SURFACE AND BOREHOLE ELECTRIC AND ELECTROMAGNETIC METHODS FOR HYDROGEOLOGICAL INVESTIGATIONS

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ABSTRACT

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The widespread problems in supplying increasing quantities of good quality drinking water call for both highly detailed geophysical investigations and regional hydrogeophysical coverage. This requires the development of efficient methods for the measurement and interpretation of the geophysical data, and the strategic aspects of data collection and interpretation become particularly important. The field data presented in his paper were acquired with two novel electrical methods: the Pulled Array Continuous Electrical Profiling (PACEP) and the Ellog auger drilling method. These, together with transient electromagnetic soundings have been combined into an efficient scheme for hydrogeophysical investigations. The dense data coverage and the combination of methods can provide the detailed resolution desired, and the quality and the reliability of the data are much improved, particularly in densely populated areas where cultural noise and man-made conductors can prove problematic. The approach is illustrated by a large-scale hydrogeophysical investigation from the Beder area in Denmark.

KEY WORDS: hydrogeophysics, electrical profiling, auger drilling, transient electromagnetic soundings, high-resolution surveys.

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INTRODUCTION

The use of geophysical methods for Hydrogeological investigations has received much attention during the last decade. During the last forty years there has been a steadily increasing demand on water resources for industrial and domestic use. In many areas in the industrialised world - especially near urban centres - more groundwater has been extracted than natural infiltration can replenish. This situation has brought a decrease in the easily extractable water resources. Oxidation of pyrite in recently developed aerobic zones above lowered water tables cause sulphate to infiltrate into the upper regions of aquifers. The quality of the ground water is also threatened - and in many areas already spoiled - by infiltration of nitrates from excess fertilisers from agricultural land use and from leakage from waste deposits and dump sites. Lately it has become clear that pesticides have infiltrated the ground water in many areas. The severity of the problems is indicated by the fact that conflicts over the availability of water is one of the most important research themes of political institutions.

The threat to what may be called the most important basic substance for human existence has spurred a number of developments in geophysical methods and strategies to aid in the mapping of ground water resources. It is generally recognised that there is a need for more detailed data coverage of larger areas than has hitherto been the case, and that the effectiveness of the methods applied and the strategy of the field work is of increasing importance. This is particularly true in Denmark which has a very decentralised structure for water supply. Denmark with an area of 43,000 km^2 has more than 3,500 municipal water plants, or 12,000 when small plants with only a few users are counted. There is a general political agreement that this structure is desirable and should be continued because of its resilience to localised catastrophes, but it requires a high awareness of the vulnerability of groundwater resources and detailed regional planning. The ambition of modern hydrogeological investigations is to construct a hydraulic model of the area of interest, which has been calibrated against traditional hydrogeological data such as hydraulic head, precipitation, infiltration, base flow, hydraulic conductivities inferred from test pumpings, and geological conditions estimated from borehole information, which will allow a prediction of hydraulic head and ground water movements under specified natural variations and human extraction rates. The main obstacle for obtaining this goal is that observations of hydraulic head and borehole information is spatially sparse, and the fact that hydraulic conductivities interpreted from test pumpings are averaged over large areas. This combined with the high degree of equivalence in inverse hydraulic modelling makes it very attractive to find methods for reducing the number of possible solutions. One technique is to make use of improved geological models derived from hydrogeophysical investigations.

The objectives of a hydrogeophysical investigation may vary, but among the fundamental aims are the delineation of the aquifer geometry, the estimation of the vulnerability of the aquifer to leakage of polluting substances from the surface, the distribution of hydraulic properties within the aquifer, information on water quality, and the geochemical condition in relation to the lithology of the aquifer. Among the methods applied in hydrogeophysical investigations, electrical and electromagnetic methods have gained a central position (Buselli, 1990; Fittermann and Stewart, 1986; McNeill, 1990). This fact is due to the ability of the electromagnetic and resistivity methods to distinguish between formations of different electrical conductivity or its inverse, resistivity. Resistivity is often strongly correlated with the porosity and the hydraulic conductivity. The basic distinction in the hydrogeophysical investigations of unconsolidated sediments is between clayey and sandy formations. The success of a survey does not only depend on the efficiency of the methods applied, but also on the quality of the interpretation of the measured data. The large volumes of data acquired in modern surveys demand rapid inversion procedures and open up the possibility of two- and three-dimensional (2-D and 3-D) interpretation. Furthermore, an integrated interpretation of data from different methods significantly improves the quality of the interpretation and reduces equivalence problems inherent in any individual geophysical method. Thus, by using an integrated approach, the resolution of the subsurface conductivity structure may be significantly enhanced.

In an attempt to solve some of the problems of hydrogeophysical surveys, the combination of geoelectrical profiling, transient electromagnetic soundings, and Ellog drillings has proved very effective for the Quaternary formations of the glacial landscapes in Denmark. In the following, methods and strategies of application will be illustrated by an example of a hydrogeophysical investigation in the Beder area, Denmark.

THE VULNERABILITY OF AQUIFERS

The rate of infiltration of polluting substances from the surface depends strongly on the vertical hydraulic conductivity of the near-surface material. The infiltration through clays can be as much as a factor of 10,000 slower than for sandy deposits. This increases the time interval where biological activity may decompose the chemicals transported by the infiltrating water and thus reduce their concentration before they reach the ground water. It is, however, a complication that clayey tills can have cracks and fissures, which may cause the hydraulic conductivity to increase substantially. Under all circumstances it is very important to map the distribution of near-surface clays and sand to estimate the vulnerability of an underlying aquifer.

With geoelectrical profiling methods the lateral variation of the subsurface conductivity is mapped. In hydrogeophysical investigations the benefit of geoelectrical profiling with multiple electrode arrays is that inhomogeneous formations like capping clays can be mapped, locations with sandy deposits identified, and the degree of vulnerability of the aquifer evaluated. The regional character of the infiltration problems requires that large areas are surveyed, an operation which is quite expensive using traditional electrical methods with steel rod electrodes.

To meet the demand that spatially dense measurements over large areas can be cost-effectively performed, the method of Pulled Array Continuous Electrical Profiling (PACEP) has been developed (see Fig. 1). An electrode array is towed across the field behind a small vehicle and measurements with three sets of electrodes with different separations are performed continuously and simultaneously while actively towing the electrode array. A system with 3 Wenner electrode separations (10 m, 20 m, and 30 m) has been used extensively since 1988 and has now measured more than 10,000 km of profile.

The data are presented as contoured apparent resistivity maps, one for each electrode configuration. In the case history presented, data were recorded at 1 m intervals along the survey lines, with the distance between lines being 50-300 m. With the PACEP method, two people can complete 10 to 15 km of profile in one day. This represents an efficiency at least 10 times better than that of traditional electrical profiling with implanted steel rod electrodes. Furthermore, the PACEP method provides a much denser data coverage and hence significantly improves the reliability of interpretation (Sørensen, 1994a).

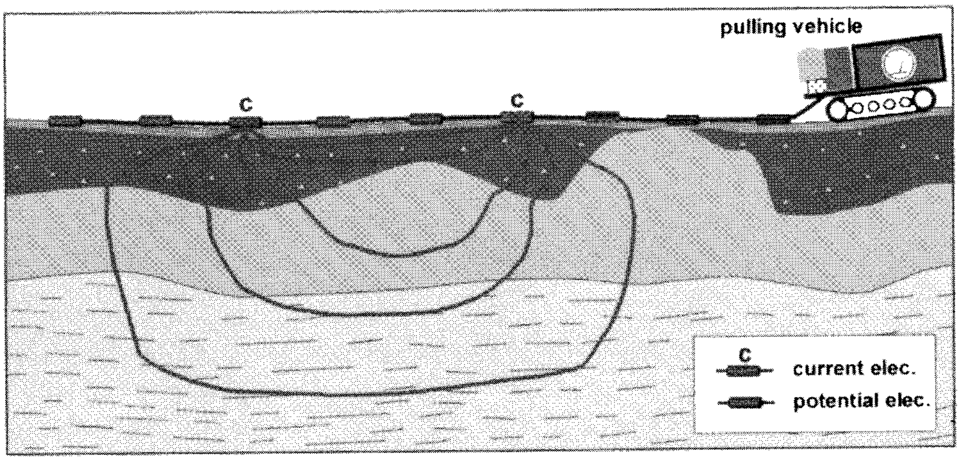

Fig. 1. Principal sketch of the PACEP equipment.

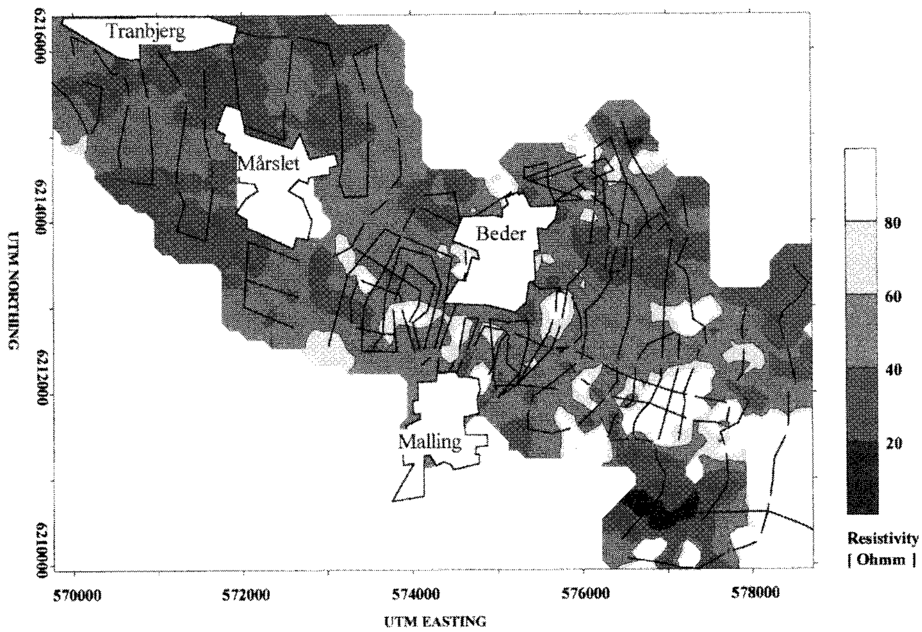

Fig. 2. Iso-resistivity map of the PACEP data for the 10m Wenner array in the Beder area.

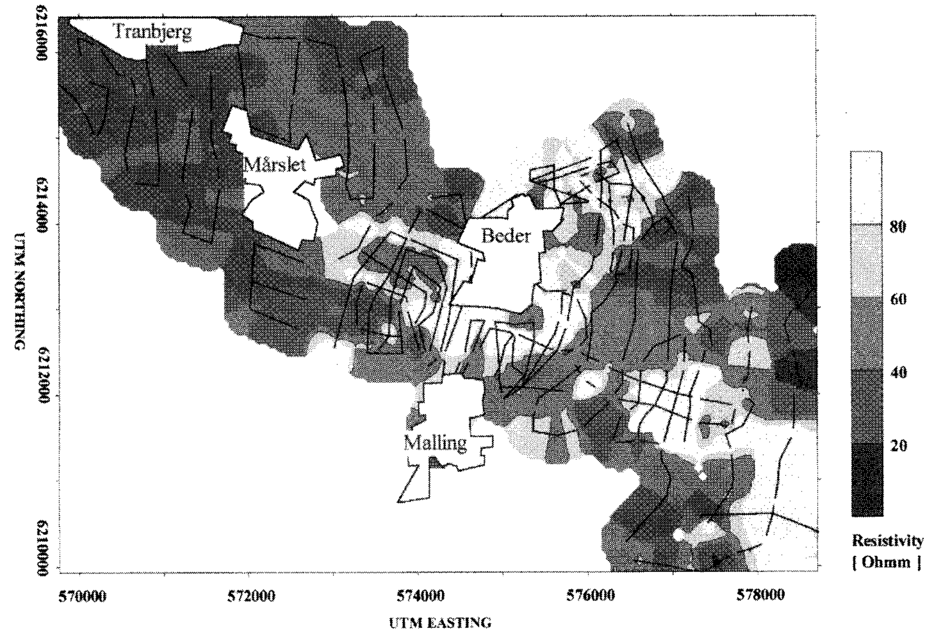

Fig. 3. Iso-resistivity map of the PACEP data for the 30m Wenner array in the Beder area.

At present, an electrode array with eight electrode spacings (PACES) has been developed, which essentially constitutes a continuous geoelectrical sounding (Sørensen, 1995a; Sørensen and Effersø, 1995; Møller and Sørensen, 1995). The dense sampling along the profiles justifies a 2-D interpretation of the data. However, the high productivity of the PACEP and PACES methods makes it impossible to use ordinary iterative least squares inversion programs for the whole profile. A fast approximate interpretation procedure based on the Born approximation has been developed, which performs a deconvolution of the profile data in the wavenumber domain (Møller et al., 1996). Even when only three datasets have been recorded, as is the case with the PACEP system, the profiles can be deconvolved to give a much better resolution especially for the deeper parts (Møller and Sørensen, 1997).

In the Beder area, 15 km south of Aarhus, Denmark, a large scale hydrogeophysical survey has been carried out in collaboration with Aarhus County. Figs. 2 and 3 show iso-resistivity maps for electrode spacings of 10m and 30m, respectively. In the 10m map the general picture shows apparent resistivities below 60 Ωm and in some parts below 40 Ωm. In particular, the NW part of the investigated area has fairly low apparent resistivities. Around the town of Beder, patches of higher apparent resistivities can be seen. In the NW half of the area, the 30 m map shows the same low apparent resistivities and to the far NW even lower apparent resistivities indicating a thick clay cover with decreasing resistivity with depth. An aquifer below this part would thus be well protected. In a 1-2 km wide stretch around the town of Beder striking NE-SW and in a 1 km wide area between the towns of Beder and Mårslet the 30 m map shows higher apparent resistivities, above 60-80 Ωm, indicating that the clay cover is thin and superficial and that an aquifer would be poorly protected compared to the NW part of the investigated area.

Areas with high resistivities on both maps indicate a potential window through which infiltration of pesticides from agricultural land use, together with excess nitrates from fertilisers, can be expected to be high. To protect the underlying ground water resources, restrictive measures should be considered, e.g. to avoid chemically intensive farming and polluting industries. Such regulations have been imposed in a few places and are under general political discussion in Denmark.

THE DELINEATION OF AQUIFERS

Due to pollution and higher groundwater extraction, more interest is given to deeper lying aquifers. An important group of these are composed of Quaternary sand and gravel formations in Tertiary valleys eroded in heavy clays. Many hydrogeophysical investigations are concerned with mapping these buried valley aquifers which are not generally indicated by the surface morphology. The transient electromagnetic (TEM) sounding method has proved to be very efficient in delineating the depth to very conductive heavy Tertiary clays which form the base of aquifers (Spies and Frischknecht, 1991; Hoekstra and Blohm, 1990). Soundings have been made over the target area with a density of 16-25 per km^2 and based on 1-D interpretations, a map can be produced of the depth (or the elevation above mean sea level) of the conductive clays which define the boundaries of the aquifer.

In Aarhus County, where the Beder investigation has been carried out, the average density of drillholes reaching a depth of 50 m is one per km^2, and to a depth of 100 m, is only one per 15 km^2. These figures are expected to be generally valid for Denmark. Clearly, only very general maps of the subsurface can be inferred from such sparse data. Taking the highly varying Danish Quaternary geology into account, one should regard such maps with caution. In fact, compared with the much more detailed maps based on dense TEM soundings the interpolation between borings often proves erroneous. The high density of TEM soundings serves several purposes. First of all, a dense data set will improve the lateral resolution of the geological structures. Secondly, it will help to alleviate the problems of noise and man-made good conductors, which are the two main problems in connection with TEM soundings in densely populated areas.

The high background noise level close to urban areas varies considerably from place to place, even within a limited area of a few hundred metres. By measuring densely there is a greater chance of finding those locations where soundings are successful. Experience shows that the mean effective noise level (the noise level as seen from the instrument after stacking and averaging) is around 0.1 nV/m^2 in uninhabited areas rising to 10 nV/m^2 on the outskirts of urban areas. Another problem is the high density of man-made good conductors like power lines and buried cables, telephone lines and other infrastructure. Experience shows that depending on the dimensions of the cable system a safe distance is approximately 100 m. As a thorough examination of all available maps of power lines and other cables and a detailed strategy of measurement according to the findings is very time consuming, it is our experience that it is more efficient just to go ahead and measure but to keep a distance of approximately 100 m from roads, buildings, windmills, and other cultural noise sources. A high density of measurements ensures that the coverage is not impaired by the purging of those soundings affected by man-made good conductors. On average, around 10% of the soundings must be categorised as non-interpretable because of the above mentioned effects.

The high density of soundings also makes it possible to estimate to what extent the sounding can be adequately interpreted with a 1-D earth model. 2-D and 3-D effects will show up where the lateral gradient in subsurface conductivity is large (Auken, 1995; Goldman et al., 1994) and a 1-D interpretation must be used with caution. Fig. 4 shows the result of the TEM soundings from the hydrogeophysical investigation in the Beder area, presented as a contoured map of the elevation of the good conductor. Information from boreholes reaching the Tertiary clay has been included in the map. The topographic elevation in the area is 50-70 m. A deep valley is observed in the central part of the area striking NW-SE. Between the towns of Beder and Mårslet the valley is very deep. Though the existence of the valley was known from borings in the area, the map based on the TEM soundings is more detailed.

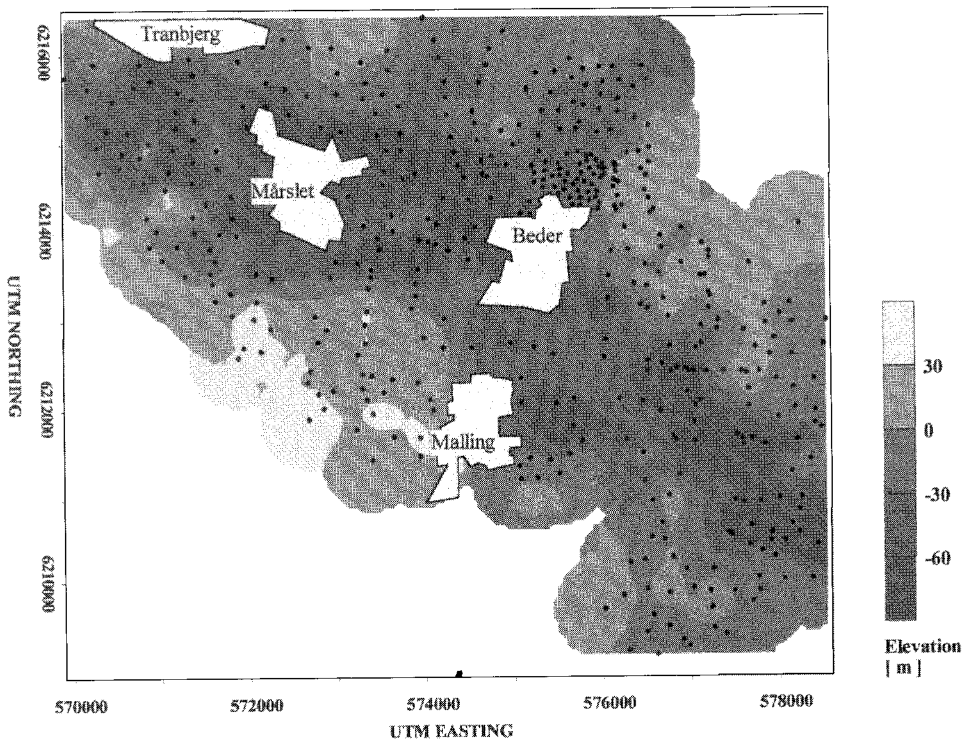

Fig. 4. Iso-elevation map (metres above mean sea level) of the good conductor determined from the TEM soundings in the Beder area over the same area as in Fig. 2 and 3. The TEM soundings are marked with a dot.

The three-dimensional character of the information obtained from the 1-D interpretations of the TEM soundings can be difficult to visualise. As an aid, 1-D TEM sounding models can be concatenated into a traverse line and contoured. These are "vertical" model cross-sections and they demonstrate the conductivity as a function of depth and profile coordinate. Another way to visualise the results of the TEM interpretations is by making "horizontal" model slices or depth slices. To avoid spurious effects from minor model details, an average resistivity within a depth interval is calculated for each sounding and a contoured map of the averaged resistivity is produced for each depth interval. The mean resistivity is the integral over the depth interval of the resistivity as a function of depth as defined by the 1-D interpretation of the TEM soundings, divided by the length of the interval:

$$\bar{\rho} = [1/(z_2 - z_1)] \int_{z_1}^{z_2} \rho(z)dz \ .$$

For the 1-D interpretations the function is a piecewise constant function. The presence of high resistivities on the contoured maps is interpreted as sand/gravel deposits constituting a possible aquifer.

Fig. 5 shows a contoured mean interval resistivity map for the Beder area. In Fig. 5 which is from the elevation interval -10 m to $+10$ m corresponding to approximately 60 m below the surface, we see extended areas of resistivities over 60 Ωm indicating sand and gravel deposits in the saturated zone, i.e., an aquifer is present. In the north-western part of the area where the continuous geoelectrical profiling indicated good protection, there appears to be no aquifer. In the area between the towns of Beder and Mårslet an aquifer is clearly indicated. However, in this part the protective clay cap was thin, so the aquifer is poorly protected.

The TEM soundings are thus used for the dual purpose of finding the depth to the good conductor, which is always well determined from TEM soundings, and to indicate the presence of higher resistivities above the conductive clay formation. Higher resistivity layers are not particularly well determined by TEM soundings. All inductive EM methods are sensitive to absolute rather than relative conductivity and, for the TEM survey parameters used, it was difficult to distinguish resistivities above 60-80Ωm. However, if a high resistivity layer is not too thin, its presence is indicated though the actual resistivity is not well determined.

The ability of TEM soundings to find the depth to the good conductor will also delineate the base of the interesting parts of an aquifer in limestone or sandy deposits, where salt water intrusion or residual salt water is present.

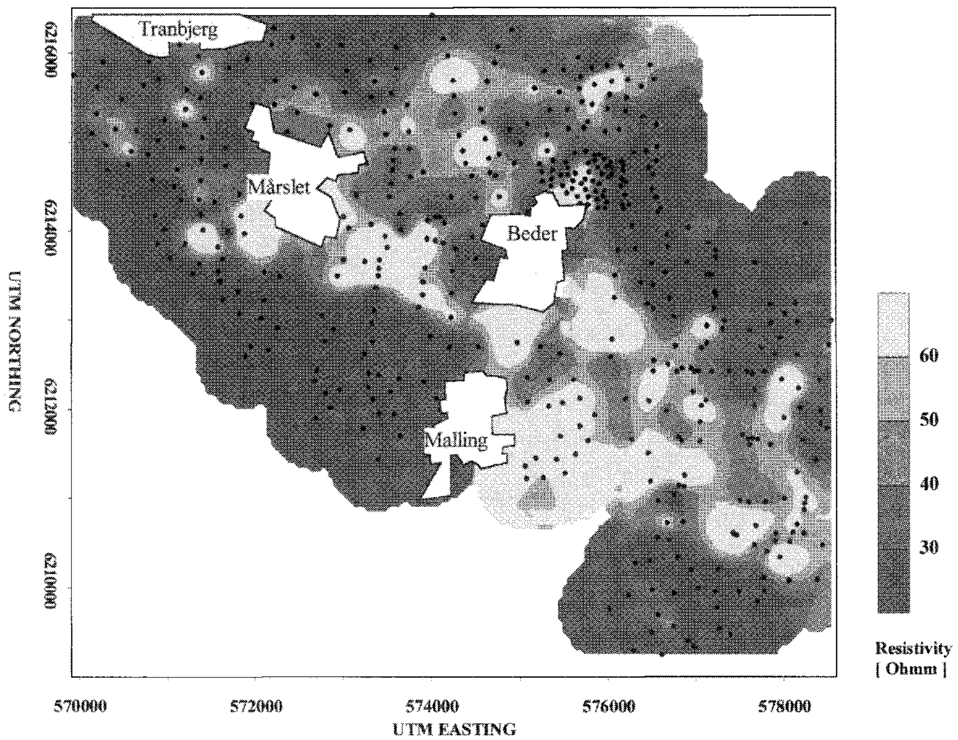

Fig. 5. Mean interval resistivity map for the elevation interval from -10m to 10m for the Beder area.

A new TEM measuring system based on the concept of continuous measurements, where transmitter and receiver are towed behind a vehicle during measurements, has been developed as a consequence of the success of the transient method for hydrogeophysical investigations. This equipment will enable a cost-effective dense sampling of transient soundings over extended areas as is the case with the PACEP technique in connection with geoelectrical profiling, thus providing an improved spatial control (Sørensen, 1995b).

WATER QUALITY AND GEOCHEMICAL CONDITIONS OF AQUIFERS

At key locations selected on the basis of the investigations with surface geophysical methods, Ellog drillings with water sampling are performed, enabling a more precise identification of the lithology and its interrelation with the chemical composition of the ground water.

The Ellog method is an auger drilling method, by which an electrical log and a gamma log are measured continuously while actively drilling, using tools integrated in the hollow drilling stem, see Fig. 6 (Sørensen, 1994b). Because drilling mud is not used, no invasion zone exists, and the measured resistivity of the formation provides a very good estimate of the true formation resistivity. With the Ellog it is also possible to measure the formation resistivity of the unsaturated zone. The resistivity is measured with a vertical Wenner configuration with an electrode spacing of 0.2 m. The electrodes are mounted in insulating material about 1 m from the cutting head of the stem (Sørensen, 1989). Measurements are taken on average every 2-4 mm, each measurement being an average of 80 samples, resulting in an extremely detailed log with a high vertical resolution. As the drilling is performed with an auger drill stem with a cutting head and a flight to transport the loose material to the surface there is a minimal pressure on the formation and thereby minimal disturbance of the resistivity of the formation.

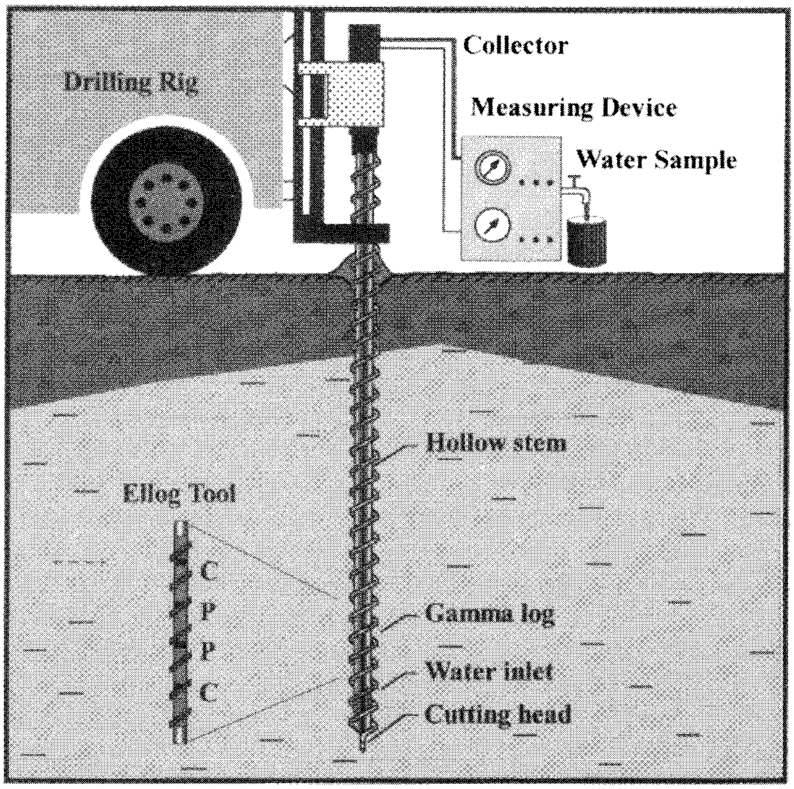

Fig. 6. Principal sketch of the Ellog auger drilling equipment.

The flight of the auger is only 16 mm high and tank experiments have shown that the material transported by the flight, though it may be different from the material immediately outside the electrodes, will have a negligible effect on the measured resistivity (Sørensen, 1989).

The integral gamma log is recorded with a 2 inch scintillation crystal mounted inside the hollow auger stem. The slow drilling speed of 10-30 cm per minute gives excellent resolution in the gamma log. Values of the gamma activity are summed for every 1 second corresponding to a depth interval of 2-4 mm. The time constant of the system can thus be said to be 1 s, but one must realise that the averaging is done digitally with equal weight to each of the counts in contrast to an analogue gamma device where averaging tapers off exponentially for past counts.

Next to the cutting head the drilling stem has narrow 10 cm high inlets through which water samples can be taken into an internal chamber, and the conductivity of the pore water can be measured. Additionally, water can be pumped to the surface for chemical analysis using pressurised nitrogen. The pumping takes place through a closed circuit to avoid oxidation of the water samples and thereby ensure that the chemical analysis is reliable. The well defined depth and the small vertical dimension of the inlets mean that the water samples are extremely depth-specific. The water sampling density depends on the problem addressed. For a general survey, measurements are taken for every one half to one metre. In the case where a detailed picture is needed, e.g. the distribution of sulphate from oxidised pyrite in a recently developed unsaturated zone, the sampling interval can be as small as 10 cm. The drilling operation is momentarily stopped during pumping. After completion of the drilling process the tools inside the drilling stem can be dismantled and pulled to the surface, and the cutting head can be removed. This enables multiple monitoring pipes to be mounted in the borehole for subsequent water sampling. Also, bentonite can be pumped into the formation and along monitoring pipes to seal any unwanted hydraulic connections arising from the drilling.

The combination of the detailed electrical and gamma logs, and the chemical analysis of the water samples, makes it possible to relate changes in chemical composition to changes in geology. This is necessary to understand the hydrochemical processes in the aquifer and to draw conclusions about the consequences of changed extraction patterns on water quality. The electrical log and the gamma log also contribute to the knowledge of the subsurface lithology within the investigated area in general. The mean value of the resistivities of a certain formation found in different boreholes can be used as *a priori* information in a subsequent re-interpretation of the surface electric and electromagnetic data.

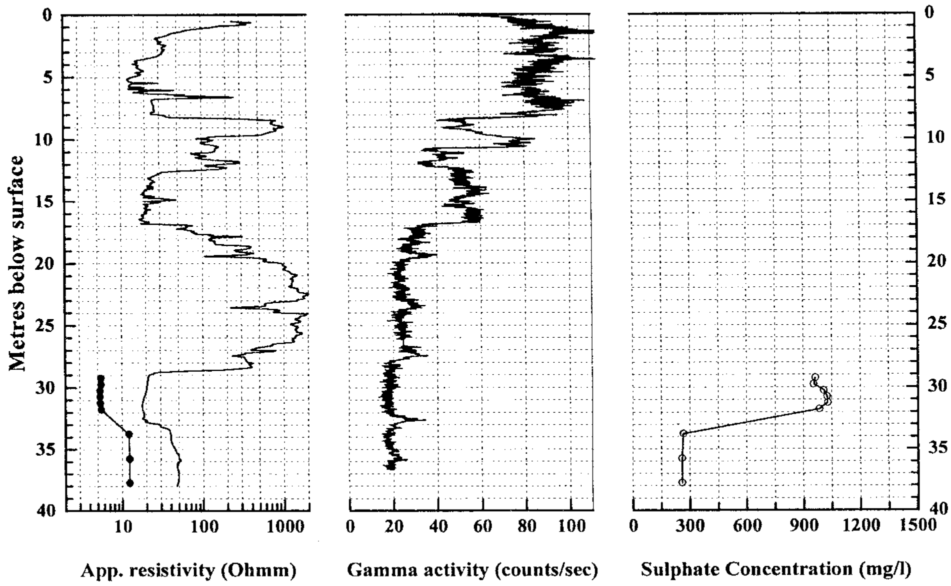

Fig. 7. The Ellog Rokballe 3. The figure shows logs of the electrical formation resistivity with the pore water resistivity, the gamma activity, and the sulphate content of the groundwater.

Fig. 7 shows an Ellog from the Beder area from the location Rokballe 3. The plots show the electrical log with a log of the pore water resistivity, the gamma log, and a chemical log. Except for a very thin surficial layer the first 8 m of the log are characterised by low resistivities and high gamma counts, indicating heavy clays. From 8-13 m the resistivity increases and the gamma count decreases. In the 8-10 m depth interval, resistivities go as high as 1000 Ωm indicating unsaturated sand and gravel, while the interval from 10-13 m shows saturated sand and gravel (secondary water table). From 13 m to 17 m, heavy clays with a low resistivity are found, effectively sealing off the top aquifer from the sequence below. Note that the gamma count in this interval is not as high as in the top 8 m because it is water saturated. Below about 17 m we find unsaturated sand and gravel with more fine grained material in the top of the sequence. From 17-29 m we see an unsaturated zone. This unsaturated zone has been created over the past 15 years by the extraction of groundwater exceeding infiltration. The groundwater table is found at a depth of 29 m. The resistivity in the top part of the aquifer is as low as 20 m and this layer could be mistaken for clay had it not been for the low gamma count and the pore fluid resistivity log indicating the decrease in resistivity to be caused by more conductive pore water. In Fig. 7 one of the analyses made of the water samples is shown, namely the sulphate content. As can be seen, the lowering of the pore water resistivity is caused by an extremely high sulphate content around 1000 mg/l.

This sulphate was created by oxidation of the pyrite of the newly created unsaturated zone. Below 34 m the sulphate has reached a more normal level of 250 mg/l. Note the very detailed character of the logs which reveals very thin layers, e.g., the sand layer at 6.7 m embedded in clay, the clay layer at 19.5 m and 23.7 m embedded in unsaturated sand and gravel, and the clay layer at 32.5 m. These thin layers can be seen in both the resistivity and the gamma log.

INTEGRATED STRATEGY - DISCUSSION AND CONCLUSION

A strategy for the application of electromagnetic and resistivity methods in hydrogeophysical investigations has been outlined. The most important point is that data should be collected with high spatial density over large areas to form an adequate basis for interpretation, and that the physical and geological interpretation should be based on a joint consideration of data sets from different methods. The high density of measurement improves the spatial quality control of the data in densely populated areas affected by cultural interference and makes it possible to discern 2-D and 3-D effects in the datasets.

With the application of the above methods, a large amount of information relevant to hydrogeophysical investigations can be obtained. The combination of the methods can map the vulnerability of an aquifer, disclose the morphogenetic structure of the geology, and determine the depth to the boundaries and the internal geological character of an aquifer. Furthermore, the inter-relationship between the water quality and the lithology within the aquifer can be determined. The strategy has been successfully applied to studies of the Quaternary geology of Denmark in a number of investigations, and should be applicable under similar circumstances in other parts of the world.

It may be argued that this kind of investigation is costly. An investigation such as the one outlined above collects a huge amount of information. On the basis of the results of one method the application of subsequent methods can be optimised to maximise the information gained and to minimise the costs of the total investigation. The costs of just a few unsuccessful traditional drillings can cover the expenses of a geophysical investigation using surface methods with a dense data coverage. In the highly variable Quaternary geology such as exists in Denmark, the only alternative to densely measured surface geophysics would be a comprehensive - and very expensive - drilling program. When compared to the costs of constructing a new water plant or the investment in pipelines and other infrastructure elements, the costs of the geophysical survey in a hydrogeological investigation is small.

In this context it should be noted that the information collected with this type of investigation is also relevant for a range of other physical planning purposes, including prospecting for raw materials such as sand/gravel and clay, estimates of the vulnerability of the aquifer to seepage from dump sites and waste deposits in the investigated area, detection of salt water intrusions, decisions on where to place polluting industries, and the construction of roads. Thus, one single investigation supplies information for a number of purposes, and there is no need to perform a separate investigation for each new task. However, these cost savings will depend on how the public administrative system is organised, and the ability of different administrative units to cooperate.

ACKNOWLEDGEMENTS

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