Prior uncertainty investigation of density-viscosity dependent joint transport of heat and solute in alluvial sediments

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Introduction and Motivation

Imaging preferential pathways of transport processes in heterogeneous porous media is critical to reduce uncertainties in transport simulations and predictions. In heterogeneous aquifers such as the alluvial sediments at the Hermalle-sous-Argenteau test site (Liege, Belgium), preferential flow paths and non-gaussian effects are often observed. Such phenomena are not easily captured by deterministic approaches, which tend to smooth spatial parameter distributions and therefore reduce heterogeneity. Stochastic approaches allow considering larger uncertainty and heterogeneity and do not rely on the unique prediction obtained by deterministic calibrations. However, there are often too computationally expensive to be used in practice. Bayesian Evidential Learning (BEL) relies on a limited number of Monte Carlo simulations sampling the prior distribution of model parameters to analyze the global sensitivity of parameters [1]. It is used to produce a statistical forecast based on a statistical relationship between historical and forecast variables in conjunction with the actual production data and is called direct forecasting Prediction-Focused Approach (PFA) [2].

Beyond model sensitivities, the motivation is to realistically quantify uncertainty for transport predictions instead of having a single deterministic simulation/inversion. This is very important, in particular when field data are sparse and prior uncertainty is large. Beside the modelling approach in itself, data from joint heat and solute tracer tests have been integrated in the model. These data allow complementing the information provided by the traditional solute advection-dispersion processes, with data related to diffusion and conduction component of heat tracer, to better quantify the immobile water and solid phase and to compare both tracer apparent velocities [3]. In this paper, we present the preliminary results of a joint interpretation of heat and solute tracer tests using a deterministic approach combined with BEL.

Approach

A joint heat and solute tracer test was performed on the site of Hermalle-sous-Argenteau [4]. A model of the aquifer was calibrated against heat data [5] using HydroGeoSphere (HGS) [6] and is further extended in this work to jointly model heat and solute transport, using the BEL approach. This is performed considering fluid density and dynamic viscosity as a function of the temperature (i.e. resulting from heat injection).

Although distributed heat data are available and out of the combined heat and solute tracer test a measured solute tracer breakthrough curve at the pumping well can be added for an integration in a joint heat and solute transport inversion. For comparisons and global sensitivity analysis, the existing model is used to derive for each simulation a realistic geostatistical model parameter distribution for hydraulic conductivity K and porosity θ values between 10^{-5} m s^{-1} and 10^{-2} m s^{-1}, and between 0.05 and 0.15, respectively. Simulated preferential flow paths will be inherent to this simulated spatial heterogeneity.

Results

As shown in Figure 1a, the dynamic viscosity and density effects with temperature are very well modelled by HGS. By injecting hot water at 39 °C for 24 h and 20 min, the density changes in the model are lower than 0.2 % (i.e. not significant), while the dynamic viscosity shows a temporary decrease reaching a maximum of 25 % after one day (Figure 1b).
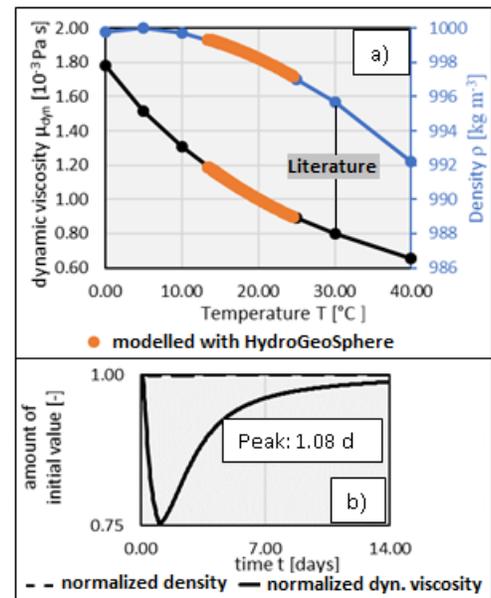

Figure 1: a) Simulated density and dynamic viscosity changes with HGS compared to known literature values. b) Changes (in %) in function of time.

E.g. the temperature breakthrough curve peak time in the deterministic model is relatively well reproduced, but the tailing and the maximum temperature difference are not easy to fit (Figure 2a). Nevertheless, this deterministic model can be considered as the best current version for modelling heat and solute transport simultaneously and model the tracer breakthrough curves at the 19 observation points. This model is used for a comparison of the modelled apparent heat and solute tracer velocities which are in this case for the breakthrough peak time (v_{dom}), because of the fitting (Figure 2b). For the pumping well, the real measured tracer and heat breakthrough curve are added. In the comparison, two clusters are visible. Modelled peak velocities showing a difference greater than 50 % are excluded, because such differences aren't realistic.

In comparison, the simulations performed using the BEL approach surround the observed data (Figure 2c). This means that spatial heterogeneity introduced in the model is able to better reproduce specific behaviors of the breakthrough curve such as the sharp decrease of temperature after the peak. From these curves, a global distance sensitivity analysis will be performed to identify the most sensitive parameters of the model [7]. In a second step, BEL will be used for prediction of the solute tracer distribution within a realistic uncertainty range and the prediction will be compared with the deterministic model results.

Conclusions

In the deterministic model, the heat injection causes a significant influence on the dynamic viscosity, while density effects can be neglected. The clusters in the velocity comparison from modelled heat and solute breakthrough curves represent groups with different peak (apparent) velocities accounting for different flowpaths, but with unknown uncertainty because of the deterministic calibration. With the use of the BEL framework, calibration is avoided, and a global sensitivity analysis is possible. This is probably one possible way to obtain a realistic uncertainty range in the velocity determination, as shown by the shape of the breakthrough curves obtained by prior simulations.

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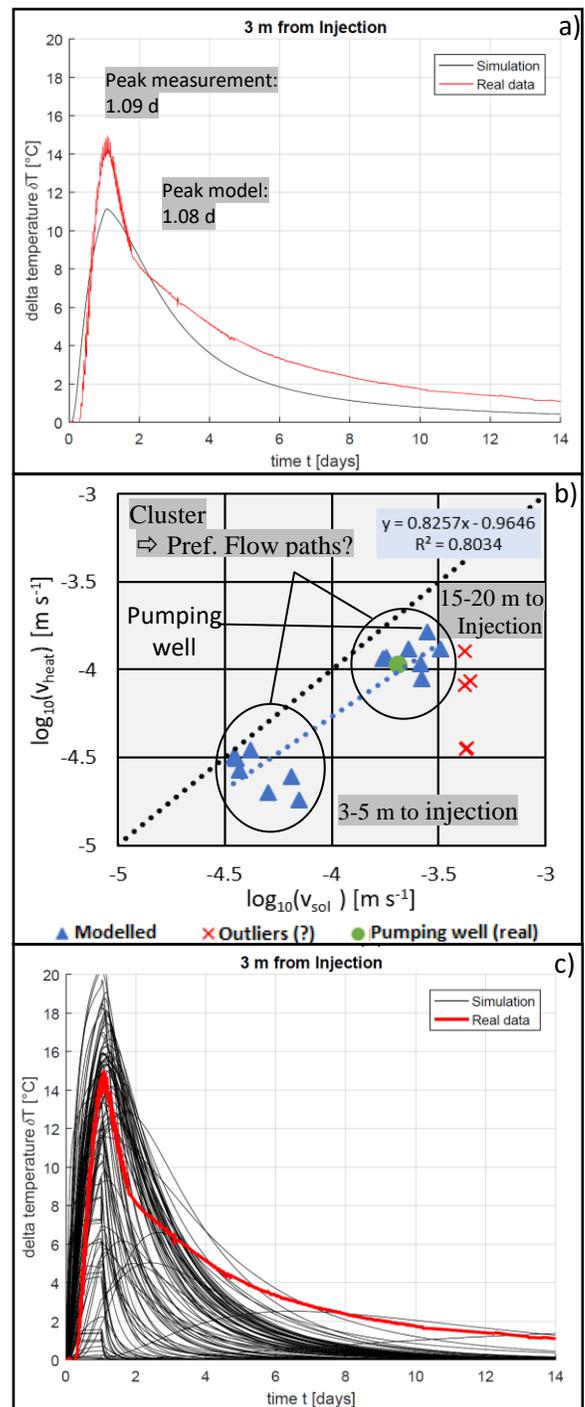
Figure 2: a) Temperature breakthrough with the forward deterministic model. b) Comparison of the heat and solute tracer. c) Temperature breakthrough with 100 simulations of the prior model (BEL).