The Impact on Geological and Hydrogeological Mapping Results of Moving from Ground to Airborne TEM

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ABSTRACT

In the past three decades, airborne electromagnetic (AEM) systems have been used for many groundwater exploration purposes. This contribution of airborne geophysics for both groundwater resource mapping and water quality evaluations and management has increased dramatically over the past ten years, proving how these systems are appropriate for large-scale and efficient groundwater surveying. One of the major reasons for its popularity is the time and cost efficiency in producing spatially extensive datasets that can be applied to multiple purposes. In this paper, we carry out a simple, yet rigorous, simulation showing the impact of an AEM dataset towards hydrogeological mapping, comparing it to having only a ground-based transient electromagnetic (TEM) dataset (even if large and dense), and to having only boreholes. We start from an AEM survey and then simulate two different ground TEM datasets: a high resolution survey and a reconnaissance survey. The electrical resistivity model, which is the final geophysical product after data processing and inversion, changes with different levels of data density. We then extend the study to describe the impact on the geological and hydrogeological output models, which can be derived from these different geophysical results, and the potential consequences for groundwater management. Different data density results in significant differences not only in the spatial resolution of the output resistivity model, but also in the model uncertainty, the accuracy of geological interpretations and, in turn, the appropriateness of groundwater management decisions. The AEM dataset provides high resolution results and well-connected geological interpretations, which result in a more detailed and confident description of all of the existing geological structures. In contrast, a low density dataset from a ground-based TEM survey yields low resolution resistivity models, and an uncertain description of the geological setting.

Introduction

The transient electromagnetic (TEM) technique has been applied for hydrogeological mapping in numerous cases, in very different parts of the world, and with different levels of success (Auken *et al.*, 2003; Fitterman and Stewart, 1986). The technique owes its popularity to its relative ease of operation, cost efficiency, and a strong affinity between its output and key geological and hydrogeological parameters. The ground-based TEM method has been used extensively in Denmark in the past decade and has proven to be a powerful tool in hydrogeophysical investigations as well as groundwater exploitation management (Auken *et al.*, 2003).

The logistical simplicity of the TEM methods results from the inductive energizing of the subsurface

over a relatively small area of the Earth's surface, while at the same time obtaining significant penetration depths; the TEM ratio of penetration depth to loop size can be much greater than 1, as opposed to geoelectrics, where deep penetration always comes at a cost of much longer electrode arrays. An experienced crew can acquire 5–10 ground-based TEM soundings in different locations per day, covering large areas in a relatively short time and hence, at low cost.

In terms of data processing, 1-D inversions for electrical resistivity can provide a very good representation of the "true" geometry of the subsurface, particularly for layered sedimentary environments. In some cases, resistivity models can then be directly transformed into representations of aquifers and aquitards. Refer to Nabighian and Macnae (1991) and

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Christiansen *et al.* (2009) for an in-depth discussion on the ground-based TEM methodology. In this paper, we focus on the improvements to the geophysical and geological modeling and mapping and the hydrogeological management that can be obtained by moving from ground-based to airborne TEM data.

The application of airborne electromagnetic (AEM) methods to hydrogeological mapping of large areas has been on the rise over the past decade (Wynn, 2002; Jørgensen et al., 2003; Paine et al., 2005; Møller et al., 2009; and Oldenborger et al., 2013). Geological survey organizations across the globe have promoted (Australia, Canada), carried out (e.g., Germany) and/or supervised (e.g., Denmark, U.S.) large AEM surveys. Private enterprises dealing with large-scale hydrogeological mapping have also turned to AEM, integrated with other sources of information. The most important reasons for its popularity are the time and cost efficiency in producing high quality, spatially-extensive datasets that can be applied to multiple purposes. Here we carry out a simple, yet rigorous, simulation showing the impact of an AEM dataset towards hydrogeological mapping and management, compared to having only a ground-based TEM dataset, as well as to having only borehole data.

We investigate the differences between airborne and ground TEM surveys not only in terms of spatial resolution of the output resistivity model, but also in terms of the level of accuracy of the geological interpretation, keeping in mind the uncertainty in groundwater resources evaluation and management. We carry out the simulation by down-sampling an AEM dataset over the Spiritwood Valley Aquifer in Manitoba, Canada, down to the data density characteristic of high resolution large-scale ground TEM surveys.

Geological Setting

Buried valleys are a common feature in glacial terrains of the Canadian Prairies. Particularly where the underlying bedrock consists of easily eroded sediments, such as shale, numerous valleys were cut into Cretaceous and Tertiary bedrock units prior to the initiation of continental glaciations (Batcher *et al.*, 2005). Alluvial deposits, in particular sands and gravels, are generally thought to have been transported from the Rocky Mountains to the west and rest on the underlying bedrock in parts of many of these valleys. During the Pleistocene, considerable modification occurred to many of the older valleys and new valleys were formed by meltwater erosion most likely during glacial retreats. By the end of the Pleistocene, many of the valleys had been partially or completely infilled with glacial sediment (Russel *et al.*, 2004; Cummings *et al.*, 2012). Cummings *et al.* (2012) presented a conceptual geological model for Prairie buried-valley incision, pointing out "clasts provenance" as one of the main criterion used to interpret buried valley origin. Preglacial fluvial incision driven by tectonic uplift and tilting is typically invoked to explain buried valleys lined with Rocky Mountain clasts (Andriashek, 2003). Buried valleys that cross bedrock slope, stratigraphically overlie till, and contain Precambrian Shield clasts along their bases are commonly inferred to have been incised by proglacial meltwater streams (Kehew *et al.*, 1986). A subglacial origin has been inferred for some buried valleys that stratigraphically overlie till and contain Precambrian Shield clasts (Andriashek, 2003).

The Spiritwood Valley Aquifer system lies within a till plain with little topographic relief. The underlying bedrock is the electrically conductive, fractured silicious shale related to the Odanah Member of the Pierre Formation (Randich and Kuzniar, 1984). The stratigraphy within the valley is variable and includes a basal shaly sand and gravel overlain by clay-rich and silty till units. Where coarse-grained sediments fill the eroded valleys, the potential for significant aquifers exists.

Introduction to AEM

Airborne electromagnetic systems have been used for more than 50 years. Initial AEM development was driven by mineral exploration, with the survey objectives being to cover large areas at a reasonable cost and to detect anomalies in the measured data. Therefore, a significant consideration has always been the achievement of high signal-to-noise ratios in order to better detect potential mineralization. AEM systems are being constantly improved in terms of increased sensitivity to small, shallow-intermediate as well as deeper structures with the use of a wider range of frequencies and different coil configurations. As a result of AEM improvements, the method has been adapted and employed for hydrogeological studies, which leads to the possibility to obtain quantitative information for groundwater modeling and management. Some of the AEM systems most widely applied, with different levels of success, to hydrogeological mapping in the past decade around the world are Resolve (frequency domain EM) (Abraham et al., 2012), Tempest (Fixed wing TEM) (Sattel and Kgotlhang, 2004), SkyTEM, AeroTEM and VTEM (Helicopter TEM) (Cannia et al., 2012; Oldenborger et al., 2013; Legault et al., 2012). Allard (2007), Thomson et al. (2007), Fountain (2008) and Sattel (2009) provide reviews of recent developments of some AEM systems.

A typical AEM survey measures on the order of 1,000 line km of data, with cross-line spacing ranging

from 100 m for very high resolution mapping, to greater than 1 km for regional mapping. As a consequence, the surface covered ranges typically from 100 km^2 to greater than 1,000 km², with data density on the order of tens to hundreds of soundings/km².

AEM systems have a distinct advantage over ground-based methods in that they can be deployed in transition zones such as rivers (Fitzpatrick *et al.*, 2007), lakes, lagoons (Kirkegaard *et al.*, 2011), wetlands, coasts, the open sea (shallow bathymetry) and in rough topographic conditions.

Spiritwood Valley AeroTEM Survey

As part of its Groundwater Geoscience Program, the Geological Survey of Canada (GSC) has been investigating buried valley aquifers in Canada using airborne TEM techniques. To obtain a regional threedimensional assessment of complex aquifer geometries for the Spiritwood Valley Aquifer, both geophysical and geological investigations were performed. Buried valleys are important hydrogeological structures in Canada providing sources of ground water for drinking, agriculture and industrial applications. Hydrogeological exploration methods such as pumping tests, borehole corings, or ground-based geophysical methods (seismic and electrical resistivity tomography) are limited in spatial extent and are inadequate to efficiently characterize these aquifers at the regional scale.

In 2010, the Geological Survey of Canada contracted an airborne electromagnetic (AeroTEM III) survey covering 1,062 km² (3,000 line km) over the Spiritwood Valley Aquifer in southern Manitoba (Oldenborger, 2010a, 2010b). Refer to Fig. 1 for the location of the survey. This survey required approximately five days of flight time to cover the entire survey block (although weather restrictions resulted in approximately four weeks of deployment time). A thorough reprocessing and inversion of the AeroTEM data with Spatially Constrained Inversion (SCI) (Viezzoli et al., 2008), including different iterations to fine tune the results, took approximately three months. The total number of 1-D models extracted from this dataset is on the order of 100,000, equal to a spatial density of approximately 100 soundings/km².

The AeroTEM system is based on a rigid, concentric-loop geometry with the receiver coils placed in the center of the transmitter loop (Balch *et al.*, 2003). A transient current in the transmitter loop produces a primary magnetic field which gives rise to eddy currents in the earth. The induced currents generate a secondary magnetic field detected by a receiver coil sensor. The transmitter waveform is a triangular current pulse of 1.75 ms duration operating at a base frequency of 90 Hz.

The transmitter loop has an area of 78.5 m^2 , with a maximum current of 480 A. The receiver coils are oriented one in a vertical plane (Z-axis) and one in an inline horizontal plane (X-axis). The collected data consist of a series of 16 on-time gates and 17 variable width off-time gates (70 µs to 3 ms after turn-off). Raw collected data are stacked, compensated, drift corrected and microleveled.

A disadvantage of concentric coil systems is that the strong primary field present during the on-time can extend into the off-time as a high system transient and overpower the weaker secondary field. The AeroTEM system overcomes the primary field problem on some of the earlier gates by means of a bucking coil that reduces the amplitude of the primary field at the Z-axis receiver coil by greater than four orders of magnitude (Walker *et al.*, 2008). Variations in the residual primary field are then removed from the Z-axis coil by a post-processing algorithm that includes deconvolution of the system's current waveform.

During Fall 2011, Geotech also conducted a helicopter-borne geophysical survey over the Spiritwood Valley. This area was chosen as a test area for the full waveform VTEM system implementation (Legault *et al.*, 2012). The VTEM data strategically cover the Spiritwood area with a few lines to the north, the center and the south part of the AeroTEM survey block. It is not the purpose of this article to provide a detailed comparison between the two AEM systems, nor indepth discussion on the accuracy of the AEM data.

Several ground-based datasets have also been collected at the Spiritwood survey area in the past few years, including 42 km of high resolution landstreamer seismic reflection data (Pugin *et al.*, 2009) and over 10 km of electrical resistivity data (Oldenborger *et al.*, 2013). In addition, downhole resistivity logs were collected that provide information on the electrical model relative to the geological layers (Crow *et al.*, 2012).

Simulated Ground TEM Survey

To simulate the ground TEM dataset, we start from the AEM dataset. These data are then spatially down-sampled to a uniform sounding density over the entire survey block. We produced two versions of the ground TEM survey. The high resolution survey has less than 1 sounding/km² and a total of 700 soundings (Fig. 1(B)). The reconnaissance survey has ~ 0.1 sounding/km² and a total of 100 soundings (Fig. 1(C)). Recall that the AEM survey provided approximately 100,000 soundings, and 100 soundings/km².

The simulated ground TEM soundings were obtained with an energizing moment of 250,000 Am²,



Figure 1. Spiritwood Valley Aquifer location map (adapted from Google Earth satellite image). The black box indicates the survey area. A) Black dots indicate the 1,062 km² HTEM survey block. B) Simulated high resolution ground TEM survey. The AEM data have been averaged spatially using a trapezoid filter of 100 seconds resulting in approximately 1 sounding/km². C) Simulated reconnaissance survey. 100 soundings were picked manually over the area to obtain a data density of about 1 sounding every 3 km².

equal to that of the AeroTEM system. Given that a standard ground TEM system outputs up to 10 Amps, but more often less, a ground loop of greater than 100-m \times 100-m sides or multiple turns is required to achieve this moment. To carry out both the high resolution and reconnaissance ground-based TEM surveys would be lengthy and logistically demanding. We estimate that the high resolution survey (700 ground soundings) would require no less than 15 weeks of continuous acquisition for a crew with three operators in conditions of clean paddocks and crop fields. Similarly, the reconnaissance survey (100 soundings) would require 3-5 weeks. Weather constraints, temporary limitations to site accessibility (e.g., because of ground thawing or presence of crops) invariably add a significant amount of time to complete the survey.

Another relevant, time consuming, and at times unsurpassable obstacle to a ground survey aiming at obtaining an even data density throughout the area are the permits needed to access the station sites, even in periods when no crops are on the fields. Beside data acquisition, approximately 2–4 weeks would be needed to carry out the detailed processing and inversion of the data for hydrogeological applications.

Description of Processing and Inversion Methodology

For both ground-based and airborne EM data, the aim of data processing is to prepare data for the inversion. This includes data import, altitude corrections (for airborne only), and filtering and discarding of distorted or noisy data contaminated by culture. Data

are then averaged spatially using trapezoid filters that allow increasing signal-to-noise levels without compromising lateral resolution. Inversions are carried out using the quasi 3-D Spatially Constrained Inversion (Viezzoli et al., 2008). Oldenborger et al. (2013) presented a resistivity model for the Spiritwood area using a conductive depth image (CDI) technique (Huang and Rudd, 2008), and noted that the recovered resistivity appeared to be underestimated and of reduced range, with respect to ground electrical resistivity tomography (ERT) measurements. Given the existing differences between the induced currents into the ground from the two methods (horizontal for EM and vertical/horizontal for ERI/DC methods), as noted by Keller and Frischknecht (1966) and Christensen (2000), Oldenborger et al. (2013) attribute much of the reduced range to the CDI algorithm, concluding that "discrimination of aquifer material is hampered."

As opposed to the CDI, the SCI is a full non-linear damped least-squares inversion based on exact forward solution, in which the transfer function of the instrumentation is modeled. The system transfer function includes transmitter current, turn-on and turn-off ramps, gate times, low pass filters and system altitude. The SCI is therefore expected to provide a better agreement with the ERT than the CDI. In the SCI scheme, the model parameters for different soundings are tied together spatially with a partially dependent covariance which is scaled according to distance. Models are constrained spatially to reflect the lateral homogeneity expected from the geology (either vertical or horizontal layer resistivity, boundary thickness or depth). Constraints include boundary conditions and delimit changes of values within a defined deviation. The flight altitude is included as an inversion parameter, but with an a priori value and standard deviation assigned. However, over very densely forested areas (which is not the case for the Spiritwood area), canopy effects might affect a proper altitude estimation of the frame. This requires additional manual corrections of the altitude data to avoid shallow artifacts in the output resistivity model. The depth of investigation (DOI), based on an analysis of the Jacobian matrix, was also calculated for the output models. The DOI represents the maximum depth at which there is sensitivity to the model parameters (Christiansen et al., 2012). The inversions are started with a homogeneous half space of 20 Ω -m. Before data inversion, late time noise assessment was performed to maximize resolution at depth and to remove effects caused by the raw data leveling from flight to flight. Despite primary field compensation and leveling, self-system response is still observable for some time gates (i.e., primary field bias). Therefore, we have removed the first two time gates (with gate centers

earlier than 100 μ s) and the last time gate from all inversions. The inversion is parameterized with 29 layers, each having a fixed thickness, but a free resistivity (with moderate vertical constraints). The model was discretized to 200-m depth, with layers of logarithmically increasing thickness.

We have treated the simulated ground TEM data as if they really had been acquired with a ground TEM system. They were processed for noise and coupling individually (Fig. 2). No lateral averaging was carried out. Even the leveling that is usually carried out on the EM data as preprocessing by the AEM contractors before they are delivered has insignificant effect over kilometric distances between soundings.

The inversions were carried out with the same forward and inversion algorithms used for the AEM data, the only difference being that no spatial constraints were applied to the model parameters, as a consequence of the significant distance between soundings. The derived resistivity maps from the 1-D models were then interpolated with a kriging algorithm applying a search radius of 5,000 m and a node spacing of 100 m for the simulated TEM survey.

Geophysical Results and Derived Geological Interpretations

Before deriving geological interpretations from the geophysical results and comparing the results between those of the actual AEM survey and the simulated ground TEM surveys, we elaborate further on the representativeness of the simulated ground TEM data of a true ground TEM survey in terms of depth of investigation and lateral resolution. Arguably, while having the same transmitter (Tx) moment, a ground TEM system can obtain better signal-to-noise ratio (even closer to, *i.e.*, a power line) than an airborne system. This is because of significantly greater stacking, a smaller footprint, the absence of motion induced noise in the receiver, and better coupling between the ground and the Tx coil. On the contrary, dense sounding spacing of the AEM data allows noise to be better identified, particularly for galvanic coupling response (Danielsen et al., 2003). One might argue that in the simulated ground soundings the signal falls into noise faster as compared to true ground TEM soundings. However, in this particular case, this bears very little influence, as the conductive bedrock (Cretaceous shale) is shallow enough to be resolved by the simulated soundings, and conductive and thick enough to make any deeper layer irresolvable by virtually any TEM system. This can be readily seen by comparing the AeroTEM results to the VTEM data from coinciding lines (Fig. 3). Despite its significantly better signal-to-



Figure 2. Processing example of a coupled TEM response compared to an undisturbed neighboring sounding. Galvanic coupling results from induced currents in man-made conductors, such as power lines, cables or fences, through the transmitter loop. The predicted models show an incorrect low resistivity value that is easy to recognize by comparing with neighboring soundings.



Figure 3. SCI inversion result of AEM data related to AeroTEM and VTEM surveys over coinciding lines at the north subset of the Spiritwood area. The inset box shows both VTEM and AeroTEM flight lines in blue and black, respectively. The AeroTEM dataset provides rich information content in terms of lithological detail and detection of bedrock morphology. As expected, earlier time gates from the "full waveform" VTEM system provide better resolution in terms of shallower geological layers and resistive infilling sediments. In general, models show consistent agreement in terms of main resistive structures detected amongst the conductive bedrock.

noise ratio, the VTEM system does not penetrate below the shale. The only exception to the argument above could be in areas where tunnel valleys erode deep into the shale where a ground TEM sounding might have reached the shale in places where the simulated one does not.

On a sounding by sounding basis, the footprint of the simulated soundings in the near surface is slightly lower (i.e., higher lateral resolution) than that of an actual 100-m \times 100-m loop. In the deeper parts of the models, they are almost equivalent. It is worth noticing also that, in general, ground-based soundings are less affected by system bias (primary field not completely removed) than airborne soundings. This is because of the decreasing level of secondary signal resulting from the vertical displacement of the Tx with respect to the ground. Some AEM systems are more effective than others in the removal of the primary field, with the AeroTEM III deployed in the Spiritwood being one of the worse. The simulated ground TEM survey might therefore reveal less near-surface resolution than an actual one. We contend that the individual simulated TEM soundings are a good representation of actual ones, especially in the context of deeper features, and that the illustrative purpose of this paper remains valid.

Average resistivity maps at different depth intervals are produced to visualize the results of the inversion of the different datasets (Fig. 4). Figure 5 shows the average resistivity maps in a close up where particularly interesting features are in focus. The average resistivity maps in Fig. 4(B) clearly show the existence of a valley as an elongate, resistive feature (known as the Spiritwood Valley Aquifer). It is approximately 10-km wide and has a conductive background, which according to boreholes consists of the Cretaceous shale bedrock. Along the middle of this valley we observe a much more narrow structure (1 km), interpreted to be an inset valley that follows the main valley from the north to the south (Fig. 4(C, D), left). In addition to the main incised valleys, multiple valley-like features outside of the main valley are observed (Fig. 6(B, C), left) (see also Oldenborger et al., 2013). Some of the observed buried valleys are very narrow and reveal a complex glacial setting with many cross-cutting buried valleys of several generations (Fig. 4(C), left and Fig. 5(C), left), which are also documented in similar settings in Denmark (Jørgensen and Sandersen, 2006).

In general, the electrical resistivities from the AEM model are normally below 10 Ω -m for the Cretaceous shale layers, between 20 and 30 Ω -m for clay till to silty/ sandy till, and above 40 Ω -m for sandy and gravely layers. To obtain this range of values, a statistical approach in the model space in addition to the observed similarities with water well stratigraphy information

and, not shown here, direct comparison between electrical resistivity tomography has been performed. AEM spatially constrained inversion results reveal, with good correlation of absolute values, the resistive and conductive structures imaged by the ERT profile. However, AeroTEM system limitations to resolve the near-surface (early time data) make it difficult to provide similar detail of the near surface. The depths of the main buried valleys are recorded to exceed 100–110 m, while most of the secondary valleys are between 40- and 80-m deep (Fig. 4(C, D) and Fig. 5(C, D)).

The resistive features attributable to sand and gravel filling the main buried valleys are well defined in the obtained resistivity models. However, inversion results of the AEM dataset provide a high variability of the resistivity values across the whole area (Fig. 4, left). Therefore, it indicates that those resistive sediments, interpreted to be the response of sand and gravel, fill the main valley as well as partially covering the two inset valleys and the other small valleys. According to resistivity maps, another resistive body is found in the center of the survey area (Fig. 4(A), left). As noted by Wiecek (2009), inter-till sands are found down to a depth of approximately 30 m in this area, so the resistive body could likely be corresponding to these sands (Oldenborger *et al.*, 2013).

In the following, we describe how a first approximation of hydrogeological units can be derived directly from the geophysical datasets with semi-automated procedures. As an example, we can produce a map of elevation of (or depth to) the shale, applying given search criteria so as to query the model space. See for example, on Fig. 6, where the solid line represents the elevation of the bedrock (as a surface) obtained searching through the resistivity model for a deep conductor (resistivity < 15 Ω -m). In particular, a statistical analysis of the relative frequency of model values indicates a general bi-modal distribution. We interpret the low resistivity peak (around 8–9 Ω -m) in the histogram to be attributable to the shale bedrock, and we use these parameters to guide the search criteria to draw out this surface. It is obvious that similar derived products, which are based on empirical correlation of different parameters, are more robust the greater the statistical population. Beyond that, applying spatial constraints in the inversion over dense datasets, like AEM, improve the lateral coherence of the resistivity models, and hence of the derived products. Figure 7 shows the surface of the resulting elevation of the shale over the entire area for the AEM, the high resolution and the reconnaissance survey. For reference, we also present the shale elevation map derived from water well data alone, which has required extensive interpolation with a 3-km wide search radius (as the

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Figure 4. Average resistivity maps at A) 10–20 m, B) 40–50 m, C) 70–80 m, and D) 100–110 m depth, calculated from AeroTEM data for the Spiritwood Valley survey block. Kriging with 600-m search distance and 50-m cell spacing is used for contouring AEM data, while 2-km and 5-km search distances with 100-m node spacing were used for the high resolution and reconnaissance ground TEM simulated survey, respectively. Shown from left to right are the results from the "true" AEM, simulated high resolution ground TEM, and reconnaissance survey. The black outline (A) indicates the subset represented in Fig. 6. The dashed black lines outline the main Spiritwood Valley aquifer (B, left side) and the inset valley (C, left side).

same for the reconnaissance survey) since the boreholes are not evenly spaced (Fig. 8).

In terms of water well data, the direct comparison of water well data to TEM results is complicated by two factors. Firstly, the water wells are not high-quality geotechnical boreholes and the stratigraphic logs represent driller's observations, which are subject to well-towell inconsistency and observational errors. Secondly, provincial water well locations are reported on a quarter-section basis such that the true well location is not known and several wells from different locations may be assigned to the center of the same quarter section. In effect, the water well locations have an uncertainty of approximately ± 600 m in the case of the Spiritwood. Figure 9 shows a profile along the longest inset valley that includes all the water wells located

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Figure 5. Average resistivity maps at A) 10–20 m, B) 40–50 m, C) 70–80 m, and D) 100–110 m in depth of a small subset in the south westward side of the survey area. The "true" AEM (left) show in detail a network of interconnected tributary valleys and the two inset channels into the main, resistive, Spiritwood Valley set amongst the conductive bedrock. The high resolution ground TEM survey (center) shows these features and reveals the main Spiritwood valley as a resistive structure without any evidence of the inset channels. The simulated reconnaissance TEM survey (right) has no evidence of any of the existing morphology in the first 50-m depth, and also clearly underestimates the main Spiritwood Valley structure.

above the thalweg of the valley. Out of the eight wells encountered, four wells indicate the presence of shale bedrock where the AEM model suggests the presence of a resistive body, interpreted to represent the infilling materials of the buried valley. From a geological perspective, we could assume that this bedrock contact should be easily recognized because of the significant lithological contrast (although this may not always be the case for hard tills, fractured shale and water well logs that are based on cutting observations and drill resistance). Therefore, we attribute this discrepancy to the combination of low resolution of the water well locations and a high degree of spatial heterogeneity associated with the inset valley. As a consequence, even large-scale geological structures like the main Spiritwood Valley are difficult to map in detail using existing water wells alone. This also implies the difficulty to compare well data with other available geophysical data to generate a reliable geological model. However, the well data seem generally to agree with the geophysical data on a regional scale, for example with regard to the presence of a sloping bedrock towards the east, northeast and southeast (Fig. 8).

Compared to the full AEM survey, the results of the simulated ground survey (both data density levels) show much less detail in terms of structural geometry of features; the clear network of secondary valley features disappears completely (Fig. 4 and Fig. 7). For the reconnaissance survey (Fig. 4, right side), we still observe the bulk of the main Spiritwood Valley as a resistive signature that crosses the entire area, but with

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Figure 6. Example of an AEM flight line SCI inversion result. We interpret the high resistivity range to be attributable to the valley fill materials (till, sand and gravel), and the low resistivity peak to be attributable to the conductive shale bedrock. The black solid line represents the obtained elevation for the conductive shale bedrock.

diffuse boundaries and uncertain total extent and geometry. The same picture is seen in Fig. 7 in terms of bedrock elevation, where the valley incision into the bedrock gets very diffuse and difficult to follow for the reconnaissance survey. The high resolution ground survey (Fig. 4, central panels) provides a sharper image than the reconnaissance survey of the long, resistive middle feature, and also hints towards the presence of possible secondary elements of the valley network.

The above observations are more evident in Fig. 5. It is obvious, particularly for the reconnaissance survey, that there is no evidence of the detailed valley network filled with resistive materials. In the derived maps of the elevation of the shale (Fig. 7), the difference in the

resolution of the valley network between the surveys is even more pronounced than in the resistivity maps.

The near-surface inter-till area in the central part of the area (Fig. 4(A)) is seen in all surveys, but its appearance loses detail in the ground TEM surveys. The overall scale of this geological structure is large enough to be captured by the limited spacing of the TEM soundings, but it appears that the scale length of detailed features related to the structure is not rendered adequately.

In general, the spatial variability of the resistive sediments within the valleys, both large and small, as well as within the inter-till formation, is captured by the true AEM survey, but much less by the ground surveys.



Figure 7. Maps represent the derived elevation surfaces of the bedrock (conductive shale) from AEM results (left), and the two simulated ground TEM surveys (high resolution in the center and reconnaissance survey on the right).



Figure 8. Shale elevation surface derived from water well information. The low density of wells results in a limited estimation of the bedrock topography.

A very high data density is required for delineating the detail in the inter-till formation and to outline and orientation of the buried valleys in complicated systems like the Spiritwood Valley. It is difficult to establish the connection between individual buried valleys if the only geophysical contribution comes from sparse ground TEM measurements.

Discussion on the Implications for Hydrogeological Interpretations and Management

As mentioned above, the ground TEM surveys would take approximately 3–5 months and 1–2 months, for the high resolution and the reconnaissance survey, respectively. Even though such difference in time will be reflected in the costing, we estimate the cost of such undertakings to be on the order of a hundred thousand dollars (USD). In comparison, the AEM survey took approximately four weeks to acquire, and a couple of months for accurate re-processing and inversions, with a total investment estimated at 2 to 3 times higher than the simulated ground-based surveys. However, the unit cost of one sounding drops two orders of magnitude from the ground surveys (a few hundred USD/sounding) to the airborne survey (few USD/sounding). In our opinion, the extra bulk budgetary investment required for an AEM survey should be given serious consideration, given the added value in large-scale groundwater programs.

In general terms, we will discuss the issue of general hydrogeological mapping of aquifer geometry, aquifer vulnerability, and flow models for sustainable development of groundwater resources.

As demonstrated, AEM provides high resolution results and detailed geological interpretations, which result in a more connected (and hopefully more accurate) description of the entire set of existing structures. On the contrary, a low density dataset based on ground TEM surveys (i.e., reconnaissance survey) results in a low resolution resistivity model and a less detailed and disconnected description of the geological setting; smallscale but potentially important structures are lost and these omissions can propagate into hydrogeological models. For example, bedrock elevation or aquitard elevation is often an important starting point for a variety of hydrogeological investigations such as groundwater modeling or siting exploitation drilling. However, the elevation maps of the conductive bedrock derived from insufficient data would result in an incorrect contribution to this crucial part of the hydrogeological understanding (compare Fig. 7(C) with 7(A)).

In a hydrogeological context like this, where potential aquifers appear to be relatively small and complex, the most relevant implication for groundwater resource mapping and management is the ability to resolve the aquifer geometry. If we only consider a ground TEM result, e.g., the reconnaissance survey, any mapping of aquifers is almost impossible because of the low density of collected data. Most of the deep aquifer targets in the area are situated within relatively small valley structures and, without the detailed AEM data, these aquifers are very difficult to map and target for drilling. Given only the ground-based surveys, drill targets for finding high potential aquifers would be sporadic along the long inset valley (Fig. 4(C), middle and right), but the uncertainty related to putting the boreholes at most optimized locations is high. Establishing locations for new groundwater exploration drillings or well fields is much safer with the maps generated from the AEM data at hand, i.e., location of a lot of small aquifers are indicated by the scattered resistive bodies within the valley structures, and optimized positions for drilling can be determined by locating the exact position of the valley thalwegs from the shale elevation map (Fig. 7(A)). This is an important aspect since the presence of resistive material enhances permeability into the valleys and may result in a potential groundwater reservoir. Despite the obvious advantage in using AEM for mapping groundwater resources at high resolution, it must also be pointed that ground TEM data alone did produce results that allowed better hydrogeological mapping than the one based solely on boreholes.



Figure 9. A N–S oriented profile section through the longest inset valley observed in the survey area is plotted below the contour map. a) Shows the conductive bedrock surface and location of the profile (dashed white line). b) Example of water well data with associated stratigraphic information (legend on the left indicates lithology detail). c) The profile connects all the boreholes that come across the buried valley. A small buffer zone was applied to take into account only the boreholes that are located within the inset valley.

According to the AEM data, the valley aquifers are often covered by clavey to silty\sandy sediments (i.e., till) giving them some kind of natural protection against pollution from the surface. However, where the valleys are cut by younger valleys filled by sandy material they can be exposed and vulnerable. Thus, vulnerability assessments of important deep aquifers in the area would also be much harder and complicated to perform solely based on the ground-based surveys. In the area where extensive inter till sands are interpreted to cover the deeper setting including aquifer-hosting valleys, a detailed knowledge of the spatial extension and internal composition of this sand formation is important. Like the buried-valley geology, this formation is much better resolved by the true AEM survey than by the ground survey.

Glaciated areas are typically complex, and detailed information and models are essential if the goal is to predict groundwater pathways to well fields based on flow modeling (Troldborg *et al.*, 2008; Troldborg *et al.*, 2007). Especially with the presence of buried-valley geology, such predictions are challenging and require high resolution models, where the individual valleys must be resolved (Shaver and Pusc, 1992; Jørgensen *et al.*, 2008; Andersen *et al.*, in press). Groundwater flow will tend to follow the often coarse-grained sediments in the valleys, but in cases where clay-filled valleys cut such pathways they can constitute effective barriers. Therefore, the groundwater flow in the Spiritwood area is intricately connected to the existing geometry of the valley aquifer. The true AEM survey maps the valley network in detail, whereas the groundbased survey does not. Thus, a flow model based solely on the true AEM survey would be able to produce useful results for groundwater management, *i.e.*, catchment area calculation.

Given the effective mapping of aquifer location and potential for detailed groundwater flow prediction, a true AEM survey can identify virgin aquifers to be exploited as local resources of fresh water. In addition, an accurate, wide area, high resolution model obtained from AEM can assist the managing body with identifying and assessing issues linked to the varying quality of ancillary information. For example, it can serve as a base

to screen for inconsistencies in existing databases, *e.g.*, borehole stratigraphy.

Complementary AEM and Ground-based TEM Surveys

AEM and ground-based TEM can serve a complementary role in a hydrogeophysics survey. Ground TEM can probably provide greater depth of investigation in areas where the AEM might fail to reach the target. Perhaps an even more important contribution would be to deploy a calibrated ground-based TEM system to check and post-calibrate, if necessary and possible, the AEM dataset. Provided a ground TEM system had been calibrated, as was done by Foged *et al.* (2013) over the Danish national test site of Lyngby, then it could be used to acquire data over diverse locations within the AEM survey area to provide a series of local 1-D resistivity reference models for comparison with the AEM data and derived models. If necessary, the reference models could be used to re-calibrate the AEM data.

Conclusions

In this paper, we describe the shortcomings in hydrogeological interpretation and management that could arise if a ground TEM survey is used rather than an AEM survey. Output resistivity models from groundbased TEM data reveal how the mapping of hydrogeological features of great relevance, such as buried valleys as well as minor valley networks, could be inaccurate and poorly detailed in terms of structures morphology. Furthermore, derived products of high density AEM inversion results, *i.e.*, elevation of bedrock, can be readily integrated and compared with other available data, either geophysical or geological.

Integrated with ancillary information, AEM provides rapid and cost effective robust results in terms of aquifer geometry and vulnerability mapping. It also provides a solid basis for subsequent flow modeling.

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