A HYDROGEOPHYSICAL INVESTIGATION OF THE ISLAND OF DREJØ

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ABSTRACT

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Small islands in sedimentary areas commonly encounter difficulty in supplying drinking water extracted from local aquifers. One typical problem for small islands is caused by saltwater intrusion in well fields due to hydraulic contact between aquifers and the sea. Another problem is surface contamination from human activities, such as farming. These problems are not particular to islands, but often more troublesome as the alternatives for water supply are limited. It is therefore important to establish efficient and inexpensive techniques that can be used to delineate potential aquifers, which are protected from surface contamination by low permeability geologic layers occurring above groundwater.

On a small Danish island, Drejø, a combination of the transient electromagnetic method, the vertical electrical resistivity sounding method, the pulled array continuous electrical profiling method and the Ellog drilling method were used to delineate aquifers, to determine the integrity of the confining geologic layers, and to estimate chemical parameters. These geophysical techniques were integrated into an efficient scheme to provide a basis for the decision on mediation measures for contaminated groundwater, setting of new exploratory wells and restricting land use.

KEY WORDS: transient electromagnetics (TEM), electrical sesistivity, geoelectrics, hydrology, electromagnetic, hydrogeology, logging.

INTRODUCTION

Over the last decade, a growing need for groundwater exploration and characterisation has brought new uses to geophysical methods. This is particularly true for methods characterising the electrical resistivity of the subsurface, and its relationship to pore fluid salinity and effective porosity.

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Keywords

Previous applications of the transient electromagnetic (TEM), and vertical electrical sounding (VES) methods have demonstrated the potential of these methods for delineating aquifer boundaries (Sandberg, 1987; Sandberg and Hall, 1990; Urish and Frolich, 1990; Paillet, 1995; Meju et al., 1999; Poulsen and Christensen, 1999). This paper describes the application of the TEM, VES, pulled-array continuous electrical profiling (PA-CEP) (Sørensen, 1996), and Ellog drilling methods (Sørensen, 1989) for delineating aquifers on the Danish island Drejø.

Drejø Island, located in south central Denmark as shown in Fig. 1, is inhabited by 80 people in the winter, rising to 200-300 in the summer, and covers a total area of 2.5 km^2. The island is intensively cultivated and leakage of nitrate and pesticides related to agricultural use is in danger of contaminating the groundwater. Within a few years in the late nineties, the municipal water supply on the island experienced a deteriorating water quality as a consequence of rising chloride and nitrate content. The increasing chloride content was caused by saltwater intrusion into the well fields due to hydraulic contact between water-bearing layers and the sea. Fertilisers used in farming activities were expected to be the cause of the increasing nitrate content. The presence of sulphate, an oxidation product of nitrate, is also of concern.

In 1994 the municipal water supply of Svendborg and the University of Aarhus initiated a geophysical survey on the island of Drejø to address these problems. The objectives of the investigation were to:

1. delineate aquifers as well as their protective confining layers against surface contamination,
2. obtain information on variability in water quality and
3. locate new sites for exploratory wells.

The study was successful at demonstrating the usefulness of the TEM and VES methods for delineating the aquifers, the PA-CEP system for mapping the protective layers, and the Ellog drilling and logging technique for providing detailed information on lithology and chemical condition of the groundwater.

GEOLOGY AND HYDROSTRATIGRAPHY OF THE SURVEY SITE

Geology

Drejø is located south of the major island Funen, Denmark (Fig. 1). In southern Funen the thickness of Quaternary deposits varies between 2 and 88 m, but is generally between 40 to 60 m. Landscapes are predominantly formed by the Weichselian glaciation from which deposits of three ice advances have been identified. The Quaternary deposits consist of tills or glaciofluvial clays,

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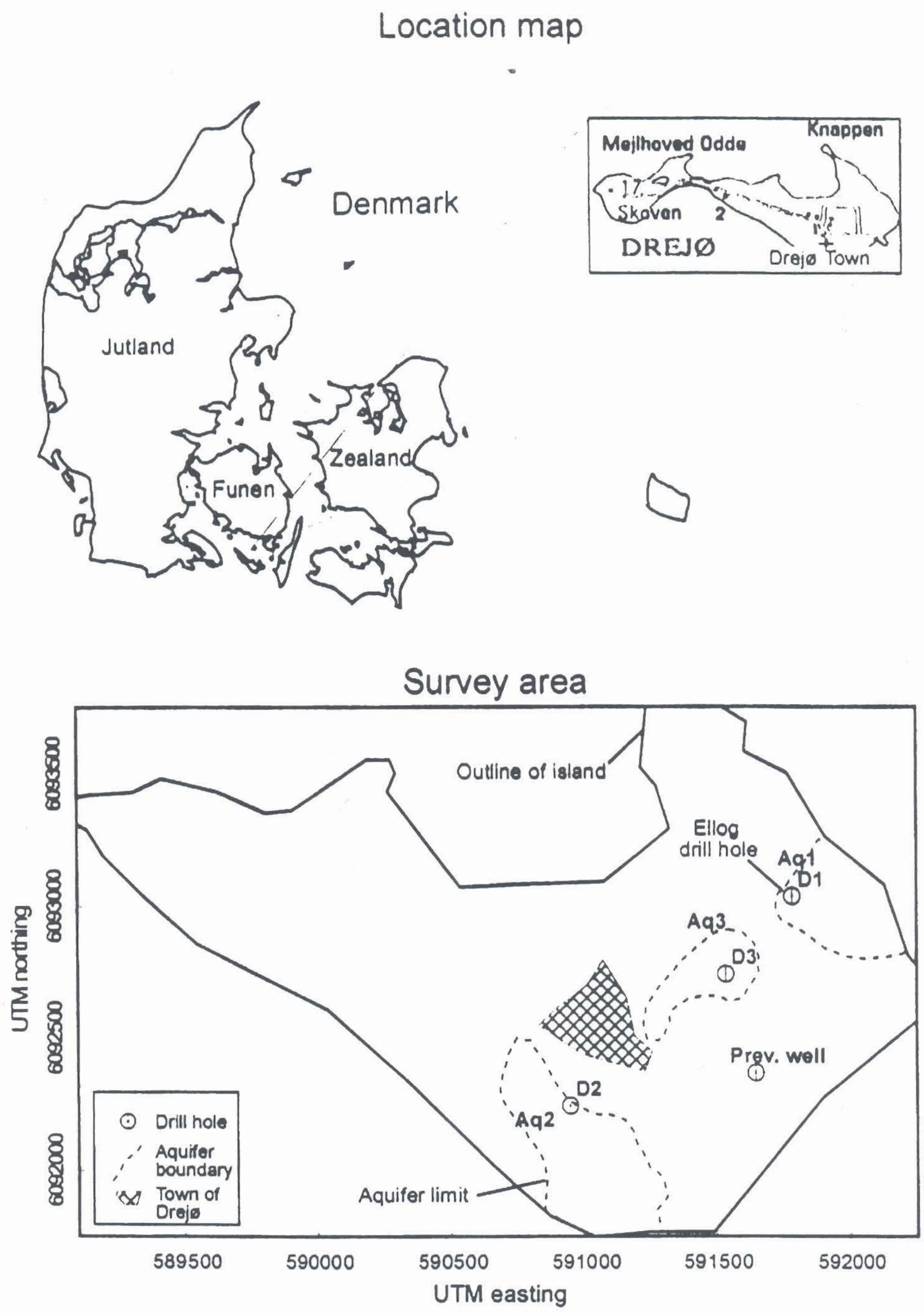

Fig. 1. Geographic location of the island of Drejø, and the survey area on the island.

sand and gravel. Clays containing weathered products and local surface material taken up during the ice advance dominate the tills. The PreQuaternary deposits on the surface consist of clays of Oligocene and Pliocene age.

On the island of Drejø, the Quaternary deposits are about 40 m thick and the PreQuaternary surface is located about 35 m below sea level (mbs). The Quaternary deposits consist of till clays and sands forming a moraine plain with smooth topographical variations. The terrain rises to about 10 m at the highest level in the centre of the island.

Stratigraphic mapping with downhole methods

Geophysical logs are usually recorded in open boreholes stabilised by drilling mud, which is associated with an invasion zone. Drilling mud and the presence of an invasion zone result in distortion of resistivity and induction log readings. These problems are diminished in the Ellog drilling method (Sørensen, 1989): an auger technique by which a resistivity and a gamma log are gathered simultaneously while drilling. No drilling mud is used so the disturbed zone is significantly smaller than in a traditional logging situation. The resistivity log is recorded using a 0.20 m Wenner array mounted in an insulating material on the drill stem. At discrete levels within the saturated zone, samples of the pore fluid may be taken through slots next to the auger head for conductivity measurements and geochemical analysis.

Resistivity and gamma logs recorded in three Ellog drill holes, D1, D2 and D3, are presented in Figs. 2a, 2b and 2c, respectively. Pore fluid samples recovered in the drill holes were analysed for concentrations of nitrate, chloride and sulphate in laboratory. Based on knowledge of the site geology, the resistivity and gamma logs were interpreted lithologically, indicating that the drill holes have penetrated formations of changing layers of till clays and sands. In none of the resistivity or gamma logs are there any indications of penetration into Tertiary clays or high-salinity groundwater. In either case, this would have been associated with low-resistivity readings and presumably high-gamma readings in the former case.

Utilising the geophysical logs correlated with the drill cuttings, the hydrogeology is grouped into three major hydrostratigraphic units: the Bottom unit (I), the Aquifer unit (II) and the Till clay unit (III).

I. The bottom unit consists primarily of impermeable Tertiary clays including saline groundwater. This unit is not encountered in any of the recorded geophysical logs, but in the previous well, noted in Fig. 1. The top of the unit is located approximately at -35 m in the PreQuaternary deposits and forms the effective boundaries for the aquiferous layers. Resistivities lower than 10 ohm·m are expected for this unit.

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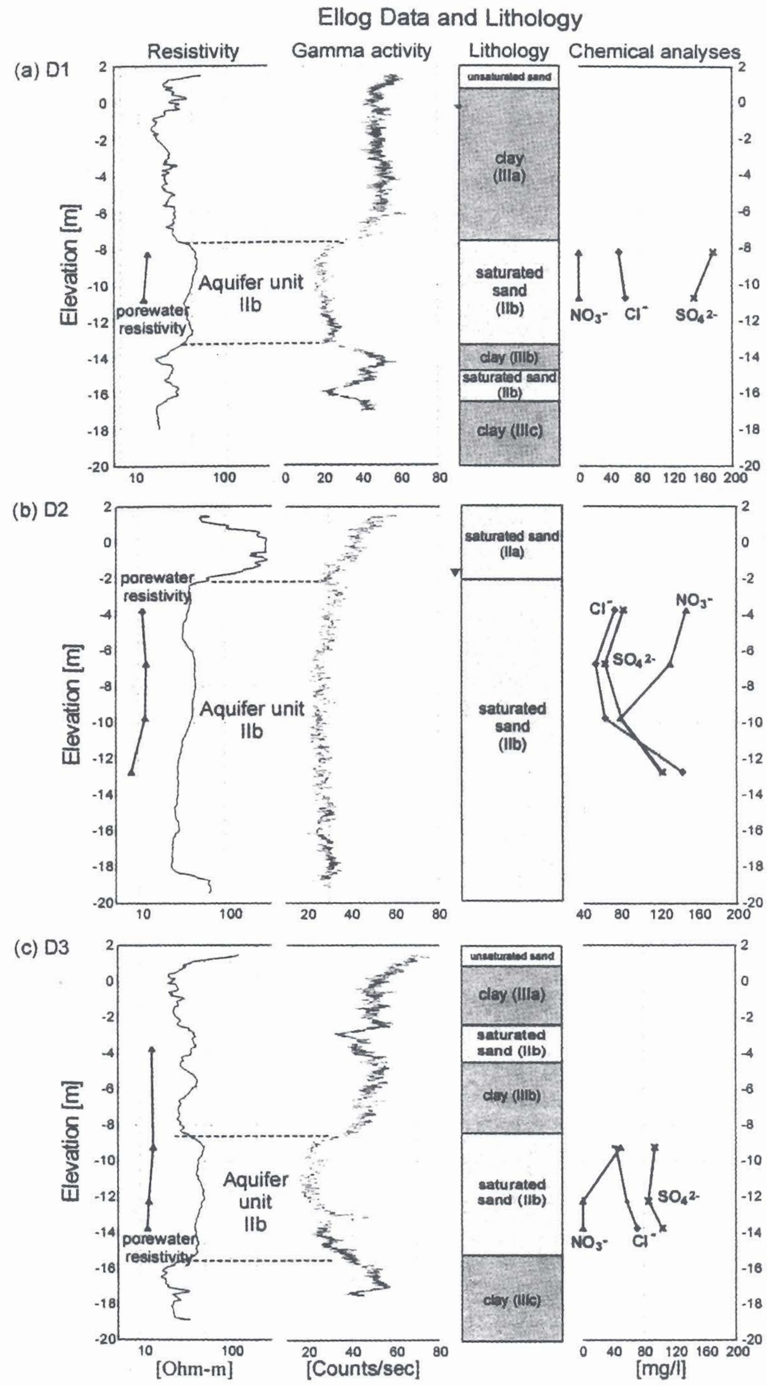

Fig. 2. Resistivity and gamma logs, and chemical data obtained in drill holes (a) D1, (b) D2 and (c) D3 with the Ellog method. The lithological units are identified from the geophysical data correlated with drill cuttings.

II. The Aquifer unit consists of highly permeable till sands and gravel that constitute the water-bearing layers; the unsaturated portion of the unit is denoted IIa and the saturated part IIb. Presumably, this unit is only sporadically present, but may in some areas reach from ground level to the Bottom unit. In some areas the Aquifer unit is probably in hydraulic contact with the sea. An interval consisting of saturated deposits (IIb) is defined in the depth interval from −7.7 to −13.2 m in D1 (Fig. 2a) and in D3 (Fig. 2c). A thinner layer is also present in D3 from −2.5 to −4.5 m. In contrast D2 (Fig. 2b) shows a much thicker layer of IIb in the interval of −2 to −19 m. Resistivities and gamma readings are approximately 30-50 ohm·m and 20 counts/sec, respectively. In D2 there is also an interval of the Aquifer unit near the surface above Unit IIb, containing the unsaturated deposit (IIa) that has significantly higher resistivities, but unchanged values in gamma activity.

III. The Till clay unit consists of low permeable till clays and is subdivided into the upper (IIIa), the middle (IIIb) and the lower (IIIc) portions. Unit IIIc overlies the Bottom unit in most parts of the island. The middle unit is interlayered with the saturated sands of IIb in D2, and IIIa overlies the Aquifer unit II and is defined in the depth interval −0.3 to −7.7 m in D1, and −0.3 to −2.5 m in D3. The Till clay unit III is absent in D2. Resistivities and gamma readings are approximately 20-30 ohm·m and 50 counts/sec, respectively.

SURFACE GEOPHYSICAL MEASUREMENTS AND PROCESSING

TEM and VES

The TEM method is particularly suitable for determining the resistivity and thickness of highly conductive targets such as clays and saline groundwater (Fitterman and Stewart, 1986; Mills et al., 1988). Hence, TEM may provide depth information on conductive clays and saltwater invading the aquifers. The TEM method can be used to map the thickness of resistive sediments when they are thick in comparison with the overburden. Moderate resistivities of 60 to 100 ohm·m are generally related to highly permeable deposits such as sand and gravel (Mazác et al., 1985), although it may also be indicative of low permeable silts. Accordingly, TEM can be used to map potential aquiferous layers, so indicated as sediments with relatively high resistivity.

To delineate potential aquifers, 49 TEM soundings were made on the island with a density of 15-25 soundings per km^2. The TEM data were collected in the central-loop configuration using a Geonics EM-47 with a 40 x 40 m square transmitter loop, and the ultra-high, very-high and high-repetition frequency bands. The VES sounding sites were located at TEM sounding sites

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where the electrical profiling indicated small lateral variations in resistivity. In order to maintain an even sounding density, additional VES soundings were made at sites where TEM soundings were prohibited due to cultural conductors. The VES soundings employed a Schlumberger array with a logarithmic scale of ten electrode half-spacing (AB/2) per decade in the range 1 to 251 m. The maximum sensitivity with depth for the Schlumberger array is roughly one quarter the electrode half-spacing (AB/2).

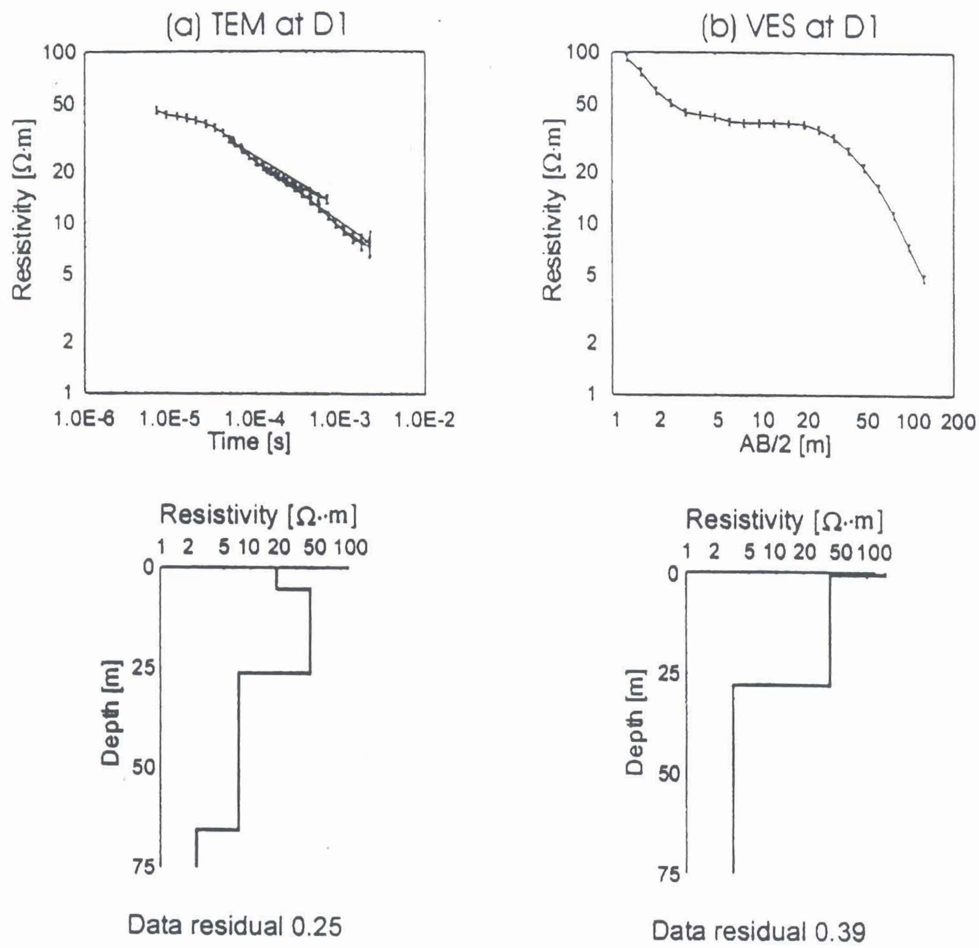

Fig. 3. (a) TEM and (b) VES sounding data and 1D inversion models with model response and data residual for data acquired near drill hole D1. TEM data are presented as late-time apparent resistivity.

The TEM and VES data were processed separately with a one-dimensional (1-D) least-squares, iterative inversion program (Christensen and Auken, 1992). Data were inverted for a minimum number of homogeneous and transversely isotropic layers. No model parameters were constrained. The inversion program provides a sensitivity analysis of the resulting model so that uncertainties in estimated model parameters are appraised. Figs. 3a and 3b show the observed data together with the inverted 1-D model section, data residuals, and model responses for a selected TEM and VES site, respectively. The TEM data are parameterised as late-time apparent resistivity weighted by the noise level measured at the sounding site (Munkholm and Auken, 1996). The noise level is generally quite low, because of the limited infrastructure on the island.

The inverted TEM and VES sections are presented as mean interval resistivity (MIR) maps in Fig. 4. In general the VES data give information on the shallower parts of the section, while the TEM data provides estimates of the subsurface resistivity at greater depths. Averaging the resistivity over an interval is a robust method for presenting depth cuts of single sounding inversion results. The mean interval resistivity for the level interval [A;B] is given by:

$$1/(B - A) \int_A^B \rho(z)dz \ ,$$

where $\rho(z)$ are the resistivities obtained in the 1-D inversions. The MIR-maps of Figs. 4a, 4b and 4c present mean resistivities for particular intervals 0 to −10 m, −10 to −20 m, and −20 to −30 m, respectively.

On the basis of the mean interval resistivities and the foregoing definition of hydrostratigraphic units, potential aquifers are distinguished. In this regard unit resistivities are used in a conservative sense. Mean interval resistivities greater than 40 ohm·m are interpreted as the Aquifer unit II. Thin layers may not be resolved by the TEM and VES methods, but both techniques supply an average resistivity for the depth interval. Hence, mean resistivities greater than 40 ohm·m provide information on the presence of high resistivity deposits in the depth interval, although the exact thickness of such layers is undetermined.

Electrical profiling

Electrical profiling is used to map the resistivity of the near-surface sediments. Low resistivity sediments are indicative of low permeability deposits such as clays. Because of their low permeability clay layers overlying aquifers may serve as protection against groundwater contamination caused by infiltration of pollutants.

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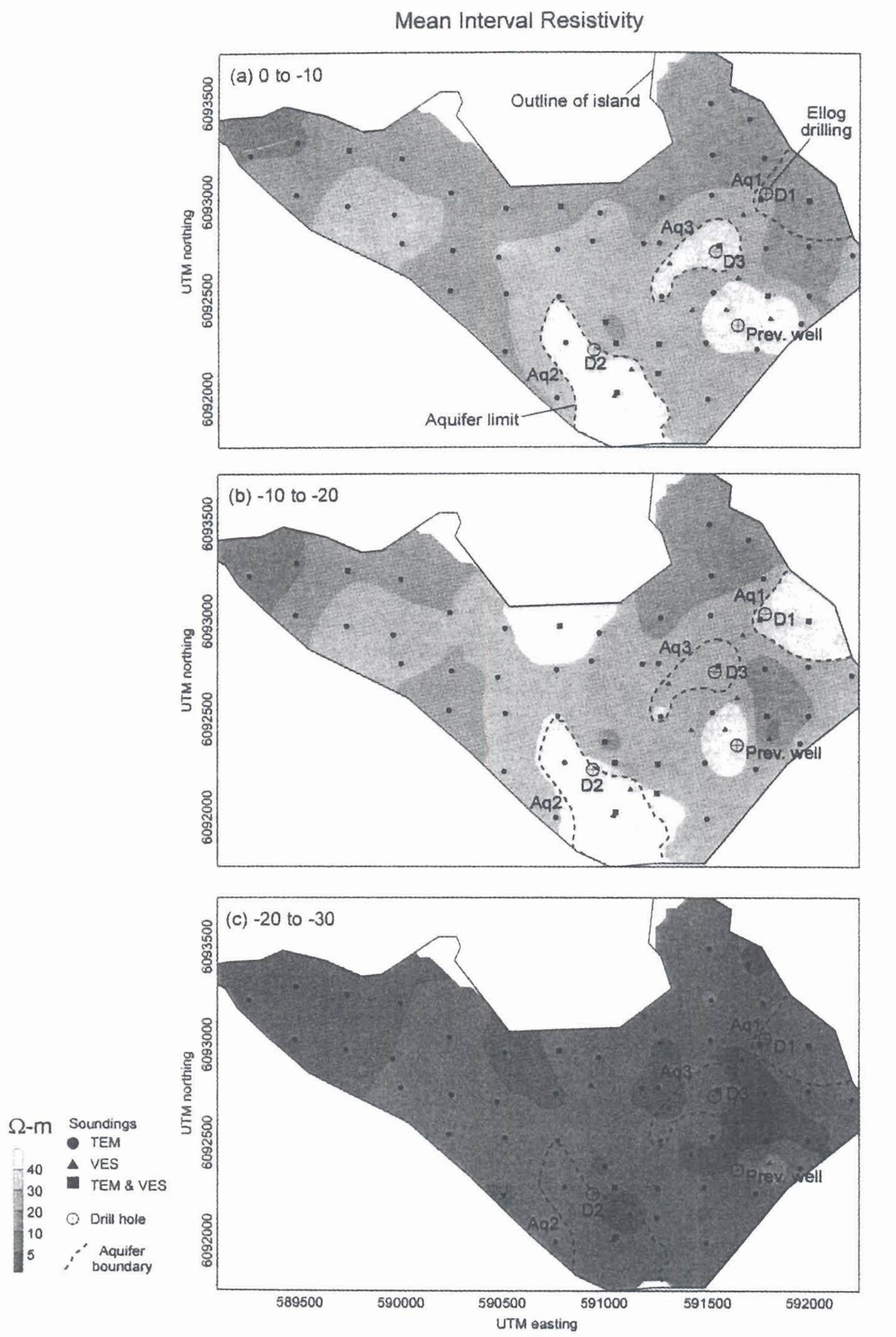

Fig. 4. Mean interval resistivities (MIR) maps computed from TEM and VES 1D inversion results in the depth intervals from (a) 0 to −10 m, (b) −10 to −20 m, and (c) −20 to −30 m. Resistivity values are contoured in ohm·m.

The PA-CEP system is a particularly efficient technique for electrical profiling. At present PA-CEP is used on a routine basis for mapping groundwater protection in Denmark (Sørensen, 1996). Profile lines were spaced about 250 m apart in order to obtain a sufficient spatial distribution. Three Wenner arrays of 10 m, 20 m and 30 m electrode separation, a, were mounted in the electrode tail that is dragged on the surface by a small tracked vehicle while simultaneously measuring at all three electrode spacings. Measurements were made at 1 m intervals, providing a high data density along the profile lines. For logistic reasons, it was necessary to use conventional electrical resistivity equipment in the town of Drejø. In this area measurements were made at 10 m intervals using electrode spacings of 10 m and 30 m.

Data typical for the survey are presented for electrode spacings a = 10m and a = 30 m in Fig. 5. The peak sensitivity for the Wenner array is roughly one third the a spacing, hence the depth of investigation is approximately 3 to 5 m and 10 to 15 m for spacings of a = 10 and a = 30 m. Apparent resistivity data for electrode spacings of a = 10 m and a = 30 m are presented as iso-resistivity maps in Figs. 6a and 6b, respectively. On the basis of these maps and the previously defined hydrostratigraphic units, aquifer protection was assessed in the studied area. Sediments pertaining to the till clay unit III are characterised as low permeable layers with resistivity < 30 ohm·m and good aquifer protection, whereas the sediments pertaining to the aquifer unit II are characterised as layers of high permeability, resistivity > 30 ohm·m and poor groundwater protection.

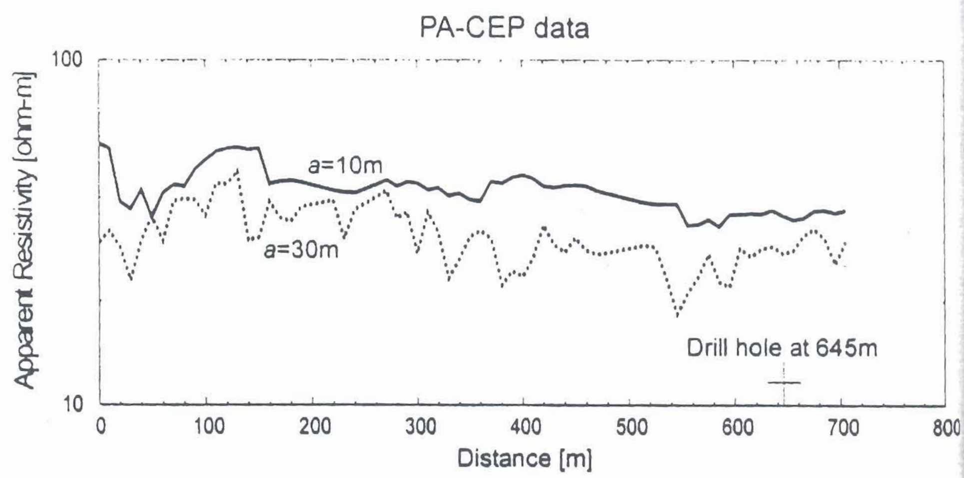

Fig. 5. Electrical profiling data near drill hole D1 for electrode spacing of a = 10m and a = 30m, presented as apparent resistivity in ohm·m.

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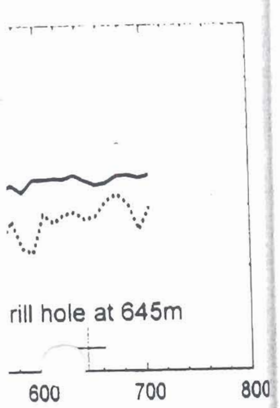

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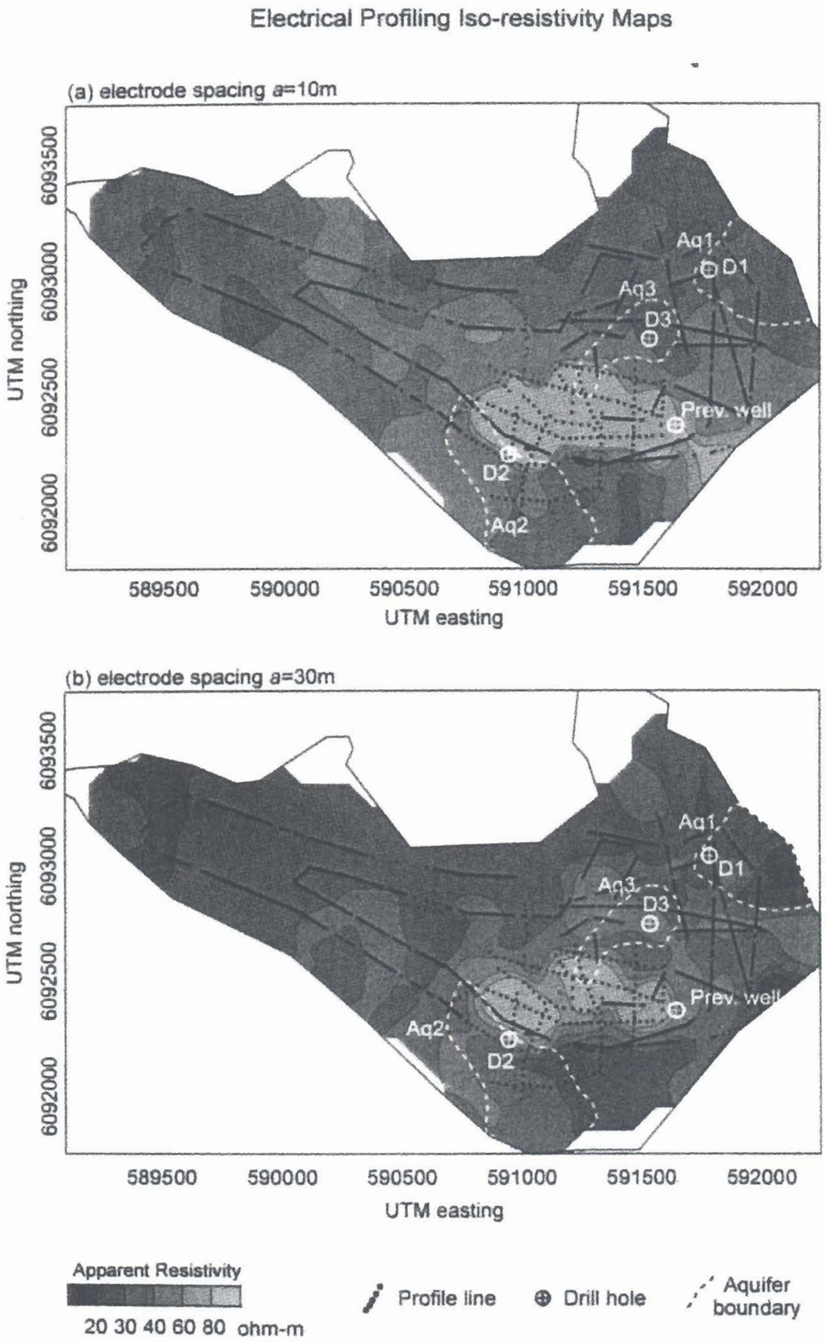

Fig. 6. Iso-resistivity maps for electrode spacing of (a) a = 10 m and (b) a = 30 m from electrical profiling data. Contoured apparent resistivity values are in ohm·m.

Table 1 summarises the values of the geophysical surface measurements from Figs. 4 and 6 at the locations of drill holes D1, D2 and D3, for comparison with the Ellog data in Fig. 2. Table 2 summarises the geophysical parameters determined by the Ellog, VES, TEM and electrical profiling data that are used to define the stratigraphy of the protective Till clay unit (III), the Aquifer unit II, and the Bottom unit I.

Table 1. Summary of geophysical surface measurements at the drill hole locations.

Drill hole	$\rho_a(a=10)$ ohm-m	$\rho_a(a=30)$ ohm-m	$\rho_{MIR}(0\text{-}10)$ ohm-m	$\rho_{MIR}(10\text{-}20)$ ohm-m	$\rho_{MIR}(20\text{-}30)$ ohm-m
D1	30-40	30	30	>40	5-10
D2	60	50	40	>40	5-10
D3	30-40	40	>40	30-40	5-10

Table 2. Summary of geophysical parameters for identification of stratigraphic units.

Stratigraphic Units	ρ_{Ellog} ohm-m	ρ_{MIR} ohm-m	ρ_{iso} ohm-m
I (Bottom)	---	<10	<10
II (Aquifer)	30-50	>40	>30
III (Till clay)	20-30	<40	<30

INTERPRETATION

Aquifer delineation

Analysis of the MIR maps for intervals of 0 m to 10 m and 10 to 20 m (Figs. 4a and 4b) indicates the presence of the Aquifer unit (> 40 ohm·m) in several large areas. Three of these areas, labelled Aq1, Aq2, and Aq3 on the maps, were interpreted to be potential aquifers for water supply. In each of these aquifers, Ellog measurements were carried out in drill holes D1, D2, and

D3. Note that the previous well field is located in an area of the Aquifer unit as defined in MIR maps 4a and 4b.

The MIR maps of Fig. 4a and 4b indicate that both the Aq1 and Aq2 aquifers may be in hydraulic contact with the sea. As seen on these maps, this could also be the case for the aquifer in the previous well. Consequently, due to the possible hydraulic contact with and the proximity of the sea, water extraction from these aquifers is likely to result in saltwater intrusion. Regarding Aq3, which is located further away from the sea than Aq1 and Aq2, the MIR maps suggest that Aq3 is confined by deposits pertaining to the Till clay unit. Hence it is possible to avoid saltwater intrusion when extracting from Aq3, rather than from Aq1 and Aq2, all other factors being equal.

Aquifer protection

In sediments of low permeability, the vertical time-of-travels (TOT) for a given solute is longer than in highly permeable sediments. Longer TOTs result in more extended decomposition of chemical compounds compared to lower TOTs (Kalinski et al., 1993). Occurrence of low-permeable layers, such as clays above the aquifers, may provide protection by reducing surface contamination of groundwater. By mapping the resistivity of the near surface, electrical profiling can be used to detect the presence of protective layers above aquifers.

For Aq1, the iso-resistivity map of Fig. 6b shows resistivities somewhat higher than those assigned to the Till clay unit in the upper depth interval represented by the short a-spacing, which has a depth of investigation of roughly 3 m. This can be explained by inspection of the resistivity log in Fig. 2a. There appears to be a thin resistive layer of roughly 1 m at the surface, identified as an unsaturated sand. This layer would increase the bulk resistivity of the top 3 meters, resulting in a somewhat higher resistivity for the Till clay layer. Sediments clearly defined as the Clay till unit are represented by the long a-spacing (Fig. 6b).

In the northern section of Aq2, both the iso-resistivity maps for a = 10m and a = 30 m show resistivities within the Aquifer unit II. The a = 10 m map shows somewhat more resistive features, indicating the presence of the unsaturated unit IIa, which is in agreement with data from drill hole D2. Resistivities decrease to the south and there appears to be a strip of the Till clay unit in Fig. 6b to the southeast. It can be inferred that the majority of Aq2 is not protected by a clay layer.

As in drill hole D1, data from hole D3 indicate a thin, roughly 1.5 m resistive layer at the surface that is reflected in the slight increase in apparent resistivity values in the a = 10 m iso-resistivity map. At depths of roughly 10m, the a = 30 m map shows Aq3 to be composed of the Aquifer unit II becoming more resistive to the south. This is consistent with data from drill hole D3, which shows interlayering of the Till clay and Aquifer units. Hence the presence of a protective layer is marginal to non-existent.

Water quality

The pore fluid samples taken in the three drill holes (D1, D2, and D3) were analysed for concentrations of nitrate (NO_3^-), chloride (Cl^-) and sulphate (SO_4^{2-}): fertiliser is a source for nitrate, sulphate an oxidation product of nitrate, and seawater incursion a source of chloride. In drill hole D1 a confined aquifer, approximately 6 m thick, is identified in the level range from −8 to −14 m; the confining layer is between 2 m and 10 m thick. Analysis of the two pore fluid samples from the aquifer shows no nitrate content, a low concentration of chloride of < 80 mg/l, and a high concentration of sulphate between 140 and 190 mg/l, as depicted in Fig. 2a.

Logs from drill hole D2 indicate sand over the total length of the hole. The uppermost four metres consist of unsaturated sand. Four samples of the pore fluid were taken below the water table at −2 to −13 m. Analysis of the samples indicates increasing chloride and sulphate concentrations with depth. The chloride concentration rises from about 75 mg/l to about 145 mg/l and the sulphate concentration from about 80 mg/l to about 120 mg/l. The nitrate concentration increases from 80 mg/l in the middle sample to 120 mg/l in the deepest sample.

Two saturated sand layers are identified in drill hole D3 (Fig. 2c). Three pore fluid samples were taken from the lower layer, showing moderate concentrations of chloride from 40 to 70 mg/l and sulphate from about 90 to 105 mg/l. The uppermost sample shows a high concentration of nitrate (50 mg/l), whereas no nitrate was detected in the two lowest samples, indicating the presence of a nitrate boundary at −12 m in the upper part of the saturated zone.

CONCLUSIONS AND RECOMMENDATIONS

The integrated use of TEM, VES, PA-CEP, and the Ellog drilling method has demonstrated its usefulness in hydrogeologic characterisation of the island of Drejø. (1) Potential aquifers were delineated by the use of the TEM and VES methods; (2) aquifer protection was mapped by the use of electrical profiling; and (3) a detailed map of vertical variation in lithology and chemical conditions was developed with the Ellog drilling method. Three potential aquifers, Aq1, Aq2, and Aq3, for water extraction were delineated in the study area.

Analyses of fluid samples obtained in Aq1, located to the northeast by the sea, indicate low concentrations of nitrate and chloride, but high concentrations of sulphate. Lithological interpretations of the geophysical logs obtained in this aquifer indicate that it is located only 10 m below the surface. Although the electrical profiling indicated presence of the Till clay unit to a depth of roughly 10 m, groundwater protection is fairly limited. It is generally recognised that clay layers have to be 20 to 30 m thick in order to provide sufficient groundwater protection. Fig. 4c indicates that the aquifer is in direct hydraulic contact with the sea, but water extraction may still be feasible because of the low concentrations of chloride and nitrate. However, extraction should be supplemented by monitoring of the chloride concentration in an adjacent well closer to sea, so that saltwater intrusion in the well field might be prevented if there is an indication of mobilisation of saline groundwater.

For Aquifer Aq2, located in the southern part of the island, the MIR map for depths of −20 to −30 m (Fig. 4c) indicated that it might be in hydraulic contact with the sea. Chemical analyses of pore fluid samples indicated that the chloride, nitrate and sulphate concentrations are increasing with depth, reaching high levels above 120 mg/l. The iso-resistivity maps and Ellog data from D2 indicate that no protective layer is present. Hence, water extraction from Aq2 is not recommendable due to the unfavourable chemical conditions and possible hydraulic contact with the sea.

Aquifer Aq3 is located further inland than Aq1 and Aq2, and there is no indication of a hydraulic link between the sea and the aquifer. Electrical profiling indicate that the presence of a protective layer above the aquifer is marginal or non-existent. Chemical analyses showed low concentrations of nitrate, chloride and sulphate, except for a high nitrate concentration in the upper part of the aquifer. These good chemical results and the fact that Aq3 is furthest from the sea make it the best candidate as potential aquifers for water extraction.

Aquifer Aq2 already appears to be contaminated. In order to prevent surface contamination of groundwater in Aq1 and Aq3, it is advisable to restrict land use, particularly farming activities, above these aquifers. The reasons for this assessment are the few alternatives for water supply and the poor thickness (< 15 m) of protective layers occurring above the aquifers.

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