CONSTRAINING A 2D DENSITY-DEPENDENT SALTWATER INTRUSION MODEL USING ELECTRICAL IMAGING DATA

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ABSTRACT

We propose an innovative methodology to calibrate a saltwater intrusion model using electrical resistivity tomography (ERT). A qualitative, preliminary assessment of this methodology was performed using numerical experiments. For this purpose, we conducted steady state simulations of a vertical 2D saltwater intrusion in an unconfined coastal aquifer of simple geometry with homogeneous and anisotropic hydraulic properties. Although the intrusion model was synthetic, the geometry and the applied hydrological parameters were based on data from the coastal aquifer of the Andarax River Basin, SE Spain. ERT data acquisition of the intruding saltwater was then simulated, using one surface line and two boreholes, which also mimic a future permanent ERT installation in the aquifer. The surface line is 900 m long and has an electrode spacing of 10 m, whereas the borehole is 90 m deep with 5 m electrode spacing. The results of the preliminary assessment revealed that standard dipole-dipole ERT imaging has a clear potential of monitoring the saltwater intrusion front with good accuracy over a large lateral distance. Further research is needed for understanding the relation between system design and ERT data quality, but also its usefulness in parameter identification in modelling saltwater intrusion processes.

1. INTRODUCTION

In groundwater modeling, calibration is one of the critical aspects that determine the model's reliability and applicability in terms of e.g. system understanding, groundwater quality predictions, and general use in water resources context. The result of a groundwater model calibration is determined by different factors, where both data quantity and quality are of crucial importance.

The focus of this study is to assess the possibility of using electrical resistivity tomography (ERT) to calibrate a density-dependent saltwater intrusion model. Compared to conventional measurement techniques which usually give relatively few point information (e.g. depth specific monitoring wells), ERT provides spatial information on the resistivity distribution on a much larger scale and thereby enabling simultaneous monitoring of the intrusion front over large distances. In theory this implies that the ERT method has the potential of supplying much more spatial data on the concentration distribution compared to well logging methods. Until now, application of geophysical methods in saltwater intrusion studies has mostly been concentrated on mapping and delineating the location of the intruding saltwater, often in combination with geochemical data (Albouy et al., 2001;Ebraheem et al., 1997;Wilson et al., 2006).

Inverse calibration of coupled flow and transport models started few decades ago (Cirpka and Kitanidis, 2000;Medina and Carrera, 1996;Sun et al., 1995;Wagner and Gorelick, 1987). Despite the fact that various tools have been developed that can solve the inverse problem of density-dependent flow, e.g. PEST (Doherty, 2004) and UCODE (Poeter et al., 2005), there is still limited amount of literature on the subject of trial-and-error and/or inverse calibration of saltwater intrusion. One of the reasons being insufficient data, i.e., long time series of both groundwater level and concentrations are needed for the inverse parameter identification process. Iribar et al., (1997), obtained acceptable results by combining long-term transient head data and concentration data for automatic calibration of seawater intrusion in a confined delta aquifer. In that study, density effects were neglected. Van Meir and Lebbe (2005), developed a tool for simultaneous identification of both hydraulic and solute transport parameters based on pumping and upconing test of saltwater where density effects were included. Satisfactory results were obtained.

To our knowledge, there are few studies which use geophysical data for model calibration of density-dependent saltwater flow. Lebbe, (1999), calibrated a density-dependent flow and solute transport model in a shallow shore environment using head measurements and borehole resistivity logs. The procedure included flow and solute transport parameters as well as parameters of the resistivity-salinity relation. Calibration was conducted on a realistic synthetic model and, subsequently, on a model of the real field site. The study illustrated that it was possible to identify horizontal and vertical hydraulic conductivities, longitudinal and transverse dispersivities, and effective porosity.

The use of ERT implies additional efforts. Indeed, more spatial information may be obtained, yielding more accurate calibration and mapping of eventual anomalies (e.g. pumping or preferential flow), on the other hand, ERT is an active research area where complex issues such as resolution, sensitivity and petrophysical relationships have to be quantified to assess the reliability of ERT imaging. However, these latter issues are not in the scope of this paper but need to be addressed (Kemna et al., 2006).

The aim of this paper is to (1) introduce the methodology that will be applied to assess the potential of using standard ERT for calibrating a saltwater intrusion model, and (2) to conduct a preliminary assessment of the usefulness of the ERT in imaging the saltwater intrusion process and its potential of being applied to calibrate a saltwater intrusion model.

2. METHOD

Figure 1 outlines the methodology applied to assess the applicability of ERT to calibrate a saltwater intrusion model.

The illustrated method includes the following steps:

Step 1: Set-up a 2D vertical density-dependent saltwater intrusion model and define the “true” flow and solute transport parameters (hydraulic conductivities, porosity, dispersivity etc.). When available, model parameter values were based on hydrological parameters from the Andarax coastal aquifer, otherwise realistic values were applied.

Step 2 & 3: A forward simulation of the intrusion process, yielding the true salinity distribution. The simulation can either be steady state or transient.

Step 4: A petrophysical relationship is defined to relate groundwater salinity to bulk sediment conductivity (salinity concentration ⇒ water electrical conductivity ⇒ bulk electrical conductivity).

Step 5: Simulation of ERT data acquisition with both standard (dipole-dipole) borehole and surface arrays. Different array configurations can be tested in order to investigate which configuration applies best to the current shape of the intrusion front.

Step 6: Realistic levels of noise are added.

Step 7: Inversion of ERT data is performed. The resistivity distribution from ERT is converted to salinity distribution using the same petrophysical model as in step 4. The obtained salinity distribution is used as input data for the calibration procedure.

Step 8 & 9: Calibration of a saltwater intrusion model using the ERT derived salinity distribution. Depending on the objectives, as well as a priori information, different flow and transport parameters may be chosen for the calibration procedure. Calibration of both steady state and transient models will be undertaken.

Step 10 Evaluation of the performance of using ERT data for intrusion model calibration:

a) Initial assessment of the ERT data quality is conducted by comparing the true salinity distribution to the ERT derived salinity distribution. How well does it reproduce the true distribution? Where is there discrepancy and why?
b) Comparison of calibrated parameter values and true parameter values.

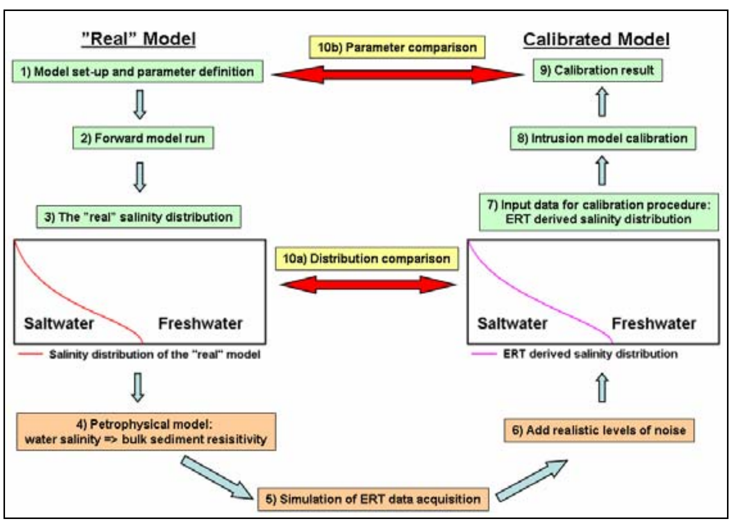

FIGURE 1. A flow diagram illustrating the methodology.
Steps 1 – 3 and 7 – 9 (green) involve flow and transport modeling,
steps 4 – 6 (orange) ERT acquisition modeling and step 10 (yellow) is results.

3. NUMERICAL MODELING METHOD

To simulate saltwater intrusion a vertical 2D density-dependent saltwater intrusion model was established using the finite-difference heat and solute transport code, HST3D (Kipp, 1987). ERT data acquisition and inversion was done using a 2.5D finite-element code developed by (Kemna, 2000).

3.1 Discretization of the saltwater intrusion model

Since the aim of this study is to calibrate the dispersivities and subsequently to evaluate the performance by comparing the true dispersivities to the calibrated ones, it is evident that minimizing numerical inaccuracies of the finite-difference code is of crucial importance. Numerical stability was obtained using a centered-in-space and fully implicit-in-time difference scheme with a horizontal grid spacing of 10 meters and vertical spacing of 1 meter. This scheme eliminates numerical dispersion caused by space differencing, but not by time differencing. In order to evaluate the importance of time differencing related numerical dispersion, different time step sizes where tested. No significant numerical dispersion was observed with a time step size of up to 20 days.

3.2 Boundary conditions and hydrological parameters

A cross sectional model was established to simulate saltwater intrusion. The model domain was rectangular with a length of 3000 m and a depth of 90 m (Figure 2). The flow system was defined by two fixed pressure (Dirichlet) boundaries. A hydrostatic pressure distribution equivalent to a 0 m and 2.5 m was applied at the sea- and upstream boundary, respectively. The bottom boundary was no flow and the top was a free-surface (water table) boundary. For the solute transport, associated concentrations as scaled mass fractions were used for both the sea- and upstream boundary, with a value of 1 and 0, respectively. The system parameters are listed in Table 1.

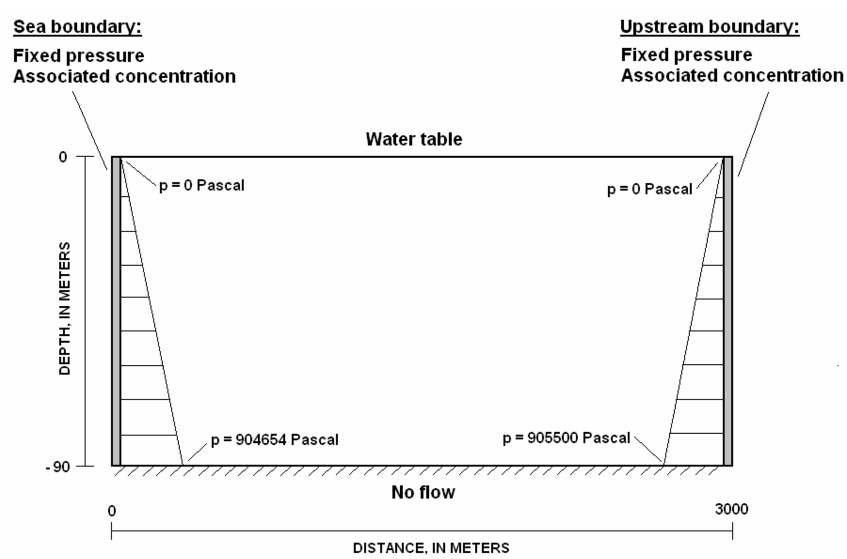

FIGURE 2. Domain geometry and boundary conditions for the synthetic saltwater intrusion model (not to scale).

In order to obtain steady state conditions the simulation ran for 50000 days. With an initial condition of freshwater in the whole domain, the saltwater starts intruding from the sea boundary in the form of a wedge in the lower part of the aquifer (Figure 3). When saltwater meets the freshwater from the upstream boundary, the two fluids mix and a transition (mixture) zone forms between them. The shape of the intruding wedge and the thickness of the transition zone is governed by the hydraulic conductivity and the dispersivity values. Ultimately a dynamic equilibrium is obtained when the amount of salt entering through the lower portion of the sea boundary equals the salt leaving through the upper part of the sea boundary.

TABLE 1. System parameters.

Parameter	Value
Permeability, k	1.2e-10 m^2 (≈ 100 m/d)
K_h / K_v	100
Effective porosity, ε	0.30
Horizontal dispersivity, α_L	10 m
Transversal dispersivity, α_v	0.5 m
Freshwater density, ρ_f	1000 kg/m^3
Seawater density, ρ_s	1025 kg/m^3
Seawater mass fraction, w	0.0357
Diffusion coefficient, D_m	0 m^2/s
Viscosity, μ	1.0e-3 kg/m*s
Fluid compressibility, β_p	0 kg/m*s^2
Matrix compressibility	0 kg/m*s^2

3.3 ERT data acquisition modelling

The electrode layout (Figure 3) was chosen in order to fit a future permanent installation in the framework of the European project ALERT. This layout consists of a 1 km surface line and two approximately 90 m deep boreholes. The surface line is equipped with electrodes every 10 m whereas the borehole electrodes have a 5 m vertical spacing, allowing better resolution at depth. The chosen measurement protocol is a standard skip 1 dipole-dipole. Simulated resistances exhibiting very low values ($<10^{-4}$ Ohm), corresponding to very large geometric factors, were disregarded in order to simulate a minimum voltage that can be reliably determined by typical ERT instruments, here e.g., 0.5 mV for a current of 1 A (Vanderborght et al., 2005). This resulted in approximately 2400 transfer resistance measurements. For this preliminary study, no noise was added to the data.

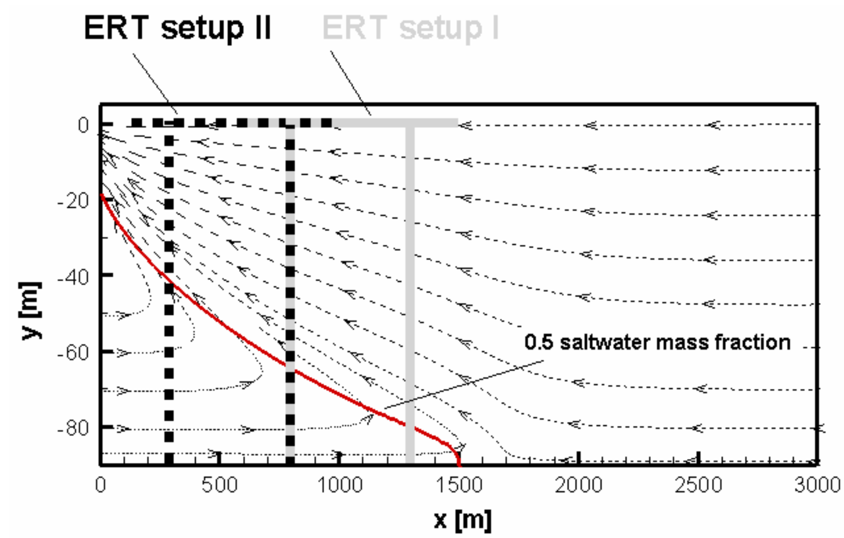

FIGURE 3. Location of surface and borehole electrodes for ERT setup I & II. Location of 0.5 saltwater mass fractions at steady state and associated flow lines.

In ERT, the spatial distribution of bulk electrical conductivity, *sb*, is reconstructed from a data set of transfer resistance measurements. This involves the discretization of the *sb* distribution in a finite element or finite difference grid, forward modeling of the data set for a given sb distribution, and the minimization of an objective function (Daily et al., 1992). Here, the inversion scheme was done according to Occam's razor (plurality should not be postulated without necessity). Regularization is performed by seeking the 'smoothest' model subject to fitting the data. This is accomplished by formulating the inverse problem as an optimization problem and incorporating the smoothness constraint within the associated objective function (e.g. Kemna, 2000).

4. RESULTS AND DISCUSSION

Two electrical model setups were tried for the same forward intrusion model, ERT setup I & II (Figure 3). The difference between the setups was the location of the electrode arrays relative to the sea boundary. Comparison of the ERT results and the intrusion model results is illustrated in Figures 4 and 5. In Figure 4, when the borehole arrays are located at 800 m and 1300m, and the surface array at 600 m to 1500 m from the sea boundary, it is evident that the ERT image is not able to detect the transition zone very well, except for the upper most part of it (i.e. mass fraction of 0.1). This reflects lower sensitivity of the ERT image with depth as well as lower resistivity in-between the borehole arrays. By locating the electrode arrays closer to the sea boundary, the boreholes at 300 m and 800 m, and the surface line at 100 m to 1000 m, enables a larger part of the transition zone to be captured (Figure 5). The reason for this is because the saltwater is located higher up in the aquifer, compared with Figure 4. Figure 5 illustrates that the ERT image is able to detect the transition zone up to a mass fraction of 0.4 with very high precision over the whole distance between the borehole arrays (i.e. 500 meters). Data of this quality, with such an extensive lateral extension, gives very valuable information about the shape, position and width of the transition zone, which eventually can be related to groundwater flow and transport parameters (through inverse modeling).

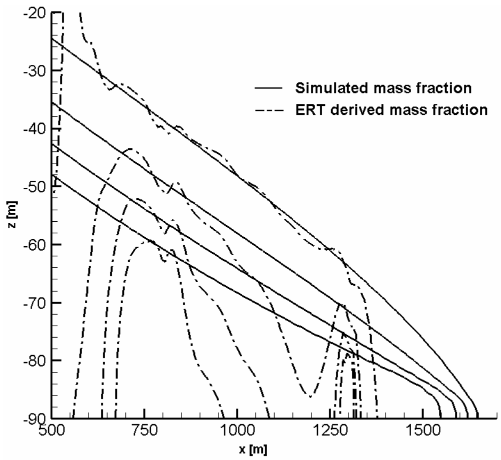

FIGURE 4. Comparison of simulated and ERT mass fractions, using ERT setup I as illustrated in Figure 3.

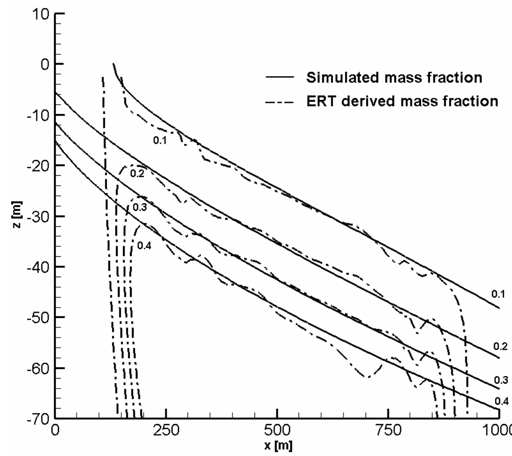

FIGURE 5. Comparison of simulated and ERT mass fractions, using ERT setup II as illustrated in Figure 3.

The results also illustrate that the quality and consequently the applicability of the data for calibration purposes, is highly dependent on ERT system parameters e.g. electrode array location. In order to assess the applicability as well as the limits of the method in a saltwater intrusion context, the importance and the effect of ERT system parameters has to be systematically studied. Future and ongoing studies are therefore focusing on the assessment of ERT in imaging and characterizing saltwater intrusion by applying e.g. different ERT system designs and measurement schedules. These studies are the basis for obtaining reliable ERT derived mass fraction maps which can be used in calibration of a saltwater intrusion models.

5. CONCLUSIONS AND PERSPECTIVES

An initial evaluation of ERT in imaging saltwater intrusion was conducted using numerical experiments. Preliminary results indicate that ERT images have the potential to calibrate saltwater intrusion models. In particular, mass fraction derived from ERT resistivity maps were found to match closely the one predicted by the density driven flow and transport models. However, the use of such images require their appraisal, in terms of resolution (Day-Lewis and Lane, 2004) and reliability of petrophysical relationships (Day-Lewis et al., 2004). Future work will include study of transient saltwater intrusion, yielding time-lapse electrical resistivity data and inverse calibration of hydrological parameters based on simplified models or transfer functions.

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References

Albouy, Y., P. Andrieux, G. Rakotondrasoa, M. Ritz, M. Descloitres, J. L. Join and E. Rasolomanana, Mapping Coastal Aquifers by Joint Inversion of DC and TEM Soundings-Three Case Histories, *Ground Water, 39*(1), 87-97, 2001.

Cirpka, O. A. and P. K. Kitanidis, Sensitivity of temporal moments calculated by the adjoint-state method and joint inversing of head and tracer data, *Advances in Water Resources, 24*(1), 89-103, 2000.

Daily, W., A. Ramirez, D. Labrecque and J. Nitao, Electrical-Resistivity Tomography of Vadose Water-Movement, *Water Resources Research, 28*(5), 1429-1442, 1992.

Day-Lewis, F. D. and J. W. Lane, Assessing the resolution-dependent utility of tomograms for geostatistics, *Geophysical Research Letters, 31*(7), 2004.

Day-Lewis, F. D., Singha, Kamini and A. M. Binley, On the pitflls and limitations of applying petrophysical models to tomograms - examples in cross-borehole radar and electrical resistivity tomography: EOS Trans., AGU, *Jt. Assem. Suppl. , Abstract NS13A-03, 85*(17), 2004.

Doherty, J., PEST: Model-Independent Parameter Estimation. User Manual: 5th Edition., *Watermark Computing, 336 pp,* 2004.

Ebraheem, A. A., M. M. Senosy and K. A. Dahab, Geoelectrical and Hydrogeochemical Studies for Delineating Ground-Water Contamination Due to Salt-Water Intrusion in the Northern Part of the Nile Delta, Egypt, *Ground Water, 35*(2), 216-222, 1997.

Iribar, V., J. Carrera, E. Custodio and A. Medina, Inverse modelling of seawater intrusion in the Llobregat delta deep aquifer, *Journal of Hydrology, 198*(1-4), 226-244, 1997.

Kemna, A., Tomographic inversion of complex resistivity - theory and application, Ph.D. thesis, *Bochum University, Germany (also: Der Andere Verlag, Osnabrück),* 2000.

Kemna, A., F. Nguyen, A. Antonsson, P. Engesgaard and P. Tsourlos, Characterization of saltwater intrusion using electrical imaging: a numericl simulation study (abstract), *Abstract for the 1st SWIM-SWICA Meeting (19th Salt Water Intrusion Meeting, 3rd Salt Water Intrusion in Coastal Aquifers), Cagliari - Chia Laguna Italy September 24 - 29,* 2006.

Kipp, K., HST3D, A computer code for simulation of heat and solute transport in three-dimensional ground-water flow systems., *U. S. Geol. Surv. Water-Resour. Inv. Report 86-4095, 517 pp,* 1987.

Lebbe, L., Parameter identification in fresh-saltwater flow based on borehole resistivities and freshwater head data, *Advances in Water Resources, 22*(8), 791-806, 1999.

Medina, A. and J. Carrera, Coupled estimation of flow and solute transport parameters, *Water Resources Research, 32*(10), 3063-3076, 1996.

Poeter, E. P., M. C. Hill, E. R. Banta, S. Mehl and S. Christensen, UCODE_2005 and Six Other Computer Codes for Universal Sensitivity Analysis, Calibration, and Uncertainty Evaluation, *U. S. Geological Survey Techniques and Methods 6-A11, 283p,* 2005.

Sun, N. Z., M. C. Jeng and W. W. G. Yeh, A Proposed Geological Parameterization Method for Parameter-Identification in 3-Dimensional Groundwater Modeling, *Water Resources Research, 31*(1), 89-102, 1995.

Van Meir, N. and L. Lebbe, Parameter identification for axi-symmetric density-dependent groundwater flow based on drawdown and concentration data, *Journal of Hydrology, 309*(1-4), 167-177, 2005.

Vanderborght, J., A. Kemna, H. Hardelauf and H. Vereecken, Potential of electrical resistivity tomography to infer aquifer transport characteristics from tracer studies: A synthetic case study, *Water Resources Research, 41*(6), 2005.

Wagner, B. J. and S. M. Gorelick, Optimal Groundwater Quality Management Under Parameter Uncertainty, *Water Resources Research, 23*(7), 1162-1174, 1987.

Wilson, S. R., M. Ingham and J. A. McConchie, The applicability of earth resistivity methods for saline interface definition, *Journal of Hydrology, 316*(1-4), 301-312, 2006.