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Improving Groundwater Models by Electromagnetic Measurements - Case of Elbe-Weser Estuaries

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SUMMARY

In coastal areas salinity of groundwater may pose problems for the sustainable exploitation of fresh groundwater. Groundwater flow modelling is the adequate tool to produce valid predictions of future development in the groundwater system. In order to set up the groundwater models it is essential to have a comprehensive understanding of the geological subsurface. How geophysical methods can contribute to the geological understanding is shown for the model area Elbe-Weser estuaries at the German North Sea coast. Techniques used are electromagnetic soundings (airborne and ground-based), magnetic resonance soundings and 2-D electrical resistivity tomography.

Introduction

In coastal areas, monitoring and protection of groundwater systems are important issues to safeguard the future water supply. An intense analysis of possible degradation of water quantity and quality triggered by climatic and demographic change is necessary. Tools for this analysis include hydrogeological models, water balance models, and density driven flow modelling. Furthermore, the present and future system of water supply and use needs to be analysed. Within the NAWAK project several pilot areas are selected at the German North Sea coast with the aim to examine the effects of climatic and demographic change on the coastal water supply in order to develop customised adaptation strategies for water supply companies. The required hydrogeological models use 1-D geological borehole data supplemented by 2-D or 3-D data obtained from hydrogeophysics. The data acquisition for the hydrogeological modelling is subject of this paper.

Model region "Elbe-Weser triangle"

The model region "Elbe-Weser triangle" is situated between the estuaries of the Elbe and Weser rivers. The area is characterised by high-lying sandy geest ridges in the hinterland and wet marshlands just above sea level parallel to the banks of the rivers. Additionally, the geological setting in this area contains tunnel valleys which developed as sub-glacial melt-water channels during glacial regression. The channels were subsequently filled with Quaternary sediments, so that they are completely hidden from the surface (Kuster and Meyer, 1979). In many places, the uppermost channel fill is a clay layer with a thickness of some tens of metres. The groundwater situation is restricted to unconsolidated Quaternary deposits underlain by Tertiary sediments and aquifers ranging to depths of 250 m. The thickness of aquifer (coarse grained sandy sediments) and aquitard layers (fine grained clayey strata) shows high lateral and vertical heterogeneity. In some areas the aquitard layer is missing and, thus, the upper and lower aquifers are hydraulically connected. Lower parts of the aquifer are saline starting from the coastline and reaching inland. Two areas are selected for groundwater modelling where its borders are set according to hydraulic boundary conditions (Figure 1).

Methods

Due to the electrical conductivity (inverse of resistivity) contrast between freshwater and saltwater and between clay and sand the results from electromagnetic and geoelectrical measurements are used to investigate the existing groundwater structures. Especially airborne electromagnetic (AEM) data deliver a good database for locating the freshwater-saltwater boundary and for interpolation between boreholes (Siemon et al., 2009). The AEM data used in this model region were collected during three airborne surveys with a frequency-domain helicopter-borne electromagnetic (HEM) system operated by BGR in 2000, 2004, and 2008/2009 (Siemon et al., 2014). The interpretation of resistivity results alone is prone to ambiguity concerning lithology and salinity. Furthermore, depth-penetration and resolution of AEM data is limited. Therefore, ground-based measurements were conducted in order to support the AEM inversion by using prior constraints.

In the pilot area Dollern, joint transient electromagnetic (TEM) and magnetic resonance soundings (MRS) were conducted along a transect perpendicular to the Elbe river where saltwater intrusion is assumed. Additionally, 2-D electrical resistivity tomography (ERT) profiles were measured to obtain information about the dimensionality of the subsurface.

The HEM data are generally inverted to resistivity-depth models using standard 1-D inversion methods (Sengpiel and Siemon, 2000). In the pilot area Wanna, the HEM data were inverted to resistivity-depth models using an advanced 1-D inversion method, in particular the spatially constrained inversion (SCI) method (Viezzoli et al., 2008). It simultaneously inverts many adjacent data sets using spatial constraints and provides a quasi-3-D inversion result.

Additionally, geological borehole data for both pilot areas were provided by the State Authority for Mining, Energy and Geology (LBEG, http://nibis.lbeg.de/cardomap3).

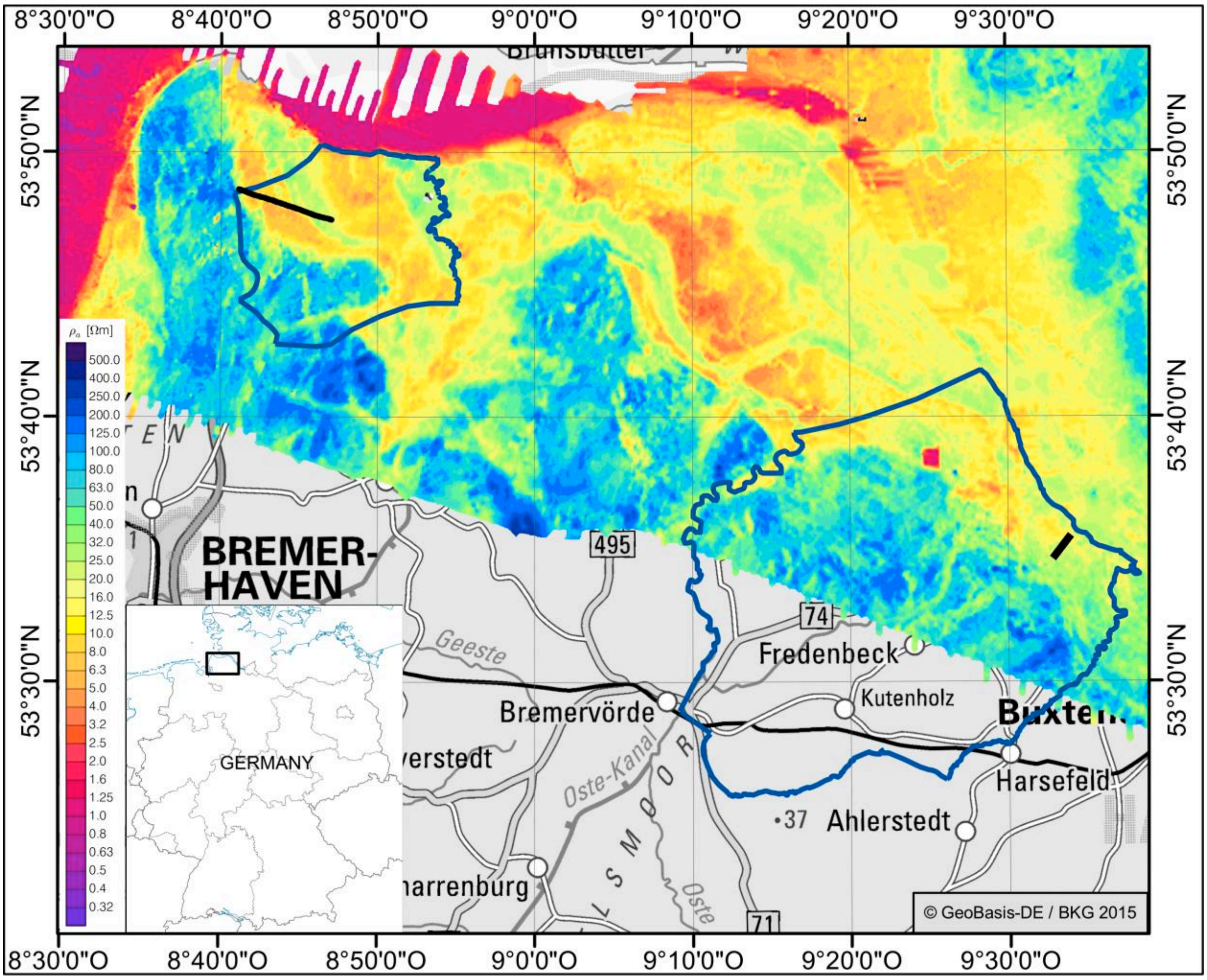

__Figure 1__ Model region "Elbe-Weser triangle" with its two pilot areas Wanna (left) and Dollern (right) marked by blue polygons. The Elbe river is the northern and north-eastern boundary of the pilot areas Wanna and Dollern, respectively. The black lines indicate the location of cross-sections along which various results are presented. Colours refer to the apparent resistivity ρ_a *[Ωm] at a frequency of 40 kHz derived from frequency-domain helicopter-borne electromagnetic surveys and reflect near surface structures.*

Results

In the pilot area Dollern, the 1-D results of HEM/TEM and the 2-D results of ERT displayed in Figure 2 all show a thin clayey cover layer above a sandy layer with varying resistivities, lower in the north-eastern part and higher in the south-western part. Beneath, another clayey layer follows. The TEM results are able to give information about deeper structures. Below a depth of about 220 m, the resistivity in the 1-D model decreases which could be interpreted as a Tertiary clay layer. MRS measurements are very noisy and can only provide lithological hints, the boundary between the clayey cover layer and the sandy aquifer is resolved. Additionally, the combination of water content and resistivity obtained from MRS and ERT measurements, respectively, allows deriving the fluid conductivity and, thus, the amount of total dissolved solids (TDS) alias the salinity in the aquifer (Figure 2) after Todd and Mays (2005).

In the pilot area Wanna, the three different resistivity-depth maps displayed in Figure 3 show the saltwater front invading from the north and the northwest, i.e. from the North Sea or the Elbe river. The increase of salinity with depth is mapped very well. The elongated conductive structure visible in the western part of depth slice 42 m - 50 m indicates the clayey cover layer on top of a tunnel valley.

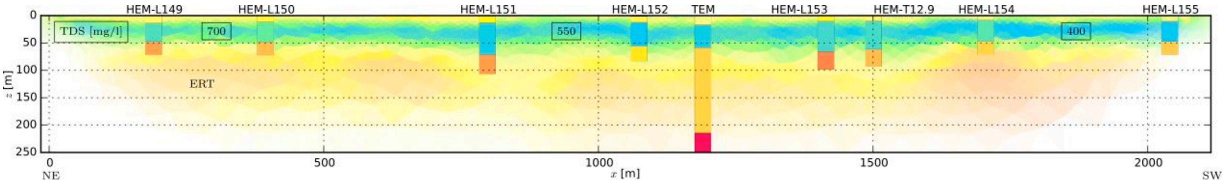

Figure 2 *Comparison of HEM/TEM resistivity-depth models along the ERT profile and estimated values of salinity in the aquifer along the cross-section in the pilot area Dollern. For resistivity colour scale and location see Figure 1.*

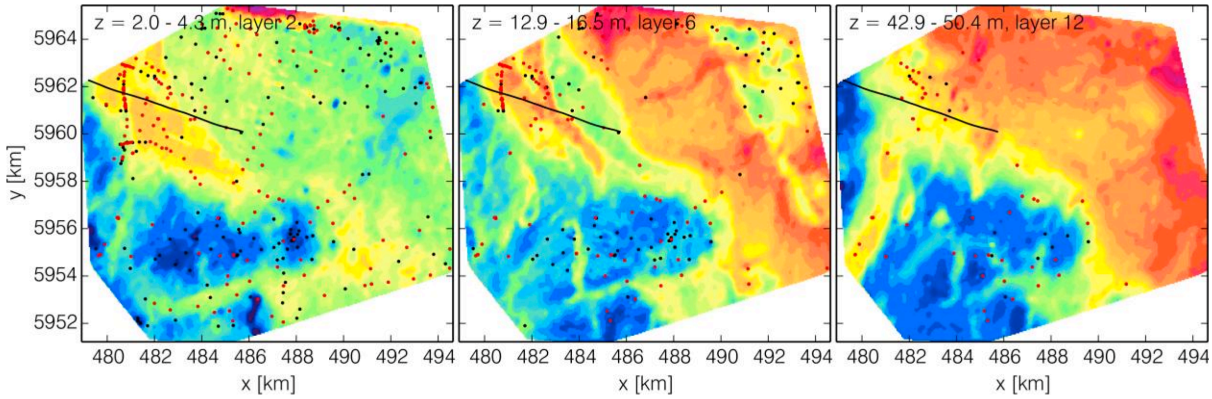

Figure 3 *Resistivity maps for three depth intervals from spatially constrained inversion (SCI) of HEM data for the pilot area Wanna. Black dots mark available geological borehole data in each depth interval. Red dots show where clay or silt layers of thickness > 2 m are present (independent of depth interval). The black line indicates the location of the cross-section displayed in Figure 4. For resistivity colour scale see Figure 1.*

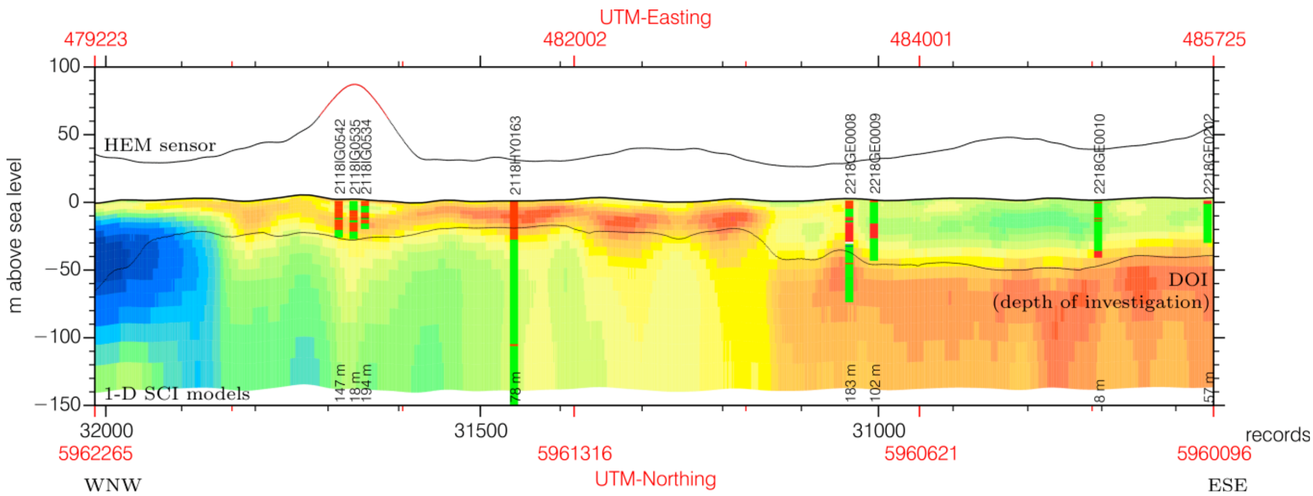

Figure 4 *Vertical resistivity section of 1-D SCI models along the cross-section in the pilot area Wanna (about 6800 m long). Lithology derived from nearby geologic borehole data is colour-coded: green colours indicate sand, red colours represent clay. For resistivity colour scale and location see Figure 1.*

Figure 4 illustrates the complex settings by a vertical resistivity cross-section. The eastern part shows the aquifer in the upper part with embedded clay lenses and no protecting cover layer. The lower part is saline. In the middle part of the cross-section, there is a clayey cover layer on top of the aquifer. The very low resistivities here point to a combination of clay and saltwater, which presumably infiltrated from former flooding events. The western part of the cross-section displays the sandy aquifer of the geest ridge with a thin cover layer on top. At this site, the resolution capability of hydrogeophysics is limited to about 50 m (see depth of investigation, Figure 4).

Conclusions

In both pilot areas, the HEM data prove to be extremely useful in delineating hydrogeological regions.

In the pilot area Dollern, the 1-D results of HEM/TEM and the 2-D results of ERT are consistent. The combination of the results from HEM/TEM/ERT and MRS measurements allows deriving hydraulic properties, e.g. the salinity in the aquifer. The results from the geophysical measurements match the geology.

In the pilot area Wanna, using a spatially constrained inversion method to invert the HEM data improves the resulting resistivity-depth models compared to standard inversion procedures. The interpretation of resistivity results alone cannot provide a differentiation between lithology and salinity. Further MRS measurements could help to resolve this issue.

The next steps will comprise inversion of HEM data with a-priori information from borehole lithology, continuously updating of the 3-D hydrogeological model with the HEM data, and interpretation of HEM data into meaningful parameters in geological and hydrological modelling.

Acknowledgements

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