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A filtering method to correct time-lapse 3D ERT data and improve imaging of natural aquifer dynamics

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ABSTRACT

We have developed a processing methodology that allows crosshole ERT (electrical resistivity tomography) monitoring data to be used to derive temporal fluctuations of groundwater electrical resistivity and thereby characterize the dynamics of groundwater in a gravel aquifer as it is infiltrated by river water. Temporal variations of the raw ERT apparent-resistivity data were mainly sensitive to the resistivity (salinity), temperature and height of the groundwater, with the relative contributions of these effects depending on the time and the electrode configuration. To resolve the changes in groundwater resistivity, we first expressed fluctuations of temperature-detrended apparent-resistivity data as linear superpositions of (i) time series of river-water-resistivity variations convolved with suitable filter functions and (ii) linear and quadratic representations of river-water-height variations multiplied by appropriate sensitivity factors; river-water height was determined to be a reliable proxy for groundwater height. Individual filter functions and sensitivity factors were obtained for each electrode configuration via deconvolution using a one month calibration period and then the predicted contributions related to changes in water height were removed prior to inversion of the temperature-detrended apparent-resistivity data. Applications of the filter functions and sensitivity factors accurately predicted the apparent-resistivity variations (the correlation coefficient was 0.98). Furthermore, the filtered ERT monitoring data and resultant time-lapse resistivity models correlated closely with independently measured groundwater electrical resistivity monitoring data and only weakly with the groundwater-height fluctuations. The inversion results based on the filtered ERT data also showed significantly less inversion artefacts than the raw data inversions. We observed resistivity increases of up to 10% and the arrival time peaks in the time-lapse resistivity models matched those in the groundwater resistivity monitoring data.

1. Introduction

Growing scientific and regulatory interest in interactions between surface water and groundwater has led to the increased use of geophysical methods for characterizing hyporheic processes and aquifer systems that are connected to the sea, lakes, and rivers. Geophysical methods are used to derive conceptual models of contact zones (e.g., river beds), define the interior structure of connected aquifers (e.g., Acworth and Dasey, 2003; Crook et al., 2008; Doetsch et al., 2010b; Hatch et al., 2010; Nguyen et al., 2009; Slater et al., 2010), and obtain information about surface water–groundwater interactions. The latter is achieved by analyzing geophysical time series or time-lapse inversion models following natural (e.g., de Franco et al., 2009; Fàlgas et al., 2009; Nyquist et al., 2008; Ogilvy et al., 2009; Slater et al., 2010) or artificial perturbations of the system, for example, in the form of saline tracers injected into a river (Ward et al., 2010).

There are numerous hydrological methods for studying river water–groundwater interactions (e.g., Cook et al., 2003; Kalbus et al., 2006). Many of them exploit natural fluctuations of state variables (e.g., temperature) or isotope concentrations. One well-established approach is to compare river and groundwater heights to determine if a river is losing or gaining water. Similar information is obtained at larger scales by analyzing differences in discharge between river cross sections (Harvey and Wagner, 2000). Temperature variations in a river and in adjacent groundwater can be used to identify recharge or discharge zones and to quantify water fluxes at the river-aquifer interface (Anderson, 2005); fiber-optic-distributed sensors now make it possible to obtain temperature data at very high spatial and temporal resolutions (e.g., Selker et al., 2006; Slater et al., 2010). As for temperature measurements, electrical resistivity time series of river water and groundwater can be used to infer traveltimes of water

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moving from rivers to groundwater observation boreholes (e.g., Cirpka et al., 2007; Vogt et al., 2010). However, using these techniques alone makes it extremely difficult to delineate the evolution of three-dimensional (3D) groundwater flow patterns in the vicinity of rivers. Geophysical methods may provide key complementary 3D information.

Natural sources in the form of fluctuations of river water resistivity offer several advantages over artificial ones when studying surface water and groundwater dynamics using geophysical techniques. The resultant data provide more integrated information because they are unaffected by local heterogeneities close to the injection points, the field experiments are less expensive, and permits are easier to obtain. Furthermore, using natural sources is the only viable option for obtaining meaningful geophysical responses when working in large rivers or catchments (Yeh et al., 2008).

A major complication of geophysical monitoring based on natural-source signals is that the effects of interest are often superimposed on other unwanted signals. As a consequence, geophysical monitoring can only provide spatial and temporal distributions of a time-varying property if the corresponding geophysical signal dominates or if it can be isolated from signals originating from other time-varying phenomena (Rein et al., 2004). Electrical resistivity tomography (ERT) monitoring data used in this study are not only affected by resistivity (salinity) variations in the pore water (i.e., the natural tracer of interest), but also by variations in groundwater temperature and height. ERT methodology is treated by Binley and Kemna (2005) and the relationships between electrical and hydrogeological properties and state variables are reviewed by Lesmes and Friedman (2005).

Different approaches for removing unwanted temporally-varying contributions from ERT data or inversion models have been proposed. For example, Olofsson and Lundmark (2009) performed long-term ERT monitoring to evaluate how de-icing salt affects the roadside subsurface. They evaluated temporal variations by comparing them with models obtained in areas with similar geological characteristics, but where no de-icing salt had been applied. This approach can be problematic as a good reference site is often difficult to find. Hayley et al. (2007, 2009, 2010) sought to image variations in pore-water salinity. This task was complicated by variations in temperature and water content that also affected the ERT measurements. They evaluated two possible ways to remove the unwanted effects. The first approach was to apply post-inversion corrections to the inversion models and thereby convert them to reference temperature and saturation conditions (Hayley et al., 2007, 2009). This method required specific petrophysical relationships between the unwanted variables (temperature and water saturation) and the electrical properties, together with measurements of these variables at discrete locations. A better performing approach involved applying pre-inversion corrections to the data based on differences between simulated data from unreferenced and referenced inversion models obtained from the first approach (Hayley et al., 2010).

Only a few geophysical studies have exploited natural variations to characterize river-groundwater interactions. Nyquist et al. (2008) investigated such interactions by performing an electrical resistivity survey within a river; two ERT profiles collected at different river stages were compared and the differences in the resistivity models were interpreted in terms of groundwater discharge patterns. Slater et al. (2010) provided constraints to a conceptual model describing flow pathways of contaminated groundwater leaking into a river by combining continuous waterborne electrical imaging with high-resolution temperature monitoring; static inversion of the ERT and time-domain induced polarization data provided a general hydrogeologic zonation, whereas the temperature variations indicated the locations of river and groundwater exchange.

We have acquired more than one year of 3D crosshole ERT monitoring data close to the Thur River in Switzerland (Fig. 1a). The electrical stratigraphy of the aquifer is known from an earlier study (Coscia et al., 2011). Here, we investigate the extent to which infiltrating river water can be used as a natural tracer for imaging aquifer dynamics. Electrical resistivity fluctuations in the river water and groundwater have previously been used at this site to infer traveltime distributions (Cirpka et al., 2007). In contrast, we focus on ERT apparent-resistivity data that we eventually want to use to image 3D groundwater flow patterns.

To achieve this ultimate goal, we develop here a temporal filtering methodology to remove the effects of seasonal variations in temperature and relatively rapid groundwater-height fluctuations from our apparent resistivity time series before performing time-lapse inversions. Minimizing these effects is crucial for obtaining time-lapse images that are primarily related to changes in groundwater resistivity. Our method involves expressing the temperature-detrended ERT data variations as a function of two variables: the filtered variations of river-water resistivity and a quadratic expression of the instantaneous river height. A one-month period of data was used to estimate, for each electrode configuration, the filter function and the coefficients of the quadratic expression by deconvolving apparent resistivity time series with river-water resistivity and river height time series.

After introducing the study site and the various data sets, we outline how we correct the river-water and groundwater resistivities and ERT apparent resistivities for seasonal temperature variations. We then concentrate on our method for minimizing the effects of changing groundwater height on the temperature-detrended apparent resistivities before describing the time-lapse inversions and initial comparisons with groundwater monitoring data.

2. Study site, experiment, and data

2.1. Study site and experimental description

Our study site is located at Widen in the Thur catchment of north-eastern Switzerland (Fig. 1a). At this location, the Thur River infiltrates an adjacent aquifer consisting of silty gravel (Cirpka et al., 2007; Diem et al., 2010). The aquifer is approximately 7 m thick. It is embedded between an overlying 3-m-thick layer of loam and an underlying aquitard of fine lacustrine clay (Fig. 1c).

Details on the site, instrumentation, installation, and our recording strategy are given by Coscia et al. (2011). Only a summary of this information is provided here. The experimental set-up includes eighteen ~11-m-deep boreholes evenly spaced at 3.5 m intervals (Fig. 1b and c). They each contain a slotted plastic casing and a geoelectric cable with 10 electrodes spaced 0.7 m apart along the length of the aquifer section. The cables are centered in the middle of the boreholes with the borehole fluid providing the electrical contact between the electrodes and the aquifer. An ERT measuring device, a computer that controls the measurements, and a wireless system that allows the computer and recorded data to be accessed remotely are installed in a flood-proof hut. A number of boreholes are also equipped with sensors and loggers at three different depths (~4.6 m, ~6.6 m, and ~8.6 m) to measure groundwater height, temperature, pressure, and resistivity every 15 min. Sensors and a logger are also installed at a river station ~50 m downstream of the study site.

Under normal river conditions (i.e., river discharge ~47 m^3/s; data from www.hydrodaten.admin.ch), the upper ~1 m of the gravel aquifer is unsaturated. Under very high discharge conditions (i.e., >500 m^3/s), the aquifer is fully saturated and it behaves as a confined system. The geometric mean of the aquifer's hydraulic conductivity estimated from borehole slug tests is 4.2×10^{-3} m/s (Diem et al., 2010).

Using an innovative circulating 3D electrode measuring scheme (Coscia et al., 2011), one apparent-resistivity measurement was made for each of 15,500 different electrode configurations every ~7 h. The internal structure of the aquifer was studied in detail through static 3D ERT inversions of one of these 7-h data sets collected during stable hydrological conditions (Coscia et al., 2011). The aquifer was characterized