Airborne Electromagnetic Surveys for Groundwater Characterization

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SUMMARY

Airborne electromagnetic (AEM) surveys provide densely sampled data over large areas (typically several hundred sq. km) that cannot be covered effectively using ground-based methods. AEM data are inverted to estimate the three-dimensional distribution of electrical resistivity structures from shallow depths to several hundred meters. These models convey unparalleled details that are used to make inferences about hydrogeologic properties and processes at the watershed and local scale. This information is being used in groundwater models that are critical to water management decisions, to better understand geologic frameworks, and to improve climate change models. The U.S. Geological Survey (USGS) has been engaged in the application of AEM to many watershed and local scale groundwater projects within United States. We present the results of several frequency- and time-domain AEM surveys acquired by the USGS that have been used for mapping alluvial valleys, buried glacial aquifers, fault-bounded basins, and understanding permafrost distributions.

Key words: airborne, electromagnetic, hydrogeologic, geologic, management,

INTRODUCTION

Airborne electromagnetic (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 quickly with minimal impacts to local activities and the environment. A unique value to these surveys is that data can be quickly collected without disturbing delicate environments and economically important agricultural crops. AEM datasets are processed, inverted, and interpreted to provide information on the structure of the geological and hydrogeological environment.

Often the data used in building hydrogeologic frameworks consists of sparse borehole lithology and geophysical logs combined with surface geologic maps and occasional surface geophysical soundings. For many regional studies this is adequate. However, groundwater models at the watershed and local scale generally lack adequate spatial data coverage for reliable parameterization, calibration, and validation, which is important for detailed resource management. A consequence is that the models lack detail and cannot reliably resolve local variations. For the detailed studies being done to better understand local aquifers and surface water systems, the long distances between existing data points introduces too much uncertainty into the three dimensional framework to accurately represent site conditions.

The addition of airborne geophysical surveys throughout a watershed provides nearly continuous data that can be calibrated to existing borehole logs and other mutually supportive data, creating a quantitative and precise subsurface map. 3-D maps, produced by integrating airborne geophysics with other information, provide powerful tools for locating local features of the aquifer system important to water managers. These maps can be combined with a water table elevation map to provide the geometry of the aquifer including, locations of the most saturated thickness, heterogeneity of aquifer materials, recharge zones, lithologic barriers to groundwater flow, and connections to the surface water system. The maps also indicate where preferential flow paths may exist, which is particularly important for understanding base flow to streams and interpreting water quality samples in relation to the various stresses in the system. Ultimately, this information will be used to site wells, focused-recharge areas, facility construction, and many other areas of interest when considering impact to the aquifer. Water managers often put this data directly into groundwater models to do predictive analysis of management scenarios.

METHOD AND RESULTS

Both frequency- and time- domain (FD and TD) AEM systems can be used to accurately acquire detailed information on the hydrogeological framework. The selection of the proper AEM system to use should be based on the electrical conductivity-versus-depth relationship and the requirements for groundwater management. All other previous knowledge of the geologic materials within the study area, combined with a conceptual understanding of the groundwater 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 the hydrogeological system, great care needs to be exercised regarding AEM system calibration and stability.

Due to the large aerial extent of many watersheds and groundwater management areas (~250,000 square kilometers) and the limited resources to gather information, an innovative approach to AEM data collection is needed. It is essential to have information about the conceptual hydrogeological model as well as preliminary groundwater model results. Analysis of this information indicates areas where groundwater model performance is poor. These areas are then mapped with AEM surveys in two distinct manners. One flight-plan configuration is to fly the blocks in a typical fashion, with survey lines at a specific orientation and even spacing from 100- to 400-m separation. The second flight-plan configuration uses widely spaced lines oriented in the direction that provides the widest areal coverage possible for delineating the hydrogeological features. These widely spaced lines are termed reconnaissance lines and are used to provide an image of the subsurface in areas where the groundwater model is poorly constrained. The reconnaissance lines can then be used to guide further, more-detailed mapping.

A detailed and accurate calibration and inversion of AEM data to recover electrical properties with depth is a 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 a robust inversion method, which provides an accurate image of the subsurface, using well suited for hydrogeologic mapping (Farquharson et al., 2003, Auken et al., 2005, Viezzoli et al., 2008). 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; Christiansen, et al., 2011). This metric allows the plotting of the inversion with a cutoff value to provide transparency to regions below the DOI. The DOI metric provides the geophysicist and geologist with a level of confidence in interpreting resistivity values related to the feature being mapped. A more advanced analysis of model uncertainty using stochastic parameter estimation tools has been developed as additional means of understanding and quantifying uncertainty (Minsley, 2011) and is used as part of our model assessment procedure.

Results from Selected Watersheds

Alluvial Valleys

The North and South Platte River valleys, including Lodgepole Creek in western Nebraska, USA are dominated by a fluvial history. The objective of the AEM surveys was to map the aquifers and bedrock topography of selected areas to help improve the understanding of groundwater–surface-water relationships to be used in water management decisions.

Inversion, in conjunction with sensitivity analysis, lithology determined from boreholes, and geologic interpretation, were used to characterize hydrogeologic features. This method of creating hydrogeologic frameworks improved the understanding of the actual flow path orientation by redefining the location of the paleochannels and associated bedrock highs.

An example on the impact of the AEM data on the saturated thickness of the aquifer is shown in figure (1). Figure (1) is a north-south cross section of the inverted and interpreted AEM data indicating the new base of aquifer compared with the old base of aquifer, water table, and the borehole lithology. The AEM-derived base of aquifer has much more detail than the old base of aquifer, which was derived solely form the boreholes. The AEM-derived base of aquifer honors all the boreholes within 250 m of the flight line. The impact on the groundwater system is indicated by the increased saturated thickness as delineated by the water table. The point is that the interpretation of the old base of aquifer from the boreholes was only able to resolve the hydrogeological system at the scale of the borehole spacing, and logistically there could never been adequate borehole spacing to adequately describe the base of aquifer in this area.

Buried Glacial Aquifers

Buried glacial features constitute major aquifers in many regions of central North America. A major focus of interest in concealed glacial aquifers is buried or tunnel valleys and how they control groundwater resources. Other glacial geomorphic features such as outwash deltas, eskers, and moraines may also constitute important local aquifers. North American and European studies suggest that airborne geophysical methods can be critical to development of planning strategies for management of groundwater resources.

FD AEM surveys were completed in the glaciated region of eastern Nebraska, USA. The depth of mapping for AEM applications is heavily dependent on the amount and thickness of silt or clay in the glacial till overburden. This area is dominated by varying thickness of till (10-100 m) overlying the Crete-Princeton-Adams Ground Water Reservoir (Divine et al., 2009). Hydraulic transmissivity contour lines, based on information compiled from registered irrigation wells, suggested a buried glacial feature. More detailed and spatially complete data on the occurrence and nature of the glacial sediments was required to assist local water managers in further refining well head protection boundaries.

AEM data provided an improved picture of the subsurface 3-D resistivity distribution than information from the well logs alone. Figure (2) is a 3-D representation of a resistivity isosurface at 80 ohm-m. Note that test wells drilled before the HEM survey did not intersect the resistive zone in figure (2). The 3-D model also shows the lower elevation of the gravels in the Big Nemaha River Valley which is a younger feature. There are also isolated areas of high resistivity which represent discontinuous gravels. Thus, the AEM data, considered in combination with present geomorphology and known glacial geology, constrains the interpretation of the time sequence of glacial features and associated groundwater resources at a level that was not achievable with using boreholes and irrigation wells alone.

Fault-bounded basins

In the Mojave Desert of the southwestern USA, groundwater is compartmentalized within a series of fault-bounded basins. As part of an effort to understand and manage groundwater resources in arid environments, the USGS is investigating basins within the Fort Irwin National Training Centre through a combination of hydrologic, geophysical, and geochemical approaches. TD AEM data were collected within the Leach Basin, a geologically complex, internally-drained basin bisected and flanked by a number of Quaternary age faults, including the Garlock fault and the Death Valley fault zone (Yount et al., 1994).

The AEM data provide subsurface constraints down to approximately 200 m in depth, and show abrupt changes in earth response across faulted boundaries, reflecting the strong lateral resistivity contrast between igneous rocks and basin sediments. Intra-basin faults are additionally identified, and to a lesser extent faults within the igneous basement can be traced. The distribution of faults throughout the basin and within the subsurface can thus be directly obtained from the airborne data (figure 3).

A resistivity stratigraphy was developed using borehole geophysical logs, ground-based gravity, ground-based time-domain electromagnetic soundings, and lab resistivity measurements from nearby basins. The results are applied to the airborne resistivity models and used to trace the hydrostratigraphic framework throughout the basin. Interpreted parameters include the depth to basement, the base of the primary aquifer, depth to water, saturated thickness and variations in groundwater salinity. Together with hydrologic investigations, these results are being used to estimate groundwater storage within the basin.

Permafrost distributions

Concerns over the impacts of climate change have recently energized research on the potential impacts thawing permafrost may have on groundwater flow, infrastructure, forest health, ecosystems, energy production, CO2 release, and contaminant transport. There is typically little knowledge about subsurface permafrost distributions, such as thickness and where groundwater–surface-water connections may occur through taliks. A frequency-domain AEM survey was flown over the area of Fort Yukon, Alaska, USA in order to map the 3-D distribution of permafrost and provide information for the development of groundwater models within the Yukon River Basin. Prior to the development of these models, information on areas of groundwater-surface water interaction was extremely limited.

Lithology determined from a borehole drilled in Fort Yukon in 1994 agrees well with the resistivity depth sections inferred from the airborne survey. In addition to lithology, a thermal imprint appears on the subsurface resistivity values (figure 4). In the upper 20-50 m, the sections show continuous areas of high electrical resistivity, consistent with alluvial gravel deposits that are likely frozen. Unfrozen gravel deposits near surface water features have intermediate-to-high resistivity. At depth, frozen silts have intermediate resistivity and unfrozen silts have low resistivity. Under the Yukon River and lakes where the subsurface is not frozen, zones of moderate resistivity intermix with areas of low resistivity.

The AEM survey provides unprecedented 3-D images of subsurface electrical properties that reveal changes in lithology and the presence or absence of permafrost. These geophysical data fill an important gap between sparsely sampled boreholes, regional hydrogeologic measurements, and remote sensing data.

CONCLUSIONS

Using AEM methods has greatly improved conceptualization of a wide variety of diffrent hydrogeologic framework at watershed and local scales in groundwater models to an extent that is not achievable using traditional methods. AEM surveys along with the companion data inversion and stochastic, statistical analysis add realism and confidence to the data which profoundly assists water-resource managers develop management plans that are efficient, economical, and easily understood. Water management over the coming decades will be based on the highly accurate groundwater flow models created by these datasets.

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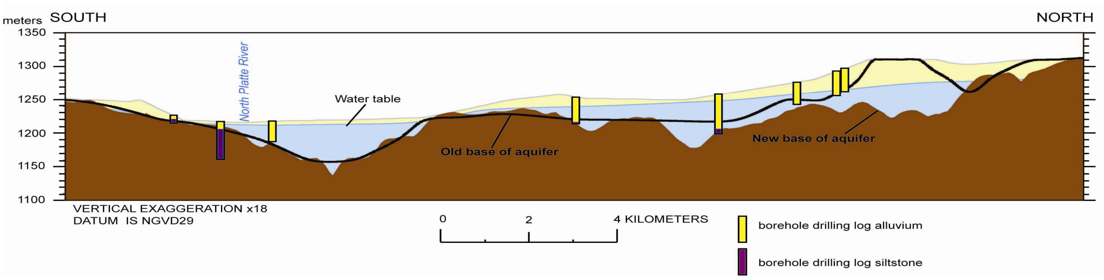

Figure 1. An interpreted AEM profile from western Nebraska, USA, new AEM derived base of aquifer (brown area), old base of aquifer (black line), water table (blue area), and borehole drilling logs (yellow for alluvium, purple for siltstone).

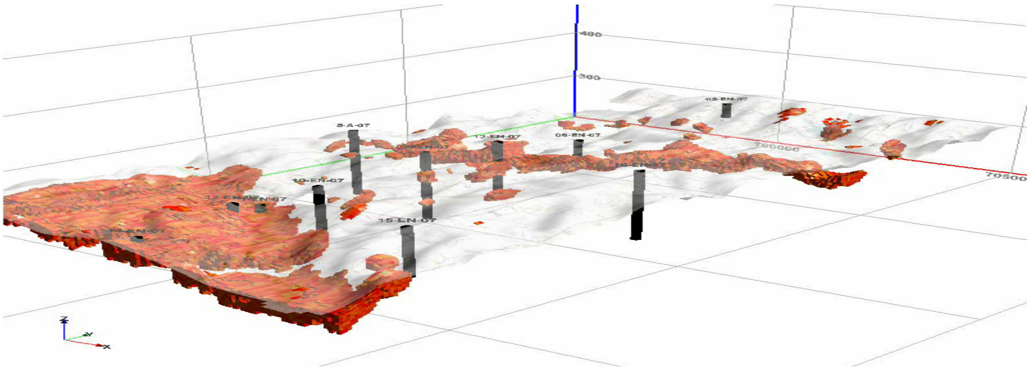

Figure 2. 3-D representation of sand and gravel units (red isosurface at 80 ohm-m) within a glacial till in eastern Nebraska, USA. Black tubes represent boreholes drill prior to AEM data collection.

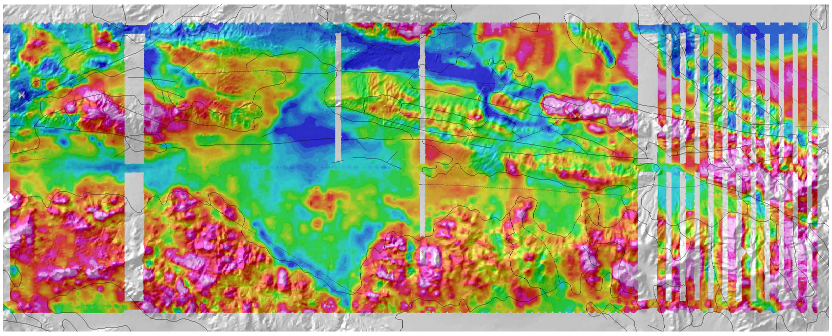

Figure 3. Leach Basin resistivity model at 50-m depth. Colour scale is from 10 Ohm-m (blue) to 400 Ohm-m (red). Line work shows geologic boundaries and faults from the Geologic Map of California. Horizontal axis is 50 km long.

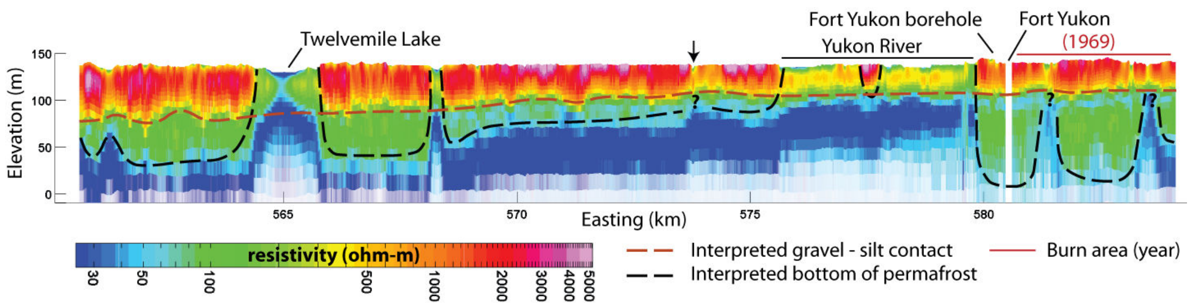

Figure 4. Resistivity cross sections along the three transects from near Fort Yukon, Alaska, USA with relevant surface features annotated. The downwards-pointing arrows indicate the location of a sinuous side-channel of the Yukon River. Interpreted lithologic and permafrost boundaries are superimposed as dashed lines. Vertical exaggeration 1:25.