Contribution of Nuclear Magnetic Resonance for supporting hydraulic model generation

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INTRODUCTION

In order to understand the dynamics of saltwater/freshwater interfaces and to predict future processes in a changing climate, density-driven groundwater modeling (e.g., Sulzbacher et al. 2012) becomes an inevitable tool. Realistic hydraulic models must include the three-dimensional distribution of lithological units and their hydraulic properties in the subsurface. Boreholes do often not provide the sufficient spatial density to describe the typical heterogeneity of glacial sedimentary settings, and borehole logs can hardly provide the needed quantities. The most important parameter in groundwater models is the hydraulic conductivity K, but also porosity and specific storage. In density-driven models, as often used in saltwater intrusion problems, additionally the groundwater salinity of the current state is needed. Geophysical measurements can help to close the gaps between boreholes and to derive these parameters. Particularly electrical and electromagnetic (EM) methods are successfully applied since the electrical conductivity is sensitive to both clay content and fluid salinity (e.g. Wiederhold et al. 2013). However, the inversion proves to be ambiguous, i.e. a variety of models can fit the data. Furthermore, the main problem for the interpretation of results is to distinguish whether a good conductor indicates clay/silt or increased salinity.

Data from nuclear magnetic resonance (NMR) - applied at the laboratory, in boreholes or from the surface - directly reveal the water content of the investigated unit. Furthermore, the measured relaxation time T of the signal is proportional to medium pore size. Main disadvantage of surface NMR is its sensitivity to noise and its inability to detect fast-decaying signals from very small pores, e.g. clay, due to instrumental dead times. In the last years, instrumentation, measurement schemes, and data analysis methods have developed rapidly and made it applicable in a wide range of settings to characterize sediments from gravel to silt. Recently, Dlugosch et al. (2013) found a new model for computing K of clay-free sediments from porosity Φ and T providing better calibration and an upper limit for K.

Surface NMR, as one-dimensional method also called magnetic resonance sounding (MRS), is applied by deploying an increasing current though a transmit loop and measuring signals from the precessing protons in a receiver. While first inversion routines used only the initial amplitudes, a simultaneous inversion of the whole data space, i.e., inversion including T, is state-of-the-art now. Model discretization is either blocky (a limited number of layers with variable thickness, water content and T) or fixed with smoothness constraints on both quantities. As the resistivity distribution in the subsurface is needed to calculate the MRS sensitivity, the inversion of resistivity measurements is either done before (Vouillamoz et al. 2012) or jointly with MRS (Günther and Müller-Petke 2012). A simultaneous two-dimensional inversion of Φ and K was recently presented by Dlugosch et al. (2014).

EXAMPLES

Case 1: Investigation of a freshwater lens

Within the EU funded project CLIWAT (CLImate and WATer) the dynamics of the fresh-water lens beneath the North Sea Island Borkum was investigated. The whole island was covered by an helicopter electromagnetic (HEM) survey accompanied by several methods: seismics, vertical electric sounding (VES), ground penetrating radar (GPR), direct push, borehole measurements and fluid probes (Wiederhold et al. 2012). Four MRS were conducted in the eastern part of the island with good to excellent noise conditions.

In order to decrease ambiguity and to improve accuracy of the results, the soundings were jointly inverted with neighboring VES using a block model of common layer boundaries (Günther and Müller-Petke, 2012). This procedure improved the accuracy of the resulting three primary properties water content, T and resistivity significantly compared to two separate inversions. The parameters and their uncertainties were used to calculate the secondary (target) parameters *Φ*, K and salinity and their uncertainties (Figure 1). For the latter, fluid and direct push measurements were used to fit a modified Archie equation. For hydraulic conductivity we used the model of Dlugosch et al. (2013). The necessary calibration was achieved using a pumping test in one of the boreholes (Sulzbacher et al., 2012) and a collocated sounding.

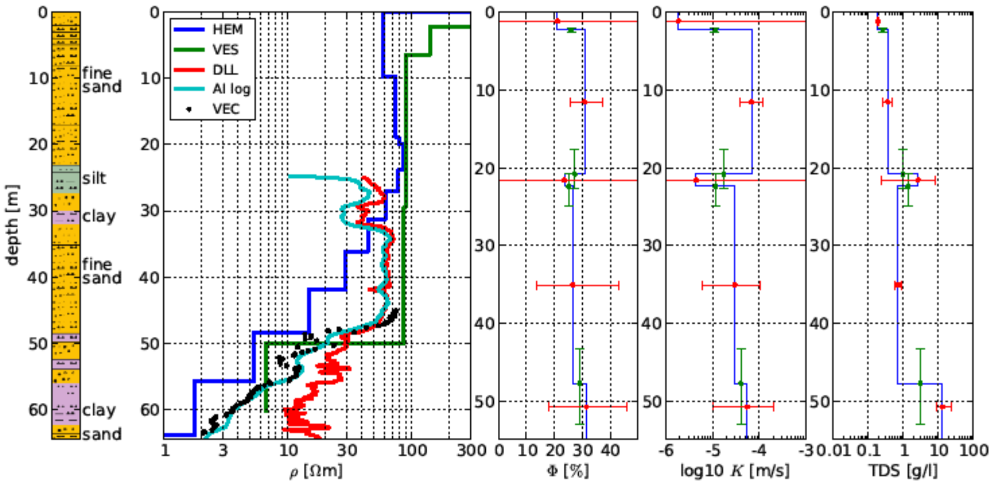

Figure 1. Geophysical results at the borehole CLIWAT 2 in Borkum: lithology (left), resistivity from different borehole and surface measurements (middle), and hydraulic parameters (*Φ*, K and salinity) derived from MRS/VES joint inversion results (after Günther and Müller-Petke, 2012, and Wiederhold et al., 2013).

The sounding presented in Figure 1 is used for verification since a research borehole was drilled there, logged with borehole tools and equipped with a buried electrode chain. The inversion results can be very well attributed to the present lithology. Furthermore, the derived hydraulic parameters show realistic values with moderate uncertainty due to the pumping activity that influenced the measurements. Soundings at other locations show even lower error bars and parameters with reliability comparable to standard hydrology methods. Of course, the number of locations was too small for generating a hydraulic model, but the model parameters of Sulzbacher et al. (2012) could be confirmed and adjusted.

Example 2: Two dimensional characterization of a shallow glacial channel

While initially only one-dimensional soundings were conducted, experiments with several overlapping loops lead to two-dimensional subsurface images, however firstly only of water content. Dlugosch et al. (2014) presented a scheme that inverts for both water content and relaxation time with results from the investigation site Eddelsdorf, where a shallow glacial channel of silty sediments is embedded in a sandy aquifer. These lithological setting was reconstructed (Figure 2) by jointly interpreting the images with the two parameters from surface NMR and with the resistivity from an electric resistivity tomography (ERT). .

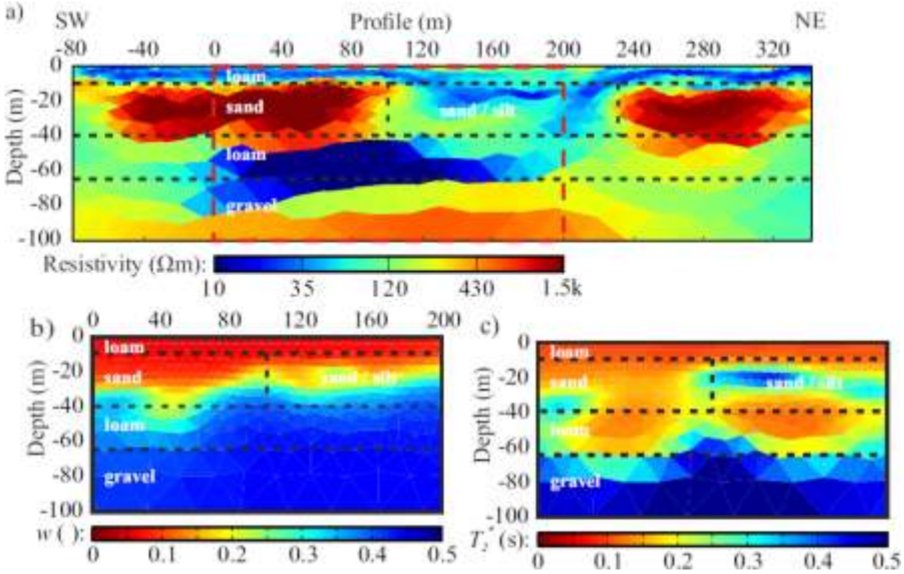

Figure 2:Resistivity (a), water content (b) and relaxation time (c) from 2D ERT and surface NMR experiments, respectively, at Eddelstorf (after Dlugosch et al., 2014).

Example 3: Vadose Zone characterization

The soil physical parameters of the vadose zone are of importance for quantifying groundwater recharge of aquifers and their protection against contaminants. MRS with small loops is in principle able to image the capillary fringe above a shallow water table. However, subsequent inversion and fitting of the water content leads to unreliable values. Costabel and Günther (2014) inverted MRS amplitude data directly for water retention (WR) parameters using three different WR models and show that reliable values for saturated water content, fringe height and pore distribution index are obtained for a sandy soil (Figure 3).

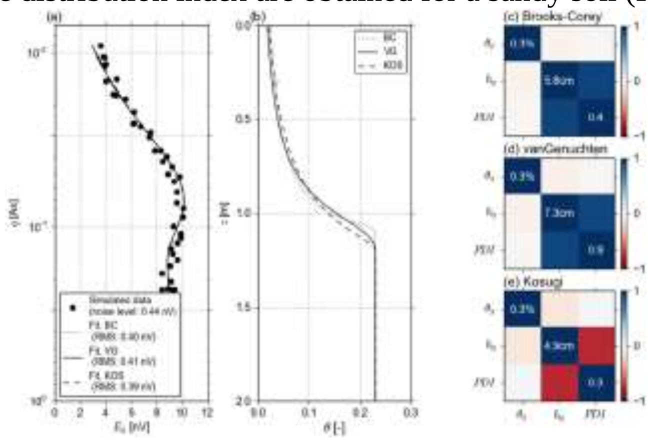

Figure 3: Data and model response (a) of inversion results using three different water retention models for describing the capillary fringe (b), uncertainty and covariance of parameters (c-e) for the Barnewitz/Nauen site (from Costabel and Günther, 2014).

DISCUSSION AND CONCLUSIONS

The application of surface NMR measurements can provide valuable information that helps to feed hydraulic models. This is particularly important in the context of salt-water problems where a differentiation between lithology and salinity must be made. It requires the knowledge of electrical conductivity, which can be obtained using electrical or electromagnetic measurements. A joint inversion of all data decreases ambiguity in the interpretation, and reduces the uncertainty of the obtained parameters.

However, surface NMR is mostly applied in form of soundings or relatively short profiles as its use becomes extensive, particularly in case of significant electromagnetic noise. Therefore it is not straightforward to create three-dimensional models in the catchment scale. Only spatial HEM or fast ground EM methods can provide line or areal data in limited time. Methods need to be developed which interweave point-wise information from combined soundings or boreholes with spatially dense data.

Calibration is needed and can typically be obtained by using pumping tests or samples in the laboratory. However, the developed petrophysical relations allow for narrowing the limits of the final quantities which in turn improves the reliability of the groundwater models.

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