HYDROGEOPHYSICS GROUP

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MAGNETIC RESONANCE SOUNDING IN COUNTY OF NORTHERN JUTLAND – RESULTS AND EVALUATION

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1 INTRODUCTION

This report serves as an evaluation of the feasibility project of engaging magnetic resonance soundings (MRS) in the county of Northern Jutland.

The aim of the project is to investigate the application of MRS on the hydrogeological settings in Northern Jutland. Can MRS provide information prior to drillings which is unattained by the geophysical methods used on a routine basis, namely the transient electromagnetic (TEM), the pulled array continuous electrical sounding (PACES) and the continuous vertical electrical sounding (CVES) methods?

This feasibility project is made in a cooperation between the county of Northern Jutland, GeoFysikSamarbejdet and Institut de Recherche pour le développement, IRD. The county has supported funding of the field work of the project, GeoFysikSamarbejdet has financed the evaluation of the project and, hence, this report. The IRD has provided the necessary expertise and equipment to perform this project as well as salary for the two geophysicists, Anatoly Legtchenko and Henri Robain.

In August 2003, seven MRS soundings were performed, five on a profile at Høgsted south of Hjørring, one at Sæby and Næsby (Løgstør). A priority list of areas of interest was made beforehand by the County of Northeren Jutland and GeoFysikSamarbejdet. However, the exact location of the soundings were pointed out by Anatoly Legtchenko of IRD who is familiar with methodology considerations of the MRS method.

To accompany the MRS soundings a number of TEM soundings were made in the same period.

Included in this report is a data report written by Anatoly Legtchenko. It is included as is, while the scope of this report is to put the result into context regarding the applicability of MRS in the county of Northern Jutland and in Denmark in general.

The report is written by Jens E. Danielsen, GeoFysikSamarbejdet. Esben Auken, GeoFysikSamarbejdet, Anatoly Legtchenko, IRD and Lone Davidsen, University of Aarhus have read proofs of the report. By appoinment with the County of Northern Jutland the report is written in English.

2 ACKNOWLEDGEMENTS

We take the opportunity to acknowledge the support of Institut de Recherche pour le développement, represented by Henri Robain and Anatoly Legtchenko. Without their support and expertise the introduction of MRS in Denmark had not been made.

Furthermore, we acknowledge Hanne Birch Madsen and Anne Mette Nielsen from the County of Northern Jutland for their interest in the project and their understanding of the geological settings in the survey areas.

3 SOUNDING SITES

An overview of the sounding sites is given in Figure 3.1.

Figure 3.1 Overview of northern Jutland. The three sounding sites are marked by red dots.

The areas of interest were selected by the county of Northern Jutland and GeoFysikSamarbejdet in cooperation. A list of priority was made as the exact number of MR soundings were unknown prior to the survey. The selection of areas of interest was based on current hydrogeological problems in the county. Furtermore, it was desired to try out MRS in different hydrogeological environments.

After the overall area was selected, GeoFysikSamarbejdet narrowed the sounding areas based on existing TEM-soundings. The exact and final positions of the MRS soundings, however, were decided by Anatoly Legtchenko in the field to ensure optimal conditions for the method.

Other sites were considered as potential sounding sites. The time available for the survey and the required time to gain maximum pe-netration of the MRS did not allow us to visit more than three sites.

3.1 HØGSTED AT HJØRRING

The main effort of the campaign was concentrated on a profile at Høgsted, southeast of Hjørring. Five MRS and twenty TEM soundings were performed on a profile striking north-south. The location of the profile is based on a TEM survey and a collection of the available information made by Rambøll in the summer of 2003. The northern part of the profile is located in an area where the subsurface is dominated by an extensive high-resistive layer and great depth to the Ældre Yoldia clay, which is heavy and low-resistive. The southern part of the profile show smaller depth to the clay and a generally less-resistive formation. It was desired that a drilling in the high-resistive, deeper part of the profile could reveal a high yielding aquifer, which could supply Hjørring with water. A similar promising resistivity signature has previously led to a drilling in low-permeable silty sediments.

A drilling down to the Ældre Yoldia clay with logging tools and test pumpings was performed in September 2003. MRS was performed to get an indication of the water content of the subsurface prior to the drilling, and to compare the result of the MR sounding with ground truth.

Figure 3.2 shows the location of the drilling and the sites for TEM and MR soundings.

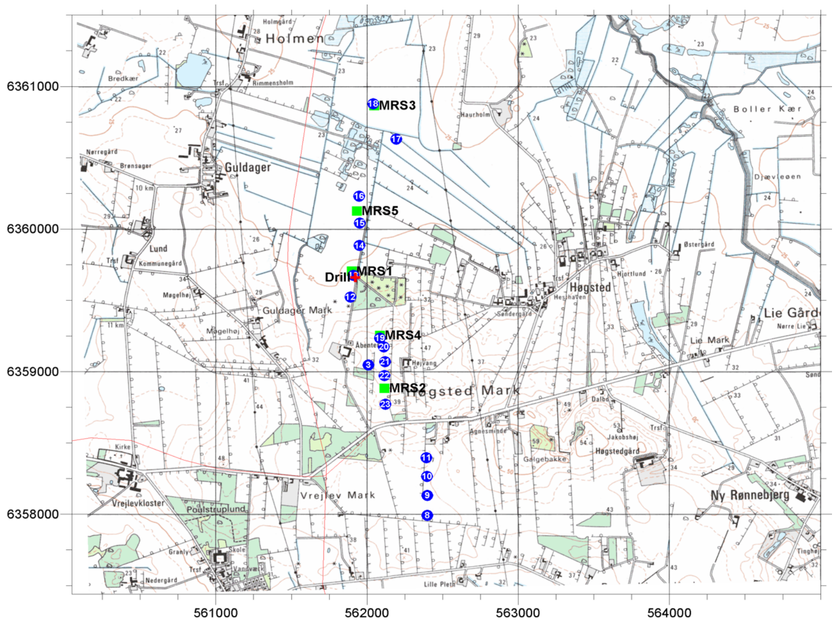


Figure 3.2 Location map of the Høgsted profile. UTM coordinates in projection ED 1950, zone 32. Blue circles are TEM soundings, green squares are MR soundings and the red cross is the drilling.

3.2 NÆSBY

One MR sounding was performed at Næsby together with three TEM soundings. At Næsby the general TEM survey indicated a high-resistive layer of a thickness of 70 metres. The high-resistive layer render probable the presence of a potential aquifer. However, a test drilling made in November 2002 revealed that the high-resistive consisted of only 15 metres of saturated sand, while the remaining 55 metres are silt with a high chalk content without any significant water content. This scenario cannot be resolved by the geophysical methods used in the Danish hydrogeophysical mapping. The resistivity contrast between the two formation s is simply too small. As MRS measure the amount of free water, this is not an issue for this method. Hence, MRS might supply the geophysical information to differentiate between dry and waterbearing sediments within the same resistivity range. The Næsby site is shown in Figure 3.3.

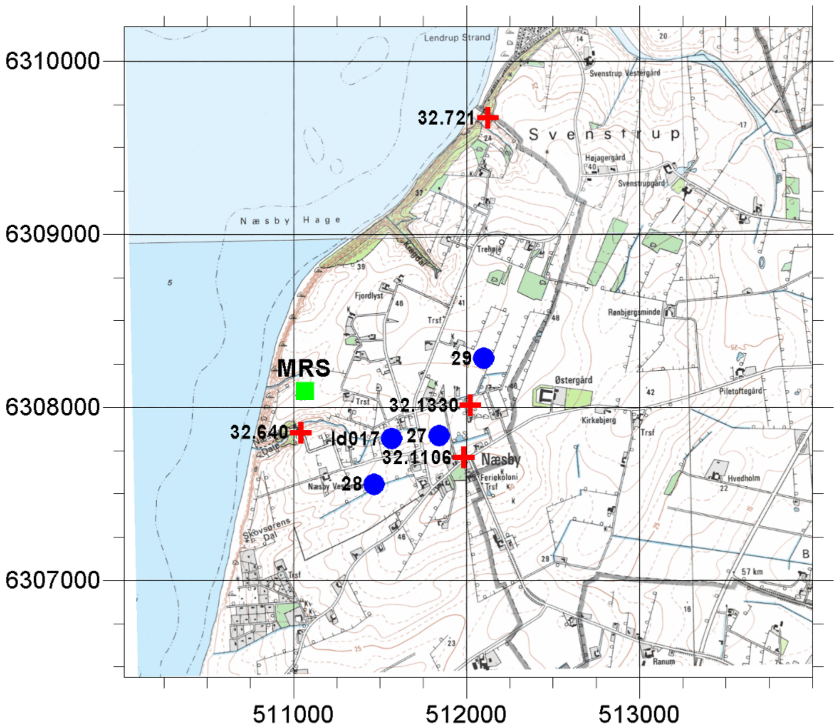


Figure 3.3 A map of the Næsby site. UTM coordinates in projection ED 1950, zone 32. Blue circles are TEM soundings, green square is MR sounding and red crosses are the drilling sites.

3.3 SÆBY

At Sæby, one MR sounding and 3 TEM soundings were performed. A general TEM survey in the area indicate a buried valley structure, which currently serves as aquifer for Sæby. It is an erosion structure in the Ældre Yoldia clay surface, which is filled with various Quaternary sediments. A drilling was performed close to the MR sounding site in September 2003. It was logged with various geophysical tools. This allows for a comparison between the MR sounding and the drilling. The locality map of the Sæby site is shown in Figure 3.4.

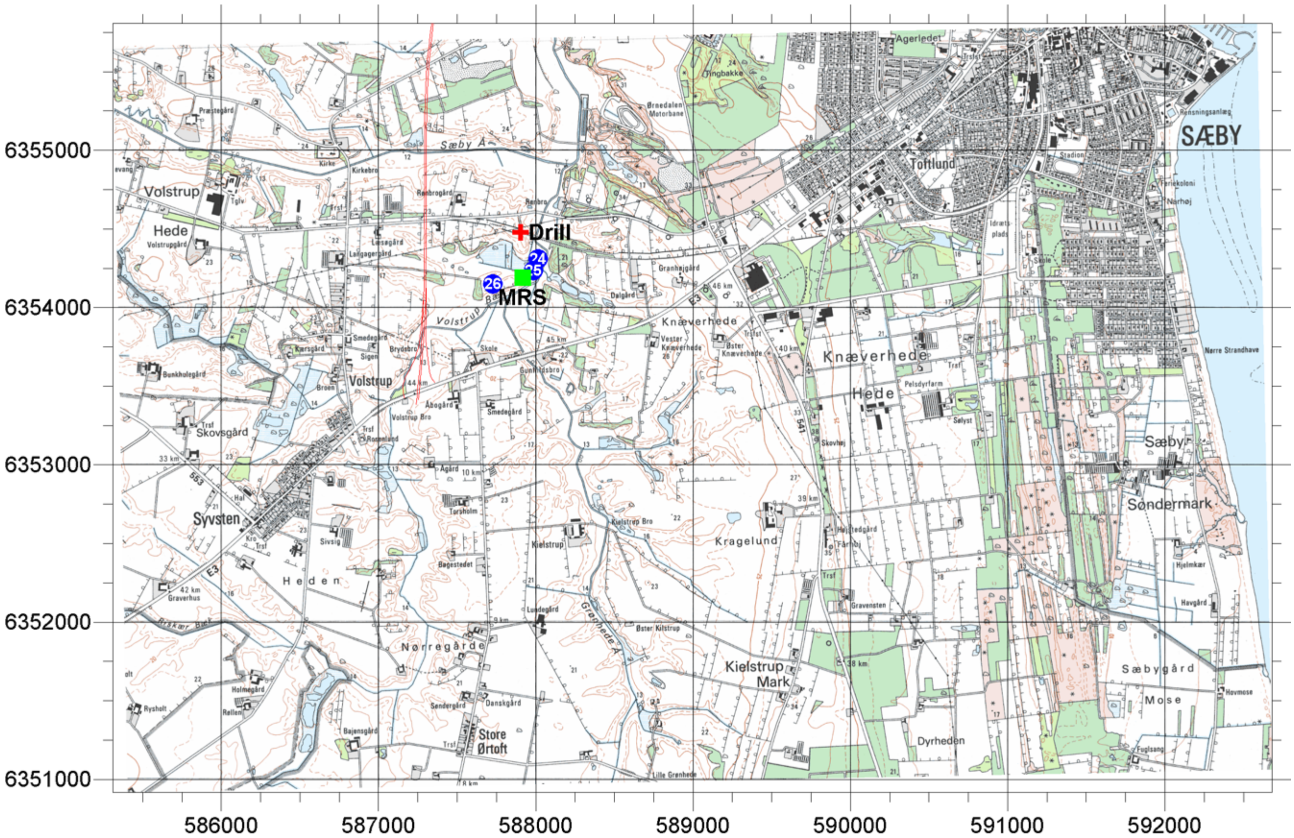


Figure 3.4 Location of the sounding site at Sæby. UTM coordinates in projection ED 1950, zone 32. Blue circles are TEM soundings, green square is MR sounding and red cross is drilling.

4 THE MRS METHOD

In this chapter, a short introduction of the Magnetic Resonance Sounding (MRS) method is given. For a thorough description, see the chapter "Further reading" on page 23 or the IRD data report enclosed in "Data report by Legchenko and Robain" on page 25.

4.1 THE PHYSICAL BACKGROUND

As opposed to other surface geophysical methods, MRS assesses the water content directly. The interpratation error that may occur from the translation from geophysical parameters (e.g. resistivity, seismic P-velocity) to lithology and hydrogeological properties is not present. The method even provides rough estimates of the latter.

The MRS method takes advantage of the fact that the protons of a water molecule have a magnetic dipole moment. Under normal circumstances the dipoles orientate parallel to the Earth magnetic field. However, an applied magnetic field can change the orientation of the dipoles. In order to do so, the applied magnetic field must be transmitted at the resonance frequency of the system, the Larmor frequency. The Larmor frequency is given by the product of the magnitude of the geomagnetic field and the gyromagnetic ratio of the water molecules. The latter is a material constant.

A MRS sounding is performed by laying out a loop on the surface of the earth. An alternating current $\boldsymbol{I_0}$ at the Larmor frequency is transmitted into the loop. This will cause the water molecules of the underlying formation to orientate after the applied magnetic field. It is the component perpendicular to the Geomagnetic field that excites the protons.

After the time t, the current is turned off, and the dipoles flip back to the initial condition, parallel to the earth magnetic field. This is the socalled relaxation of the protons, and it induces a measureable voltage in the loop on the ground. The induced voltage follows a cosine function oscillating at the Larmor frequency with an exponentially decreasing envelope. The time it takes from turn-off to the natural condition has restored is called the relaxtion time.

The product of $\boldsymbol{I_0}$ and t is called the pulse moment. The higher the pulse moment the deeper in the formation are protons deflected. Hence, an NMR sounding consists of measurements for different values of the pulse moment to obtain full depth coverage. The principle of an MRS soundings is shown in Figure 4.1.

4.2 THE WATER CONTENT

The amount of water of the subsurface is directly related to the size of the induced voltage immediately after turn-off of the alternate current. By inversion the water content in horizontal, plane-parallel layers are derived from the measured data. In the computation no contributions are included below 1.5 multiplied by the side length of the loop. Hence, this is the theoretical maximum penetration depth; in practice the penetration depth is unlikely to exceed 80 m for quantitative interpretation, in the

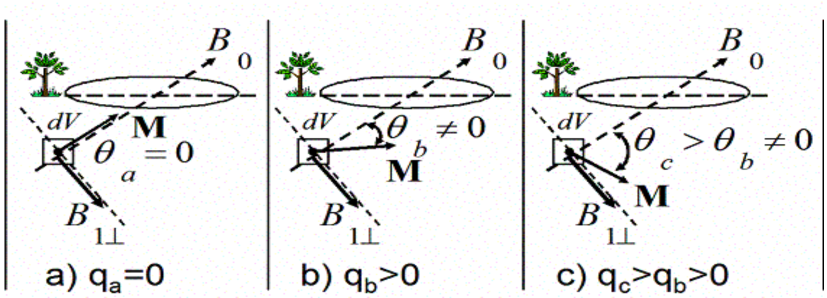


Figure 4.1 Basic principles of the MRS method. dV is a water sample in the formation B_0 is the Geomagnetic field, $B_{1\perp}$ the component of the applied magnetic field perpendicular to the Geomagnetic field. At a) the Pulse Moment q is zero and the deflection angle, θ, of the protons is zero. At b) q is nonzero and the protons are deflected from the direction of the Geomagnetic field. At c) q is increased compared to b). The deflection angle θ has consequently also increased. From Legchenko and Robain, 2003.

Danish case with 100x100 m^2 loop. As the gradient of the applied magnetic becomes smaller with increasing depth, the resolution of the MRS method follows a similar pattern.

Empirical evidence has shown that for the capillary bound water of the formation relaxation times are so short- that they are unmeasureable by the instrument due to technical limitations. Hence, the water responding to the MR soundings is the free water of the formation.

4.3 HYDRAULIC CONDUCTIVITY

MRS measurements can be used to estimate the permeability of the subsurface. The estimation is based on the already obtained water content and the relaxation time. The latter is proportional to the mean pore size of the formation: The longer the relaxation time, the larger the mean pore size. This, however, also depends on the magnetic susceptibilty of the sediments. If the magnetic susceptibilty is zero (e.g. limestone), the relaxtion time is longer than for strongly magnetic susceptible sediments (e.g. iron-rich sediments) for the same mean pore size. Hence, an increase in magnetic susceptibilty of the sediments will indicate a lowering of mean pore size. It is important to keep in mind that estimates of hydrogeological properties depend on this, often unknown, value, and for a better determination the estimates should be calibrated against local borehole values.

The estimates of hydraulic conductivity are based on an empirical relationship between porosity, hence MRS signal, and hydraulic conductivity obtained from borehole measurements. The relationship depends on constants describing the porosity type. These factors are unknown as MRS is usually performed prior to drillings. To use as accurate values as possible, the interpreter needs regional values from neighbouring drillings. If no values are available, the accuracy of the hydraulic conductivity estimate may be challenged. The transmissivity is often shown as it depicts the resolution of the method, as it is defined as the hydraulic conductivity through a column of the earth, in other words, the integrated hydraulic conductivity. Considering the depth of investigation and that water is the target, there is practically no diiference between hydraulic conductivity and permeability (Legchenko, personal communication).

In MRS the signal-to-noise ratio S/N is a limiting factor. The signal level is controlled by the amount and burial depth of the free water, while the noise level is a sum of cultural electromagnetic noise and instrument noise. The cultural noise is mainly due to the power distrubution grid. The stochastic components of the noise level may be reduced by stacking. To improve the signal to noise ratio, the equipment is left measuring for several hours, which makes the mehod rather time consuming compared to other surface geophysical methods.

If S/N drops below 1, a quantitative interpretation is impossible. However, a qualitative interpretation offers the maximum volume of water within the loop area, and it is possible that no water is present.

4.4 INTERPRETATION

MRS data are converted to a model by inversion, just as most other geophysical data sets. The inversions presented in this report was performed by Anatoloy Legtchenko using the software "NUMIS^{PLUS}".

The underlying earth model is a 1-dimensional, minimum structure model. It consists of 40 layers. The layers are thin in the top of the model and becomes thicker by increasing depth. This reflects the resolution capabilities of the MRS method. The geophysical properties, in this case water content, between two adjacent layers are tied together with a constraint factor which prevents abrupt changes in geophysical property. It is assumed that changes are slow in nature as well.

The result of minimum structure inversion is a smooth model where the property changes slowly over the fixed layer boundaries. It aims at producing as little structure as possible.

5 THE TEM METHOD

In this chapter a brief outline of the Transient Electromagnetic method is given. See "Further reading" on page 23 for a more thorough description of the method.

5.1 THE PHYSICAL BACKGROUND

In a transient electromagnetic measurement a current pulse is transmitted into a coil giving rise to a primary magnetic field through the coil center. The current is turned off abruptly, and the primary field disappears. At very early times after turn-off, a current will run just below the transmitter coil to compensate for the vanished primary field. Due to ohmic resistance of the ground, this current will decay and diffuse deeper into the earth as time passes. The current may be described as a system of horizonally circulating currents decaying down- and outward in the formation. The decay is resistance-dependent. The current system induces an also decaying secondary magnetic field, which is measured on the surface by an induction coil. The interaction of the fields is indicated by Figure 5.1.

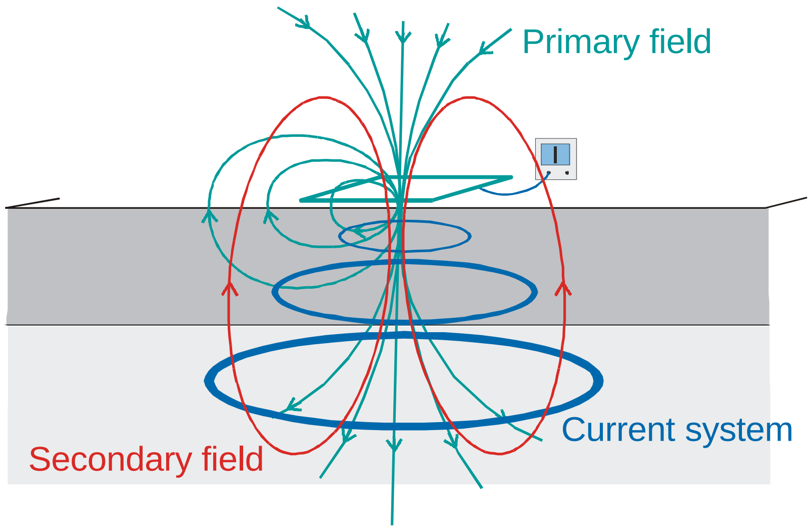


Figure 5.1 The turn-off of the primary field gices rise to a decaying current system which induces the secondary, resistivity dependent magnetic field.

The resistance dependency and the propagation of the current system mean that a recorded time series contains information of the resistivity (the specific resistance) distribution of the subsurface. A one-dimensional earth model consisting of thicknesses and resistivities may be derived from the time series by inversion.

The underlying physics of the method mean that the method is sensitive to contrasts in conductivity (conductivity= 1/resistivity). Hence, the main force of the method is to determine the resistivity and thickness of and depth to any layer of low resistivity. The determination of high-resistive layers is more uncertain. The resolution capabilities of the method weaken when the depth increases.

The penetration of a given TEM system depends on the signal-to-noise ratio, S/N. A higher signal or a lower noise level lead to undisturbed data later in the time series, when the current system has propagated deeper into the earth. The signal level depends on:

- the transmitter moment
- the resistivity of the earth, hence the geology

The transmitter moment is the area of the transmitter loop mulitplied by its number of turns and the transmitted current. A higher moment raises the signal level proportionally, which leads to an improved S/N and higher penetration depth. A large transmitter moment is turned off slower than a small transmitter moment. As a consequence, the former lacks resolution of the earth at shallow depth. Therefore, a sounding often consists of measurements made with both high and low transmitter moments in order to cover both early and late times.

The underlying geology affects S/N as the signal level increases when the resistivity of the earth decreases, since the current system decays slower in a low-resistive medium.

The noise level in a TEM measurement is the sum of the electromagnetic background noise and the internal instrument noise.

The background noise depends on locality and time, while the instrument noise is strictly connected to a specific equipment. The stochastic noise is decreased by stacking of many measurements. Hence, many repetitions lower the noise level and increase the penetration depth.

A limitation to the TEM method in space is the coupling of the transmitted field to man-made conductors. e.g. buried wires, power lines, animal fences, gas pipes, etc.. The couplings add a non-earth response to the measurements, which cannot be excluded. A coupled sounding must therefore be excluded from further interpretation. The magnitude of a coupling depends on distance between the instrument to the conductor. In practice, a safety distance of 150 m should be kept to potential coupling sources.

Data from a TEM-measurement are normally interepreted by a one-dimensional earth model with parallel and horizonatlly infinite layers. The layers are characterized by their thicknesses and resistivities. This interpretation is a geophysical interpretation, since it is in terms of physical rather than geological units.

5.2 DATA PROCESSING

Processing of the TEM data was carried out in SiTEM. SiTEM provides the opportunity to plot data as dB/dt and apparent resistivity, Rhoa. Furthermore data are averages, and bad data points are removed.

The ASCII raw data from the PROTEM instrument are read into SiTEM, where they are combined with information on measurements geometry, low pass filters, transmitter waveforms and calibration parameters.

The data uncertainty is calculted as the standard deviation of the data stack, added a uniform standard deviation of 5 % (in dB/dt).

REMOVAL OF BAD DATA POINTS
The transition from clean to noisy data points happens relatively fast. At this transition, data are said to drown in noise. Data drowned in noise do not contain usable information of the earth resistivity and, hence, have to be removed. The transition is considered by visual inspection of the data curve as well as an analytical calculation of the standard deviation of the stack.

Coupled soundings are per definition unusable. Coupled soundings are sought by comparison to neighbouring soundings and by the distance to potential manmade conductors.

When the soundings have been processed, they are written into a temfile, which contains data as well as instrument specific parameters.

5.3 INTERPRETATION

In the geophysical interpretation a physical model is estimated from the measured data. The models are onedimensional with planeparallel , horizontal and homogeneous layers. Each layer is characterized by a resistivity and a thickness. The bottom layer of the models continues to infinite depth.

INTERPRETATION PROGRAM
The interpratation is made by the program SEMDI. The underlying inversion algorithm is em1dinv. During interpretation the full system response is modelled, i.e. transmitter waveforms and receiver low pass filters are taken into account.

Initially, the data sets are interpreted with 2-, 3-,4- and 5-layer models. By inspection of the interpratation results, the final interpretation model is selected. The selected model must have:

- A satisfying fit to data
- Realistic model parameters

The selected model is the model with the lowest number of layers fullfilling the criteria above.

Apart from the estimated model, the interpretation also yields an analysis of the accuracy (or the degree of determination) of the model parameters. This is the model parameter analysis. The uncertainties are stated as factors within a confidence interval of 67%. The calculation of the analysis is made under assumptions which are only partly fullfilled. The analysis is therefore only an indication of the determination of the model parameters. As a rule of thumb, factors may be translated as:

- Well-determined - if the factor lies between 1 and 1.3
- Determined - if the factor lies in the interval from 1.3 to 1.5
- Poorly determined - if the factor lies in the interval from 1.5 to 2
- Undetermined - if the factor is larger than 2

6 RESULTS

This chapter presents the results of the performed MRS and TEM soundings. The results are presented in profiles showing the measured MRS and TEM soundings and the relevant drill holes. For Høgsted and Sæby the order on the profile approximately reflects the geometry of the survey in the field, but for Næsby this was not possible. TEM soundings and drillings at Næsby are shown as a function of distance to the MRS sounding for Næsby. On all three profiles the topography is taken into account in the visualization.

The following information is shown:

- TEM - the few layer models obtained from inversion. The resistivity distribution as a function of depth.
- MRS - multi-layer models obtained from inversion. The water content and the permeabilty as a function of depth.
- Drillings - the lithological logs of the drillings are simplified from the DGU descriptions. Natural gamma, resisitivity, conductivity and Neutron logs are shown when available.

The profiles are included at the end of the chapter.

6.1 HØGSTED

The Høgsted area had the highest priority in the investigation. The profile shows 5 MR soundings and 16 TEM soundings The drilling was made in September 2003, a few weeks after this survey was carried out. These results were therfore not available.

As the leftmost map indicates, the Høgsted profile consists of 4 subprofiles. The profiles are differentiated by three black dots, indicating discontinuity in distance or orientation between two neighbouring soundings. The following presentation starts to the north and moves south on the map, or from left to right on the profile presentation.

MRS03
MR sounding MRS03, on the northernmost subprofile, indicates a water bearing layer approximately 20 m thick and with a maximum water content of 7 %. The maximum permeability is estimated at the same depth. This indicates the presence of a rather sandy water bearing layer centered at 35 m depth. This is confirmed by TEM18 performed at the same location, where the waterbearing layer corresponds nicely to a high-resistive layer in the TEM sounding. In TEM17, approximately 100 m away, the high resisitivty layer has moved slightly downwards, but the three models are in good agreement with a water bearing layer at rather shallow depth. After the peaks in both water content and permeability at 35 m in MRS03, both parameters go towards zero with increasing depth. The water content reaches zero at 80 m and permeability already at 60 m. This is also in agreement with the adjacent TEM soundings, which show resistivities between 20 and 40 Ωm. This resisitivity signature is likely to be more silty and clayey than the formations above.

MRS05
MR sounding MRS05 indicates the presence of an aquifer at similar thickness and depth. The water content is slightly higher, i.e. 10 %, and the permeability is higher as well. In fact this MR sounding shows the highest

potential from an exploitational point of view. MRS05 is performed in between TEM16 and TEM15 with approximately 40 m to either side. The waterbearing layer is confirmed by 150 to 200 Ωm layers in the TEM soundings. At the northernmost sounding of the two, TEM16, the layer is thicker than at TEM15, and it is absent in TEM14 further to the south. The high-resistive layer seems to correspond to the shallow aquifer as it was the case at MRS03. TEM15 and TEM16 shows a higher resistivity of layer three than TEM17 and TEM18. The resistivity is in the range of 80 to 90 Ωm, which by a stand-alone interpretation may be interpreted as a water-bearing, sandy formation. In that case the interpreter might expect a 100 m thick reservoir. However, MRS05 shows a decreasing water content and especially a decrease in permeability below 40 m.

MRS01

MRS01 was made at the drill location. The drilling was placed partly based on a regional TEM survey. The TEM measurements surrounding the location do not exclude the presence of a thick water-bearing, sandy layer.

MRS01 shows a peak in permeability of a similar size as at MRS03 at 25 m depth. This is slightly shallower than at MRS03 and MRS05. As opposed to MRS03 and MRS05, MRS01 does not show a peak in water content at the same depth. The water content increases to 6 %, at the peak of permeability, and this value is slightly increased by increasing depth. Below 80 m the model is uncertain and should not be evaluated. At depths greater than 25 m the permeability decreaes rapidly, and it must be concluded that the present water is hard to extract. An aquifer would have to be confined to the depth interval from 15 to 45 m. This is confirmed by the drilling. Looking at the lithological log, the more sandy part of the column is from 10 to 55 m, with medium- and coarse-grained sands in the interval from 30 to 41 m. This is likely to be the most permeable part of the column. Below 55 m the formation becomes more fine-grained and, hence, less permeable. The natural gamma log shows the lowest intensity in the depth interval from 20 to 41 m suggesting the lowest clay content in this interval.

TEM14 yields a depth to a conductor at 135 m. This is confirmed by natural gamma, resistivity and conductivity logs. In the lithological log this boundary coincides with a transition from fine-grained sand to clay.

Considering MRS03, MRS04, MRS01 and the adjacent TEM soundings, it is tempting to associate the shallow high-resistive layer in TEM soundings TEM15 to TEM18 with the more permeable and water-bearing interval in MRS03 and MRS05, especially since this depth interval has other characteristics in TEM13, TEM14 and MRS01. In TEM12, 75 m south of MRS01, the high-resistive layer reappears. If the high-resistive layer corresponds to the depth interval with the highest potential as aquifer, it is unfortunate that the drilling is placed where no such layer is present.

MRS04

This MR sounding is in the northern end of the third subprofile. It distinguishes itself from MRS03, MRS05 and MRS01, as it shows virtually no permeability of the upper 40 m. The water content is a minimum around 25 m but rises to exceed 10 % at 60 m and it continues increasing down to the maximum exploration depth of 80 m. At MRS01 a higher water content was measured at depths greater than 40 metres, and a similar trend is observed at MRS04. MRS05 showed us that it does not extend further north. At MRS04 the permeability also rises, which makes it possibe to exploit the water at greater depth. However, the depth investigation is insufficient for reliable quantitative characterization of this aquifer.

The change in the MR soundings is reflected by the TEM soundings as TEM19 to TEM22 introduce a 50 Ωm second layer at 20 m depth. At TEM 19, at the same spot as MRS04, the boundary to the third layer coincides with the rise in water content and permeability. The depth to the conductive layer, presumed to be clay as at the drill site, has increased to 170 m. This is the trend for all TEM soundings south of the drill site on the profile. This increased depth adds to the expectations of a deeper aquifer, but the experience from TEM15 and TEM16, where a similar resisitivity of 100 Ωm contained no water, cools the expectations. The presence of a deeper aquifer is certain due to the qualitative information from the MR soundings, but it is not possible to determine the potential, given the present data.

MRS02
MRS02 is located 150 m south of MRS04, between TEM22 and TEM23. Neither a considerable water content nor permeability is detected at this location, thus limiting the southern extension of any deeper aquifer. MRS04 is the only MR sounding showing both a significant water content and permeability below 40 m. The site of MRS02 has by far the lowest potential as drilling site. TEM23, neighbouring to the south, has the same characteristics as TEM19 to TEM22, even though the second layer has a somewhat higher resistivity.

According to Rambøll (2003a) the southernmost subprofile is located on the Jyske Ås. No MRS soundings were placed here as the preceeding TEM sounding revealed a lower magnitude of sediments in the resistivity range 80 to 100 Ωm. This is supported by the new TEM soundings, TEM11 to TEM08, where the depth to the conductive clay has decreased to below 100 m. The thickness of the resistive layer decreases as we move south suggesting the soundings are on the northern slope of the outskirts of the Jyske Ås.

The investigation carried out in the area prior to the MRS survey suggested the location MRS01 as the best place to perform an investigation drilling. After evaluation of the MR soundings it appears that the most promising site is MRS05, if you omit the more uncertain potential of the deep aquifer.

6.2 NÆSBY

The efforts at Næsby include one MR sounding and three TEM soundings. At Næsby, it proved to be impossible to carry out the MR sounding where the TEM soundings were performed, close to drilling 32.1330, due to the presence of wind mills close to the preferred site. This provides a less favorable basis for comparison between MRS, TEM and drilling results than at Høgsted. Consequently, several drillings and an additional TEM sounding, ld017 by Dansk Geofysik, have been included for comparison to the MR sounding.

We do not present the comparison of the data models as profiles or subprofiles. Instead, the drillings and TEM soundings are arranged by their distance to the MR sounding. The distances are written above the models.

The MR sounding shows little aquifer potential at this site. The water content peaks at 25 m with 4 %. At 50 m the water content is zero. At the site the signal-to-noise ratio and the stacking time were insufficient for a safe quantitative evaluation of water content and permeability. The water content shown in the figure must be considered as a maximum value, and we cannot expect to find water at depth at this site. Note that the axis of the permeability plot has much lower values than at the Høgsted profile. The displayed permeability has the same order of magnitude as MRS02 at Høgsted. It must be emphasized that the values cannot be compared, for two reasons:

1. The signal-to-noise ratio is too low at Næsby. No safe quantification can be made.
2. They are not measured in the same area. The permeability estimate is an empirical relation building on certain constants describing the formation. These constants are for the presented interpretations transferred from MRS investigations in other post-glacial environments. Hence, they may deviate from the actual values making the absolute permeabilty estimates uncertain.

A relative evaluation of the permeability in a single sounding or between soundings in a limited area as Hoegsted is rather safe. So even though we cannot compare Høgsted and Næsby, it is possible to conclude that the permeability peaks at 25 m depth as the water content. The rather low maximum water content and a thickness of 15-20 m excludes this site as an exploration prospect.

Drilling 32.640 is the closest addtional data set to be found in the vicinity of the MRS site. A quick hydrogeological interpretation based on the lithological log of 32.640 would show rather low permeable sediments down to the chalk at 65 m depth, except for a thin layer of meltwater gravel at 10 m depth, which should be a considerable anomaly in permeability. Compared to the MR sounding the thickness is too little, while the water content is presumably too low. This might be due to layer equivalence. The inverse problem of the data interpretation is ill-posed leading to determination of the product of thickness and water content or permeability, respectively (Legchenko and Robain, 2003). This is similar to the high-resistivity equivalence of the DC geoelectrical method. So the aquifer at the MR sounding site may in fact be thinner but with a higher water content and permeability. An exaggeration of layer thickness is implicit in the nature of multi layer interpretation, as the equality constraint between two layers prevents rapid changes in geophysical property.

The remaining drillings, however, show thicker (up to 8 m in 32.1330), and expectedly less permeable (sand rather than gravel), sediments at depths varying form 15 to 40 m. This points towards the interpretation of the MR sounding, but discrepancy in localities excludes further considerations on the matter.

At the 32.640 the chalk is shallow, at 65 m. Nevertheless no indication of aquifers in the upper part of the chalk is detected. 32.1330 penetrates the chalk at 107 m depth. A depth which is more agreeable with the depth picked by the TEM27, TEM28 and TEM29 where the depth the chalk is estimated to 130 m. A water sample taken in the chalk shows that the groundwater has a resistivity below 1 Ωm (Dansk Geofysik, 2003), which explains why the TEM soundings do not detect the transition from clay to chalk. The sticky clay is encountered at 82 m and stretches to the depth of the chalk surface. This transition is clear cut on both the natural gamma, the resistivity and the conductivity logs. This depth is picked up accurately by all the TEM soundings in the area.

Drilling 32.1330 was made as a TEM survey showed 80 m thick layers with resistivities up to 80 Ωm. This is in the signature range for a sandy aquifer. However, the drilling revealed that only 15 of the 80 m were aquifer, the remaing 65 m were clay till. A MR sounding on the site prior to the drilling would probably have cooled the expectations. However, the aquifer is well-protected and of sufficient yield to interest the county.

6.3 SÆBY

At Sæby one MR sounding and three TEM soundings were performed. The drilling site was already picked from a TEM survey in the area, and the drill was put down in September 2003. The drill site was next to a power line and the TEM and MRS soundings had to be moved 150 m to the south.

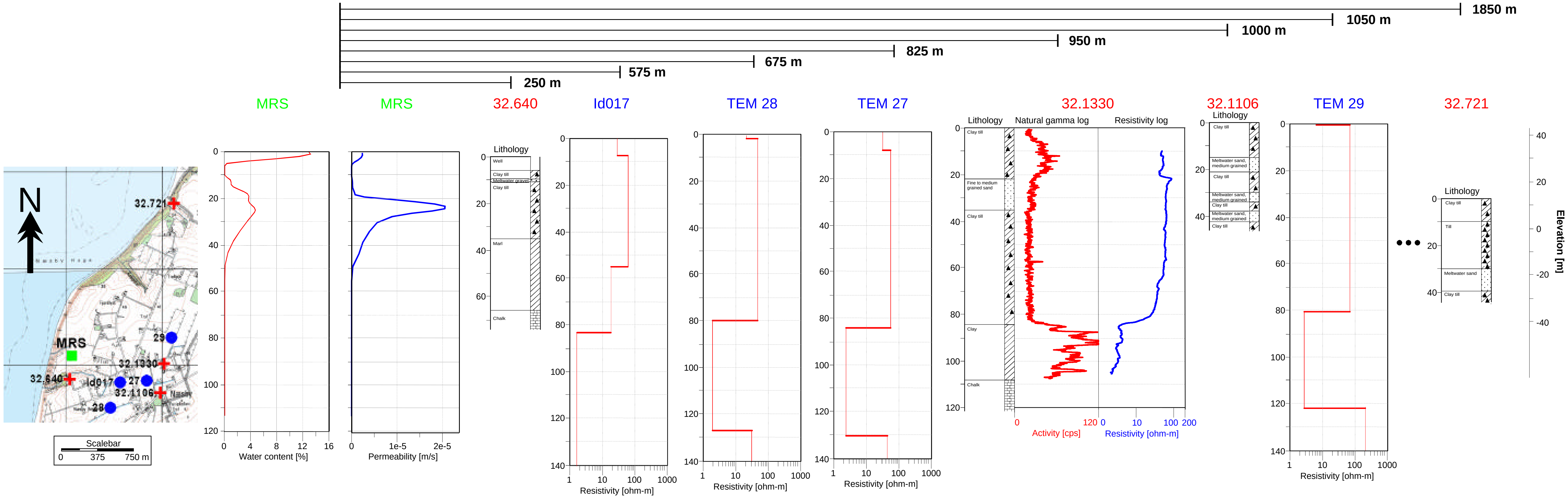
As at Næsby, the signal-to-noise ratio was insufficient for a quantitative interpretation of data. Hence, the water content should be considered as a maximum possible value. The MR sounding indicates that the water content peaks at 7.5 m depth and then stabilizes around 2 % at increasing depth. The permeabiliy is the same order of magnitude as at Næsby, but much smaller than at Høgsted. There is clear peak in permeability around 10 m depth, whereafter it falls to zero, literally speaking. Among all the measured locations, this location shows the least potential for exploration. TEM25, performed very close to the MRS, has 40 Ωm in the upper 25 m, while TEM26 has a 120-Ωm layer above a 40-Ωm layer from 20 to 30 m depth. TEM24 has 20 Ωm, less than 10 m thick in the top.

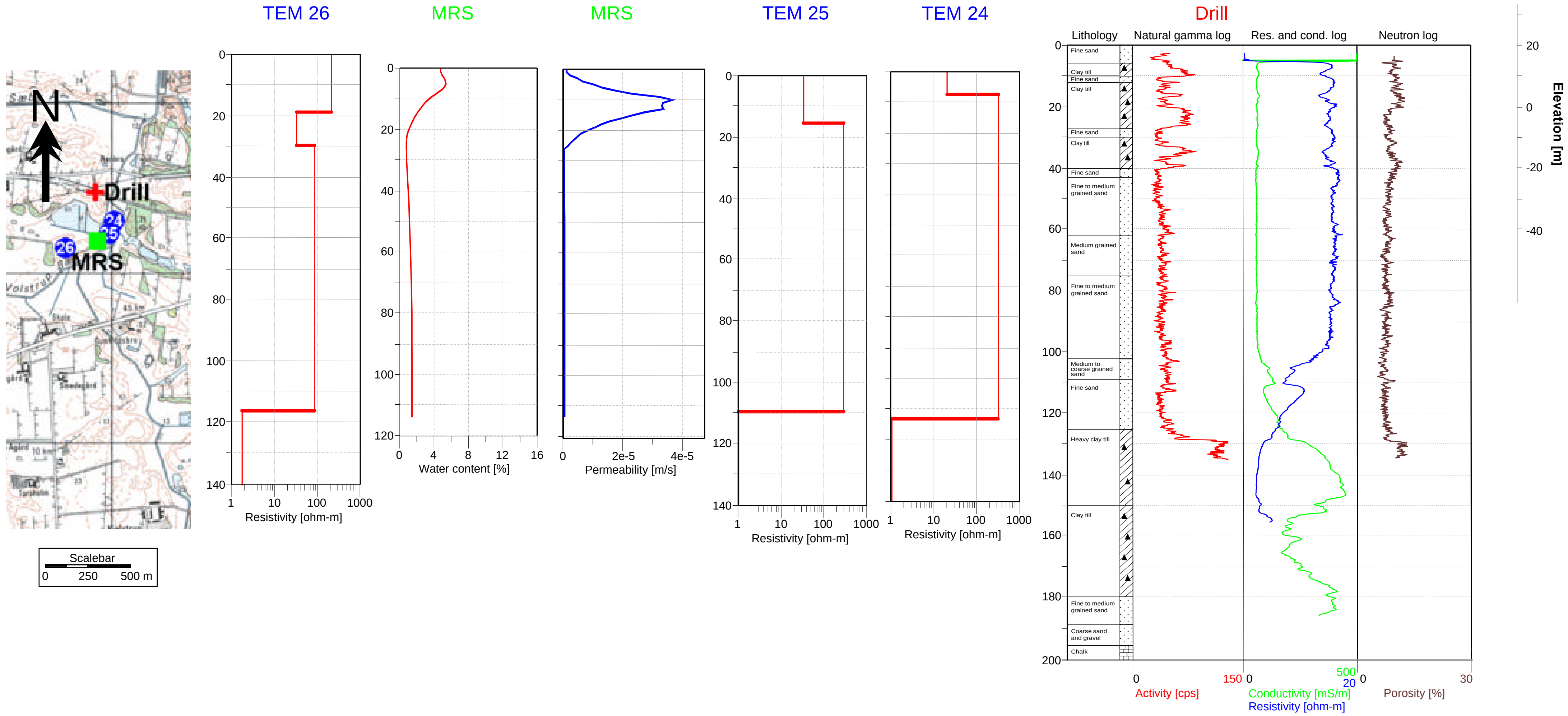
In all three TEM soundings, a 100 m thick layer with a resistivity around 100 Ωm is present. This layer is the reason for the drilling to be placed here. According to the MR sounding it hardly contains any water at all.

As to the drilling, the upper 40 m consist of clay till and fine sand. Below 40 m the lithology is dominated by fine- and medium-grained sands down to 125 m. The natural gamma log does show a higher clay content in the upper 40 m, while there is no transition in the resistivity and conductivity logs. The Neutron log, measuring the porosity, shows a relatively high level of porosity in the upper 20 m. This is, in fact, the highest level measured down to 130 m, which is beyond the penetration of MRS. This supports the MRS which had the highest permeability in the upper 20 m. It is counter-intuitive that the sandy part of the drilling has lower porosity and permeability than the clay tills, but the sandy part of the formation has a high content of silt.

The transition from clay till to more sandy formations at 40 m depth is marked by a shift from intermediate to high resistivity in the TEM soundings. They also find a conducting layer in depths around 110 m. This depth corresponds to a lowering in resistivity (rising in conductivity) in the geophysical logs in the drilling, while the lithology shows fine sand at this depth. Rambøll (2003b) reveals that the groundwater at this depth is salty, which lowers the resistivity. The transition seen in lithology and natural gamme log at 125 m from sand to heavy clay till has too little contrast to be picked up by the TEM sounding. The boundary is hardly recognizable in the resisitivty and conductivity logs.

MRS3
MRS5
Drill
MRS1
MRS4
MRS2
Scalebar
0 125 250 m
TEM 18
MRS 03
MRS 03
TEM 17
TEM 16
MRS 05
MRS 05
TEM 15
TEM 14
MRS 01
MRS 01
Drill
TEM 13
TEM 12
MRS 04
MRS 04
TEM 19
TEM 20
TEM 21
TEM 22
MRS 02
MRS 02
TEM 23
TEM 11
TEM 10
TEM 09
TEM 08
Depth [m]
Resistivity [ohm-m]
Water content [%]
Permeability [m/s]
Lithology
Natural gamma log
Res. and cond. log
Activity [cps]
Conductivity [mS/m]
Resistivity [ohm-m]
Elevation [m]


1850 m
1050 m
1000 m
950 m
825 m
675 m
575 m
250 m
MRS
MRS
32.640
Id017
TEM 28
TEM 27
32.1330
32.1106
TEM 29
32.721
N
32.721
MRS
29
32.1330
32.640
Id017
27
32.1106
28
Scalebar
0
375
750 m
Water content [%]
Permeability [m/s]
Lithology
Resistivity [ohm-m]
Natural gamma log
Resistivity log
Activity [cps]
Elevation [m]



N
Drill
MRS
24
25
26
Scalebar
0
250
500 m
TEM 26
Resistivity [ohm-m]
MRS
Water content [%]
MRS
Permeability [m/s]
TEM 25
Resistivity [ohm-m]
TEM 24
Resistivity [ohm-m]
Drill
Lithology
Natural gamma log
Res. and cond. log
Neutron log
Activity [cps]
Conductivity [mS/m]
Resistivity [ohm-m]
Porosity [%]
Elevation [m]

7 CONCLUSIONS

This chapter summarizes the conclusions to be drawn and the experiences made in the MRS survey in Northern Jutland. A series of perspectives for the method in a Danish context as well as recommendations for further investigations and developments are also stated.

7.1 CONCLUSIONS

The MRS survey was a success as the results confirmed (or were confirmed by) the drillings and TEM soundings in the area. Especially at the Høgsted profile, the agreement between the three data types is excellent.

If the MR soundings performed at Høgsted, Næsby and Sæby had been completely aimed at production, none of the investigated sites would be subsequently drilled with an explorational purpose. At Sæby and Næsby the water content is too low, and at Høgsted the potential is higher but inadequate. The drillings already performed, it is safe to post-rationalize and claim that the sites should probably not have been drilled.

The penetration depth of the method does not exceed 80 m for quantitative evaluation of results, if the setup of this investigation is used. Hence, MRS should be used in areas where the aquifers are comparably shallow, such as e.g. Northern Jutland county, the counties on Seeland and Storstrøms county. The method will probably not be able to resolve the deep buried valley structures of eastern and western Jutland.

A limiting factor for the penetration depth is the size of the cultural noise, which in Denmark is fairly high. To compensate for a high noise level, the measurement stack should be increased to improve the signal-to-noise ratio. To obtain sufficiently high data quality for quantitative interpretation, the equipment measured for 24 hours on single sites at Høgsted. It is clear that such low production rate does not invite for data coverage over large areas. MRS should rather be employed as an intermediate step between the standard area covering methods and drillings. The work flow should be:

- Acquire traditional data types, such as TEM and geoelectrical data.
- Select potential drill sites based on these surveys.
- Perform MR soundings
- and proceed with drilling if the MR sounding indicate a satisfying amount of water.

In a production situation, the operator would not leave the equipment running for 24 hours as at Høgsted. Like at Sæby and Næsby, the operator would measure until it was clear that the aquifer potential was low. The low signal-to-noise will typically be a reflection of a low water content.

At Næsby and Sæby, we experienced that we cannot apply the method anywhere in the terrain. A safety distance of at least 150 m should be kept to power lines and wind mills. As opposed to TEM, it is not the presence of the conductor itself that is disturbing. It is the presence of magnetic fields associated to running currents and trasients. The potential drill sites should be picked with such a safety distance to avoid discrepancy in location. This is, of course, not always possible, as the drilling, not the MRS, is the scope of a standard survey.

7.2 PERSPECTIVES

These introductory experiments with Magnetic Resonance Soundings in Denmark had a positive outcome. It seems that the method can provide a foundation to reject drilling sites which have resistivity signatures in the aquifer range. However, no verification of the method has been made on a location with a large aquifer at shallow depth. This has been done in other countries, but it would be reassuring to see a such result from Denmark to make sure the method behave similarly here. The MRS signal amplitude depends on the water content, as the TEM signal amplitude depends on the earth resistivity. It is more challenging from a technical point of view to perform measurements in an area with little signal, but measurements in high signal areas are often more convincing as the less disturbed data clearly shows that the physics of the method works. Furthermore, there is a certain psychological effect by a positive result.

In any case, the method should be applied in different geological settings to see how it reacts.

Intentionally, no comparisons between test pumping data and MRS permeabilities have been made so far. The relationship between MRS water content and MRS relaxtion time and permeability is empirical, and no investigations exist to scale it. The material constants applied in this survey to obtain permeability values were adopted from surveys in other postglacial environments in Russia and Canada. They are likely to vary to some extent, and the permeability values obatined are uncertain.

Pumping tests have been made in the upper aquifer in drilling 32.1330 at Næsby. According to Dansk Geofysik (2003) a filter was set in the aquifer from 23 to 35 m and the transmissivity measured was 6.86e-4 m^2/s. The aquifer in the MRS sounding, also from 20 to 35 m has a predicted transmissivity of 1.8e-4 m^2/s (the transmissivity is defined as the integrated permeability within the depth range). This is the right order of magnitude, but off by a factor of three. Apart from the uncertainty on the empirical relaionship just mentioned, the poor signal to noise ratio and the 1 km between the MRS and drilling site question the justification of comparison.

Pumping tests were also performed in two drillings in the vicinity of the Høgsted soundings, at the Høgsted village in 1976 (Rambøll, 2003a). Filters were set in the depth intervals 35 to 42 m and 37 to 44 m. They indicate a transmissivity in the aquifer between 4.6e-3 and 5.2e-3 m^2/s. At MRS5 the maximum calculated transmissivity for a seven m depth interval is 1.5e-3 m^2/s. The same order of magnitude but off by a factor of three to four. For a larger depth interval a higher value is obtainable.

If the MRS is to be used on a regular basis in Denmark, it is recommended to launch an investigation to calibrate the relationship between MRS signal and permeability in different Danish geological environments.

INSTRUMENTAL PERSPECTIVES

At the Department of Earth Sciences, University of Aarhus research is done in Remote Reference. The basic concept is to measure noise and data simultaneously at localities close to each other. If the noise depends more on time than distance, the noise may be deconvolved from the noise-affected data, leaving a clean sounding curve. This is developed for use in TEM, but may be applied in MRS as well. It would significantly improve the signal-to-noise ratio and, consequently, the penetration depth for a given stacking time.

An existing technique for lowering of electromagnetic noise implies a figure-of-eight shaped loop, where incoming noise induces electromotive forces with opposite sign in the two "subloops", hence neutralizing each other. This should be attempted in the next phase of MRS in Denmark.

INTERPRETATIONAL PERSPECTIVES
The inversion results of the MR soundings at Høgsted (MRS1, MRS3 and MRS5) and at Sæby has distinct peaks. All four of them show that the shallow flank of the peak is steep while the deep flank is less steep. This might be due to the equality constraints in the minimum structure inversion. When the constraint becomes harder and the data more uncertain with increasing depth, relative weight is put from data to constraint in the inversion.

In the interpretation of the traditional hydrogeophysical methods few layer models are usually used in Denmark. For few layer models both geophysical property and layer boundaries are optimized by inversion. In the given case, the few layer inversion would have forced layer boundaries, and the data would decide the lower boundary of the aquifer. It would be interesting to apply the few layer inversion scheme on the MRS data.

Furthermore, it would be interesting to attempt Mutually Constrained Inversion (MCI) between TEM and MRS. The layer boundaries would then be determined by a combination of the the two data sets. This is relevant since resistivity correlates to hydrogeological property, e.g. resistivity below 5 Ωm indicates heavy clay which is a barrier in a hydrogeological context.

Even if the TEM soundings do not show the aquifer, as we have seen in this survey, the information contributed by the MRS might provoke the aquifer in the TEM soundings. An increased water content will allways have a different resisitivity than the surrounding layers, but the contrast can be so small that it is indistinguishable from the TEM data alone. By MCI the aquifer extension might be extrapolated from a MR sounding in to neighbouring TEM soundings.

7.3 CONCLUSIONS AND PERSPECTIVES - SUMMARY

CONCLUSIONS
- The MRS method is capable of estimating the water content in the upper 80 m of the earth. Hence, it may be a valuable tool in areas where resistivity signatures are unequivocal.
- The noise level in Denmark is high, which means MRS is time-consuming.
- MRS should enter a stage between area-covering methods and drilling.
- Safety distance of 150 m to electromagnetic noise sources should be kept.

PERSPECTIVES
- MRS on high-signal location.
- Investigation of calibration of the empirical relationship between MRS water content and MRS relaxation time and the permeability.
- Development of remote reference for noise reduction and increased penetration depth.

- Develop few layer inversion of MRS data.
- Development of Mutually Constrained Inversion of MRS and TEM data with respect to layer boundaries.

8 REFERENCES

Dansk Geofysik, 2003. Nordjyllands Amt - Løgstør Kommune - Undersøgelsesboring DGU nr. 32.1330 ved Næsby, p. 37. Data report.

Legchenko, A. and Robain, H., 2003. Field tests of NUMIS^{PLUS} MRS equipment in Northern Denmark (August 2003), p. 71. IRD data report.

Rambøll, 2003. Hjørring Kommune - Sammenstilling af eksisterende materiale - udpegning af borested, p. 45. Data report.

Rambøll, 2003b. Nordjyllands Amt - Undersøgelsesboring ved Sæby, DGU 11.1245.

9 FURTHER READING

MRS

Legchenko, A. Baltassat, J.-M., Beuce, A. and Bernard, J., 2002. Nuclear magnetic resonance as a tool for hydrogeologists. Journal of Applied Geophysics, 50, 21-46.

Legchenko, A. and Shushakov, O.A., 1998. Inversion of surface NMR data. Geophysics, 63 (1), 75-84.

Legchenko, A. and Valla, P., 1998. Processing of surface proton Magnetic resonance signals using non-linear fitting . Jounal of Applied Geophysics, 39, 206-214.

Legchenko, A. and Valla, P., 2002. A review of the basic principles for proton magnetic resonance sounding measurements. Journal of Applied Geophysics, 50, 3-19.

Yaramanci, U., Lange, G. and Knödel, K., 1999. Surface NMR within a geophysical study of an aquifer at Haldensleben (Germany). Geophysocal Procpecting, 47, 923-943.

TEM

Auken, E., Jørgensen, F. and Sørensen, K.I., 2003. Large-scale TEM investigations for groundwater. Exploration Geophysics, 34,188-194.

Christensen, N.B. and Sørensen, K.I., 1998. Surface and borehole electric and electromagnetic methods for hydrogeological investigations. European Journal of Environmental and Engineering Geophysics, 3, 75-90.

Danielsen, J.E., Auken, E., Jørgensen, F., Søndergaard, V. and Sørensen, K.I., 2003. The application of the transient electromagnetic method in hydrogeophysical surveys. Journal of Applied Geophysics, 53, 181-198.

Fitterman, D.V. and Stewart, M.T., 1986. Transient electromagnetic sounding for groundwater. Geophysics, 59, 889-901.

10 LOCAL TEST SITE AT HØGSTED

As soundings were performed in Høgsted over several days, a local test site was established to ensure the repeatability of the TEM equipment. The soundings are shown in Figure 10.1.

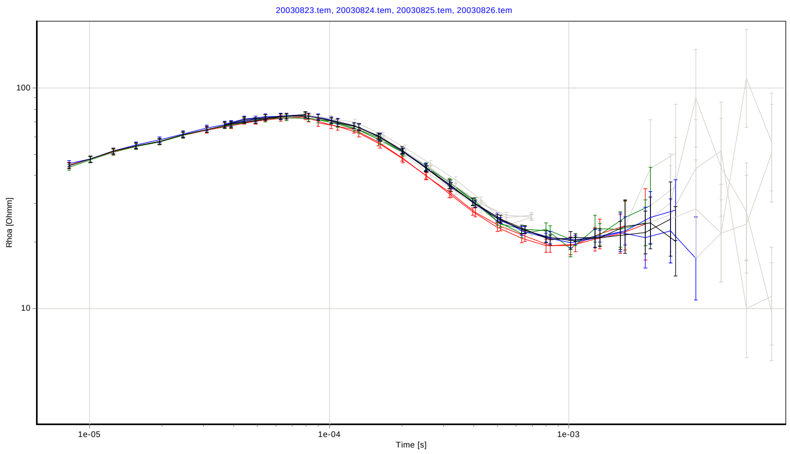


Figure 10.1 The data curves for the soundings at the local testsite at Høgsted. 20030823.tem is red, 20030824.tem is green, 20030825.tem is blue while 20030826.tem is black.

The test sounding performed on 23 August 2003 is slightly off the three others which coincide completely. It deviates at intermediate times, which is odd as instrument trouble is usually seen at early times. It looks more like a discrepancy in the exact location of the local test site. However, the difference at intermediate times is within the allowed 10 %.

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DATA REPORT BY LEGCHENKO AND ROBAIN

Field tests of NUMIS^{plus} MRS equipment in northern Denmark (August 2003)

September 2003

IRD report

Institut de Recherche pour le Développement

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Field tests of NUMIS^{plus} MRS equipment in northern Denmark (August 2003)

Anatoly Legchenko and Henri Robain

September 2003

IRD report

Key words: geophysics, groundwater, magnetic resonance sounding, nuclear magnetic resonance, MRS, NMR, SNMR.

In bibliography, this report should be cited as follows:

Anatoly Legchenko and Henri Robain, (2003) – Field tests of NUMIS^{plus} MRS equipment in northern Denmark (August 2003). IRD report, 71 p., 28 fig., 3 tabl., 1 ann.

Abstract

Magnetic Resonance Sounding (MRS) is distinguished from other geophysical tools used for ground water investigation by the fact that it measures a magnetic resonance signal generated directly from subsurface water molecules. An alternating current pulse energizes a wire loop on the ground surface and the MRS signal is generated; subsurface water is indicated, with a high degree of reliability, by non-zero amplitude readings. Measurements with varied pulse magnitudes then reveal the depth and thickness of water-saturated layers. The hydraulic conductivity of aquifers can also be estimated using boreholes for calibration. MRS can be used for both predicting the yield of water supply wells, and for interpolation between boreholes, thereby reducing the number of holes required for hydrogeological modeling.

With a goal of testing the efficiency of this technique in Denmark, field tests were carried out in cooperation with Aahrus University (Denmark) by the Institut de Recherche pour le Développement (IRD, France) in northern Denmark between 20 and 29 August 2003. During the fieldwork the NUMIS^{plus} MRS instrument produced by IRIS Instruments (France) was used.

In this report, the basic principles of the method and the results of the field tests are presented.

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Introduction

Magnetic Resonance Sounding (MRS) is sensitive specifically to ground water because subsurface water molecules generate a magnetic resonance signal that can be recorded. This direct detection of subsurface water is the main advantage of MRS compared with other geophysical tools used for hydrogeological investigation.

MRS is a large-scale method, and the investigated volume can be approximated by a cube of $1.5 \times a$ where $10 \le a \le 150$ m is the side of a square loop. The method, with 'HYDROSCOPE' equipment, was developed in Russia during the early nineteen eighties (Semenov et al. 1989) and proved the possibility of non-invasive detection of aquifers using magnetic resonance measurements. At that time, only the geometry and water content of water-saturated layers could be obtained using MRS. Further developments, and experience of MRS practical applications, made possible the estimation of aquifer hydraulic conductivity, for which the water content w and relaxation time T_1 were derived from MRS measurements and used with an empirical relationship borrowed from Nuclear Magnetic Resonance Logging (NML). In practice however, it is often more reliable to use MRS estimates of transmissivity than hydraulic conductivity, and there is generally good correlation between MRS transmissivity estimates and those indicated by borehole pumping tests.

In August 2003, a field survey was carried out in northern Denmark by the Institut de Recherche pour le Développement (IRD, France) in cooperation with Aahrus University (Denmark). The goal of this work was to test the efficiency of a combined geophysical approach (TEM+MRS) applied to localization of glacial deposits that are potential aquifers in Denmark and characterization of their hydrodynamic properties. For the fieldwork, NUMIS^{plus} MRS instrument produced by IRIS Instruments (France) and GEONICS (Canada) Transient EM system PROTEM were used.

In this report, the basic principles of the MRS method and the results of the field tests are presented.

1. Magnetic Resonance Sounding method

1.1. BASIC PRINCIPLES

To an outside observer, the MRS field set-up appears very similar to that of Transient EM with a coincident transmitting/receiving loop. A wire loop is laid out on the ground, normally in a circle of 10 m to 150 m diameter depending on the depth of the target aquifer. The loop may also be laid out in a square or, to improve signal to noise ratio (S/N), in a “figure of eight” shape (Trushkin et al. 1994).

The method is based on fact that protons possess a non-zero magnetic moment. The resonance behaviour of proton magnetic moments in the geomagnetic field ensures that the method is selective and sensitive only to ground water. The resonance frequency $\omega_0 = 2\pi f_0$ is given by the spin Larmor resonance condition $\omega_0 = \gamma_p B_0$, with B_0 being the magnitude of the geomagnetic field and $\gamma_p / 2\pi = 4.257707 \times 10^7$ Hz/T the gyromagnetic ratio for protons. The Larmor frequency is obtained from measurements of the geomagnetic field (B_0) on the surface using a proton magnetometer. Depending on the global geographical location of the investigated area, the geomagnetic field varies between approximately 20,000 and 60,000 nT, and the Larmor frequency correspondingly varies between 800 and 2800 Hz.

Using the classical model (Slichter 1990), in which the coordinate system rotates with an angular frequency $\omega = -\gamma B_0$, the local macroscopic spin magnetization of protons in a water sample dV can be presented as vector $\mathbf{M}$ with the amplitude $M = |\mathbf{M}| = M_0 dV$, where $M_0 = 3.287 \times 10^{-3} B_0$ at 293°K (20°C) and is the spin magnetization of hydrogen protons per unit volume. In the equilibrium position, $\mathbf{M}$ is oriented along the geomagnetic field and the angle θ between the spin magnetization and the geomagnetic field is equal to zero ($\theta = 0$) as it is shown in Figure 1a.

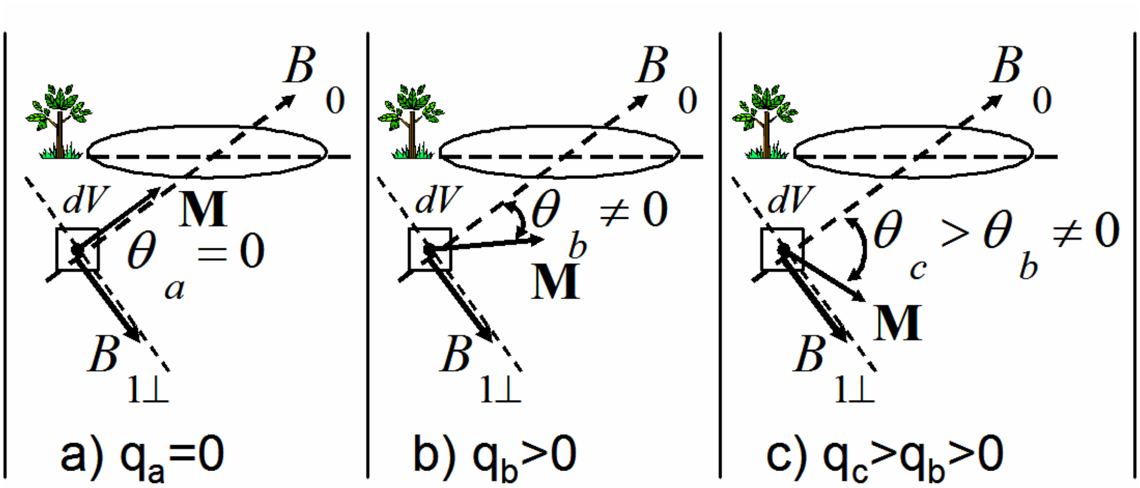


Figure 1. Precession of spin magnetization in rotating with the Larmor frequency coordinate system.

The magnetic resonance signal is generated only by a perpendicular to the earth's magnetic field component of the spin magnetization $M_{\perp} = M\sin(\theta)$, so no signal exists at this time. A pulse of alternating current then energizes the MRS loop:

$$i(t) = I_0 \cos(\omega_0 t), \quad 0 < t \leq \tau, \qquad (1)$$

where I_0 and τ are respectively the pulse amplitude and duration. The pulse causes precession of the spin magnetization around the geomagnetic field, which produces a non-zero flip angle (Figure 1b):

$$\theta = \frac{\gamma_p B_{1\perp}(\mathbf{r})}{2I_0} q, \qquad (2)$$

where $q = I_0 \tau$ is the pulse parameter, $B_{1\perp}(\mathbf{r})$ is a perpendicular to the geomagnetic field component of the loop magnetic field, and $\mathbf{r} = r(x, y, z)$ is the coordinate vector. For a sample $dV(\mathbf{r})$, the flip angle θ is larger for larger values of the pulse parameter q (Figures 1b and 1c). Transmissions from the loop magnetic field can be calculated accurately (Weichman et al. 2000), but in general they decrease with increased distance r between the loop and the sample $dV(\mathbf{r})$ as a cubic function ($B_{1\perp} / I_0 \sim 1/r^3$). Consequently, for fixed q, the flip angle θ depends on the water location. The magnetic resonance signal is proportional to θ ($M_\perp = M \sin(\theta)$) and thus, by measuring the signal on the surface for various values of the pulse parameter q, the location of a water sample $dV(\mathbf{r})$ can be derived from Equation 2. This is the principle of Magnetic Resonance Sounding.

Water content

Precession of the spin magnetization $\mathbf{M}$ around the geomagnetic field caused by the current pulse in the loop creates an alternating magnetic field that can be measured, using the same loop, after the pulse cut-off. Oscillating with the Larmor frequency, the magnetic resonance signal $e(t)$ has an exponential envelope and is a function of the pulse parameter q:

$$e(t,q) = e_0(q) \exp\left(-t / T_2^*(q)\right) \sin\left(\omega_0 t + \varphi_0(q)\right), \qquad (3)$$

where $T_2^*(q)$ is the spin-spin relaxation time, and $\varphi_0(q)$ is the phase.

The signal induced in the receiver loop is proportional to the sum of the flux of all precessing magnetic moments $M_\perp$. Using the reciprocity theorem, and neglecting the higher harmonics of the pulse and a possible frequency offset between the Larmor frequency and the current frequency, the induction in the loop voltage thus becomes (Legchenko et al. 2002a)

$$e_0(q) = \frac{M_0 \omega_0}{I_0} \int_V B_{1\perp}(\mathbf{r}) e^{j2\varphi_0(\mathbf{r})} \sin\big(\theta(\mathbf{r},q)\big) w(\mathbf{r}) dV(\mathbf{r}), \qquad (4)$$

where φ_0 is the phase shift caused by electrically conductive rocks, and $0 \le w(\mathbf{r}) \le 1$ is the water content. As both $M_0 = \gamma_p B_0$ and $\omega_0 = \gamma_p B_0$ are proportional to the geomagnetic field, it follows from Equation 4 that the amplitude of the magnetic resonance signal depends on the geographical location of the investigated area $e_0 \sim B_0^2$ (Legchenko et al. 1997).

Assuming that the stratification is horizontal, and the vertical distribution of resistivity is known, Equation 4 of the signal amplitude e_0 can be simplified to a Fredholm linear integral equation of the first kind (Legchenko and Shushakov 1998):

$$e_0(q) = \int_0^L K(q,z) w(z) dz, \qquad (5)$$

where $K(q,z) = \frac{M_0 \omega_0}{I_0} \int_{x,y} B_{1\perp}(\mathbf{r}) \sin\big(\theta(\mathbf{r},q)\big) dx dy$.

Numerical results show that distant protons produce a negligibly small signal and, hence, integration can be limited by approximately $x^2 + y^2 < (1.5D)^2$, where D is the loop diameter (or side for a square loop). Consequently, $L = 1.5D$ can be considered as the maximum possible depth of water detection by MRS, and a cube with side $1.5D$ as the approximate maximum possible volume. It should be noted that in heterogeneous geological environments, MRS data about aquifers are the averages of readings for a volume proportional to the size of the loop.

The vertical distribution of water content $w(z)$ is resolved by Equation 5. This linear equation may be solved by projecting it onto finite dimensional subspace, as approximated by the projected equation

$$\sum_j \left(h_j(q_i) w_j \right) = e_{0i}, \tag{6}$$

where $i = 1,2,..,I$, $j = 1,2,..,J$ and $h_j(q)$ is a set of kernel vectors obtained by projecting the kernel $K(q,z)$ on a set of basis functions $b_j(z)$, so that

$$w(z) = \sum_j \left(w_j b_j(z) \right), \tag{7}$$

and $h_j(q) = \int_0^L K(q,z) b_j(z) dz$.

From a physical point of view, the problem allows the basis functions to be assumed as box-car functions. Hence, the kernel vectors are the elementary responses from the layers of water ($w_j = 1$), characterized by their depth z and thickness Δz. If the depth intervals are $0 \le z \le L$, $\Delta z_j = z_{j+1} - z_j$ and $L = \sum_{j=1}^{J} \Delta z_j$ then the basis functions are $b_j(z_j \le z < z_{j+1}) = 1$, $b_j(z < z_j, \quad z \ge z_{j+1}) = 0$ and the kernel vectors are

$$h_j(q) = \int_{z_j}^{z_{j+1}} K(q,z) dz. \tag{8}$$

In a matrix notation, projected Equation 6 can be written as

$$\mathbf{Aw} = \mathbf{e_0}, \tag{9}$$

where $\mathbf{A} = \left[a_{i,j} \right]$ is a rectangular matrix of $I \times J$ with the elements $a_{i,j} = h_j(q_i)$, $\mathbf{e_0} = (e_{01}, e_{02}, .., e_{0i}, .., e_{0I})^T$, $e_{0i} = e_0(q_i)$ being the set of experimental data, $\mathbf{w} = (w_1, w_2, .., w_j, .., w_J)^T$, $w_j = w(\Delta z_j)$ being the vertical distribution of water content, and the symbol T denoting transposition. The inversion was carried out according to the well-known Tikhonov regularization method (Tikhonov and Arsenin 1977).

The MRS inverse problem is ill-posed. It means that it is impossible, for a particular layer, to know both the layer thickness and the water content, what is giving rise to layer equivalence. Two layers at the depth z_e with the thicknesses $\Delta z_1, \Delta z_2 < \Delta z_e$ are equivalent if $w_1 \Delta z_1 = w_2 \Delta z_2$. The equivalent layers cannot be resolved. The thickness Δz_e is defined by the vertical resolution of the method which depends on the magnetic field created by the loop; the larger the gradient of the field, the better the resolution. The magnetic field of a loop on the surface with a current passing through is well known; the gradient of the field is large close to the surface and decreases with increasing depth. Consequently, the resolution of the MRS is also better close to the surface. Figure 2 shows the relative errors of resolution for a synthetic model consisting of a 10-m-thick layer ($w = 20\%$) versus the layer depth. A square 100-m-side loop is assumed.

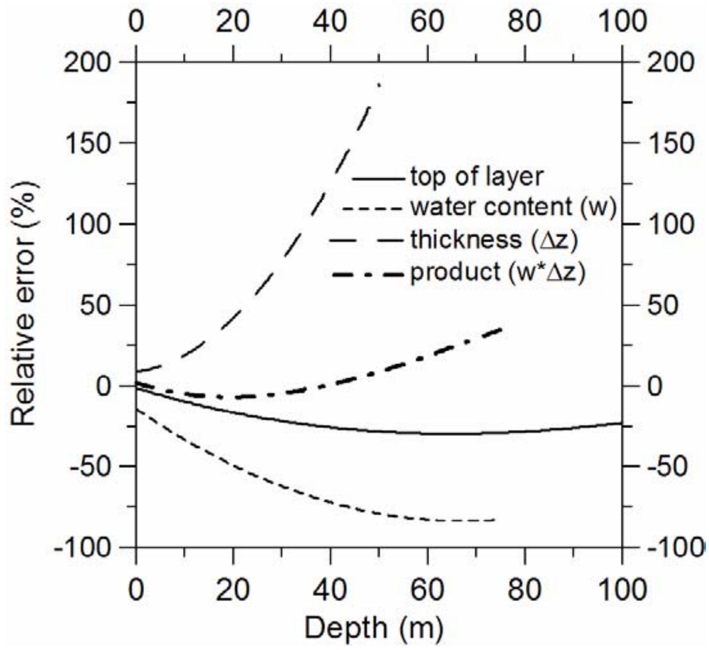


Figure 2. Numerical modeling: resolution of a 10 m-thick layer when using 100 m-side square loop.

The errors were calculated as $\varepsilon = 100\% \times (P_{inv} - P_{\mathrm{mod}}) / P_{\mathrm{mod}}$, where P_{inv} and P_{mod} are, respectively, a parameter from the inversion and its true value given by the model. It can be seen that both the water content and the thickness are better resolved when the layer is close to the loop, and that errors increase with distance from the loop. At a depth greater than about one half of the loop side, the 10-m-thick layer cannot be resolved. However, note that the resolution accuracy of the product $w \times \Delta z$ is much better.

In practice, measurement of the signal is not possible without an instrumental delay ("dead time") of τ_d. Consequently, for each value of q, the initial amplitude e_0 cannot be measured but is obtained by the extrapolation

$$e_0 = e(\tau_d)\exp(\tau_d / T_2^*) . \qquad (10)$$

The non-linear fitting scheme of Legchenko and Valla (1998) is used for estimating $e(\tau_d)$ and T_2^* from records after the pulse time series. The pulse duration for currently available MRS instruments is about 40 ms and the "dead time" is $\tau_d = 30 \div 40$ ms; this is a limitation that does not allow measuring short signals with $T_2^* < 30$ ms.

The water content derived from MRS data is calculated as follows:

Let V be the total volume of the subsurface; V_W and V_A, the parts of subsurface filled with water and air respectively, and V_R the part of subsurface occupied by rocks. Thus, $V = V_W + V_A + V_R$. The water (V_W) can be separated into two parts: water V_{short}, characterized by a very short MRS signal which cannot be measured by MRS instruments, and water V_{long} that produces a measurable signal with sufficiently long relaxation time ($V_W = V_{short} + V_{long}$). Thus, the MRS water content can be defined as the part of the total volume of the subsurface occupied by measurable MRS water: $w = \frac{V_{long}}{V} 100\%$.

Water in porous media can be divided into two parts (after Castany 1982): capillary-bound water and free water ($V_W = V_{bound} + V_{free}$). The capillary-bound water (V_{bound}) is attached to grain walls and cannot be extracted by gravity. The free water (V_{free}) is located some distance from the grain walls and, therefore, can be extracted by gravity. Capillary-bound water generally dominates in the unsaturated zone, but both capillary-bound and free water are normally present in the aquifer. In highly permeable water-saturated rocks such as sand or gravel, most of the water is free. On the contrary, in water-saturated rocks with low permeability, such as clay, most of the water is capillary-bound. Experiences of magnetic resonance measurements in porous media show that capillary-bound water is characterized by shorter relaxation times, and free water by longer relaxation times (Chang et al. 1997). In some rocks, capillary-bound water may have $T_2^* < 30$ ms, and free water $T_2^* > 30$ ms. As MRS instruments are able to measure only relatively long signals ($T_2^* > 30$ ms), it is clear that in these rocks MRS is sensitive mostly to free water (Schirov et al. 1991).

In nuclear magnetic resonance logging, the magnetic resonance response is correlated with the effective porosity. Obviously, MRS water content w is also related to the effective porosity, but there is currently insufficient experimental data to establish a quantitative relationship.

The relationship between measured signal $e_0(q)$ and water content $w(z)$ shown in Equation 5 was verified experimentally in the early 1980s, when field measurements were carried out on an ice (0.8 m thick) covered lake in Russia using HYDROSCOPE equipment (Schirov et al. 1991). The magnetic resonance signal from bulk water in the lake has a long relaxation time ($T_2^* > 800$ ms) and, hence, all the water contributes to the MRS water content. The theoretical signal calculated for the model of a 10-m-thick water body ($w = 100\%$), derived from mapping the lake bottom, fits particularly well with the initial part of the experimental data where the contribution of lake water into the total signal is maximal (Figure 3). No information was available about possible aquifers below the lake, so MRS data for greater depths could not be evaluated.

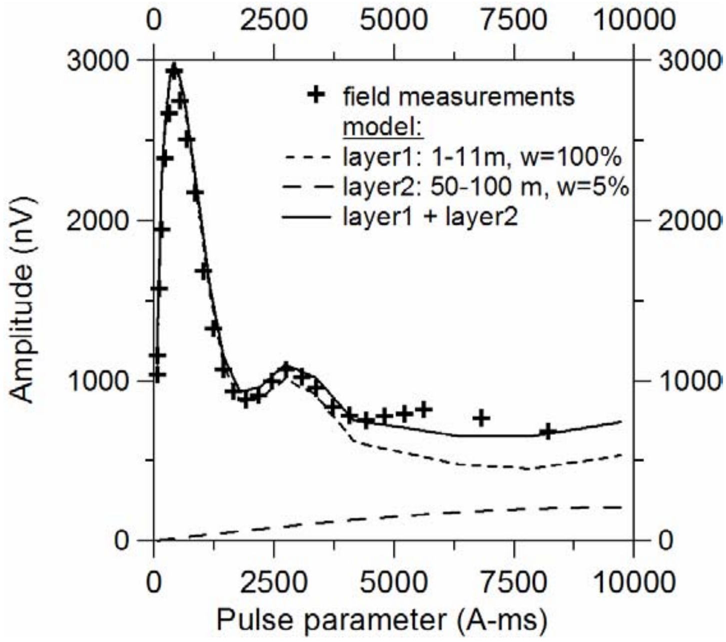


Figure 3. Frozen lake experiments (Schirov et al. 1991): comparison of measured and theoretical signals.

Relaxation Times

Other important characteristics of the magnetic resonance signal are; longitudinal relaxation time T_1, transverse relaxation time T_2, and the observed relaxation time T_2^* (Slichter 1990). In porous media, the relaxation times T_1 and T_2 ($T_1 \approx 1.5 \times T_2$) are proportional to the mean pore size (Kleinberg et al. 1994; Kenyon 1997):

$$T_{1(2)} \approx \frac{V_p}{\rho_{1(2)} S_p}, \tag{11}$$

where S_p and V_p are the surface and volume of pores respectively; and $\rho_{1(2)}$ is the surface relaxivity (when using T_1 or T_2), which depends on rock mineralogy. In magnetic resonance logging, both T_1 and T_2 are used for estimating aquifer permeability.

Because of technical difficulties with measuring T_1 and T_2 in large volumes from the surface, only the MRS T_2^* relaxation time, which can be derived from the envelope of the magnetic resonance signal (Equation 3), was used initially (Schirov et al. 1991). Whilst it is known that T_2^* is proportional to T_2, T_2^* is also sensitive to local inhomogeneities in the geomagnetic field ΔB_0 caused by rocks (Farrar and Becker 1971);

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma_p (\Delta B_0 / 2)\,, \qquad (12)$$

which makes T_2^* less reliable than T_1 or T_2 for pore size estimation.

Examples of T_2^* and T_1 measurements in rocks with different magnetic properties are presented in Table 1 (Legchenko et al. 2002b).

Rock type	Magnetization (A/m)	Susceptibility (SIU)	T_2^* (ms)	T_1 (ms)	Comments
Reef limestone (Cyprus)	1×10^{-4}	-9.1×10^{-6}	80	220	Unsaturated zone
Fractured limestone (Cyprus)	2.8×10^{-4}	-8.5×10^{-6}	130	430	Aquifer
Highly fractured limestone (France)	8.1×10^{-3}	1.5×10^{-3}	280	800	Aquifer
Karst limestone (Cyprus)	4.5×10^{-5}	-7.2×10^{-6}	460	1000	Aquifer
Clay and fine sand (France)	1.4×10^{-3}	1.4×10^{-4}	70	310	Aquifer
Medium sand (France)	3.9×10^{-4}	2.9×10^{-5}	120	420	Aquifer
Gravel and coarse sand (France)	7.5×10^{-4}	4.4×10^{-4}	330	600	Aquifer
Sandstone (USA)	3.2×10^{-4}	2×10^{-4}	80	-	Aquifer
Basaltic gravel (Cyprus)	1.3×10^{-1}	4.8×10^{-3}	10	-	Aquifer

Table 1. Magnetic properties of rocks and MRS relaxation times.

The magnetization and magnetic susceptibilities of the rocks were measured in the laboratory with rock samples prepared either as 8 cm^3 solid cubes or 5.4 cm^3 powder volumes, depending on the rock material. Measurements were carried out using a JR5 instrument (AGICO, Geofysika) with a sensitivity of 2.4×10^{-6} A/m, and a KLY-3S instrument (AGICO, Geofysika) with a sensitivity of 3×10^{-8} SIU. Relaxation times were measured from the surface with a NUMIS MRS instrument that covered large volumes. In limestone, the signals from both free and capillary-bound water were relatively long ($T_2^* > 70 \div 80$ ms), considering the threshold of the MRS instruments (30 ms). On the contrary, in basaltic gravel even the signal from free water was very short ($T_2^* \approx 10$ ms) and, therefore, cannot be measured with a standard MRS instrument.

For this reason, measurements in the basaltic gravel were carried out using a NUMIS non-standard setup, which was adapted to the spin echo technique (Farrar and Becker 1971) especially for these experiments.

Thus, in non-magnetic rocks like limestone, both free and capillary-bound water contribute to MRS water content. In magnetic rocks however, even free water cannot be detected. It should be also added that other factors, such as surface relaxivity, and the temperature and salinity of water, may influence MRS measurements (Dunn et al. 2002). This suggests the possibility of correlating MRS responses with different geological formations.

The saturation recovery method (Dunn et al., 2002) can be used for measuring T_1. This consists of applying two pulses, separated by a delay τ_p, to the investigated sample and measuring the magnetic resonance response after the second pulse. Each pulse flips the spin magnetization to the exact angle of $\pi/2$. Under laboratory conditions, only small samples are investigated and special care is taken to have both the static and alternating magnetic fields as homogeneous as possible inside the sample. In the laboratory, therefore, the pulses can be set up so that the flip angle is equal to exactly $\pi/2$. In field conditions however, the flip angle in a volume dV depends on its distance from the surface loop and, within the studied volume, the flip angle caused by the same pulse may vary widely for different samples $dV(\mathbf{r})$, which is why T_1 cannot be measured directly.

The saturation recovery method, however, can be adapted to MRS. Two pulses are applied to the investigated volume and, after the first pulse, the spin magnetization $\mathbf{M}$ of the sample dV is turned off at the angle θ (Equation 2), as shown in Figure 1. During the delay τ_p, it builds up towards equilibrium along the geomagnetic field with the time constant T_1. Assuming the spin system to be linear, and neglecting relaxation during the pulse, ($\tau << T_2^*, T_2, T_1$), the perpendicular to the earth's magnetic field component of the spin magnetization after the second pulse can be described by the equation:

$$M_{\perp}(\tau_p) = M_0 \exp(-\tau_p / T_1) \sin(\theta + \theta_2) + M_0 \left(1 - \exp(-\tau_p / T_1)\right) \sin(\theta_2), \quad (13)$$

where θ_2 is the flip angle caused by the second pulse. If both pulses are set to be equal ($q_1 = q_2 = q$) and the phase shift between the current of the second pulse is equal to 180° relative to the current of the first pulse, then $\theta_2 = -\theta$ and Equation 13 can be simplified to:

$$M_{\perp}(\tau_p) = -M_0 \left(1 - \exp(-\tau_p / T_1)\right) \sin(\theta). \quad (14)$$

For calculating the amplitude of a MRS signal measured after the second pulse, Equation 4, which describes the amplitude after the first pulse will be replaced by:

$$e_{02}(q, \tau_p) = \frac{M_0 \omega_0}{I_0} \times \int_V \left(1 - \exp\left(-\tau_p / T_1(\mathbf{r})\right)\right) B_{1\perp}(\mathbf{r}) e^{j(2\varphi_0(\mathbf{r}) + \pi)} \sin\left(\theta(\mathbf{r}, q)\right) w(\mathbf{r}) dV(\mathbf{r}) . \quad (15)$$

If horizontal stratification is assumed and:

$$x(z) = 1 - \exp\left(-\tau_p / T_1(z)\right), \quad (16)$$

then Equation 15 can be resolved by applying the same approach as for the resolution of Equation 4. Thus, using the notations introduced for Equation 9, and just one value for the delay between the pulses fixed at $\tau_p = (2 \div 3) \times T_2^*$, it follows that:

$$(\mathbf{Aw})\mathbf{x} = \mathbf{e}_{\mathbf{02}}, \quad (17)$$

where the water content $\mathbf{w}$ is obtained by the resolution of Equation 9, $\mathbf{e}_{\mathbf{02}}$ is the set of experimental data measured after the second pulse, and $\mathbf{x} = (x_1, x_2, .., x_j, .., x_J)^T$ is the solution vector. Equation 16 allows easy calculation of $T_{1j} = -\tau_p / \log(1 - x_j) = T_1(\Delta z_j)$, which is a vertical distribution of the relaxation time T_1. If it is possible to carry out measurements with different values of τ_p, then this will improve the accuracy of results, but will also increase time required for the data acquisition.

It is instructive to now compare T_1 measurements at two different sites. The Site 1 aquifer is composed of coarse sand, and the borehole yield is about 120 m^3/h. The Site 2 aquifer is composed of chalk, and the borehole yield is about 3 m^3/h. For demonstration purposes, T_1 was measured for just one value of the pulse parameter q, with varied delays between the pulses τ_p, which gives the apparent relaxation time $T_{1a}(q)$ rather than real one $T_1(z)$. However, as only one aquifer exists at each of these sites, the apparent T_{1a} may be considered as the real T_1. Normalized amplitudes measured at each site versus the delay τ_p are shown in Figure 4. As expected, a longer T_1 was observed at the site where the aquifer has a larger yield.

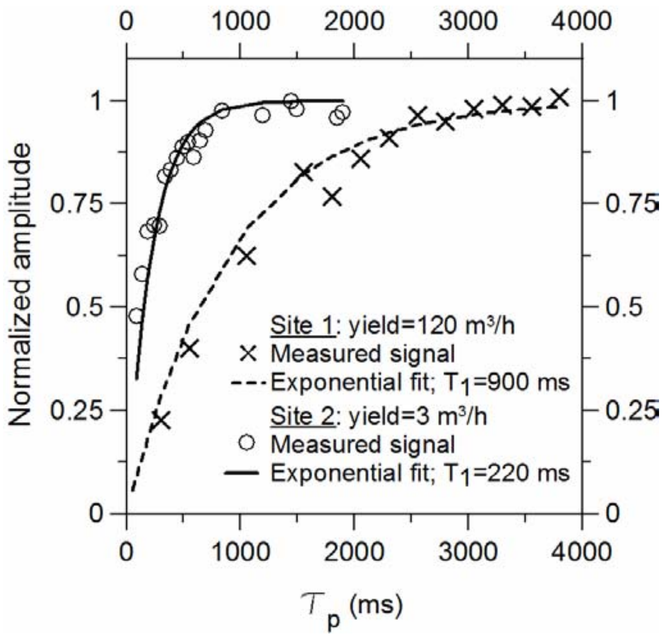


Figure 4. Comparison of two different aquifers: normalized amplitude of the MRS signal measured after the second pulse versus the delay between the pulses.

MRS estimation of hydraulic conductivity

In nuclear magnetic resonance logging, the permeability of water-saturated porous media can be estimated as (Chang et al. 1997; Kenyon 1997):

$$k_{NML} = a\phi_{NML}^{b} T_{1}^{c}, \qquad (18)$$

with k_{NML} being the permeability estimated using magnetic resonance data, ϕ_{NML} and T_1 the porosity and the relaxation time derived from NML measurements, and a,b,c are empirical constants. Other formula, such as $k_{NML} = aT_2^b / F^c$, where a,b,c are empirical constants and F is the electrical formation factor, have been also suggested (Wyllie and Spangler 1952). Both formula work equally well within experimental errors. Different estimation methods, based on Equation 18, have also been developed; first, $b=1$ and $c=2$ were proposed by Seevers (1966), and later it was shown that, for sandstones, better accuracy can be achieved using $b = 4$ and $c = 2$ (Timur 1968, 1969a, 1969b; Kenyon et al. 1988). In MRS, a formula based on Equation 18 is actually used for estimating the hydraulic conductivity

$$K_{MRS} = C_p w^a T_1^b . \qquad (19)$$

Hydraulic conductivity is a scale-dependent parameter. Taking into account that MRS results are averaged over a large area defined by the loop size, the pumping tests, which also provide results averaged over a large volume, are used for calibration.

Pumping test transmissivity values reflect the hydraulic conductivity and thickness of the aquifer $T_{bh} = K_{bh} \Delta z_{bh}$. Estimates of both hydraulic conductivity and aquifer thickness can be derived also from MRS measurements, and the MRS transmissivity estimate is:

$$T_{MRS} = \int_{\Delta z} K_{MRS}(z) dz , \qquad (20)$$

where $K_{MRS}(z) = C_p w^a(z) T_1^b(z)$, and Δz is the thickness of the aquifer estimated by MRS.

Two estimators, based on Equation 19 ($\sim wT_1^2$ and $\sim w^4 T_1^2$), were tested using MRS measurements in France (an area between Chartres and Orleans). For each estimator, the constant C_p was selected so that the MRS estimated transmissivities matched the best pumping test transmissivities. It was found that, when applied to MRS measurements, the ($\sim wT_1^2$) estimator gave better results than the reportedly more accurate ($\sim w^4 T_1^2$) estimator. A comparison between the MRS and borehole pumping test results is shown in Figure 5; the error bars were calculated taking into account the accuracy of MRS data and possible equivalent solutions.

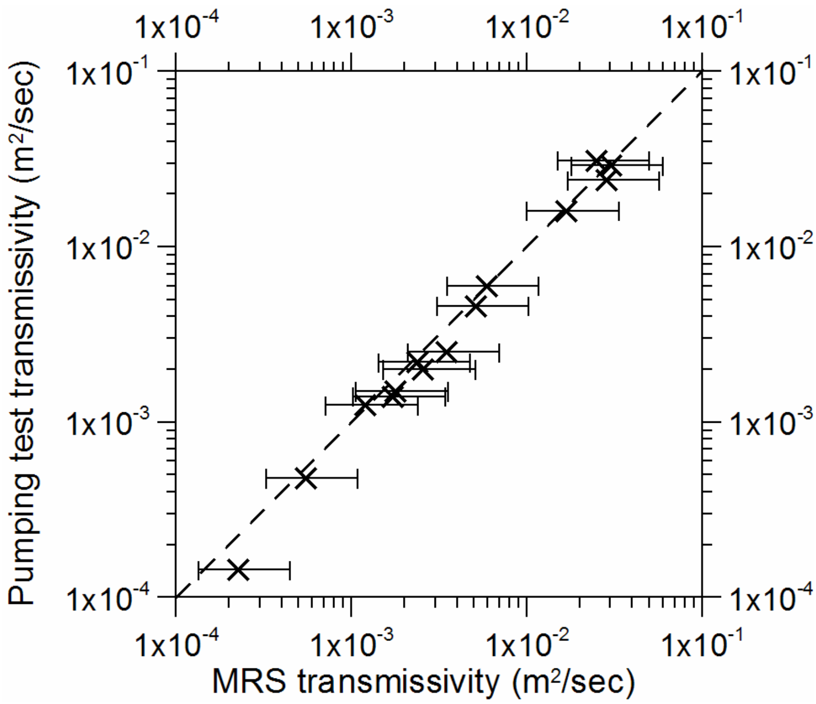


Figure 5. Comparison of MRS transmissivity estimation with that given by pumping tests.

In conclusion, we need to discuss the principal limitation of the applicability of MRS to non-invasive estimation of the permeability.

Hydraulic permeability of geological formations is scale-dependent. Samples investigated in laboratories, using borehole NMR tools or performing MRS measurements all have very different scale. Thus, results obtained with these methods might be different. An example of two aquifers of different type is presented in Figure 6.

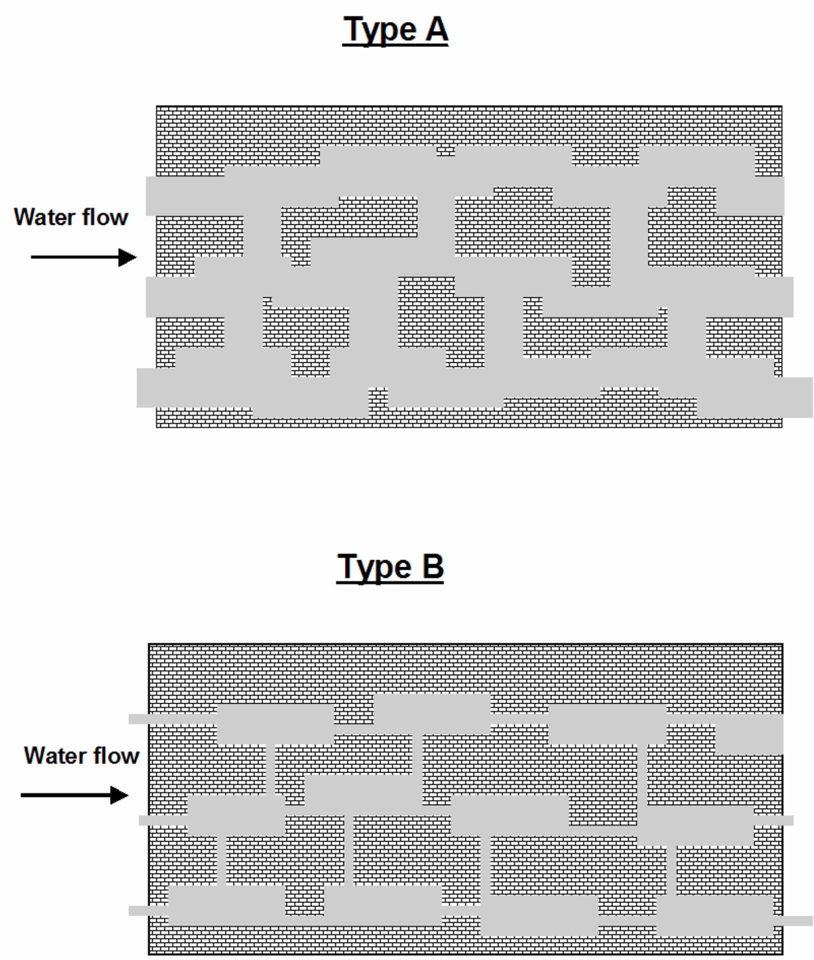


Figure 6. Permeability of aquifers : type A – single porosity; type B – double porosity.

In aquifer with a single porosity (type A), the water is located in similar pores and permeability of this aquifer is closely related to the pore size. In this case, information about the aquifer derived from magnetic resonance measurements is also related to permeability even if investigated samples are of a different volume.

In aquifer with a double porosity (type B) shown in Figure 6, most of the water is located in large pores, but permeability mostly depends on small pores. In this case, if the volume of investigated sample is small (lab. measurements), result of permeability estimation depends on whether the selected sample represents small or large pores. A large-scale method like the MRS will provide us with information mostly related to large pores, as they contain larger quantity of water than small pores. Obviously, the permeability estimation is much less accurate in this case.

In practice, different types of porosity are usually mixed, and measured magnetic resonance signal is often composed of a sum of signals decaying with different relaxation times and thus, contains information about different pores.

1.2. THE DEPTH OF INVESTIGATION

The magnetic resonance signal is sensitive to different natural factors what makes the performance of the method site-dependent. The most common and practically important variations in the magnetic resonance signal are related to the natural geomagnetic field and the electrical conductivity of rocks (Semenov, *et al.*, 1989; Shushakov, 1996; Legchenko, *et al.*, 1997; Valla and Legchenko, 2002). The electrically conductive subsurface attenuates alternative electromagnetic fields by a factor characterized by the "skin depth" that is proportional to $\sqrt{\rho/f}$, where ρ is the resistivity of the subsurface, and f is the frequency of the electromagnetic field. The Larmor frequency used in MRS is proportional to the geomagnetic field magnitude $f_0 \sim H_0$. Consequently, in areas with a low geomagnetic field (towards the equator), the frequency is smaller, and the attenuation caused by the subsurface is less important than in areas with a high geomagnetic field (towards the poles). However, the magnetic resonance response is proportional to square of the geomagnetic field ($E \sim H_0^2$), what improves the signal to noise ratio in areas with a high geomagnetic field even taking into account the attenuation caused by the subsurface. The inclination of the geomagnetic field also modifies the magnetic resonance signal (Legchenko, *et al.*, 1997). A numerical demonstration of influence of these natural factors on the maximum depth of investigation of the MRS method is presented in Figure 7. The maximum depth of detection of a one meter thick infinite horizontal layer of water (100% of the water content, and $T_2^*=1000 ms$) in a noiseless environment is depicted versus the half-space resistivity. Calculations were performed for different geomagnetic fields using NUMIS^{PLUS} standard configuration: a square loop with a side of 100 m, a signal detection threshold of 10 nV, and a maximum pulse of 12000 A-ms. We can see that magnitude and inclination of the geomagnetic field is a major factor that defines MRS performance when the subsurface is non-conductive. Influence of electrically conductive layers becomes important when the resistivity of these layers is less than 50 ohm-m approximately.

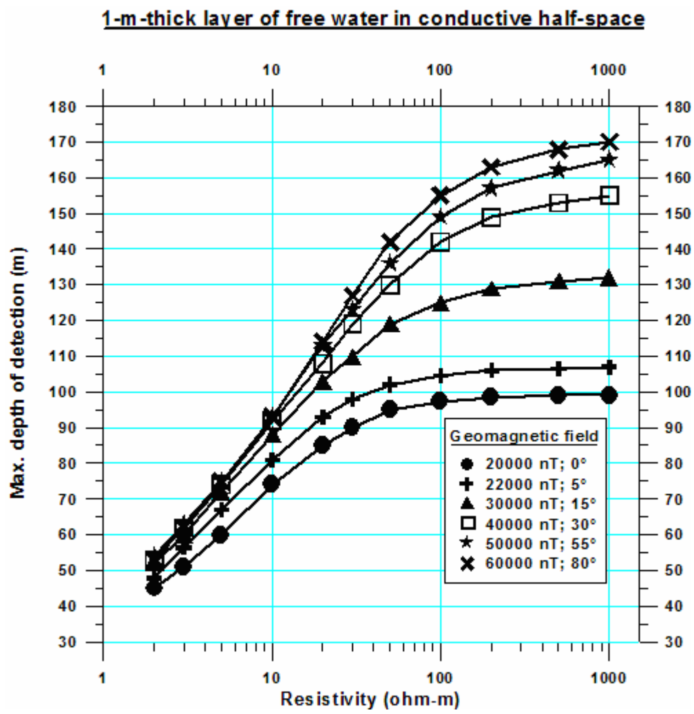


Figure 7. The maximum depth of detection calculated for a 1-m-thick layer of free water (w=100%) versus the half-space resistivity.

Inversion of MRS data ($E_{0d}(q)$ and $T_2^*(q)$), provides the depth (z), the thickness (Δz), the water content (w), and the relaxation times T_2^* and T_1 for each water-saturated layer. However, like many other geophysical problems, the MRS inverse problem is ill-posed and therefore the solution is non-unique (Legchenko and Shushakov, 1998). We present "smooth inversion" results performed following the Tikhonov regularization method, but other methods like the linear programming and Monte Carlo inversion could also be used (Guillen and Legchenko, 2002; 2002a).

The resolution of the MRS method decreases with increasing depth. In order to demonstrate the MRS vertical resolution against the depth, we compute MRS signals from an inclined 10-m-thick water-saturated layer that is shown in Figure 8. We assume that soundings are performed along a profile from the deepest part of the layer toward the shallow part. Results of 1D inversion for the water content (w), and for the relaxation time (T_2^*) are plotted versus the distance (Figure 9). The dashed lines in the plot show the model. We can see that the resolution degrades progressively with increasing depth. While the top of the layer (z) is relatively well resolved down to 100 m, the thickness of the layer is still resolved down to about 60-70 m. Below 70 meters the thickness (Δz) and the water content (w) can not be derived from MRS data. The relaxation time (T_2^*) is well resolved down to 100 m for this model.

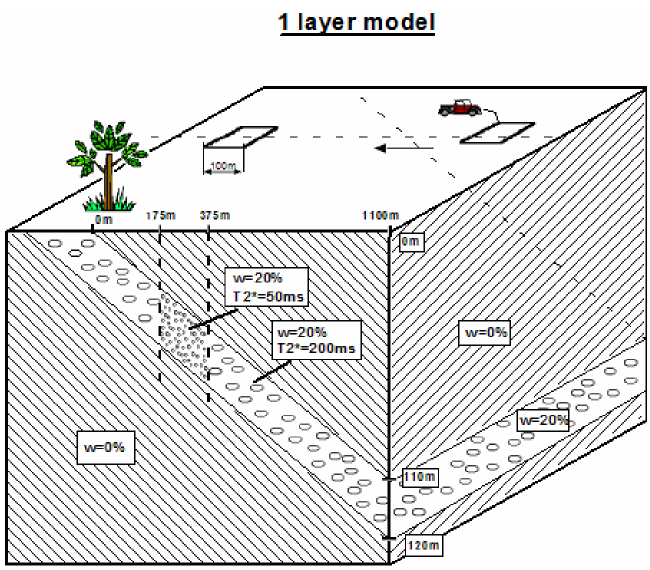


Figure 8. One layer model.

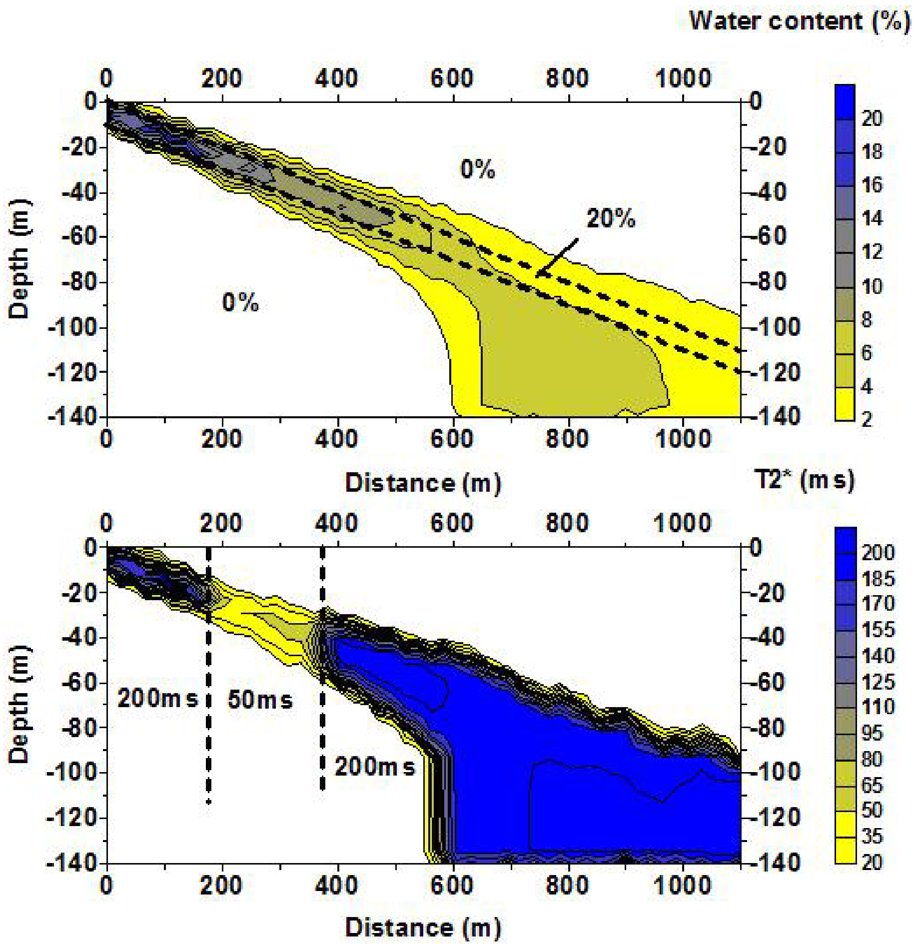


Figure 9. Resolution of the one layer model.

1.3. EXAMPLE OF MRS RESULTS

Example of MRS results obtained in France is presented in (Figure 10). Investigated aquifer is composed essentially of medium to coarse sand. Field measurements were carried out near a borehole where the pumping tests were fulfilled.

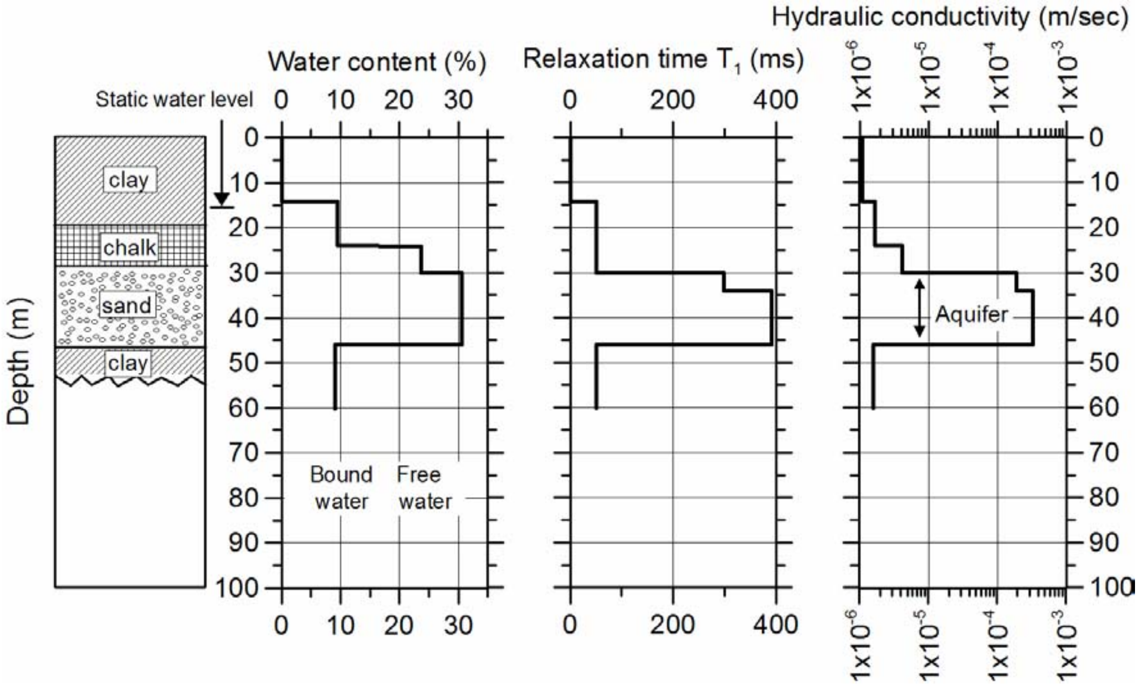


Figure 10. Example of MRS results.

Increase in the water content observed in the MRS log corresponds to the water table indicated by borehole. However, the relaxation time corresponding to this zone is short ($T_1 \approx 50ms$). It means that the permeability of the rock between 15 and 30 meters is low and that most of the water is capillary-bound water. Increase in the relaxation time corresponds well to top of the aquifer indicated by the lithological log. The MRS permeability estimation also shows that the top of the aquifer is about 15 m below the water static level. A good agreement between the transmissivity estimated by MRS ($T_{MRS} = 4.7e-3(m^2/\sec)$), and that derived from pumping tests ($T_{bh} = 4.6e-3(m^2/\sec)$) is observed. Unfortunately, lack of data about the effective porosity does not allow us to calibrate the MRS water content.

1.4. NUMIS^{PLUS} MRS EQUIPMENT

The NUMIS ^{PLUS} instrument consists of an oscillating-current generator, a receiver, a PMR signal detector, an antenna and a microprocessor (Figures 11, 12). The antenna is used for both transmission of the oscillating magnetic field and reception of the PMR signal. The microprocessor switches the antenna from generator to receiver mode by an electronic switch. It also controls the generation of the reference frequency equal to the Larmor frequency. An envelope of the signal from the phase-sensitive detector is recorded by the microprocessor in digital form. A portable PC is used for data processing. The PC is connected to the microprocessor by a standard RS-232 serial link.

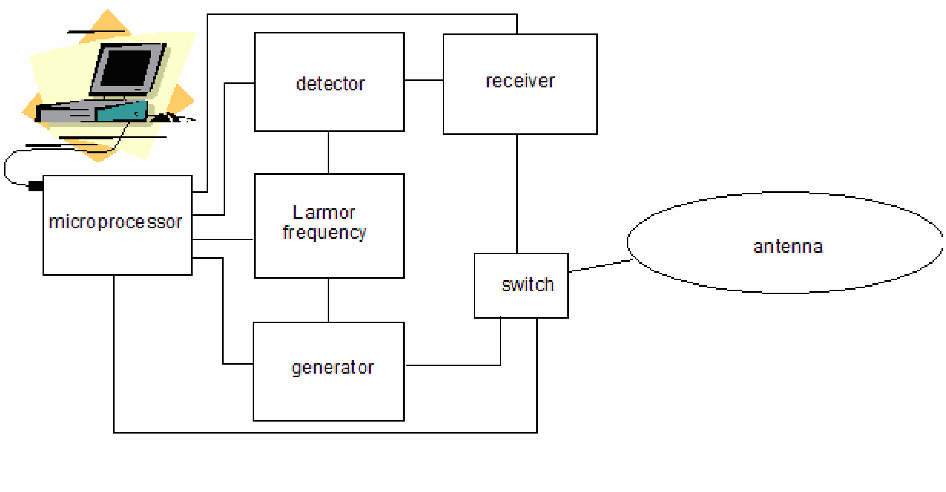


Figure 11. Scheme of NUMIS^{plus} instrument.

Figure 12. NUMIS^{plus} equipmen in a field.

1.5. OUTPUT OF NUMIS^{PLUS} SYSTEM

The data interpretation software developed for NUMIS^{plus} system is very flexible and provides to users a wide range of possibilities to configure the output page. In this report, the configuration presented in Figure 13 is used.

Site: haddam meadows profile, sounding 7
Loop: 4 - 37.5 Date: 18.11.2000 Time: 13:13
NUMIS data set: C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\Haddam_Meadows-2000\HM7.inp
matrix: C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\MATRIX\Had_mead-8sq.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 72 degr, magnitude= 53399.06 nT

filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 2.89; EN/IN = 1.46
fitting error: FID1 = 17.06%; FID2 = 34.19 %
param. of regular.: modeling
permeability constant Cp = 7.00e-09

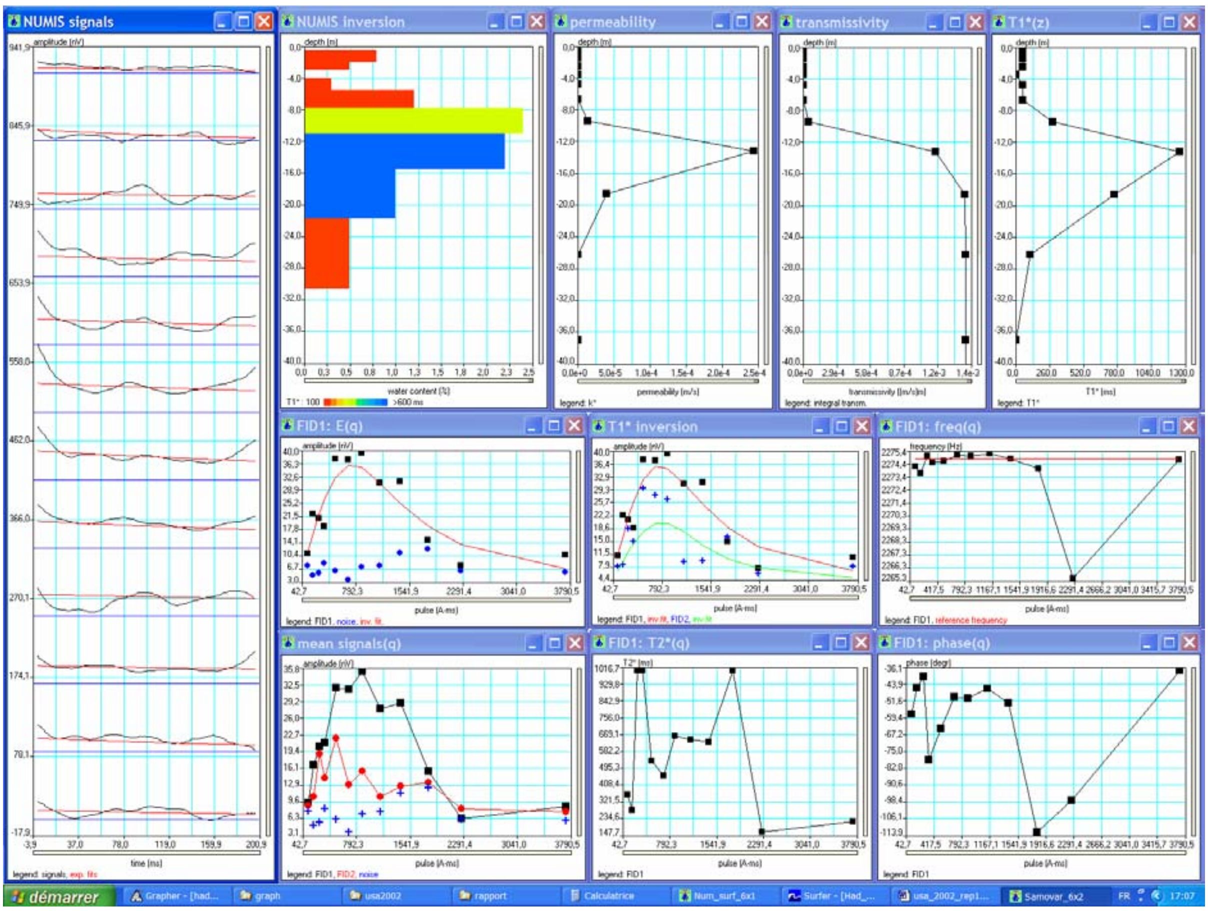


Figure 13. Example of NUMIS^{plus} output page.

MRS results are presented by following graphs:

1) **NUMIS signals** - free induction decay signals after the first pulse (FID1) and inversion fits versus the time are arranged by increasing pulse parameter from the bottom to top.
2) **NUMIS inversion** – vertical distribution of the water content with the relaxation time T_1 presented by the color scale.
3) **Permeability** – MRS estimation of the permeability versus depth.
4) **Transmissivity** - MRS estimation of the transmissivity versus depth.
5) **T_1^*(z)** - vertical distribution of the relaxation time T_1.
6) **FID1: E(q)** – amplitude of the FID1 signal, inversion fit and an average noise versus the pulse parameter.
7) **T_1^* inversion** – amplitude of the FID1 and FID2 signals and the inversion fit.
8) **FID1: freq(q)** – the Larmor frequency measured after the first pulse.
9) **Mean signals(q)** – average through the data acquisition window signals (FID1 and FID2) and the noise.
10) **FID1: T_2^*(q)** - relaxation time T_2^* versus the pulse parameter.
11) **FID1: phase(q)** – phase of the signal measured after the first pulse.

In the header, information about parameters used for the interpretation is presented.

1.6. NUMIS^{PLUS} DATA: QUALITY ESTIMATION

Currently, the MRS method is able to detect water in aquifers composed of non-magnetic rocks. The magnetic resonance signal may vary from 0 to about 4500 nV (4.5e-6 V). Typical range for Europe is 0 – 500 nV, but for igneous rocks it is 0 – 150 nV. NUMUS^{plus} instrument has an instrumental noise of about 3-5 nV what puts the threshold of reliable measurements of magnetic resonance signal to 5-10 nV approximately.

For MRS data quality estimation, the following parameters can be used:

1) External noise level after stacking and filtering is compared with the NUMIS instrumental noise as

   $EN / IN = (ext.noise)/(instr.noise) = noise / 5$. (21)

   In ideal case, when the external noise is very small, the EN/IN ratio is about equal to 1. When the magnetic resonance signal is very small, the stacking should be carried out until $EN / IN \cong 1$. When $EN / IN \cong 1$ the sounding can be considered as of a good quality, even if the signal has not been detected.

2) The signal to noise (observed noise includes both external and instrumental noises) ratio

   $S / N = signal / noise$. (22)

   Usually data are considered of a good quality when S/N>2. In this case, a quantitative interpretation of MRS data is possible, and reliable information about aquifers can be derived from MRS data. When S/N>2, it is not necessary to have $EN / IN \cong 1$.

   If $EN / IN \cong 1$ and S/N=1 (signal is not detected), a quantitative interpretation of MRS data is not possible. However, it can be concluded that there is no water (detectable by MRS) in the subsurface. Approximately, the threshold of the detectable water content for NUMIS instrument is about 0.5-1%.

   When $EN / IN > 1$ and S/N=1, the sounding cannot be considered as of a good quality. The only conclusion can be derived from the data is that the amplitude of MRS signal is smaller than the noise level. For example, if $EN / IN = 5$ and S/N=1, one can conclude that the signal is smaller than 25 nV.

3) The frequency of the MRS signal must be stable and close to the Larmor frequency given by a proton magnetometer. The difference in-between is usually less then 3-4Hz.

4) The phase of the MRS signal must be stable or vary smoothly. The phase helps for discrimination between the MRS signal (phase is stable or vary smoothly) and a cultural noise: the frequency of a cultural noise might stable (but not necessary close to the frequency given by a proton magnetometer) but the phase of noise is always random.
5) The relaxation time $T_2^*(q)$ is the parameter the most sensitive to data quality. For data of a good quality $T_2^*(q)$ is stable or varies smoothly between 50 and 400ms.

When quantitative interpretation of MRS measurements is not possible, an estimation of the maximum possible volume of water per surface unite can be made:

$$V_{MRS} = \int_{\Delta z} w(z)dz \, . \qquad (23)$$

V_{MRS} can be used when large-yield-aquifers is a target and caracterization of small aquifers is out of scope of survey. In this case, just achieving $V_{MRS} < V_{MRS}^{\lim it}$, where $V_{MRS}^{\lim it}$ is considered as a limit for an acceptable aquifer for the investigated area, sounding can be stopped without spending more time in the field.

2. Test sites

In this report, we present three areas in northern Denmark where MRS method was tested. Five MRS stations along a profile in Hogsted area, one station in Saby and one station in Nosby were carried out. Transient EM measurements were performed at all MRS stations.

No detailed geological description of the test sites is available for writing this report. According to general information, the subsurface is composed of rather heterogeneous glacial deposits. The hydrodynamic properties of this material vary a lot and aquifers of interests are essentially located in ancient valleys. However, even in the valleys rocks may have very low permeability what makes the knowledge about the location of these valleys not sufficient for reliably implantation of water supply wells.

2.1. SABY AREA

Location of MRS station in Saby area is presented in Figure 14.

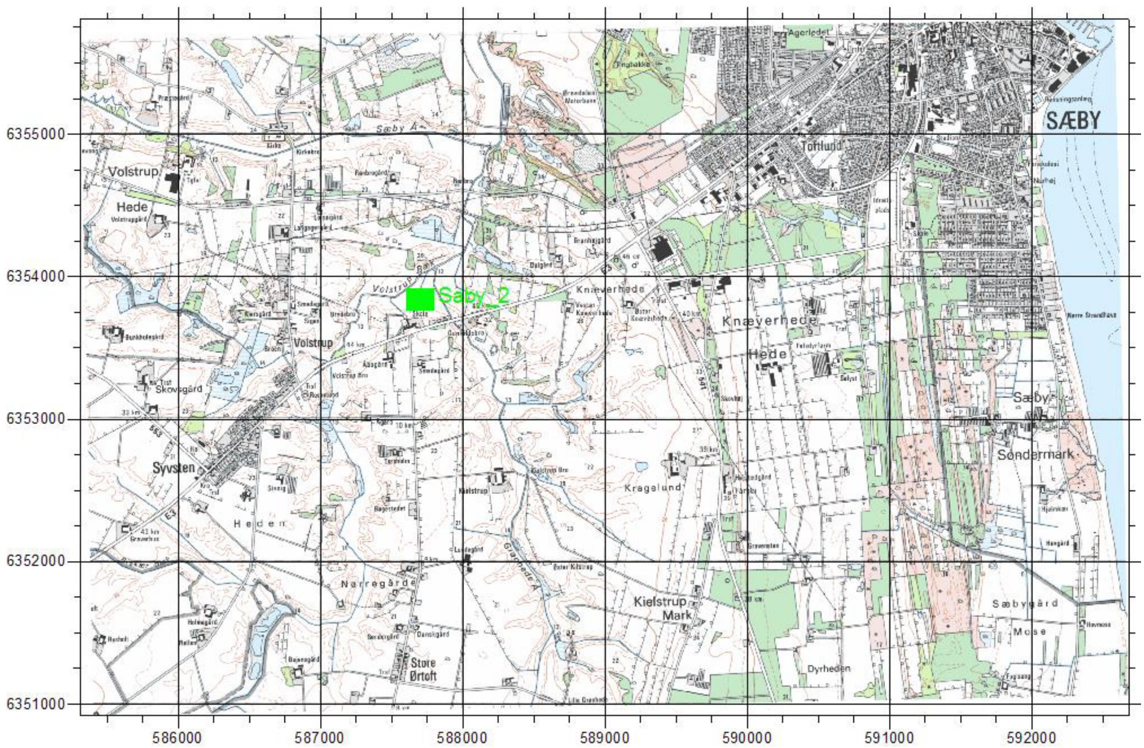


Figure 14. Location of the MRS station in Saby area.

2.2. NOSBY AREA

Location of MRS station in Nosby area is presented in Figure 15.

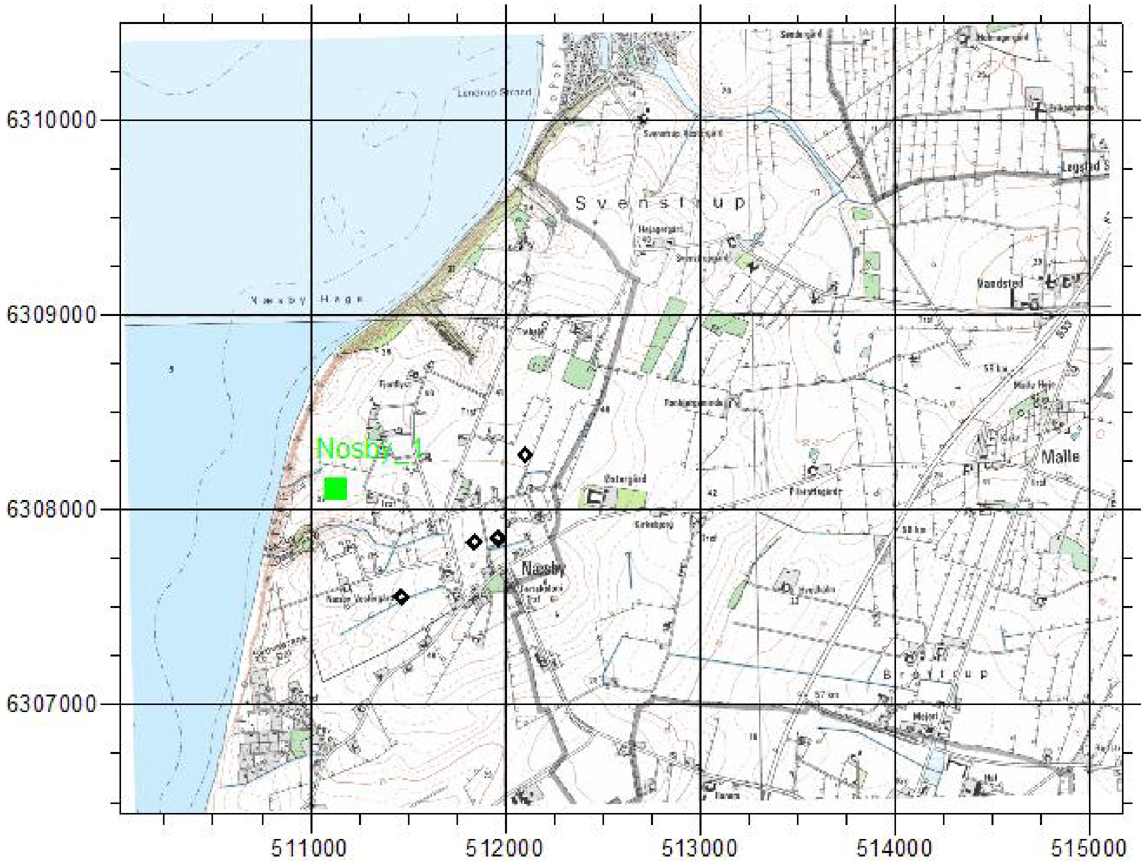


Figure 15. Location of the MRS station in Nosby area.

2.3. HOGSTED AREA

Location of MRS stations in Hogsted area is presented in Figure 16.

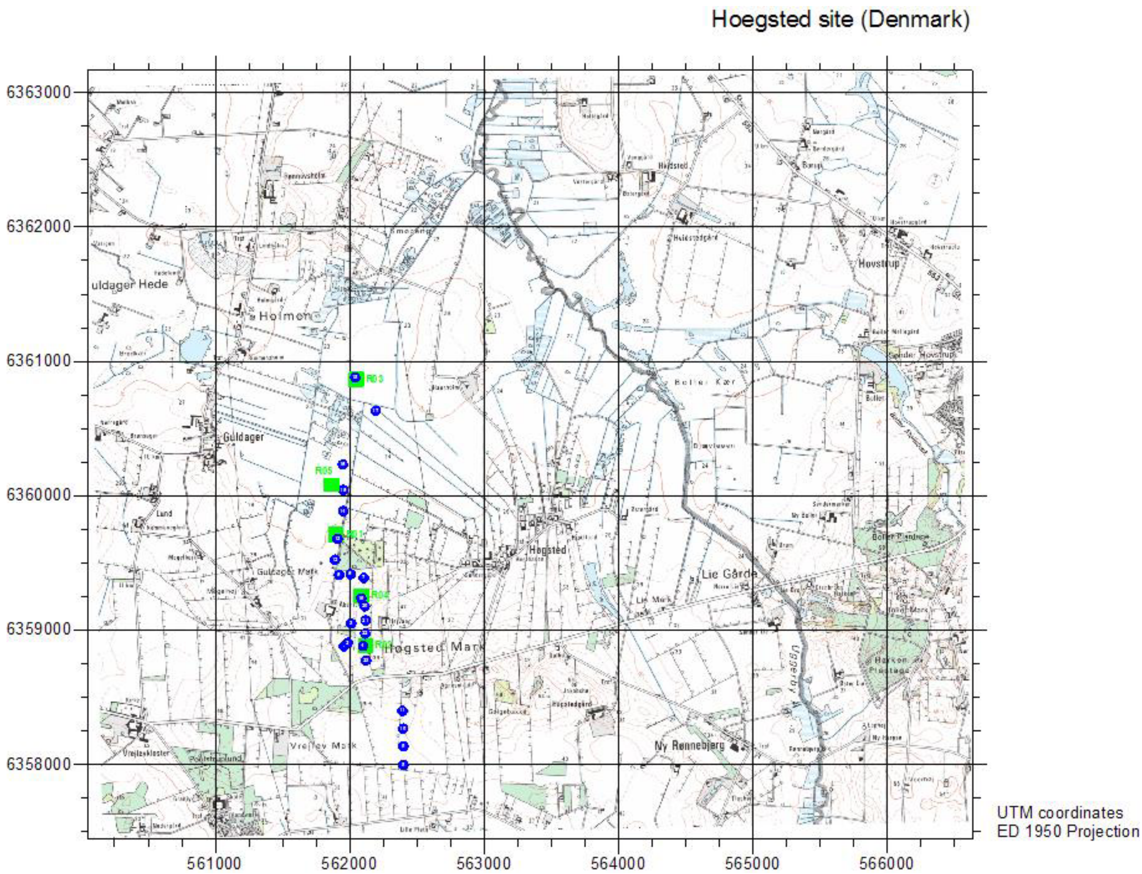


Figure 16. Location of MRS stations in Hogsted area (R01-R05).

3. Results and discussion

3.1. SUMMARY

Totally, 7 soundings are presented in this report. All MRS measurements were carried out using NUMIS^{plus} instrument manufactured by IRIS Instruments. The data processing was performed using NUMIS standard interpretation software. The electrical conductivity of rocks was not taking into account. The subsurface was considered as a 100 ohm-m half-space. The depth of MRS investigation depends on the antenna size. With the square loop of 75-m-size used for all soundings the depth of investigation is about 100 meters.

Results of NUMIS data interpretation are presented in Annexes 1.

GPS co-ordinates and estimation of the quality of MRS data are presented in Table 2.

MRS Station	T_Easting	T_Northing	EN/IN	S/N	Signal	Interpretation
Saby	587918,1	6354191,6	13.7	0.99	No	Qualitative
Nosby	511063,8	6308095,0	26.8	0.8	No	Qualitative
Hogsted_1	561894,0	6359716,8	15.5	1.58	Yes	Quantitative
Hogsted_2	562115,4	6358884,7	11.9	1.57	Yes	Qualitative
Hogsted_3	562047,8	6360865,5	7.1	2.1	Yes	Quantitative
Hogsted_4	562085,6	6359255,1	29.4	1.2	Yes	Quantitative
Hogsted_5	561933,5	6360127,7	28	3	Yes	Quantitative

Table 2. GPS co-ordinates and quality of MRS data.

During the survey a very high level of industrial noise was observed. As the depth of investigation of at least 80 meters was required, application of eight-shape-loop of 37-m-side which allows improving S/N at the factor of about 10 and is a standard setup for NUMIS system was excluded. Unfortunately, sufficient amount of wire was not foreseen in the beginning, and thus application of larger eight-shape-loop (75-m-side) for investigating greater depth was not possible. Quality of data necessary for reliable interpretation of MRS measurements was achieved by using the notch-filtering and great number of stacks (500). With 500 stacks one sounding takes about 10 hours. Even time-non-efficient, this setup allows answering to the principal question about the applicability and geophysical efficiency of MRS in Denmark.

When the MRS signal is detected (5 soundings), a quantitative interpretation of MRS data reveals the geometry, water content, and permeability of aquifers. In two cases the magnetic resonance signal was not detected. A qualitative interpretation reveals only an estimation of maximum possible MRS water volume inside of the loop area. This estimation only guarantees that it is not possible to have more water than is given by the maximum possible volume. However, it is also possible that there is no water at all at this site.

For example, MRS amplitudes measured at all seven test sites in Denmark are presented in Figure 17. It can be seen that the MRS signal is smaller for the sites Saby 2, Nosby and Hogsted 2 and thus, a poor signal to noise ratios for these sites can be explained by not much higher noise, but smaller signals. After our experience, in the subsurface composed of glacial deposits smaller signals are often associated with compact low permeable silt/clay-type material.

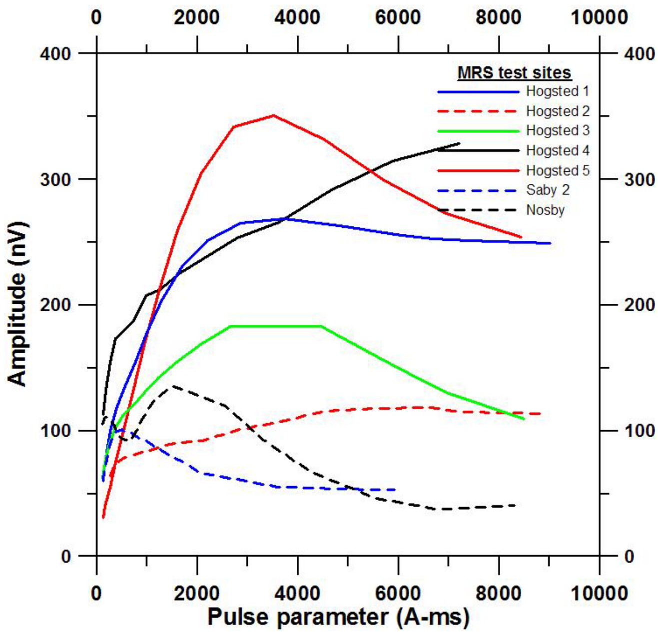


Figure 17. Comparison of MRS amplitudes.

Summary of MRS results in Denmark is presented in Table 3.

MRS Station	*Top (m)*	*Bottom (m)*	V_{MRS} *(m^3/m^2) (<100m)*	T_{MRS} *(m^2/s) (<100m)*	k_{MRS} *(m/s)*	Comments
Saby	6	18	<0.2	-	-	Insufficient S/N.
Nosby	16	36	<0.9	-	-	Insufficient S/N.
Hogsted_1	20	>100	>8.8	$>4x10^{-3}$	Shallow: $1.2x10^{-4}$ Deep: $2x10^{-5}$	Thickness is not defined. Significant contribution of shallow aquifer.
Hogsted_2	36	>100	<2.4	$<6x10^{-4}$	$<1x10^{-5}$	Thickness is not defined.
Hogsted_3	25	55	2.2	$2x10^{-3}$	$1.1x10^{-4}$	Only shallow aquifer is detected.
Hogsted_4	45	>100	>8	$>6x10^{-3}$	$1.4x10^{-4}$	Thickness is not defined.
Hogsted_5	25	>100	>9	$>6x10^{-3}$	Shallow: $1.7x10^{-4}$ Deep: $4x10^{-5}$	Thickness is not defined. Major contribution of shallow aquifer.

Table 3. Aquifers detected by MRS in Denmark.

With NUMIS setup which was used during the survey in Denmark, the maximum depth of investigation is about 100-120 meters, but quantitative results can be obtained down to 80 meters approximately. For this reason quantitative characterization of thick aquifers between 60 and 160 meters is limited by the depth of 80, possibly 100 meters.

As we have no experience in MRS application in Denmark, we do not know whether there is a correlation between the hydrodynamic properties of glacial material for shallow (first 100 m) and deep parts of ancient valleys (between 100 and 200 m). If such a correlation does exist, then after MRS results it can be concluded that all the investigated during this survey aquifers are composed of rather fine material and cannot be recommended for implantation of high-yield-wells for the water supply. If more coarse material may exist below 100 meters, then nothing can be said about rocks between 100 and 200 meters.

3.2. SABY

Data are of poor quality ($EN / IN = 13.7$), and no signal was detected ($S / N \cong 1$, frequency and phase are unstable). Aquifers cannot be reliably characterized in this case. Only estimation of maximum possible volume of water can be done (Table 3). MRS log is presented in Figure 18.

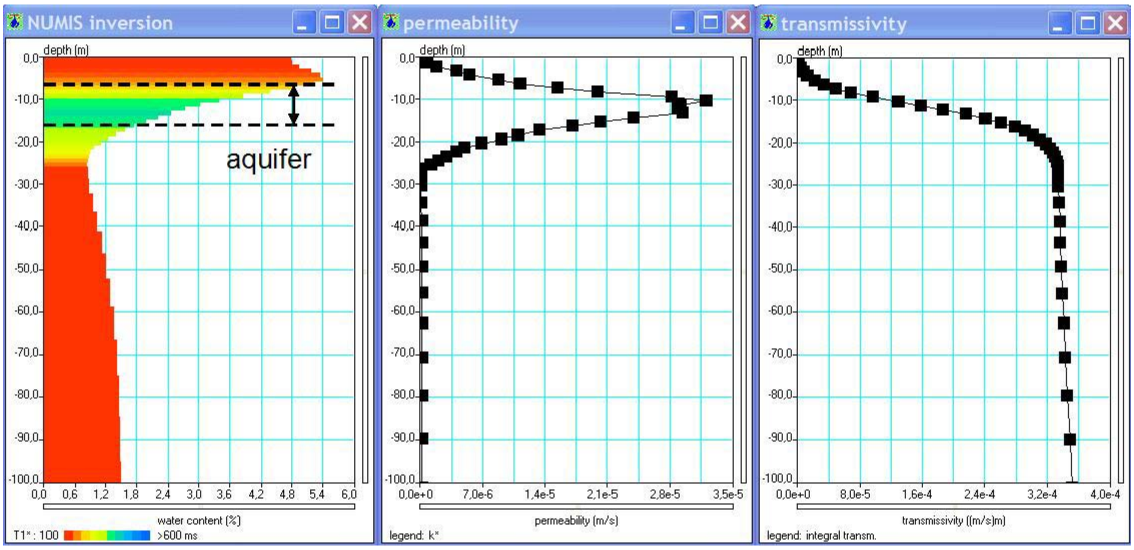


Figure 18. MRS log in Saby.

MRS provides only qualitative information about absence of aquifers that could be used for water supply purposes down to about 80-100 meters.

3.3. NOSBY

Data are of poor quality ($EN / IN = 26.8$), and no signal was detected ($S / N \cong 1$, frequency and phase are unstable). Aquifers cannot be reliably characterized in this case. Only estimation of maximum possible volume of water can be done (Table 3). MRS log is presented in Figure 19.

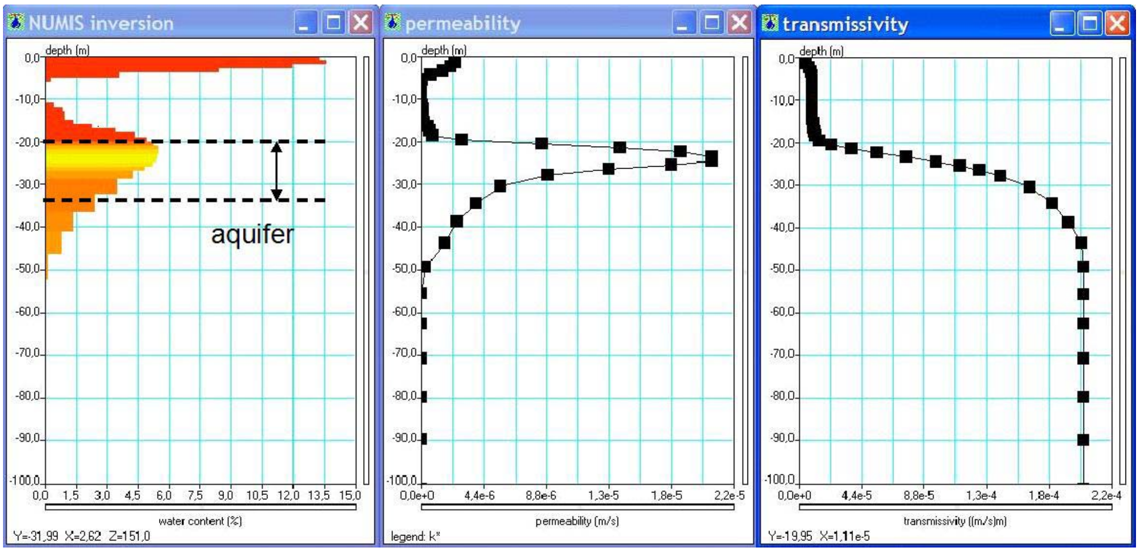


Figure 19. MRS log in Nosby.

Because of field-time for working in this area was limited, number of stacks that would be sufficient for achieving the necessary quality of data for quantitative characterization of aquifers has not been implemented. Consequently, MRS provides only qualitative information about absence of aquifers that could be interesting for water supply purposes down to about 80 meters.

3.4. HOGSTED

Five soundings along the profile were performed in Hogsted area. Location of MRS stations is shown in Figure 16. Quality of the data allows characterizing aquifers quantitatively (Table 2).

Large variations in the amplitude of the magnetic resonance signal along the MRS profile were observed (Figure 20). These variations can be explained by lateral in-homogeneities of the subsurface.

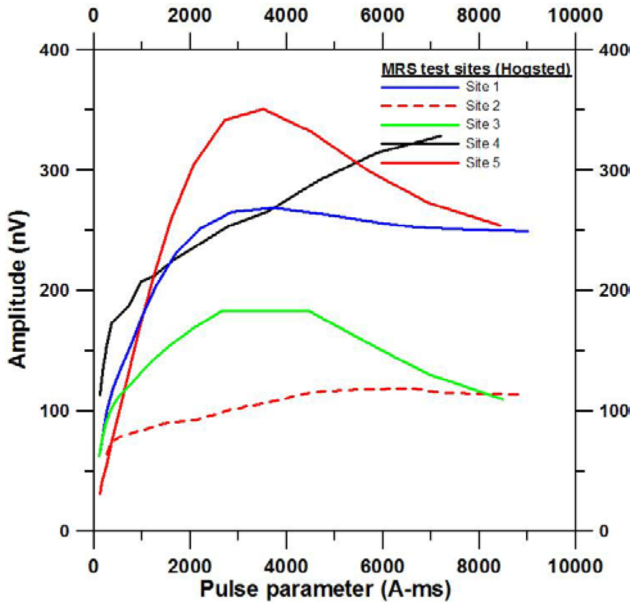


Figure 20. Amplitude of MRS signals in the Hogsted area.

MRS logs in Hogsted area are presented in Figures 21-25.

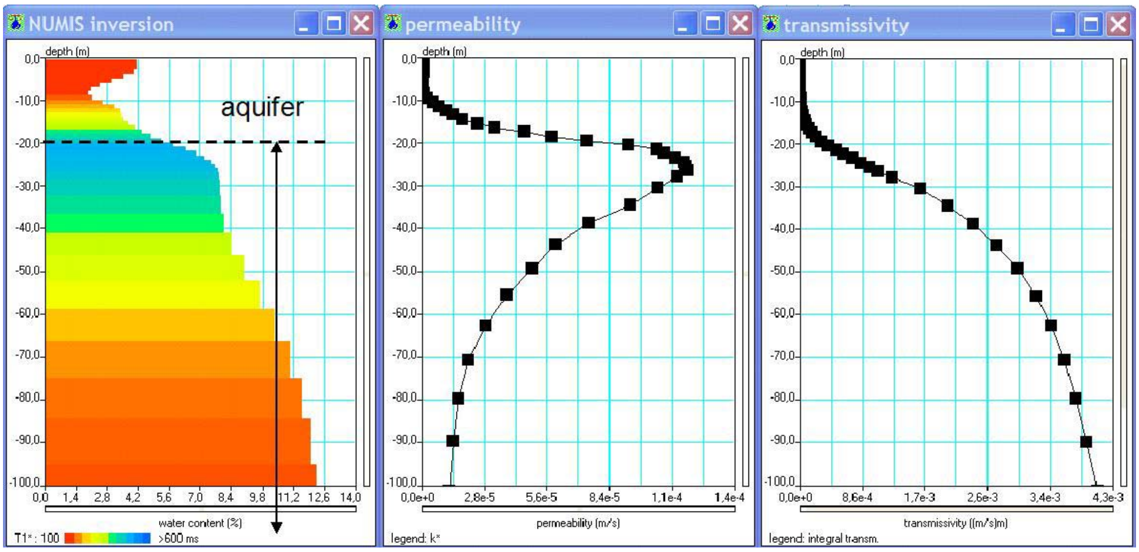


Figure 21. MRS log in Hogsted, Site 1.

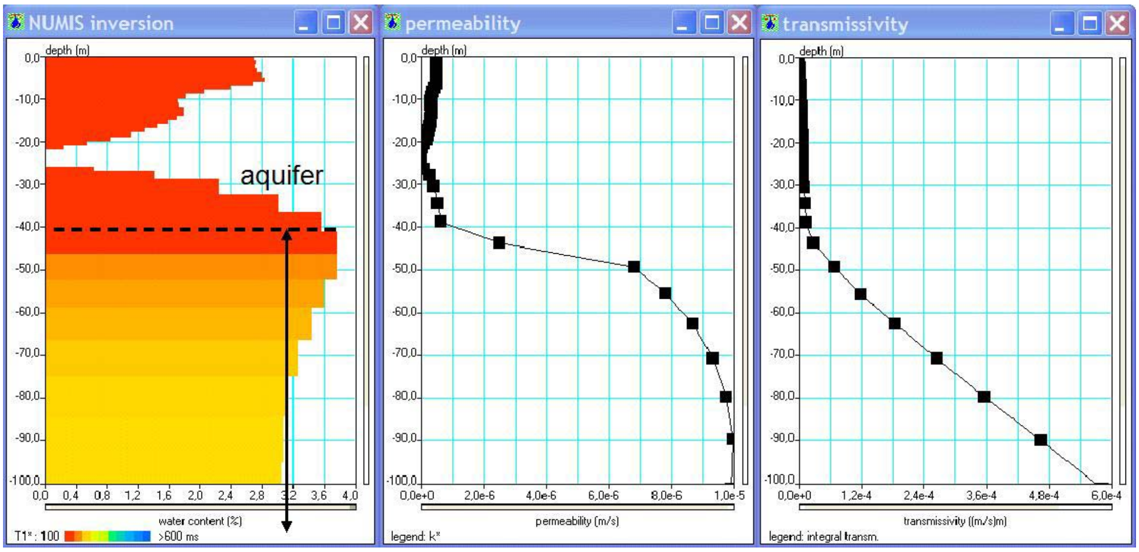


Figure 22. MRS log in Hogsted, Site 2.

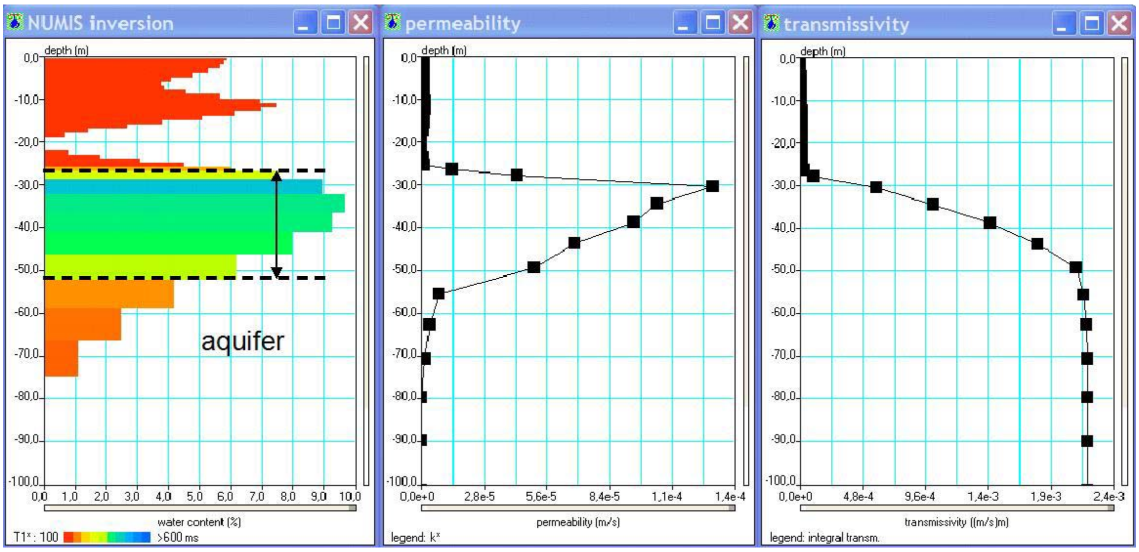


Figure 23. MRS log in Hogsted, Site 3.

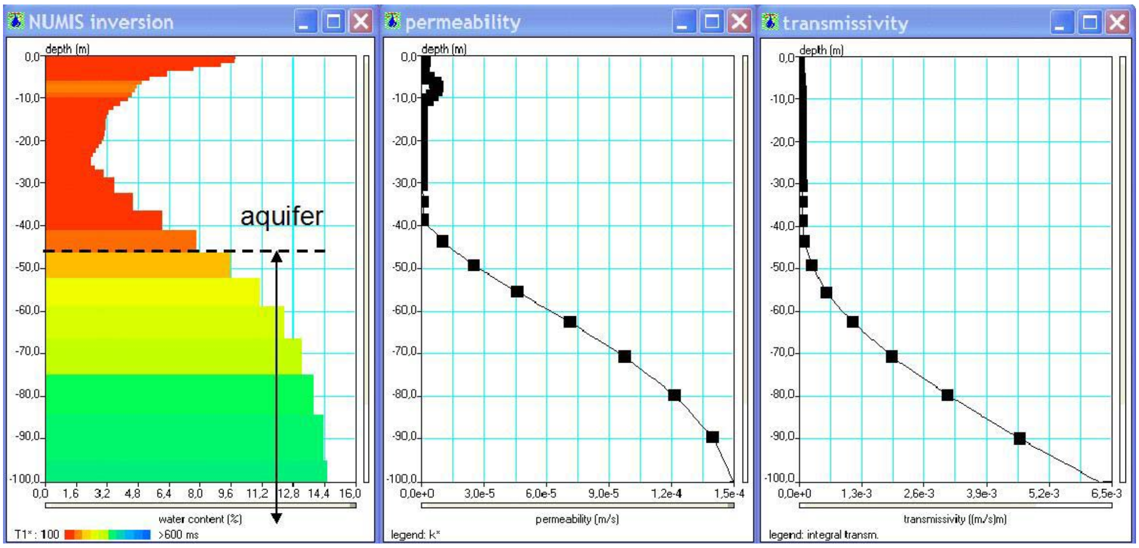


Figure 24. MRS log in Hogsted, Site 4.

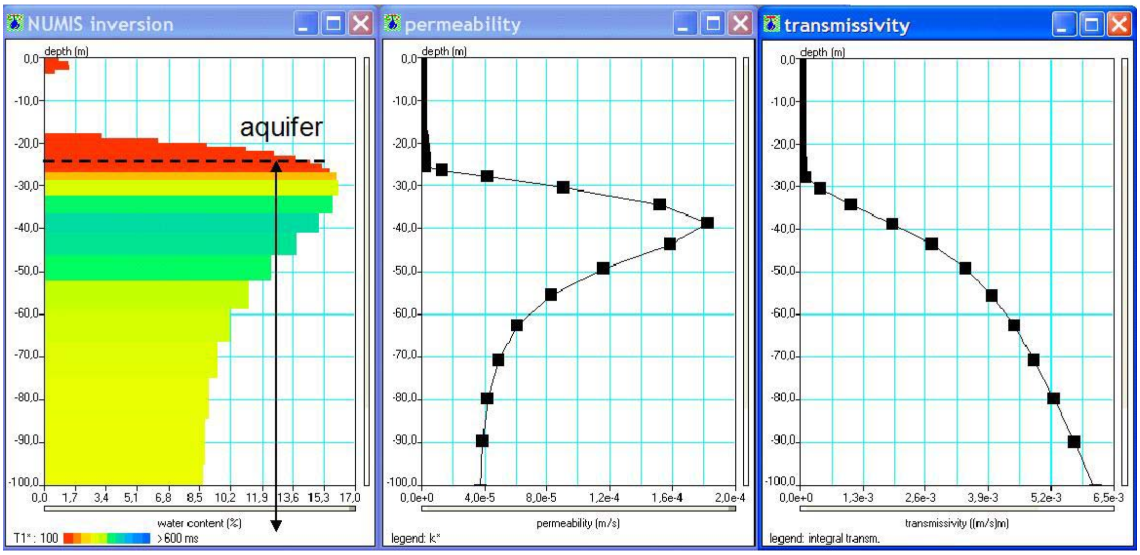


Figure 25. MRS log in Hogsted, Site 5.

The water content and the permeability cross-sections derived from MRS data along the profile in Hogsted are presented in Figure 26.

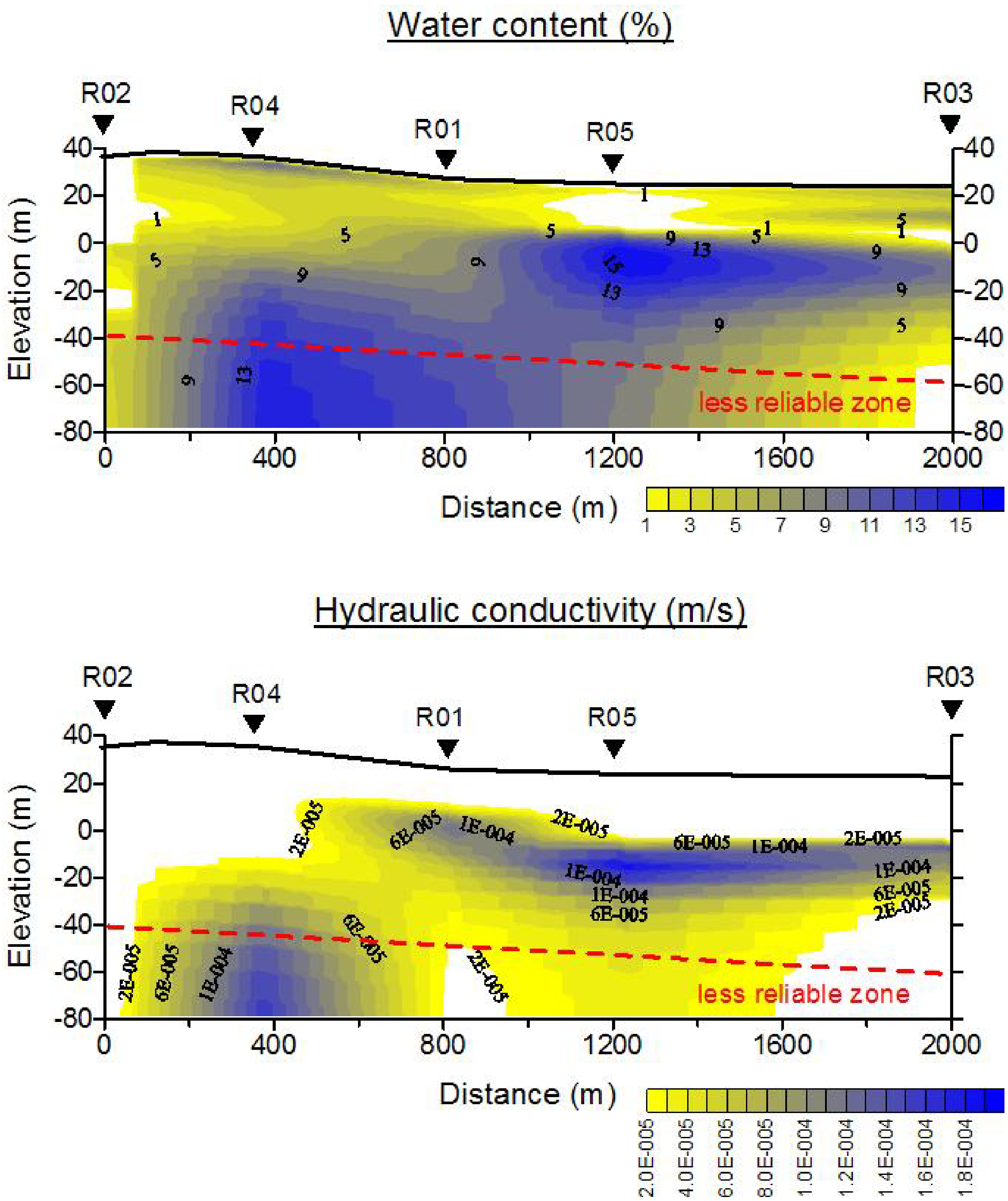


Figure 26. MRS cross-sections in Hogsted area.

Two aquifers are detected by MRS. A shallow aquifer at a depth between 20 and 50 meters (MRS stations 1, 3, 5). The permeability of this aquifer is varying along the profile and has the maximum at the Site 5. A deep aquifer, which is probably corresponding to an ancient glacial valley, is detected by stations 1 and 4. Station 2 shows that this deep aquifer is not continuing towards the north. As the depth of investigation is not sufficient for reliable characterization of this deep aquifer, one should be careful for when selecting the location for drilling between MRS stations 1, 4 and 5. For that, we would recommend to use more geological and probably geophysical information about this area.

MRS users should be aware that MRS is not able to identify rocks. It is only estimating the water content (through the amplitude of the MRS signal) and the mean size of pores (through the relaxation time of the signal). However, using the experience from other surveys and the knowledge that the subsurface is composed of glacial materials, we can propose a possible geological interpretation. We assume deposits with very low permeability as the “till”, more permeable parts of the subsurface as the “very fine sand”, “fine sand” and “fine to medium sand”.

Proposed geological interpretation of the MRS results along the profile in Hogsted area is presented in Figure 27.

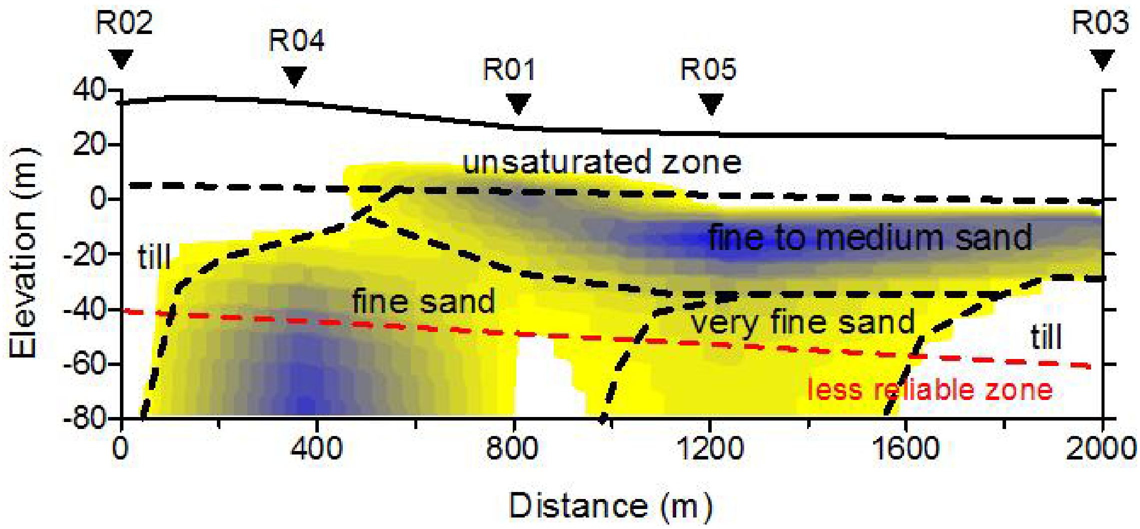


Figure 27. Possible geological interpretation of MRS results along the profile in Hogsted area.

Conclusions

Very high level of manmade noise was observed during this survey. However, our conclusion is that NUMIS system may be efficient when optimized to these conditions. After two-weeks experience in northern Denmark, the main conclusion can be made that the MRS method works well and, especially for the first 100 meters of the subsurface, is a useful geophysical tool for groundwater investigation.

Totally 7 MRS stations were investigated in northern Denmark in August 2003. Five measurements in Hogsted area were carried out along a 2-km-long profile. One measurement was performed in Saby and one in Nosby areas.

In Saby and Nosby, the magnetic resonance signal was not detected. In both cases, MRS cannot be used for the quantitative characterization of the subsurface. However, the insufficient for quantitative interpretation signal to noise ratio can be explained not only by very high noise, but also by small signals. Thus, it can be concluded that for the first 80-100 meters of the subsurface no major aquifers that can be used for water supply purposes exists at investigated sites.

In Hogsted area MRS results provide quantitative information about aquifers: geometry and estimation of hydrodynamic properties (MRS estimation of the water content and hydraulic conductivity). Two aquifers are detected in this area. The shallow aquifer between 20 and 50 meters is composed of a rather permeable material, possibly of fine to medium sand ($k \approx 2\times10^{-4}$ m/s); and it can be used for implantation of water supply wells. The deep aquifer, which may correspond to an ancient glacial valley, is composed of a material with a relatively low permeability ($k < 1\times10^{-4}$ m/s). As the depth of investigation by MRS was limited by NUMIS setup to 80-100 meters, the thickness of this aquifers and its permeability in the deepest part cannot be estimated. Basing on our experience outside of Denmark we expect a relatively small yield and would not recommend drilling a water supply well in such a material. However, taking into account that this aquifer is about 100-m-thick, other data (if available) and experience in local environment may help to find the best solution.

References

Castany G. 1982. *Principes et méthodes de l'hydrogéologie*. Bordas, Paris.

Chang D., Vinegar H., Morriss C., and Straley C. 1997. Effective porosity, producible fluid and permeability from NMR logging. *The Log Analyst*, March-April, 60-72.

Dunn K.-J., Bergman D.J., and Latorraca G.A. 2002. *Nuclear magnetic resonance petrophysical and logging applications*. Elsevier Science Ltd, UK.

Farrar T.C., and Becker E.D. 1971. *Pulse and Fourier transform NMR*. Academic Press, Inc, New York.

Kenyon W.E., Day P.I., Starley C., and Willemsen J.F. 1988. A three-part study of NMR longtitudal relaxation properties of water-saturated sandstones. *SPE Formation Evaluation*, September 1988, 622-636.

Kenyon W.E. 1997. Petrophysical Principles of Applications of NMR Logging. *The Log Analyst*, March-April, 21-43.

Kleinberg R.L., Kenyon W.E., and Mitra P.P. 1994. Mechanism of NMR relaxation of fluids in rock. *Journal of Magnetic Resonance*, Series A 108, 206-214.

Legchenko A., and Valla P. 1998. Processing of surface proton magnetic resonance signals using non-linear fitting. *Journal of Applied Geophysics* 39, 77-83.

Legchenko A.V., Beauce A., Guillen A., Valla P., and Bernard J. 1997. Natural variations in the magnetic resonance signal used in PMR groundwater prospecting from the surface. *European Journal of Environmental and Engineering Geophysics*, 2, 173-190.

Legchenko A.V., and Shushakov O.A. 1998. Inversion of surface NMR data. *Geophysics*, 63 (1), 75-84.

Legchenko A., and Valla P. 2002a. A review of the basic principles for proton magnetic resonance sounding measurements. *Journal of Applied Geophysics*, 50, 3-19.

Legchenko A., Baltassat J-M., Beauce A., and Bernard J. 2002b. Nuclear magnetic resonance as a geophysical tool for hydrogeologists. *Journal of Applied Geophysics*, 50, 21-46.

Legchenko A., Baltassat J-M., and Vouillamoz J-M. 2003. A complex geophysical approach to the problem of groundwater investigation. In proceedings of the *Symposium on Application of Geophysics to Engineering and Environmental Problems (SAGEEP) Annual Meeting*, 6-10 April 2003, San Antonio, USA.

Schirov M., Legchenko A., and Creer G. 1991. New direct non-invasive ground water detection technology for Australia. *Exploration Geophysics*, 22, 333-338.

Seevers D.O. 1966. A nuclear magnetic method for determining the permeability of sandstones. *Paper L, in Annual Logging Symposium Transactions: Society of Professional Well Log Analysts*.

Semenov A.G., Schirov M.D., Legchenko A.V., Burshtein, and A.I., Pusep A.,Yu. 1989. Device for measuring the parameter of underground mineral deposit. *G.B. Patent* 2198540B.

Slichter C.P. 1990. In *Principles of magnetic resonance*. 3rd edition, Springer-Ferlag, Berlin Heidelberg.

Tikhonov A., and Arsenin V. 1977. In *Solution of ill-posed problems*. John Wiley & Sons, Inc.

Timur A. 1968. An Investigation of permeability, porocity, and residual water saturation relationship. *Paper K, in Annual Logging Symposium Transactions: Society of Professional Well Log Analysts*.

Timur A. 1969a. Producible porocity and permeability of sandstones investigated through nuclear magnetic resonance principles. *The Log Analist*, January-February, 3-11.

Timur A., 1969b. Pulsed nuclear magnetic resonance studies of porosity, moveable fluid, and permeability of sandstones. *Journal of Petroleum Technology*, 21, 775-786.

Trushkin D.V., Shushakov O.A., and Legchenko A.V. 1994. The potential of a noise-reducing antenna for surface NMR ground water surveys in the earth's magnetic field. *Geophysical Prospecting*, 42, 855-862.

Weichman P.B., Lavely E.M., Ritzwoller M.H. 2000. Theory of surface nuclear magnetic resonance with applications to geophysical imaging problems. *Physcal Review*, E 62, 1290-1312.

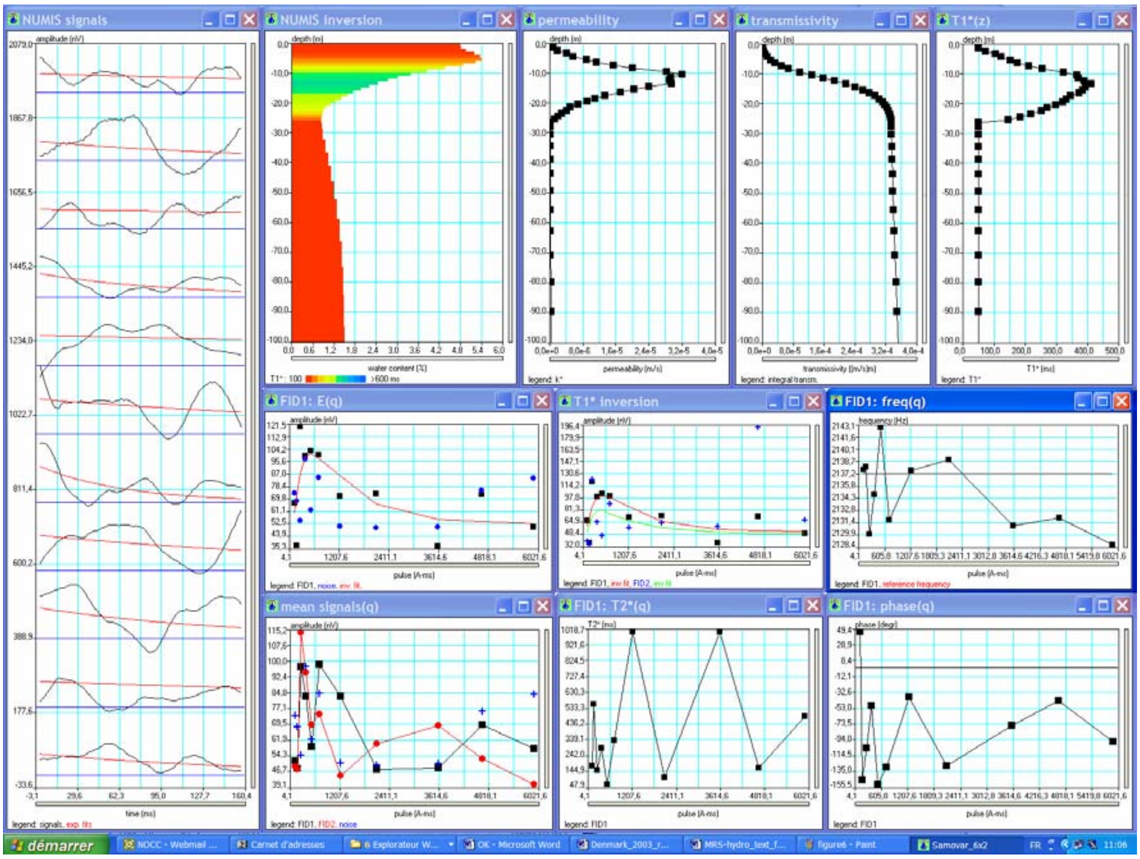
Wyllie M.R.J., and Spangler M.B. 1952. Application of electrical resistivity measurements to problem of fluid flow in porous media. *AAPG Bulletin*, 36, N2, 359-403.

ANNEXE I : MRS field results

Site: Denmark, Saby, Site_2
Loop: 2 - 75.0 Date: 27.08.2003 Time: 11:21

NUMIS data set: C:\moi\REPORTS\Denmark_2003\RMP\data_inversion\saby\SABY_2.inp
matrix: C:\moi\REPORTS\Denmark_2003\RMP\matrix\DAN_75.MRM
loop: square, side = 75.0 m
geomagnetic field:
inclination= 70 degr, magnitude= 50171.36 nT

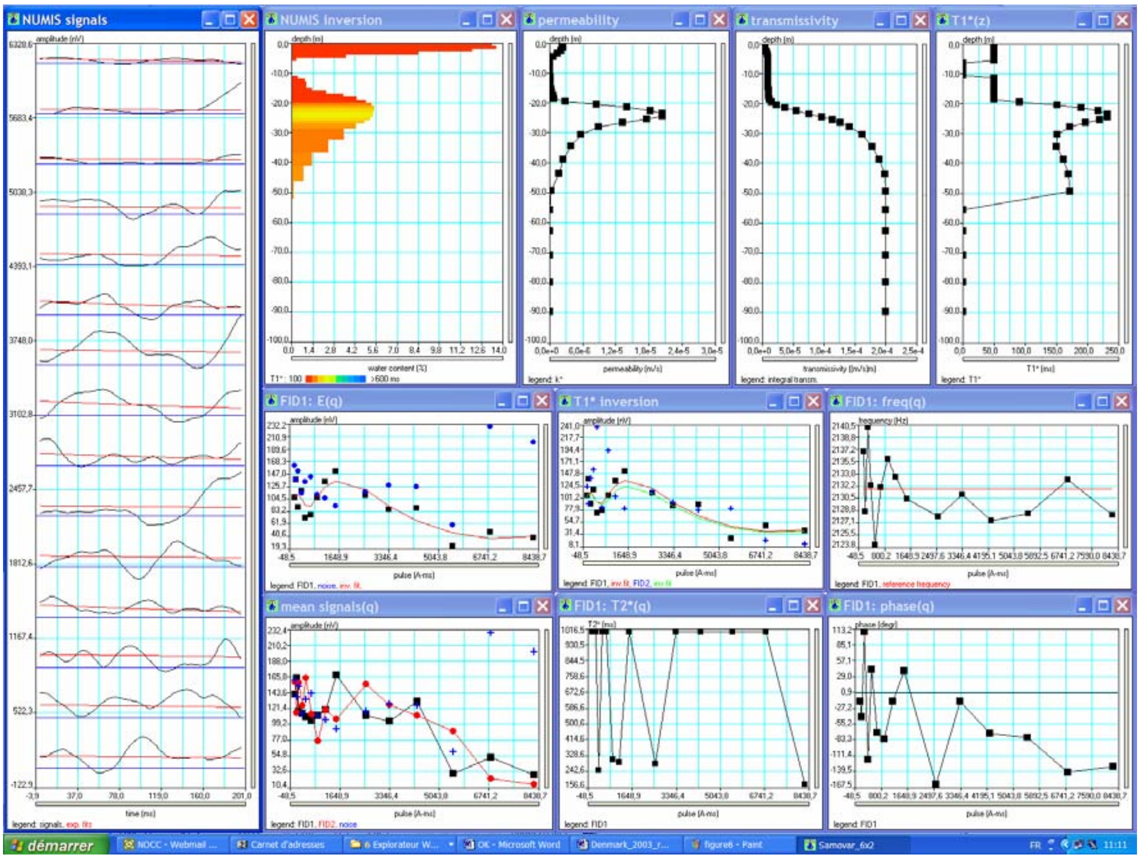
filtering window = 159.1 ms
time constant = 15.00 ms
average S/N = 0.99; EN/IN = 13.66
fitting error: FID1 = 21.54%; FID2 = 55.15 %
param. of regular.: E,T2* = 10000.0; T1* = 70.000
permeability constant Cp = 7.00e-09



Site: Denmark, Nosby, Site_1
Loop: 2 - 75.0 Date: 28.08.2003 Time: 12:55

NUMIS data set: C:\moi\REPORTS\Denmark_2003\RMP\data_inversion\Nosby\NOSB_1.inp
matrix: C:\moi\REPORTS\Denmark_2003\RMP\matrix\DAN_75.MRM
loop: square, side = 75.0 m
geomagnetic field:
inclination= 70 degr, magnitude= 50042.25 nT

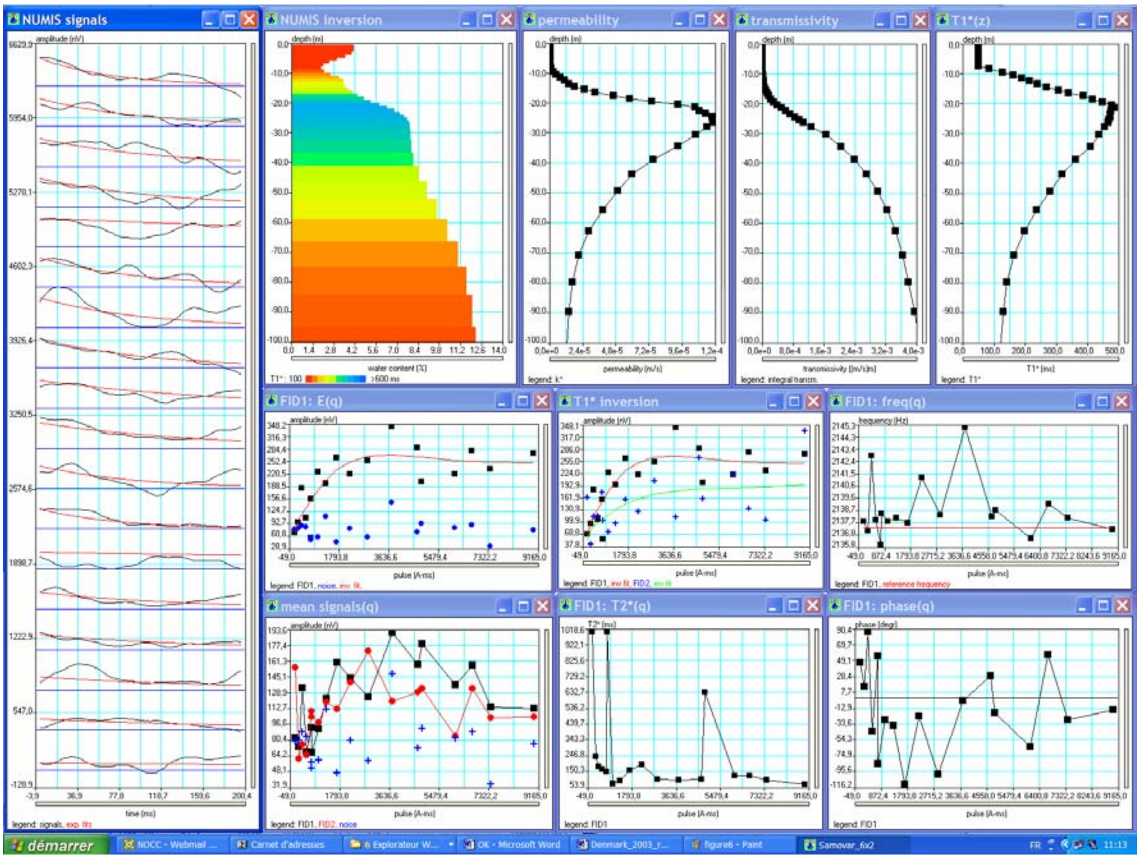
filtering window = 198.9 ms
time constant = 15.00 ms
average S/N = 0.80; EN/IN = 26.79
fitting error: FID1 = 15.55%; FID2 = 42.08 %
param. of regular.: E,T2* = 284.2; T1* = 10.000
permeability constant Cp = 7.00e-09



Site: Denmark, Hogsted, Site_1
Loop: 2 - 75.0 Date: 23.08.2003 Time: 11:13

NUMIS data set:
C:\moi\REPORTS\Denmark_2003\interpretation\data_inversion\Hogsted\HOGST_1B.inp
matrix: C:\moi\REPORTS\Denmark_2003\interpretation\matrix\DAN_75.MRM
loop: square, side = 75.0 m
geomagnetic field:
inclination= 70 degr, magnitude= 50171.36 nT

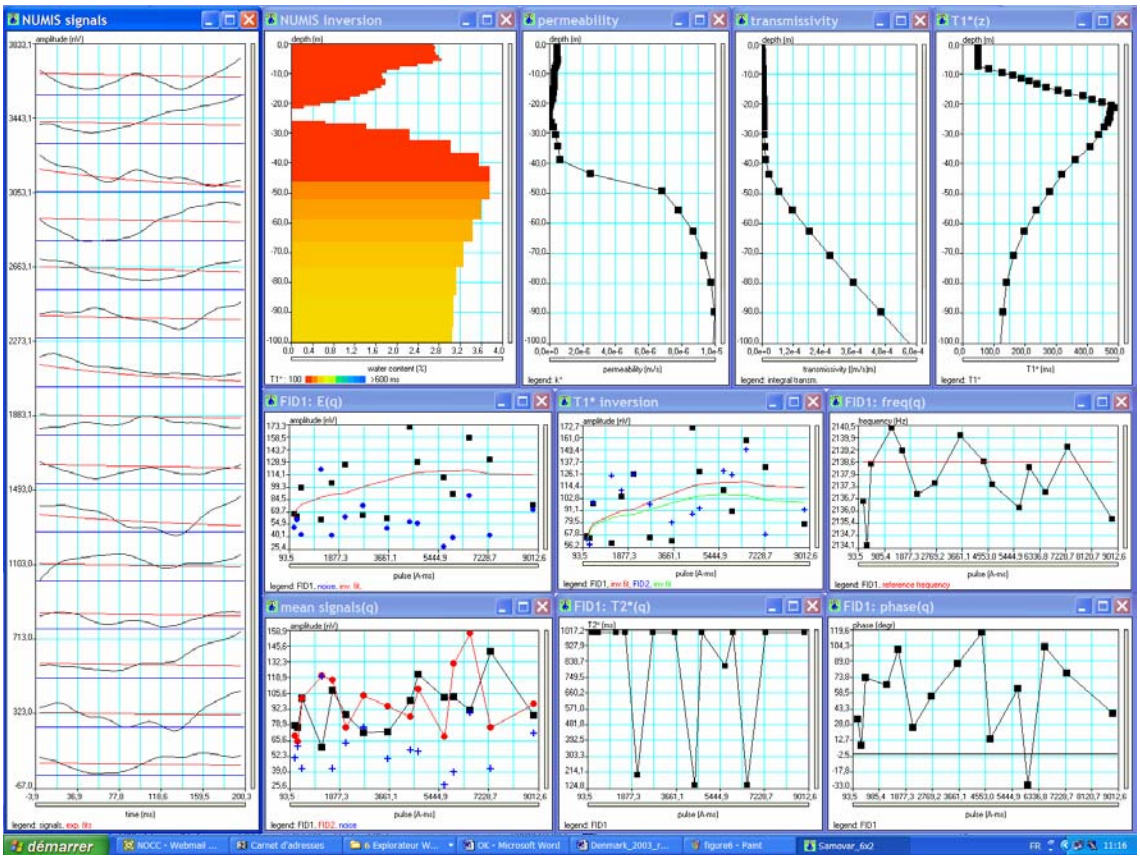
filtering window = 198.4 ms
time constant = 15.00 ms
average S/N = 1.58; EN/IN = 15.50
fitting error: FID1 = 19.16%; FID2 = 36.55 %
param. of regular.: E,T2* = 8000.0; T1* = 90.000
permeability constant Cp = 7.00e-09



Site: Denmark, Hogsted, Site_2
Loop: 2 - 75.0 Date: 24.08.2003 Time: 10:08

NUMIS data set: C:\moi\REPORTS\Denmark_2003\interpretation\data_inversion\HOGST_2.inp
matrix: C:\moi\REPORTS\Denmark_2003\interpretation\matrix\DAN_75.MRM
loop: square, side = 75.0 m
geomagnetic field:
inclination= 70 degr, magnitude= 50201.88 nT

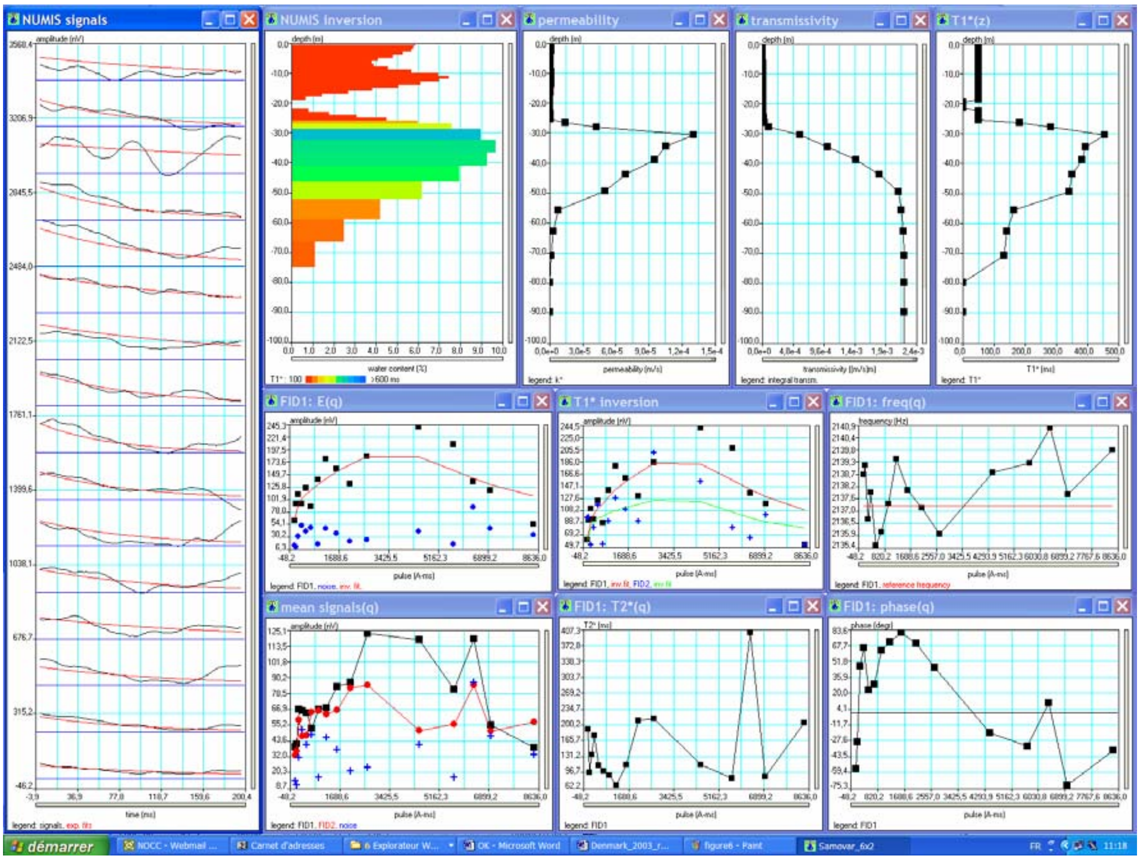
filtering window = 198.3 ms
time constant = 35.00 ms
average S/N = 1.57; EN/IN = 11.88
fitting error: FID1 = 27.54%; FID2 = 23.66 %
param. of regular.: E,T2* = 5000.0; T1* = 70.000
permeability constant Cp = 7.00e-09



Site: Denmark, Hogsted, Site_3
Loop: 2 - 75.0 Date: 25.08.2003 Time: 15:28

NUMIS data set: C:\moi\REPORTS\Denmark_2003\interpretation\data_inversion\HOGST_3.inp
matrix: C:\moi\REPORTS\Denmark_2003\interpretation\matrix\DAN_75.MRM
loop: square, side = 75.0 m
geomagnetic field:
inclination= 70 degr, magnitude= 50171.36 nT

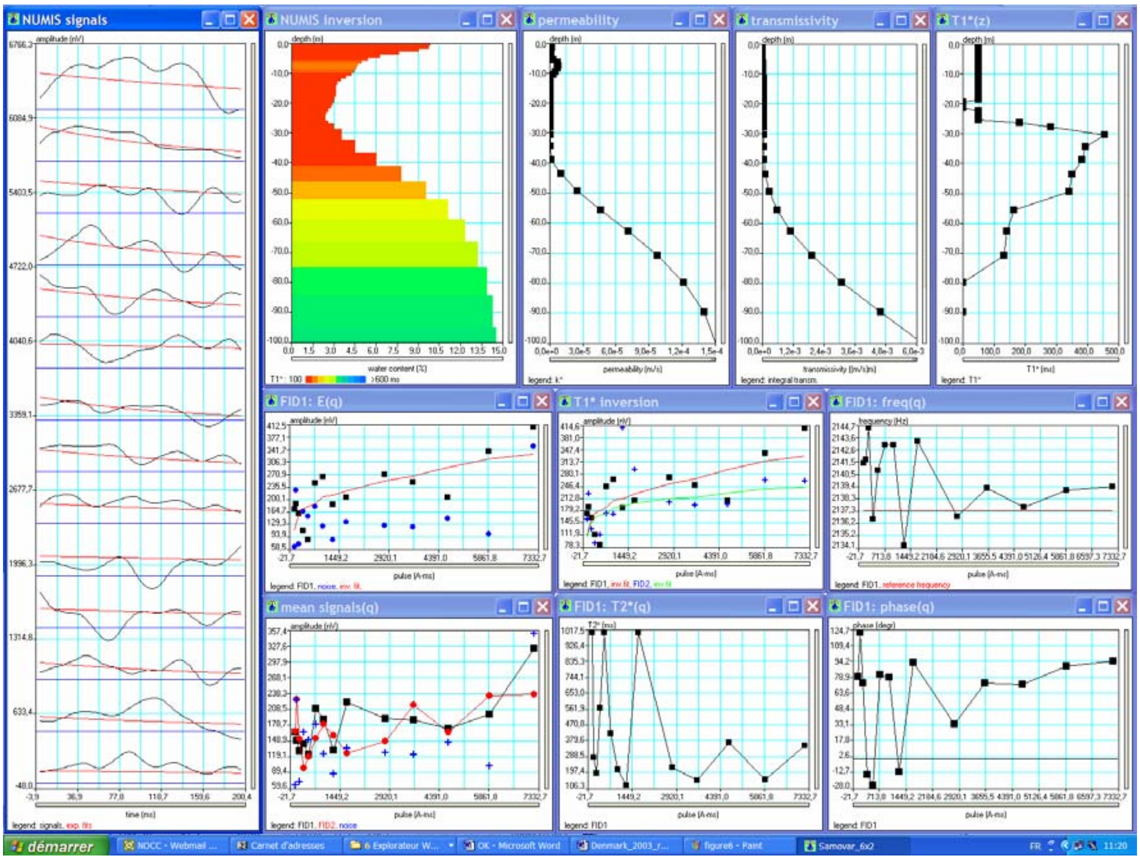
filtering window = 198.4 ms
time constant = 15.00 ms
average S/N = 2.07; EN/IN = 7.08
fitting error: FID1 = 20.77%; FID2 = 30.31 %
param. of regular.: modeling
permeability constant Cp = 7.00e-09



Site: Denmark, Hogsted, Site_4
Loop: 2 - 75.0 Date: 26.08.2003 Time: 19:04

NUMIS data set: C:\moi\REPORTS\Denmark_2003\RMP\data_inversion\Hogsted\HOGST_4.inp
matrix: C:\moi\REPORTS\Denmark_2003\RMP\matrix\DAN_75.MRM
loop: square, side = 75.0 m
geomagnetic field:
inclination= 70 degr, magnitude= 50171.36 nT

filtering window = 198.4 ms
bandpass = 5.00 Hz
average S/N = 1.24; EN/IN = 29.37
fitting error: FID1 = 23.02%; FID2 = 34.15 %
param. of regular.: E,T2* = 8000.0; T1* = 90.000
permeability constant Cp = 7.00e-09



Site: Denmark, Hogsted, Site_5
Loop: 2 - 75.0 Date: 28.08.2003 Time: 20:09

NUMIS data set: C:\moi\REPORTS\Denmark_2003\RMP\data_inversion\Hogsted\HOGST_5.inp
matrix: C:\moi\REPORTS\Denmark_2003\RMP\matrix\DAN_75.MRM
loop: square, side = 75.0 m
geomagnetic field:
inclination= 70 degr, magnitude= 50171.36 nT

filtering window = 198.4 ms
time constant = 15.00 ms
average S/N = 3.01; EN/IN = 6.89
fitting error: FID1 = 10.44%; FID2 = 27.94 %
param. of regular.: E,T2* = 1500.0; T1* = 30.000
permeability constant Cp = 7.00e-09