Lithology Identification of Alluvial and Lacustrine Aquifers in Baiyangdian Area by an Airborne Transient Electromagnetic Survey

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Abstract. An airborne transient electromagnetic (TEM) has been conducted in Baiyangdian Area to map resistivity distribution within the alluvial and lacustrine aquifers. This investigation evaluated the reliability of resistivity models of the TEM data to infer lithological distribution in alluvial and lacustrine aquifers. The collected airborne TEM data were processed and inverted using spatially constrained 1D inversion method. And the 3D electrical structure, which maps electrical resistivity trends to depths of about 160 m, can be established through interpolation. Comparison of the resistivity models to drill logs indicates resistive permeable coarse-grained sediments and conductive fine-grained sediments which are relatively impermeable. Hence, the 3D electrical structure that are related to lateral and vertical variation in lithology, can serve as baseline information for groundwater potential identification. This research indicates that groundwater detection is an ideal target for mapping with airborne TEM techniques because of the high electrical resistivity of permeable coarse-grained deposits and its contrast with impermeable fine-grained deposits.

1. Introduction
Lake Baiyangdian, the largest freshwater lake in northern China, is located in the center of Xiong'an New Area. Delineation of spatial extent of freshwater aquifers in Baiyangdian area is of great significance to the evaluation of regional groundwater resources. Traditional hydrogeological investigation with well log data is time-consuming and expensive to cover large areas. The application of airborne geophysical techniques to investigating environmental problems has increased dramatically due to the rapid data acquisition and high data density over large areas[1].

The applicability of electrical methods to groundwater detection is based on the high resistivity of permeable coarse-grained sediments, in contrast to surrounding clay, silt, or soil, which are relatively impermeable. A helicopter-borne time-domain electromagnetic system was used to collect TEM data over Baiyangdian area[2]. We inverted the TEM data to map resistivity versus depth. Spatially constrained 1D inversion method[3] was adopted and drilling constraints were imposed to reduce the geophysical non-uniqueness. Borehole geophysical measurements made in a selected set of observation wells were used to determine the relation between formation resistivity and specific lithologies. By applying this relation to the TEM resistivity model, lithological distribution can be inferred[4].

2. Data acquisition of airborne TEM survey
We performed a helicopter TEM survey over Baiyangdian area using the Aeroquest AeroTEM IV time domain electromagnetic system, as shown in Figure 1. An Eurocopter AS350 B3 helicopter was used
as survey platform. The magnetometer sensor is installed 17 m below the helicopter, and the electromagnetic bird is towed 50 m below the helicopter. Radar altimeter is used to record terrain clearance, and a power line monitor was used to collect 50 Hz power-line noise. The current AeroTEM IV transmitter dipole moment is 220,000 A.m² at 75 Hz.

![Figure 1. The magnetometer bird (A) and AeroTEM IV EM bird (B).](image)

![Figure 2. ATEM flight lines and boreholes in Baiyangdian area](image)
The survey range occupies an area of approximately 2500 km². The helicopter travels at an average speed of 50 km/h in closely-spaced parallel lines across the study area (Figure 2). Distance between adjacent lateral lines is 250 m. The EM bird is about 46 m above ground on average. There is a sampling point about every 3 meters along the flight line. To evaluate the resolution and reliability of TEM resistivity model, high density resistivity (HDR) method and airborne TEM method were both employed for two N-S test lines in the north of the study area. Borehole geophysical data collected from a total of 9 boreholes within the survey range was used as prior information.

3. TEM data processing and inversion
Interference factors, such as high-voltage power lines, could significantly distort the electromagnetic signal, resulting in large data deviation and low reliability near these power lines. So the data contaminated with power line noise and other disturbances were removed prior to inversion. Data collected at heights greater than 65 m above the ground surface were also removed due to low signal-to-noise level. During the automatic processing, DGPS data were filtered using a step-wise polynomial filter and the altitudes were corrected using a series of polynomial filters. Next, the data were filtered using a trapezoidal spatial averaging filter.

In this paper, the collected TEM data were processed and inverted using the spatially constrained inversion (SCI) algorithm of the Aarhus Workbench software v.5.7.00 (Aarhus Geosoftware, 2018). Similar to laterally constrained inversion (LCI) algorithm, which uses nearby soundings along the flight lines as constraints, SCI inversion sets constraints laterally both along the flight lines and across the flight lines, resulting in 3D constrained model space. For SCI inversion, the data requires less smoothing, thus keeping the detailed earth information in the data. Additionally, we used the resistivity logging curves as constraints in the SCI inversion processes. The non-uniqueness in the solution of inversion poses a major problem in data interpretation. Integrating electric logging information and TEM data in geophysical inversion can decrease the effect of non-uniqueness. An 8-layer model was used for the SCI inversion of TEM data. When using this type of layered model, both resistivity and layer thickness are changed during the process of iteration.

Figure 3(a) shows the HDR inversion image of L1 test line, and Figure 3(b) displays the LCI inversion result of airborne TEM data for L1 test line. LCI inversion of airborne TEM data appears to be robust as it gives similar results with HDR inversion, both the HDR model and the LCI TEM model contain a high-resistivity layer lying at a depth between 50 m to 100 m to the north. The LCI TEM model reveals yet another high-resistivity thin layer at a depth of about 130 m to the south, which is also verified by nearby logging data (Figure 4). Figure 3(c) shows the SCI inversion with resistivity logging curves of GB023 and GB029 as prior constraints. Obviously, SCI inversion with prior constraints provides results with higher resolution which facilitate better interpretation.

1D models of resistivity versus depth derived from the airborne TEM data were evaluated at the point scale through comparison with borehole resistivity logs. A qualitative evaluation included comparison of 1D resistivity models from the nearest airborne flight line, L1 test line, and resistivity logs at the two boreholes, GB023 and GB029 (Figure 4). The 1D resistivity models were unresolved below approximately 160 m depth, no matter we used LCI inversion or SCI inversion. The resistivity logs and resistivity models display higher values in water bearing sand layers, in contrast to clay and silt which are relatively impermeable.
Figure 3. Resistivity section for L1 profile: (a) high density resistivity measurement, (b) LCI inversion of airborne TEM data, (c) SCI inversion with resistivity logging curves of GB023 and GB029 as prior constraints.

Figure 4. Resistivity logs of (a) GB023, (b) GB029 and 1D resistivity models of airborne TEM data near the boreholes.

4. Inferred lithology based on resistivity and drill logs
Lithologic distributions were inferred using a combination of available drill logs and resistivity distributions mapped by airborne TEM data.
Resistivity values for major lithologies in alluvial and lacustrine aquifers of Baiyangdian area are defined by available drilling data (Table 1). Resistivity values range from less than 25 Ω.m for clay or silt intervals to more than 62 Ω.m for medium-to-coarse sand intervals that include little clay. Groundwater in Baiyangdian area is generally fresh, except the east and south part of the study area where some brackish water in shallow aquifers — over 2000 mg/l TDS — has been identified. Such brackish water is generally held in silty fine sand. Regardless of the inability to distinguish silty fine sand saturated with brackish water from clay and silt using electric resistivity features, low resistivity values are indicative of sediments with low permeability or high salinity, which are not suitable for most water-supply needs.

Table 1. Generalized electrical resistivities for sediments at 0 - 200m depth of Baiyangdian area

| Lithologic description           | Saturated resistivity/Ω.m |
|---------------------------------|---------------------------|
| Clay, silty clay, and silt      | 14 - 25                   |
| Silty sand and silty fine sand  | 10 - 38 (saturated with brackish water) |
|                                 | 30 - 58 (saturated with fresh water) |
| Fine sand and medium sand       | 46~80                     |
| Medium-coarse sand              | 62~95                     |

Interpolated resistivity distribution results are illustrated in Figure 5, which shows the 3D resistivity model of Baiyangdian area and the resistivity results at 50 m, 100 m, and 150 m below land surface. Known from the drilling data, some brackish water exists at about 50 m below surface in the east and south part of the study area. According to Figure 5(b), high salinity can contribute to low-resistivity values in the south and east portion of the surveyed area. It’s difficult to distinguish silty fine sand saturated with brackish water from clay and silt based on resistivity features only, but information from the lithologic logs can be used as a reference. The high-resistivity values in the northeast indicate the range of fresh water approximately (Figure 6). Since the brackish/fresh water interface is less than 70 m deep, so the low-resistivity area (dark blue) in Figure 5(c) indicates the range of clay and silty clay.

5. Conclusions

The reliability of the 1D resistivity models of airborne TEM data to map aquifer lithology in Baiyangdian area was evaluated through comparisons with resistivity logs and lithologic descriptions from drill logs. With the reference of resistivity logs and lithologic logs, airborne TEM data can be used to map important lithologic distributions and infer aquifer hydraulic properties in alluvial and lacustrine aquifers. Regardless of the difficulty to distinguish silty fine sand saturated with brackish water from clay and silt using electric resistivity features, low resistivity values are indicative of sediments with low permeability or high salinity, which are not suitable for most water-supply needs. High resistivity zones could indicate fresh groundwater potential areas, which correspond to permeable coarse-grained sediments, such as medium-to-coarse sand or fine sand.
Figure 5. 3D resistivity model of Baiyangdian area and resistivity distribution at a depth of 50 m, 100 m, and 150 m.

Figure 6. Inferred lithology at a depth of 50 m from the resistivity result of airborne TEM survey.
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