Ten years of AEM in Nebraska: Stitching surveys together

Jared D. Abraham
Aqua Geo Frameworks
Golden, CO USA
jabraham@aquageoframeworks.com

Theodore H. Asch
Aqua Geo Frameworks
Georgetown, CO USA
tasch@aquageoframeworks.com

James C. Cannia
Aqua Geo Frameworks
Mitchell, NE USA
jcannia@aquageoframeworks.com

SUMMARY

The use of AEM technology to map and evaluate groundwater resources has gained momentum over the last 20 years in the United States and abroad. The State of Nebraska has been on the forefront of implementing AEM in the United States for water resources management over the last decade with projects across the state in a variety of geologic settings. An introduction to the history of the many AEM surveys in Nebraska that were acquired with nine different AEM systems is presented beginning with surveys in 2007 and continuing in 2009, 2013, 2014, 2015, 2016, and on into 2018. These data total over 35,000 line-km that were collected by nine different AEM systems. The staggered pace of investigation has occurred because of the finite resources that can be allocated to AEM data gathering and the dynamic needs of the Natural Resources District's within Nebraska. This has led to the requirement that the systems be well calibrated and that the inversions be able to be integrated together to provide an evolving picture of the hydrogeological framework in Nebraska. With careful calibration and inversion, a multi-year acquisition plan can be successful, providing more information to the districts on the hydrogeological framework that can be utilized in their management of their natural resources.
Key words:
Hydrogeology, Hydrogeological Framework, Nebraska,

INTRODUCTION

The use of AEM technology to map and evaluate groundwater resources has gained momentum over the last 20 years in the United States and abroad. The State of Nebraska has been on the forefront of implementing AEM in the United States for water resources management over the last decade with projects across the state in a variety of geologic settings. The Eastern Nebraska Water Resources Assessment (ENWRA) has coordinated efforts between area Natural Resources Districts (NRDs), the Nebraska Conservation and Survey Division (CSD), the United States Geological Survey (USGS), and Aqua Geo Frameworks, LLC (AGF) in support of several projects designed to characterize the hydrogeology across the state.

The ENWRA project was formed in 2006 with sponsors from six NRDs (Lewis and Clark, Lower Elkhorn (LENRD), Papio-Missouri River, Lower Platte North (LPNNRD), Lower Platte South (LPSNRD), 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 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 thin glacial till near Firth, Nebraska and areas of thick glacial till near Oakland, NE (Smith et al., 2008; Abraham et al., 2011a; ENWRA, 2015). In the following years, individual reports utilizing the AEM data collected in 2007 were released by the USGS and CSD. In 2009, a multi-faceted investigation incorporating the 2007 AEM data and ground-based geophysical techniques was conducted by the USGS to characterize the hydrogeologic setting near Oakland, Nebraska (Abraham et al., 2011b). In 2009, the LPNNRD funded the USGS and CSD for the development of a 3D hydrostratigraphic framework of the subsurface near Swedeburg, Nebraska based on an AEM survey (Smith et al., 2009a; ENWRA, 2015). Also, in 2009, the LPSNRD funded the USGS and CSD for a similar investigation of the hydrostratigraphy near Sprague, Nebraska (Smith et al., 2009b; ENWRA, 2015). Based on the recommendations of Abraham et al. (2011b), in 2013, the LENRD conducted an AEM survey near the towns of Clarkson and Howells, Nebraska in order to characterize the extent of the Quaternary aquifer beneath the thick tills in the area following the drought of 2012 (Abraham et al., 2015). Also, in 2013, an AEM survey was performed covering portions of Butler and Saunders counties northwest of the city of Lincoln, Nebraska (Abraham et al., 2018). The AEM survey revealed buried paleovalley aquifers beneath thick sequences of loess and/or till. LENRD began to map their district with ~4.8 km AEM grids in the fall of 2014 (Abraham et al., 2015). In 2014-2015 the ENWRA funded 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). In 2016, a study showed that the information gained from the AEM survey in and around the Firth and Sprague areas provided unique details that assisted in the management of the groundwater resources (Korus et al., 2016). In 2016, nine NRD's collected 10,000 line-km of AEM data to provide detailed 3D hydrogeologic frameworks (ENWRA, 2018). Thus, AEM surveys of the glacial terrain in Nebraska have followed a progressive, long-term plan spanning nearly 10 years. In 2018 an additional 10,000 line-km of AEM data will be collected to continue to infill the area of ENWRA.

The western portions of Nebraska have also utilised AEM surveys. The North Platte (NPNRD) and South Platte NRD's began a series of surveys with the USGS in 2008 that continued into 2010 with the addition of the Twin Platte (TPNRD) (Smith et al., 2009a; Smith et al., 2010; Abraham et al., 2010; Abraham, 2011a; and Hobza et al., 2014). The TPNRD and Central Platte NRD's conducted an AEM survey in 2016 (ENWRA, 2018). These studies provided detailed information on the elevation of the base of aquifer and the configuration of the aquifers. Data from the Morrill Block within the NPNRD has been used in several research projects by others (Bedrosian et al., 2015; Friedel et al., 2016; Gulbrandsen et al., 2017). The AEM data have also provided information directly into a groundwater model in the North

Platte NRD (Peterson et al., 2015). These data total over 35,000 line-km that were collected by nine different AEM systems over the past decade including: Aeroquest AeroTEM IV, CGG Resolve, CGG HeliTEM, SkyTEM 301, SkyTEM 304, SkyTEM 304M, SkyTEM 508, VTEM2009, and VTEM2012. Additional AEM surveys have been flown for mineral exploration within Nebraska but are not included in this total due to their proprietary nature.

These multiple surveys can provide a challenge when they need to be integrated together as they typically occur in overlapping regions. This patchwork type of data collection is based on the availability of finite resources leading to the use of reconnaissance surveys to better refine an area for locating denser flight blocks. Good system calibration and an understanding of the bandwidth of the systems is critical for proper inversions and for integrating, i.e. stitching, these surveys together.

METHODS AND RESULTS

As just mentioned, many of AEM surveys in ENWRA contain reconnaissance lines that were flown as part of regional geological mapping studies (ENWRA, 2018) Figure 1 presents a plot of the AEM surveys collected in Nebraska through 2016. In 2014 and 2015 several widely spaced reconnaissance AEM lines were collected. These lines provided regional geological structure that allowed further infill to occur in 2016 and 2018. Typically, the existing AEM data are not reinverted before integration if their initial processing and inversion was of sufficient quality. Plus, there are limited resources available for reinverting the data, as resources are relegated to the collection of additional data. Note that this is not always the case as some data are reinverted in areas of dense block flights such as those used for well head protection studies. To this end, the quality of the AEM inversions need to be adequate to allow for the integration of new data, very likely from different systems, into the database. To ensure comparable results, calibration of the AEM systems is essential (Viezzoli et al., 2013). Some systems are provided as a calibrated response, while other systems require the calibration to be done after acquisition. The calibration procedure is unique to each vendor, but the basics include the forward modelling of an electrical earth model from the acquisition area and then the subsequent comparison of that forward modelled response to the acquired data. These data can be in the form of electrical downhole logs or ground based geophysical measurements. Details of the specifics of calibrating frequency domain systems and time-domain systems can be found in several publications including: Deszcz-Pan et al. (1998), Minsley et al. (2011a), and Foged et al. (2013).

Another critical element that needs to be taken into account during integration is the bandwidth of the system that was used to acquire the data. Vendors have designed systems over the years that have different bandwidth for different depths of investigation and target discrimination. A high-resolution frequency system will not see as deeply nor through as conductive as material as a high-powered time-domain system is able to, and conversely several time time-domain systems will not allow high resolution of the near surface or in resistive materials. Hodges and Chen (2015) provide a means to analyse this concept as they titled it "Geobandwidth". To this end, the different systems can potentially image different depths and have different sensitivities to earth materials. This impacts the resolution of the product from combining surveys.

The inversions methodologies that were utilized on the AEM data included University of British Columbia EM1DFM (Farquharson et al., 2003) and Aarhus Workbench (Viezzoli et al., 2008). These are both deterministic inversions. Experiments were run using a stochastic inversion (Minsley, 2011b) on CGG Resolve data collected in the Morrill Block in western Nebraska (Abraham et al., 2013, Gulbrandsen et al., 2017). However, this approach while helpful in limited areas and for specific research questions, was not used throughout the Nebraska dataset due to the time consuming and computationally expensive inversion process of the stochastic methods (Gulbrandsen et al., 2017) and the robustness of the deterministic inversions.

Selected areas within Nebraska where multiple AEM surveys have been flown are presented below to show the process and impact of stitching surveys together. The Bazile Groundwater Management Area (BGMA) was created to address the impacts of non-point source nitrate contamination of groundwater. The area covered includes 1,958 km^2 that are within four NRD's. Two types of AEM systems have been flown in the area including the SkyTEM508 in 2014 and the SkyTEM304M in 2016. These data were calibrated by the vendor and were inverted separately using Aarhus Workbench Spatially-Constrained Inversions (ENWRA, 2018). The 2014 data were combined with the 2016 AEM data along the lines that the data abutted each other and continued the reconnaissance lines that were planned in the BGMA or that were contained within the BGMA AEM survey area. This combination did not include reinverting the 2014 data but included merging the 2014 inversions into the 2016 inversions database. When examining the combination of the two separate data sets that were collected by different systems at different times and inverted separately, it is important to note if both data sets were properly calibrated and that any system bias was removed prior to inversion. Inspection of profiles created from combined lines displaying inverted resistivity at the same colour scale can indicate locations of issues with calibration and incomplete bias removal.

Figure 2 is a north-south line that was combined from the 2016 SkyTEM304M AEM inversions (north end) and the 2014 SkyTEM508 AEM inversions (south end). Figure 3 is an east-west line that was combined. Inspection of Figure 2 and Figure 3 shows a small break in the data coverage at the meeting point of the two datasets; however, the resistivity values continue across the line until the top of the interpreted Cretaceous Carlile Shale (***Kc***) is encountered in the 2016 SkyTEM304M inversions. This is due the differences of the depth of investigation (DOI) of the SkyTEM304M and the SkyTEM508.

CONCLUSIONS

An introduction to the history of the many AEM surveys in Nebraska that were acquired with nine different AEM systems has been presented. The staggered pace of investigation has occurred because of the finite resources that can be allocated to AEM data gathering and the dynamic needs of the NRD's within Nebraska. This has led to the requirement that the systems be well calibrated and that the inversions be able to be integrated together to provide an evolving picture of the hydrogeological framework in Nebraska. It is acknowledged that the individual systems have differing bandwidths and differing depths of investigation. With careful calibration and inversion, a multi-year acquisition plan can be successful, providing more information to the NRD's on the hydrogeological framework that can be utilized in their management of their natural resources.

ACKNOWLEDGMENTS

This work was funded over the past decade by the Nebraska Water Sustainability Fund; The Nebraska Environmental Trust Fund; Lower Elkhorn, Lower Platte South, Twin Platte, Papio-Missouri River, Central Platte, North Platte, Lower Platte North, South Platte, Lewis and Clark, Lower Loup; Upper Elkhorn, Nemaha, and Lower Niobrara Natural Resources Districts; Nebraska Department of Natural Resources; Nebraska Conservation and Survey Division; and the U.S. Geological Survey.

REFERENCES

Abraham, J.D., Cannia, J.C., Peterson, S.M., Smith, B.D., Minsley, B.J., and Bedrosian, P.A., 2010, Quantitative hydrogeological framework interpretations using heliborne electromagnetic surveys for the North Platte Valley western Nebraska groundwater model: in abstracts of the ASEG Sydney, Australia Aug 20-24, 2010.

Abraham, J.D., Cannia, J.C., Bedrosian, P.A., Johnson, M.R., Ball, L.B., and Sibray, S.S., 2011a, Airborne electromagnetic mapping of the base of aquifer in areas of western Nebraska: USGS-SIR2011-5219. https://pubs.er.usgs.gov/publication/sir20115219

Abraham, J. D., Bedrosian, P.A., Asch, T.H., Ball, L.B., Cannia, J. C., Phillips, J.D., and S. Olafsen-Lackey, 2011b, Evaluation of Geophysical Techniques for the Detection of Paleochannels in the Oakland Area of Eastern Nebraska as Part of the Eastern Nebraska Water Resource Assessment: USGS-SIR2011-5228. https://pubs.usgs.gov/sir/2011/5228/

Abraham, J.D., Cannia, J., Minsley, B.K., and Esfahani, A., 2013, Comparing/Contrasting Manual and Stochastic Interpretations of AEM Data: in abstracts from AEM 2013, Kruger National Park, South Africa, Oct 10-11.

Abraham, J.D., Cannia, J.C., Cameron, K., and Asch T.H., 2015, Watershed scale characterization of glacial and bedrock aquifers in eastern Nebraska: in abstracts from NovCare 2015, Lawrence, Kansas, 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.

Bedrosian, P.A., Schamper, C., and Auken, E., 2015, A comparison of helicopter-borne electromagnetic systems for hydrogeologic studies: Geophysical Prospecting, 2016, vol. 64, 192-215.

Deszcz-Pan, M., Fitterman, D.V., and Labson, V.F., 1998, Reduction of inversion errors in helicopter EM data using auxiliary information: Exploration Geophysics, vol. 29, 142-146.

ENWRA, 2015, Media and downloads, A Website for data distribution: http://www.enwra.org/downloads.html

ENWRA, 2018, Results of 2016 AEM Surveys, A Web site for data distribution: http://enwra.org/aem2016.html

Farquharson, C.G., Oldenberg, D.W., and Routh, P.S., 2003, Simultaneous one-dimensional inversion of loop-loop electromagnetic data for magnetic susceptibility and electrical conductivity: Geophysics, vol. 68, 1857–1869.

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, vol. 78, E95-E106.

Friedel, M.J., Esfahani, A., and Iwashita, F., 2016, Toward real-time three-dimensional mapping of surficial aquifers using a hybrid modelling approach: Hydrogeology Journal, vol. 24, 211-229.

Gulbrandsen, M.L., Ball, LB., Minsley, B.J., Hansen, T.M., 2017, Automatic mapping of the base of aquifer — A case study from Morrill, Nebraska: Interpretation, vol..5, no.2, T231-T241.

Hobza C.M., Abraham, J.D., Cannia, J.C., Johnson, M.R., and Sibray, S.S., 2014, Base of Principal Aquifer for Parts of the North Platte, South Platte and Twin Platte Natural Resources Districts, Western, Nebraska: U.S. Geological Survey Scientific Investigations Map 3310. https://pubs.usgs.gov/sim/3310/

Hodges, G., and Chen T., 2015, Geobandwidth: comparing time domain electromagnetic waveforms with a wire loop model: Exploration Geophysics, vol. 46, 58-63.

Korus, J. T., Joeckel, R. M., Divine, D. P. and Abraham, J. D., 2016, Three-dimensional architecture and hydrostratigraphy of cross-cutting buried valleys using airborne electromagnetics, glaciated Central Lowlands, Nebraska, USA. Sedimentology, vol. 64, 553-581.

Minsley, B.J., Hodges, G., Smith, B.D., and Abraham, J.D., 2011a, Multi-Elevation Calibration of Frequency Domain Electromagnetic Data: in abstracts from the EEGS SAGEEP Charleston, SC, April 10-14.

Minsley, B. J., 2011b, A trans-dimensional Bayesian Markov chain Monte Carlo algorithm for model assessment using frequency-domain electromagnetic data: Geophysical Journal International, vol. 187, 252–272.

Peterson, S.M, Flynn, A.T., Vrabel, J., and Ryter, D.W., 2015, Simulation of groundwater flow and analysis of the effects of water-management options in the North Platte Natural Resources District, Nebraska: USGS-SIR2015–5093, 67 p. http://dx.doi.org/10.3133/sir20155093

Smith, B.D., Abraham, J.D.., 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: USGS-OFR2008–1018, 16 p. http://pubs.usgs.gov/of/2008/1018/

Smith, B.D., Abraham, J.D., Cannia, J.C., and Hill, P., 2009a, Helicopter Electromagnetic and Magnetic Geophysical Survey Data for Portions of the North Platte River and Lodgepole Creek, Nebraska. June 2008: USGS-OFR2009-1110. http://pubs.usgs.gov/of/2009/1110/

Smith, B.D, Abraham, J.D., Cannia, J.C., Minsley, B.J., Deszcz-Pan, M., and Ball, L. B., 2010, Helicopter electromagnetic and magnetic geophysical survey data, portions of the North Platte and South Platte Natural Resources Districts western Nebraska, May 2009: USGS-OFR2010-1259. http://pubs.usgs.gov/of/2010/1259/

Smith, B.D., Abraham, J.D., Cannia, J.C., Minsley, B.J., Ball, L.B., Steele, G.V., and Deszcz-Pan, M., 2009b, Helicopter Electromagnetic Geophysical Survey Data, Swedeburg and Sprague Areas, Eastern Nebraska: USGS-OFR2010-1288. https://pubs.usgs.gov/of/2010/1288/

Viezzoli A., Christiansen A.V., Auken E. and Sørensen K., 2008, Quasi-3D modelling of airborne TEM data by spatially constrained inversion: Geophysics, vol. 73, F105–F113.

Viezzoli A., Jørgensen F. and Sørensen C., 2013, Flawed processing of airborne EM data affecting hydrogeological interpretation: Groundwater, vol. 51, 191–202.

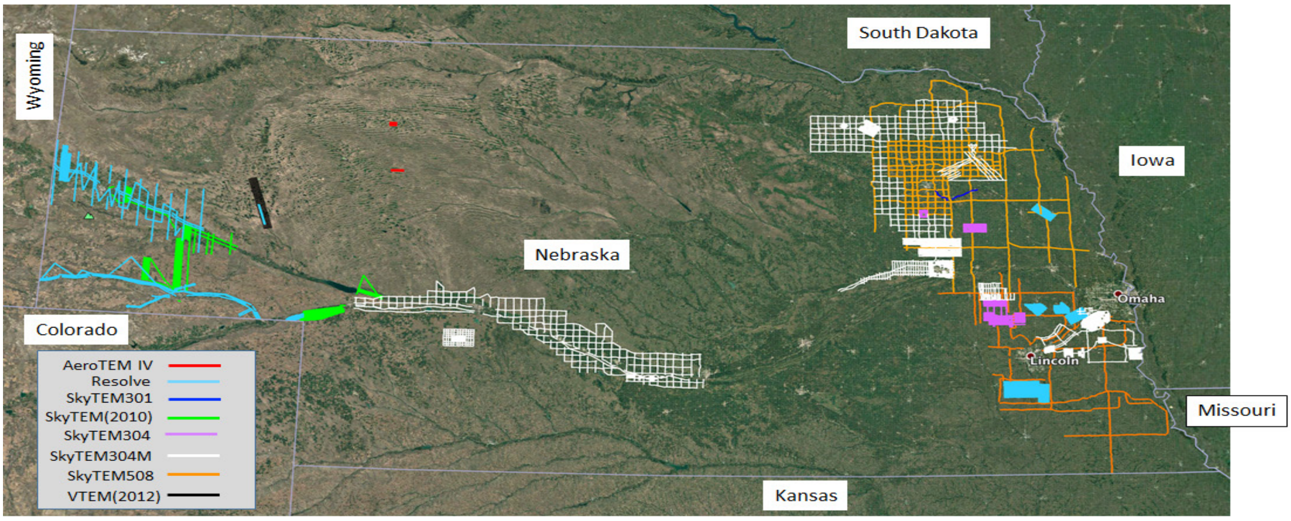

Figure 1. Location of the AEM surveys in Nebraska. Two areas in western Nebraska were acquired with multiple systems along the same flight lines; only one system is shown in the figure.

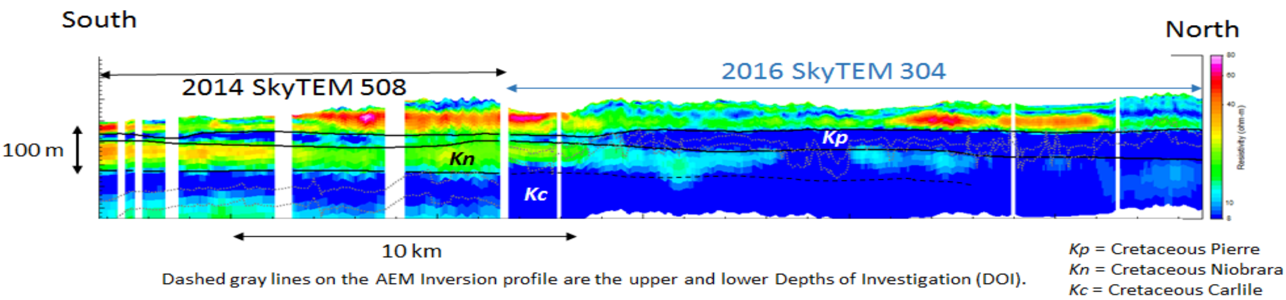

Figure 2. 2D north-south profile of inverted resistivity showing the SkyTEM508 and the SkyTEM304M within the BGMA. Black lines are interpreted geological contacts and are dashed where inferred.

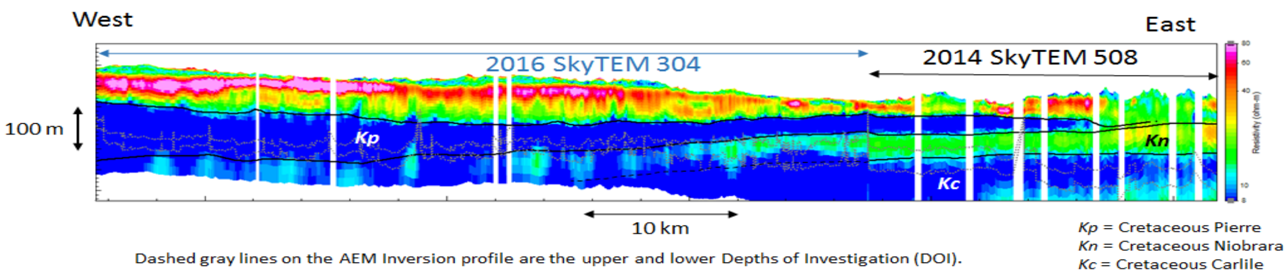

Figure 3. 2D east-west profile of inverted resistivity showing the SkyTEM508 and the SkyTEM304M within the BGMA. Black lines are interpreted geological contacts and are dashed where inferred.