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Interpretation of numerical transport experiments in alluvial sediments with single-domain, dual-porosity and dual-permeability models

F. Baratelli (1,2), L. Cattaneo (1), C. Vassena (1), M. Giudici (1), and G. Parravicini (2)

(1) Università degli Studi di Milano, Dipartimento di Scienze della Terra "A.Desio", Milano, Italy (fulvia.baratelli@unimi.it), (2) Università degli Studi di Milano, Dipartimento di Fisica, Milano, Italy

Alluvial aquifers are characterized by heterogeneity of the sediments at the fine scale, which significantly affects groundwater flow and solute transport at the macroscopic scale. In particular, the spatio-temporal evolution of a solute's plume released in an aquifer strongly depends on the hydrofacies connectivity, which controls the existence of preferential flow paths or hydraulic barriers.

In order to investigate the effects of heterogeneity and to understand how to deal with it in the modeling of solute transport in aquifers, three blocks of alluvial sediments from the Ticino basin (Northern Italy), each with a volume of about 6 cubic meters, have been examined and the conductivity field was estimated with a resolution of 2 centimeters (Zappa et al., 2006, doi:10.1016/j.jhydrol.2005.10.016). Numerical experiments of convective transport of a tracer under stationary saturated flow conditions were conducted on each block with a particle tracking technique. These experiments simulate the instantaneous injection of a mass of solute through the upstream face of the blocks.

In some cases, the resulting breakthrough curves show the typical effects of heterogeneity, as early arrivals, long tails and double peaks, that cannot be described by the classical approach of a single-domain model, which is based on the Advective-Dispersive Equation (ADE) and considers the heterogeneous domain as an equivalent homogeneous domain.

Therefore the cumulative breakthrough curves were fitted with dual-domain models, that consider the heterogeneous porous medium as a superposition of two domains. In particular, the dual-porosity model assumes that water can flow in one of the two domains (mobile domain) but not in the other (immobile domain) and that the two domains can exchange solute. The dual-permeability models, instead, assume that both domains are mobile and that, in general, they have different Darcy's velocities and dispersion coefficients; two formulations of such models can be defined depending on whether the two domains are considered as coupled, i.e. they can exchange solute, or uncoupled.

For the initial and boundary conditions adopted, the single-domain and the uncoupled dual-permeability models admit an analytical solution.

The dual-porosity and the coupled dual-permeability models, instead, were implemented with a Crank-Nicholson finite difference scheme, an upwind technique for the convective term, and a second-order correction to reduce numerical dispersion due to truncation errors.

The calibration of the different transport models was conducted with the Levenberg-Marquardt algorithm. The number of parameters to be identified ranges from two for the single-domain model to seven for the coupled dual-permeability model.

The results show that, in the case of the blocks of sediments where the presence of preferential flow paths was more evident, the uncoupled dual-permeability model is able to significantly improve the fit of the experimental cumulative breakthrough curve with respect to the single-domain and dual-porosity models. The introduction of the exchange term between the two domains of the dual-permeability model, instead, does not lead to a significant further improvement of the fit.