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Solute transport with time-variable flow paths during upward and downward flux in a heterogeneous unsaturated porous medium

Clemens Cremer (1), Insa Neuweiler (1), Michel Bechtold (2), and Jan Vanderborght (3)

(1) Institute of Fluid Mechanics and Environmental Physics in Civil Engineering, Hannover, Germany, (2) Thünen Institute of Climate-Smart Agriculture, Braunschweig, Germany, (3) Forschungszentrum Jülich, Jülich, Germany

To acquire knowledge of solute transport through the unsaturated zone in the shallow subsurface is decisive to assess groundwater quality, nutrient cycling or to plan remediation strategies. The shallow subsurface is characterized by structural heterogeneity and strongly influenced by atmospheric conditions. This leads to changing flow directions, strong temporal changes in saturation and heterogeneous water fluxes during infiltration and evaporation events.
Recent studies (e.g. Lehmann and Or, 2009; Bechtold et al.,2011) demonstrated the importance of lateral flow and solute transport during evaporation conditions (upward flux). The heterogeneous structure in these studies was constructed using two types of sand with strong material contrasts and arranged in parallel with a vertical orientation. Lateral transport and redistribution of solute from coarse to fine media was observed deeper in the soil column and from fine to coarse close to the soil surface. However, if boundary conditions are reversed due to precipitation, the flow field is not necessarily reversed in the same manner, resulting in entirely different transport patterns for downward and upward flow. Therefore, considering net-flow rates alone is misleading when describing transport under those conditions. In this contribution we analyze transport of a solute in the shallow subsurface to assess effects resulting from the temporal change of heterogeneous soil structures due to dynamic flow conditions.

Two-dimensional numerical simulations of unsaturated flow and transport are conducted using a coupled finite volume and random walk particle tracking algorithm to quantify solute transport and leaching rates. Following previous studies (Lehmann and Or, 2009; Bechtold et al., 2011), the chosen domain is composed of two materials, coarse and fine sand, arranged in parallel with a vertical orientation. Hence, one sharp interface of strong material heterogeneity is induced. During evaporation both sands are assumed to stay under liquid-flow dominated evaporation conditions (“stage 1”). Simulations considering dynamic (infiltration-evaporation) and steady (solely infiltration) boundary conditions are carried out. The influence of dynamic boundary conditions (intensity and duration of precipitation and evaporation events) is examined in a multitude of simulations. If flow rates smaller than the saturated hydraulic conductivity of both materials are chosen to be applied as boundary condition, simulation results indicate that the flow field within the domain is exactly reversed. However, if applied flow rates exceed the saturated hydraulic conductivity of one material, the flow field is not just reversed, but different flow paths during downward and upward flow are observed. Results show the tendency of faster solute leaching under dynamic boundary conditions compared to steady infiltration conditions with the same net-infiltration rate. We use a double domain transport method as an upscaled model to reproduce vertically averaged concentration profiles with net flux only and compare the model parameters for information about flow dynamics and soil heterogeneity.