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Preferential fluid flow and chemical transport in saturated fractured porous media and in heterogeneous vadose zones: Two sides of the same coin

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Preferential fluid flow and chemical transport occur on scales ranging from pores to aquifers and catchments, in both fully and partially water-saturated geological formations. Preferential flows can be considered, in a general sense, manifestations of self-organization that hinders perfect mixing within a system, and leads to faster throughput of water and chemicals. However, unified concepts for the onset, spatiotemporal patterning, and magnitude of such preferential flows are generally difficult to define; and this is compounded by the difficulty – or practical impossibility – of obtaining detailed measurements of the structure and hydraulic functioning of vadose zones, catchments, and aquifers. We propose that conceptualizations and quantitative characterizations of preferential fluid flow and chemical transport in all of these systems can be unified in terms of tools that connect them in a dynamic framework. Here, we discuss key, shared features of fluid flow and chemical transport dynamics in each of these two systems, based on both laboratory and field measurements, and numerical simulations. We show how even well-connected fracture networks can display highly non-uniform preferential paths for fluid and chemicals. We then recognize that this behavior is similar to that of rapid infiltration in soils and the vadose zone, which exhibits strongly localized preferential pathways in root channels, cracks, worm burrows or connected inter-aggregate pore networks. Moreover, both types of domains can display “memory effects”, in terms of the location and functioning of preferential paths even during perturbations in the velocity gradient and/or rates of infiltration. We argue that the ubiquity of unresolved (or uncharacterized) heterogeneity at all spatial and temporal scales necessitates the use of effective medium models that enable an accounting of a wide range of flow and transport behaviors. For chemical transport, we focus on a probabilistic modelling framework that can capture the dynamics in heterogeneous vadose zones and fractured (or otherwise heterogeneous) geological formations. We then demonstrate application of this model to interpret field-scale tracer breakthrough curves (concentration vs. time) in a highly fractured karst formation over length scales of up to more than 7 km.