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Jared D. Abraham
Crustal Geophysics and Geochemistry Science Center, jdabraha@usgs.gov

James C. Cannia
Nebraska Water Science Center

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AIRBORNE ELECTROMAGNETIC SURVEYS FOR 3D GEOLOGICAL MAPPING

Jared D. Abraham[1] and James C. Cannia[2]
[1]United States Geological Survey, Crustal Geophysics and Geochemistry Science Center, United States of America, jdabraha@usgs.gov,
[2]United States Geological Survey, Nebraska Water Science Center, United States of America

Abstract

The U.S. Geological Survey and its partners have collaborated to create 3D geologic maps for areas of the North and South Platte River valleys, including Lodgepole Creek, in western Nebraska using airborne electromagnetic surveys. The objective of the surveys is to map the 3D configuration of aquifers and bedrock topography created by the paleochannels of the ancestral Platte River. The ultimate goal is to gain a new understanding of groundwater–surface-water relationships to improve water management decisions through the use of groundwater management models. This goal was not achievable using traditional mapping methodologies, including surface geologic maps and borehole drilling logs. Airborne electromagnetic surveys provided nearly continuous information (data is collected every 3 to 20 meters along a flight path) of the subsurface electrical-resistivity variations (immediately below the sensor) at a depth range of 2 to 300 m below ground surface. To make the geophysical data useful for 3D geologic mapping, numerical inversion is necessary to convert the measured data into a depth-dependent subsurface electrical-resistivity model. The electrical-resistivity model, combined with sensitivity analysis, geological ground truth (boreholes), and geologic interpretation, is used to characterize geologic features. The 3D map provides the groundwater modeler with a high-resolution geologic framework and a quantitative estimate of framework uncertainty. This method of creating geologic frameworks improves the understanding of the actual flow-path orientation by redefining the location of the paleochannels and associated base of aquifer highs. The improved models depict the hydrogeology at a level of accuracy not achievable using previous data sets.

1. INTRODUCTION

Water resources in the North and South Platte River valleys, inclusive of Lodgepole Creek (Figure 1), are critical to the socioeconomics of western Nebraska and the management of endangered species along the Platte River corridor. Water, both surface water and groundwater, is a heavily used and regulated resource in the project area and in the entire Platte River Basin. Agriculture and power generation are the main drivers of the socioeconomics of western Nebraska and are the largest users of water. Another priority use for water is in management activities for recovery of threatened and endangered species in the Platte River Basin.

Surface water passes through many reservoirs, canal systems, and tributaries, providing a large percentage of recharge to the aquifers within valleys; in turn, the groundwater eventually returns to the river as base flow. This process is repeated many times as water passes through the Platte River corridor. The aquifers of the area are predominately ancestral Platte River paleochannels that are filled with alluvium. The paleochannels are incised into the Tertiary White River Group siltstone and, in the western part of the area, undifferentiated Cretaceous units, both of which act as hydrologic confining units. Groundwater flow within the aquifers is restricted by the topography of the confining units creating intricate flow paths. The combination of surface water use and the geologic composition of the valleys leads to the complex groundwater–surface-water relationships of the North and South Platte Rivers and Lodgepole Creek. Resource managers need an understanding of the groundwater–surface-water system to better control the limited supplies of water. This understanding is achieved by development of Groundwater Management Models (GMMs) which replicate the hydrology of the system and test management scenarios.

The first GMMs for the North and South Platte Rivers were developed using regional, low-resolution 2-D geologic maps and borehole drilling logs. These GMMs were effective in running simulations that tested large-scale general questions relating to management scenarios. However, as demand increased for more detailed analysis of explicit scenarios from the GMMs, it was determined that the regional models were not the best tool to accomplish the task. New GMMs were developed using local, high–resolution, 3D geologic maps based on data from the 2-D maps combined with airborne electromagnetic (AEM) surveys. The AEM geophysical method acquires data sensitive to the variability in the electrical resistivity of the subsurface. Examples of these new GMMs are the USGS High Plains Groundwater Water Availability Study (Qi and Christenson, 2010) and the Cooperative Hydrology Study (COHYST) (Cannia et al. 2006). Refinement of aquifer configuration within the geologic framework from regional, low-resolution to local, high-resolution 3D maps improves the performance of these models.

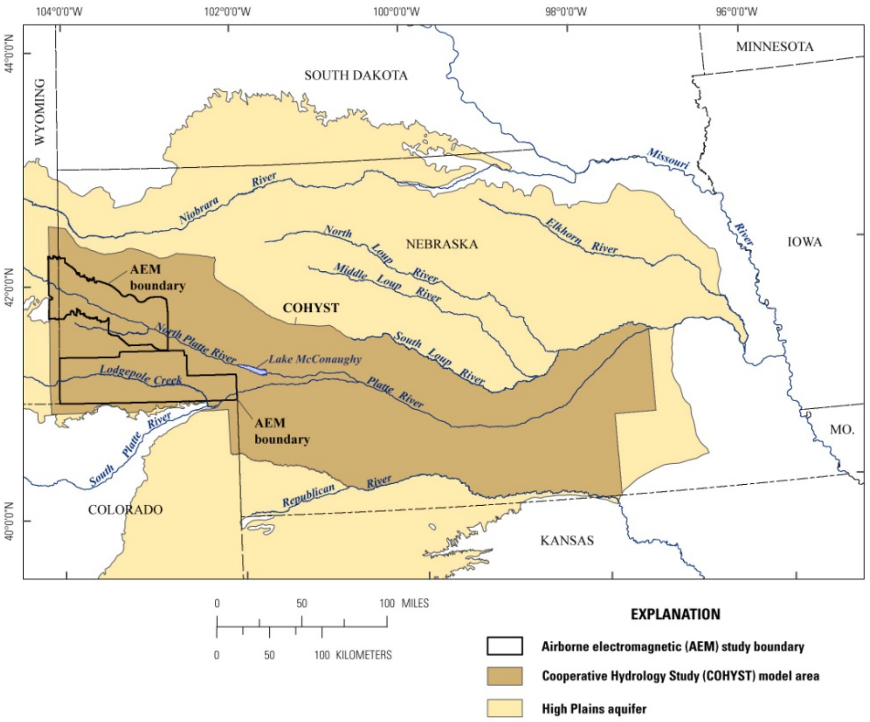

Figure 1. Location map of the AEM survey project area in western NE.

2. AIRBORNE ELECTROMAGNETIC METHOD

AEM surveys have been used recently to provide subsurface information for hydrogeological characterization (Siemon et al. 2009). Airborne surveys have the ability to cover large areas with minimal impacts to local activities and the environment. A unique value of these surveys is that data can be quickly collected without disturbing delicate environments and economically important agricultural crops. These AEM datasets are then processed, inverted, and interpreted to provide information on the structure of the geological and hydrogeological environment.

The selection of the proper AEM system to use should be based on the electrical conductivity-versus-depth relationship and the requirements for the 3D geological map. Previous knowledge of the geologic materials within the study area combined with a conceptual understanding of the geological system needs to be evaluated. Geological data gathered from boreholes is an absolutely critical part of study design and implementation, establishing confidence in the interpretation of lithology from resistivity. In addition to understanding as much as possible about the hydrogeological system, great care needs to be exercised regarding AEM system calibration and stability. A detailed and accurate calibration and inversion of AEM data to recover electrical properties with depth is an important requirement. After initial limited processing by the airborne service provider, the data goes through an advanced processing procedure where cultural couplings are removed and the calibration of the AEM system is confirmed or adjusted to remove as much systematic bias as possible. The techniques we use are the result of work done over recent years to understand and properly calibrate AEM systems (Fitterman and Deszcz-Pan 1998; Christiansen, et al. 2011).

The processed and calibrated AEM data are inverted using methods well suited for hydrogeologic mapping (Farquharson et al. 2003). After data inversion, a depth of investigation (DOI) metric is calculated in order to convey information about the depth to which the data are sensitive (Oldenburg and Li 1999). The DOI metric provides the geophysicist and geologist with a level of confidence in interpreting resistivity values related to the feature being mapped. Using stochastic parameter estimation tools, a more advanced analysis of model uncertainty has been developed as additional means of understanding and quantifying uncertainty (Minsley 2011), and is used as part of our model assessment procedure.

An interpretation for the location of a hydrogeological feature is typically completed in a Geographical Information System (GIS) that provides X, Y, and Z coordinates. Each of the interpreted locations, or picks, of the base of an aquifer, for example, is compared with the DOI metric for an AEM sounding location. A confidence value, between 1 and –1, for each feature location is calculated, with 1 being the highest confidence (picked horizon is well within the depth of investigation) and –1 being the lowest confidence (picked horizon is well below the depth of investigation) (Abraham et al. 2010).

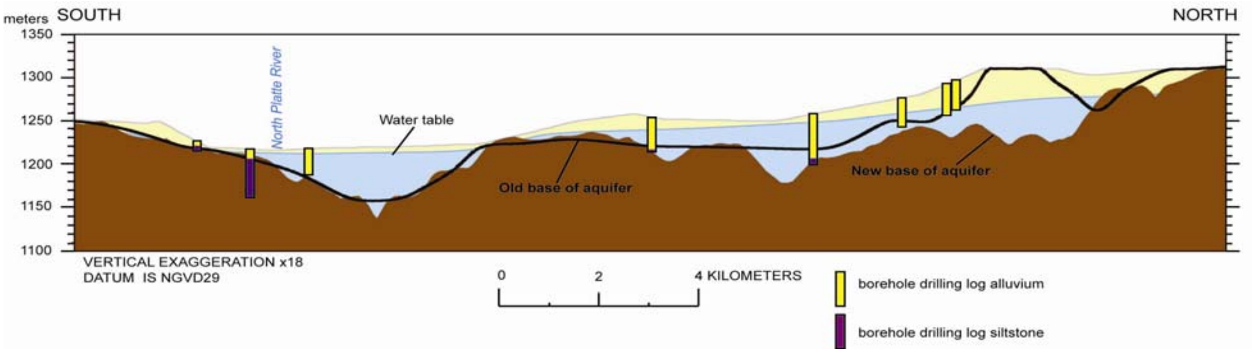

Figure 2. A selected NS profile from the 3D map, old BOA (black line), and borehole drilling logs (yellow for alluvium, purple for siltstone).

3. DEVELOPMENT OF 3D MAPS

Development of the 3D geologic maps used a process of interpretation that had the geophysicist, hydrologist, and geologist manually pick locations with elevation of the new base of aquifer (BOA) on the displayed AEM profile. These locations or “picks” of the BOA were then stored in a georeferenced database. The “pick’ was made by comparing the geophysical resistivity profile from the airborne survey along a flight line to the known lithology of the area based on borehole drilling logs and other available information. GIS was subsequently used to view all of the available data at one time in a spatially correct manner; this imparts a high degree of confidence in the elevation value for the “picks”.

The geodatabase of “picks”, from the interpretation of the new BOA elevation, combined with the information from the borehole drilling logs and the 2-D geological maps, was used to create the new BOA contours. The large number and density of the new AEM data points along with the borehole drilling logs and surficial geology maps allowed for greater accuracy of the placement of the contour lines. Once the contour lines were generated they were converted to a grid. The BOA was combined with the digital elevation model to produce a 3D grid of the alluvial aquifer. Additionally, the new BOA was coupled with the water table to create a 3D grid of saturated thickness. Figure 2 is a selected profile from the 3D map showing the relationship between the new BOA, the old BOA (based on only regional 2-D geologic map and borehole drilling logs), borehole drilling logs (within 100 m of the profile), the water table, and land surface.

The old BOA was generated from the 2-D regional geologic map and the borehole drilling logs. As seen in Figure 2, the old BOA does not show the same complexity as the new BOA, which can only be derived from the addition of the AEM data. Both the old and new BOAs honor the geological control of the borehole drilling logs and surface geologic map. The example shown in Figure 2 illustrates the impact of the AEM data on the development of the 3D geologic map. Figure 3 is a view looking east of selected profiles from the 3D geologic map, visualizing the complex paleochannel dominated geology of the North Platte River valley.

The water table in combination with the new BOA illustrates a much more complicated system for groundwater flow and the amount of saturated thickness. There are several locations along the profile where high elevations of the BOA cause barriers or constrictions to groundwater flow from the tableland on both the north and south sides of the river. These barriers and constrictions have a direct bearing on whether a stream is hydrologically connected to the principal aquifer. The improved BOA also allows for more accurate calculations of the saturated thickness compared to the old BOA.

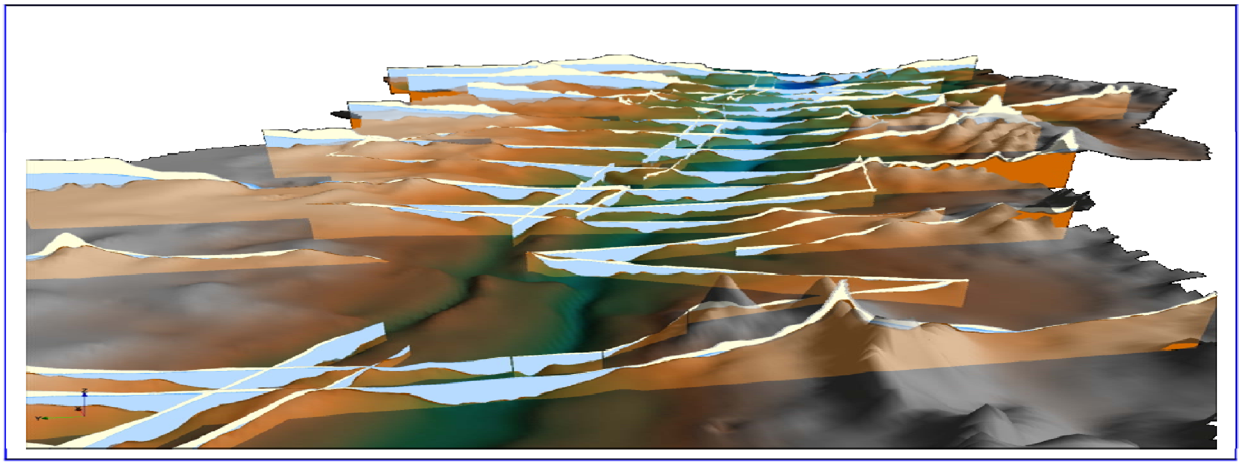

Figure 3. 3D view of the semi-transparent base of aquifer surface with selected cross sections extracted from the 3D model, looking east (down) the North Platte River Valley.

4. SUMMARY

The AEM survey provided considerable improvement to the understanding of the 3D geologic framework of the Platte River valley, and was employed to improve groundwater models of the area. This degree of accuracy was not achievable using traditional mapping methodologies, including surface geologic maps and borehole drilling logs. AEM surveys provide nearly continuous information (data is collected every 3 to 20 meters along a flight path) of the subsurface electrical-resistivity variations immediately below the sensor at a depth range of 2 to 300 meters. The AEM data improved the 3D geological map of the alluvial aquifer allowing for more accurate calculations of the saturated thickness. An enhanced understanding of the complex groundwater–surface-water relationships of the Platte River allows managers to better control the limited supply of water for all uses, including endangered species.

5. ACKNOWLEDGMENTS

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