The German North Sea Coast in Focus of Airborne Electromagnetic Investigations: The Freshwater Lenses of Borkum

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Abstract

Helicopter-borne electromagnetic (HEM) measurements were conducted over the North Sea island of Borkum to determine the size of the freshwater lenses. Additionally, geoelectrical measurements were carried out at locations where data of 13–17 years old *Schlumberger* soundings exist. HEM successfully revealed the lateral extension as well as the thickness of the freshwater lenses of the island of Borkum. At several locations the depth of the freshwater/saltwater boundary determined by HEM was confirmed by the results of the Schlumberger soundings. No significant changes of the freshwater/saltwater boundary were found at the locations where old and new *Schlumberger* soundings exist. Regarding the results of direct-push and borehole measurements, the HEM related resistivity structure could be determined more precisely and additional to the freshwater/saltwater boundary thin clay layers were revealed. Based on the HEM inversion results the volume of the freshwater resource was estimated.

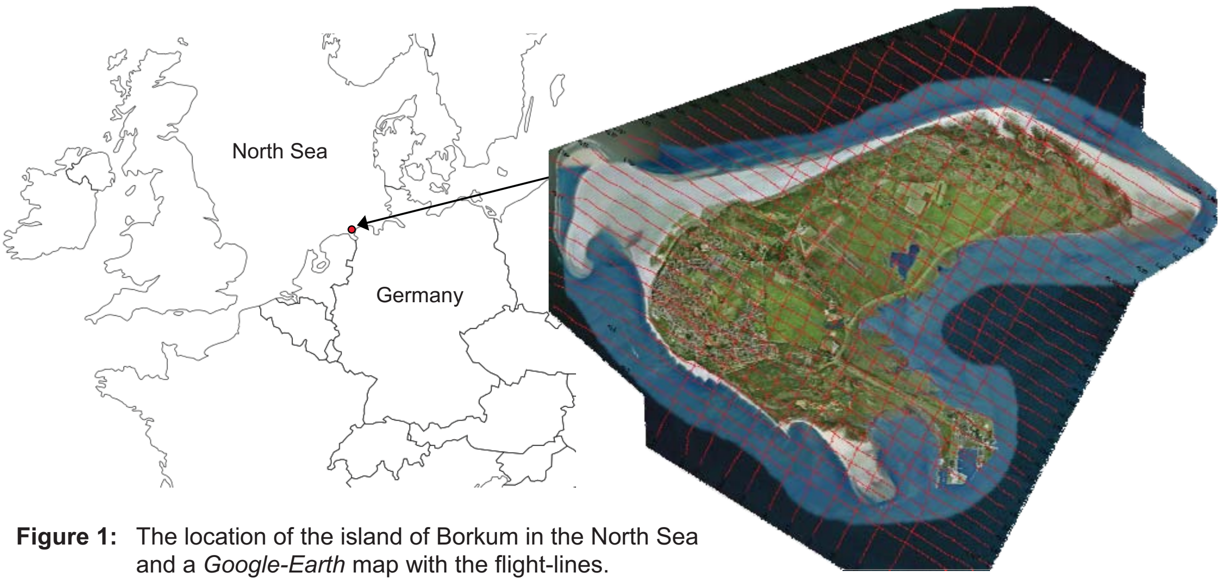

Figure 1: The location of the island of Borkum in the North Sea and a *Google-Earth* map with the flight-lines.

Introduction

Since 2008, the German North Sea Coast has been in the focus of airborne geophysical investigations carried out by the *Federal Institute for Geosciences and Natural Resources (BGR)* and the *Leibniz Institute for Applied Geophysics (LIAG)*. Especially electromagnetics is the most versatile of the airborne geophysical methods and widely applied in hydrogeological investigations as the measurements respond to both lithologic and water-chemistry variations. The applications comprise geologic mapping and aquifer structure, delineation of soil and groundwater salinization, saltwater intrusion into coastal aquifers etc.

Here, we present the HEM results for the North Sea island of Borkum, which was the first of the five HEM project areas investigated in 2008-2009, and compare them with DC *Schlumberger* soundings, lithological logs and direct-push measurements. These data will be used for a hydraulic modelling of the freshwater lenses of the island of Borkum in the *CLIWAT project* (http://cliwat.eu, *EU Interreg IVB North Sea Region*). Additionally we show an estimation of the volume of the freshwater lenses calculated by *Siemon et al. (2009b)*.

Other HEM results for the Wadden Sea, the North Sea islands of Langeoog and Spiekeroog, and the Elbe estuary are shown by *Schaumann et al. (2010)* in this volume. *Wiederhold et al. (2009)* presented the results of two *SkyTEM* surveys at the North Sea island of Föhr and the saltdome Bad Segeberg, which were conducted in 2008 by *SkyTEM Aps* by order of *LIAG*.

HEM Survey

The Borkum survey covers an area of 88 km² and was flown within two days in March 2008. The flight-line spacing was 250 m and the tie-line spacing was 500 m, totalling to about 412 line-kilometres (Figure 1). The *BGR* helicopter-borne geophysical system simultaneously uses frequency-domain EM, magnetics and radiometrics (Figure 2).

The HEM system, a *RESOLVE* bird manufactured by *Fugro Airborne Surveys*, operates at six frequencies ranging from 386 Hz to 133 kHz.

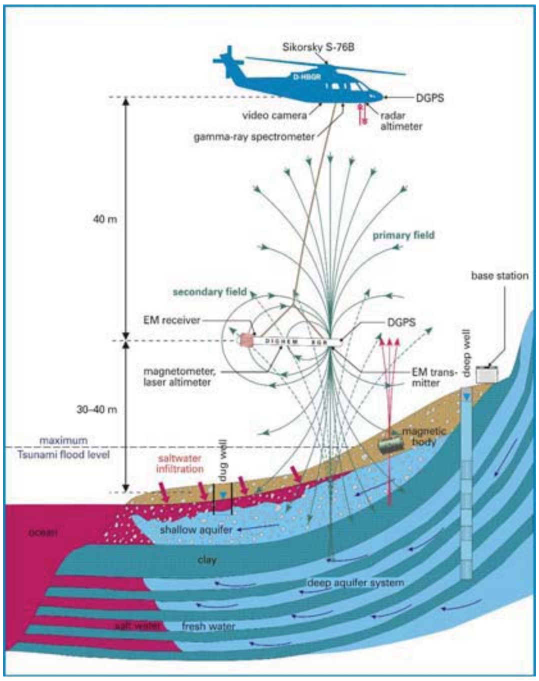

Figure 2: *BGR* helicopter-borne geophysical system:

Electromagnetics:

RESOLVE (Fugro Airborne Surveys)

Frequencies:	386, 1 823, 5 495, 8 338, 41 430 and 133 300 Hz
Coil separations:	~8 m
Coil orientation:	5× horizontal coplanar 1× vertical coaxial
Investigation depth:	1–70 m (at Borkum)
Magnetics:	Cs magnetometer
Radiometrics:	256 channel gamma-ray spectrometer

Navigation/Positioning:

GPS / radar and laser altimeter

Bird altitude:	~ 34 m
Flight speed:	~140 km/h
Sampling distance:	~4 m

The investigation depth increases with decreasing frequency. The EM fields of the lowest frequency penetrate the freshwater lenses nearly completely as seen in the apparent resistivity maps (Figure 3). Here, higher resistivities are represented by green and blue colours (freshwater) and lower resistivities by red colours (saltwater). The apparent resistivity maps, which are based on the half-space approximation, provide a first insight into the subsurface conductivity distribution.

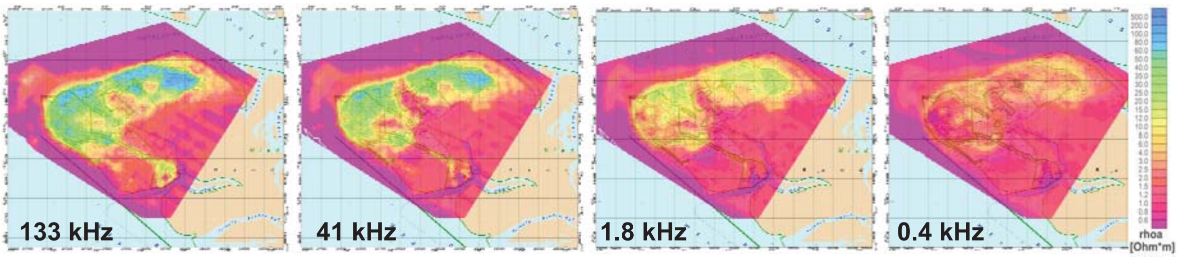

Figure 3: Apparent resistivity maps: The investigation depth increases with decreasing frequency. The freshwater lenses – represented by higher resistivities (green & blue) – are nearly completely penetrated by the EM fields of lowest frequency.

The HEM data were also inverted using *Marquardt-Levenberg* 1-D inversion technique based on a layered half-space model (*Siemon et al., 2009a*). Starting models required were derived automatically from the apparent resistivities *vs.* centroid depth sounding curves. Resistivity maps at selected depths and stitched together vertical resistivity sections were derived from these 1-D inversion models. The lateral extensions as well as the thicknesses of the freshwater lenses were mapped successfully with HEM, as shown in the resistivity maps and the vertical resistivity sections of Figure 4.

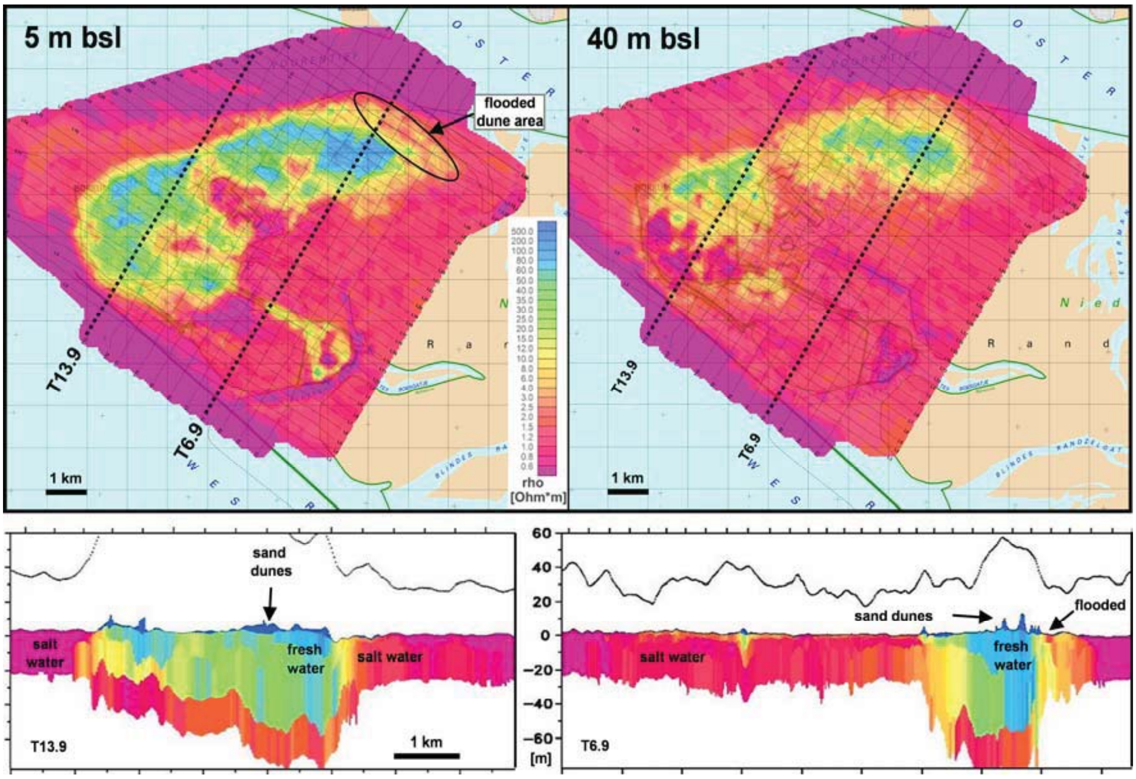

Figure 4: Resistivity maps at 5 and 40 m bsl and vertical resistivity sections along the tie lines T13.9 and T6.9.

The first layer represents the resistive dry dune sands above the groundwater table (dark blue) and the bottom layer the conductive saltwater-filled sediments (red) below the freshwater lenses (blue). The two layers in-between are associated with sediments filled with fresh or brackish water. The freshwater/saltwater boundary was detected down to about 60 m depth.

DC survey: Comparison of measurements 16 years apart

In 2008, 36 *Schlumberger* soundings were carried out at sites already measured between 1991 and 1995 (*Worzyk, 1995a and 1995b*).

All the sounding curves at Borkum have a Q-type shape with three or more layers (*e.g.* Figure 5). Higher resistivities are due to dry and freshwater filled sediments, whereas the lower resistivities at the end of the sounding curves are due to saltwater-filled sediments underlying the freshwater lenses.

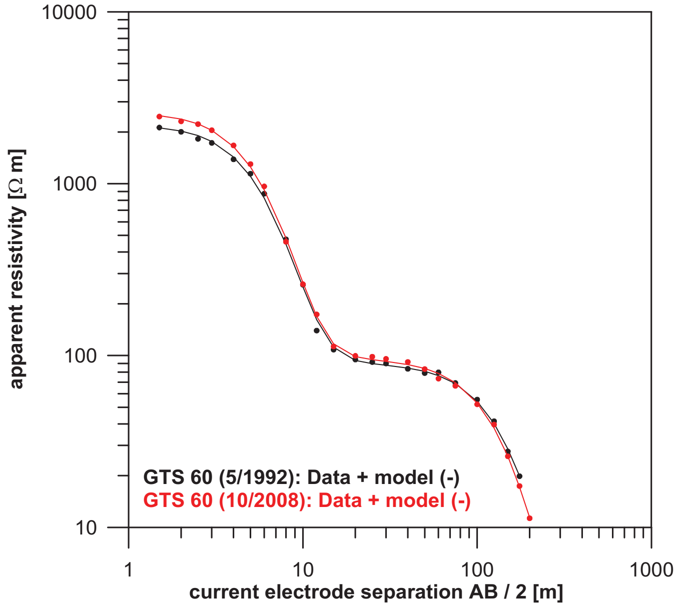

Figure 5: DC sounding curve of site GTS 60.

In 1992, the freshwater filled sediments were associated with resistivities between 70 and 110 Ωm in the water catchment area Ostland; these resistivities were almost reproduced in 2008. The underlying saltwater-filled sediments showed resistivities below 10 Ωm, but these values were not determined exactly. Taking equivalent models into consideration the thickness of the freshwater lens can be determined with an accuracy of about 6–8 m.

No significant changes of the freshwater/saltwater boundary were found at the locations where old and new *Schlumberger* soundings exist.

Combined analysis

At several locations the depth of the freshwater/saltwater boundary determined by HEM was confirmed by the results of the *Schlumberger* soundings (*e.g.*, Figure 6).

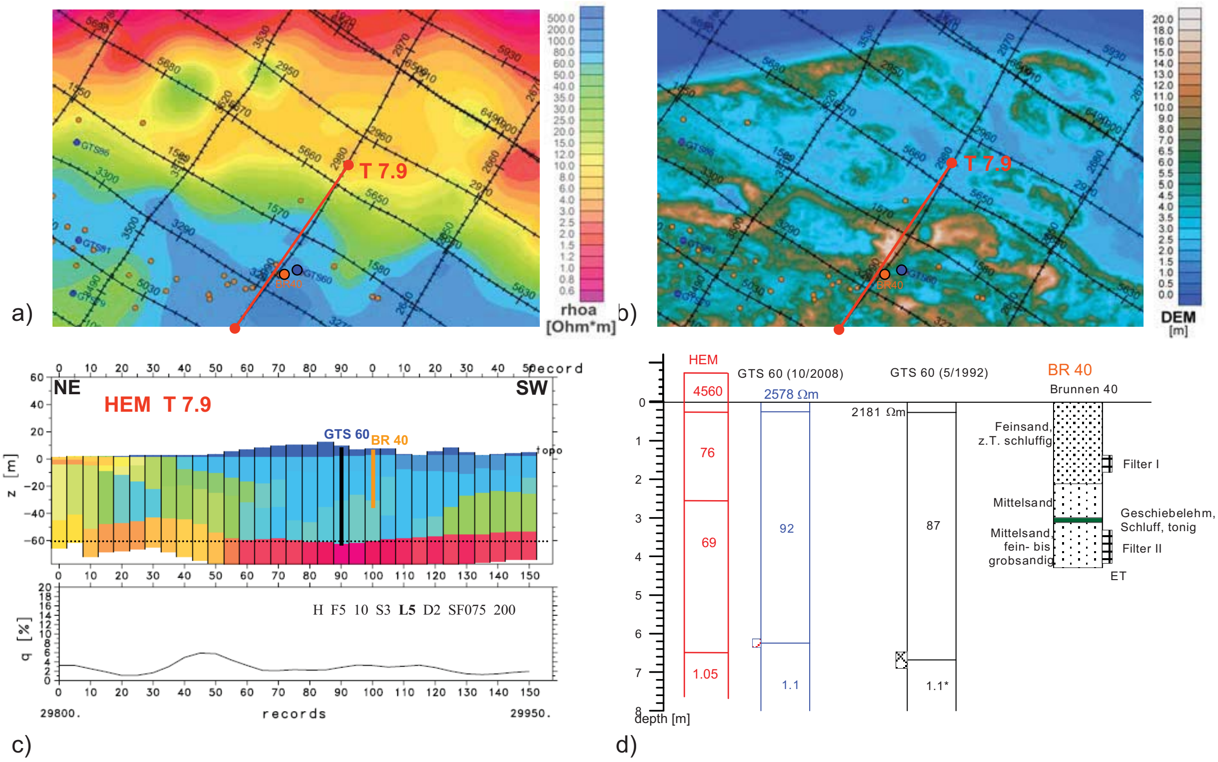

Figure 6: a) Resistivity map (5 mbsl) with the location of a part of flight-line T7.9 (red line), the lithological log BR40 (orange circle) and the DC site GTS 60 (blue circle). b) Digital elevation model revealed from laser scan data of *NLWKN*. c) Vertical resistivity section T7.9 as result of a 5-layer 1-D inversion (every 5th model is shown). d) Comparison of 1-D inversion results of HEM and DC reveals the freshwater/saltwater boundary at a similar depth of about 60 mbsl.

The elevation map in Figure 6b shows the location of the *Schlumberger* sounding GTS 60 (blue circle), the drilling BR 40 (orange circle) and a part of flight-line T 7.9 (red line). The flight-line crosses a dune and the *Schlumberger* sounding is located about 80 m apart from the flight-line in a dune valley. The vertical resistivity section of this part in Figure 6c shows that the saltwater/freshwater boundary was determined by the HEM 1-D inversions at about 60 m depth. This is confirmed by the 1-D inversion result of the *Schlumberger* sounding of 2008 which has not changed significantly since 1992 (Figure 6d).

Regarding the results of *direct-push* (*Winter, 2008*) and borehole measurements, the HEM related resistivity structure could be determined more precisely. A more detailed 6-layer approach revealed additionally to the freshwater/saltwater boundary thin conductive layers at about 10 m depth, not seen in the 4-layer models of the standard inversion procedure (Figure 7b). Partly, they were identified as clay layers by lithological logs; and also the result of a *direct-push* measurement shows an increasing conductivity at 10 m depth (Figure 7c). The depth of the freshwater/saltwater boundary remains nearly constant and has a layer with little higher resistivity above, which could be interpreted as transition zone of brackish water. The data misfit q [%] of the 6-layer inversion is smaller than the misfit of the 4-layer inversion, especially in the south-eastern part of the section.

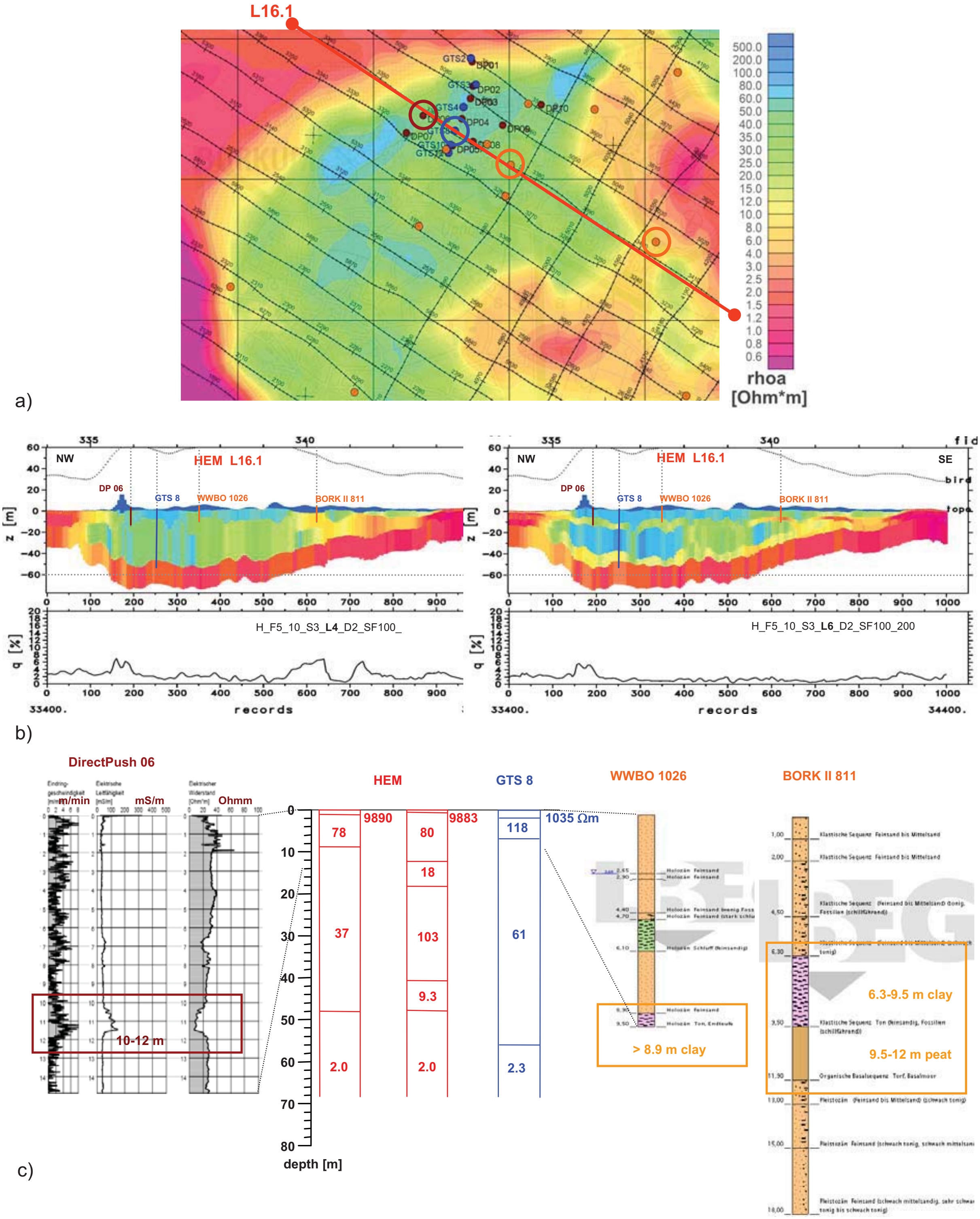

Figure 7: a) Apparent resistivity map (41 kHz) with the location of the vertical resistivity section L16.1, the lithological logs and the *direct-push* measurement. b) Comparison of HEM 1-D inversion results (4- and 6-layer models) along L16.1 with c) lithological logs (WWBO 1016 and BORK II 811) (*LBEG*), *direct-push* results (DP 06) (*Winter, 2008*) and DC 1-D inversion results (GTS8).

Estimation of the aquifer thickness

The aquifer thickness was estimated using *Archie's law* with the following approach: The resistivity of freshwater is assumed to be higher than 5.6 Ωm (180 mS/m) and thereby the resistivity of freshwater saturated sediment with 33% porosity and a formation factor of 4 should be above 23 Ωm (*Siemon et al., 2009b*). Based on that, the accumulated layer thickness with resistivities of 30–500 Ωm is defined as aquifer thickness and is shown in Figure 8. From that, the freshwater volume was estimated to 175 x 10^6 m³.

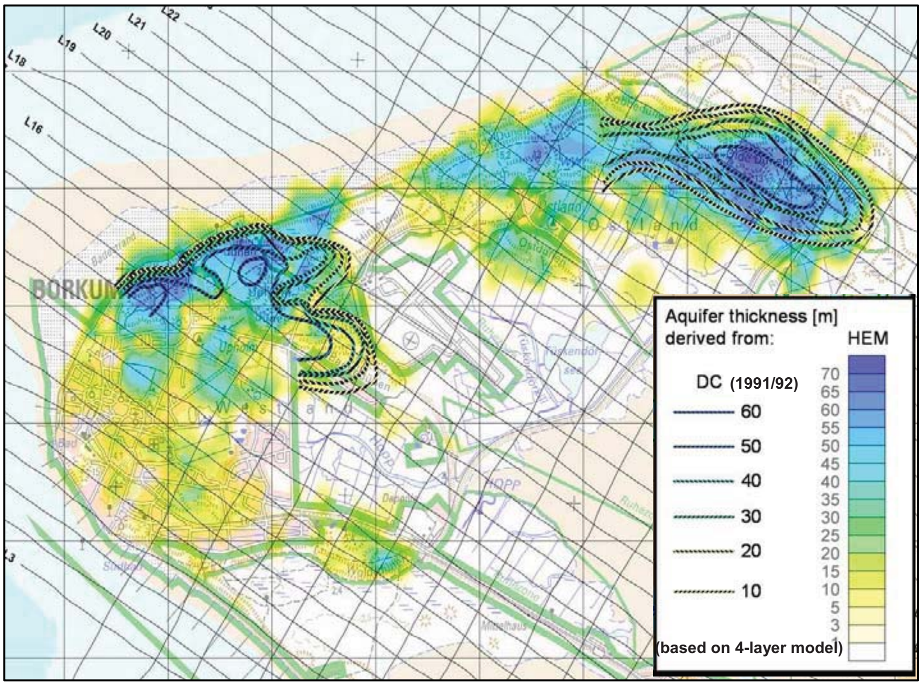

Figure 8: Aquifer thickness derived from DC and HEM.

Conclusions

At several locations the depth of the freshwater/saltwater boundary as derived by the HEM inversion was confirmed by *Schlumberger* soundings. The DC measurements were carried out at the same sites as 16 years before, no significant changes of the freshwater/saltwater boundary were found.

Regarding *direct-push* and borehole data, the HEM inversion provided more information about resistivity structure. A 6-layer approach revealed additionally to the freshwater/saltwater structure thin clay layers.

Based on the HEM inversion results the volume of the freshwater resource was estimated.

Acknowledgments

The HEM survey was funded by *LIAG/BGR* project "Airborne Geophysical Investigation of the German North Sea Coastal Area" (*Wiederhold et al., 2008*):

http://www.liag-hannover.de/forschungsschwerpunkte/grundwassersysteme-hydrogeophysik/salz-suesswassersysteme/flaechenhafte-befliegung.html

http://www.bgr.bund.de/cln_101/nn_328750/DE/Themen/GG__Geophysik/Aerogeophysik/Projektbeitraege/D-AERO/deutschlandweite__aerogeophysik__befliegung__D-AERO.html

The lithological logs were taken from the *LBEG Map Server* (http://www.geophysics-database.de/) of the *Niedersächsisches Landesamt für Bergbau, Energie und Geologie (LBEG).*

The direct-push results were provided by the *Ingenieurbüro für Hydrogeologie, Sedimentologie und Wasserwirtschaft (HSW) (Winter, 2008)*.

The digital elevation model was provided by the *Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN),* Forschungsstelle Küste, An der Mühle 5, 26548 Norderney.

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Wiederhold, H., Kirsch, R., Schaumann, G., Scheer, W. & Steuer, A. [2009] Airborne geophysical investigations for hydrogeological purposes in Northern Germany. Extended Abstracts Book of the 15th European Meeting of Environmental and Engineering Geophysics – Near Surface 2009, Dublin, Ireland, 7.-9.9.2009.

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Worzyk P. [1995a] Geoelektrische Tiefensondierungen auf der Insel Borkum – Untersuchungen zur Veränderung der Süßwasserlinse im Ostland. NLfB Archives no 111751, Hannover.

Worzyk P. [1995b] Geoelektrische Tiefensondierungen auf der Insel Borkum – Untersuchungen zur Struktur der Süßwasserlinse im Einzugsbereich des Gewinnungsgebietes Waterdelle. NLfB Archives no 114088, Hannover.