Utilizing Time-Domain Electromagnetics (TEM) to Map Subsurface Groundwater Resources and Assessing Their Vulnerability

Anders Edsen, WSP Denmark
Patrick Mah, WSP Canada

Summary

Nearly 100% of Denmark's water supply is sourced from subsurface groundwater. Given Denmark's dense population and the fact that 60% of its land is used for intensive farming, understanding the distribution and vulnerability of groundwater resources is crucial for future sustainability. Over the last 30 years, geophysical methods have proven highly valuable in mapping of subsurface geology, as well as mapping of hydrological pathways from contaminated surface sites to subsurface groundwater aquifers.
The relatively recent developed ttowed TEM method is one of the latest available tools for this task. The tTEM system has shown an unprecedented ability to map complex geological layering and structures down to depths of 80 to 100 meters.
The applicability of the towed TEM method is shown here in two cases representing different geological settings and hydrogeological targets.

Introduction

From 1999 until 2015, the Danish environmental authorities launched a massive groundwater mapping program, which initiated development of new geophysical methods focused on mapping the uppermost 100–200 m of the subsurface. The large-scale mapping task, combined with a relatively complicated glacial geology, spurred the development of methods capable of continuous data collection and survey designs that enabled dense data coverage. In this period, the Pulled Array Continuous Electrical Sounding method (PACES; Christensen and Sørensen, 2001) and, later, the airborne electromagnetic method SkyTEM (Sørensen and Auken, 2004) were developed by a research group at the Department of Geoscience at Aarhus University (Denmark). One of the latest developments is the Towed Transient ElectroMagnetic (tTEM) method (Auken et al, 2019; Maurya et al., 2020; Sandersen et al.,2021; Maurya et al., 2023)

The tTEM Method

The tTEM system is a product of focused research conducted at the Department of Geoscience at Aarhus University between 2015 and 2020. The system is now commercialized and marketed by the TEMCompany in Aarhus, Denmark (https://www.temcompany.com/).

tTEM is essentially a ground based Transient ElectroMagnetic system reduced in size. The total length of the system is almost 15 meters, and the relatively small size allows the system to be towed by an All-Terrain Vehicle (ATV).

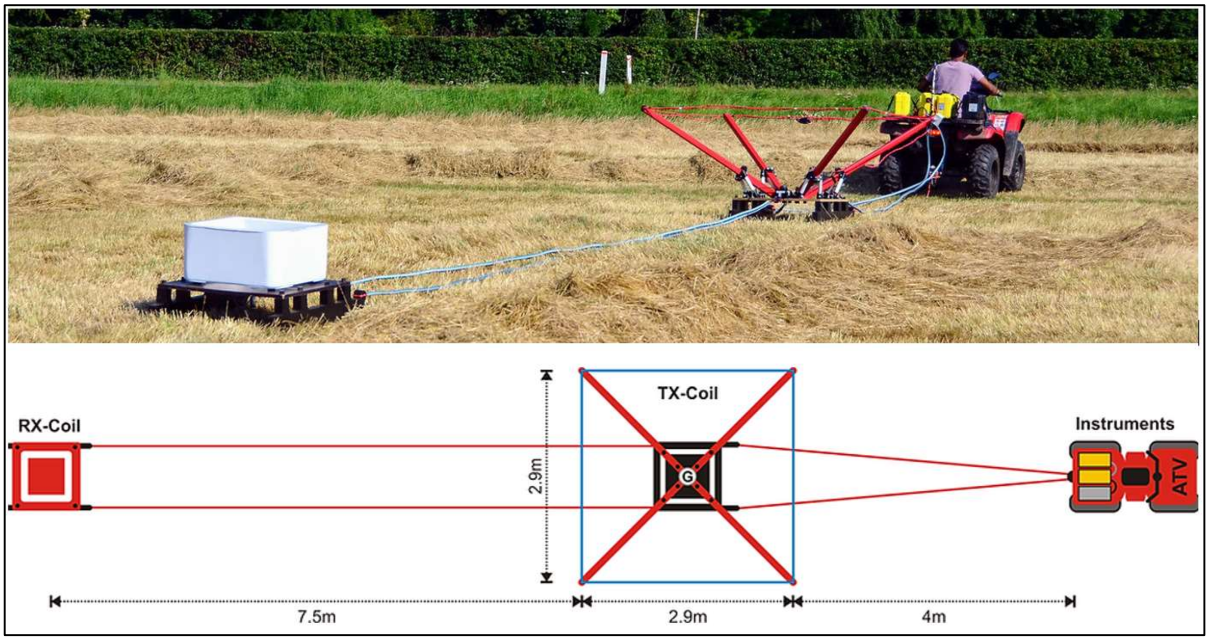

Figure 1 The 3x3 tTEM system (Courtesy TEMCompany (https://www.temcompany.com/)).

tTEM induces a primary magnetic field using a transmitter coil (TX-coil). A secondary magnetic field, originating from eddy currents in the subsurface, is measured in the receiver coil (RX-coil). The decay measured in the RX-coil is stored in the instruments mounted on the ATV. From these data, the variation of the subsurface electrical resistivity can be determined (Figure 1).

tTEM is a Dual Moment (DM) system, and the magnitude of the transmitted current alternates between a Low Moment (LM) mode and a High Moment (HM) mode. The system automatically switches between HM and LM and thus, data related to the shallow part as well the deeper part of the subsurface are obtained. Data are collected continuously, while driving at a speed of 15 to 20 km/h. The smaller size, in combination with the DM capacity, enable the tTEM system to produce high resolution imaging of the subsurface, both horizontally and vertically, down to depths of 80 to 100 meters.

A tTEM survey comprises survey lines with a mutual distance of 10-35 meters and soundings compiled every 5 to 10 meters. Each sounding is transformed into a 1D multilayer resistivity model of the subsurface and within each hectare (100x100 m), the total number of 1D models often exceeds hundred. This high data density enables the construction of geological and hydrogeological models with a 3D resolution typically needed for detailed hydrological models and contaminated site investigations.

tTEM Survey Results

The Voldum Case

At a farm site, large amounts of pesticides have been poorly handled by an agricultural contractor in the period from 1951 to 2014. Soil samples and samples from shallow boreholes at the site show traces of 34 different pesticides (e.g. phenoxy herbicides) and concentrations up to 65 µg/l.

An abstraction well supplying the local community with drinking water is located 180 m from the contaminated site.

The Central Denmark Region, responsible for the site investigations, ordered a tTEM survey with the purpose of determining the geology beneath the site, possible hydrological pathways from the site towards the abstraction well and the location of the groundwater aquifer beneath the abstraction well.

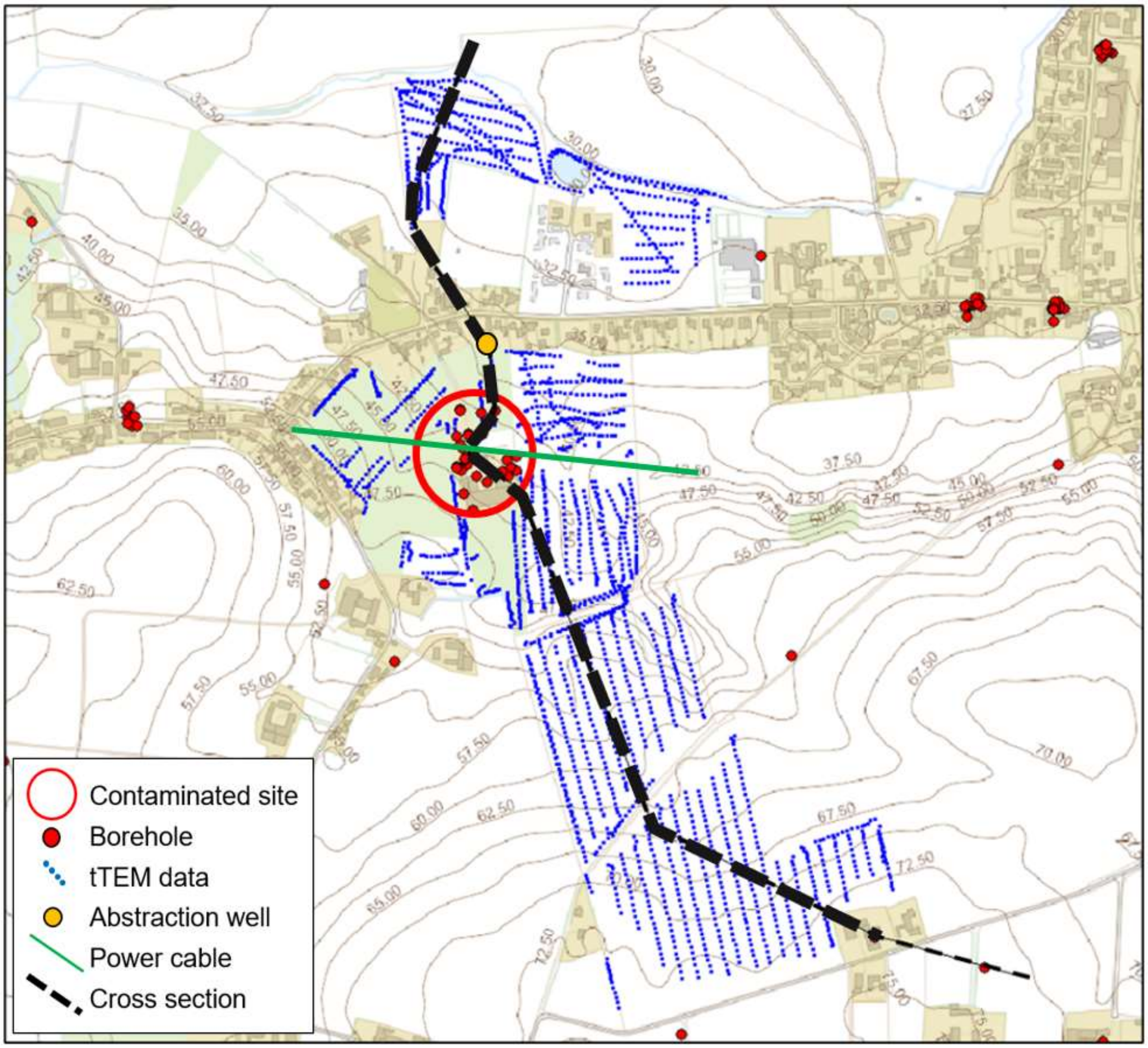

Figure 2 The tTEM survey at the Voldum site (courtesy of the Danish Central Region).

The tTEM survey covered an area of 50 hectares and data were collected in 4 hours with a driving speed of 15 km/h. In the open fields, data were collected with a 25 m line separation whilst in the vegetated areas data were collected where ATV access was possible.

During data processing, some data had to be deleted due to a power cable crosscutting the survey area (Figure 2).

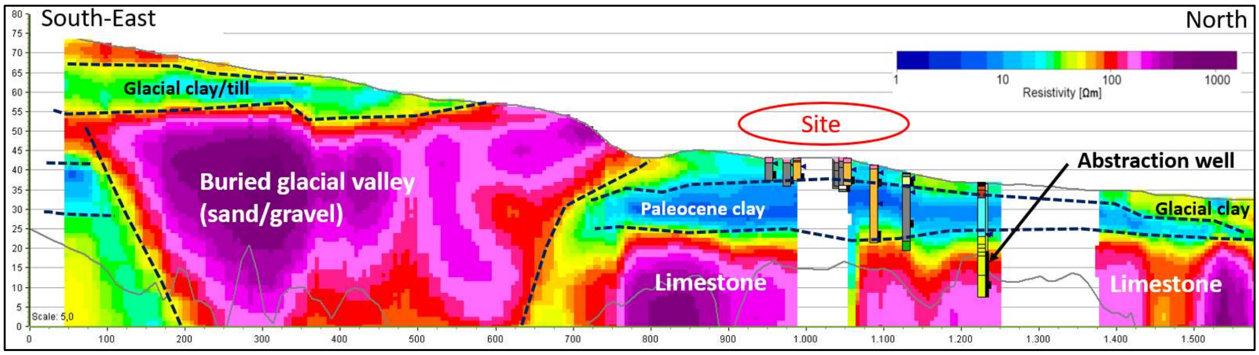

Figure 3 Cross section through the tTEM resistivity models at the Voldum site. Geological interpretation with courtesy of Geologist PhD Flemming Jørgensen at the Danish Central Region.

The subsurface resistivities determined by the tTEM data enabled the construction of a detailed geology model in 3D. The tTEM survey results revealed a deep buried valley structure otherwise unseen from the surface. Possible flow pathways related to the contaminated site could be determined and improved the basis for a robust risk assessment for the groundwater resources related to the contaminated site.

Furthermore, the tTEM survey results near the abstraction well show that the Paleocene clay seen in the borehole log extends some 500 meters upstream and thus, the risk of contamination reaching the abstraction well from the contaminated site can be assessed to be minimal.

The Restrup Case

At the Restrup site, the review of historical information from two adjacent former horticulture locations revealed large oil storage facilities and potential stocks of pesticides. A few soil samples showed hydrocarbon concentrations exceeding 70 times the permitted levels for drinking water and the soil were immediately excavated and removed from the sites. Shallow borehole groundwater samples showed contamination with pesticides in 6 of 7 boreholes exceeding 5 µg/l total pesticide concentration. Other similar, yet to be investigated, sites within the same area had similar potential for soil and groundwater contamination.

The general geological setting in the area is glacial deposits of varying thickness overlaying limestone that holds the primary groundwater resource in the area.

The North Denmark Region, responsible for the site investigations, decided to launch a regional tTEM survey with the purpose of determining the thickness of the glacial sediments and ascertain whether they offer natural protection of the groundwater resource.

The tTEM survey covered an area of 349 hectares that was primarily characterized by open farmland. Data were collected in 2 days with a driving speed of 15 km/h and a 25 m survey line separation. During data processing, some data had to be deleted due to a gas pipeline and power cables crosscutting the survey area (Figure 4).

The subsurface resistivities determined by the tTEM data showed that the glacial sediments overlaying the limestone were of very limited thickness and that they only occasionally consisted of clay rich materials. Thus, these sediments cannot provide any natural protection of the deeper primary groundwater resource.

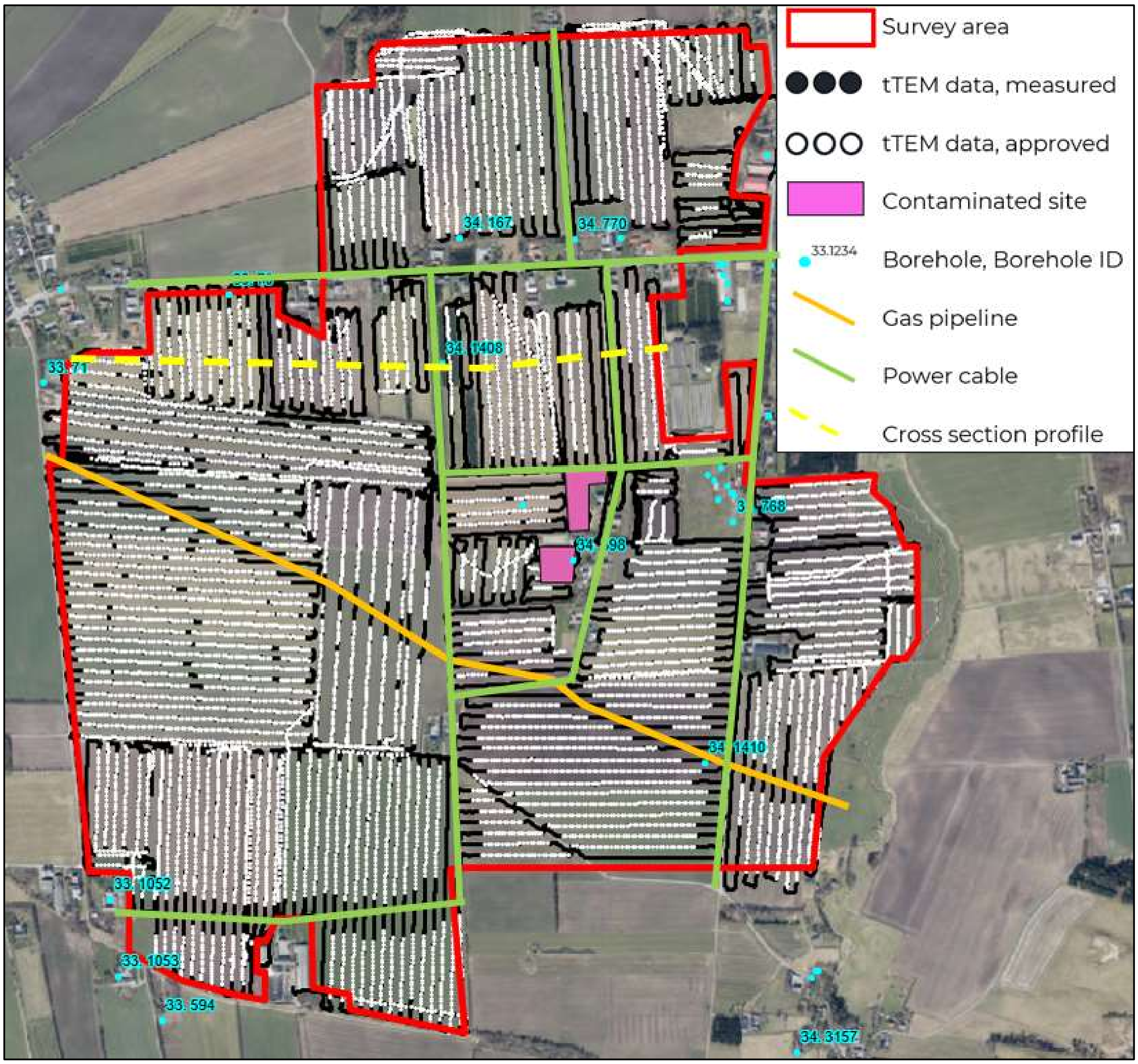

Figure 4 The tTEM survey at the Restrup Area (courtesy of The North Denmark Region).

One striking feature came to light from the tTEM resistivity results. It is widely known that marl enriched horizons are present in the limestone deposits in this area. However, these horizons have previously only been mapped via direct exposures in excavation pits or from geophysical borehole logging results. With the tTEM survey results, the marl enriched horizon came to light as a continuous layer, and it can be followed almost all over the surveyed area (Figure 5).

The marl enriched horizons are of specific interest as in several locations they have shown to be a hydrological barrier. In some locations the hydrological groundwater head are seen to be higher at the limestone aquifer below the horizon compared to the groundwater head above the horizon.

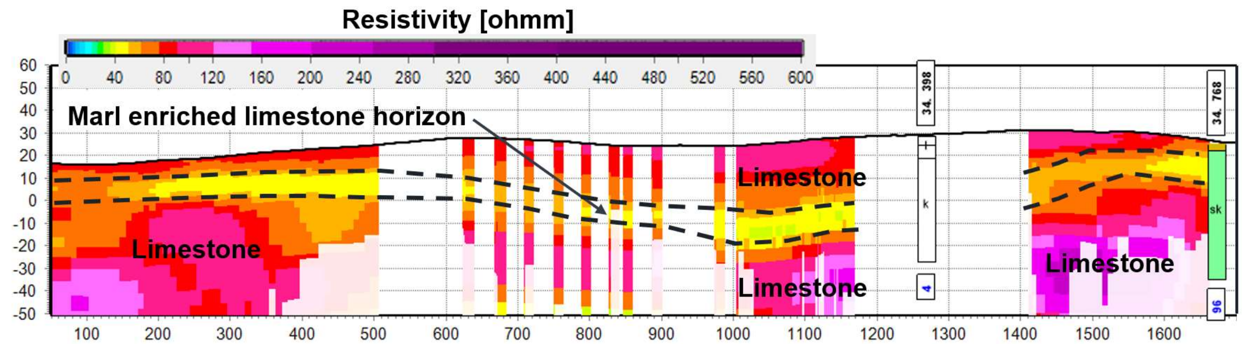

Figure 5 Cross section through the tTEM resistivity models in the Restrup survey area with the identified marl enriched limestone horizon indicated by dashed lines.

In the Restrup area, despite the glacial sediments turning out to be too thin to pose a natural protection, the aquifer beneath the marl enriched horizon is not exposed to the same risks as the shallow aquifer above the horizon.

Conclusions

In our experience, the tTEM method has shown to be an efficient and powerful mapping tool and, when combined with geological knowledge from boreholes, provides a unique 3D insight into shallow geological structures and properties of sedimentary units. However, the full potential of the method can only be realised when used in a dense grid and at appropriate driving speeds.

Based on numerous applications of the method during 2020-2024, the experiences can be summarized with the following advantages and limitations:

Advantages: Easy to employ in open rural terrain, results are detailed 3D coverage and not only profiles, fast mapping of large areas with relatively low costs compared to other geophysical methods, very efficient in mapping high conductive structures.

Limitations: Unable to cover soft terrain areas, possible damage to crops in some seasons, sensitive to buried cables and power lines, reduced resolution in the upper 2 meters.

The gained value relates to the cost-effective nature of the method, as large areas can be mapped very effectively, and because the survey results are of high lateral and vertical resolution. Furthermore, the high density of the data means that even though the data has been collected with one application in mind, the results can be used in other aspects and applications without the need for additional processing or supplementary data collection.

Acknowledgements

The authors wish to express our gratitude to The North Denmark Region and The Central Denmark Region for the permission to show the case examples.

References

Auken, E, Foged, N, Larsen, JJ, Lassen, KVT, Maurya, PK, Møller Dath, S & Eiskjær, TT 2019, 'tTEM — A towed transient electromagnetic system for detailed 3D imaging of the top 70 m of the subsurface', *Geophysics*, vol. 84, no. 1, pp. E13-E22.

Christensen, NB & Sørensen, K 2001, 'Pulled array continuous electrical sounding with an additional inductive source: an experimental design study', *Geophysical Prospecting*, vol. 49, pp. 241-254.

Maurya, PK, Foged, N, Madsen, LM & Christiansen, AV 2023, 'Comparison of towed electromagnetic with airborne electromagnetic and electrical resistivity tomography in a hydrogeophysical context', *Geophysical Journal International*, vol. 235, no. 1, pp. 817-830.

Maurya, PK, Christiansen, AV, Pedersen, J & Auken, E 2020, 'High resolution 3D subsurface mapping using a towed transient electromagnetic system - tTEM: case studies', *Near Surface Geophysics*, vol. 18, no. 3, pp. 249-259.

Sandersen, PBE, Kallesøe, AJ, Møller, I, Høyer, AS, Jørgensen, F, Pedersen, JB & Christiansen, AV 2021, 'Utilizing the towed Transient ElectroMagnetic method (tTEM) for achieving unprecedented near-surface detail in geological mapping', *Engineering Geology*, vol. 288, 106125.

Sørensen, KI & Auken, E 2004, 'SkyTEM - A new high-resolution helicopter transient electromagnetic system', Exploration Geophysics, vol. 35, pp. 191-199.