

# Geophysical methods and data administration in Danish groundwater mapping

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Groundwater mapping in Denmark has high priority. It was initiated in the 1990s when the pressure on groundwater resources increased due to urban development and pollution from industrial and agricultural sources. In some areas, the groundwater mapping included survey drillings, modelling based on existing knowledge and geophysical mapping with newly developed methods that made area coverage on a large scale possible. The groundwater mapping that included development of new geophysical methods showed promising results, and led to an ambitious plan to significantly intensify the hydrogeological mapping in order to improve the protection of the Danish groundwater resources. In 1999 the Danish Government initiated the National Groundwater Mapping Programme with the objective to obtain a detailed description of the aquifers with respect to localisation, extension, distribution and interconnection as well as their vulnerability to pollution (Thomsen *et al.* 2004). This mapping programme covers around 40% of the area of Denmark designated as particularly valuable water abstraction areas. Water consumers finance the mapping programme by paying 0.04 € per cubic metre of consumed water. At the end of the programme in 2015, the total cost is estimated to be about 250 000 000 € with a significant part spent on geophysical mapping.

The mapping programme is administered by seven local offices under the Ministry of Environment, but most of the practical work is carried out by private consulting companies, and involves

the use of geophysical survey methods, survey drillings, well logging, water sampling and hydrological mapping, as well as geological and groundwater modelling. In major parts of the particularly valuable water abstraction areas, it is important to obtain spatially dense geophysical data covering large continuous areas.

## Geophysical methods used in the hydrogeological mapping

The choice of geophysical methods depends on the geological setting of the aquifers. Those of interest for drinking water are primarily found within the upper 250 m of the subsurface. The aquifers can be grouped into three main types. In

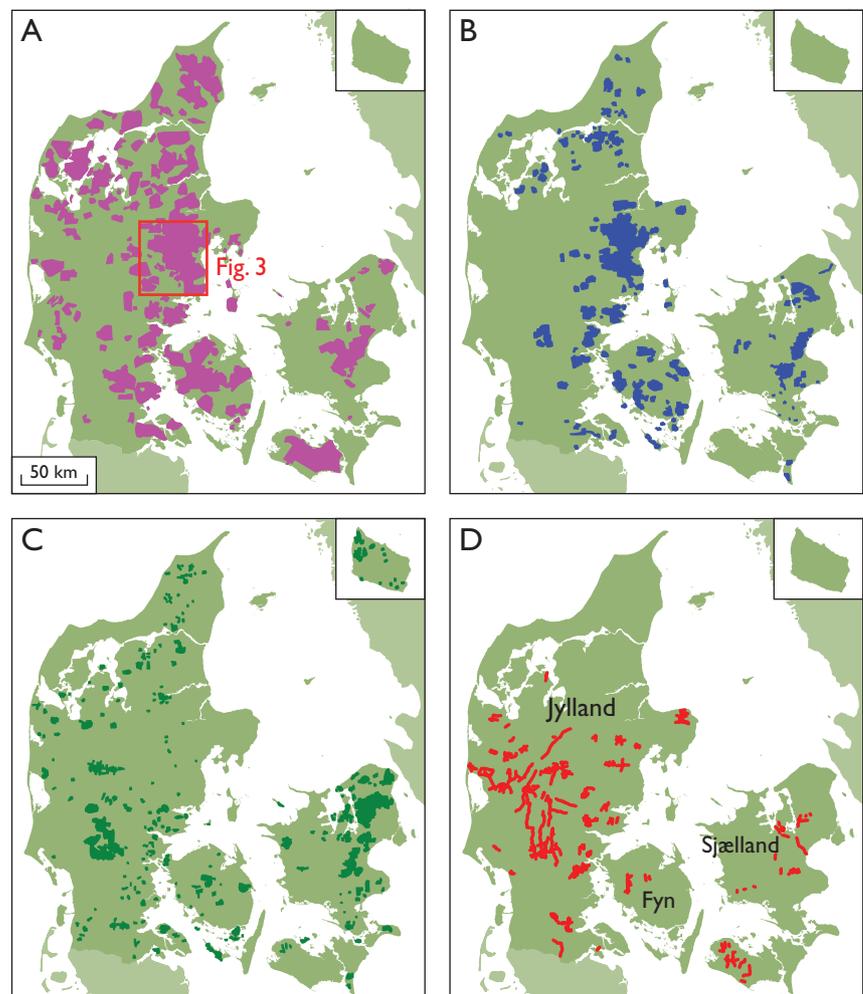


Fig. 1. Areal extent of data collected by the end of 2008. **A:** Areas with TEM and SkyTEM soundings, **B:** Areas with PACES profiles, **C:** CVES profiles. **D:** Seismic profiles.

the western part of Denmark, extensive Quaternary and Pre-Quaternary sand deposits dominate. In the central part, the most important groundwater resources are located in Quaternary sand deposits often found in Quaternary valley structures deeply eroded into Palaeogene clay deposits. In the northern and eastern parts of the country, most of the important aquifers are found in Upper Cretaceous and Danian limestone.

The most important geophysical methods are electrical and electromagnetic methods, combined with reflection seismic profiling and borehole logging at selected localities. Differences in electrical properties between sandy aquifers and clay sediments favour the use of the electrical and electromagnetic methods (Sørensen *et al.* 2005), but the ability of seismic methods to reveal detailed internal structures within the aquifers is also important.

The most commonly used geophysical method in the groundwater mapping programme is the airborne transient electromagnetic method, SkyTEM (Sørensen & Auken 2004), which is one of the new methods that has been developed to improve and optimise groundwater mapping. The first SkyTEM groundwater mapping project was carried out in 2003. Since then the SkyTEM method has been developed further and has proved faster and more powerful than the ground-based, single-site transient electromagnetic method, TEM, which was previously widely used. The SkyTEM method is used for mapping to a maximum depth of 250–300 m. Numerous buried valleys have been mapped in Denmark by the TEM method, in particular in the central parts of the country, where highly impermeable and low-resistive Palaeogene clay layers form the lower boundaries of the aquifers and the valleys are easily detected. At the end of 2008, TEM and SkyTEM data cover an area of more than 11 000 km<sup>2</sup> (Fig. 1A), which is about one quarter of the area of Denmark.

Electrical methods are used for near-surface mapping purposes. The pulled array continuous electrical sounding method (PACES; Sørensen 1996) has been extensively used to map layers within the upper 20–30 m. This method works well in combination with TEM measurements, and the combined methods provide data from the surface down to 200–300 m. This combination of methods has mainly been used in eastern Jylland and on Fyn. A total of around 9000 effective line kilometres of PACES data have been collected, corresponding to a coverage of more than 3000 km<sup>2</sup> (Fig. 1B).

The continuous vertical electrical sounding method (CVES; e.g. Dahlin 1996) is used in areas where it is unnecessary to map deeper layers, and where the subsurface resistivity values are too high for the SkyTEM method. About 4000 line kilometres have been collected, mainly in the central part of Jylland and on the eastern part of Sjælland (Fig. 1C).

The reflection seismic method is also of great value as a geophysical groundwater mapping tool, particularly following the development of a land-streamer and a new vibroseismic system (e.g. Vangkilde-Pedersen *et al.* 2006). Although the reflection seismic method is expensive, it can be successfully combined with SkyTEM measurements, and the decision about where to acquire seismic data can be based on the SkyTEM results (Jørgensen *et al.* 2003). Successful mapping of the outline of buried valleys and their internal structures has been based on the interpretations of seismic profiles; SkyTEM data do not allow such interpretations. The reflection seismic method has also been used successfully to map Palaeogene and Neogene sediments in the western part of Denmark (Rasmussen *et al.* 2007), where thick and extensive layers of sandy deposits constituting important aquifers are bounded by thinner layers of clayey deposits, and to map faults in Danian and Cretaceous limestone in the eastern part of Denmark. Around 1400 km of seismic lines have been collected, particularly in the western and central parts of Jylland (Fig. 1D).

Borehole logs are crucial for the geological and hydrological interpretation of boreholes. It is now common practise to log boreholes following survey drilling, and older water supply wells have also been logged. Particularly in areas with chalk and limestone or Neogene groundwater reservoirs log stratigraphy has provided valuable information. About 1500 boreholes have been logged.

## Administration of the geophysical data

The Groundwater Mapping Programme is split up into many smaller areas to ease the administrative handling and to be able to meet priority criteria. Careful and standardised treatment of data is required to ensure that the resulting 'patchwork' is of high and uniform quality and has no visible seams. Therefore, standards and guidelines are worked out for geophysical data acquisition, calibration of instruments, data processing, interpretation (e.g. HydroGeophysics Group 2007a) and geological modelling (Jørgensen *et al.* 2008).

Without a predefined system of archiving the geophysical data and modelling results, the data logistics of the groundwater mapping programme would be overwhelming. The national GEophysical Relation DATABASE (GERDA; <http://gerda.geus.dk>) hosted at the Geological Survey of Denmark and Greenland (GEUS), is used for archiving these geophysical data. The development of the database began more than ten years ago. The database contains geophysical data of various types such as Wenner profiles, Schlumberger soundings, pulled array continuous electrical soundings, continuous vertical electrical soundings and induced polarisation, transient electromagnetic data including the airborne SkyTEM data,

frequency domain electromagnetic data, reflection seismic profiles and borehole logs. Various kinds of 1-D models and 2-D models resulting from inversion of electrical and electromagnetic data are also saved, securing an immediate use of the results. All information about data acquisition, data processing and inversion can be stored, which facilitates reprocessing of data and makes the inversion and interpretation of data transparent.

GEUS also hosts another database (Jupiter; <http://jupiter.geus.dk>) for borehole data. Jupiter contains information on, for example, geological and lithological descriptions, groundwater level and water quality observations. Both the Jupiter and GERDA databases have web-based graphical user interfaces, where any user can search for and download data free of charge.

Geophysical data are handled from data processing to geological interpretation in an integrated system formed by the GERDA and the Jupiter databases and two software packages, the Aarhus Workbench and the Geoscene3D in combination with a geological model database hosted at GEUS (Fig. 2; Møller *et al.* in press). The Aarhus Workbench (HydroGeophysics Group 2007b) has modules for handling, processing, inverting, interpreting and visualising electrical and electromagnetic data, all combined on a common GIS platform and a common database. The Aarhus Workbench enables anybody to work with the geophysical data in the GERDA database without having to know the complicated data model of GERDA or to be able to carry out a database query. By using the GIS platform at the Aarhus Workbench it is easy to produce various types of maps compiled from the geophysical data.

The different maps are entered into the 3-D visualisation and modelling tool Geoscene3D (I-GIS, <http://www.i-gis.dk>) together with all the geophysical data stored in GERDA and the borehole information stored in Jupiter, and the geophysical data are ready to be used in the geological modelling process carried out in Geoscene3D.

An example of the strength of the integrated data handling system is illustrated for a  $50 \times 60 \text{ km}^2$  area in eastern Jylland (Fig. 3). Large parts of this area are covered by TEM soundings (*c.* 83 000 soundings), collected during more than 90 mapping campaigns (Fig. 3B) and with five different TEM methods (Fig. 3C) over a time span of more than ten years. Figure 3A shows a map of the surface of the deepest low-resistive model layer based on interpretation of all the TEM soundings in the area. The deepest low-resistive model layer represents Palaeogene clay deposits except in the north-eastern corner, where it represents salty pore water in Danian limestone. The most prominent features found in the area are a large number of buried valleys incised into the Palaeogene clay deposits. The buried valleys show no direct correlation to

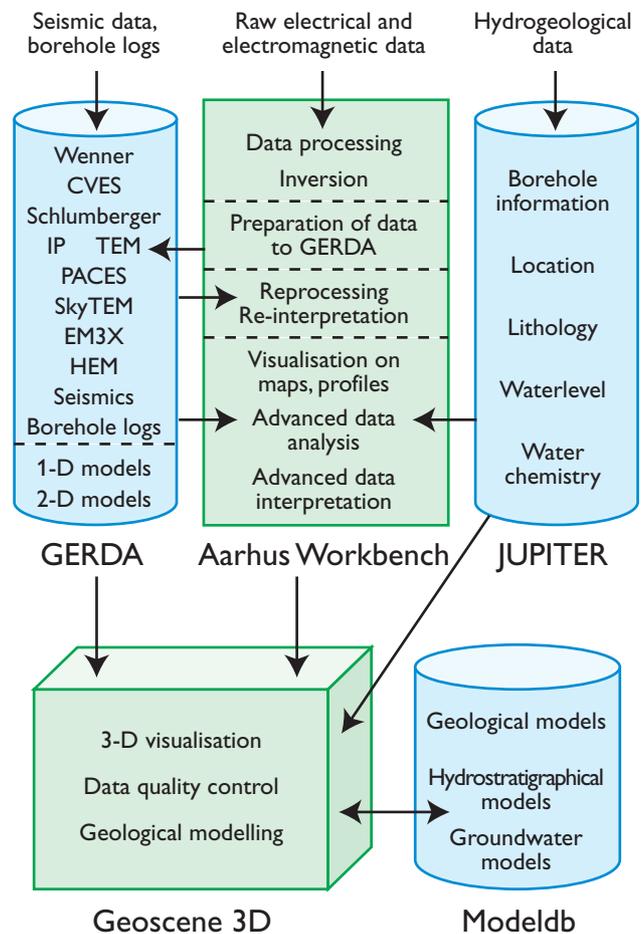


Fig. 2. Sketch of the integrated system of databases and program packages handling geophysical data and geological modelling. The arrows show the flow of data between the geophysical database GERDA, the borehole database Jupiter, the Aarhus Workbench program package, the Geoscene3D visualisation and modelling tool and the geological model database Modeldb.

the overall topography. Even though the data have been acquired by different companies, with different instruments and methods, and at different times, the data can be combined without showing any discrepancies at survey borders.

## Concluding remarks

Geophysical measurements play an important role in the National Groundwater Mapping Programme and have contributed significantly to the mapping of aquifers in Denmark. In heterogeneous regions the data density needs to be high in order to provide acceptable mapping results. Geophysical methods like TEM/SkyTEM and electrical methods can provide sufficient data density and reflection seismic profiles can resolve internal structures in specific areas in combination with detailed borehole information such as lithological descriptions, geophysical logs, data on water chem-

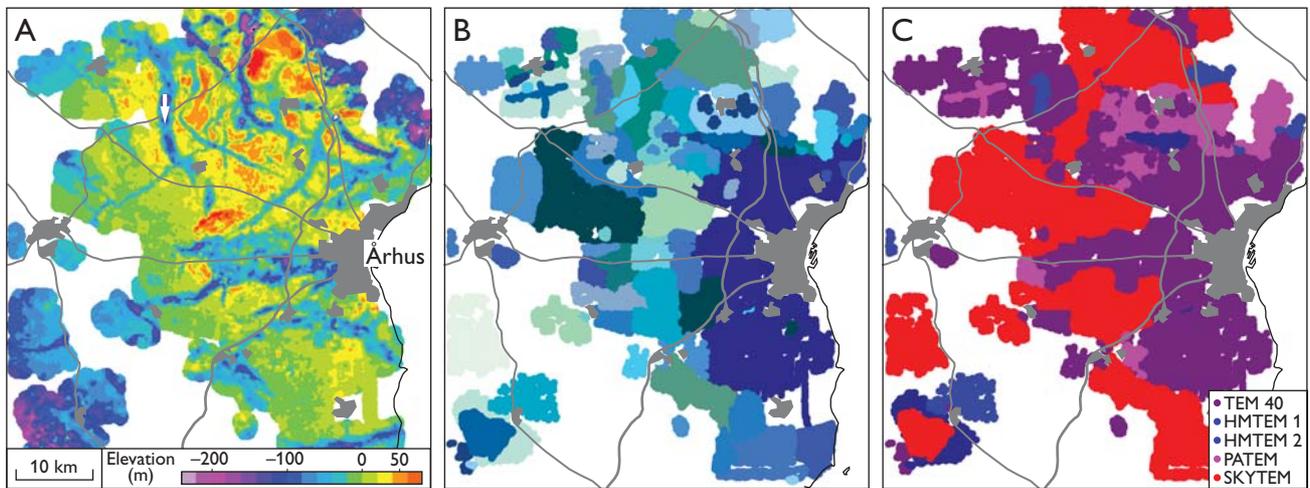


Fig. 3. Data coverage and results from an area in eastern Jylland. For location see Fig. 1. **A:** Map showing the elevation of the surface of the deepest low-resistive layer in the area relative to sea level. **B:** The data come from 94 different mapping projects (shown by different colours). **C:** Five different TEM methods were used to produce map A.

istry and hydraulic parameters. These data form the basis for detailed hydrogeological models. An integrated data handling system makes it possible to merge geophysical data acquired over long periods by different companies with different instruments. This is of great value for future mapping and administrative purposes.

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