Geophysical investigation of a managed freshwater lens on the North Sea island of Langeoog

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ABSTRACT

A case study is presented that demonstrates the benefit of combining different geophysical methods, in particular electromagnetic methods and the relatively new method of magnetic resonance sounding. The survey on the island of Langeoog shows that geophysics can reliably provide lithological characterization of the subsurface and estimates of groundwater salinity.

INTRODUCTION

Within the project Freshwater Lens Investigation (FLIN) of the German Federal Institute for Geosciences and Natural Resources (BGR), the freshwater lens on the North Sea island of Langeoog was investigated. Besides geochemical and hydrogeological methods (Houben et al. 2014), different geophysical techniques were applied: Frequency-domain helicopter-borne electromagnetics (HEM, e.g. Siemon et al. 2009), transient electromagnetics (TEM, e.g. Fitterman and Stewart 1986), electrical resistivity tomography (ERT, e.g. Ernstson and Kirsch 2006), and magnetic resonance sounding (MRS, e.g. Yaramanci and Müller-Petke 2009). While the first three methods provide the resistivity (ρ) distribution in the subsurface, the latter measures the water content (Φ_{MRS}) directly and is sensitive to pore size as it is based on the nuclear magnetic resonance of the proton spins in the groundwater molecules. The NMR relaxation time T_2* increases with increasing pore size of the material investigated. Using this additional information, we expected a benefit regarding the lithological interpretation at places where boreholes are not available.

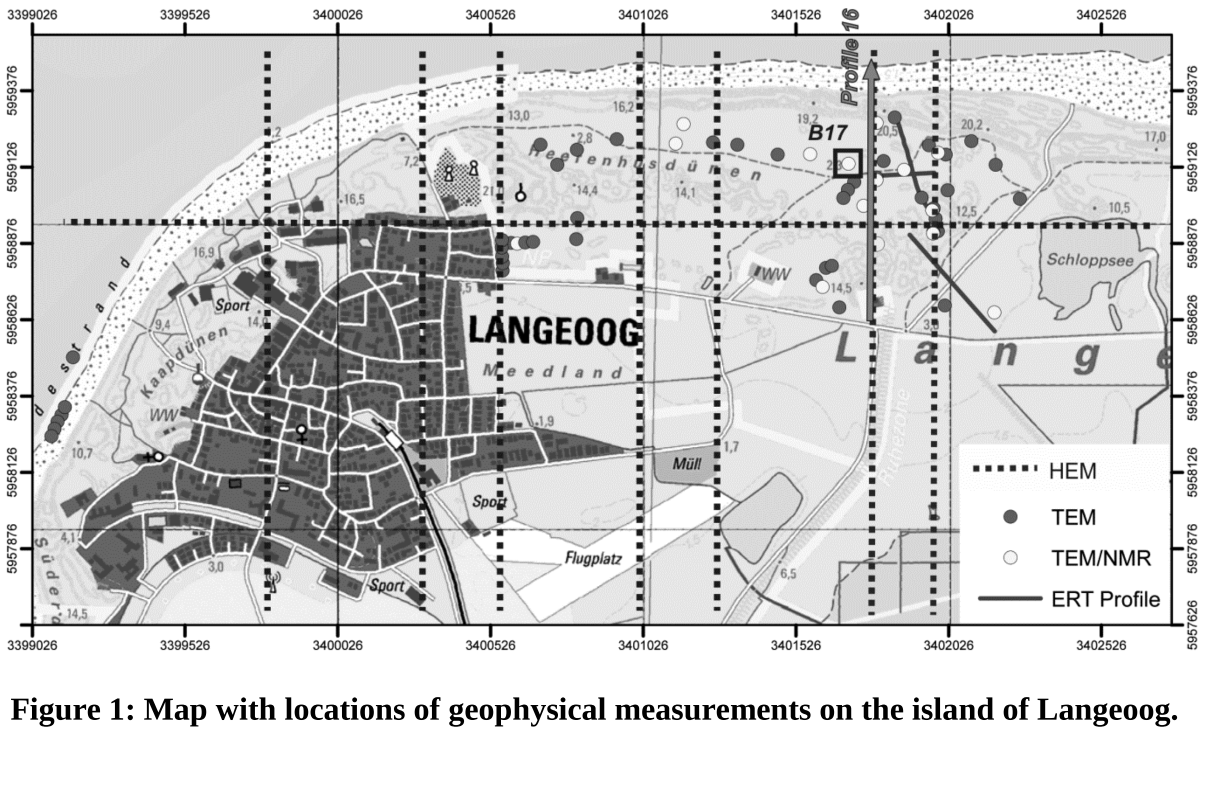

Figure 1: Map with locations of geophysical measurements on the island of Langeoog.

The interpretation of geophysical ρ measurements alone is naturally non-unique, because ρ is affected by both groundwater mineralization and lithology. On the other hand, the sensitivity of MRS to the ρ distribution in the subsurface is very low; so it cannot be used as stand-alone method regarding saltwater intrusion problems. The objectives of the survey on the island of Langeoog were 1) the localization and characterization of the freshwater-saltwater boundary, 2) the identification of clay layers inside the lens, 3) the prediction of the groundwater salinity over depth. Figure 1 shows an overview of the area of investigation and the measurement locations.

FRESHWATER-SALTWATER INTERFACE

The HEM method provides a regional overview of the freshwater/saltwater conditions (Siemon et al. 2014). Additional TEM measurements were conducted in the area of the managed freshwater lens to gain detailed information. Figure 2 compares the results of HEM and TEM along an S-N profile (Profile 16, see also Figure 1). Saltwater-bearing sediments (ρ < 1.5 Ωm) are found in a depth of 40 to 50 m. In the middle of the lens, the freshwater (ρ = 30-200 Ωm) extends down to a depth of 30 m, while at the edges, as expected, its thickness decreases. Interestingly, a transition zone between freshwater and saltwater with ρ = 5-20 Ωm and with a thickness of 10 to 20 m was detected. As the lithology interpretation from drillings and MRS measurements indicates, this zone cannot be related to lithology changes (dashed lines in Figure 2). In the North of the profile, a thin layer with ρ = 1-3 Ωm was found at a depth of 10 to 15 m. Compared to HEM, the TEM results reveal this layer with a similar resistivity, but 5 m deeper. We preliminary interpret this layer as saltwater on top of a thin clay layer, probably a relic of an ancient flooding. The clay layer itself could not be detected by the EM methods.

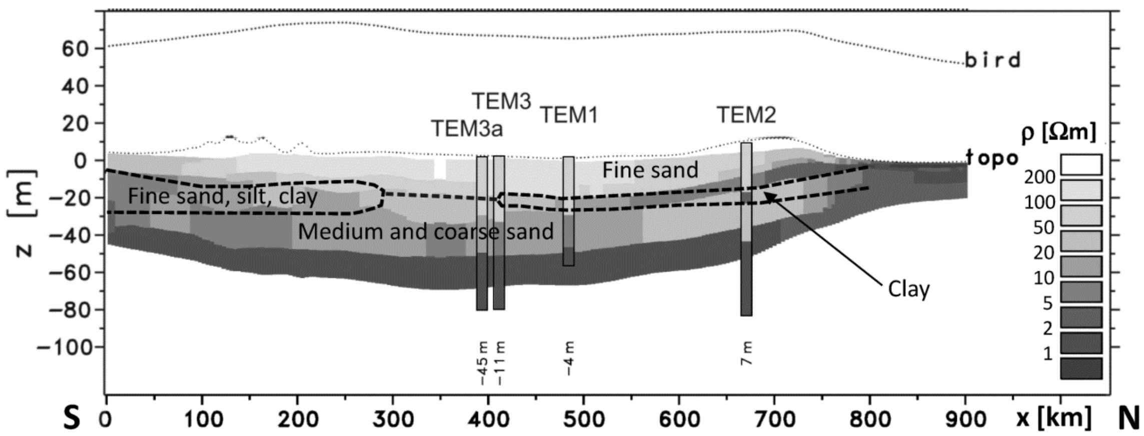

Figure 2: Comparison of HEM and TEM (loop size: 50 m) results, lithological interpretation from drillings and MRS measurements on Profile 16.

LITHOLOGICAL CHARACTERIZATION

With small TEM loops (25 m square), indications for thin clay layers above the saltwater were found at a depth of 20 to 30 m with a resistivity of about 7 to 10 Ωm (not shown), while larger TEM loops did not resolve these layers (Figure 2). Using ERT, we tried to track their lateral extent, but the bad coupling of the electrodes with the dry dune sand caused very inaccurate measurements and ambiguous results. Besides borehole interpretation, which is sparsely available on the island of Langeoog, also MRS measurements allowed for a lithological characterization to some extent. Figure 3 shows an example for a TEM (Figure 3a) and an MRS measurement (Figure 3b and c) at borehole B17 (see also Figure 1), both measured with a square loop of 50 m side length. As at B17 no lithology interpretation was available, the lithological information over depth depicted in Figure 3d was taken from another borehole at a distance of about 150 m. The well screen of B17 ranges from 35 to 65m depth and so we took the opportunity to measure the groundwater salinity in the transition zone directly in this borehole (Figure 3e). We note that TEM does not reveal the clay layer at 22 to 26 m depth, whereas Φ_{MRS} is clearly underestimated in this region. This is because clay and silt exhibit T_2* times smaller than the instrumental dead time. Consequently, the MRS signal from such fine-grained material is not detected completely and the corresponding Φ_{MRS} is underestimated. The differentiation between fine and coarse sand is possible due to different T_2* times (fine sand: 100 to 250 ms and medium to coarse sand: 350 to 500 ms).

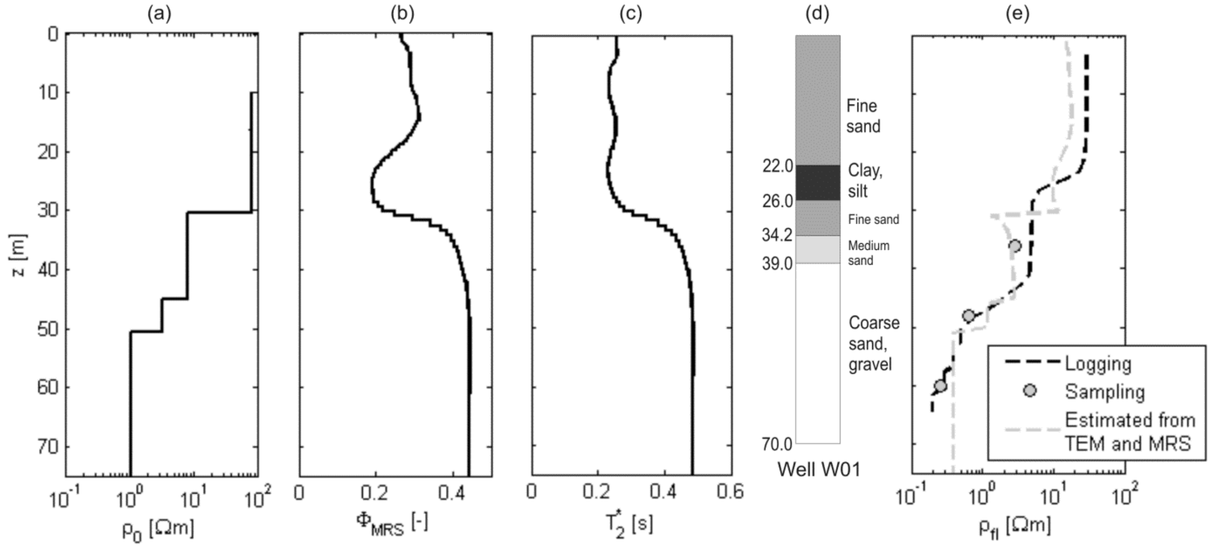

Figure 3: Results of a TEM and an MRS measurement at borehole B17: (a) resistivity distribution from TEM, (b) MRS water content distribution and (c) relaxation time distribution compared to (d) lithology interpretation from drilling, (e) estimated groundwater resistivity distribution compared to reference from salinity logging and sampling in B17.

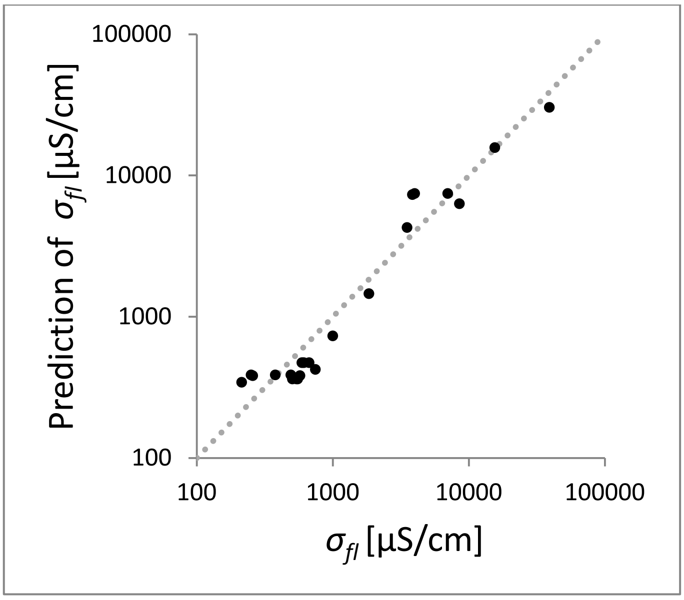

Figure 4: Comparison of predicted and measured electrical conductivity of groundwater.

ESTIMATING THE ELECTRICAL CONDUCTIVITY OF GROUNDWATER

Using the ρ distribution from TEM and the Φ_{MRS} distribution from MRS, the groundwater resistivity ρ_{fl} (and its inverse, the electrical conductivity σ_{fl} as a measure of groundwater salinity) was estimated using the equation of Archie (1942):

$$\rho_{fl} = a\rho\Phi_{MRS}^{n}$$

For our estimations, the Archie exponent n was set to 1.3 (literature value for unconsolidated sand) and the linear factor a was set to 1. Figure 3e shows the estimated ρ_{fl} resulting from the TEM/MRS data example in Figure 3a to c compared to ρ_{fl} as measured in B17. The estimated ρ_{fl} distribution is in good agreement with the reference. In Figure 4, we compare further σ_{fl} estimates from TEM/MRS measurements on the island with reference values from groundwater sampling. In total, at 22 sites of investigation both groundwater samples and TEM data were available. At some of these sites (8 points in Figure 4), MRS could not be applied due to intense EM noise. In such cases, we used the MRS water content of the nearest MRS measurement for estimation. The good correlation in Figure 4 shows that groundwater salinity can reliably and non-invasively be estimated by combining EM and MRS measurements.

CONCLUSIONS

The geophysical case study on the island of Langeoog demonstrates the successful combination of EM and MRS measurements, which provides additional information on both lithology and groundwater salinity. This information will be included in a hydrogeological model and will to support the hydrodynamic modelling of the freshwater lens in the future.

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