ELECTRICAL IMAGING OF TRACER MIGRATION AT THE MASSACHUSETTS MILITARY RESERVATION, CAPE COD

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Abstract

Electrical resistivity tomography (ERT) is examined as a method to provide spatially continuous information about aquifer properties through imaging of tracer flow and transport in an unconfined aquifer. Field data were collected at the Massachusetts Military Reservation, Cape Cod, Massachusetts, during the summer of 2002. High-resolution images in both space and time of the movement of an electrically conductive sodium-chloride tracer in three dimensions (3-D) help delineate aquifer heterogeneity. Sixty 3-D data sets were collected between four corner-point wells for 20 days following the 9-hour injection. Concentrations were measured at a 15-point multilevel sampler centrally located within the ERT array, at the production well, and at two wells external to the central array.

The tomograms indicate movement of the saline tracer consistent with measured concentration data. The resistivity tomograms serve as an appropriate surrogate for concentration maps that are otherwise impossible to obtain. Under reasonable assumptions, estimates of groundwater velocity and hydraulic conductivity can be obtained by tracking the tracer.

Introduction

In order to predict the fate and long-term transport of contaminants, an accurate depiction of the spatial variability of the hydraulic conductivity field is essential. Hydraulic conductivity measurements, or measurements that can be used in inverse flow and transport modeling, such as hydraulic head or concentrations, are generally too spatially sparse to obtain a high-resolution image of the subsurface. A considerable volume of data is required to develop an accurate model of groundwater flow and transport, and if reasonable correlations between geophysical and hydrologic parameters exist, geophysical methods can contribute appreciably to the three-dimensional information about the subsurface. In this study, electrical resistivity tomography (ERT) is used to monitor transport of a conductive saline tracer.

Over the past 30 years, a good understanding has been developed of the electrical properties of geological materials based on laboratory and theoretical studies (*Olhoeft*, 1975; *Brace*, 1977; *Knight and Dvorkin*, 1992; *Slater and Lesmes*, 2002). Most of this work has involved laboratory studies of small homogeneous samples, and the theories developed correspond to small homogeneous systems. It is widely acknowledged that these results may not hold for field conditions, since real aquifers are anisotropic and heterogeneous at multiple scales (*Ezzedine et al.*, 1999).

Recent work has shown that ERT is sensitive to changes in fluid electrical conductivity from saline tracers (*Slater et al.*, 1997a; *Slater et al.*, 1997b; *Stubben et al.*, 1998; *Versteeg et al.*, 2000), including numerous studies that link fluid resistivity to bulk electrical resistivities (*Binley et al.*, 1996; *Slater et al.*, 2000; *Kemna et al.*, 2002; *Slater et al.*, 2002). Perhaps the most effective way of using ERT to monitor transient flow through the subsurface is via differential imaging (*Park*, 1998; *Birken and Versteeg*, 2000; *Versteeg and Birken*, 2001). The ultimate goal of this study is to map aquifer heterogeneity in a field setting in greater detail than what is captured through traditional hydrologic testing. The work presented in this paper is the first step toward this goal; the objectives for this phase of the project are to map tracer movement in greater detail than possible through traditional hydrologic testing, and to quantify the relation between bulk electrical resistivity and tracer concentration. Integrated data analysis is key to accurate analysis and characterization of the subsurface.

This work represents the first step in a larger effort toward incorporating ERT into the problem of aquifer property estimation. Hydraulic head, fluid concentration, and geophysical data were collected over a month-long tracer injection. The geophysical data reflect changes in electrical resistivity due to groundwater salinity changes from the presence of the tracer. The relations between tracer concentration and electrical resistivity can be made for co-located data, assuming some equivalence in scale. Electromagnetic (EM) induction logs and fluid conductivity measurements also were collected at the injection well to define the source shape in time and space. The reconstructed resistivity images can be converted to maps of tracer concentration by using a relation similar to Archie's Law (*Archie*, 1942). Ultimately, by using flow and transport simulations that include these data in the inversion process, detailed maps of hydraulic conductivity can be developed.

Site Background

The field research was conducted at the U. S. Geological Survey Toxic Substances Hydrology Program research site at the Massachusetts Military Reservation (MMR) in western Cape Cod, Massachusetts (Figure 1), during the summer of 2002. The MMR was a major installation for the U.S. Air Force from 1948 to 1973; groundwater beneath the base has been contaminated as the result of a number of activities, including a landfill, a sewage-treatment facility, and several chemical and fuel spills. The study area has been the focus of numerous research projects since the early 1980s, including studies in subsurface contaminant hydrology, microbiology, and inorganic and organic chemistry (*Morganwalp*, 1994).

The field site is composed of unconsolidated glacial deposits and outwash plains, consisting primarily of stratified sand and gravel (*Oldale*, 1969). At the site, the glacial outwash is about 35 meters (m) deep. The deposits generally become finer-grained with depth, and the outwash is underlain by finer, less permeable, sand, silt, and clay pro-glacial lake deposits (*Garabedian and LeBlanc*, 1989; *Masterson et al.*, 1997). The bedrock surface, beneath approximately 100 m of unconsolidated materials, is irregular and considered much less permeable than the overlying glacial deposits, and thus, the bottom of the regional groundwater system (*Garabedian and LeBlanc*, 1989; *Masterson and Barlow*, 1994). The unconsolidated deposits form an unconfined aquifer that serves as the region's only source of drinking water. Groundwater flows predominantly though the shallow parts of the aquifer, where coarse grained sediments exist. The estimated horizontal hydraulic conductivity ranges from 85 to 115 meters per day (m/d) in the medium to coarse sands and gravels, as characterized by numerous aquifer tests (*Masterson et al.*, 1997). The effective porosity is estimated to be 39 percent *(LeBlanc et al., 1991)* and the average groundwater velocity is 0.2-0.7 m/d (*LeBlanc*, 1984).

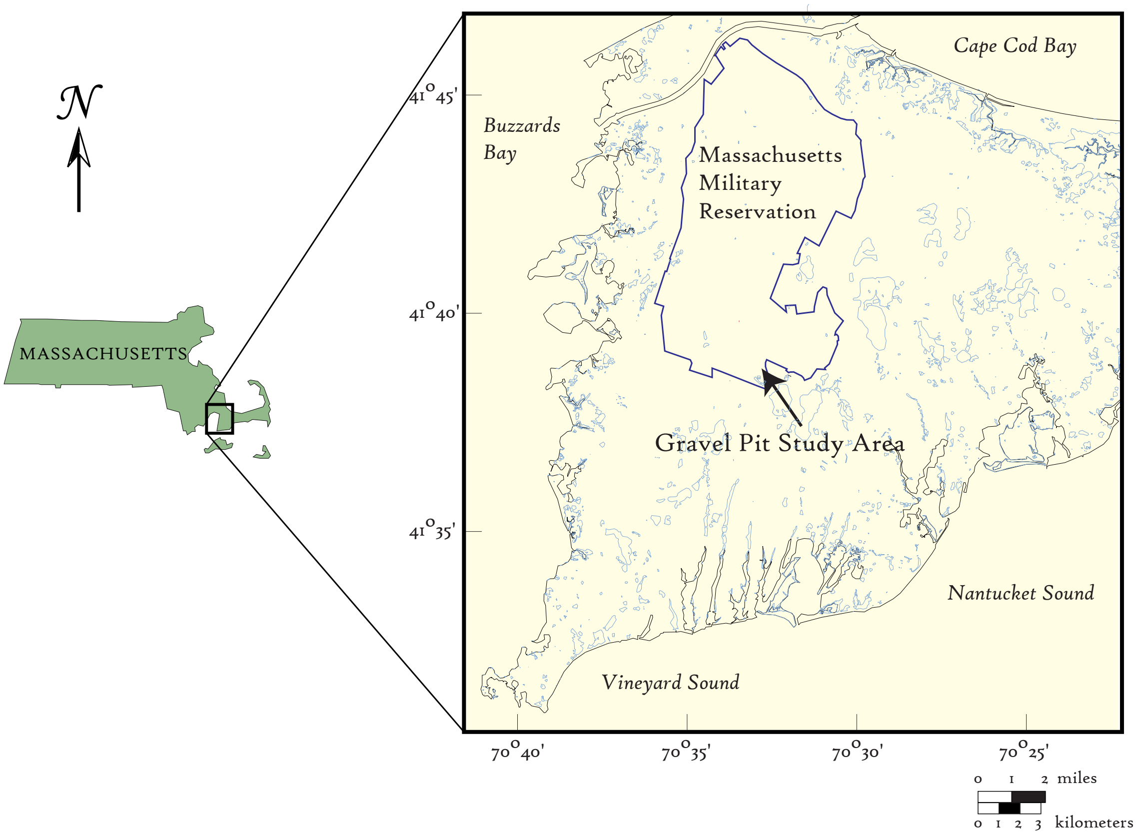

Figure 1. Location of field site at the Massachusetts Military Reservation, Cape Cod, Massachusetts.

Eight polyvinylchloride (PVC) wells and a multilevel sampler were installed at the MMR gravel pit test site for this experiment. The wells were aligned in two perpendicular planes (Figure 2). The four ERT wells (A-D), which are 33.0 m deep, and the injection and pumping wells (I and P), which are 26.5 m deep, are fully screened. The average depth to water during the test was 5.6 m. In the center of the well array is a multilevel sampler, which consists of 15 polyethylene tubes threaded through a PVC pipe at 1.8-m intervals below the water table to a depth of 31.1 m below land surface (Figure 3a). Two other wells, external to the central array, each had a single screen set from 29.9 to 31.1 m below land surface, and were used for fluid sampling.

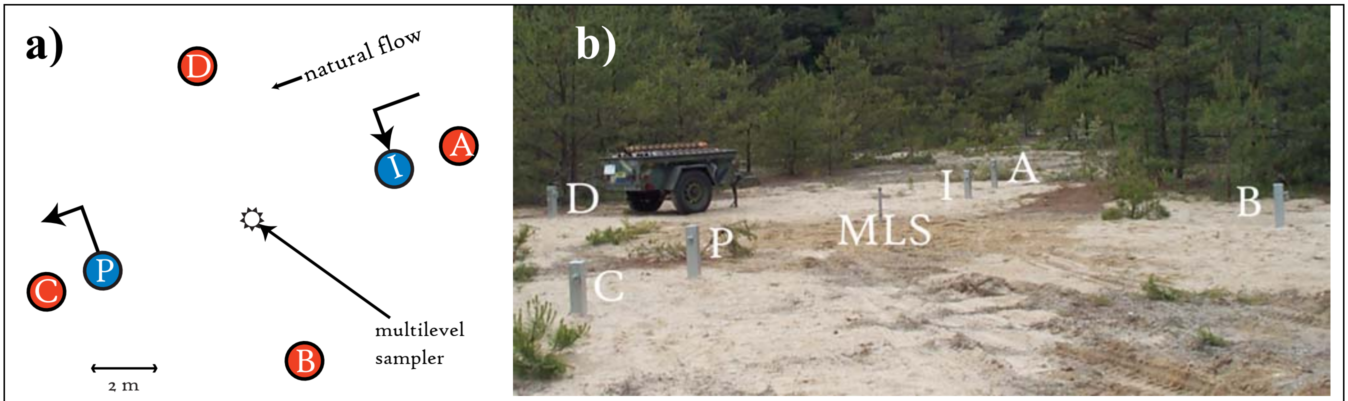

Figure 2. Geometry of wells in map view (a). Photo of field site (b). ERT wells are shown in red and are labeled A-D. Injection and pumping wells are blue and are labeled I and P, respectively. MLS is multilevel sampler.

Experiment Description

During the summer of 2002, data were collected in conjunction with a forced gradient tracer test. ERT was used to track the transport of an electrically conductive sodium-chloride tracer (NaCl) introduced over 9 hours during the two-well tracer test. Sixty 3-D data sets were collected between four corner-point wells for 20 days following the injection. The four ERT cables had 24 electrodes with a 1-m spacing, for a total of 96 electrodes. The electrodes used in the ERT survey were positioned beneath the water table. Flexible Kevlar well liners were inserted in the ERT wells after the electrode cables were emplaced to secure the cables against the casing in a manner that prevented salt water from entering the well and affecting the resistivity data (Figure 3b).

For each ERT data set, 3,200 unique resistance measurements were collected using a schedule that combined circulating dipole-dipole, bipole-bipole, and dipole-bipole measurements. Reciprocal measurements, as described in *Binley et al.* (1995), were collected for every quadripole, which were also stacked twice. A complete dataset was collected every 6 hours. High-resolution electrical images of the movement of a conductive saline tracer in 3-D were collected and analyzed to help delineate properties controlling the movement of the tracer.

The tracer injection line in the fully screened injection well extended from 7.0-22.2 m below land surface. Concentration data were measured at 15 ports in a multilevel sampler centrally located within the ERT array from depths of 5.4 to 31.1 m, at two partially screened sampling wells, and at the fully-screened production well every 2 hours. Heads were continuously measured at eight wells in and around the array. The regional temporal trend in the water table was monitored using wells outside the area of pumping influence.

A steady hydraulic gradient between the injection and pumping wells was established prior to saline injection using freshwater from a downgradient supply well. An injection rate of 13.3 liters per minute (L/min) and a pumping rate of 38.6 L/min were held steady for the duration of the test. After steady-state was achieved, 7,600 L of a 2-gram per liter (g/L) NaCl tracer solution (with a fluid conductivity of 4.7 milliSiemens per centimeter (mS/cm)) were injected into the injection well over a 9 hour period. The tracer concentration was chosen to maximize the change in measured resistivity while minimizing density-dependent flow under pumping conditions. EM induction logs were

Figure 3. Construction of multilevel sampler (a), insertion of Kevlar well liner (b).

collected immediately after the tracer injection, and freshwater injection from the supply well was restarted in the injection well. The pumping continued post-injection for 20 days.

Results and Discussion

Head and concentration measurements were collected during the tracer test to estimate hydraulic conductivity through inverse flow and transport modeling. Changes in head associated with pumping were minor. Pumping at 38.6 L/min in the extraction well caused a drop in head of 3 mm in a well 2 m away. The drop in the water level within the pumping well was 1.5 cm. Concentration measurements were collected 250 times over the course of the tracer test from the multilevel sampler, the pumping well, and the two partially-screened sampling wells. The deepest port in which a measurable change in concentration was observed in the multilevel sampler was 25.6 m (Figure 4). The port beneath, at 27.5 m, showed no tracer breakthrough. Some density-induced sinking may exist; although the tracer was injected through a porous soaker hose 22.2 m in length, the wellbore itself was fully screened to a depth of 26.5 m. EM induction logs and fluid conductivity measurements in the injection well post-tracer show tracer entering the formation largely between the water table and a depth of ~22 m; however some tracer appears to have entered into the formation at slightly greater depths (Figure 5). The tracer, observed to 27.5 m in the multilevel sampler, may have sunk as a combination of the density effects in the formation and in the injection well itself, leading to a slow injection below the bottom of the soaker hose.

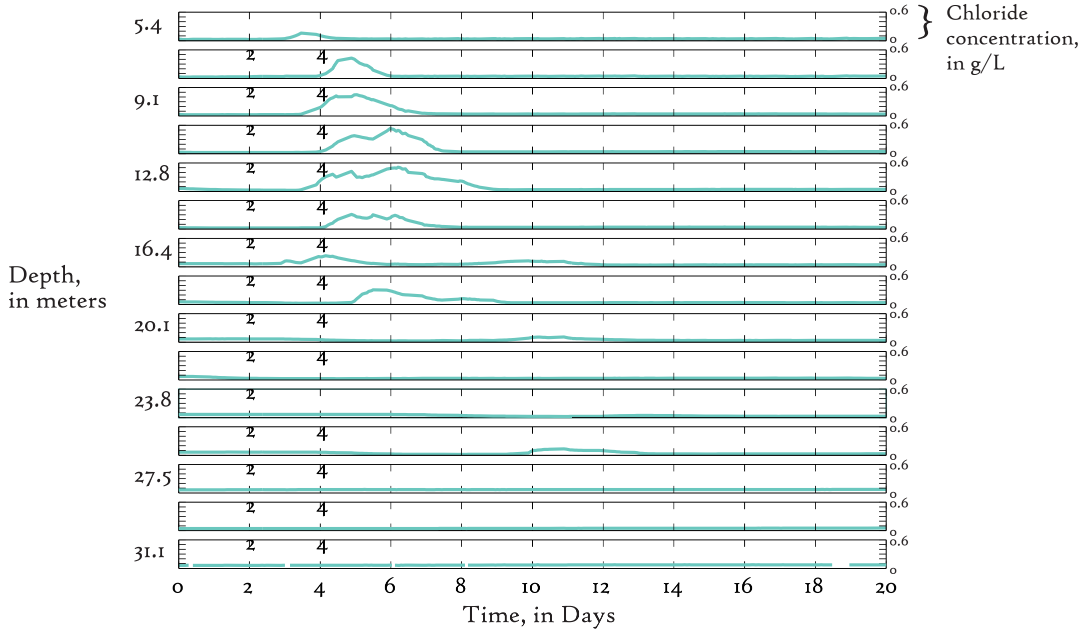

Figure 4. Measured fluid concentration, with depth and time, at the central multilevel sampler. Maximum value of 0.54 g/L occurs on Day 6 at 10.9 m below land surface.

The ERT data from this field experiment have an average reciprocal error of less than 1 percent. The interior of the site was 10 x 14 x 30 m and was discretized into approximately 26,000 cells in 3-D with a cell size of 0.5 m on a side. A dataset prior to tracer injection was used as the background electrical resistivity model. The data shown here are differenced absolute inversions rather than difference inversions (*Daily and Owen*, 1991; *LaBrecque et al.*, 2000). Undoubtedly, difference inversions would appear somewhat different because systematic errors from the field and discretization errors in the forward modeling tend to cancel out.

The fluid conductivity in the supply well used for flushing the tracer was lower than that on site (0.024 mS/cm compared to 0.15 mS/cm), and shows up in the electrical data as a resistive plume ahead of and beneath the tracer. Qualitatively, the percent differences in electrical resistivity associated with the arrival of the tracer match the tracer concentration measurements fairly well, both in time and space (Figure 6). The match is poorer for the tail of the tracer because the fluid measurements only indicate mobile tracer, whereas the ERT measures mobile and immobile salts. Changes in electrical resistivity associated with the injection of the NaCl tracer are on the order of 15 percent. Quantitatively, the measured changes in electrical resistivity match co-located changes in tracer concentration, as inferred from measured fluid resistivity (Figure 7). The shapes of the bulk resistivity and concentration curves are similar. An increase in tracer concentration, or a positive percent difference, correlates closely with a decrease in resistivity, or a negative percent difference. Thus, the electrical resistivity data can be converted to tracer concentrations, assuming a linear relation between tracer concentration and fluid resistivity. The ERT data can therefore provide concentration data at scales that cannot otherwise be attained in the field from typical sampling, and be used to constrain inverse flow and transport models. ERT is not a perfect surrogate, however, the concentration measurements collected at the multilevel sampler indicate greater spatial variability than the co-located ERT estimates. The resolution of an electrical measurement is difficult to quantify (*Daily and Ramirez*, 1995). However, the support volume of an ERT measurement is certainly larger than that of a "point" measurement of tracer concentration. A 60-milliliter fluid sample, assuming a porosity of 0.39, samples a volume slightly larger than 5 cm on a side. The ERT will not be able to detect such detail, so the inclusion of hydrologic measurements into combined inversion is necessary to improve aquifer property estimation. However, the general shape of the tracer cloud is delineated in the ERT data, and these data will largely control the estimation of hydraulic conductivity, as the direct measurements are spatially sparse.

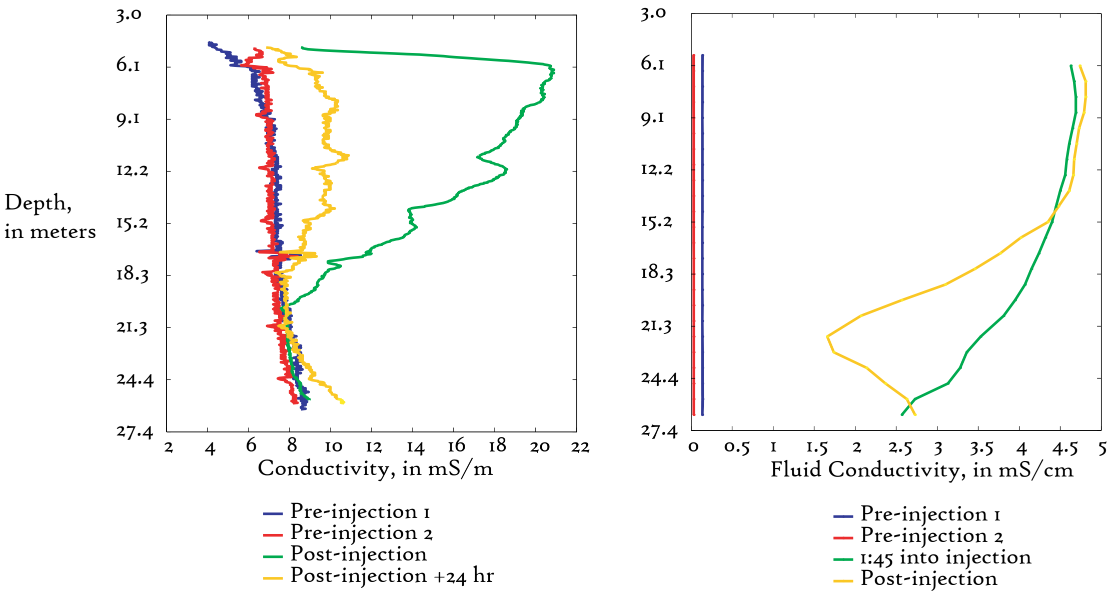

Figure 5. EM induction logs and fluid conductivity measurements collected in the injection well before and after tracer injection.

Conclusions

ERT allows for high-resolution imaging of the flow and transport of a conductive tracer. The arrival time of the tracer estimated using electrical methods matches well with direct measurements of tracer concentration at the multilevel sampler at the center of the ERT array. Estimates of tracer concentrations can be made using relations between the change in electrical and fluid resistivities measured in the field. The results of the ERT inversions approximate direct measurements of concentration, although they are not able to capture detail seen in the fluid measurements. Quantifying the relation between fluid concentration and bulk electrical resistivity in the field is key for estimating of hydraulic conductivities at this field site.

Future plans include the implementation of an inversion methodology for identifying fine-scale hydraulic conductivity values of the subsurface by incorporating tracer, head, and electrical resistivity data.

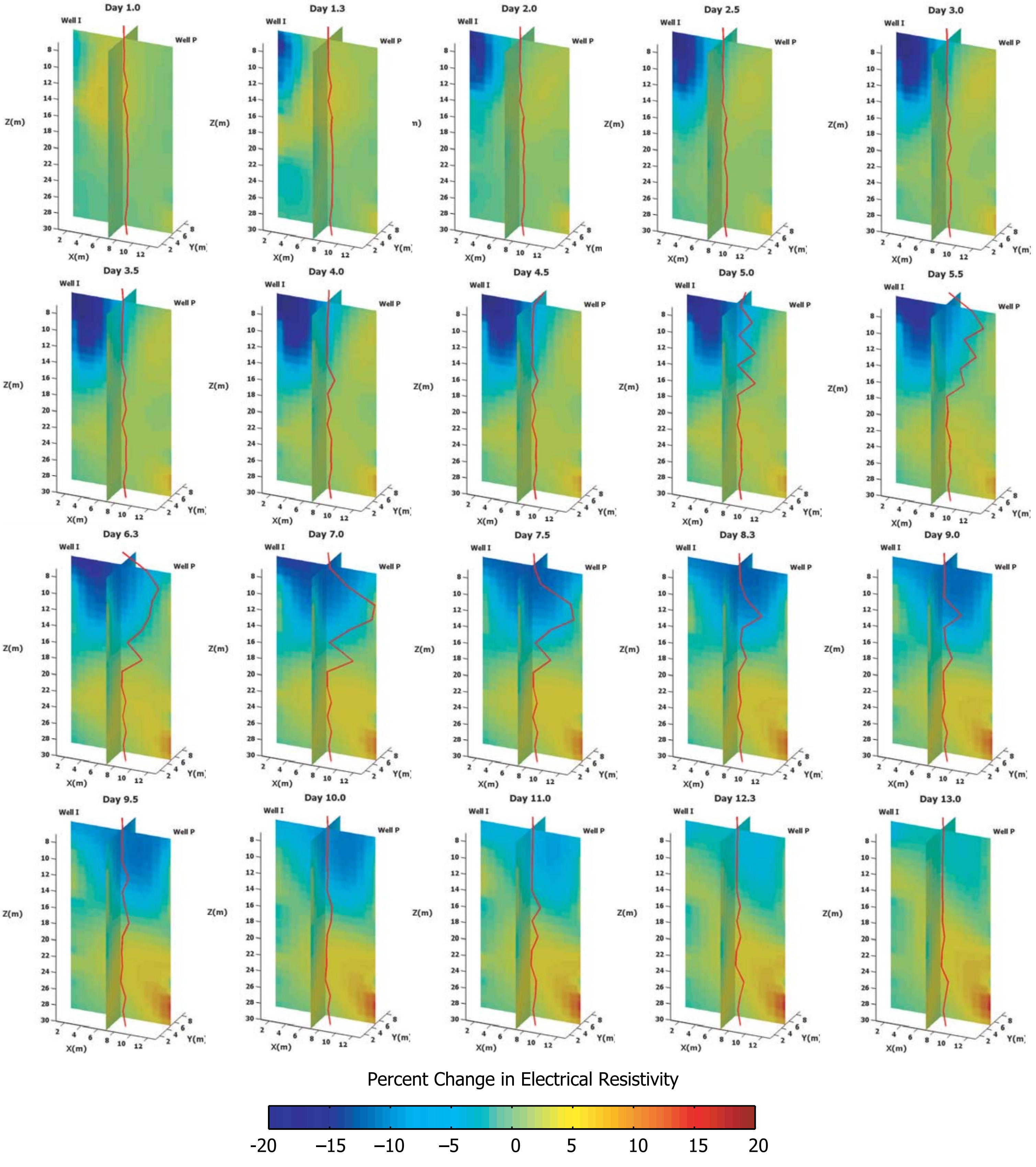

Figure 6. Selected slices from differenced 3-D ERT inversions. Negative percent change in resistivity (blue) indicates the presence of electrically conductive tracer. Overlain on inversions are tracer concentration measurements collected at central multilevel sampler (scale: 0-0.6 g/L).

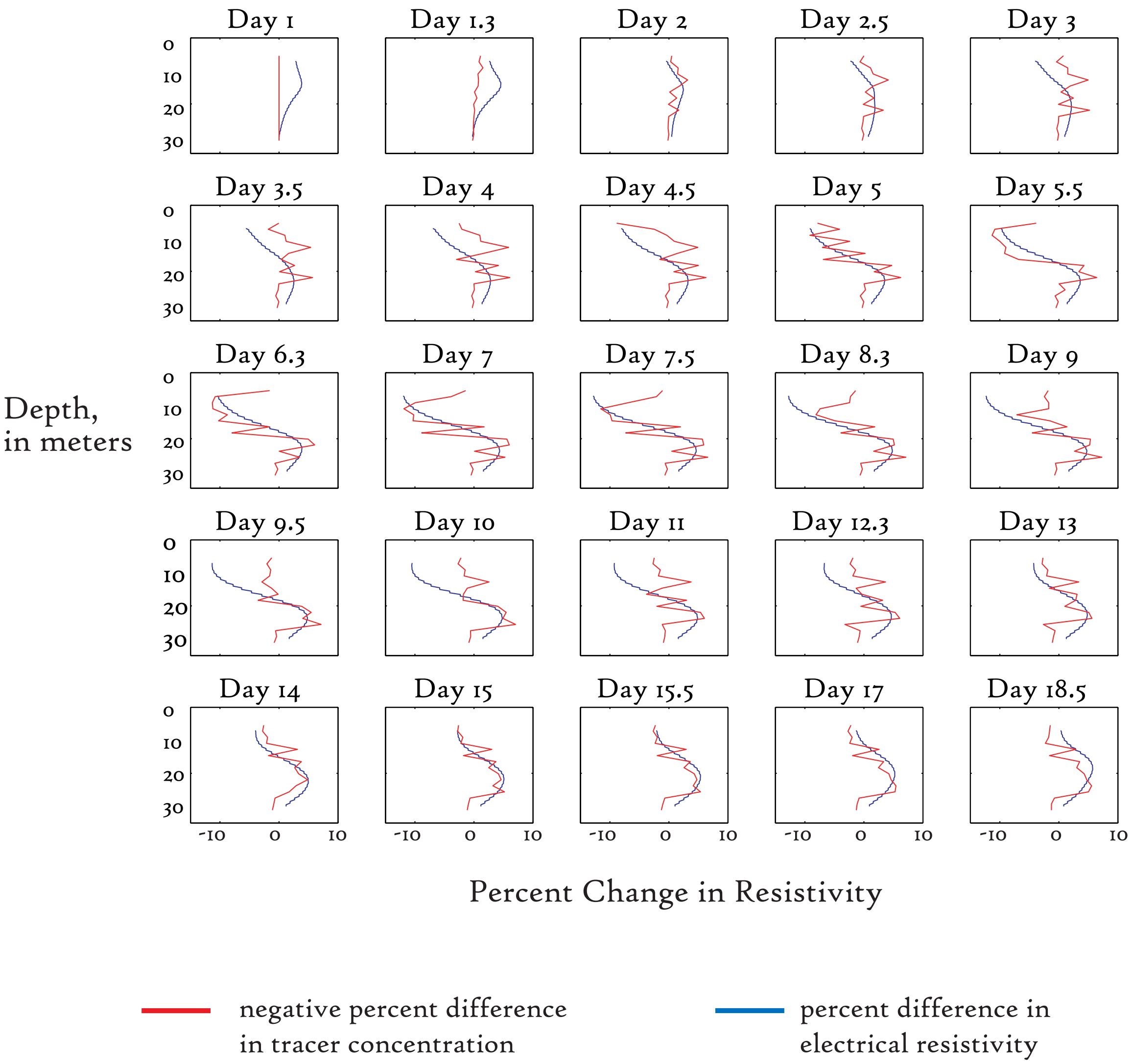

Figure 7. Percent difference in electrical resistivity and tracer concentration, as inferred from fluid resistivity measurements, from the central multilevel sampler. Tracer concentration is plotted as negative percent difference to show correlation.

Acknowledgments

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