Multiple-purpose MRS in Multidisciplinary Projects

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SUMMARY

In Denmark there is a long tradition of governmental groundwater management based on detailed groundwater mapping as part of the environmental plans of ensuring high quality drinking water supply based solely on naturally clean and chemically untreated groundwater.

Groundwater mapping in Denmark is conducted through multidisciplinary projects within each survey area. In several stages of these multidisciplinary projects the Magnetic Resonance Method (MRS) has been implemented with multiple purposes.

In 2013 a large groundwater mapping project consisting of nine different Danish survey areas were performed with a total of 125 MRS with multiple purposes.

The MRS results have contributed greatly to several different stages of the large multidisciplinary groundwater mapping project. Research borehole locations were determined partly based on the MRS results. New and previous unknown hydrostratigraphic structures were indicated by MRS and subsequently confirmed by research boreholes. In other cases research boreholes were spared since the hydrological conditions were evaluated as being satisfactory described by MRS. The MRS results were beneficially used in the hydrostratigraphic 3D-models. In certain areas the existing geophysical SkyTEM data did not resolve the hydrostratigraphic structures of the area, since no resistivity contrast was present between the quaternary sandy aquifer and the prequaternary mica sediments. However, MRS succeeded in discriminating these formations and thus, the MRS results gave crucial input to the hydrostratigraphical modelling. Finally, the MRS results provided essential input to the sparse hydraulic data input to the numerical hydrological models.

Key words: Groundwater, geological modelling, groundwater modelling, MRS.

INTRODUCTION

The MRS method has proven to be an effective tool together with traditionally applied geophysical methods in Denmark allowing more detailed hydrogeological characterisation from geophysical surface measurements (Chalikakis et al., 2008), (Ryom Nielsen et al., 2011).

In 2013 the Danish Nature Agency initiated a large project in Denmark consisting of nine different survey areas in which Ramboll performed a total of 125 MRS soundings with multiple objectives. The nine survey areas were; Hammel, Silkeborg N, Silkeborg S, Hedensted V, Djurs V, Randers S, Hindsholm, Sydsjælland og Rønnede. The locations of the 125 MRS are illustrated in Figure 1.

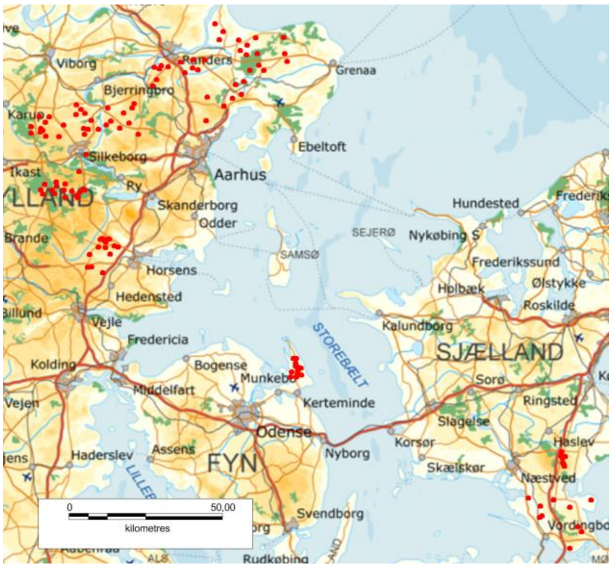

Figure 1. Locations of the 125 MRS in the nine survey areas.

The first objective of the MRS survey was identifying optimal locations for research boreholes. The locations for research boreholes must be carefully selected, since they are expensive and therefore the quantity is limited. The purpose of the research boreholes is to obtain new information about geological structures and aquifer characteristics. For example in several cases buried valleys were indicated in previous SkyTEM surveys. Some MRS were performed within these structures, and depending on the results research boreholes could be prioritised or not. In some cases boreholes were performed to verify the SkyTEM and MRS results, and in other cases research boreholes were not prioritised since the structures were evaluated to be satisfactory described by SkyTEM and MRS combined.

The second purpose was to implement the MRS results into the hydrostratigraphical modelling together with other geophysical data and borehole information. The MRS results were employed to improve the resolution of the hydrostratigraphic sequence and to improve the hydrogeological characterisation of the geophysical surface measurements. In some cases MRS succeeded in resolving sequences by discriminating the hydrological differences in the geological formations, which could not be resolved by SkyTEM because of lacking resistivity contrast.

The third purpose of the MRS survey was to improve the data input for the numerical hydrological models. The MRS results were employed in the zoning of the spatial distribution of hydraulic conductivity. Hydraulic conductivity often exhibits complicated spatial variation in a model area and optimal zoning of the spatial distribution of hydraulic conductivity requires a data coverage that is often not available from borehole data only. The MRS contribution improved the spatial distribution of hydraulic conductivity significantly.

DANISH GROUNDWATER MAPPING

In Denmark groundwater mapping is performed in accordance with the Danish Government's environmental goals of ensuring high quality drinking water supply based solely on naturally clean groundwater. This national groundwater mapping is performed as a part of the Act of Environmental Goals from 2004, which is the Danish implementation of the EU Water Framework Directive (European Parliament and Council, 2000). This law stipulates extensive groundwater mapping of particularly valuable groundwater abstraction areas comprising 37 % of Denmark. In these areas groundwater has first priority. The results of the groundwater mapping in these areas are used by the municipalities in plans involving protection of the groundwater resource.

The national Danish groundwater mapping is performed by the Danish Ministry of the Environment with participation from consultants, universities and the national geological survey, GEUS. There is a long tradition of performing these multidisciplinary projects in accordance with official requirement specifications and with focus on ensuring knowledge sharing. When projects are concluded all data, reports and results are uploaded to public national databases.

The groundwater mapping is funded by a surcharge of approx. € 0.05 per m^3 of drinking water paid by the consumer (Thomsen et al., 2004). The mapping will be completed ultimo 2015 with an estimated cost of € 20 mil. per year.

The mapping is performed through multiple disciplines consisting of summary reports of existing data, geophysical mapping, drilling, logging, geochemical mapping, synchronous hydraulic head measurements, pumping tests, hydrostratigraphical modelling, numerical hydrological modelling, mapping of land use and pollution sources, assessments of vulnerability and regulation areas and final summary reports. The primary data for all disciplines arise from boreholes and geophysics.

The national Danish borehole database consists of more than 240,000 boreholes, corresponding to an average of approx. 5.5 boreholes per km^2. However, even in areas with high borehole density, hydrogeological mapping based exclusively on borehole data is too inadequate to fulfil the standards demanded by the Danish Ministry of the Environment. Therefore, dense geophysical mapping of the subsurface is a central discipline in the groundwater mapping. Geophysical mapping is performed primarily with the aim of determining the extension of the aquifers and amount of clay in the top layers, forming a natural protection of groundwater resources. The geophysical results are employed together with borehole data in the geological modelling, hydrostratigraphic and numerical groundwater modelling.

The inputs from the traditional geophysical methods are physical properties of the geological formations. This information of geophysical properties is valuable when correlated with boreholes, and support the interpolation between boreholes in the assessments of the groundwater resource. However, the geophysical properties are only indirectly interpreted to hydrogeological information. In contrast the Magnetic Resonance Method (MRS) is able to directly estimate hydrological properties of the subsurface. This fact makes MRS beneficial in several different stages of the groundwater mapping.

METHOD

The MRS method is based on the principle of Nuclear Magnetic Resonance (NMR) and allows the non-invasive detection of free water in the subsurface. The MRS method is well described by Legchenko, A. et al. (2002 and 2013b). For this project the NUMIS^{poly} equipment by Iris Instruments was used.

For all MRS measurements an extra dataset was acquired in order to be able to estimate the relaxation time, T_1, satisfactory and hence to be able to estimate hydraulic conductivity satisfactory (Chalikakis et al., 2009). The extra T_1 dataset was collected by applying different decay times between the double pulses as described by Walbrecker, J. O. and Behroozmand, A. A. (2012).

A ground based TEM (Transient Electromagnetic) sounding was acquired at each MRS site. The use of the TEM method in Denmark is well known (Christiansen, A. V. and Christensen, N. B., 2003). For this project we used PROTEM 47/TEM47 instrument by Geonics with the 40 m x 40 m setup.

The MRS data was preprocessed in Proview by J. F. Girard, 2013 and flowingly processed and inverted in Samovar v. 11x6 (Legchenko, A., 2013a), using primarily smooth but in some cases also block inversion. TEM data was processed and inverted in SiTEM/SEMDI v. 2.1.10.81 (Hydrogeophysics Group, 2010) and used to determine the Kernel.

EXAMPLES OF THE MRS APPLICATIONS

In the groundwater mapping project a total of 125 MRS were performed within the nine survey areas. For the majority of the soundings the obtained data qualities were very good. The MRS results have contributed greatly to several different stages of the multidisciplinary project.

Research borehole locations were decided based on the MRS results. In the survey area Silkeborg S a buried valley structure was indicated in a previous SkyTEM survey and very few boreholes described the structure. The Danish Nature Agency wanted more certainty concerning the existence of the structure as well as information about the variability of the hydrological properties of the aquifer within the structure. Three MRS were performed within the presumed structure and they all confirmed the existence of the aquifer. They also indicated variations in the hydrological conditions within the aquifer. Subsequently a research borehole was established close to one of the MRS. The borehole also found the deep quaternary aquifer which confirmed the presence of the buried valley. This information about the buried valley, and the aquifer condition within the structure, is crucial input to the hydrostratigraphical modelling. Figure 2 illustrates a profile from the hydrostratigraphical model in the Silkeborg S area, through the buried valley structure. The profile illustrates the MRS results and the research borehole together with SkyTEM models and the hydrostratigraphical model layers. The results correspond well. The aquifer interpreted with MRS corresponds exactly with the aquifer described in the borehole. The bottom of the aquifer is below the maximum investigation depth of the MRS. The hydrogeological parameters estimated with MRS and the new borehole contributed to zoning of the hydrological model of Silkeborg S.

In other similar cases research boreholes were spared since the hydrological conditions were evaluated as being resolved satisfactorily with MRS for the purpose of establishing the hydrostratigraphical model and hydrological model. This was the case in e.g. the Hindsholm and Silkeborg N survey areas.

A general challenge to resolving the hydrostratigraphic structures of the area with traditional geophysics e.g. SkyTEM was observed in particular in the Silkeborg N and S survey areas since often no resistivity contrast was present between the quaternary sandy aquifer and the prequaternary mica sediments. However, in the MRS results there was a clear difference in the hydrological parameters in the quaternary and prequaternary sediments. An example of this issue is illustrated in profile from the hydrostratigraphical model in the Silkeborg N area in Figure 3. The MRS show to separate aquifers with the top aquifer having significantly higher hydraulic conductivity than the deep aquifer. This corresponds with the borehole information about the quaternary and prequaternary aquifers. This made the MRS input very important in the hydrostratigrafical modelling, where the model interpretations often are based mainly on MRS and boreholes, and less on SkyTEM.

Finally, the MRS results provided essential input to the sparse hydraulic data input for the numerical hydrological models. This project has provided a unique set of transmissivity correlations between MRS and new research boreholes as well as MRS and existing boreholes which is presented in Figure 4. The MRS transmissivities are estimated based on the extra T_1 dataset and the correlation is overall very good.

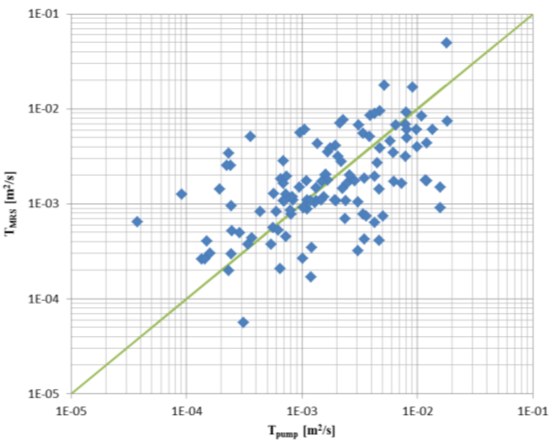

Figure 4. Transmissivities estimated with MRS correlated to transmissivities estimated in the closest boreholes.

CONCLUSIONS

125 MRS were performed in nine different survey areas and implemented in several stages of the multidisciplinary groundwater project. New hydrostratigraphically structures were indicated by MRS and subsequently confirmed by research boreholes. In other cases research boreholes were spared since hydrological conditions were evaluated to be satisfactory described by MRS. It was proved possible with MRS to discriminate and characterise hydrological parameters of quaternary and prequaternary aquifers. The MRS input to the hydrostratigraphical and numerical hydrological models were crucial to resolve the geological compositions and to obtain a satisfactory spatial distribution of hydraulic conductivity.

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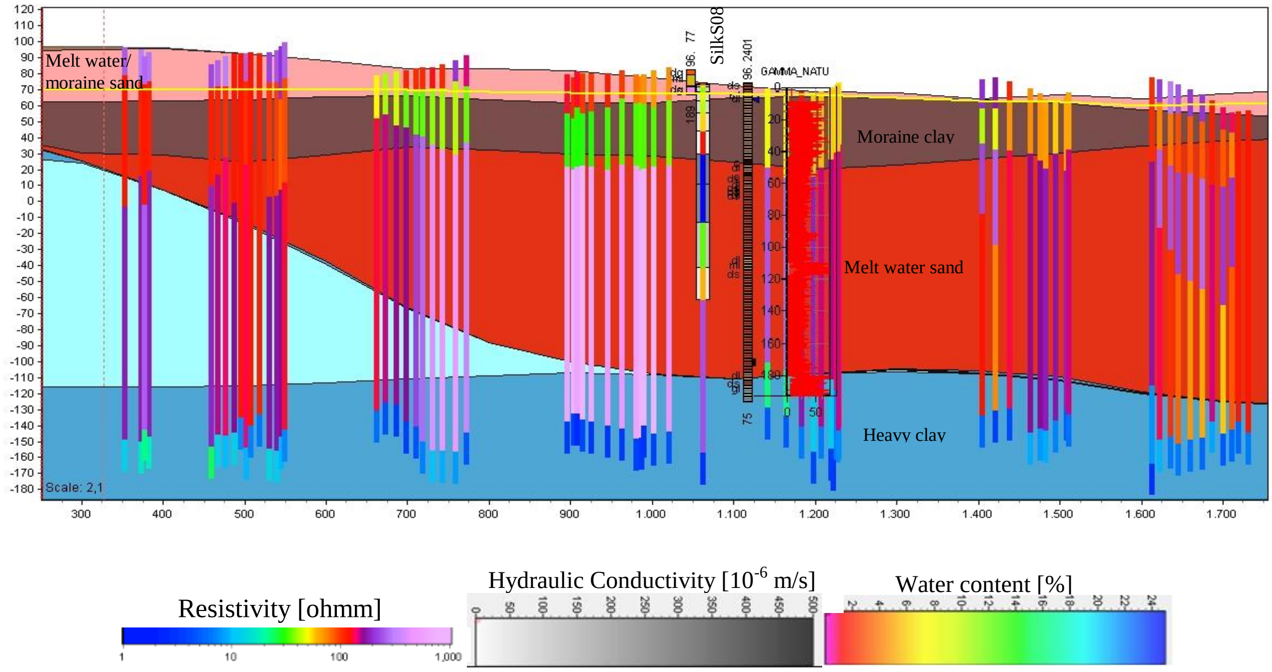

Figure 2. Profile from the Silkeborg S hydrostratigraphic model with interpreted hydrostratigraphic model layers (background colours), boreholes (short bars with id-number above), TEM/SkyTEM models (layered bars categorised according to the resistivity colour scale), one gamma log and one MRS SilkS08 (Inner layered bar categorised according to the water content colour scale, and the outer layered bar categorised according to the hydraulic conductivity colour scale).

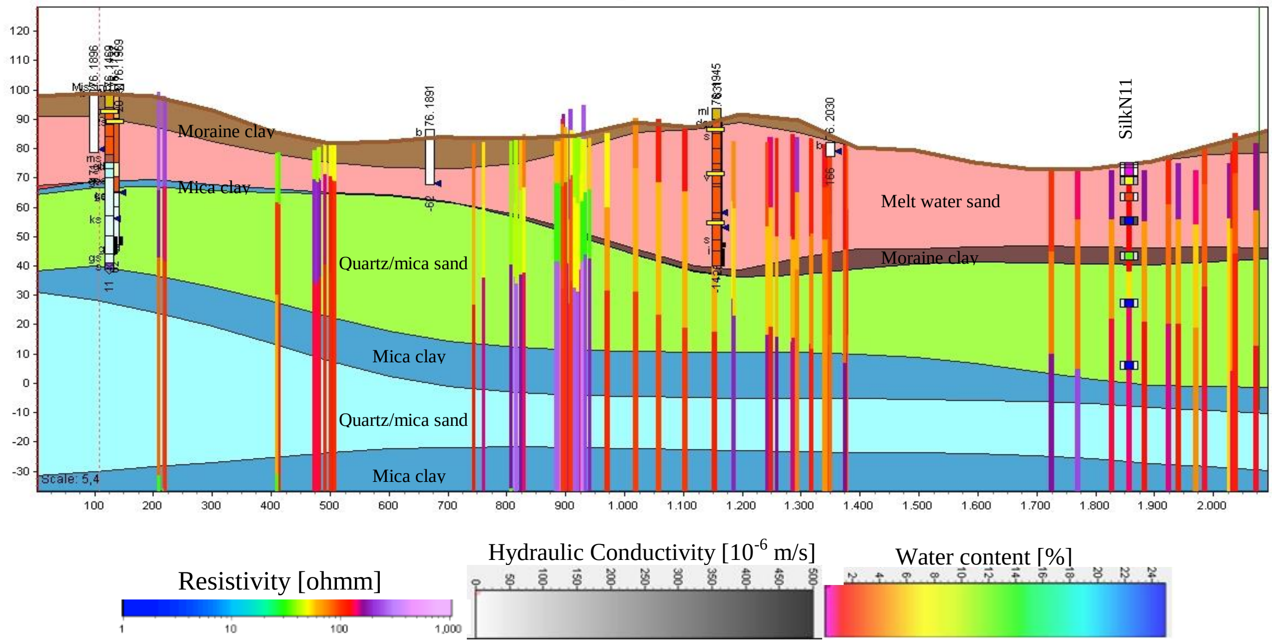

Figure 3. Profile from the Silkeborg N hydrostratigraphic model with interpreted hydrostratigraphic model layers (background colours), boreholes (short bars with id-number above), TEM/SkyTEM models (layered bars categorised according to the resistivity colour scale) and one MRS SilkN11 (Inner layered bar categorised according to the water content colour scale, and the outer layered bar categorised according to the hydraulic conductivity colour scale).