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Structure-based geoelectrical models derived from genetic algorithms: A case study for hydrogeological investigations along Elbe River coastal area, Germany

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ABSTRACT

Vertical electrical sounding (VES) and electrical resistivity tomography (ERT) surveys are performed to assess the hydrogeological conditions along Elbe River coastal area, Germany. Because the interpretation of actual resistivity data still has a degree of non-uniqueness and ill-conditioning, linear and non-linear inversion methods have been applied in this paper for optimal interpretation of the measured data. The 1D model generation using hybrid genetic algorithms (GA) represents an accurate and quick solution to image the subsurface resistivity distributions; freshwater aquifer and two highly conductive zones of perched saltwater and seawater intrusion. The longitudinal conductance of the interpreted layers above the water table is calculated to explain why the vulnerable zone to the perched saltwater concentrates at the central and southern parts of the area investigated.

Two-dimensional layered-earth models consisting of undulating interfaces are generated by the 2D hybrid GA. These structure-based models are then compared to the cell-models derived from the conventional smoothness-constrained inversion in view of available borehole data. A finite element forward 2D modeling scheme is used for the calculation of theoretical data. This survey example demonstrates that the combined use of the GA with structure-based model and conventional derivative-based inversion with cell-model provides valuable information to constrain the number of interfaces to interpret the DC resistivity measurements for hydrogeological investigations. The limitations of conventional inversion methods under the presence of conductive layers can be overcome by the use of GA with a structure-based model. However, the structure-based parameterization is not practical in the case of significant and sudden discontinuities along the lateral direction.

1. Introduction

The most widespread and serious sources of environmental coastal impact are saltwater contamination and erosion. Nowadays, coastal areas are often densely populated, where dense population and touristic development are coupled to scarce water resources and require intense exploitation of groundwater. Below the withdrawn freshwater in coastal aquifers, there often exists a saltwater zone formed by recirculation process (Cameo, 2006). In coastal areas, a saltwater wedge-like feature can be observed. This wedge develops because freshwater, which floats on the top of saltwater, is less dense than saltwater. The boundary between saltwater and freshwater is not definite; the zone of dispersion, the transition zone or saltwater interface, is brackish with saltwater and freshwater mixing. The natural movement of freshwater towards the sea prevents saltwater from entering freshwater aquifers (Barlow, 2003). Accordingly, seawater intrusion is an inevitable problem in coastal areas of many countries.

The DC resistivity technique has received considerable attention as a result of its potential applications in hydrogeology and imaging the near-surface geology and saltwater intrusion (e.g. Attwa, 2012b; Eleraki et al., 2010; Gemail et al., 2011; Hwang et al., 2004; Khalil, 2012; Supper et al., 2014). In addition to being an efficient technique for lithological discrimination, the DC resistivity method has led to much research on estimation of hydrogeological parameters of aquifers (e.g. Purvance and Andricevic, 2000; Attwa et al., 2009; Khalil, 2010; Attwa et al., 2014). Relationships between aquifer characteristics and the electrical parameters of geoelectrical layers have been studied and reviewed by many authors (e.g. Asfahani, 2007; Attwa and Günther, 2013; Chandra et al., 2010; Khalil, 2009; Sayed et al., 2004).

Determination of saltwater/freshwater conditions of coastal areas can be improved through the optimization of geophysical prospecting and monitoring procedures, aimed at the detailed geometrical reconstruction and physical characterization of the aquifer, with particular interest to the intrusion wedge. Several papers discuss the inversion techniques used to solve a wide range of complex geophysical inverse problems (e.g. Demirci et al., 2012; Günther et al., 2006; Martorana et al., 2013). The majority of current geophysical inversion approaches

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depends on derivative-based inversion (DBI) methods, such as Gauss–Newton methods (deGroot-Hedlin and Constable, 1990; Pratt et al., 1998; Sasaki, 1994), conjugate gradient methods (Newman and Alumbaugh, 2000) and steepest decent techniques (Roy, 2002). In the conventional regularized inversion scheme, the 2D forward modeling is constructed in the form of small cells. This cell-based model is widely used for environmental and hydrogeological investigations and a human interpreter delineates the interfaces from the gradient of resistivity values in the constructed 2D model. However, such parameterization together with a 2D regularized inversion usually results in a smooth or blurred image of the actual subsurface structures, and in many cases, the lower boundary of conductive layers cannot be resolved using cell-based models due to the smearing (Attwa et al., 2011; Corriols et al., 2009; Szalai et al., 2013). Consequently, new parameterizations were developed for the direct extraction of lithologic units with sharp boundaries and sharp variation in intrinsic resistivities (Blaschek et al., 2008; Kis, 2002; Olayinka and Yaramanci, 2000). For example, the L1 inversion method tends to give a more blocky appearance of model sections, but the layer boundaries are still smeared as noted by Auken and Christiansen (2004). To overcome this problem, a model consisting of some interfaces can be used to represent the subsurface more consistent with the geological situation in a sedimentary environment referred to as structure-based (SB) model by Akca and Basokur (2010).

In the SB parameterization, the geological units are separated by undulating interfaces and have distinct resistivity values in which moderate resistivity variations are permitted in lateral direction. The conventional inversion methods strictly rely on an initial guess inside the global valley in the error energy map. But, providing a reasonable initial guess will be almost impossible without knowing the solution in advance. This restricts the use of any derivative-based inversion for complex structural models. For these reasons, Akca and Basokur (2010) used a hybrid genetic algorithm (GA) for DC methods and Chen et al. (2012) used stochastic methods for the magnetotellurics to derive a 2D structure-based model.

Here, we will attempt to delineate saltwater/freshwater boundaries and saltwater intrusion along Elbe River tidal coastal area as a case study (Fig. 1). DC resistivity surveys (1D sounding and 2D imaging) are aimed to construct the main geological and hydrogeological situation. We will describe the application of GA with a structure-based model to characterize the hydrogeological conditions and then the results will be compared with those derived from the conventional cell-based regularized inversion technique. To check the performance of the applied parameter estimation methods, the results will be compared with lithologic and hydrogeological borehole information.

2. Geological setting

The survey area is an open tidal flat coastal area located at the estuary of Elbe River, in northern Germany, (Fig. 1). The tidal sediments consist of fine sand, silt and clay layers deposited in sheltered or open tidal flats as well as in the brackish-water environment of coastal lagoons and estuaries alternating with peat layers which were formed in coastal bogs (Streif, 2004).

Fig. 3 shows information concerning a borehole drilled for scientific purposes in the Coastal Aquifer Test Field (CAT-LUD 1) at Cuxhaven area (Fig. 1a). This borehole was used to set up the geological, hydrogeological and geochemical properties in Cuxhaven area (Binot et al., 2002). It can be noted that the surface cover overlies 25 m of two interglacial (Holocene and Eemian periods) tidal flat sedimentary sequences, which have a medium hydraulic conductivity of $k_f = 10^{-5}$ to 10^{-6} m/s (Panteleit et al., 2006). These inter-finger with mud of brackish lagoonal type and with onshore peat deposits. This horizon overlies Pleistocene coarse sediments of Elster and Saale glaciations with sand and gravel. The logs in Fig. 3 delineate a transition zone between freshwater and saltwater from 45 m to 65 m depth. The gamma ray log gives a good indication of increasing clay content within tidal flat deposits (Holocene and Eemian sediments) compared to Pleistocene deposits.

Sindowski (1969) indicated that the post-Eemian clay (Upper Pleistocene), which was deposited above the Middle Pleistocene

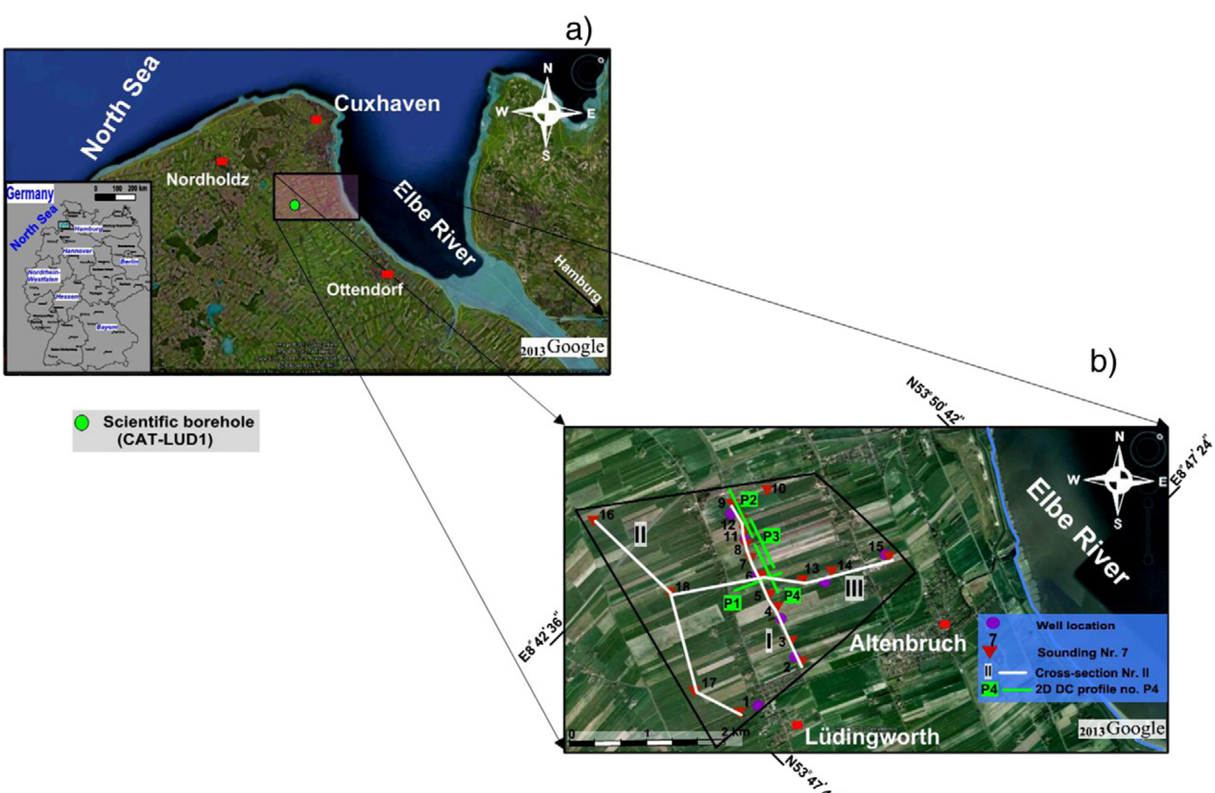

Fig. 1. (a) Map of the study area. (b) Location of the electrical sounding sites and the ERT profiles.