Integrated use of geophysics, drillings, logs and geochemistry in large scale groundwater mapping.

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Summary

The aim of this abstract is to give a short description of the essential ideas of the Danish national strategy concerning groundwater mapping.

Emphasis will be put on a description of the advantages obtained by combining acquirement of spatially dense geophysical data covering large areas with information from an optimum number of new investigation boreholes, existing boreholes, logs and water samples to get an integrated and detailed description of the groundwater resources and their vulnerability (Thomsen et al., 2004).

The national mapping project was initiated in 1999. Development of more time efficient and airborne geophysical data acquisition platforms (e.g. SkyTEM) have since then made large-scale mapping even more attractive and affordable in the planning and administration of groundwater resources.

The handling and optimized use of huge amounts of geophysical data covering large areas, however has required a comprehensive database, where data can easily be stored, documented, extracted, interpreted, recombined and reused one time after the other. After a hard startup where existing data had to be reported to the new system and efficient software was developed, the database has now become the tool for interpretation, data analysis and data exchange between partners.

In the presentation the above mentioned issues with focus on geophysical aspects will be illustrated by examples from different actual mapping projects.

Introduction

The objective of the groundwater mapping project is to get a well described picture of the aquifers with respect to localization, distribution, extension, interconnection etc. and to prepare groundwater vulnerability maps. These maps are used by the authorities and the water works to establish site-specific groundwater protection zones in order to minimize future groundwater contamination.

The water supply in Denmark is decentralized. 99% of the water supply is based on groundwater of a high natural quality. The groundwater resources are mainly located in Quaternary sands, Tertiary sands and limestone.

Contamination from urban development as well as industrial and agricultural sources however imposes increasing threats to the groundwater resources. At the end of 1998 it was therefore decided by the Government to launch a spatially dense hydro-geological mapping program within the 37% of the area of Denmark designated as particularly valuable water abstraction areas (OSD).

According to this program mapping of the groundwater resources should be based mainly on geophysical survey methods, survey drillings and logging, water sampling and hydrological modeling.

The groundwater mapping is financed by the water consumers, who pay insignificant 4 cents per m^3 of water to cover the mapping expenses.

Aquifer characterizations

In Denmark the abstraction of groundwater is based on three main types of aquifers:

In the western part of the country extensive Quaternary and Pre-Quaternary sand deposits predominate. These aquifers can be partly protected from contaminants leaching from above by higher-lying layers of clay or layers containing organic matter, but this is far from always the case.

In the central part the most important groundwater resources are located in Quaternary sand deposits in deeply cut valley structures. In many cases these sandy aquifers are protected against leaching of nitrate etc. by relatively thick layers of moraine clay, which do not always offer equal protection against a number of other contaminants.

In the northern and eastern part of the country the most important aquifers are related to limestone from Upper Cretaceous and Danien.

Heterogeneity and data density

The quality of groundwater mapping is of course highly depending on the data density and the degree of heterogeneity in the mapping area.

In Denmark the aquifers of interest are found within the upper 250m of the subsurface. The Quaternary deposits reveal a very complicated and varying geology which can not be mapped adequately by carrying out spot measurements. The hydrological models have to be used for locating abstraction areas, calculating effects of natural and man-made changes in flow conditions etc. For a hydrological model to be trustworthy with these purposes in the public land administration and given the geological environment, it has to be based on a high density of accurate geological input.

Fortunately all boreholes drilled since 1927 are registered in a national database. Each borehole has a unique identity and position, technical specifications, information about lithology, water chemistry, logs etc. The amount of information in the national borehole database is quite good, though the borehole density is rather uneven. The density of pre-existing borehole information amounts to an average of around 3 boreholes per km^2. This information contributes significantly when mapping near surface geology, but most boreholes are too shallow to contribute to the picture of the deeper seated and more important aquifers. If we require the boreholes to be deeper than 100m only 1 borehole per 10 km^2 is found! – and these boreholes are in fact clustered around existing well sites.

All electric, electromagnetic and seismic data measured during the last 10-20 years have been reported to a national database called GERDA (GEophysical Relation DAtabase). GERDA is hosted by GEUS (The National Geological Survey of Denmark and Greenland) and is Oracle based. Extracts from the Oracle database can be made in more manageable formats as e.g. Firebird or even Access. The database is public and data can be extracted by anyone who might be interested. GERDA contains measured data as well as a geophysical interpretation of the data. Most geophysical measurements carried out more than about 20 years ago often lack information about instrumentation and other important parameters in which case they are not supposed to meet a quality suitable for being reported to the database.

To give an impression of the size of the database it contains some 75000 ground based transient electromagnetic soundings, 30000km of SkyTEM data, 40000km of continuous electrical data and 10000km of multi electrode resistivity data. On top of that there are several thousands Schlumberger soundings, hundreds of km of Wenner profile data and more than 1500 geophysical borehole logs.

Mapping strategy

Mapping of the aquifers and their vulnerability heavily rely on information from two sources: boreholes and geophysical measurements.

The mapping strategy includes two steps.

In step 1 a preliminary geological model of each mapping area is established based on existing data from the databases and other relevant information.

In step 2 the new detailed mapping is carried out. Based on the analysis of the existing data in step 1 it is decided what kind of further information is needed and how the information is best obtained.

The most suitable combination of geophysical methods is chosen. The geophysical measurements will normally be carried out at the beginning of step 2, because the results are used to decide where new investigation boreholes are best located for obtaining most information about the geology.

The boreholes provide key information for the translation of the geophysical interpretations into geological model parameters. The dense geophysical measurements on the other hand are crucial when one wants to understand how far the detailed information from the boreholes can be extrapolated away from the borehole location, especially in heterogeneous areas.

Lithology, color, grain size and other parameters are described carefully for each sample from the borehole. A combination of normal logs and gamma logs (and a few other logs) are carried out in the borehole before casing. Based on the results from sample descriptions and logging results it is decided where and how many screens are adequate in order to get the best description of the vertical distribution of the water quality in the aquifer at the borehole location. When the well is established water samples and hydraulic parameters can be obtained to complete the data collection at the new borehole location.

Hydraulic heads, water analysis and other information from existing wells in the area are used as a supplement to the new survey data in order to get the best possible data density.

Along with the progression of the data collection the combined and integrated interpretation and description of the different kinds of data takes place.

Geophysical mapping methods

The use of hydrogeophysical methods plays a major role in the groundwater mapping project.

In order to be able to interpret both large and small scale geological structures revealed by the geophysical measurements in terms of relevant geological terms and structures experiences have shown that the best results are obtained when covering large adjoining areas with similar types of geophysical measurements.

The most appropriate geophysical methods to be used in Denmark are considered to be DC resistivity and transient electromagnetic methods combined with seismic profiles and geophysical borehole logs at selected locations.

Cooperation between scientists at The Department of Earth Sciences, University of Aarhus and the authorities responsible for the mapping project was established to ensure, that the use of geophysics would be carried out according to the highest possible standards. Another aim of the cooperation was to further improve instrumentation and field work as well as the processing, interpretation and visualization of the geophysical data. Finally, but equally important, a comprehensive and on-going in-service training was essential, not only for professionals working in the public administration but also professionals working in the consulting companies.

The airborne, transient electromagnetic method, SkyTEM (Sørensen and Auken, 2004), is one of the new methods, that was developed to improve and optimize groundwater mapping. The first SkyTEM groundwater mapping project was launched only five years ago. During the five-year period the method has existed, it has been further developed and has proved to be extremely useful. It is now the most commonly used geophysical method in the mapping of groundwater resources in Denmark.

As mentioned, highly impermeable and low resistivity Tertiary clay layers constitute the lower boundaries of the aquifers in larger areas of Denmark and a wide spread system of buried valleys has been mapped primarily by means of the TEM-method (Jørgensen et al., 2003). The subsurface valley structures are important targets for groundwater mapping because they often contain sand and gravel deposits with significant amounts of groundwater. Until five years ago measurements were carried out as ground based TEM-measurements but now the airborne SkyTEM-method has replaced the traditional TEM-method in all larger surveys. Because of the high spatial resolution needed the line spacing is normally as low as 150 – 200 m.

DC electrical methods are used for near-surface mapping purposes – primarily for estimating the aquifer vulnerability. The pulled array continuous electrical sounding method, PACES (Sørensen et al., 2005), has been extensively used to map layers within the upper 20–30m below surface. Thus it is a very well suited method to be combined with TEM/SkyTEM-measurements in order to get information right from the surface down to 250– 300m.

The multi electrode profiling method (CVES) can be used, where there is no need for larger mapping depths, and where the actual resistivities of the different layers of interest are too high to be distinguished by the SkyTEM-method.

Seismic profiles are also of great value as a geophysical groundwater mapping tool. As seismic profiling unfortunately is rather time consuming, expensive and can not be carried out as dense measurements in most areas it is recommended to combine SkyTEM-measurements with seismic profiles at selected sites. The decision about where the seismic profiles should be located must rely on the results from the TEM survey in order to be optimal.

It has to be noted that information from seismic profiles has successfully been used to map buried valley structures that could not be revealed by the interpretation of SkyTEM-measurements.

Aquifers and aquifer vulnerability

When the localization, size and outline of the aquifers have been described as well as hydraulic parameters and groundwater chemistry one of the next steps to be taken is to point out areas, where actions to protect the groundwater against nitrate leaching should be taken.

In Denmark nitrate has been one of the major pollution threats to groundwater resources in larger parts of the country. This is due to very intensive farming. The vulnerability towards nitrate leaching is determined by a combination of several parameters. One of these parameters is observed to be the thickness of clay layers between the surface and the actual aquifer.

When determining aquifer vulnerability it is appropriate to use several mutually independent indicators. Borehole observations and interpretations from geophysical measurements can usually serve as independent indicators.

In the Aarhus Workbench a GIS-related facility, SSV, has been developed to estimate clay layer thickness based on the combined use of geophysical data and the thickness of clay layers described in boreholes. SSV is the abbreviation for geoStatistical estimation of Structural Vulnerability.

The PACES-method is often used as a basis for the estimation of the total thickness of clay layers in the upper approximately 30m below surface. An area would be characterized as potentially vulnerable to nitrate if less than half of the upper 30m below surface consists of clay (clay resistivity is typically low, often less than 50 ohmm).

Not only the observed thickness of the clay layers in boreholes is of interest when dealing with vulnerability, also the oxidation depth is essential. This parameter can be reasonably well determined from the colour description of the penetrated layers. The oxidation depth in a borehole is defined as the greatest depth to which reddish, red-brown, brownish, yellow-brown and yellowish sediment layers were observed. Shades of greyish, greenish and black colors indicate reduced conditions.

Mapping results have demonstrated a very high degree of correlation between an estimated clay thickness of less than 15m and large oxidation depths based on the color description of sediments from boreholes. This is likely to indicate that the areas where the total estimated clay thickness is less than 15m within the upper 30m below surface coincide with the areas where the oxidation front has reached the greatest depths. Nitrate can in such areas be expected to reach considerable depths thus affecting the water quality in the aquifers.

As the density of boreholes is often low it is very important also to be able to extract information from the dense geophysical data to delineate areas that are likely to be vulnerable to the leaching of nitrate and other pollutants which could penetrate to greater depths under similar conditions.

Integrated utilization of hydrogeophysical data

As is obvious from what has already been described about the national mapping project the amount of especially the geophysical data is increasing rapidly.

The only way to handle the challenge of the enormous amount of mapping data is to establish an integrated system, where the different tools in the system connect to, and interact with each other in a transparent and intelligent manner. Work must be carried out directly on a copy of the geophysical database, where data are stored, and all relevant information on each data point and model must be accessible for use any time during the analysis and interpretation procedure.

Such a system has been developed in Denmark during the last decade. This system, the Aarhus Workbench, builds heavily on the geophysical database GERDA. The Aarhus Workbench is a sophisticated software package that facilitate different electrical and electromagnetic field-data to be imported and stored in GERDA. When extracted the data can be processed, inverted, analyzed, evaluated and visualized in the Aarhus Workbench. The software also includes a GIS tool and facilities for geological interpretation. It has been developed in close corporation by scientists at The Department of Earth Sciences, University of Aarhus during the former mentioned ongoing cooperation with the authorities being responsible for the groundwater mapping.

The large amount of data, which is now stored in GERDA, originate primarily from the groundwater mapping program and all collected data are continuously being uploaded.
The mapping of more than 7500 km^2 have by now been concluded and geophysical measurements have been carried out in a further 4000 km^2.

The integrated system of GERDA and the Aarhus Workbench is now used by all involved consulting companies as well as all authorities responsible for the groundwater mapping. The benefits of the large amount of geophysical data gathered in the GERDA database and utilized by the Aarhus Workbench are invaluable for all future groundwater planning and administration.

Conclusions

Some of the future challenges will obviously be to further improve the transformation of geophysical information into geological and hydrogeological information. The integrated system based on the Aarhus Workbench referred to in this abstract is an important tool solving some of the serious problems and giving a lot of opportunities for future developments.

In the public there is a broad agreement that the limited costs of the mapping campaign are fully justified by the aim of ensuring high quality, clean and un-treated groundwater not only to us, but also to our descendants.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2008 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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