# Groundwater Modelling by Automated Integration of Borehole Information and Airborne Transient Electromagnetic Data

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## Introduction

To a very high degree, the accuracy of predictions made from groundwater models rely on the quality of the input to the groundwater model. Especially the description of the subsurface structures is known to affect the predictions, even though this structural input is rarely needed to calibrate the models against available hydrological observations.

Hence, to estimate groundwater flow in subsurface systems, the groundwater modeler must establish a structural representation of the subsurface. Such models can be derived based on a variety of data from the area of interest. Traditionally, borehole lithological information has been the cornerstone of such modelling efforts. However, the logistical challenges and the financial expense associated with making boreholes often limit their spatial density, especially when large depths are required over regional areas. Such limited data coverage is a significant challenge when constructing reliable subsurface models. This is especially true in complex geologic environments and as an example we use a formerly glaciated area, where glacial tectonics and subice landforms (e.g. tunnel valleys and eskers) form a highly heterogeneous subsurface architecture. To model these subsurface structures effectively, the data density must be increased significantly compared to that obtained from boreholes. Various geophysical methods can be used to increase the data density, but airborne measurements, such as the SkyTEM system (Sørensen and Auken, 2004) with high near-surface resolution capabilities, have proved to be especially well-suited methods.

In the present case, we will outline the possibilities for development of both structural models and groundwater models, given availability of high-resolution airborne geophysical data that covers large areas combined with relatively sparse lithological information from boreholes.

## Background

The investigated area is referred to as Kasted. It is located northwest of the city of Aarhus, Denmark, and covers ~470 km$^2$. It has been subject to several geological and geophysical campaigns due to its interesting geological structures and the rich groundwater resources located primarily in buried valley structures (Jørgensen and Sandersen, 2006). The water utility company, Aarhus Water, extracts drinking water from the area, supplying the 350,000 inhabitants in the city of Aarhus. However, Aarhus is growing rapidly, and the water company expects a shortage of water in the near future. Hence, they are looking for new well-fields. One of the main goals for the Kasted field campaign was to find a suitable location for a new well field by means of a detailed hydrogeological model from boreholes and SkyTEM data (Figure 1).

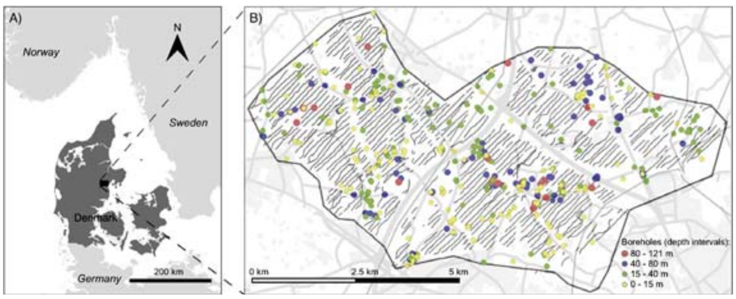


*Figure 1: A) Location of the study area and B) location of the data. Black dots in (B) mark positions of SkyTEM soundings remaining after processing. Soundings are so closely spaced that they appear as black lines. Boreholes within the study area are shown with colors according to their depths (figure: Høyer et al. (2015)).*

The hydrogeology in the study area is dominated by the presence of buried valley structures. Borehole studies show that the buried valleys are primarily incised into Paleogene clay deposits and that the infill comprises Quaternary sand, gravel, and till deposits originating mainly from the Weichsel and Saale glaciations. Locally, Miocene sandy units overlie the Paleogene clay layers. Based on the findings of Høyer, et al. (2015), at least five generations of valley structures are crosscutting in the area around the pumping wells. Some of these valleys are filled with coarse sediments, thereby being potential aquifers, and others are filled up with clay. Valleys containing coarse sediments can be mapped effectively using the Transient Electromagnetic Method (TEM), because of the low resistivity of the surrounding Paleogene clay deposits. Several mapping campaigns have been conducted in the area using conventional ground-based TEM methods and the airborne SkyTEM system.

The importance of the valley structures for the drinking water supply is evident from the fact that approximately 70% of the screened boreholes in the area are located within known buried valley structures. Minor aquifers also exist locally on the plateaus between the buried valleys. However, these aquifers are mainly used for groundwater extraction to single households or small communities.

The local focus area of this study is shown in Figure 1. The area is of major interest due to the presence of existing well-fields. According to descriptions from boreholes in an east-west trending valley, the aquifer here is made up of coarse sand and gravel. The valley is easily seen in Figure 5B as the East-West trending structure outlined in blue. The bottom of the valley is located approximately 100 m below ground surface. Despite the thick sequence of coarse grained deposits, the yield of the aquifer is limited by the valley structure. Studies performed on groundwater extraction from similar valley structures in North America (van der Kamp and Maathuis, 2012), showed that the extraction of groundwater is expected to induce a significant drawdown, which will spread over long distances in the valley system. The hydraulic connection from the well field towards the northeast through the valley structure is limited by the presence of a hydraulic barrier (clays), which will further increase the drawdown.

## Properties

Two physical properties are central in this case history. Firstly, starting from the groundwater model, the crucial parameter is hydraulic conductivity of the subsurface units. The hydraulic conductivity is estimated from groundwater model calibration. Secondly, the other main property is the electrical resistivity estimated from the SkyTEM measurements. Expected resistivity values for the different sediments in the Kasted region are displayed in Table 1. The determination of the resistivity values in Table 1 are based on direct comparison of borehole data with measured resistivities from TEM-surveys, but also with resistivity log data. Measurements of resistivity values for different sediment types have also been conducted directly on borehole samples.

The buried valleys are shaped like bowls, where the bottom consists of Paleogene clay and the infill (where water is typically found) consists of sand and gravel. This makes the geological setting an ideal target for TEM since there is a strong resistivity contrast between the geological units.

| GEOLOGICAL UNIT | RESISTIVITY RANGE (Ωm) |
|---|---|
| Paleogene clay | 1-10 |
| Clay till | 25-60 |
| Sand till | > 50 |
| Meltwater sand and gravel | > 60 |
| Glaciolacustrine clay | 10-40 |
| Miocene silt and sand | > 40 |
| Miocene clay | 10-40 |
| Sand | > 40 |

*Table 1:*
*Resistivity ranges expected for the different geological units in the Kasted area.*

## Survey

The airborne transient electromagnetic transects (Figure 1) were acquired with the SkyTEM system. SkyTEM is a helicopter-borne time-domain electromagnetic system designed for hydrogeophysical, environmental and mineral investigations. The system is shown in operation in Figure 2. The SkyTEM system is carried as an external sling load independent of the helicopter. The transmitter, mounted on a lightweight frame of composite material in an eight-sided polygon configuration, is a four-turn about 340 $m^2$ loop divided into segments for transmitting a low moment (LM) in one turn and a high moment (HM) in all four turns. The LM transmits about 10 A with a turn-off time of about 3.3 microseconds; the HM transmits approximately 110 A and had a turn-off time of about 49 microseconds for the Kasted survey. This yields a maximum magnetic moment of approximately 150,000 $Am^2$, more than sufficient for groundwater exploration where the accuracy of the data is crucial.

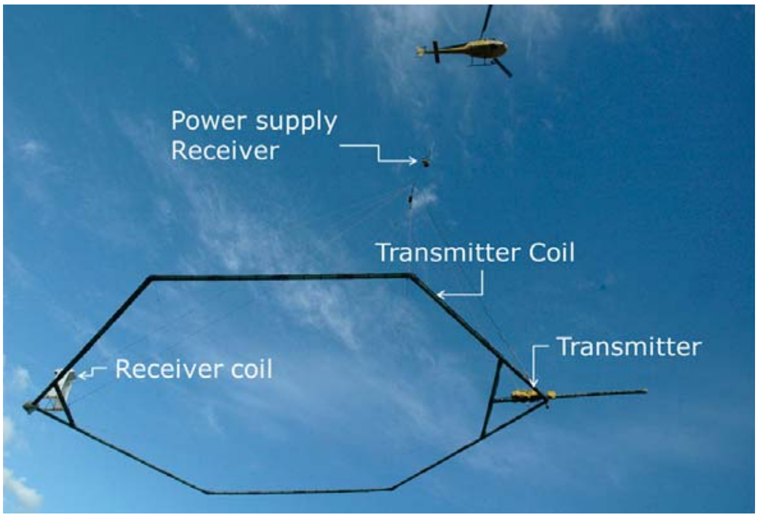


*Figure 2: The SkyTEM system with key system parts identified. On top of the shown devices, there is a comprehensive set of GPS receivers, laser altimeters, and inclinometers to monitor the exact location and orientation of the frame in the airspace.*

In this survey, we obtained unbiased early-time data from as early as 7 μs after the beginning of ramp down (equivalent to 3 μs from end of ramp) for the LM. The last gate was at 9 ms. The very early times carry information about thin layers, in the order of a few meters, in the uppermost approximately 20 m. At the same time, layers can be mapped at depths greater than 250 m, although this depends upon the resistivity of the units and has decreasing lateral and vertical resolution with increasing depth. This survey covered 333 km of lines with a line spacing of 100 m (Figure 1).

## Processing

Due to the dense infrastructure in the area, many of the soundings suffered from interference with man-made conductors and were removed during the data processing, prior to the inversion.

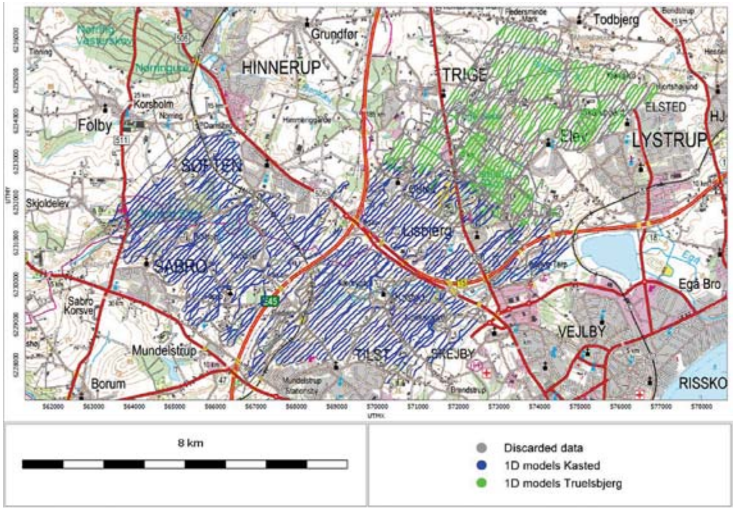


*Figure 3: Location of the survey with a thematic map over a background image. The grey dots show the discarded SkyTEM data either affected by infrastructure or considered non-productive at the turns near the end of the lines. The blue dots and the green dots show the inverted 1D models from the Kasted and Truelsbjerg areas.*

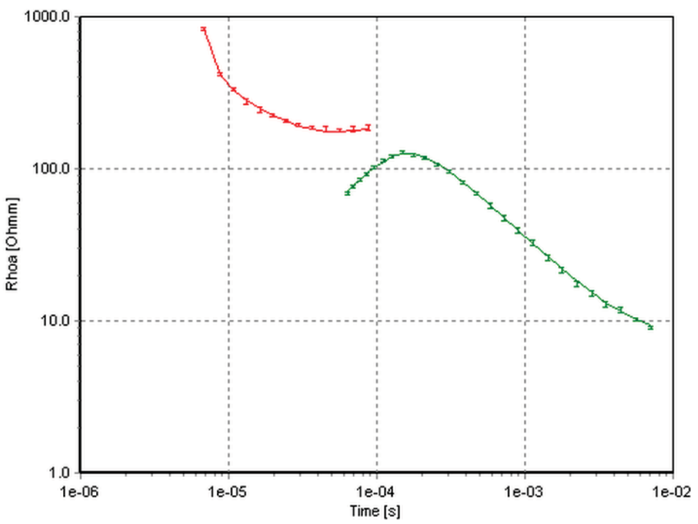


*Figure 4: Example of averaged sounding from Kasted (transformed into late time apparent resistivity), with different time gates displaying different noise levels, for low moment (red) and high moment (green).*

Failure to eliminate these data would inevitably have resulted in artefacts in the calculated resistivity models. We estimate that approximately 30% of the acquired data had to be culled (Figure 3). After culling, approximately 70% high quality data were left. This Corresponds to 9500 soundings ready for inversion. An example of a sounding curve is shown in Figure 4.

The inversion was based on the spatially constrained (SCI) quasi-3D approach: a local, 1D exact forward response, with model parameters spatially constrained in 3D. The inversion was performed with 25 layers that provided smooth transitions in the resulting models. The resistivity models were then further interpolated into horizontal grids and stacked, resulting in a 3D resistivity cube, which can be used to display the resistivity as "depth" slices at a constant elevation (5 metre elevation example in Figure 5A) or the elevation of the good conductor, which in our case is the bottom of the buried valleys (Figure 5B).

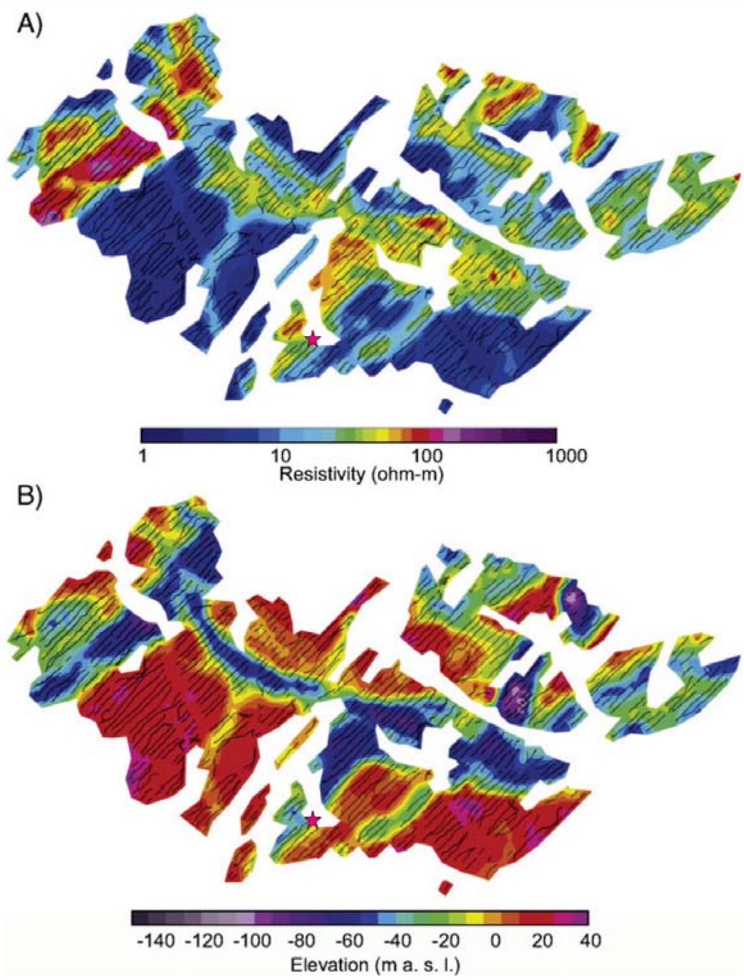


*Figure 5: Initial interpretations of the models from the edited SkyTEM data. A) Horizontal slice through the 3D resistivity model at elevation = 5 m above sea level. B) Elevation of the top of the deepest conductive layer (the Paleogene clay,as modified from: Høyer et al. (2015).The data is from the blue flight line dataset in Figure 3. The pink star is the location of the pumping well in Figure 6.*

## From Resistivity to Structures

As outlined in Table 1, the resistivity model of the subsurface contains information about the subsurface lithologies. Provided that local conditional information allowing translation from resistivity to lithology can be obtained, this information can be used to assist and constrain the construction of models representing subsurface structures. Examples of such translations from resistivity to lithology can be found in Foged et al. (2014) or Barfod et al. (2016), where they show that the translation is site dependent, and that it can have a local variability within short (kilometer) distances.

From a hydrological perspective, modelers are mostly interested in a delineation of water bearing units (aquifers) and water restricting units (aquitards). Models outlining these structures are most often referred to as hydrostratigraphic models. In glacially dominated areas, aquifers are usually composed of sand/gravel, and the aquitards are comprised of clays of various types. The three-dimensional clay-fraction methodology was developed based on this generalization of deposition (Foged et al., 2014, Marker et al., 2015). The clay fraction methodology translates lithological units in boreholes into fractions of clay present within specific depth intervals of the subsurface. These clay fractions can subsequently be correlated to the resistivity models through the area, and the optimal model that translates the resistivities into sand and clay distributions can be derived. This local calibration of the resistivity models allows for spatial variability of the translation, when justified by the lithological and the geophysical datasets. Once the translator model has been established, the geophysical data and lithological data can easily be combined in a modelling effort, where either a single mean representation or multiple equally probable representations of the subsurface can be derived. Marker et al. (2017) used this clay-fraction principle to derive multiple realizations of the subsurface through k-means clustering. Clustering is a method to reduce the number of different possible resistivity units (based on continuous variability in resistivity) and lithologies (in the form of clay fractions). This reduction in possible units typically results in a subset of 3-5 units in the hydrostratigraphic model. To fill in the gaps in data coverage, and to make multiple model realizations, Marker et al. (2017) used sequential indicator kriging (SIS), but they  could also have been made using multiple point geostatistics (MPS) (e.g. Mariethoz and Caers, 2015). The outcome of both the SIS and the MPS simulation is a set of model realizations that, given the input data used to constrain the simulations, have equal probability.

In a groundwater study, the importance of the uncertainty of the description of the subsurface structures can be analyzed both with respect to the models' ability to reproduce measured hydraulic data or the resulting influence on model forecasts. This is done by incorporating each of the model realizations into the groundwater modelling framework and calibrating these models

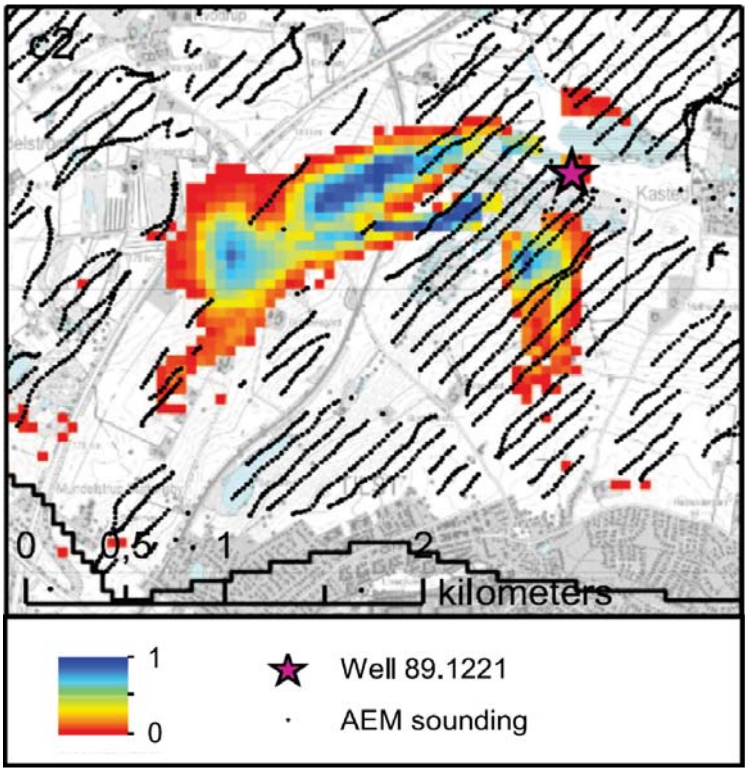


*Figure 6: Probability map of well catchment area. The map only covers the vicinity of the well shown in Figure 5. The map was derived based on structural realizations of the subsurface and backward particle tracking from the pumping well. Blue areas indicate areas of high probability for belonging to the catchment  and yellow and red areas are zones of decreasing catchment probability modified from Marker et al. (2017)*

to the available datasets. The resulting ensemble of models can then be used to relate subsurface uncertainty to the uncertainty of groundwater model forecasts. An example of the influence of subsurface uncertainty on the forecast of the catchment zone to a pumping well can be seen in Figure 6 (refer to Figure 5 for location of the pumping well).

## Conclusion and Outlook:

In highly complex geological settings such as former glaciated areas, the heterogeneity of the subsurface is at a scale that cannot be resolved relying solely on boreholes. Here, high density, high quality geophysical data are crucial for the groundwater modelling. We have shown how geophysical data can be merged with borehole information to create hydrostratigraphic input to groundwater models.

Moreover, equivalences in hydrological models, namely that multiple realizations of the subsurface structures fit a hydrological dataset equally well, poses a problem. Such equivalences can easily lure a groundwater modeler into accepting erroneous models. This problem becomes even more pronounced when making groundwater model forecasts as a means of decision support. The quality of predictions depends heavily on the subsurface structures, which points to a need to make realistic ensembles of equally probable subsurface structures in order to give realistic estimates of uncertainties related to the predictions.

In the present case, we showed the uncertainty of a well catchment zone produced using equally probable subsurface realizations generated from geophysics and borehole information. Such uncertainties can be quantified, and their influence should be taken into account in groundwater management.

The general outlook for the method presented, is that it can be used as an efficient and transparent procedure for constructing groundwater models over large areas scanned with high quality geophysics. The geology is not constrained to glacial sedimentation as in this example, but it could also have been e.g. complex delta systems or large lake systems. The ultimate goal of the models is water resource management for management of artificial recharge, water extracting for irrigation etc. Not only can such scenarios be modelled to great detail but the uncertainty can also be estimated giving a better base for decision on expensive and crucial water infrastructure investments.

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Anders Vest Christiansen is an Associate Professor at the Hydrogeophysics Group, Aarhus University, Denmark. He received his PhD in 2003 within airborne TEM methods and inversion methodologies. Overall, his research focus remains within these subjects. In the later years he has had increased focus on the integration of various data types (e.g. geophysics with borehole info and hydrological observations) with the purpose of making objective and transparent processes that generate maps and other outputs that are in better agreement with the actual needs of the end-users.

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