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On the relative importance of heterogeneity and mass transfer processes at the Macro-Dispersion Experiment (MADE) site

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Several natural gradient field tracer tests have been conducted in the last decades to gain understanding on the mechanisms governing subsurface solute transport. Among them, the Macro-Dispersion Experiment (MADE) site, which is distinguished for being representative of a highly heterogeneous system, has been the most controversial one for revealing an important anomalous behavior in the shape of the tracer plume, i.e., highly asymmetric spreading of the plume with high concentrations maintained near the source and a far and dilute reaching front of the plume. Many conceptually different transport models have been developed that can partially explain this behavior. In particular, transport models with rate-limited mass transfer processes have been claimed to better reproduce this behavior as opposed to macrodispersion caused by heterogeneity in hydraulic conductivity. Within this context, we review the most prominent achievements at the MADE site and present new stochastic models based on a different geostatistical representations of the hydraulic conductivity spatial distribution. Remarkably, we show that, when small-scale variability of hydraulic conductivity is correctly modeled at the flowmeter measurement support scale, the advection-dispersion simple model is capable of reproducing much of the tracer spreading at the MADE site. Thus, results demonstrate that the heterogeneity at this scale is the main contributor to the anomalous plume behavior, as opposed to physically based mass transfer processes. In addition, the interplay of physical nonequilibrium mass transfer and heterogeneity in hydraulic conductivity at the MADE site is analyzed, exploring not only the relative contribution from the different processes but also its interaction.