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Hydraulic continuity and flow dissipation lengths define scales of applicability for the Richards equation

D. Or and P. Lehmann

Soil and Terrestrial Environmental Physics; Institute of Terrestrial Ecosystems; Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland (dani.or@env.ethz.ch)

Availability of spatially and temporally resolved remotely sensed data and increased demand for physically-based predictions of flow and transport at various scales stimulate interest in upscaling of transport processes from lab to field and regional scales. Many predictive models rely on the Richards equation (RE) for description of flow in unsaturated porous media, beyond the mathematical formalism of upscaling, a question arises - are there natural characteristic lengths beyond which application of RE is not physically warranted? Recent studies of evaporation from porous media show that stage 1 evaporation flux is sensitive to capillary driving forces and internal transport mechanisms; at a certain natural characteristic length hydraulically continuity is interrupted along with capillary flow resulting in drastic reduction in surface fluxes. These results suggest a generalization strategy for delineating natural scales of applicability for the RE. The key ingredients defining such scales involve hydraulic continuity, magnitudes of capillary gradient and of opposing gravitational and viscous dissipation forces. We show that from water characteristic curve (WCC) we may deduce an intrinsic characteristic length for hydraulically connected pore sizes as the head difference between air entry value and onset of residual saturation. Similarly, the magnitude of capillary gradients is naturally contained in medium WCC and may be extended to heterogeneous or layered media. The extent of viscous dissipation is defined by flux density (velocity) and hydraulic conductivity and is easily incorporated into these considerations. A characteristic length for upward flow (against gravity) that considers balance of capillary, gravity and viscous forces was instrumental in predicting depths of drying front at transition from stage 1 to stage 2 evaporation as confirmed by experimental results. For lateral unsaturated flows, we show that the lateral extent over which capillary gradients dissipate is defined by the magnitude of capillary drive (linked to heterogeneity of pore sizes) and the hydraulic conductivity along the flow path. For various unsaturated flow scenarios the lateral length of applicability of the Richards equation vary from 0.1 m in clays to more than 10 m in sands, and is critically linked to the magnitude of fluxes (higher fluxes yield shorter lengths).