Joint and sequential inversion of geophysical and hydrogeological data to characterize seawater intrusion models

Jean Beaujean[1], Frederic Nguyen[1], Andreas Kemna[2] and Peter Engensgaard[3]

[1] ArGEnco Department, University of Liège, Liège, Belgium
[2] Department of Geodynamics and Geophysics, University of Bonn, Bonn, Germany
[3] Department of Geography and Geology, University of Copenhagen, Copenhagen, Danemark

ABSTRACT

The integrated water resource management problems require studying efficiently seawater intrusion at local and regional scale and identifying in real time the seawater/freshwater interface dynamic. Hydrogeological modeling is widely used to predict seawater intrusion if additional natural or man-made factors are modified. These models are currently calibrated using measured heads and salt mass fractions in boreholes, which generally result in sparse data coverage. Within this scope, non to minimally invasive geophysical techniques like electrical resistivity tomography (ERT) or time-domain electromagnetic method are becoming increasingly popular, given their relatively greater spatial horizontal resolution compared to borehole observations. We present a comparison between both a sequential and joint approach to calibrate seawater intrusion models using ERT. The former consists of constraining hydrogeological parameters using ERT derived parameters and relies on sequential inversions of the geophysical and hydrogeological data using a given petrophysical relationship. The second approach in based on simultaneous inversion of petrophysical and hydrogeological data using electrical resistance data as data. It is performed by coupling an inversion code with two hydrogeological and geophysical modeling codes through a petrophysical conversion. This investigation was performed on a density-dependent flow and transport numerical (three/two-dimensional) simulation study from complex and realistic heterogeneous models. In the sequential approach, the simulations showed that only the shallow salt concentration of the seawater/freshwater transition zone could be recovered for different time-lapse, due to poorly resolved regions in depth. The capability of image appraisal indicators (cumulative sensitivity and resolution) has been analyzed to emphasize the discrepancy between the targeted and imaged parameter values. On the other hand, the preliminary coupled inversion avoids the regularization bias introduced by ERT and addresses the non-stationarity of the petrophysical relationship.

INTRODUCTION

The management of coastal aquifers relies on the optimisation of the exploitation of groundwater resources and the control over its consequence (seawater intrusion). Sustainable management must rely on robust models and real-time observations to predict changes if additional natural or man-made factors are modified [*Bear et al.*, 1999]. This requires to understand the seawater/freshwater interface dynamics and to characterize the system accurately. Such predictions are generally based on hydrogeological models calibrated on measured heads and salt mass fractions in boreholes, which generally result in sparse data coverage [*Faust et al.*, 1989; *Hirasaki*, 1982; *Melloul and Goldenberg*, 1997; *Warwick et al.*, 1991; *Wong*, 1988]. In this context, non to minimally invasive geophysical techniques like electrical resistivity tomography or time-domain electromagnetic method (TDEM) are becoming increasingly popular [*Balia et al.*, 2003; *Cheng and Ouazar*, 2004; *Kirsch*, 2006; *Melloul and Goldenberg*, 1997; *Nguyen et al.*, 2007; *Nguyen et al.*, 2009], given their relatively greater spatial horizontal resolution compared to borehole observations, and the high sensitivity of these methods to dissolved salt in groundwater. We here present a numerical comparison between a sequential and joint approach to calibrate seawater intrusion models using ERT. Complex systems and transient regimes are simulated in order to reflect realistic conditions where the methodology could be applied. For these conditions, the limitations of geophysical tools are also discussed depending on their final use (model calibration, delineation of seawater intrusion, monitoring) using resolution indicators.

Geophysical images are being increasingly used to calibrate flow and transport processes. A recent example in the framework of seawater intrusion studies is the work of Antonsson *et al*. [2006] and Nguyen *et al*. [2009] who demonstrated inverse calibration of a homogeneous hydrogeological model based on inverted geophysical parameters and known petrophysical law (figure 1). The approach is also known as a sequential inversion and is based on a multi step process in which predicted mass fraction isolines are calibrated against ERT-derived mass fraction isoline using a model-independent parameter estimation optimizer such as PEST [*Doherty*, 2004]. A similar approach was also proposed by [*Lebbe*, 1999] using EM induction log measurements. In Nguyen *et al*. [2009], the ERT-derived data are selected with respect to a cumulative sensitivity threshold. The latter is computed based on the observation that ERT-recovered mass fraction values are deviating from the trues ones as a function of cumulative sensitivity. The so-called sensitivity-filtered mass fraction image is then used as data in the PEST objective function (figure 1).

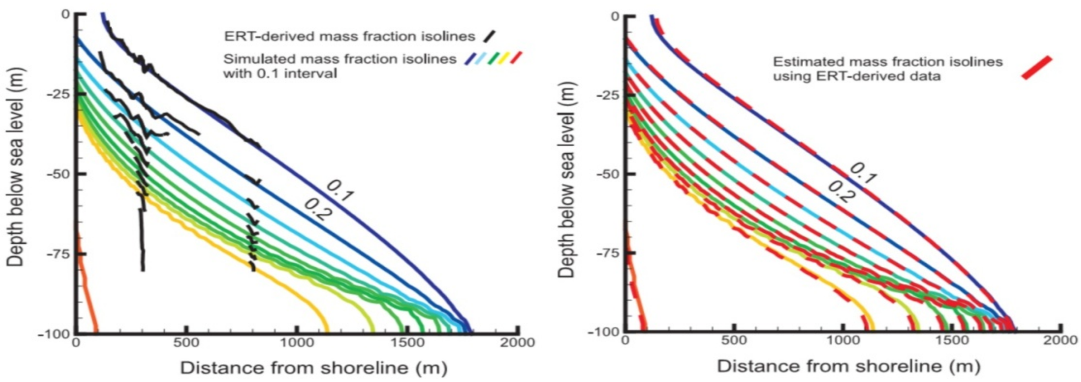

Figure 1 Simulated mass fraction isolines of a true 2D SWI model versus ERT-derived ones for the models (left) Simulated mass fraction isolines from the estimated model using the ERT-derived data for the models (right) (from Nguyen *et al*. [2009]).

Other integration techniques (i.e. joint/simultaneous inversion) of geophysical data into hydrogeological model are still under development and are rarely used [*Hinnell et al.*, 2010; *Kowalsky et al.*, 2006], in particular for calibration of density-dependent flow and transport. This approach in based on simultaneous inversion of petrophysical and hydrogeological data using electrical resistance data as data. It is performed by coupling an inversion code with two modeling codes, a hydrogeological one and a geophysical one through a petrophysical conversion. This kind of inversion only requires one step to proceed in opposition to sequential inversion and so should strongly reduce error propagation in the hydrogeological model by avoiding regularization. In addition, petrophysical parameters are part of the inversion procedure and do not need to be imposed.

NUMERICAL MODELS

Two density-dependent flow and transport (2D/3D) numerical models have been developed within HydroGeoSphere: the first one is derived from a well-known seawater intrusion Huyakorn's problem in homogeneous and transient conditions with pumping well (figure 3) whereas the second one is a more complex and realistic heterogeneous hydrogeological model in transient. The latter is based on stochastic simulation of petrophysical properties (SGeMS) and is closed to what happens in coastal aquifer with clay lenses which mimic a realistic coastal groundwater system (figure 2).

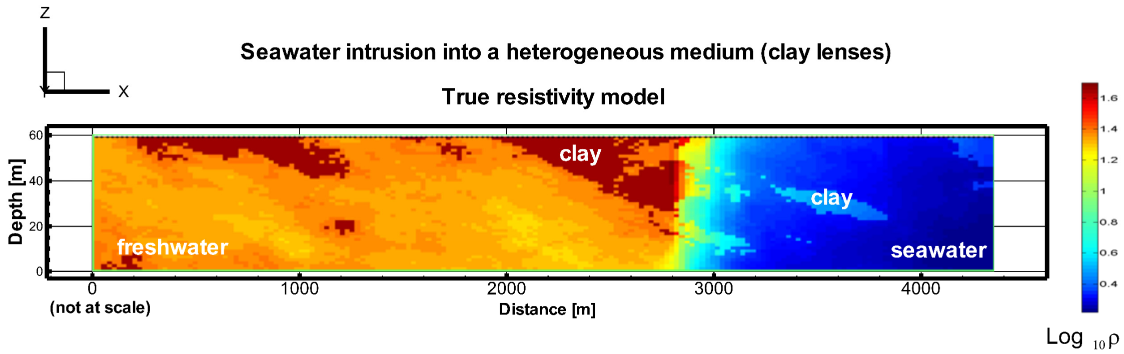

Figure 2 True resistivity model derived from simulated salt mass fraction in a heterogenous hydrogeological model generated by stochastic simulation within SGeMS

RESULTS

One part of our work consists in adopting the methodology of Antonsson *et al*. [2006] and Nguyen *et al*. [2009] to more complex systems (transient, heterogeneous and clay-layered) . As shown by [*Nguyen et al.*, 2009], ERT-derived salt mass fraction data can be high quality data for SWI parameter estimation but requires to address inherent limitations, i.e. resolution loss issues, and the representativeness of the lab-derived petrophysics, heterogeneity of petrophysics. For the sequential inversion approach, we here investigate the usefulness of additional image appraisal tools (e.g. depth of investigation, resolution matrix) to characterize SWI model (figure 3). The simulations showed that only the shallow salt concentration of the seawater/freshwater transition zone could be recovered for different time-lapse, due to poorly resolved regions in depth (not depicted in figure 3). The capability of image appraisal indicators (cumulative sensitivity,resolution and DOI) has been analyzed to emphasize the discrepancy between the targeted and imaged parameter values (figure 2). Indicators based on the matrix of sensitivity seems to offer the best compromise between quality of results and ease of implementation whereas the use of the resolution matrix requires more computation time but offer the best results. The DOI does not seem to be adapted to the task.

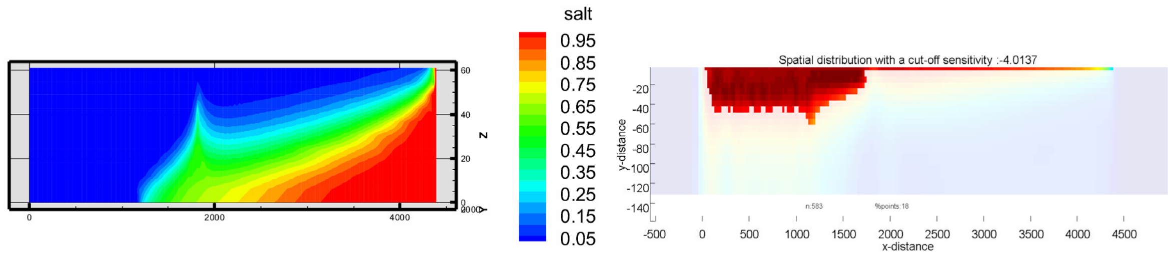

Figure 3 Seawater intrusion in an homogeneous hydrogeological model with upconing in a well pumping during 50 years from steady-state in transient conditions (top) sensitivity-filtered resisitivity image obtained for a certain cut-off of the cumulative sensitivity indicator, surface only data, dipole-dipole, 3% noise (bottom)

DISCUSSION AND PERSPECTIVES

Appropriate image appraisal tools must be selected to properly filter ERT images in order to retrieve seawater intrusion parameters in the sequential inversion approach, or to interpret the image to delineate and monitor the intrusion. Among the tested indicators, we favor the use of the resolution matrix because it seems to be more reliable than others and the cumulative sensitivity that offers the best compromise between quality of results and ease of implementation. Joint inversion computations are still in progress, we expect the coupled inversion to avoid the regularization bias introduced by smoothness constraint ERT and we plan to address the uncertainty of the petrophysical relationship.

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Contact Information: Jean Beaujean, University of Liège, Argenco Department, Chemin des chevreuils 1, Sart-Tilman, 4000 Liège, Phone: +32 4 3669262 Fax: +32 4 3669520, Email: jean.beaujean@ulg.ac.be