Helicopter-borne electromagnetics: A powerful tool for the mapping of coastal aquifers

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ABSTRACT

In recent years airborne geophysical methods have turned out to have great potential in delineating subsurface information down to some hundred metres depth. This information is essential for planning purposes for manifold geoscientific, economic or environmental questions, like, e.g., utilization and protection of freshwater resources, land utilization or industrial planning. These data integrated into a three-dimensional geographic information system provide a perfect tool for spatial planning. Beside the geologic or geophysical basic information also changes of surface and subsurface data in time and space may be documented by repeated surveys. Here, a methodical introduction to helicopter-borne electromagnetics (HEM) is given and the advance of HEM in mapping of coastal aquifers is shown. Emphasis is placed on the mapping of freshwater-saltwater interfaces, saltwater intrusions, submarine freshwater outlets as well as on the mapping of clay occurrences.

INTRODUCTION

The problem of groundwater salinization is becoming more 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. 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.

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 very important for hydrogeological interpretation as the derived electrical conductivities respond to both lithological and water-chemistry variations down to depths of the upper hundred metres (Siemon et al. 2009; Steuer et al. 2009).

METHODS

The helicopter-borne electromagnetic system

The electromagnetic system operated at BGR is a RESOLVE system consisting of six transmitter-receiver coil pairs. The electromagnetic sensors are installed in a 10 m long tube, which is towed by a Sikorsky S-76B helicopter on parallel flight lines at about 30–40 m above ground level (Figure 1).
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 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 electromagnetic 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).

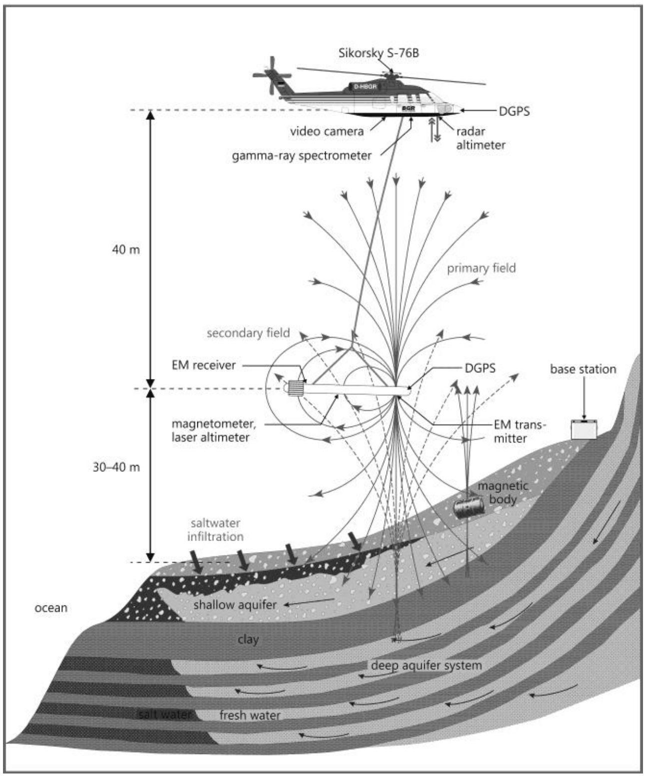

Figure 1. BGR helicopter-borne geophysical system and typical hydrogeological situation at a coast.

Modelling of the electromagnetic data

In the standard analysis, the in-phase (I) and quadrature (Q) components of the measured secondary magnetic fields are converted into resistivities (inverse of electrical conductivity) based on half-space models. Apparent resistivity ρ_a [Ωm] and centroid depth z*[m] of a homogeneous half-space (Figure 2, Model 1) are derived from the data of each single frequency (f). The resulting sounding curves, $\rho_a(z^*)$, provide the initial approximation of the vertical resistivity distribution. They are used to derive appropriate starting models for the one-dimensional (1D) inversion. A Marquardt–Levenberg inversion procedure iteratively calculates the model parameters, resistivity ρ and thickness d of the model layers (Figure 2, Model 2), from the data of all frequencies available. 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. Another approach is to use many layers with fixed thicknesses as starting model for a smooth inversion what results in more continuous intersections between geological units.

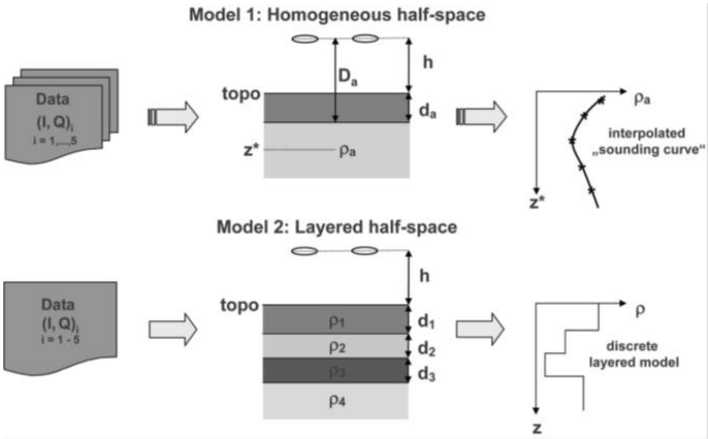

Figure 2. HEM inversion scheme based on the model of a homogeneous half-space and of a layered half-space model (Siemon and Steuer 2011).

Advanced analysis is optional and includes a priori information, e.g. borehole data, conductivities of water samples or results of other geophysical measurements, and/or constrained inversion (Gunnink et al. 2012). A further step is the integration of resistivity models into a geological or hydrogeological model and vice versa. The results of the 1D inversion are generally presented as vertical resistivity sections (VRS), resistivity and thickness/depth maps.

MAPPING OF COASTAL AQUIFERS

BGR initiated an airborne geophysical mapping project (D-AERO) in 2007, supported by LIAG for two years, in order to investigate coastal aquifers in Northern Germany (Siemon et al. 2014a). Exemplarily, Figure 3 shows some HEM applications.

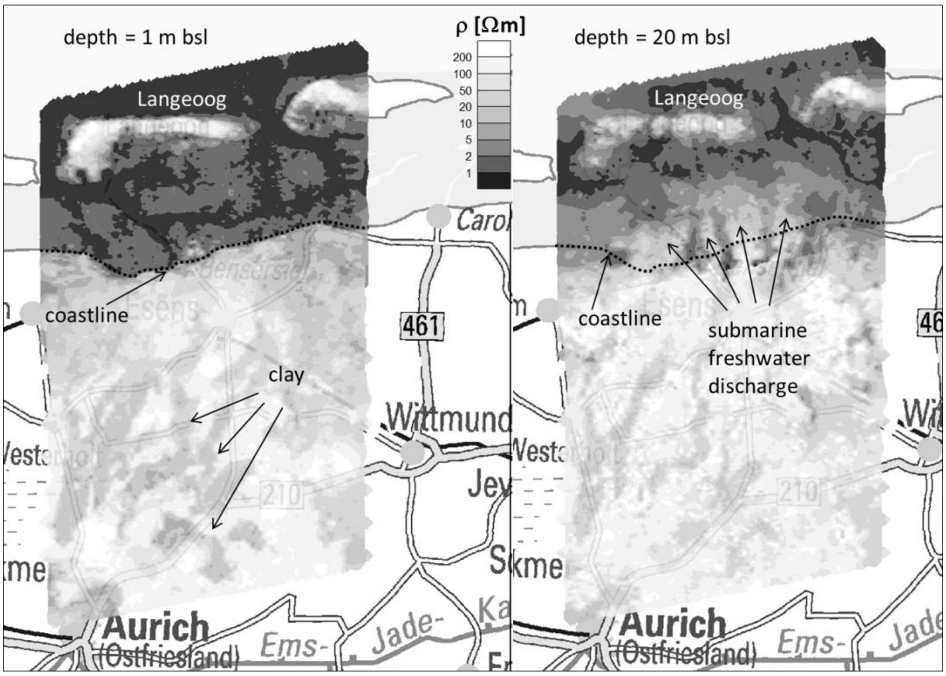

Figure 3. HEM resistivity maps at 1 and 20 m bsl plotted on a topographic map (BKG 2014). Dark colours indicate conductive areas, like saltwater. White colours indicate more resistive areas, like freshwater saturated sandy sediments.

The resistivity map at 1 m depth below sea level (bsl) clearly shows the freshwater-saltwater interface at the North Sea island of Langeoog and along the coastline. The clay distributions mapped onshore are discussed in more detail by Siemon et al. (2014b). At 20 m bsl, however, the freshwater-saltwater interface at the coast appears rather inhomogeneous. The finger-shaped interface indicates submarine freshwater discharge to the North Sea. The freshwater lens of the island of Langeoog is still present, but less extended.

DISCUSSION AND CONCLUSIONS

Mapping of coastal aquifers using HEM comprises mapping of freshwater-saltwater interfaces to outline saltwater intrusions and submarine freshwater occurrences, as well as mapping of clay distributions to estimate the vulnerability of the groundwater to pollution and to outline potential flow paths. HEM resistivity models are often used as base for further geophysical investigation (e.g. Costabel et al. 2014) or for hydrogeological modelling (e.g. Deus and Elbracht 2014). Therefore, HEM results are imported into a geographical information system (www.geophysics-database.de) which provides the data and the models.

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