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Hydrogeophysical exploration of three-dimensional salinity anomalies with the time-domain electromagnetic method (TDEM)

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SUMMARY

The time-domain electromagnetic method (TDEM) is widely used in groundwater exploration and geological mapping applications. TDEM measures subsurface electrical conductivity, which is strongly correlated with groundwater salinity. TDEM offers a cheap and non-invasive option for mapping saltwater intrusion and groundwater salinization. Traditionally, TDEM data is interpreted using one-dimensional layered-earth models of the subsurface. However, most saltwater intrusion and groundwater salinization phenomena are characterized by three-dimensional anomalies. To fully exploit the information content of TDEM data in this context, three-dimensional modeling of the TDEM response is required.

We present a finite-element solution for three-dimensional forward modeling of TDEM responses from arbitrary subsurface electrical conductivity distributions. The solution is benchmarked against standard layered-earth models and previously published three-dimensional forward TDEM modeling results. Concentration outputs from a groundwater flow and salinity transport model are converted to subsurface electrical conductivity using standard petrophysical relationships. TDEM responses over the resulting subsurface electrical conductivity distribution are generated using the three-dimensional TDEM forward model. The parameters of the hydrodynamic model are constrained by matching observed and simulated TDEM responses.

As an application example, a field dataset of ground-based TDEM data from an island in the Okavango Delta is presented. Evaporative salt enrichment causes a strong salinity anomaly under the island. We show that the TDEM field data cannot be interpreted in terms of standard one-dimensional layered-earth TDEM models, because of the strongly three-dimensional nature of the salinity anomaly. Three-dimensional interpretation of the field data allows for detailed and consistent mapping of this anomaly and makes better use of the information contained in the TDEM field dataset.

Introduction

Subsurface flow and transport modelers often work with insufficient calibration and validation data. For a number of years, geophysical methods have attracted attention as an alternative source of data. Geophysical exploration can provide innovative types of field data that are typically indirectly related to the state variables of the subsurface flow and transport models (i.e. water content, hydraulic head, concentration). A number of geophysical methods have been used in a hydrogeophysical context. For instance, electrical resistivity imaging has been used to map the spreading of salt tracer plumes (e.g. Kemna et al., 2002; Singha and Gorelick, 2005) and to investigate soil water dynamics (e.g. Daily et al., 1992; Looms et al., 2008; Zhou et al., 2001). Radar techniques have been used to map spatial soil water content variations (e.g. Lambot et al., 2004; Linde et al., 2006). Magnetic resonance techniques have provided proxy data on subsurface water content and on pore space geometries (e.g. Legchenko and Valla, 2002; Mohnke and Yaramanci, 2008). Time-lapse gravity surveys, both space-borne and ground-based, have been demonstrated to be useful for mapping the variation in total subsurface water storage (e.g. Leiriao et al., 2009).

Following the terminology presented in Ferré et al. (2009), the approach presented in this article can be described as a trial-and-error coupled hydrogeophysical inversion approach. In a coupled hydrogeophysical inversion approach, hydrological models are used to predict geophysical variables and hydrological model parameters are updated to obtain optimal agreement between simulated and observed geophysical variables.

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The coupled hydrogeophysical inversion approach has advantages over traditional geophysical inversion. In traditional geophysical inversion, one degree of freedom is placed on each element of the domain (typically cubic grid-boxes), leading to a high total number of degrees of freedom in the inversion and thus to non-unique solutions. To stabilize inversion results, the grid boxes are typically linked together by smoothness constraints or other regularization methods (e.g. Degroothedlin and Constable, 1993; Loke and Barker, 1996; Tikhonov and Arsenin, 1977). Ideally, all available prior information is used in the inversion process to further constrain the problem. In a coupled hydrogeophysical inversion, the number of degrees of freedom can be often reduced dramatically, because the inversion honors the underlying physics of the process being modeled. For example, salinity transport processes are governed by a small number of parameters (e.g. dispersivity, porosity and hydraulic conductivity) that determine the salinity distribution over large domains.

Several previous studies present examples of coupled hydrogeophysical inversion using a variety of geophysical exploration techniques. Kowalsky et al. (2005) simulated water injection into the vadose zone, converted simulated water contents into dielectric constants using the Topp equation and minimized the mismatch between simulated and observed ground-penetrating radar travel times using a Levenberg–Marquardt algorithm. Looms et al. (2008) performed a similar injection experiment and used both ground-penetrating radar and electrical resistivity data in the subsequent inversion. Kemna et al. (2002) simulated advective–dispersive tracer transport in an aquifer, converted simulated concentrations into resistivity using a petrophysical relationship and minimized the mismatch between simulated and observed apparent resistivities.

Our hydrogeophysical approach is outlined in Fig. 1. Based on prior knowledge, a conceptual model of the groundwater flow and transport system, and a priori parameter estimates, a numerical model for the subsurface flow and transport processes is developed. The spatio-temporal evolution of the salinity is predicted by this numerical model. Simulated salinity is converted into formation resistivity using Archie's law. Subsequently, the time-domain electromagnetic response over the three-dimensional subsurface resistivity distribution is computed. The mismatch between simulated and observed apparent resistivities is minimized by trial-and-error adjustment of dispersivity. Trial-and-error adjustment is used because of long computation times for the three-dimensional TDEM forward model. If the approach is used together with more efficient 3D TDEM solvers, automatic inversion (e.g. Levenberg–Marquardt) would be feasible.

The time-domain electromagnetic method (TDEM) has been widely used in hydrogeological exploration and geological mapping applications (e.g. Danielsen et al., 2003; Thomsen et al., 2004). The method has been extensively applied in studies of seawater intrusion and soil and groundwater salinization. Paine, 2003 used time-domain and frequency domain electromagnetic techniques to outline zones affected by soil salinization and to estimate the total subsurface chloride mass. In a series of papers, Goldman et al. (1991), Kafri et al. (1997), Kafri and Goldman (2005) and Yechieli et al. (2001) present the application of the TDEM method to map and delineate seawater intrusion phenomena in the Mediterranean and Dead Sea coastal aquifers of Israel.

The TDEM method measures electrical conductivity variations in the subsurface that, in water-saturated conditions, are mainly a function of groundwater salinity and clay content. Eddy currents are injected into the ground using either galvanic or inductive sources. The rate of change of the secondary magnetic field generated by the eddy currents is observed over a number of logarithmically spaced time gates. Typically, the observation time ranges from a few microseconds to several milliseconds. A typical source-receiver configuration, which was used in this study, is the central loop setup. In this setup, a large (e.g. 40 m $\times$ 40 m) current loop is used as the sender and couples inductively with the subsurface. The rate of change of the magnetic field is measured with a small receiver loop which is placed in the center of the sender loop.

Despite the popularity of the method, which is typically applied from either ground-based or airborne platforms, TDEM data have mainly been interpreted using one-dimensional layered-earth models. There are two main reasons for this: (1) the subsurface can be conceptualized as a layered structure in many cases and (2) fully three-dimensional forward simulation of the TDEM signal propagation is computationally challenging and CPU time-intensive. In contrast, one-dimensional layered-earth TDEM forward modeling can be done semi-analytically using integral transforms and digital filtering (Anderson, 1979; Ward and Hohmann, 1988).

Several solutions to the three-dimensional TDEM forward problem have been presented in the literature (Commer and Newman, 2004; Newman et al., 1986; Wang and Hohmann, 1993) and several authors have investigated three-dimensional TDEM inversion (Newman and Commer, 2005). The approach presented by Wang and Hohmann, 1993 uses analytical half-space solutions to calcu-

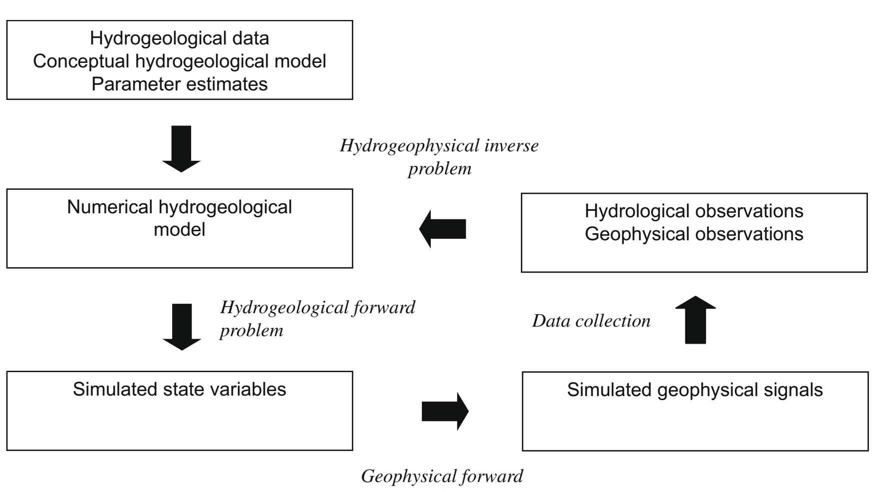

Fig. 1. The coupled hydrogeophysical inverse approach used in this study.