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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Notes for discussion:

- Preferential fluid flow and chemical transport occur on scales ranging from pores to entire aquifers, 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.
- At least some conceptualizations and quantitative characterizations of preferential fluid flow and chemical transport in porous and fractured systems – both saturated and partially saturated – can be unified in terms of tools that connect them in a dynamic framework.

Some illustrations below.
Even well-connected fracture networks can display highly non-uniform preferential paths for fluid and chemicals (Margolin et al., 1998; Copyright American Geophysical Union 1998, All Rights Reserved). Highly connected networks with large variances in apertures of pores/fractures can exhibit flow dominated by a few preferential pathways.

Figure 3. Typical spatial distributions of normalized bond discharges in three dimensions for different values of $b$ (isotropic network, $\rho = 0.5$, and $L = 20$): (a) $b = 0.0$; 400 bonds are shown, with discharges of 1.0%–2.2% of $Q_{tot}$; (b) $b = 0.5$; 1242 bonds are shown, with discharges of 1.0%–4.9% of $Q_{tot}$; (c) $b = 1.0$; 1507 bonds are shown, with discharges of 1.0%–15.9% of $Q_{tot}$; and (d) $b = 2.0$; 1529 bonds are shown, with discharges of 1.0%–20.4% of $Q_{tot}$. The thicknesses of the bonds are proportional to the relative discharges they carry.
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 (Gouet-Kaplan and Berkowitz, 2011; Copyright Soil Science Society of America 2011, All Rights Reserved).

Fig. 2. Typical processing result for new water infiltration (blue) in the lattice micromodel partially saturated by old water (red). Infiltrating flow is from top to bottom; from left to right, the partial displacement of the red dye can be followed in time. Purple regions indicate mixing of the old and new water. Note that some clusters of red dye remain uncontaminated by blue dye while others are mixed, i.e., the preferential flow of new water leaves some pockets of old water intact even after flow of blue dye reaches steady state at the outlet. Top pictures show entire micromodel with inlet and outlet; bottom pictures show a detailed area. These specific pictures are from a preliminary run, and the order of the dyes differs from the results discussed.

Vadose domain (and fracture networks) 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 (Kapetas et al., 2014).
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 use the Continuous Time Random Walk (CTRW) framework (Berkowitz et al., 2006, 2016) focus on a probabilistic modelling framework that can capture the dynamics in heterogeneous vadose zones and fractured (or otherwise heterogeneous) geological formations (Edery et al., 2014; Copyright American Geophysical Union 2014, All Rights Reserved).
Application of this model interprets field-scale tracer breakthrough curves (concentration vs. time) in a highly fractured karst formation over length scales of up to more than 7 km (Goeppert et al., 2020; Copyright Elsevier 2020).
Specific literature:


