

# Integrated management and utilization of hydrogeophysical data on a national scale

Ingelise Møller<sup>1\*</sup>, Verner H. Søndergaard<sup>1</sup>, Flemming Jørgensen<sup>1</sup>, Esben Auken<sup>2</sup> and Anders V. Christiansen<sup>2</sup>

<sup>1</sup> Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, 1350 Copenhagen K, Denmark

<sup>2</sup> The HydroGeophysics Group, Department of Earth Sciences, University of Aarhus, Høegh-Guldbergs Gade 2, 8000 Aarhus C, Denmark

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## ABSTRACT

Development of more time-efficient and airborne geophysical data acquisition systems during the past decades have made large-scale mapping attractive and affordable in the planning and administration of e.g., groundwater resources or raw material deposits. The handling and optimized use of large geophysical data sets covering large geographic areas requires a system that allows data to be easily stored, extracted, interpreted, combined and used one time after another with different purposes. Such an integrated system for management and utilization of hydrogeophysical data on a national scale has been developed during the past decade in Denmark.

This data handling system includes a comprehensive national geophysical data base (the GERDA data base), a national data base for borehole information (the Jupiter data base), a program package for processing, interpretation and visualization of electrical and electromagnetic data as well as preparation of these data for upload to the geophysical data base (the Aarhus Workbench) and finally a 3D visualization and modelling tool used for geological modelling and data quality control. The Aarhus Workbench program package allows visualization and analysis of subsets of data from the geophysical data base, which may include data from many individual mapping campaigns. The 3D visualization and modelling tool uses data from the geophysical and the borehole data bases directly; moreover, it handles maps and grids produced in the Aarhus Workbench.

The integrated system for management of hydrogeophysical data allows management of large amounts of data collected over several years in different mapping campaigns, of different consultant companies and with different geophysical methods and instrumentation. It is now used by all partners involved in the groundwater mapping in Denmark. The system promotes reuse of geophysical data and models in future mapping projects, as well as easing and promoting the use of geophysical data in the geological modelling. The integrated system secures transfer of documentation all the way from data acquisition over processing and inversion of the geophysical data to geological modelling through storage of data acquisition parameters, data processing parameters, inversion parameters and uncertainties on data and models in the geophysical data base.

The benefits of the large amount of geophysical data gathered in the national geophysical data base and utilized by the two program packages are invaluable for all future groundwater planning and administration.

## INTRODUCTION

Groundwater resource and vulnerability mapping is becoming more and more widespread and it has become a focus point in many countries around the world. Attention to this field is, of course, driven by the increasing pressure on the drinking water resources that stems from the dual forces of population

growth and water contamination; however, interest is also fuelled by the changing climate.

In Denmark, the water supply is decentralized and 99 per cent of the water supply is based on groundwater of a high natural quality. It is Danish policy to maintain groundwater of high quality for drinking water. Increasing problems with water quality in the 1990s due to urban development and contamination from industrial and agricultural sources made the Danish Government

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\* ilm@geus.dk

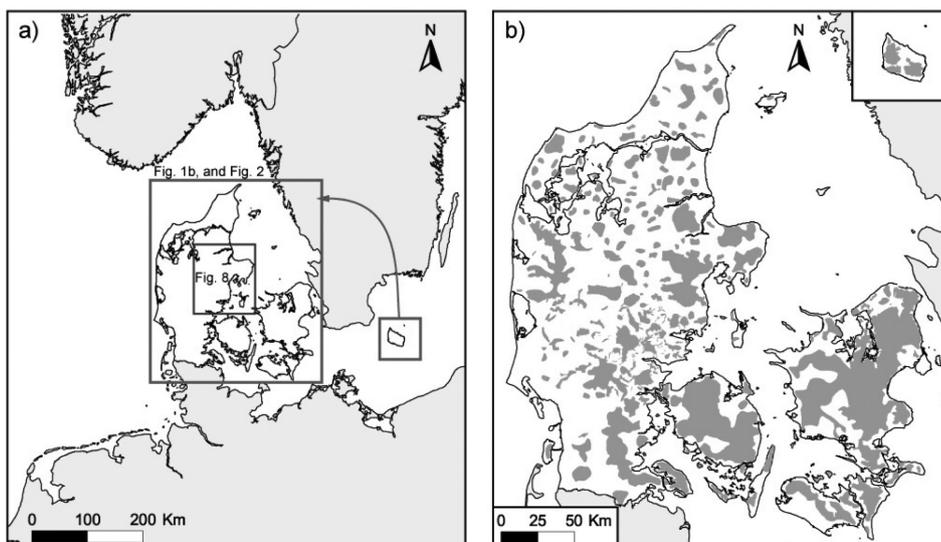


FIGURE 1

a) Denmark and the surrounding area with the extension of the maps displayed in b), Figs 2 and 8 marked as grey boxes.

b) Particularly valuable water abstraction areas.

launch an ambitious plan to significantly intensify the hydrogeological mapping to facilitate protection of national groundwater resources. In 1999 the National Groundwater Mapping Programme was initiated. The objective of the programme was to obtain a detailed description of the aquifers with respect to localization, extension, distribution and interconnection as well as their vulnerability against contaminants (Thomsen *et al.* 2004). The mapping programme now covers some 40 per cent of the area of Denmark designated as particularly valuable water abstraction areas (Fig. 1). The water consumers finance the mapping programme by paying 0.04 euros per m<sup>3</sup> consumed water. At the end of the programme in 2015, the total cost is estimated to be about 250 million euros.

The hydrogeological mapping programme involves the use of geophysical survey methods, survey drillings, well logging, water sampling and hydrological mapping as well as hydrogeological 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 geographic areas. The choice of geophysical methods depends on the geological setting of the aquifers. However, a combination of methods is typically used to cover both the shallow and deeper parts of the ground. Newly developed, efficient data acquisition systems are being intensively used, including, among others, the transient electromagnetic method (TEM), electrical methods and the reflection seismic method.

The programme is administered by seven local offices under the Ministry of Environment, even if most of the practical work is carried out by private consulting companies. The complete mapping programme is split up into many smaller surveys to ease its handling and to be able to meet priority criteria. Thus, careful and standardized treatment of data and results are required to make sure that the resulting 'patchwork' has no visible seams, so to ensure this and a high and a uniform quality, standards and guidelines are worked out. Standards and guide-

lines for the most intensively used geophysical methods have been produced first and calibration procedures have been established and, for the TEM method, applied to a test area to facilitate calibration of TEM data acquisition systems. This work is carried out by the Department of Earth Sciences at the University of Aarhus in cooperation with the authorities responsible for the mapping programme as well as with private consulting companies and the Geological Survey of Denmark and Greenland (GEUS).

Special, integrated management systems are required to manage the data of such a large and long-lasting mapping programme. It is important that data can be easily stored, extracted, interpreted, recombined and reused one time after another with different purposes. During the last decade, a system for handling and optimizing use of the large amounts of geophysical data covering large areas has been developed.

In this paper we present the integrated system for management of geophysical data in which the different system elements connect to and interact with each other in a transparent and intelligent manner. This system includes four elements: a comprehensive national data base for geophysical data (the GERDA data base), a national data base for various types of borehole information (the Jupiter data base), a program package, The Aarhus Workbench, for handling electrical and electromagnetic data and a 3D visualization and modelling tool for geological modelling and data quality control. The Aarhus Workbench has modules for processing, inversion, interpretation and visualization of electrical and electromagnetic data as well as preparation of these data for upload to the GERDA data base. The 3D visualization and modelling tool reads data directly from the GERDA and the Jupiter data bases and uses grids and maps compiled in the Aarhus Workbench.

We will illustrate how the system works through a case from a large geographic area with many data and different data types. The case shows the use of the GERDA data base and

how extracted data can be handled, managed and interpreted in the Aarhus Workbench and how they can be visualized in the 3D tool.

### GEOPHYSICAL METHODS USED IN THE HYDROGEOLOGICAL MAPPING

In Denmark, the aquifers of interest for drinking water purposes are found within the upper 250 m of the subsurface. They can be grouped into three main types: 1) in the western part of the country, extensive Quaternary and Pre-Quaternary sand deposits dominate, 2) in the central part, the most important groundwater resources are located in Quaternary sand deposits filled in deeply cut valley structures in Paleogene clay deposits and 3) in the northern and eastern part of the country, most of the important aquifers are related to limestone from Upper Cretaceous and Danian.

The most appropriate geophysical methods to be used are therefore considered to be electrical and electromagnetic meth-

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

The airborne TEM method, SkyTEM (Sørensen and Auken 2004), is one of the new methods that has been developed to improve and optimize groundwater mapping and the first SkyTEM groundwater mapping project was launched in 2003. During this five-year period, the SkyTEM method has been further developed and it has proved to be more useful than the ground-based single-site TEM surveys, which were widely used before the SkyTEM method was developed. SkyTEM is now the most commonly used geophysical method in the groundwater mapping programme in Denmark.

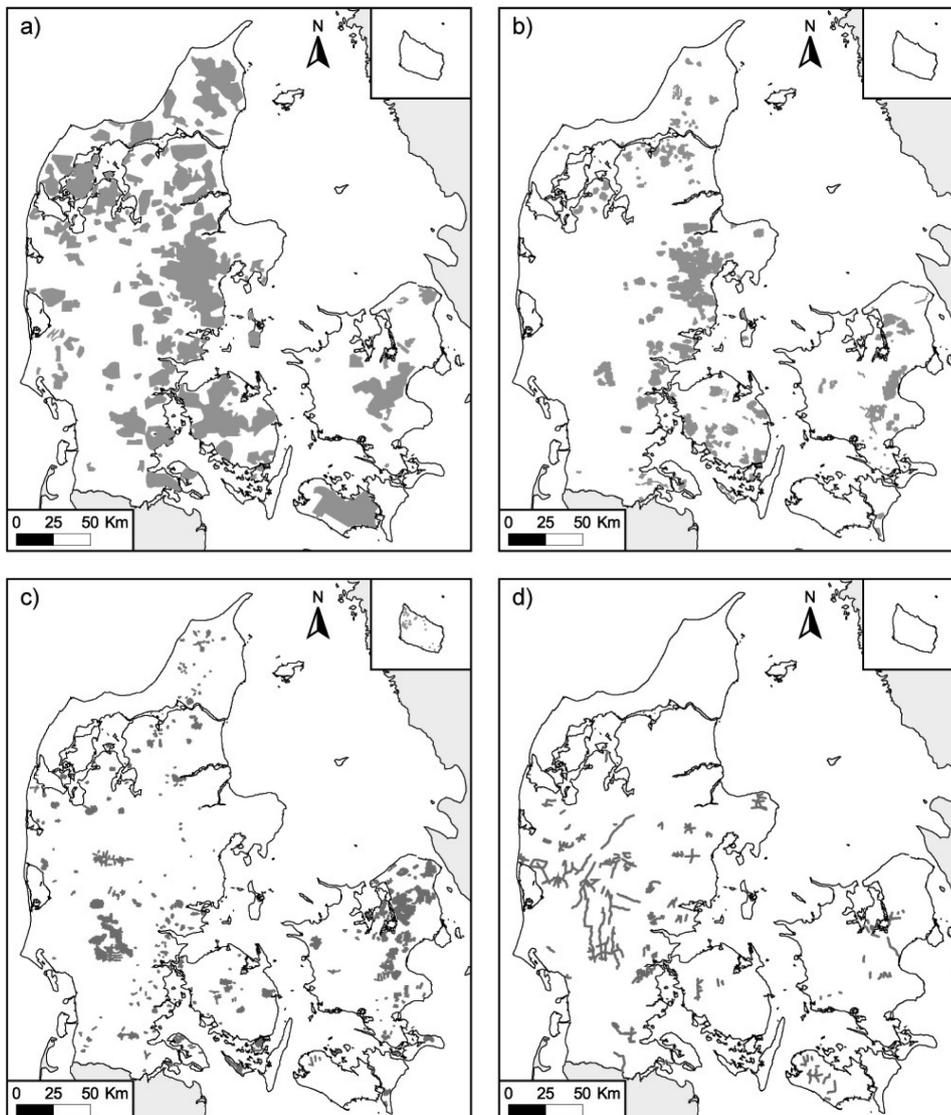


FIGURE 2  
Maps of collected data by the end of 2008. a) Areas with TEM and SkyTEM soundings, b) areas with PACES profiles, c) CVES profiles and d) seismic profiles. All data are or will be available in the GERDA data base.

TABLE 1

The amounts of geophysical data reported to the GERDA database by the end of 2008

Type of data	Amounts of data	Profiles lengths and/or area coverage	Amounts of related models
Wenner profiles	81,661 data points	1,900 line km	
Schlumberger soundings	31,979 soundings		The majority of the soundings are related to a 1D model
PACES profiles	968,846 data positions with a 3 point sounding (12%) or an 8 point sounding (82%)	9,117 effective line km (without holes) covering an area of more than 3,000 km <sup>2</sup>	The majority of the data are related to 1D models, typically results of 1D lateral constraint inversion, LCI.
CVES profiles	801,975 electrode positions, typically with a basic electrode spacing of 5 m resulting in 6,080,907 data points	3,961 line km	The data are related to 2D models and/or 1D LCI models.
TEM soundings and SkyTEM profiles	277,670 soundings of which 204,214 are SkyTEM*	A total area of 11,000 km <sup>2</sup> are mapped (incl. 2007 and 2008)	All data are related to various 1D models and the majority of the SkyTEM data are inverted using the LCI method.
Borehole logs	9,129 logging curves with 9,302,675 data points	1,475 boreholes	

\* A majority of the SkyTEM data collected in 2007 and 2008 still has to be reported to the GERDA data base, due to a long processing and interpretation process at the consultant companies.

The SkyTEM method is used for mapping to a maximum depth of 250–300 metres. Wide-spread systems of buried valleys have been mapped by the TEM method, especially where highly impermeable and low-resistivity Paleogene clay layers form the lower boundaries of the aquifers in the central areas 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. Thus, it works well combined with TEM measurements to obtain information right from the surface down to 200–300 metres.

The electrical method, the continuous vertical electrical sounding method, CVES (Dahlin 1996; Dahlin and Zhou 2006), is used in areas where there is no need for large mapping depths and where the subsurface resistivities are too high to be distinguished by the SkyTEM method. The CVES method is not as cost-effective as the above mentioned methods and it has therefore mainly been used for specific mapping purposes on a smaller scale.

Reflection seismic surveying is also of great value as a geophysical groundwater mapping tool, particularly after the introduction of a landstreamer vibroseismic system (Vangkilde-Pedersen *et al.* 2006). Although the reflection seismic method is rather cost intensive, it is often successfully combined with SkyTEM measurements. In this combination, the decision on the location of the seismic profiles relies on the SkyTEM survey

results (Jørgensen *et al.* 2003). Information from seismic profiles has successfully been used to map buried valley boundaries and to further describe internal structures in buried valleys that could not be revealed by the interpretation of SkyTEM measurements. Reflection seismic profiling is, furthermore, successfully used to map Paleogene and Neogene sediments in the western part of Denmark (Rasmussen *et al.* 2007), where extensive layers of sandy deposits constituting major aquifers are bounded by thinner layers of clayey deposits.

Figure 2 displays the amount of collected data from the mostly used geophysical methods in the hydrogeological mapping in Denmark by the end of 2008. The TEM and SkyTEM data cover an area of about 11 000 km<sup>2</sup> (Fig. 2a), which is about one quarter of the Danish area. About 9,000 effective line km of PACES data have been collected in total, which yields a coverage of more than 3,000 km<sup>2</sup> (Fig. 2b). The CVES data have been collected along c. 4,000 line km in total (Fig. 2c). The seismic method is typically used in the western and central parts of Jutland and about 1,400 km of seismic lines have been collected (Fig. 2d).

The majority of the hydrogeophysical data collected in the groundwater mapping have been reported to the GERDA data base. This includes not only the above mentioned data but also geophysical borehole logs from about 1,500 boreholes and older electrical Wenner profiles and Schlumberger soundings acquired in raw material mapping and hydrogeological mapping (Table 1).

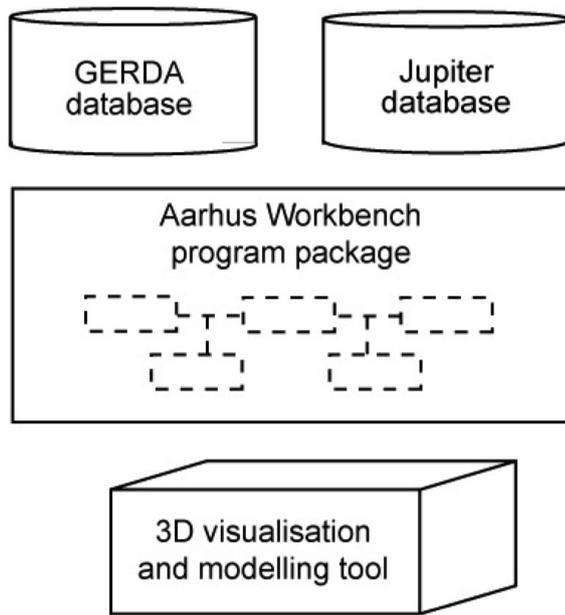


FIGURE 3 Sketch of the four elements in the system: the data base for geophysical data, the GERDA, the data base for borehole information, the Jupiter, the data processing, interpretation and visualization program package, The Aarhus Workbench and the 3D visualization and modelling tool.

**ELEMENTS IN THE INTEGRATED MANAGEMENT SYSTEM**

The integrated system for management of hydrogeophysical data consists in a comprehensive data base for geophysical data (the GERDA data base), a data base for various types of information from boreholes (the Jupiter data base), a program package for processing, interpretation and visualization of electrical and electromagnetic data as well as preparation of data for upload to the GERDA data base (the Aarhus Workbench) and, finally, a 3D visualization and modelling tool is used for geological modelling and data quality control (GeoScene3D). Figure 3 sketches the four elements contained in the system. In the following sections, the individual elements of the integrated system are described.

**The GERDA data base**

The GERDA (GEophysical Relation DATABASE) data base is the national data base for shallow geophysical data. The data base is Oracle-based and hosted by GEUS. The development of the GERDA data base was initiated in 1996–97 by a group of people from the Danish Forest and Nature Agency, the former County of Aarhus, Department of Earth Sciences, University of Aarhus and GEUS who were concerned about securing the increasing amount of geophysical data from finished and ongoing groundwater mapping and mapping for raw materials. The development was at first financed jointly by the Danish Forest and Nature

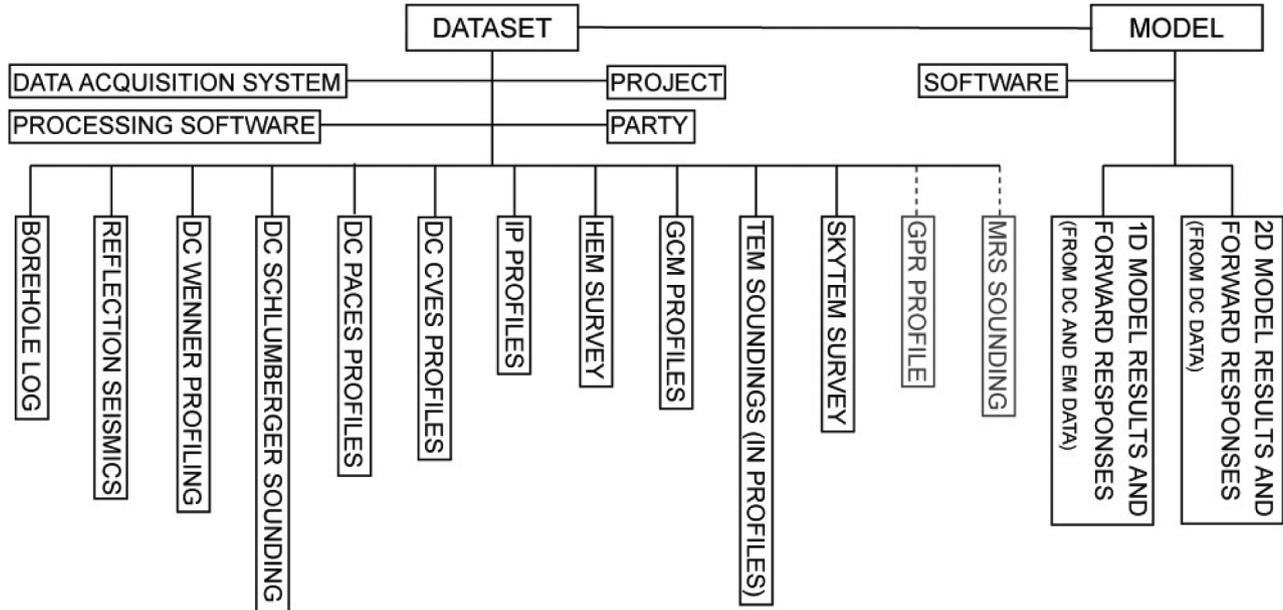


FIGURE 4 Principal sketch of the tables in the data model of the GERDA data base. General metadata on a data set are stored in the data set table, information on data acquisition systems, software, the related project and the parties involved are stored in the respective tables. The specific metadata and the data for each data type are stored in tables carrying the name of the data type. The data base supports data from borehole logging, the reflection seismic method, various electrical (DC) methods including induced polarization (IP) profiles, helicopter frequency domain electromagnetic methods (HEM), ground-based frequency domain electromagnetic methods (GCM), transient electromagnetic method (TEM) and an airborne TEM method (SKYTEM). The data base will soon be expanded with ground penetrating radar (GPR) and magnetic resonance soundings (MRS).

Agency and GEUS. Later on, users and data contributors supported the daily service and developments of the data base.

The design of the data model in the data base was devised in close cooperation between geophysicists and data base developers and the geophysicists included both specialists from private consulting companies, the University of Aarhus and GEUS. The fundamental design of the data model in the data base is static, meaning that all tables and fields therein are designated to specific data, metadata and parameters for specific methods or field techniques. All fields and tables are documented in detail. The data structure for each data type reflects the way the data have been acquired in the field and how the acquisition procedure is carried out.

The GERDA data base is continuously being developed. At the moment, the data base supports various electrical and electromagnetic (EM) data, reflection seismic data and borehole logging data (Fig. 4). In the near future, the data base will be expanded with magnetic resonance soundings and ground penetrating radar. For data types requiring advanced processing, e.g., TEM, SkyTEM and PACES data, both raw data and processed data are stored. Various kinds of 1D models and 2D models resulting from inversion of electrical and electromagnetic data are also supported, which secures immediate use of the data results. All information about data acquisition, data processing and inversion can be stored, which makes data reprocessing possible and the inversion and interpretation of data transparent. Furthermore, uncertainties about data and model parameters are stored. One of the very fundamental design ideas of the data base is that data are stored for all kinds of future use, known as well as unknown. All information on the data acquisition therefore has to be stored, which enables future processing and inversion of the data through application of improved data processing and inversion techniques.

The GERDA data base has a web page (<http://gerda.geus.dk>) with information on the data base and documentation of the entire data structure and all records in the data base. The system has data upload facilities and search and download pages. The majority of the data are exchanged with the GERDA data base in the PCGerda data base format, which is very similar to the GERDA data base structure. The PCGerda format is defined for Access, Interbase (Firebird) and SQL-server. The borehole logging data are imported in LAS files and the reflection seismic data in Seg-Y files. The web page has special upload pages for these data and specific requirements must be met for certain parameters to be present in the LAS files and Seg-Y files. Search for data (subsets of the data base) can be performed in a map view and in a query form, respectively. The selected data can thereafter be downloaded and used in different programs designed to read the PCGerda format. Access to data is open and data can be downloaded for free.

### The Jupiter data base

In 1926 a well data archive for water supply-related wells was founded at the Danish Geological Survey as a result of the first legislation passed in 1926 on groundwater data, which required

that all information obtained by drilling water supply-related wells should be reported. Later on, other types of shallow boreholes, e.g., raw material drillings and geotechnical boreholes, were also required to be reported to the archive. The borehole information is now registered in the national data base, Jupiter, hosted by GEUS.

The data base contains information from more than 240 000 boreholes. For each borehole, basic information on drilling location, time, depth and method, etc., is registered. During the drilling process, the drilling company registers, e.g., lithology, boundaries where the lithology changes and special incidents and borehole samples are collected for detailed description. Afterwards, the drilling company reports this information to the Jupiter data base and sends the borehole samples to GEUS. Geologists then make detailed lithological descriptions, geological interpretations and register this information in the Jupiter data base. Furthermore, for water supply wells, the development of the borehole with, e.g., location of screens is reported and pump tests, water level fluctuations and water chemistry are registered.

Information on the Jupiter data base can be found on its web page (<http://jupiter.geus.dk>), where search and download of data also takes place. Data can be accessed on an open basis and can be downloaded for free.

### The Aarhus Workbench program package

Since 2000 the Aarhus Workbench (Aarhus Geophysics 2008) has been under steady development to be able to meet the requirement for a single software package for handling, processing, inversion and visualization of electrical and electromagnetic data on a common geographical information system (GIS) platform. The program package also allows comparison of geological and geophysical data on cross-sections.

One of the very basic facilities in the Aarhus Workbench is the built-in storage of all parameter settings used in the visualization of data and models on maps and cross-sections, the processing and inversion procedures, etc. When geophysical data form the basis of decisions, neither data quality nor the subsequent presentation of results should be open to questions. This is of great importance in the public administration where many interests have to be considered when large infrastructure developments or changes are being planned. Also, when consulting companies deliver data processing and inversion results to the public administration, the Workbench meets requirements for quality control on the delivered products because it allows easy open access to all parameters.

The Workbench uses an open-source client server data base (Firebird 2008) to manage data and settings. The benefits of using a data base compared with flat ASCII column files should not be underestimated. Firstly, user-handled input/output is nearly eliminated, minimizing the risk of errors. Secondly, data are stored in the well-described and documented PCGerda format, which is designed for both exchange and storage of data.

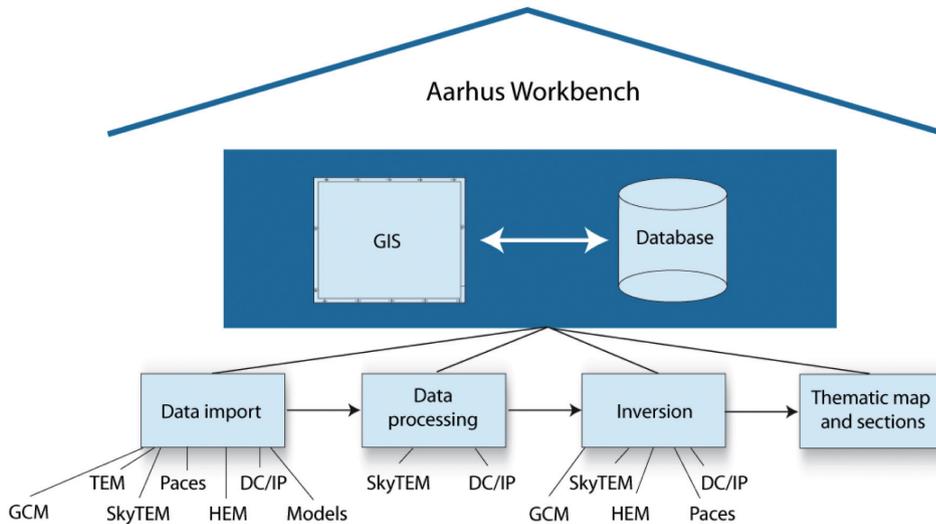


FIGURE 5

Sketch of the modular structure of the Aarhus Workbench. Common for the program package are the GIS and the data management platforms. Both are used by a number of other modules that handle data import (from instrument-specific formats to the data base), data processing, inversion and visualization on maps or cross-sections. Each module supports a number of different data types.

The Aarhus Workbench is best described as a platform gathering a number of different data handling methods and visualization modules under the same roof. This is illustrated in Fig. 5. The GIS and the data management modules are used by the other modules for data import, data processing, inversion and visualization on maps or cross-sections. The importer modules transform instrument-specific data formats to the data base format. Most of these files are proprietary ASCII files that to different degrees document the measurement process and the data. Currently, importer modules are developed for ground-based TEM, PACES, CVES and IP (DC/IP), ground conductivity meters (GCM), SkyTEM and helicopter frequency domain EM (HEM). Finally, if data are inverted using external inversion algorithms, the models can be imported and visualized in the Workbench.

The inversion module of the Aarhus Workbench implements both a user interface to the underlying inversion package (Christiansen and Auken 2008) and a graphical system for evaluation of the output from the inversion. Since the module is designed for large-scale surveys with hundred of thousands of models, inversion jobs are created within the Workbench but actually executed in a batch program that handles multiple threads and imports the results to the data base as they are being calculated. If surveys are split into parts, more than one computer can work on the data in parallel, adding the results to the common data base located on a network. The inversion package implements laterally constrained inversion (Auken *et al.* 2005) and spatially constrained inversion (Viezzoli *et al.* 2008). The corresponding user interface allows the user to build starting models and add *a priori* information on any inversion parameter – layer resistivity, layer thickness, layer depth and (in case of airborne data) altitude, pitch, roll, etc.

Inversion output can be inspected using a combination of profile plots showing models, data and forward data and sounding curves. A screen dump with SkyTEM data is shown in Fig. 6. The inversion explorer summarizes key parameters in a numeri-

cal format, while the profile windows show models and input/output flight altitude. At any point, the model and the sounding curve can be plotted and the point is interactively linked to the GIS map in the background.

Thematic maps showing single-layer properties or average resistivity as a function of depth or elevation can be created from the output of the inversion. These thematic maps are contoured using kriging or inverse distance interpolation and added to the GIS map. It is also possible to create thematic maps of layer uncertainties and inversion parameters like altitude, roll and pitch. From the GIS map, profiles can be drawn and inversion outputs can be projected onto these cross-sections. Examples are shown in the case history in the following section.

### 3D visualization and modelling

To enable full possibilities for data quality control and further use of the geophysical data, a 3D visualization and modelling tool has been developed. This tool called 'GeoScene 3D' (I-GIS 2008) has been developed in cooperation with the groundwater authorities, GEUS and the private company I-GIS. It was originally developed for visualization of the geophysical data and borehole data in 3D for public purposes. In this way it became possible to show the mapping results for decision makers like politicians but also for other related partners like water board members, consumers, etc. In the meantime, it turned out that 3D visualization of the data was also useful for data quality control because poor data within large data sets were rapidly detected owing to straightforward spatial comparison. The advantages of 3D visualization also provided an excellent basis for geological interpretation and construction of geological and hydrostratigraphical models. The tool has therefore been further developed to handle these topics.

The 3D visualization and modelling tool contains three main elements: a GIS tool, a cross-section tool and a 3D visualization scene. The GIS tool is used for geographical management, visualization of maps, position of data, cross-sections, etc. It is

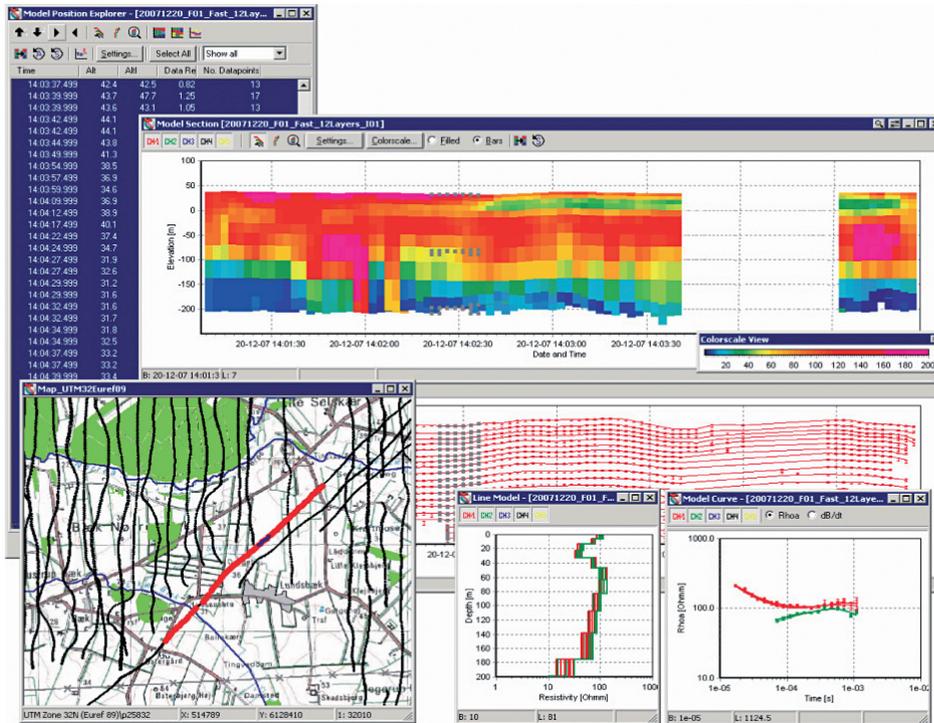


FIGURE 6

Screen dump of the windows used to inspect the output from the inversion process. The windows shown are an inversion explorer (upper left), section plot of models (top), data and forward data (middle, behind), GIS map (left, red points show the location of the soundings shown in the section plot) and, finally, inverted models and data curve plots (lower right, grey dots in the section plots show location of the models and data curve plots). The blank area of the model plot indicates data removed due to coupling to man-made structures.

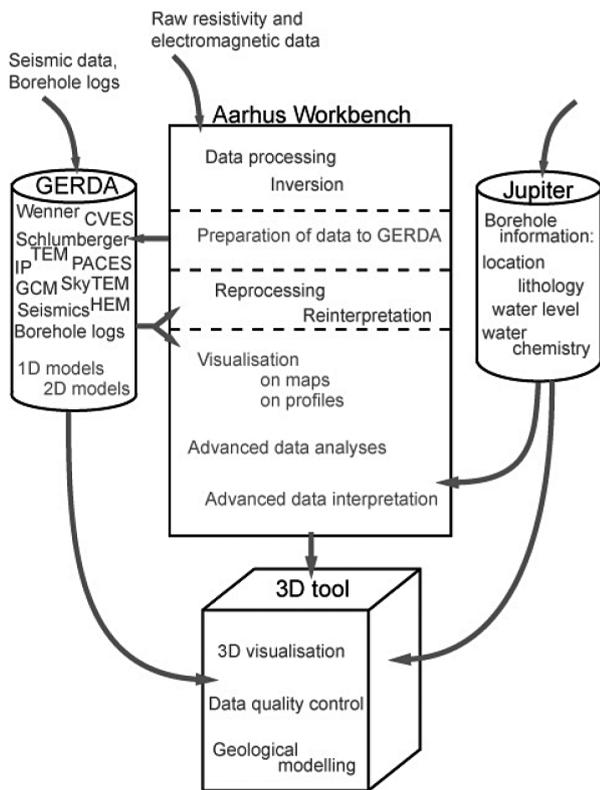


FIGURE 7 Sketch of data flow between the geophysical data base GERDA, the Jupiter data base, the Aarhus Workbench and the 3D visualization and modelling tool.

designed to control a project area larger than 50 000 km<sup>2</sup>. Once the project area has been defined, a sub area to be visualized in the 3D scene is selected. The position and size of this 3D scene is managed from the GIS tool during the visualization and modelling process.

The cross-section tool is used to show the subsurface in vertical 2D sections, whereas the 3D scene is used for the 3D visualization. All types of data can be shown on cross-sections and in the 3D scene. Also, geophysical maps and different kinds of grids produced in the Aarhus Workbench can be presented here.

Geological modelling is directly and interactively carried out in all three environments. The modelling tool meets the guidelines set out in a newly released handbook for the construction of geological models in Denmark (Jørgensen *et al.* 2008) and future models will, to a certain degree, be standardized, especially regarding data formats. This enables all geological and hydrostratigraphical models to be collected in a national data base of models.

**Data flow**

There are three main pathways for the collected data to pass through the system of tools and data bases (Fig. 7). These three main data flow pathways are described in the following:

- Seismic data and borehole logging data, which are not handled in the Aarhus Workbench, are directly uploaded to the GERDA data base. From here they can be extracted in selected subsets to be visualized and used for geological modelling in the 3D visualization and modelling tool.
- Electrical and electromagnetic raw data are processed and inverted in the Aarhus Workbench and subsequently uploaded

to the GERDA data base. As part of the geophysical data base, the data are ready for use; e.g., for geological interpretation, for groundwater management purposes. Subsets of the GERDA data base that may contain data sets from different field surveys and mapping projects can be downloaded and used directly in the 3D visualization and modelling tool. In the Aarhus Workbench, the downloaded data and models from GERDA can be used to produce different kinds of geophysical grids and maps; for instance, average resistivity maps and elevation maps of selected model layers, etc. Further interpretation and advanced data analysis can be compiled in the Aarhus Workbench and at each step the produced maps can be transferred to the modelling process in the 3D tool. In addition, data can be re-inverted or even re-processed before or within the process of interpretation and data analysis. After having finished this process, the data is again uploaded to GERDA to be replaced or supplemented with the original data.

- Selected subsets of the Jupiter data base are directly used for visualization in the Aarhus Workbench as well as in the 3D visualization and modelling tool.

### CASE HISTORY

In the following, the integrated use of the individual elements described above will be illustrated by a case history that will show how large amounts of hydrogeophysical data can be utilized and managed. Only a few aspects of the system can be discussed here and attention will therefore be given to the most important parts of the system.

To illustrate central mapping procedures, an area of  $50 \times 60 \text{ km}^2$  situated around the city of Aarhus in the central part of Denmark will be presented in the case history (Fig. 8). The topography of the area varies generally quite gently with elevations ranging from sea level to about 100 m above sea level except in a few hilly areas with elevations up to about 170 m. The most important aquifers of this area are located among Quaternary deposits mainly found in buried valleys. With a thickness between 10–200 m, the Quaternary deposits rest upon Danian limestone in the north-eastern part of the area, Paleogene clay in the central part and Neogene sand and clay in the south-eastern part of the area.

As the aim of the hydrogeological mapping is to locate aquifers within a heterogeneous geology, it is important to choose the right combination of mapping methods in order to obtain a sufficiently dense data coverage of the area. The knowledge about geology derived from existing boreholes is important but too sparse to describe the geological structures in sufficient detail to model the hydrogeology in the area. The choice of geophysical methods thus has to meet the need for dense data coverage. The chosen methods must also be able to resolve the geological structures in the survey area. Electrical and electromagnetic measurements meet these requirements because they can resolve the resistivity contrasts between sandy aquifers and the surrounding Quaternary and Paleogene clay sediments.

Electrical and electromagnetic methods have been intensively used in the case study area during a mapping period that has spanned almost 10 years. During this period, both methods have been continuously developed and geophysical data acquired with different versions of equipments are combined to produce a complete picture of the subsurface. This combination of data can only be successfully handled because there has been general agreement between all participants to meet particular standards for performing the measurements, calibrating the instruments and for processing and interpreting the data. Furthermore, without the predefined way of archiving the data and the models in the GERDA data base the logistics would have been overwhelming.

Due to different needs and priority plans within the area, the mapping has been performed in a stepwise manner, i.e., in many smaller parts during the past ten years. The data management system must therefore address the challenges of combining measurements and results from several smaller areas measured with different instruments at different times and developed to different degrees.

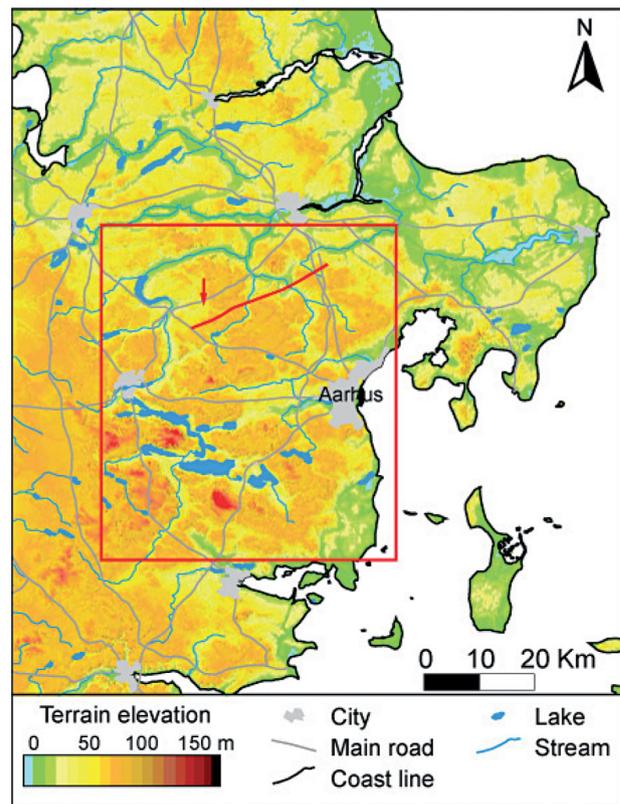


FIGURE 8

Location of the study area (marked with the red box) in the surroundings of the city of Aarhus in the central part of Denmark. A colour shaded digital terrain model (Copyright KMS) shows general topographic variations between sea level and elevations of c. 100 m above sea level. The red line marks the location of the cross-section displayed in Fig. 11 and the red arrow marks the view direction in Fig. 12.

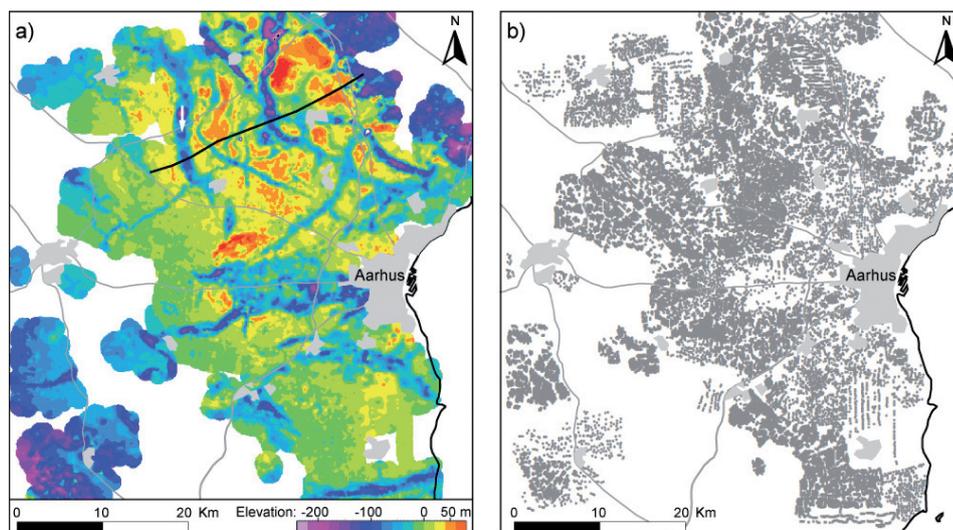


FIGURE 9

a) Map based on TEM data showing the elevation of the top of the deepest low-resistive layer in the area relative to sea level. b) The same area with all ~83,000 TEM soundings included. The black line and the white arrow in (a) mark the location of the cross-section in Fig. 11 and the view direction in Fig. 12, respectively.

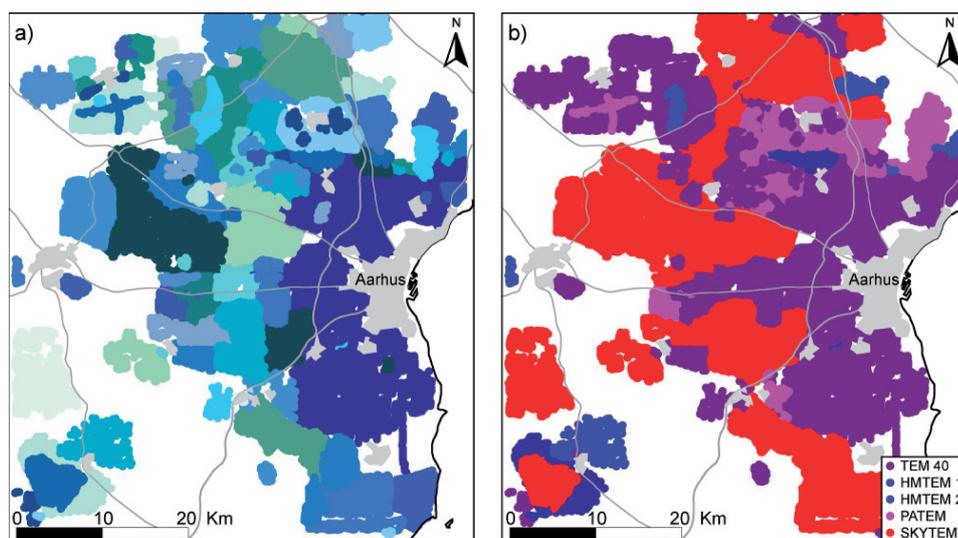


FIGURE 10

Maps displaying that data a) from 94 different mapping projects and b) collected with 5 different kinds of TEM equipment are used to produce the map in Fig. 9(a). In b) the TEM 40 is conventional ground-based TEM collected in a 40-by-40-m loop, HMTEM1 and HMTEM2 are ground-based TEM systems developed to achieve deeper penetration than the TEM 40 (Sørensen *et al.* 2005), PATEM is a ground-based mobile TEM system (Sørensen *et al.* 2005) and SKYTEM is the airborne TEM method, SkyTEM.

During the mapping period of this area, the data have been successively stored after collection, processing and interpretation. Data can at any time be downloaded from the GERDA data base and used independently of which mapping campaign they originally belonged to and without having to address issues of data validity. The downloaded data and their interpreted models can be immediately visualized and a suite of different data analyses and presentations can be created in the Aarhus Workbench.

To illustrate how in spite of being collected by different companies with different instruments and at different times the data can be combined without showing any discrepancies at mapping borders, Fig. 9(a) displays a map produced in the Aarhus Workbench. The map shows the surface of the deepest low-resistive model layer in the area based on the interpretation of all TEM soundings. This low-resistive model layer represents Paleogene clay deposits except in the very north-eastern corner, where it represents saline pore water in Danian limestone. The most prominent features found in

the area are a large number of buried valleys incised in the Paleogene clay and the buried valleys show no direct correlation to the overall topography in the area (Fig. 8). The data density in the area is high as illustrated in the map in Fig. 9(b).

As already mentioned, the TEM measurements used to create the map in Fig. 9(a) have been gathered during a number of different mapping campaigns; in fact 94 mapping campaigns during a ten year time period, as illustrated on the map in Fig. 10(a). Furthermore, the TEM data have been collected with five different types of TEM methods of which four were developed during the ten-year period (Fig. 10b). Quite remarkably, neither the many mapping campaigns nor the different types of TEM methods introduced discontinuities or other artefacts in the overall picture of the buried valleys in Fig. 9(a).

Cross-sections through the area can easily be created in the Aarhus Workbench as exemplified in Fig. 11, where interpreted models of TEM soundings are visualized. The cross-section ori-

ented WSW-ENE in the northern part of the area displays several buried valleys incised in low-resistive Paleogene clay. Borehole information can be included in the visualization of the geophysical data in order to facilitate and further improve the interpretation of the geophysical data in terms of reliable geology.

When the interpretation and different kinds of visualization of the geophysical data have been completed in the Workbench, the results will normally be an input of major importance to a geo-

logical model and a groundwater model for the mapped area. The geological modelling procedure can be carried out by using the GeoScene3D tool, where interpretations of geophysical data from the Aarhus Workbench and the GERDA data base can be combined with other information such as borehole information, water analyses, etc., from the Jupiter data base.

Figure 12 shows how some of the TEM results can be visualized and used, when creating a geological model. The 3D model

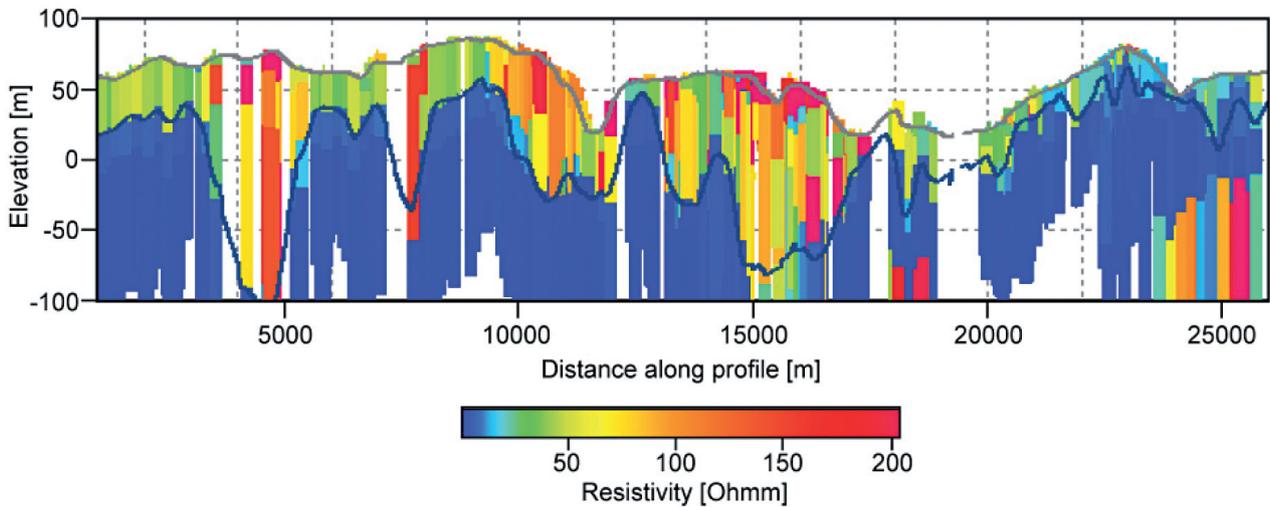


FIGURE 11

Cross-section showing how interpreted TEM-sounding models can be visualized in the Aarhus Workbench. Here the cross-section displays several buried valleys (red/orange part of the colour scale). The position of cross-section is shown in Figs 8 and 9(a), where the buried valleys are clearly seen. Note that the buried valleys show no direct correlation to the overall topography.

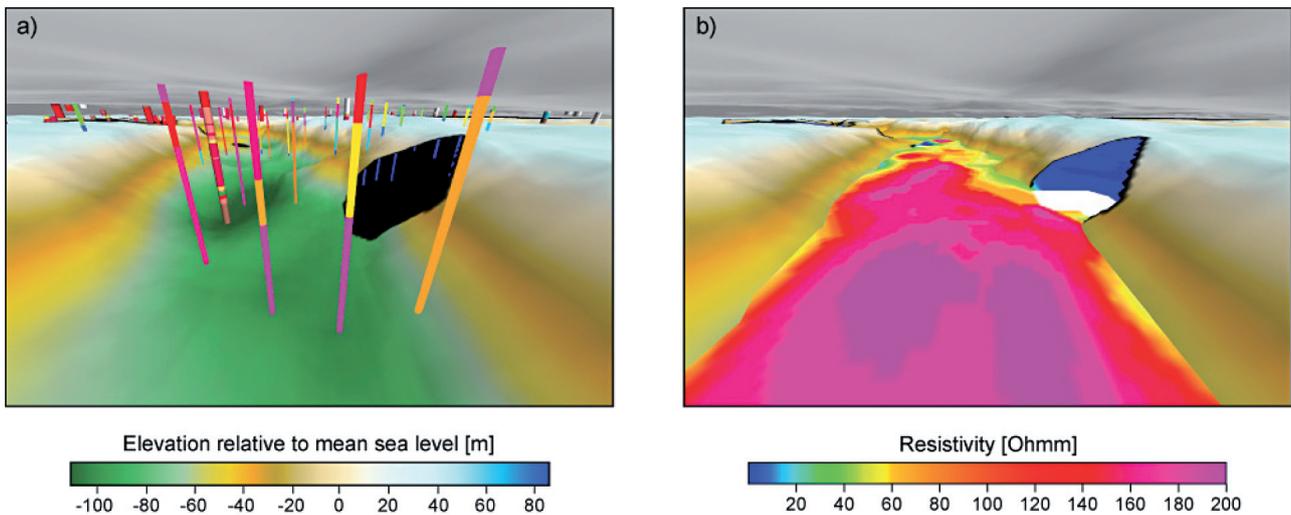


FIGURE 12

3D model/view of a buried valley in the study area (see location in Figs 8 and 9a). The valley is here shaped in the surface of the deepest low-resistive layer of the interpreted models of the TEM soundings. The view of the buried valley is seen from a point about 20 m below terrain surface and the grey shades in the top of the view is the terrain surface seen from underground. In the right-hand side of the valley, a hole is cut in the 'valley surface'. In a), thin cylinders show the interpreted models of the TEM soundings colour-coded using the shown resistivity colour scale. The thick cylinders are boreholes, where red and yellow colours indicate sandy material and brown colours indicate clay till. In b), a horizontal surface displays the average resistivity calculated from the TEM models at the level of 55 m below sea level.

view (Fig. 12) displays the surface of the deepest low-resistive layer of the interpreted models of the TEM soundings at a location in the study area where a wide buried valley is incised into the low-resistive layer (Fig. 9a). An interpretation of the type of material that is filling the buried valley can, for instance, be carried out either based on a display of each individual interpreted model of the TEM soundings and boreholes (Fig. 12a) or on a display of surfaces of average resistivity calculated from the TEM models at specific levels (Fig. 12b). The model of the TEM soundings and the boreholes as well as the resistivity surface show that the valley here is generally filled with deposits of high resistivities, most likely sandy deposits constituting a potential aquifer.

At this stage, the large amount of geophysical data and new boreholes in the area are being used in combination with all other sorts of relevant data in an effort to create a geological model and a groundwater model. The integrated data handling system has proven its great advantage in the modelling process in this area. The heterogeneous geology with a very detailed network of buried valleys holding the most important aquifers in the area requires data handling systems, where large amounts of different kinds of information can be combined, interpreted and visualized in order to meet modern society's groundwater management requirements.

## DISCUSSION AND CONCLUSIONS

To our knowledge, the integrated system for management of geophysical data on a national scale is rather unique. The development of the integrated system is promoted owing to the manner in which the National Groundwater Mapping Programme in Denmark is organized. Thus many partners are involved: central government that administers the programme, private consulting companies carrying out the main part of the work, the University and GEUS who are responsible for ongoing developments as well as the drawing up of standards and guidelines. With so many partners involved, standards and guidelines to ensure a high and uniform quality as well as easy exchange of data are required. The integrated system helps to ensure both.

The geophysical data base GERDA is, as far as we know, one of the most comprehensive national data bases in the world. It allows its users to store all information on field procedures, instruments deployed, data acquisition parameters, processing parameters, uncertainties on data, inverted models, model constraints and uncertainties on the model parameters. Typically, national geophysical data bases contain metadata on geophysical surveys about how and where the surveys have been carried out, perhaps combined with an enquiry form for data, e.g., the geophysical part of the British GeoIndex hosted by the British Geological Survey (British Geological Survey 2008). A few countries have geophysical data bases that are more advanced and where geophysical data can be downloaded directly from the data base. Examples are the Geophysical Data Centre, hosted by the Natural Resources Canada (Natural Resources Canada 2008)

and the Geophysics Information System Germany 2003 hosted by the Leibniz Institute for Applied Geophysics (Leibniz Institute for Applied Geophysics 2008).

The comprehensive amount of information stored in the GERDA data base can be seen as an important means of quality assurance of geophysical data and it ensures transparency of data acquisition, data processing and data interpretation. The comprehensive information on data acquisition also ensures that in the future data can be re-processed and re-interpreted, if better procedures are developed.

Because of its large volume and its complex structure, the GERDA data base is not particularly user-friendly on its own. The GIS platform in the Workbench used for visualization of the geophysical data in maps and cross-sections and the 3D visualization and modelling tool have therefore been developed to enable anybody to use the data and the models in the GERDA data base without having knowledge about the rather complicated data base structure and without being able to perform a query in the data base.

However, the easy access to and use of the geophysical data and their interpreted models through the integrated system can lead to misinterpretation and misuse by the geological modeller, if the geological modeller is unaware of the pitfalls in the use of the geophysical data and the models. Attention must therefore be paid to both general and system-dependent pitfalls. General pitfalls are, for instance, related to the non-uniqueness and the inconsistency in the data, leading to a variety of models that can fit the data. System dependent pitfalls build partly on the general pitfalls. Thus, subjective criteria adopted by the geophysical data interpreter may determine what is 'the best model', which is then reported to the GERDA data base. Later on, the geological modeller using the models has to judge, if the geophysical data interpreter actually did make 'the right choice'.

The possible pitfalls in using the integrated system for management of geophysical data should not be underestimated. Even so, the benefits of the system are invaluable:

- The integrated system enables us to handle large amounts of data collected over several years in different mapping campaigns with different consultant companies and with different geophysical methods and instrumentations. It also encourages re-use of geophysical data and models in future mapping projects.
- The integrated system secures transfer of documentation all the way from data acquisition over processing and inversion of the geophysical data to geological modelling through the storage of data acquisition parameters, uncertainties on data and model parameter as well as inversion parameters in the GERDA data base.
- The integrated system eases and encourages the use of geophysical data in the geological modelling.

The benefits of the large amount of geophysical data gathered in the GERDA data base and utilized by the Aarhus Workbench are invaluable for all future groundwater planning and administration.

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