EGU24-9079, updated on 23 Jun 2024
https://doi.org/10.5194/egusphere-egu24-9079
EGU General Assembly 2024

A view into the richness of processes in porous media

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Flow and transport scenarios taking place in porous media are characterized by a staggering range of physical, chemical, and biological processes. The dynamics associated with these are distributed across an astonishingly wide range of (spatial and temporal) scales, thus contributing to the challenges related to their observation and description. Direct observation and attempts to a quantitative characterization of these processes indicate that they are prone to multiple interpretations, as rendered through various conceptual and mathematical formulations and their parameterization. Even the outcomes of apparently straightforward models of flow (or chemical transport) can surprise us! As complexity related to the formulation and parametrization of processes and their feedbacks increases, so does the need to establish approaches enabling us to quantify the effect of various types of uncertainty on target quantities of interest. For example, tackling the often strong (spatial) heterogeneity of parameters embedded in a model and coping with our limited ability to describe all of the relevant details of the porous medium hosting processes of interest poses significant challenges. In this broad context, I will initiate a discussion about uncertainties related to process formulation and parametrization and the way they can propagate to model outputs such as, e.g., water availability, solute concentrations, source protection regions, or reaction rates. The discussion is set in a framework encompassing experimental studies, characterization of porous media heterogeneity, sensitivity analysis for model diagnosis, and stochastic inverse modeling. Sensitivity analyses approaches are tackled with a focus on their ability to identify the relative importance of processes (and associated parameters) embedded in a model and driving system behavior. The ensuing results are then employed to inform model calibration under uncertainty. All of these aspects are exemplified through the analysis of settings related to three distinct scales. These comprise a regional scale complex aquifer system subject to diverse forcings, a laboratory scale scenario involving dynamics of pharmaceuticals in a porous medium, and direct observations of processes acting at nanoscales and governing material fluxes associated with chemical weathering related to rock dissolution. While these systems are associated with very different scales (and processes), their analysis is unified through the use of stochastic approaches sharing common traits and leading to similar workflows for uncertainty quantification.