Geophysical Research Abstracts
Vol. 14, EGU2012-10513, 2012
EGU General Assembly 2012

Hydraulic non-equilibrium during infiltration induced by structural connectivity

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Water infiltration into heterogeneous, structured soil leads to hydraulic non-equilibrium across the infiltration front. That is the water content and water potential is not in equilibrium according to some static water retention curve. The water content increases more rapidly in more conductive regions followed by a slow relaxation towards an equilibrium state. An extreme case is preferential infiltration into macro-pores.
As flow paths adapt to the structural heterogeneity of the subsurface, there is a direct link between structure and non-equilibrium. The aim of our study is to develop an upscaled description of water dynamics which conserves the macroscopic effects of non-equilibrium and which can be linked to structural properties of the material.
However, this relationship cannot be rigorously examined without an upscaling approach that conserves non-equilibrium during averaging of state variables. We achieve this with a novel approach, that is based on flux-weighted averaging of hydraulic potential, and compare its performance to existing averaging approaches by means of infiltration simulations. Further, we set up some meaningful indicators of hydraulic non-equilibrium that can be easily compared to morphological characteristics of the infiltration front. These methods provide a sound basis to assess the impact of structural connectivity on hydraulic non-equilibrium. We generate several realizations of two-dimensional random fields originating from three heterogeneity models with distinct differences in connectivity of high-K areas and conduct infiltration simulations with them. Our results indicate, that an increased isotropic, short-range connectivity reduces non-equilibrium, whereas anisotropic, macropore-like structures enforce it. We observed a good agreement between front morphology and upscaled non-equilibrium. Our findings encourage to use flux-weighted potentials for upscaling of state variables during transient conditions. We demonstrate, that this may help improving conceptual approaches for hydraulic non-equilibrium, like the Ross & Smettem extension of Richards equation.