Helicopter-borne electromagnetics (HEM) at the Elbe estuary in Northern Germany

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Abstract

Helicopter-borne electromagnetic investigations provide a high potential for a comprehensive mapping of the upper hundred metres of the subsurface. The relevance for hydrogeological questions is given by the determination of resistivity models for revealing the distribution of sandy and clayey as well as saltwater and freshwater saturated sediments.

The survey area to the north-west of the City of Hamburg covers the estuary of the Elbe river. Here, the aquifers and their potential salinization were intended to be mapped. Parts of the results of this survey area are involved in the project KLIMZUG-NORD, in which the Technical University Hamburg-Harburg investigates the environmental effects of climate change on the estuary of the Elbe river. Due to current climate change scenarios a sea level rise in the North-Sea region is predicted and, consequently, the water level of the Elbe river will rise in an area affected by a changing sea level. That entails an intrusion of brackish water into the surrounding freshwater aquifers. Such scenarios are investigated by hydraulic flow models. Existing geological information will be complemented spatially by electrical resistivity models derived from HEM data to a geological structural model. This will be related to hydrological parameters and should therefore serve as a base for a hydraulic modelling.

Introduction

The problem of groundwater salinization is becoming increasingly important within the context of groundwater extraction and treatment, and is a latent risk for the sustainable use of aquifers. The intrusion of seawater is a natural source of coastal groundwater salinization (green colours, Figure 1). Onshore salinization is attributable to the leaching of salt domes close to the earth's surface and the upwelling of deep saline water. These natural sources of salinization are exacerbated by man-made hydraulic activities such as groundwater extraction and drainage systems. Further risks are the long-term rise in sea level, storm floods, and – in some areas – flooding caused by tsunamis. These events will also have an impact on the distribution of saltwater in the subsurface and can also jeopardise aquifers used to produce potable water.

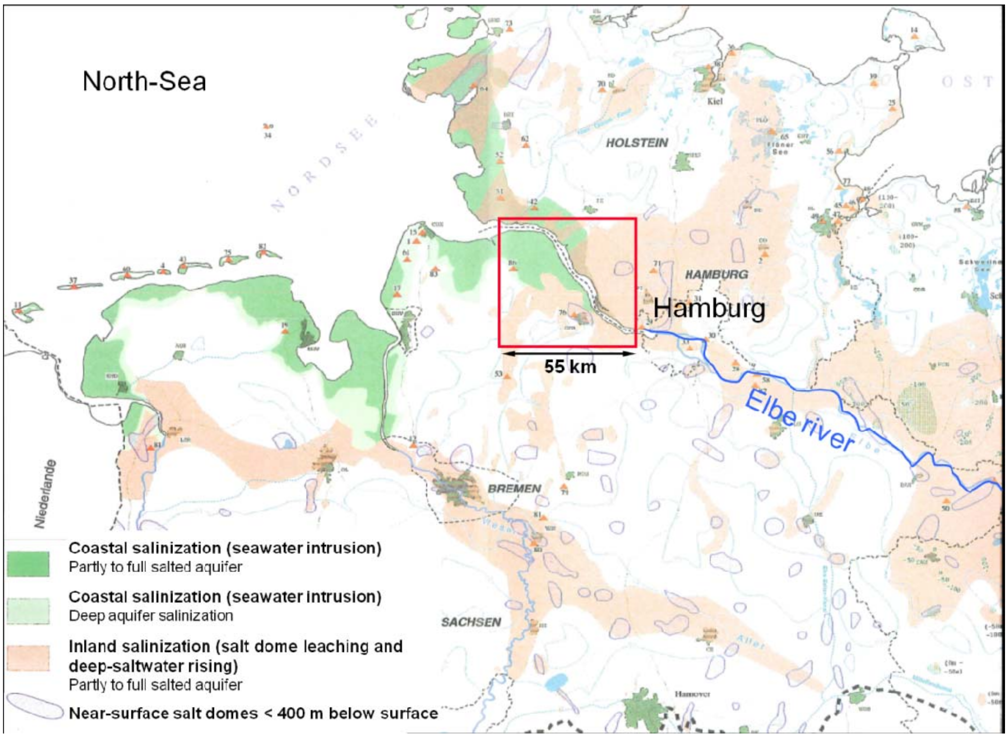

Figure 1: *Distribution of groundwater salinization in the North-German Plain (modified after Grube et al., 2000). The natural source of the coastal salinization is seawater intrusion (green colours), and of the inland the leaching of salt domes (red colours) which reach at places the surface. Hydraulic intervention by groundwater extraction and artificial drainage increase the effect of the natural sources. The red box marks the survey area at the Elbe estuary.*

Airborne geophysical surveys enable huge areas to be surveyed almost completely in a relatively short time at economic cost. The results can generally be used for geological and hydrogeological mapping. Particular the data collected by airborne electromagnetic surveys is important for hydrogeological interpretation as the derived electrical conductivities reveal the distribution of sandy and clayey sediments as well as salinization zones and freshwater occurrences down to depths of the upper hundred metres (*Siemon et al., 2009; Steuer et al., 2009a; Siemon et al., 2012*).

In 2008 and 2009, the Federal Institute for Geosciences and Natural Resources (BGR) carried out airborne geophysical measurements for saltwater-freshwater investigations in cooperation with the Leibniz Institute for Applied Geophysics (LIAG) in frame of the project D-AERO (*Wiederhold et al., 2008; Steuer et al., 2009b; Schaumann et al., 2010; Steuer et al., 2010*). In ten different survey areas located at the German North-Sea coast 13 400 and 4500 line kilometres were flown using helicopter-borne electromagnetics in frequency-domain (HEM) and time-domain (HTEM), respectively (*Wiederhold et al., 2010*). One aim of D-AERO is, to build a data set as a reference to monitor climate or man-made induced changes of the saltwater/freshwater interface at the German North-Sea coast.

The BGR airborne geophysical system

The helicopter-borne system operated at the BGR enables simultaneous measurements of three geophysical methods: electromagnetics, magnetics and gamma-ray spectrometry (Figure 2). The electromagnetic and magnetic sensors are housed in a 10 m long tube, which is towed by a Sikorsky S-76B helicopter on parallel flight lines about 30–40 m above ground level.

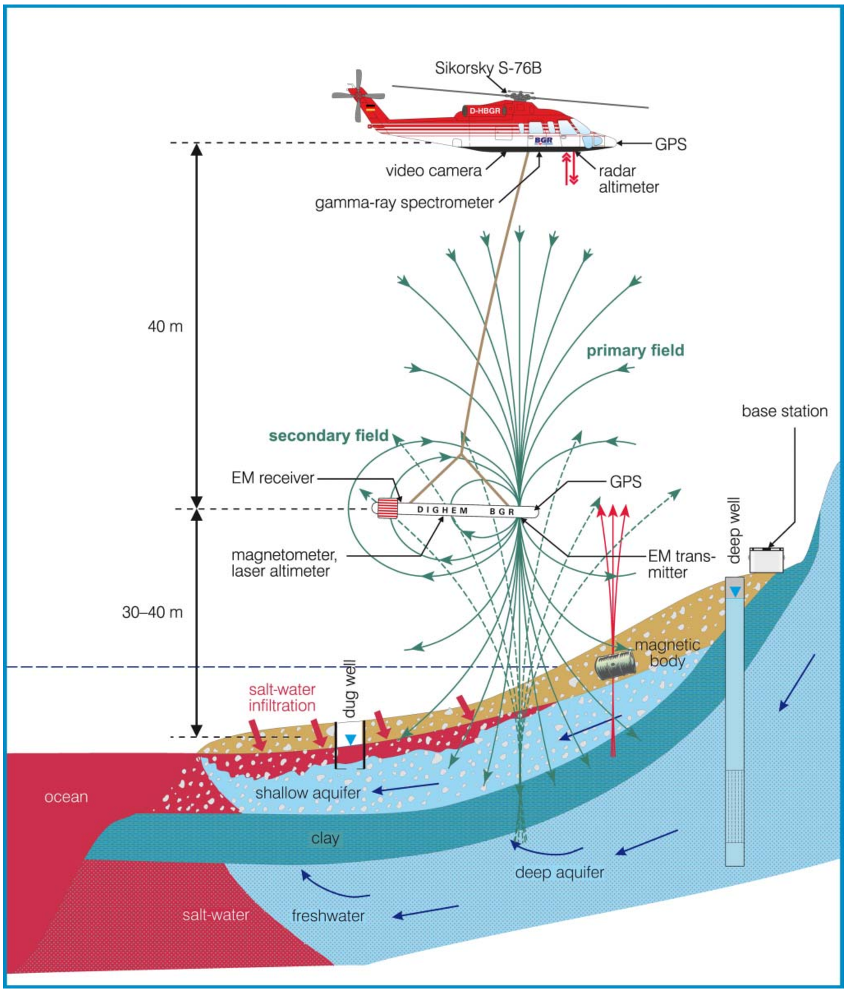

Figure 2: *BGR helicopter-borne geophysical system and a hydrogeological situation typical for coastal areas (Siemon and Steuer, 2011).*

The electromagnetic system is a RESOLVE system (manufactured by Fugro Airborne Surveys) consisting of six transmitter-receiver coil pairs. The transmitter signals, the primary magnetic fields, induce eddy currents into the subsurface which depend on the electrical conductivity distribution. The relative secondary magnetic fields from these induced currents are measured at the receiver coils in parts per million (ppm) as they are related to the primary fields. The use of different frequencies ranging from 387 Hz to 133 kHz enables the investigation of different depths: High frequencies resolve the shallower parts of the subsurface and lower frequencies the deeper parts. The depth of investigation also depends on the subsurface conductivity distribution: The higher the conductivity the lower the penetration of the electrometric fields into the subsurface. Typical maximum investigation depths of the RESOLVE system range from about 30 m (saltwater saturated sediments) to about 150 m (freshwater saturated sandy sediments or hard rock).

In addition to the electromagnetic measurements, the earth's magnetic field and the natural gamma radiation of the earth's surface are recorded. These measurements can be used to interpret the structure of the earth's crust and the mineral composition of the shallowest soil layers, respectively. The joint interpretation of this data supports three-dimensional modelling of the subsurface and is also used as a basis for planning and activities in many environmental and economic disciplines, *e.g.* for regional planning, development of water utilization and water protection concepts.

Modelling of the electromagnetic data

The in-phase (I) and quadrature (Q) components of the measured secondary magnetic fields are generally converted into resistivities (inverse of conductivity) based on half-space models. Apparent resistivity ρ_a [Ωm] and centroid depth z*[m] of a homogeneous half-space (Figure 3, Model 1) are derived from the data of each single frequency (f). The half-space models are used to derive appropriate starting models for the one-dimensional (1D) inversion.

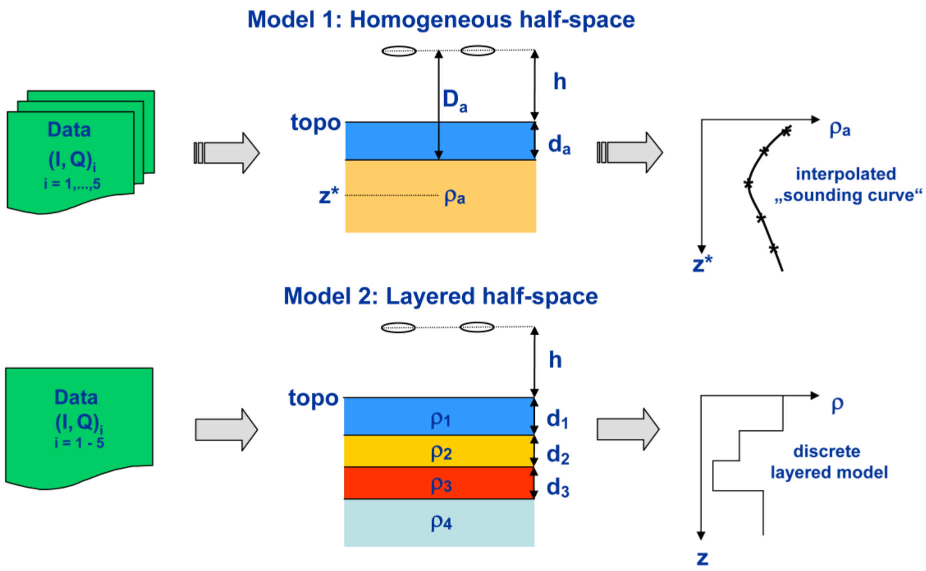

Figure 3: *HEM inversion scheme based on the model of a homogeneous half-space and of a layered half-space model (Siemon and Steuer, 2011).*

A Marquardt–Levenberg inversion procedure iteratively calculates the model parameters, resistivity and thickness of the model layers (Figure 3, Model 2), from the data of all frequencies available (*Sengpiel and Siemon, 2000*). The inversion procedure stops when a given threshold (*e.g*. 10%) is reached, which is defined as the differential fit of modelled and measured HEM data.

The results of the 1D inversion are presented as vertical resistivity sections (VRS) and resistivity maps. The VRS are constructed by placing the resistivity models for each sounding along a survey profile next to each other using the topographic relief (in m above sea level) as base line.

The survey

The helicopter-borne survey at the estuary of the Elbe river to the north-west of Hamburg (Figure 1, red box) took place in July and October 2008 and from March to April 2009 and covered an area of about 2000 km². The nominal flight-line spacing was 250 m for the 209 lines (W-E) and 2500 m for the 19 tie-lines (N-S) resulting in a total survey line length of more than 8500 km (Figure 4a).

In this area, the aquifers and their potential salinization were intended to be mapped. Parts of the results of this survey are involved in the project KLIMZUG-NORD (www.klimzug-nord.de), where the Technical University Hamburg-Harburg investigates the environmental effects of climate change on the estuary of the Elbe river (*Palm and Steuer, 2010*).

Figure 4b shows the digital elevation model (DEM, derived from SRTM data) where the higher-lying Geest ridge (brown) and the Marsch (blue) are displayed.

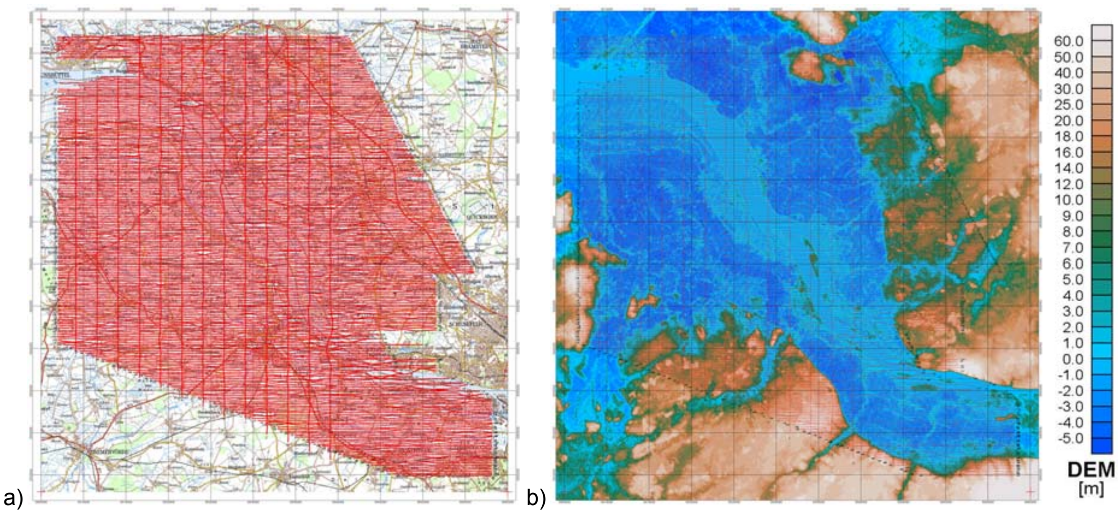

Figure 4: *a) The flight lines are displayed as red. b) Digital elevation model based on SRTM data.*

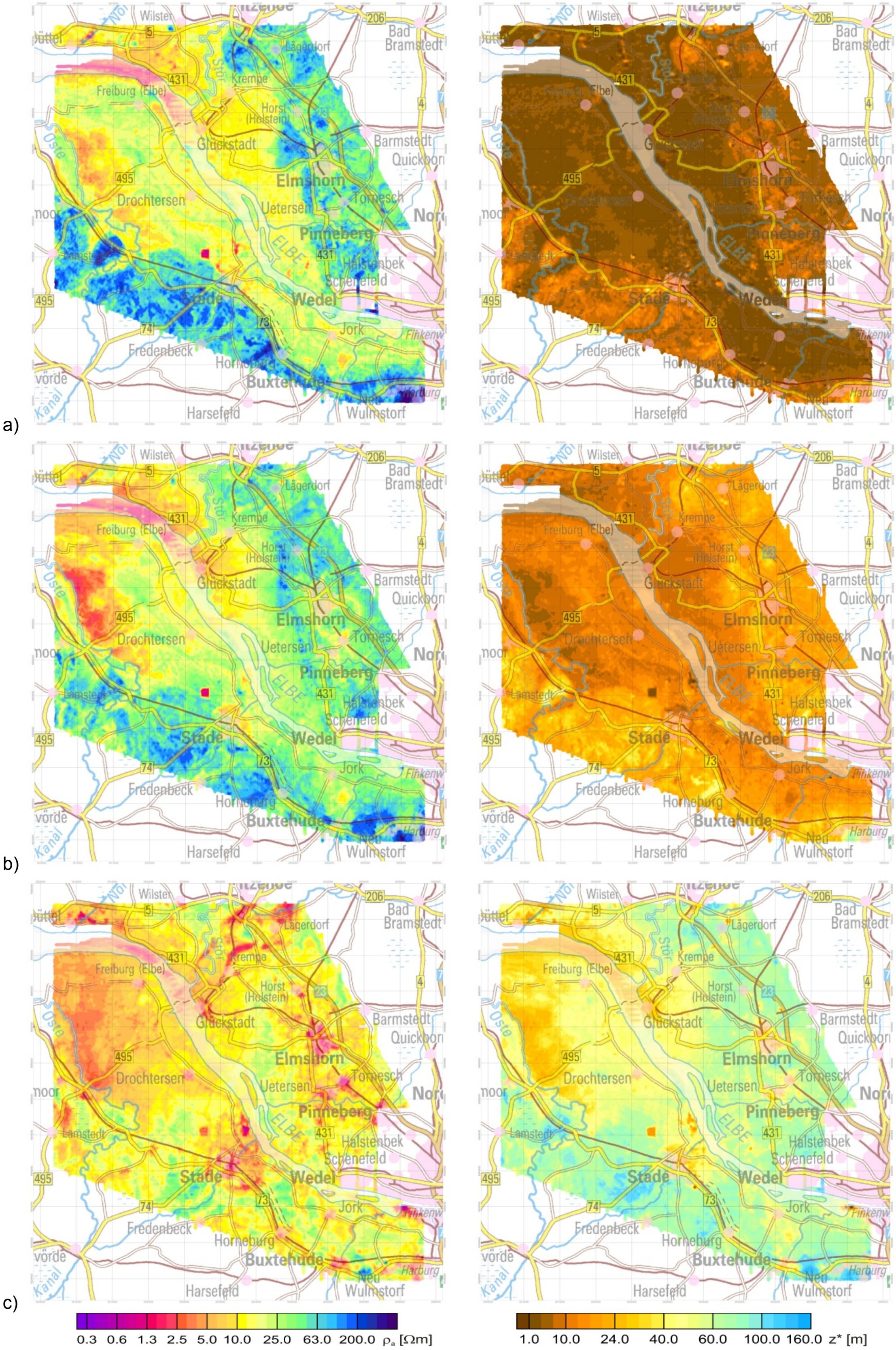

Figure 5: *Apparent resistivity (ρ_a) and centroid depth (z*) maps of a) 133 kHz, b) 8 kHz and c) 387 Hz.*

The apparent resistivity and centroid depth maps provide a first overview on the resistivity structure (Figure 5). Here, the Geest ridge (high-lying hinterland consisting of pleistocenic moraine sediments) appears resistive, whereas the Marsch (plain holocenic wet land, alluvium) appears conductive (Figure 5a and 5b). The investigation depth increases with decreasing frequency and reaches 160 m at places (Figure 5c).

The resistivity maps derived from the 1D inversion are shown in Figure 6 at selected depths of 2, 7, 14 and 25 m below sea level (bsl). On the near surface map conducting Marsch sediments appear (Figure 6, 2 m). In the northern part of the survey area the distribution of the saltwater intrusion of the Elbe river into the Quaternary aquifer was mapped (Figure 6, 25 m).

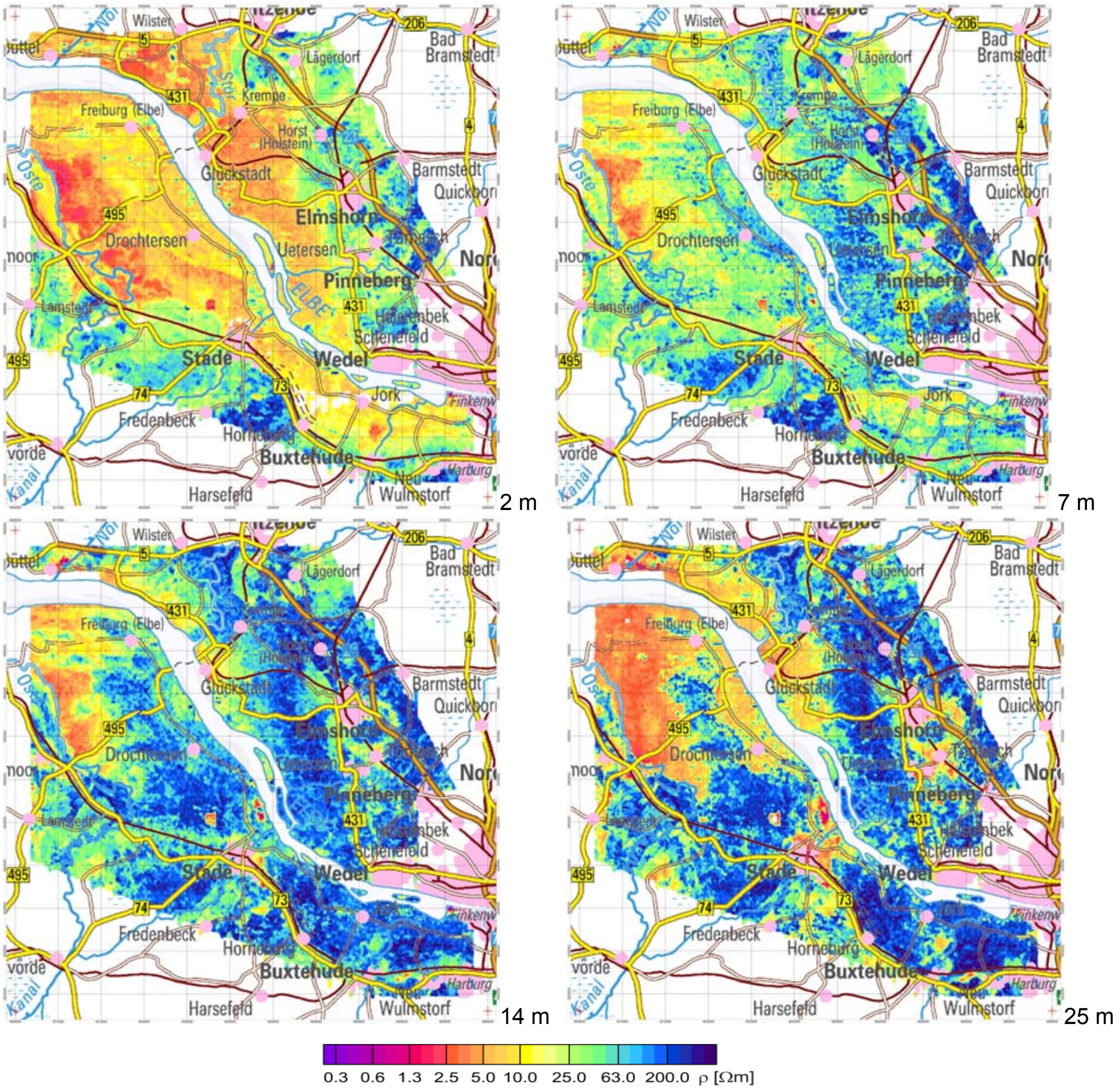

Figure 6: *Resistivity (ρ) maps at selected depths of 2, 7, 14 and 25 m bsl as result of 1D inversions.*

Saltwater-rising zone

An electrical conductivity anomaly of about 2 km diameter was detected in the southern part of the survey area (black circle in Figure 7) at a place where anthropogenic sources could be excluded. This anomaly could be caused by clay or saltwater saturated sediments. The latter is presumable as analyses of waters from drainage channels and rain ponds in that area show high NaCl concentrations (150-724 mg/L).

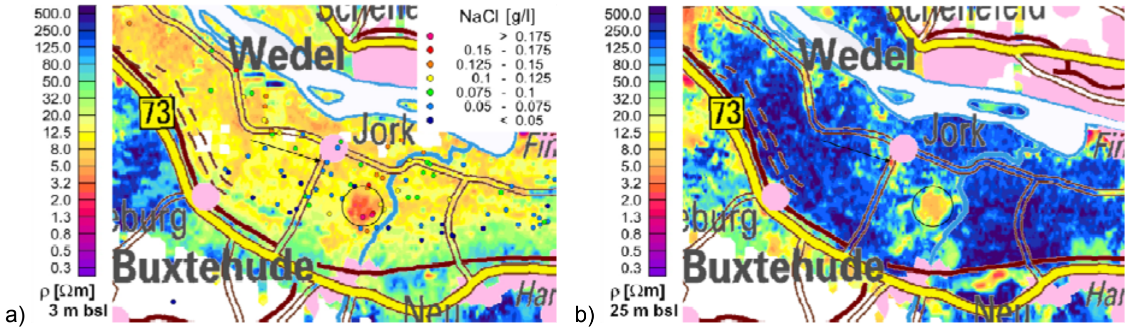

Figure 7: *Resistivity maps at selected depths of a) 3 m bsl and b) 25 m bsl as result of a 1D inversion. Additionally NaCl concentrations (Koepcke, 2010) of surface water samples are displayed in a).*

The electrical conductivity anomaly is located in the Marsch area between the higher lying Geest ridge in the South and the Elbe river in the North, as shown in the digital elevation map (Figure 8a). Below the anomaly a Quaternary valley is assumed, which is carved more than 200 m deep into the Miocene layering (Figure 8b).

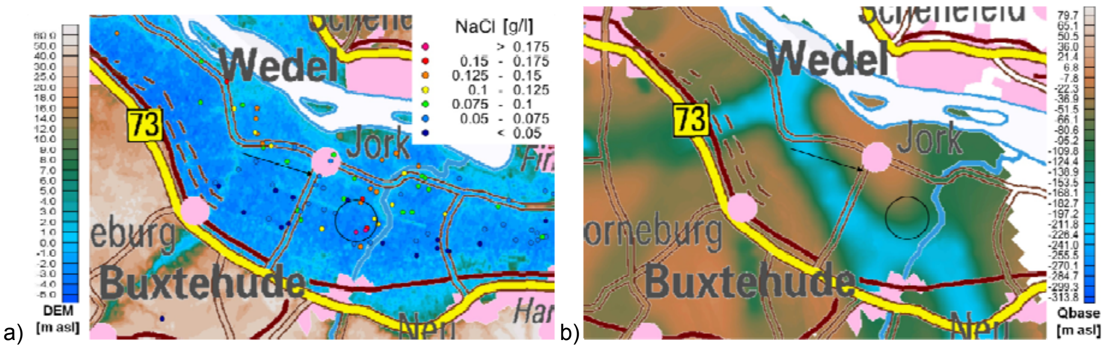

Figure 8: *a) Digital elevation model based on SRTM data. b) The map of the Quaternary base (LBEG, 2009) is the result of the interpolation of a few boreholes. The resistivity anomaly is located at the edge of a Quaternary valley which runs from south-east to north-west.*

Hydrogeological interpretation

Salinizations of the Miocenic aquifer are known in that region in places. The Miocenic aquifer is locally in hydraulic contact with the upper Quaternary aquifers by Quaternary valleys. At that places a rise of highly minerilized groundwater may occur depending on the groundwater potential differences. In the Elbe estuary region some of such risings are documented by *Grube et al. (2000)*. Figure 9 shows this hydrological situation schematically.

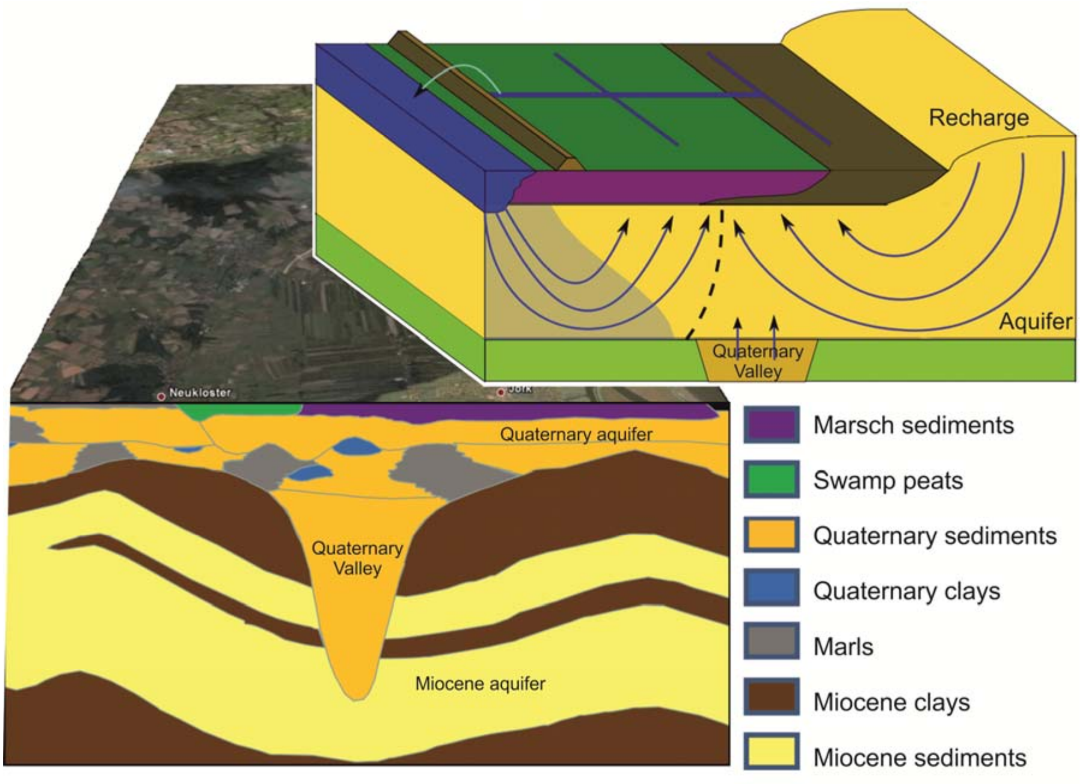

Figure 9: *Hydrogeological scheme of the survey area (modified after Palm and Steuer, 2010).*

Conclusions

The HEM method proved to be an efficient tool for resistivity mapping and revealed following results at the Elbe estuary: The Geest ridge and the swamp belt are characterized by high resistivities at the highest frequency of 133 kHz, whereas lower resistivities occur in the Marsch area. In the northern part of the survey area the distribution of saltwater intrusion was mapped. The investigation depth reaches 160 m in the southern part of the survey area. Here, a significant resistivity low obviously not affected by anthropogenic sources was detected by HEM and identified as saltwater-rising zone by water analyses and hydrogeological considerations.

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