the best locations are for these type of management efforts, but this is limited in the LPSNRD due to the abundance of fine-grained material throughout the area.

The use of Block flights for the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcom 2018 AEM survey areas illustrate the preferred method of using AEM to identify areas where the potential for recharge to the aquifer can be higher and lower. Locations where the flight lines are closely spaced showing either Aquifer or Coarse Aquifer Material at the land surface should be considered as locations for higher likelihood for recharge because of the 2D and 3D spatial nature of the aquifer material distribution. The opposite is also true where AEM data analysis shows Non-Aquifer or Marginal Aquifer Material. Those areas will likely not be optimal recharge locations. The areas throughout the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcom AEM survey areas have mixed potential recharge that is limited across most of the area due to the ***Q*** dominance of the Non-Aquifer and Marginal Aquifer materials at, or just below, the ground surface.

3.4.6 Hydrologic Connection Between Groundwater and Surface Water in the LPSNRD AEM Survey Area

The AEM data and interpretation provides detailed empirical data for determining earth materials on the surface and at depth that are related to aquifer characteristics. The ***Q*** aquifer materials are a guide, with Coarse Aquifer and Aquifer Materials being the most able to recharge, store, and provide

groundwater flow. The Marginal Aquifer Material provides limited groundwater flow with poor recharge and the Non-Aquifer Material provides virtually no groundwater flow. The areas mapped and discussed in this report show areas that contain large amounts of Marginal and Non-Aquifer deposits. These areas can be boundary conditions between different parts of the groundwater system and the surface water of the area. Any planning or detailed analysis related to groundwater and surface water relationships should take this information into account.

3.4.7 Saltwater Areas in the LPSNRD AEM Survey Area

The AEM easily detects conductive materials in the subsurface. The addition of saltwater to earth materials lowers the bulk resistivity. In many of the areas of the LPSNRD low resistivities below 4 ohm-m are detected. These areas are most certainly impacted by saltwater that are long no to exist in the areas. The maps developed in this study can be used to further delineate control areas to avoid the interception of saltwater.

3.5 Recommendations

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

3.5.1 Preparing the Results from AEM Hydrogeological Investigations for Groundwater Modeling

The LPSNRD has acquired AEM data for groundwater management purposes over the past 12 years. With the completion of this current study, it is recommended that additional work be undertaken to integrate the previous studies into a unified geologic model to describe the subsurface in detail. The output from this work can be used for monitoring well placement for water quantity and quality studies, provide detailed groundwater flow path studies for water quality that can estimate time and direction of flow, provide detailed estimates groundwater surface water relationships and create optimal datasets for use in groundwater models and assist in their use. With the investment in the AEM that the LPSNRD has undertaken this next step will provide a final product that can be easily accessed by the staff and public for future groundwater management.

3.5.2 Additional AEM Mapping

No additional AEM reconnaissance mapping is required for the LPSNRD at this time. Block data acquisition should only be considered depending on management needs of the LPSNRD for the purpose of infilling areas where the reconnaissance surveys did not provide enough detail to clearly define the hydrostratigraphy.

3.5.3 Update the Water Table map

The groundwater data used in the analyses presented in this report utilized the 1995 CSD water table map which is now 24 years old. Additional water level measurement locations would improve the water table map where groundwater conditions are unconfined. The areas of glacial till and loess covering the parts of the district will need great care in developing a water level map of potentiometric heads due to the confined to semiconfined nature of the area. Use of the data collected in this survey and future surveys will provide the best possible water table and conditions map for the district.

3.5.4 Planning new test holes and production wells

The AEM hydrogeological framework profiles, maps, and surfaces provided in this report provide great insight in 3D on the relationship between current test holes and production groundwater wells. At the time of this report, the currently available lithology data for the LPSNRD area was used in building the framework maps and profiles. Additional information from previous groundwater reports were helpful in this work. It is recommended that the results from this report be used to site new test holes and monitoring wells. Often test holes are sited based on previous work that is regional in nature. By utilizing the maps in this report new drilling locations can be sited in more optimal locations. The location of new water supply wells for communities can also use the results in this report to guide development of new water supply wells. Planners should locate wells in areas of greatest saturated thickness with the least potential for non-point source pollution. A good example of this would be confined aquifers with large volumes of coarse aquifer and aquifer material with minimal sedimentary boundary conditions. The previous AEM studies have already found use by CSD and local well drillers to locate test wells and production wells within the LPSNRD.

3.5.5 Aquifer testing and borehole logging

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

Additional test holes with detailed, functional, and well calibrated geophysical logging for aquifer characteristics are highly recommended. Examples of additional logging would be flow meter logs and geophysical logs including gamma, neutron, electrical, and induction logs. Detailing aquifer characteristics can be accomplished with nuclear magnetic resonance logging (NMR) at a reduced cost when compared to traditional aquifer tests. This is a quick and effective way to characterize porosity and water content, estimates of permeability, mobile/bound water fraction, and pore-size distributions with depth.

3.5.6 Recharge Zones

The LPSNRD hydrogeologic framework in this report provides areas of recharge from the ground surface to the groundwater aquifer. Reconnaissance-level AEM investigations provide limited detailed information between the lines for understanding recharge throughout the survey area. It is recommended that future work integrate new soils and land use maps with the results of this study to provide details on soil permeability, slope, and water retention to provide a more complete understanding of the transport of water from the land surface to the groundwater aquifer. A potential solution to water quality, quantity, and stream depletions is adding additional fresh surface water as recharge to select areas of rangeland or other areas. Additional work can be done to identify where the best locations are for these type of management efforts. This information can and has been used in Nebraska to improve Well Head Protection Areas by refining the estimated travel time estimates and the boundary areas.

3.5.7 Managed Aquifer Recharge

The areas which may have potential for managed aquifer recharge (MAR) are limited at best. However, additional detailed work focusing on this effort can provide potential sites. The detailed analysis suggested for this purpose would need to determine where viable opportunities for the LPSNRD exist and what additional information would be required for final selections of MAR sites. Additional AEM mapping in new block flight locations and along the streams in the LPSNRD would also be beneficial in locating potential MAR locations. A detailed plan for locating and developing MAR sites would be beneficial to the LPSNRD for storage and release of water for stream flow and other uses.

3.5.8 Updating previous groundwater reports and Groundwater Management Plans

The groundwater reports and management plans should be updated with the AEM information. The addition of estimates of groundwater in storage, recharge areas, hydrologic connection to streams and consideration of managed aquifer recharge sites will greatly improve and groundwater management plan.

3.5.9 Assist the LPSNRD staff with additional interpretation and data analysis for groundwater management needs

The AEM reports provided to the district are complete, but there is always a need to extract and analyze the AEM data in conjunction with a particular management need or area. Examples include using the AEM data to define areas for management practices related to water quality problems, use the AEM data to site water well development, assist groundwater modelers with input data sets for groundwater modeling, and define hydrologic connections between groundwater and surface water to name a few.

3.5.10 Development of water quality maps using the AEM

While the AEM detected areas of saltwater within the LPSNRD, no characterization of the water quality was calculated. In many other areas of the US and the world, AEM has successfully been used to calculate the 3D distribution of water quality. To accomplish this, strategically placed drill holes and water quality sampling field campaigns need to be conducted to be used to calibrate the AEM resistivity distributions of the water quality. These control points provide the volumetric mixing relationships that are needed to deconvolve the pore water resistivity from the matrix or formation/earth materials resistivity. The LPSNRD has a valuable resource in the AEM data that can then be further utilized with limited sampling and new test hole drilling to provide a district-wide water quality map.

4 Description of Data Delivered

4.1 Tables Describing Included Data Files

Table 4-1 describes the raw data files included in Appendix 3_Deliverables \Raw_Data. As discussed above, twenty-seven (27) flights were required to acquire the LPSNRD AEM data (Figure 2-5). Grouped by flight date, there are four (4) data flies included in Appendix 3\Raw_Data for each flight. These files have extensions of "*.sps" and "*.skb". The "*.sps" files include navigation and DGPS location data and the "*.skb" files include the raw AEM data that have been PFC-corrections (discussed in Section 2.4.1). Two additional files are used for all the flights. These are the system description and specifications file (with the extension "*.gex") in the GEO subdirectory and the 'mask' file (with the extension "*.lin"), in the MASK subdirectory, which correlates the flight dates, flight numbers, and assigned line numbers.

Table 4-2 describes the data columns in the ASCII *.xyz file LPSNRD2018_EM_MAG_AUX.xyz. This file contains the electromagnetic data, plus the magnetic and navigational data, as supplied directly from SkyTEM.

The result of the SCI is included in LPSNRD2018_AEM_SCI_INV_v1.xyz and the data columns of these databases are described in Table 4-3.

The interpretation results are included in the data files LPSNRD2018_Interp_AqThk.xyz, Ceresco_AqThk.xyz, DaveyRaymond_AqThk.xyz, Denton_AqThk.xyz, DwightSouth_AqThk.xyz, EmeraldPleasantDale_AqThk.xyz, GarlandMalcolm_AqThk.xyz in ASCII format. Table 4-4 describes the data columns of those files.

A new table of data has been compiled (Table 4-5) that lists, model layer by model layer, the top, middle, and bottom depths and elevations of each model cell layer along with the inverted model resistivity for that cell.

The format of the voxel grids that have been created from the AEM data in the survey area is described in Table 4-6. The voxel grids are presented as xyz files.

ESRI Arc View Binary grids of the surfaces that were used in the interpretation (DEM, water table) and derived from the interpretation (top of geological units) of the AEM and borehole are listed in Table 4-7. And stored in Appendix 3_Deliverables\Grids.

In summary, the following are included as deliverables:

- Raw Data Files - SkyTEM files *.gex, *skb, *.lin
- Raw EM Mag data as ASCII *.xyz
- SCI inversion as ASCII *.xyz in array and an individual column format by model layer.
- Interpretations as ASCII *.xyz
- ESRI ArcView files – surface, topo, etc
- Voxel Grids AEM Block areas as *.xyz
- 2D profiles and 3D fence diagrams of the AEM survey inversion results

KMZs for LPSNRD AEM flight lines and interpretations (Discussed in Section 4.2).

Table 4-1. Raw SkyTEM data files

Folder	File Name	Description
Data	..NavSys.sps, ...PaPc.sps, ...RawData_PFC.skb, ...DPGS.sps	Raw data files included for each flight used in importing to Aarhus Workbench
Geo	20180823_304_DualWaveform_60Hz_skb.gex	304M System Description
	20181002_304_446_Nebraska_skb_SR2.gex	
	20181002_304_446_Nebraska_skb_SR2.sr2	
Mask	20180613_446_NE304_LPSNRD.lin	Production file listing dates, flights, and assigned line numbers

Table 4-2: Channel name, description, and units for LPSNRD2018_EM_MAG_AUX.xyz with DEM, magnetic, DGPS, Inclinometer, altitude, and associated data.

Parameter	Description	Unit
Fid	Unique Fiducial Number	
Line	Line Number	
Flight	Name of Flight	yyyymmdd.ff
DateTime	DateTime Format	Decimal days
Date	DateTime Format	yyyymmdd
Time	Time UTC	hhmmss.sss
AngleX	Angle (in flight direction)	Degrees
AngleY	Angle (perpendicular to flight direction)	Degrees
Height	Filtered Height Measurement	Meters [m]
Lon	Longitude, WGS84	Decimal Degrees
Lat	Latitude, WGS84	Decimal Degrees
E_UTM14N_m	Easting, NAD83 UTM Zone 14N	Meters [m]
N_UTM14N m	Northing, NAD83 UTM Zone 14N	Meters [m]
E_NESP83_ft	Easting, NAD83 Nebraska State Plane	Feet [ft]
N_NESP83N_ft	Northing, NAD83 Nebraska State Plane	Feet [ft]
DEM	Digital Elevation	Meters [m]
Alt	DGPS Altitude above sea level	Meters [m]
GDSpeedL	Ground Speed	Kilometers/hour [km/h]
Curr_LM	Current, Low Moment	Amps [A]
Curr_HM	Current, High Moment	Amps [A]
LMZ_G01	Normalized (PFC-Corrected) Low Moment Z-RxCoil values array	$pV/(m^4*A)$
HMZ_G01	Normalized (PFC-Corrected) High Moment Z-RxCoil values array	$pV/(m^4*A)$
HMX_G01	Normalized (PFC-Corrected) High Moment X-RxCoil values array	$pV/(m^4*A)$
PLNI	Power Line Noise Intensity monitor	V/m^2
Bmag	Raw Base Station Mag Data filtered	nanoTesla [nT]
MAG_Raw	Raw Mag Data	nanoTesla [nT]
Mag_ED	Mag filtered	nanoTesla [nT]
Diurnal	Diurnal Mag Data	nanoTesla [nT]
Mag_Cor	Mag Data Corrected for Diurnal Drift	nanoTesla [nT]
RMF	Residual Magnetic Field	nanoTesla [nT]
TMI	Total Magnetic Intensity	nanoTesla [nT]

Table 4-3. Channel name, description, and units for LPSNRD2018_AEM_SCI_INV_v1.xyz with EM inversion results.

/Parameter	Description	Unit
LINE	Line Number	
East_NESP83FT	Easting NAD83, Nebraska State Plane	Feet (ft)
North_NESP83FT	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_ft	DEM from 100 ft grid NED NAVD88	Feet [ft]
East_UTM_M	Easting NAD83, UTM Zone 14	Meters [m]
North_UTM_M	Northing NAD83, UTM Zone 14	Meters [m]
DEm_m	DEM from survey	Meters [m]
Alt_m	Altitude of system above ground	Meters [m]
Invalt_M	Inverted Altitude of system above ground	Meters [m]
Resdata	Residual of individual sounding	
ResTotal	Total residual for inverted section	
RHO_I_0 through RHO_I_38	Inverted resistivity of each layer	Ohm-m
RHO_I_STD_0 through RHO_I_STD_38	Inverted resistivity error per layer	
SIGMA_I_0 through SIGMA_I_38	Conductivity	S/m
DEP_TOP_0_ft through DEP_TOP_38_ft	Depth to the top of individual layers	Feet [ft]
DEP_BOT_0_ft through DEP_BOT_38_ft	Depth to the bottom of individual layers	Feet [ft]
THK_0_FT through THK_38_FT	Thickness of individual layers	Feet [ft]
DEP_TOP_0_m through DEP_TOP_38_M	Depth to the top of individual layers	Meters [m]
DEP_BOT_0_M through DEP_BOT_38_m	Depth to the bottom of individual layers	Meters [m]
THK_0_m through THK_38_m	Thickness of individual layers	Meters [m]
DOI_UPPER_FT	More conservative estimate of DOI	Feet [ft]
DOI_LOWER_ft	Less conservative estimate of DOI	Feet [ft]
DOI_UPPER_M	More conservative estimate of DOI	Meters [m]
DOI_LOWER_M	Less conservative estimate of DOI	Meters [m]

Table 4-4. Channel name description and units for the interpretation results files LPSNRD2018_Interp_AqThk.xyz, Ceresco_AqThk.xyz, DaveyRaymond_AqThk.xyz, Denton_AqThk.xyz, DwightSouth_AqThk.xyz, EmeraldPleasantDale_AqThk.xyz, GarlandMalcolm_AqThk.xyz.

Parameter	Description	Unit
LINE	Line Number	
East_M	Easting NAD83, UTM Zone 14N	Meters (m)
North_M	Northing NAD83, UTM Zone 14N	Meters (m)
East_ft	Easting NAD83, Nebraska State Plane	Feet [ft]
North_ft	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
RHO [0] through RHO [38]	Array of Inverted model resistivities of each layer	Ohm-m
RESDATA	Inversion model residuals of each individual sounding	
RESTOTAL	Inversion model average of all residuals	
DEP_TOP_FT [0] through DEP_TOP_FT [38]	Depth to the top of 39 individual layers (not all arrays have 39 values)	Feet [ft]
DEP_BOT_FT [0] through DEP_BOT_FT [38]	Depth to the bottom of 39 individual layers (not all arrays have 39 values)	Feet [ft]
DOI_UPPER_FT	More conservative estimate of DOI from Workbench	Feet [ft]
DOI_LOWER_FT	Less conservative estimate of DOI from Workbench	Feet [ft]
SoilRecharge	1 = Surficial layer Non-Aquifer; 2 = Marginal; 3 = Aquifer; 4 = Coarse Aquifer Material	
WaterTable1995	Elevation of the top of the water table from the Nebraska School of Natural Resources Configuration Report, 1995.	Feet [ft]
NAT[0] through NAT[38]	Array of model cell top elevations of the Non-Aquifer Material (<12 ohm-m), if present	Feet [ft]
NAB[0] through NAB[38]	Array of model cell bottom elevations of the Non-Aquifer Material (<12 ohm-m), if present	Feet [ft]
ThkTot_NAq	Total Thickness of Non-Aquifer Material (<12 ohm-m) above bedrock	Feet [ft]
ThkWT_NAq	Total Thickness of Non-Aquifer Material (<12 ohm-m) below the water table and above bedrock	Feet [ft]
MAT[0] through MAT[38]	Array of model cell top elevations of the Marginal-Aquifer Material (12 - 20 ohm-m), if present	Feet [ft]
MAB[0] through MAB[38]	Array of model cell bottom elevations of the Marginal-Aquifer Material (12 - 20 ohm-m), if present	Feet [ft]

ThkTot_MAq	**Total Thickness of Marginal-Aquifer Material (12 - 20 ohm-m) above bedrock**	**Feet [ft]**
AMT[0] through AMT[38]	**Array of model cell top elevations of the Aquifer Material (20 - 50 ohm-m), if present**	**Feet [ft]**
AMB[0] through AMB[38]	**Array of model cell bottom elevations of the Aquifer Material (20 - 50 ohm-m), if present**	**Feet [ft]**
ThkTot_AqM	**Total Thickness of Aquifer Material (20 - 50 ohm-m) above bedrock**	**Feet [ft]**
CAT[0] through CAT[38]	**Array of model cell top elevations of the Coarse Aquifer Material (>50 ohm-m), if present**	**Feet [ft]**
CAB[0] through CAB[38]	**Array of model cell bottom elevations of the Coarse Aquifer Material (>50 ohm-m), if present**	**Feet [ft]**
ThkTot_CAq	**Total Thickness of Coarse Aquifer Material (>50 ohm-m) above bedrock**	**Feet [ft]**
ThkTot_Aq_CA	**Sum of Total Thicknesses of Aquifer Material (20 - 50 ohm-m) and Coarse Aquifer Material (>50 ohm-m) above bedrock**	**Feet [ft]**
ThkWT_Aq_CA	**Sum of Total Thicknesses of Aquifer Material (20 - 50 ohm-m) and Coarse Aquifer Material (>50 ohm-m) below the water table and above bedrock**	**Feet [ft]**
Elev4Ohmm	**Elevation of the top of zone identified as saltwater, if present**	**Feet [ft]**
Bedrock	**Elevation of interpreted bedrock surface**	**Feet [ft]**
Kgg	**Elevation of the top of the Cretaceous Greenhorn Limestone and Graneros Shale, if present**	**Feet [ft]**
Kd	**Elevation of the top of the Cretaceous Dakota Group, if present**	**Feet [ft]**
IP	**Elevation of the top of the Undifferentiated Pennsylvanian, if present**	**Feet [ft]**

Table 4-5. LPSNRD Inverted Model Structure with DEM and Layer Top-, Bottom-, and Mid-points in Depth and Elevation plus Inverted Cell Resistivities (LPSNRD_XYDEM_Dep_Elev_Rho.xyz).

Parameter	Description	Unit
Line	Line number	
East_ft	Easting NAD83, Nebraska State Plane	Feet [ft]
North_ft	Northing NAD83, Nebraska State Plane	Feet [ft]
DEM_ft	Topography at 100ft sampling (NAVD 1988)	Feet [ft]
Dep_Top_ft		Feet [ft]
Dep_Mid_ft		Feet [ft]
Dep_Bot_ft		Feet [ft]
Elev_Top_ft		Feet [ft]
Elev_Mid_ft		Feet [ft]
Elev_Bot_ft		Feet [ft]
RHO	Cell Resistivity	Ohm-m

Table 4-6. Channel name, description, and units for *_Quat_voxel.csv and *_Kd_voxel.csv. This is for the Ceresco, Davey Raymond, Denton, Dwight South, Emerald Pleasant Dale, and Garland Malcolm Blocks. All grids are 100 X 100 feet and the model layer thickness for each depth layer.

Parameter	Description	Unit
X	Easting NAD83, State Plane Nebraska	feet [ft]
Y	Northing NAD83, State Plane Nebraska	feet [ft]
Z	Depth of Voxel Node	feet [ft]
Resistivity	Voxel cell resistivity value	Ohm-m

Table 4-7. Files containing ESRI ArcView Binary Grids *.flt (Nebraska State Plane, NAD83, feet)

Grid File Name	Description	Grid Cell Size (feet)
LPSNRD_DEM_ft	Digital Elevation Model (ground surface elevation) (NAVD88 feet) of the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_WT_1995	Elevation (NAVD88 feet) of water table (1995) for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_Top_Bedrock	Elevation (NAVD88 feet) of top of bedrock for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_Top_Kgg	Elevation (NAVD88 feet) of top of Cretaceous Greenhorn-Graneros for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_Top_Kd	Elevation (NAVD88 feet) of top of Cretaceous Dakota Group for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_Top_IP	Elevation (NAVD88 feet) of top of Undifferentiated Pennsylvanian for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_Thickness_Q	Thickness (feet) of Quaternary Deposits for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_Thickness_Kgg	Thickness (feet) of Greenhorn-Graneros for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_Thickness_Kd	Thickness (feet) of Cretaceous Dakota Group for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_SaturatedThickness_Q	Saturated thickness (feet) of Quaternary Deposits for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
LPSNRD_SaturatedThick_Kd	Saturated thickness (feet) of Cretaceous Dakota Group for the LPSNRD survey area, NAD83/State Plane Nebraska, feet	100
Ceresco_4ohm_Thickness	Total thickness (feet) of material with 4 ohm or less resistivity for the Ceresco Block survey area, NAD83/State Plane Nebraska, feet	100
Ceresco_Kd_SandDominant_Thickness	Total thickness (feet) of Cretaceous Dakota Group sand/sandstone dominant material for the Ceresco Block survey area, NAD83/State Plane Nebraska, feet	100

Ceresco_Q_Saturated_AquiferCoarse_Thickness	**Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Ceresco Block survey area, NAD83/State Plane Nebraska, feet**	**100**
Ceresco_Q_Saturated_Non_Thickness	**Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Ceresco Block survey area, NAD83/State Plane Nebraska, feet**	**100**
Ceresco_Q_Total_AquiferCoarse_Thickness	**Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Ceresco Block survey area, NAD83/State Plane Nebraska, feet**	**100**
Ceresco_Q_Total_Non_Thickness	**Total thickness (feet) of non-aquifer and marginal Quaternary material for the Ceresco Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DaveyRaymond_4ohm_Thickness	**Total thickness (feet) of material with 4 ohm or less resistivity for the Davey Raymond Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DaveyRaymond_Kd_SandDominant_SaturatedThickness	**Saturated thickness (feet) of Cretaceous Dakota Group sand/sandstone dominant material for the Davey Raymond Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DaveyRaymond_Kd_SandDominant_Thickness	**Total thickness (feet) of Cretaceous Dakota Group sand/sandstone dominant material for the DaveyRaymond Block survey area, NAD83/St ate Plane Nebraska, feet**	**100**
DaveyRaymond_Q_Saturated_AquiferCoarse_Thickness	**Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Davey Raymond Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DaveyRaymond_Q_Saturated_Non_Thickness	**Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Davey Raymond Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DaveyRaymond_Q_Total_AquiferCoarse_Thickness	**Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Davey Raymond Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DaveyRaymond_Q_Total_Non_Thickness	**Total thickness (feet) of non-aquifer and marginal Quaternary material for the Davey Raymond Block survey area, NAD83/State Plane Nebraska, feet**	**100**
Denton_4ohm_Thickness	**Total thickness (feet) of material with 4 ohm or less resistivity for the Denton Block survey area, NAD83/State Plane Nebraska, feet**	**100**

Denton_Kd_SandDominant_Thickness	**Total thickness (feet) of Cretaceous Dakota Group sand/sandstone dominant material for the Denton Block survey area, NAD83/State Plane Nebraska, feet**	**100**
Denton_Q_Saturated_AquiferCoarse_Thickness	**Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Denton Block survey area, NAD83/State Plane Nebraska, feet**	**100**
Denton_Q_Saturated_Non_Thickness	**Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Denton Block survey area, NAD83/State Plane Nebraska, feet**	**100**
Denton_Q_Total_AquiferCoarse_Thickness	**Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Denton Block survey area, NAD83/State Plane Nebraska, feet**	**100**
Denton_Q_Total_Non_Thickness	**Total thickness (feet) of non-aquifer and marginal Quaternary material for the Denton Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DwightSouth_4ohm_Thickness	**Total thickness (feet) of material with 4 ohm or less resistivity for the Dwight South Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DwightSouth_Kd_SandDominant_Thickness	**Total thickness (feet) of Cretaceous Dakota Group sand/sandstone dominant material for the Dwight South Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DwightSouth_Q_Saturated_AquiferCoarse_Thickness	**Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Dwight South Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DwightSouth_Q_Saturated_Non_Thickness	**Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Dwight South Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DwightSouth_Q_Total_AquiferCoarse_Thickness	**Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Dwight South Block survey area, NAD83/State Plane Nebraska, feet**	**100**
DwightSouth_Q_Total_Non_Thickness	**Total thickness (feet) of non-aquifer and marginal Quaternary material for the Dwight South Block survey area, NAD83/State Plane Nebraska, feet**	**100**
EmeraldPleasantDale_4ohm_Thickness	**Total thickness (feet) of material with 4 ohm or less resistivity for the Emerald Pleasant Dale Block survey area, NAD83/State Plane Nebraska, feet**	**100**

EmeraldPleasantDale_Kd_SandDominant_Thickness	**Total thickness (feet) of Cretaceous Dakota Group sand/sandstone dominant material for the Emerald Pleasant Dale Block survey area, NAD83/State Plane Nebraska, feet**	**100**
EmeraldPleasantDale_Q_Saturated_AquiferCoarse_Thickness	**Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Emerald Pleasant Dale Block survey area, NAD83/State Plane Nebraska, feet**	**100**
EmeraldPleasantDale_Q_Saturated_Non_Thickness	**Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Emerald Pleasant Dale Block survey area, NAD83/State Plane Nebraska, feet**	**100**
EmeraldPleasantDale_Q_Total_AquiferCoarse_Thickness	**Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Emerald Pleasant Dale Block survey area, NAD83/State Plane Nebraska, feet**	**100**
EmeraldPleasantDale_Q_Total_Non_Thickness	**Total thickness (feet) of non-aquifer and marginal Quaternary material for the Emerald Pleasant Dale Block survey area, NAD83/State Plane Nebraska, feet**	**100**
GarlandMalcolm_4ohm_Thickness	**Total thickness (feet) of material with 4 ohm or less resistivity for the Garland Malcolm Block survey area, NAD83/State Plane Nebraska, feet**	**100**
GarlandMalcolm_Kd_SandDominant_Thickness	**Total thickness (feet) of Cretaceous Dakota Group sand/sandstone dominant material for the Garland Malcolm Block survey area, NAD83/State Plane Nebraska, feet**	**100**
GarlandMalcolm_Q_Saturated_AquiferCoarse_Thickness	**Saturated thickness (feet) of aquifer and coarse aquifer Quaternary material for the Garland Malcolm Block survey area, NAD83/State Plane Nebraska, feet**	**100**
GarlandMalcolm_Q_Saturated_Non_Thickness	**Saturated thickness (feet) of non-aquifer and marginal Quaternary material for the Garland Malcolm Block survey area, NAD83/State Plane Nebraska, feet**	**100**
GarlandMalcolm_Q_Total_AquiferCoarse_Thickness	**Total thickness (feet) of aquifer and coarse aquifer Quaternary material for the Garland Malcolm Block survey area, NAD83/State Plane Nebraska, feet**	**100**
GarlandMalcolm_Q_Total_Non_Thickness	**Total thickness (feet) of non-aquifer and marginal Quaternary material for the Garland Malcolm Block survey area, NAD83/State Plane Nebraska, feet**	**100**

4.2 Description of Included Google Earth KMZ Data and Profiles

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

Unique KMZ files were created for each individual flight line in approximate 10-mile segments or shorter. Within these specialized KMZ files, the AEM flight line is shown as well as place marks at each location where there are interpreted geologic results. The attribute data for each unique place mark contains location information as well as bedrock and the 1995 water table. These KMZ files are located within the "*Appendix_3_Deliverables\KMZ\Interpretation\LPSNRD18_Profiles*" folder. In this folder is a "*GoogleE_Readme.pdf*" file that provides instructions regarding the "*Settings*" changes that need to be made in Google Earth, and how to use the KMZ files in Google Earth including a legend of what attributes are displayed when an AEM sounding location is clicked. This LPSNRD GoogleE_Readme.pdf file is repeated below as a convenience. The LPSNRD interpretation KMZ's are presented in Figure 4-1 (full LPSNRD), the LPSNRD Block areas in Figure 4-2, the Denton Block in Figure 4-3, the Dwight South Block in Figure 4-4, the Ceresco Block in Figure 4-5, the Davey Raymond Block in Figure 4-6, the Emerald Pleasant Dale Block in Figure 4-7, and the Garland Malcolm Block in Figure 4-8.

4.2.1 Included README for the LPSNRD Interpretation KMZ's

README for:

2018_LPSNRD_Interp_pt1,_pt2,_pt3,_pt4.kmz (in 4 parts)
2018_Ceresco_Block_Interp.kmz
2018_DaveyRaymond_Block_Interp.kmz
2018_Denton_Block_Interp.kmz
2018_DwightSouth_Block_Interp.kmz
2018_EmeraldPleasantDale_Block_Interp.kmz
2018_GarlandMalcolm_Block_Interp.kmz

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

Google Earth Instructions:

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

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

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

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

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

Data presented in KMZ:

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

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

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

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

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

Soil Recharge – 1=Aquifer or Coarse Aquifer Material on Surface; 0=Non-Aquifer or Marginal Aquifer Material on Surface.

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

Sum Thick Aq CAq (ft) – Sum of the thicknesses of Aquifer Material and Coarse Aquifer Material at the sounding location.

Sum Thick NAq (ft) – Sum of thicknesses of Non-Aquifer Material at the sounding location.

Elevation Saltwater (ft) – Elevation of 4 ohm-m resistivity indicating demarcation of saltwater.

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

Elevation Kgg (ft) – Elevation of Cretaceous Greenhorn Limestone and Graneros Shale Formation (if present), in feet.

Elevation Kd (ft) – Elevation of Cretaceous Dakota Group, in feet.

Elevation IP (ft) – Elevation of Undifferentiated Pennsylvanian units, in feet.

Profile – Link to Interpreted AEM profile images.

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

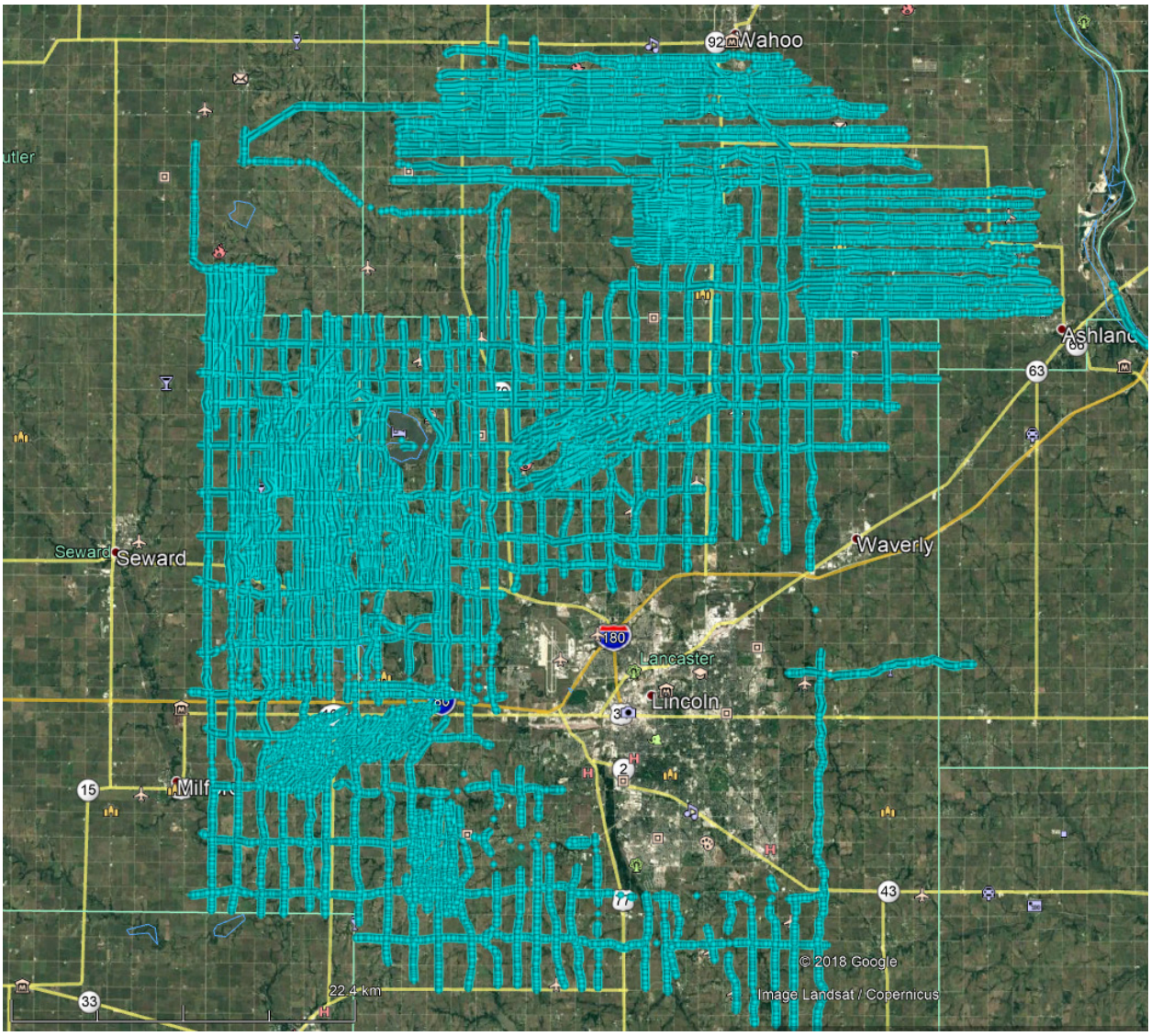


Figure 4-1. KMZ of the full LPSNRD AEM survey area. Due to the size of the data set, this kmz has been divided into four (4) parts (Pt1, Pt2, Pt3, and Pt4).

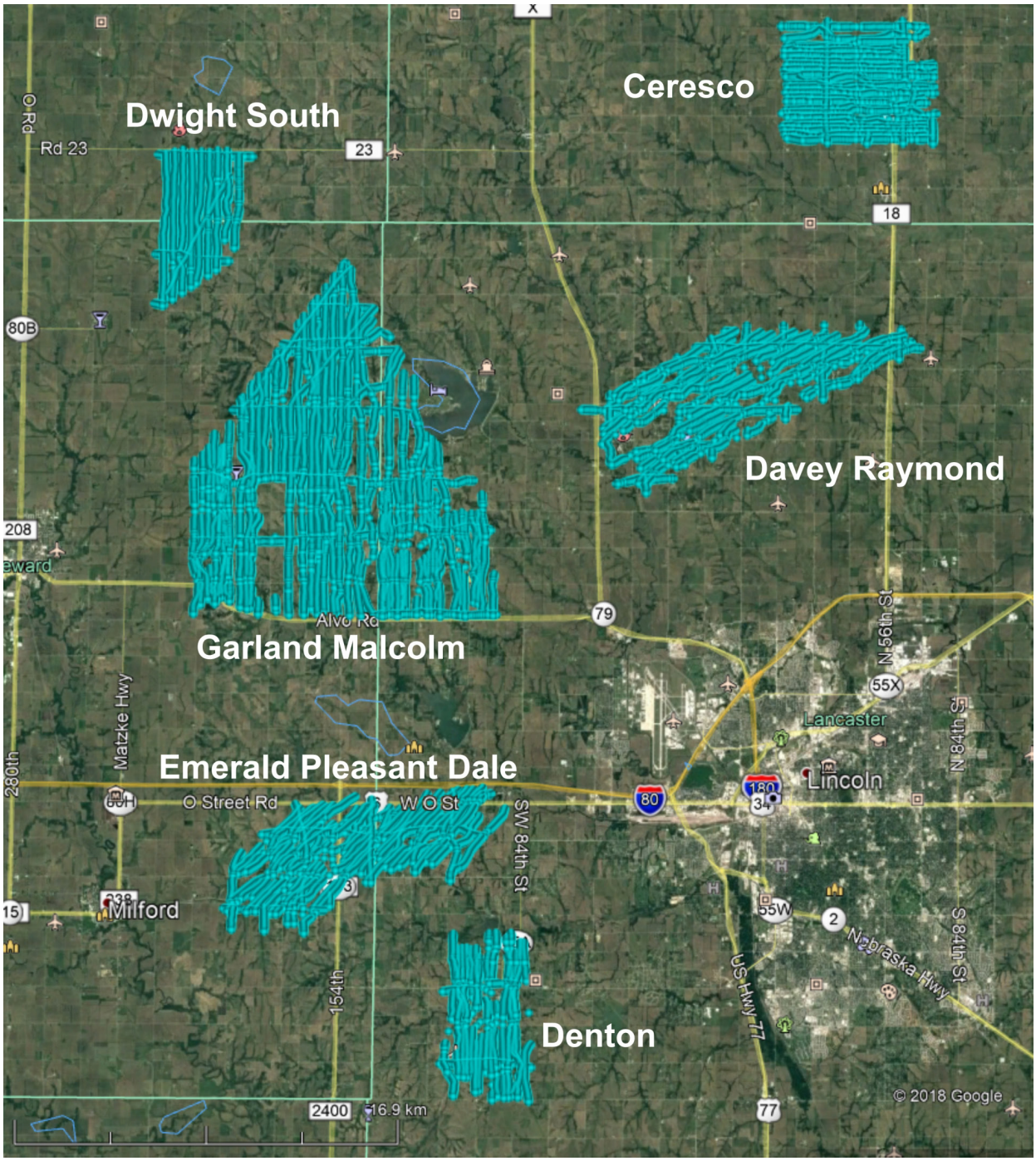


Figure 4-2. KMZ locations of LPSNRD AEM Block survey areas.

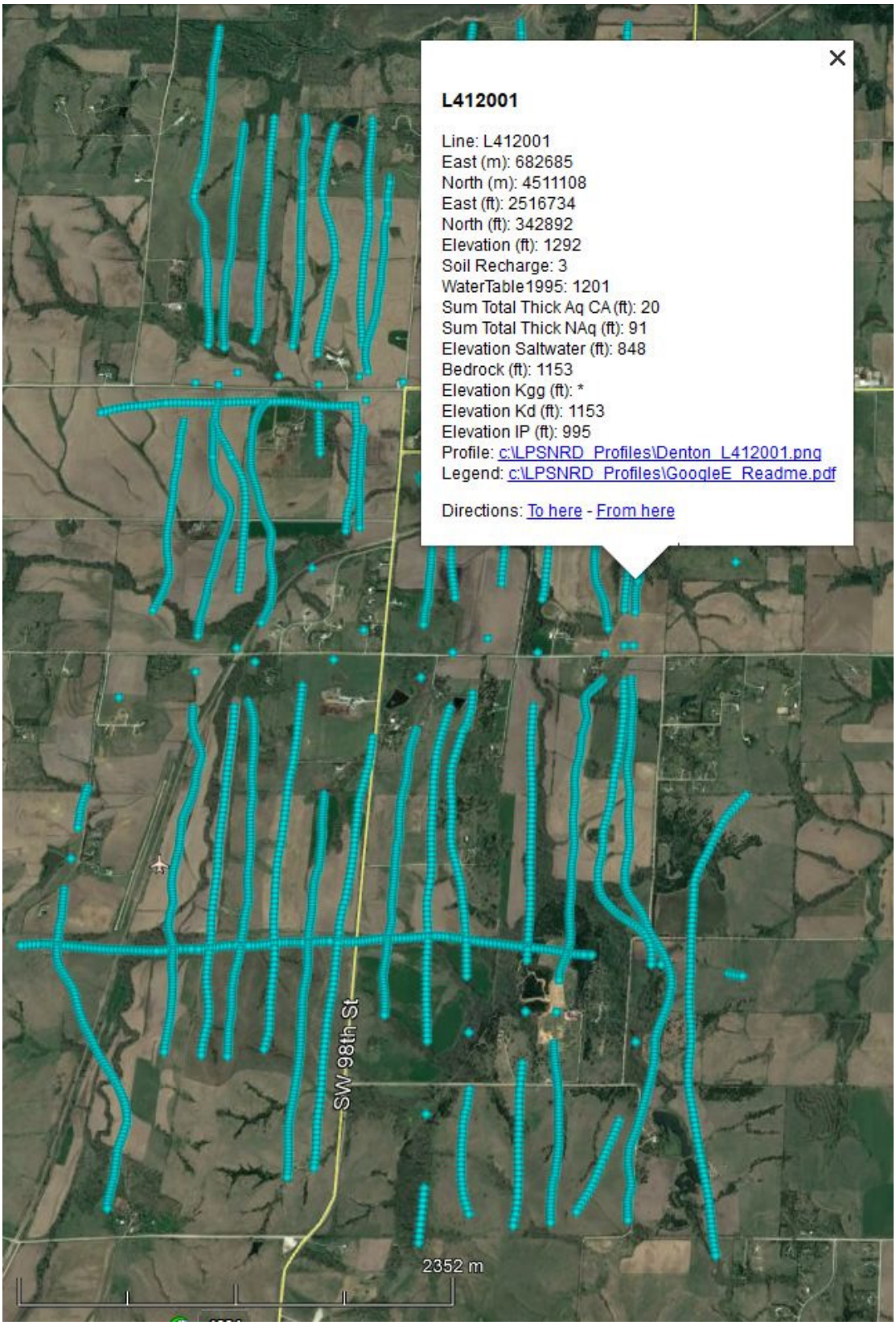


Figure 4-3. Example Google Earth image for the 2018 Denton Block Interpretation kmz showing location attributes.

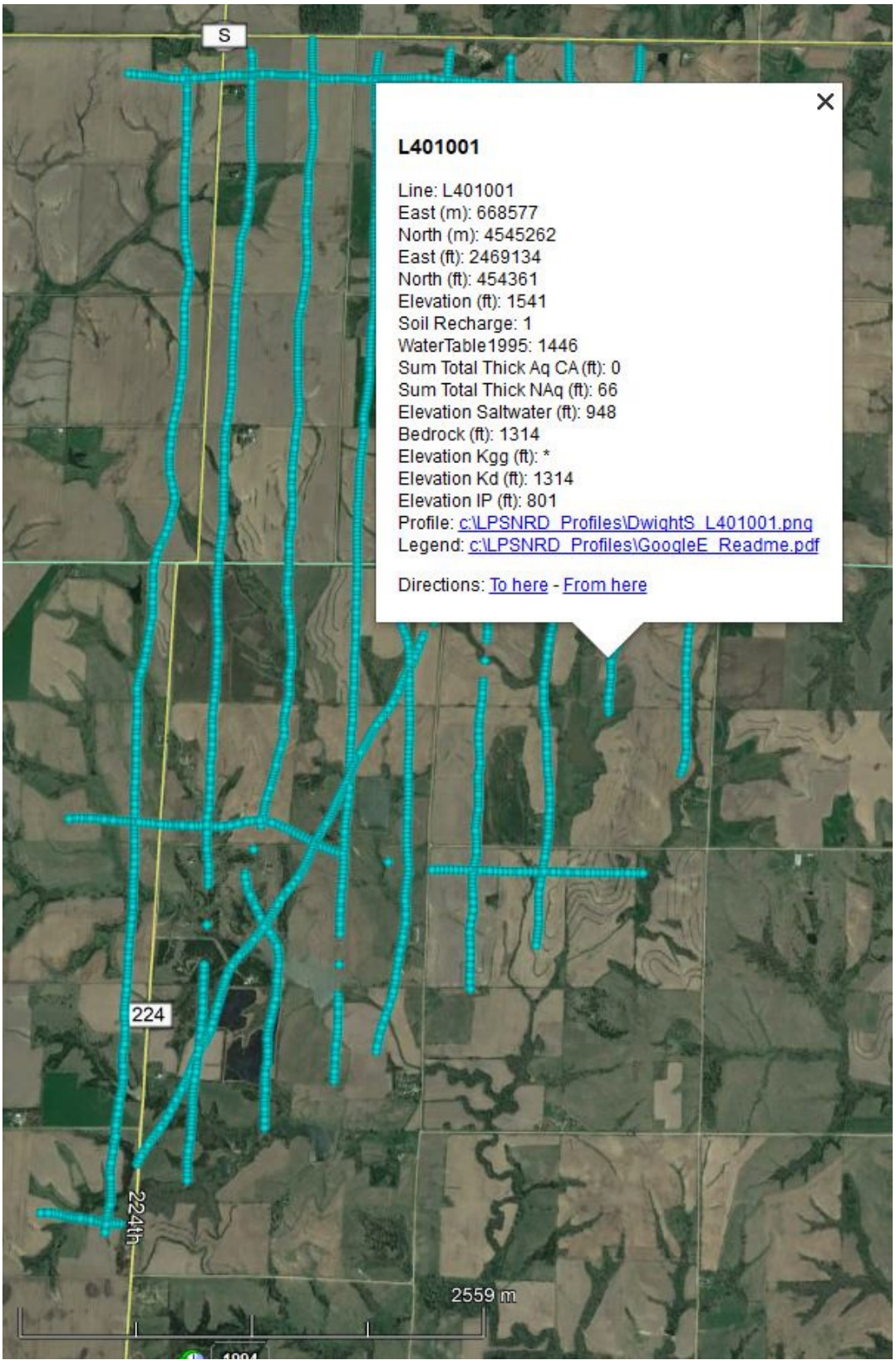


Figure 4-4. Example Google Earth image for the 2018 Dwight South Block Interpretation kmz showing location attributes.

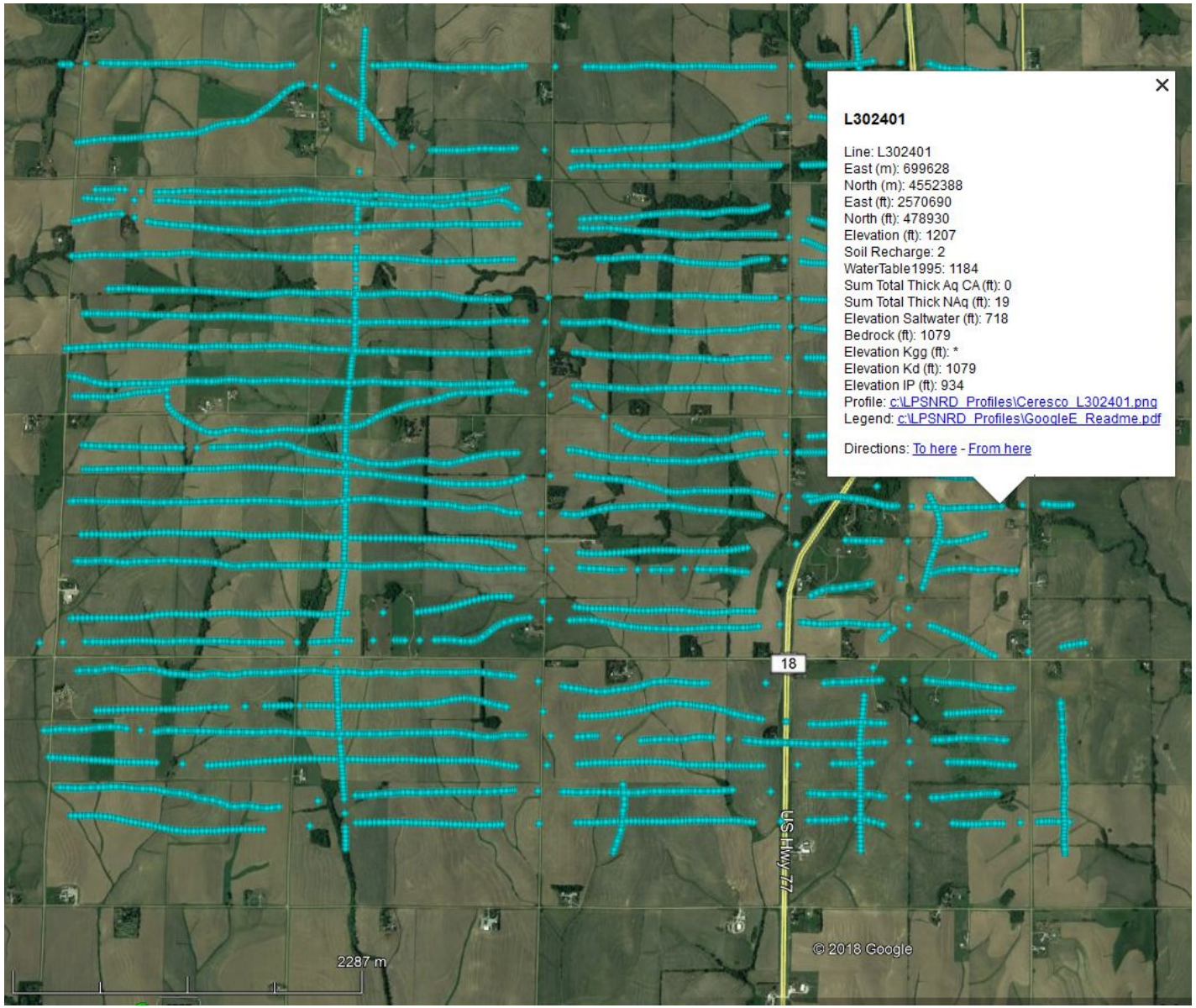


Figure 4-5. Example Google Earth image for the 2018 Ceresco Block Interpretation kmz showing location attributes.

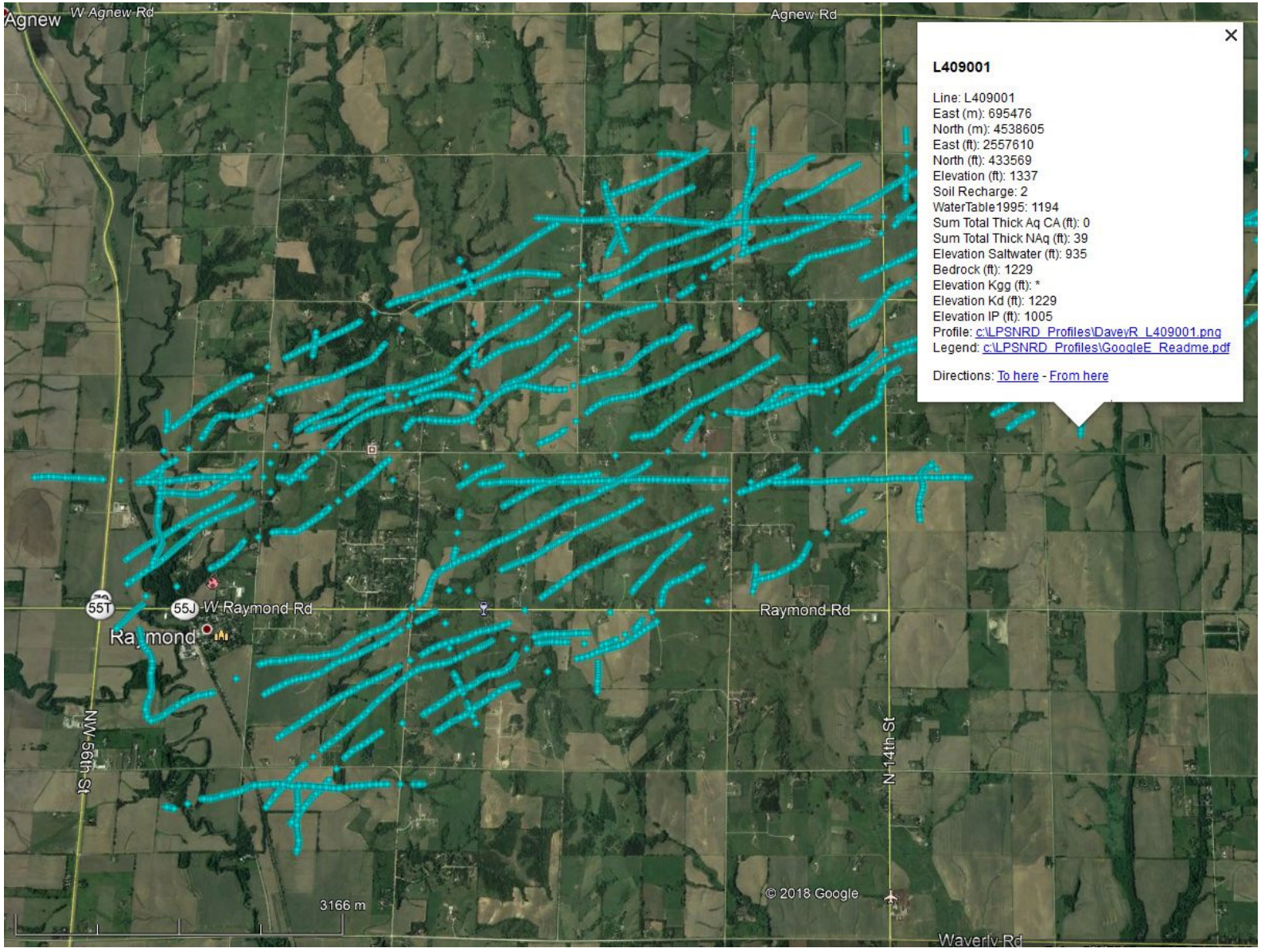


Figure 4-6. Example Google Earth image for the 2018 Davey Raymond Block Interpretation kmz showing location attributes.

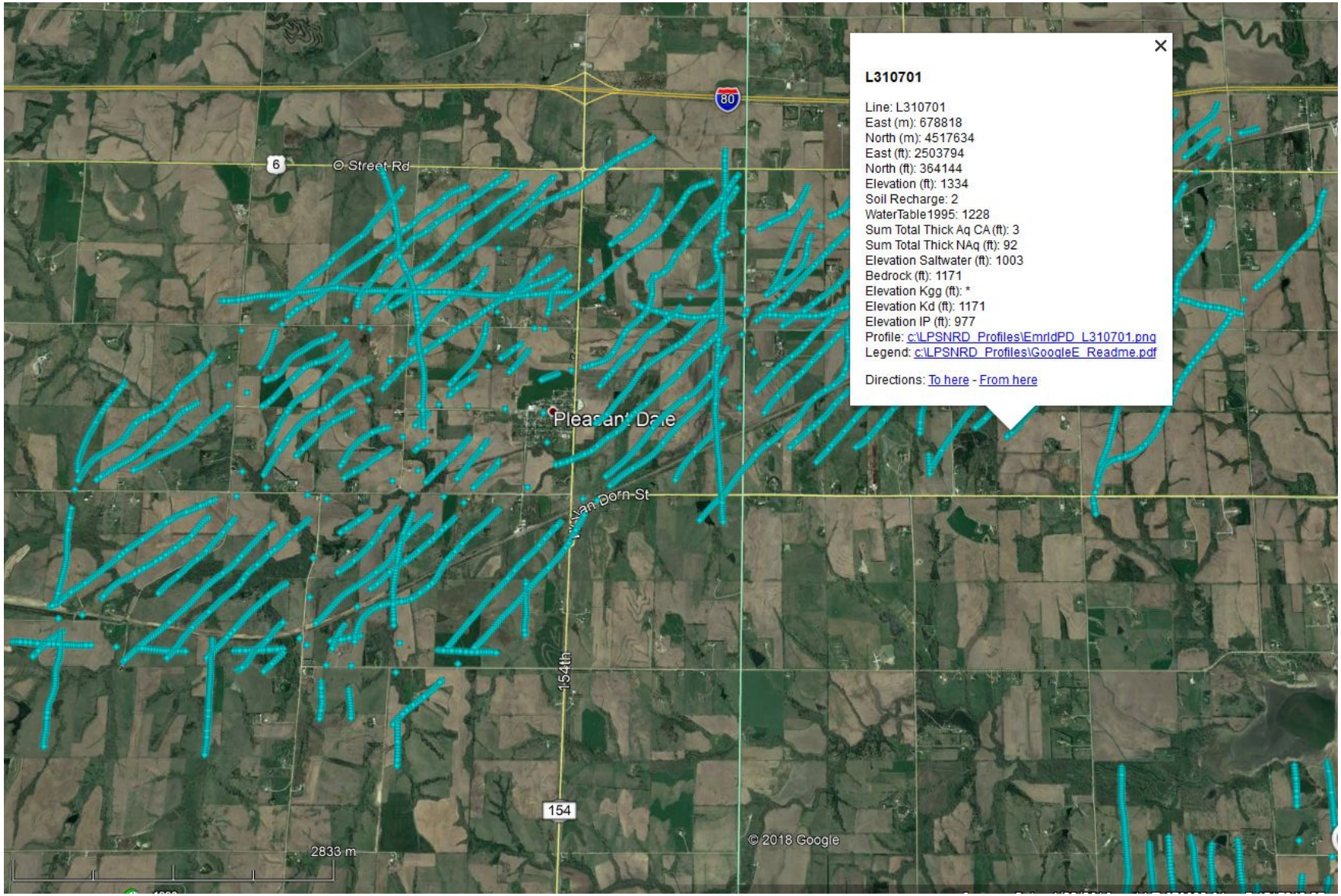


Figure 4-7. Example Google Earth image for the 2018 Emerald-Pleasant-Dale Block Interpretation kmz showing location attributes.

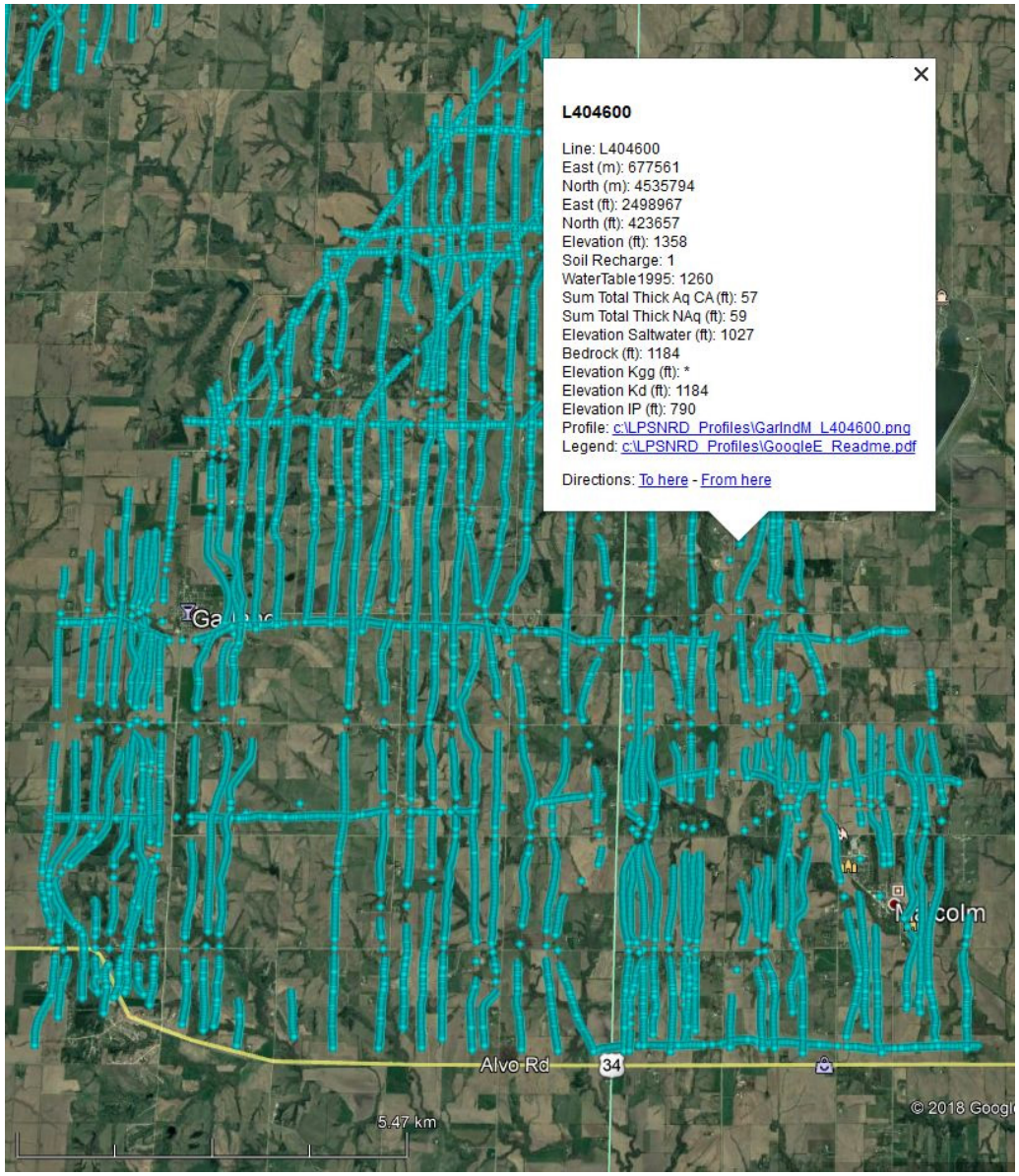


Figure 4-8. Example Google Earth image for the 2018 Garland Malcolm Block Interpretation kmz showing location attributes.

5 References

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

Abraham, J.D., Ehrman, R.L., Cannia, J.C., Asch, T.H., 2018, Impact of airborne electromagnetic (AEM) surveys in groundwater management in the Lower Platte South Natural Resources District, Nebraska, USA: in Abstracts from the AEGC 2018, Sydney Australia, Feb 18-21.

AGF, 2017, Hydrogeologic framework of selected areas in the Lower Platte South Natural Resources District, Nebraska, Prepared for the Lower Platte South Natural Resources District, November 10, 2017, by Aqua Geo Frameworks, LLC, Mitchell, Nebraska. http://www.enwra.org/aem2016.html#lpn (accessed December 1, 2019).

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

Burchett, R. R., 1986, Bedrock geology of Nebraska. University of Nebraska-Lincoln, School of Natural Resources, http://snr.unl.edu/data/geographygis/geology.aspx (accessed December 1, 2019).

Carney, C. P., Pierce, K.S., Abraham, J.D., Steele, G.V., Genco, A.G., and Cannia, J.C., 2014, "Hydrogeologic Assessment and Framework Development of the Aquifers beneath the Brainard-Valparaiso Area of the Lower Platte South Natural Resources District in Eastern Nebraska." Prepared for the Lower Platte South Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. (accessed on December 1, 2019). http://enwra.org/media/_LPS_AEM_REPORT_FINAL_text100dpi.pdf

Carney, C.P., Abraham, J.D., Cannia, J.C., and Steele, G.V., 2015a, Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for Selected Sites in the Lower Elkhorn Natural Resources District: prepared for the Lower Elkhorn Natural Resources District by Exploration Resources International Geophysics LLC, Vicksburg, MS. (accessed December 1, 2019). http://www.enwra.org/LENRD2014AEMDataDownload.html

Carney, C.P., Abraham, J.D., Cannia, J.C., and Steele, G.V., 2015b, Final Report on Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for the Eastern Nebraska Water Resources Assessment – Volume II, including the Lower Platte North, Lower Platte South, and Nemaha Natural Resources Districts: Prepared for the Eastern Nebraska Water Resources Assessment (ENWRA) by Exploration Resources International Geophysics LLC, Vicksburg, MS. http://www.enwra.org/aem%20data%20download.html (accessed on December1, 2019)

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

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

DatamineDiscover, 2019, Datamine Discover Profile Analyst, available on the world-wide web at: https://www.dataminesoftware.com/product/discover/ (accessed December 1, 2019)

Divine, D.P. and Korus, J.T., 2013, Three-dimensional hydrostratigraphy of the Sprague, Nebraska Area: Results from Helicopter Electromagnetic (HEM) Mapping for the Eastern Nebraska Water Resources Assessment (ENWRA): Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln. Conservation Bulletin 4, Link to PDF file: http://enwra.org/media/2012ENWRA_Sprague_final.pdf (accessed on December 1, 2019).

Elder, J. A., Dreesen, V. H., and Weakly, E. C., 1951, "University of Nebraska-Lincoln, School of Natural Resources." Topographic Regions of Nebraska.

Foged, N., Auken, E., Christiansen, A.V., and Sorensen, K.I., 2013, "Test-site calibration and validation of airborne and ground based TEM systems." *Geophysics* 78, No.2: E95-E106.

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

Geosoft, 2019, Oasis montaj, https://www.geosoft.com/products/oasis-montaj (accessed December 1, 2019).

Heath, R.C., 1983. Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220, 86p., http://pubs.er.usgs.gov/publication/wsp2220 (accessed December 1, 2019)

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

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

Korus, J.T., Joeckel, R.M., and Divine, D.P., 2013, Three-dimensional hydrostratigraphy of the Firth, Nebraska Area: Results from helicopter electromagnetic mapping (HEM) in the Eastern Nebraska Water Resources Assessment (ENWRA). Bulletin 3, Conservation and Survey Division, School of Natural Resources, Institute of Agriculture and National Resources, University of Nebraska-Lincoln. Link to PDF file: http://enwra.org/media/Firth_ENWRA_Bull_3_2013_small%20red.pdf (accessed on December 1, 2019).

Lower Platte South Natural Resources District, 1995, Phase I program for ground water quality and quantity: https://www.lpsnrd.org/programs/ground-water (accessed on December 1, 2019).

Nebraska Conservation and Survey Division, 1995. Configuration of the water table in 1995. Institute of Agriculture & Natural Resources, University of Nebraska-Lincoln.

Nebraska Department of Natural Resources. 2019. Registered Groundwater Wells Data Retrieval. http://nednr.nebraska.gov/dynamic/wells/Menu.aspx (accessed December 1, 2019)

Nebraska Oil and Gas Conservation Commission, 2019, Data and Publications website, http://www.nogcc.ne.gov/NOGCCPublications.aspx (accessed December 1, 2019).

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

Schamper, C., Auken, E., and Sorensen, K., 2014, Coil response inversion for very early time modelling of helicopter-borne time-domain electromagnetic data and mapping of near-surface Geologic Layers. European Association of Geoscientistis & Engineers, Geophysical Prospecting, v. 62, Issue 3, p. 658–674.

SkyTem Airborne Surveys Worldwide, 2019, SkyTEM304M, http://skytem.com/tem-systems/ (accessed December 1, 2019).

Smith, B.D., Abraham, J.A., Cannia, J.C., Steele, G.V., and Hill, P.L., 2008, Helicopter electromagnetic and magnetic geophysical survey data, Oakland, Ashland, and Firth study areas, Eastern Nebraska, March 2007: U.S. Geological Survey Open-File Report 2008-1018. Link to PDF file: https://pubs.usgs.gov/of/2008/1018/downloads/REPORT/ofr_2008_1018_v18.pdf (accessed December 1, 2019)

Smith, B.D., Abraham, J.D., Cannia, J.C., Minsley, B.J., Ball, L.B., Steele, G.V., and Deszcz-Pan, M., 2009, Helicopter Electromagnetic Geophysical Survey Data, Swedeburg and Sprague Areas, Eastern Nebraska: U.S. Geological Survey Open-File Report 2010-1288. Link to PDF file: https://pubs.usgs.gov/of/2010/1288/downloads/REPORT/ofr_2010_1288_v1_2.pdf (accessed on December 1, 2019).

United States Department of Agriculture, 2019. USDA Natural Resources Conservation Service. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/oh/technical/dma/gis/?cid=nrcs144p2_029531 (accessed December 1, 2019).

University of Nebraska-Lincoln (UNL) School of Natural Resources. 2019. Nebraska statewide test-hole database. http://snr.unl.edu/csd/geology/testholes.aspx (accessed December 1, 2019).

U.S. Census Bureau, 2019, Demographic profile, total population. http://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml (accessed December 1, 2019).

U.S. Geological Survey (USGS), 2019a, The National Map, 2019, 3DEP products and services: The National Map, 3D Elevation Program Web page, http://nationalmap.gov/3DEP/3dep_prodserv.html (accessed December 1, 2019)

U.S. Geological Survey (USGS), 2019b, Website - USGS Groundwater Data for the Nation, (accessed December 1, 2019), https://waterdata.usgs.gov/nwis/gw

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

Witzke, B.J. and G.A., Ludvigson, 1994, The Dakota Formation in Iowa and the type area: Book Chapter in Geological Society of America Special Paper 287, Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin, Shurr, G.W., Ludvigson, G.A., and Hammond, R.H., https://doi.org/10.1130/SPE287-p43 (accessed December 1, 2019)