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Comparison of manually and automatically derived fresh-saline groundwater boundaries from helicopter-borne EM data at the Jade Bay, Northern Germany

Bernhard Siemon[1], **Annika Steuer**[1], Nico Deus[2] and Jörg Elbracht[2]
[1]Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany
[2]State Authority for Mining, Energy and Geology (LBEG), Hannover, Germany

ABSTRACT

The Federal Institute for Geosciences and Natural Resources (BGR) conducted many airborne geophysical surveys in Northern Germany during the last decades. The coastal regions of Lower Saxony were investigated by frequency-domain helicopter-borne electromagnetics (HEM) to reveal the bulk resistivity of the subsurface (sediments and pore fluids). The State Authority for Mining, Energy and Geology (LBEG) is preparing a statewide "saltwater map" for Lower Saxony with a focus on the coastal aquifers influenced by seawater intrusion. For this purpose, the HEM resistivities are used in combination with groundwater data and a geological model to derive the lower fresh-water boundary. As appropriate depth values are manually picked from vertical resistivity sections, this procedure is time consuming. Therefore, we tested an alternative, which automatically derives the fresh-saline groundwater boundary directly from the HEM resistivity models. The ambiguity between brackish/saline water and clayey sediments as source for low resistivities can somewhat be reduced by the application of gradients instead of threshold values for searching an appropriate boundary. We compare results of both methods using a dataset from a coastal region at the Jade Bay.

INTRODUCTION

A modern technique for electrical conductivity mapping is airborne electromagnetics (Paine and Minty 2005; Siemon et al. 2009). BGR operates, for example, two frequency-domain HEM systems (Resolve), which have been used to survey large parts of the coastal region of Lower Saxony in Northern Germany (Siemon et al. 2014) in cooperation with the Leibniz Institute for Applied Geophysics (LIAG). These datasets are currently used to map the seawater intrusion at the German North Sea coast (Deus et al. 2015).

As the depth of the fresh-saline groundwater boundary is an important information, e.g. for water suppliers, farmers and drainage organizations, the existing overview map (LBEG 1987) is not sufficient for many problems. In order to get a detailed status quo of the fresh-saline groundwater distribution at the coastal region of Lower Saxony, we are currently generating a model containing the lower fresh-water boundary for the entire coastline. This enables us to recognize and estimate changes related to climate change effects and to develop adaption strategies.

Survey area

The survey area Varel (319 km²) is located at the Jade Bay. The airborne survey was conducted in May 2014 (Ullmann et al. 2017). It includes the southern part of the Jade Bay and ranges from the city of Wilhelmshaven in the northwest to the Weser river in the southeast. This tidal flat area was flown during low tides in order to reduce the shielding effect of seawater.

Geology

The coastal region of the German Bight containing the East Frisian Islands, the tidal flats and the marshland are the youngest landscape elements in Lower Saxony. All sediments in this area have been accrued during the Quaternary and the accumulation is still continuing. During the last 2.6 million years, the coastal region was formed due to climate changes with at least three glacial periods, which were intercepted by two interglacials (Heunisch et al. 2007). After the Weichselian glaciation, the inland ice shields melted down and the sea level has begun to rise. The characteristic series of Holocene coastal sediments have been deposited since the Weichselian glaciation. They consist of strata of fine-grained sand, silt, clay and intercalated layers of peat (Streif 2004).

Hydrogeology

The main challenge in the study of coastal aquifers in Northern Germany is the fresh-saline groundwater boundary. Intrusion of seawater is a global challenge that could be affected by sea-level rise, changes in recharge and anthropogenic effects such as groundwater extraction or surface drainage and canalization (Werner and Simmons 2009). Low groundwater recharge rates in the marshland based on the widespread Holocene brackish and marine cohesive sediments and higher recharge rates in the moraine areas are typical for the coastal regions in Lower Saxony. The groundwater table is located very close to the surface and the upper aquifer system is between 50 and 200 m thick (LBEG 2018). The main groundwater aquifer consists of Pliocene to Saalian medium to coarse sands, in which low permeability layers are enclosed.

METHODS

Airborne EM

The penetration of the EM fields generated by HEM systems into the subsurface strongly depends on both the system parameter frequency and the ground parameter resistivity (inverse of electrical conductivity). Thus, the penetration depth is low at high frequencies or low resistivities and high at low frequencies or high resistivities. The exploration depth is thus dependent on the resistivity structure and may reach maximum depths of about 150 m for fresh-water saturated sand above saline groundwater (Siemon et al. 2011).

The inversion procedure used to model the HEM data is based on a Levenberg-Marquardt approach (Sengpiel and Siemon 2000), which applies the general matrix inversion based on singular value decomposition. The included regularisation weights the singular values. The weights are automatically determined by minimising the misfit (L1 norm). A pre-set (selectable) scaling factor (normally = 1.0) controls the model smoothness. We tested the inversion with few (6) and many (20) layers and found that smooth inversion using 20 layers and a scaling factor of 2.8 produced more stable results providing smooth but consistent resistivity models. On the other hand, extreme values generally could not be derived, i.e. resistive layers (fresh water) below or sandwiched between conductive layers (saline water or clay) appeared at somewhat lowered resistivities (compared to the few-layer inversion).

Manual picking of the bottom of fresh groundwater

The manual picking uses images of vertical resistivity sections derived from 1D HEM inversion models. These images are imported into a modelling software (Skua Gocad, Paradigm). In Lower Saxony, a chloride threshold of 250 mg/l is used to bound fresh (drinking) water. Assuming a water resistivity of 10 Ωm and a mean formation factor of 3, the lower fresh-water boundary is picked at about 30 Ωm. The application of resistivity threshold values for this picking is ambiguous, because both brackish groundwater and clayey sediments can cause similar resistivity values. Therefore, the background geological model is used to distinguish between both.

Automatic detection of the fresh-saline groundwater boundary

The ambiguity of resistivity threshold values is far more critical for the automatic detection of the fresh-saline groundwater boundary (FSB). Therefore, de Louw et al. (2011) introduced a concept using the largest ratio of consecutive layer resistivities within a pre-set resistivity range (2-5 Ωm). In extension to this ratio approach, we use a spline through the model layers followed by a calculation of steepest gradients. The spline calculated from log(r) vs. log(z) data is analysed with respect to its first and second derivatives. The spline consists of 100 values, which are equidistant in log(z). Maximum steepness of the first derivative occurs where the second derivative is zero. Generally, several sufficiently steep gradients occur. Therefore, only up to four depths assigned to the both highest (positive) and lowest (negative) gradients exceeding ±10 % are selected and stored together with the corresponding resistivities. Negative gradients occur if resistive material exists on top of conductive material, e.g. fresh water or sand above saline water or clay, and positive gradients describe the reverse case.

These steepest gradients representing the prominent layer boundaries allow following scenarios:

1) Homogeneous subsurface: Fresh (F) or saline (S) groundwater;
2) Two-layer case: Fresh above saline (FS) groundwater or the reverse case (SF); the latter requires an aquitard (clay) in-between, which generally cannot be resolved;
3) Three-layer case: A clay layer (with saline groundwater on top) is sandwiched between fresh-water aquifers (FSF) or located on top of fresh above saline groundwater (SFS);
4) Four-layer case: The latter case plus fresh groundwater on top (FSFS); the reverse case, i.e. fresh groundwater below SFS, can generally not be resolved.

In order to analyse the gradients with respect to these scenarios, the first step is to check whether an aquitard (positive gradient, scenario SF) exists or not. If no (no or one negative gradient), only the three simple cases (F, S, FS) are possible and the FSB is located below (unbounded), on top (fresh-water table) or within the resistivity model (depth of FS gradient). If yes (SF and FS gradients exist), the locations of the FS gradients with respect to the SF gradient have to be checked: Above (FSF), below (SFS) or above and below (FSFS). If two FS gradients with no intercalated SF gradient occur, i.e. the resistivity decreases stepwise, the upper one is selected, except this double boundary is located above an aquitard. Finally, the averaged resistivities of the depth ranges assigned to F have to be checked whether they are above 10 Ωm. Otherwise, the FSB has to be moved upwards.

RESULTS

The survey area Varel at the Jade Bay was selected for a comparison of manual (LBEG) and automatic (BGR) identification of the fresh-saline groundwater boundary. Figure 1 shows two resistivity maps at -3 and -30 m amsl (above mean sea level), which were derived from 1D HEM inversion models. In the southwest, a resistive feature appears on both maps indicating a thick fresh-water zone. The Jade Bay area in the north and part of the adjacent onshore areas appear conductive at shallow depth and less conductive at greater depth indicating fresh or at least less saline groundwater below the saline cover, particularly in two areas: a) The extension of the SE-NW trending fresh-water zone, and b) to the south of a former island (Arngast). The fresh water aquifer in the eastern half of the survey area seems to be thinner than in the thick fresh-water zone. Furthermore, a conductive cover occurs at the northeastern edge of the area, which is obviously caused by clayey sediments.

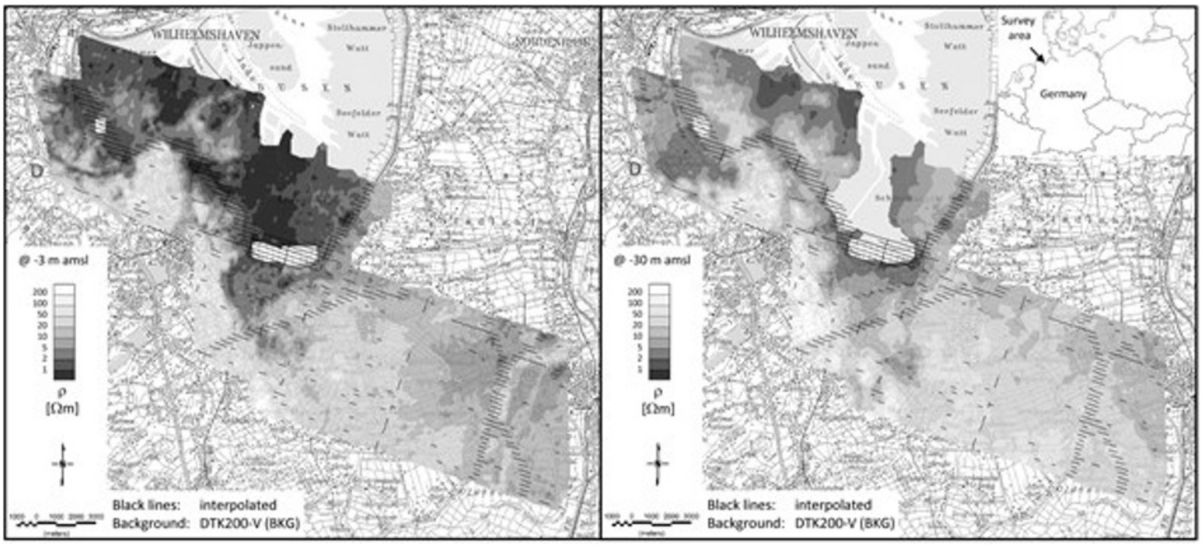

Figure 1. Resistivity at -3 m amsl (left) and -30 m amsl (right) derived from 1D HEM inversion models. The black lines mark erased and interpolated data.

Figure 2 shows the results of both LBEG and BGR approaches. They are similar, but not identical. The greatest differences occur in the southwest, where the deep fresh-water aquifer exists. There, the HEM models do not indicate a clear FSB, i.e. the fresh-water aquifer is unbounded in the models and the FSB is set onto the maximum model depth. On the other hand, the automatically derived values are generally located deeper than the manually picked values. That is not too surprising, because the manual picking searches for a boundary located at the upper level of the transition zone between fresh and saline water, whereas the automatic approach can only reveal the center of this transition zone. Thus, it depends on the thickness of the transition zone, how far apart both values are. The resulting mean difference of -16 m, however, cannot be completely explained by the thickness of the transition zone, which is assumed to be 10-15 m. The smoothness of the HEM models could be another reason for this discrepancy, because resistivity values are often lower if the corresponding resistive zone is sandwiched between or located below conductive zones. This situation affects approaches using threshold values stronger than approaches using relative values such as gradients.

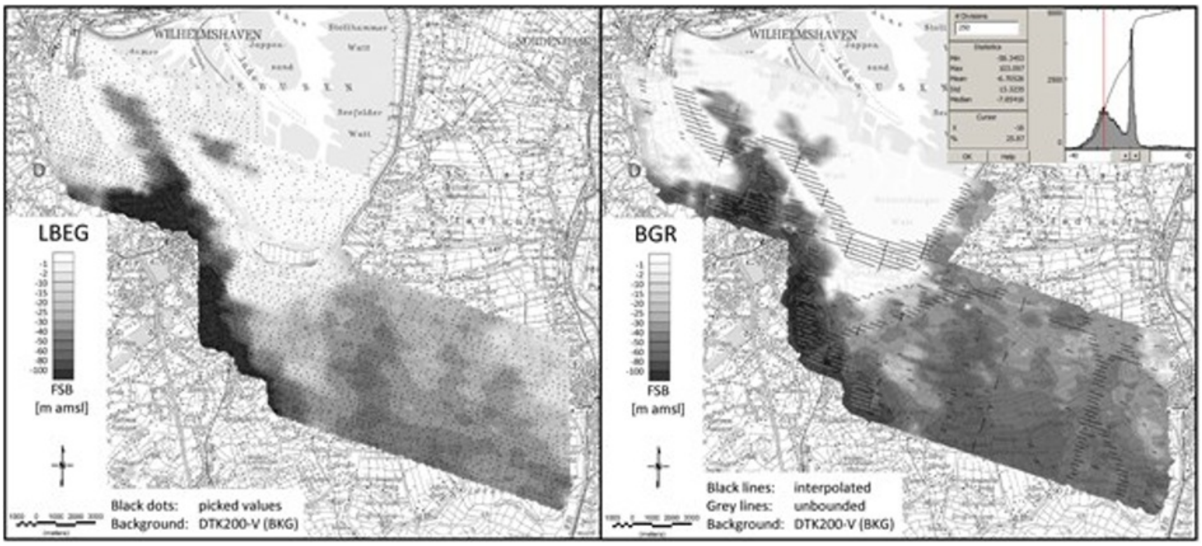

Figure 2. Elevation of fresh-saline groundwater boundaries: Manually picked (LBEG, left), automatically derived (BGR, right) from 1D HEM inversion models. A histogram of the differences (on the right map) reveals two maxima at 0 and .16 m.

DISCUSSION AND CONCLUSIONS

Airborne electromagnetics has proven to be able to reveal the fresh-saline groundwater boundary in a flat area at the Jade Bay. The HEM inversion models were used to derive that boundary by both manual picking and automatic detection. The thickness of fresh-water aquifers could be mapped onshore and offshore, even below a conductive cover such as clayey sediments saturated with saline water. Generally, the manual approach provides shallower results than the automatic approach. This is due do different targeting, because the manual approach searches for the lower drinking-water boundary and the automatic approach reveals the center of the fresh-saline transition zone. Besides this general offset, the smoothness of the inversion models has be taken into account. That particularly affects approaches applying threshold values more than approaches using relative values such as gradients.

In order to further reduce the ambiguity discussed in this paper, detailed knowledge on lithology and the influence of the diverse lithological units on the bulk resistivity is necessary. Such an approach was used to interpret the HEM data of the Province of Zeeland in the Netherlands with respect to groundwater salinity (project FRESHEM, Delsman et al. 2018). Siemon et al. (2018) discuss the differences of the FRESHEM approach and the automatic detection with respect to the fresh-saline groundwater boundary, which are rather small.

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Contact Information: Dr. Bernhard Siemon, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, D-30655 Hannover, Germany, Phone: +49-511-6433488,
Fax: +49-511-6433662, Email: Bernhard.Siemon@bgr.de