The important comment by Nimmo [this issue] focuses on water flow in soils at relatively low water contents. He states that our paper [Luckner et al., 1990] left several issues unresolved, including (1) fundamental difficulties in associating a definite physical condition with the residual water content, $\theta_{r}$, in our paper, (2) practical inadequacies of the hydraulic models at low values of the water content, $\theta$, and (3) difficulties in designating a main wetting curve.

To better understand the residual water content, and its peculiarities, we first recall some fundamental aspects of hydraulics since our parametric models (including the parameter $\theta_{r}$) are based exclusively on continuum hydromechanics. Geohydraulics based on Darcy’s law considers only the dynamics of coherently distributed phases in porous media. If we take some small representative elementary volume (REV) of the subsurface system under investigation, a phase may be viewed as a substance which is (1) uniform, (2) solid, liquid or gasous, (3) continuously distributed over the entire REV, and (4) characterized by its volume-averaged concentration or volumetric phase content (e.g., $\theta_{s}$ for soil water). In such a framework, phases and their defined boundaries are nothing else but models of reality, and hence apply only for conditions specified by the model user.

The internal energy (or entropy) of water molecules in a soil pore changes as a function of the impacting molecular attraction forces (Figure 1). The entropy state of water molecules (and therefore also the properties of “solid, liquid, or gaseous” soil water) changes continuously from location to location in the soil pore. The interface (or boundary) separating “liquid soil water” from “solid soil water” can, therefore, only be a model similar to that of a sharp interface between salt and fresh water in a coastal aquifer. Consequently, when we use $\theta_{r}$ to separate the “mobile coherent liquid soil water” phase from the “immobile water” phase (see Figure 1; our paper), the practical inadequacies of our parametric models are difficult to avoid when $\theta$ approaches $\theta_{r}$. Nevertheless, in our paper we wanted to emphasize that the “liquid and mobile” properties of the wetting phase in a soil matrix, the average entropy of molecules forming this phase in a REV is not authoritative.

Figure 1. Schematic of the distribution of water near the surface of the soil solid phase.

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water" phase no longer exists ($\theta_\text{a} < \theta_\text{w}$). We assume that $\theta_\text{a}$ is slightly larger than $\theta_\text{w}$. The SWC with ($\theta_\text{a}, \theta_\text{w}$) for the so defined PWC and the MWC would then indeed be much closer together than is shown in our Figure 2 where the PWC was constructed using a hypothetical matching point of (0, $\infty$).

Ironically, this discussion again emphasizes the necessity to introduce the geohydraulic parameter $\theta_\text{a}$, > 0. We disagree with Nimmo's statements that "it is unrealistic to represent a $\theta(h)$ curve as never becoming less than $\theta_\text{a}$", and that "in reality, as $h$ continues increasing, $\#$ continues decreasing until it is 0," as implied also by his Figure 1. We would like to emphatically repeat that we use $\theta_\text{a}$ as a convenient but empirical constitutive parameter in geohydraulic flow models (i.e., for modeling the flow of mobile coherent liquid soil water) where the hydraulic gradient (expressed as grade $h$) is the pressure gradient in the mobile coherent liquid soil water phase. Therefore, the question is not whether a system state in a soil can be reached where $\theta_\text{a}$ is less than $\theta_\text{w}$, but whether or not this state can be reached by hydrodynamical mechanisms only. Nimmo's Figure 1 and his comments based on this figure are in our opinion meaningless in the geohydraulic context of immiscible liquid phase flow because a large part of Schäffer's [1995] data points were generated and measured with techniques that had little or nothing to do with geohydraulics or liquid phase flow in soils. Thermodynamical considerations indicate that systems state functions which reflect the dependency of an extensive state variable (such as the pressure head, $A$) change when the driving forces, and hence the processes causing changes in the systems state, are qualitatively or phenomenologically different (e.g., resulting from pressure differences, freezing, or drying).

Finally, we express our appreciation for Nimmo's constructive comments on our paper. His analysis and this reply hopefully serve the purpose of clarifying the nature of the soil hydraulic functions at relatively low water contents.

References


L. Lückner, Dresden University of Technology, Nixturm, Mohnsennstrasse 13, D-0 8027 Dresden, Germany.
D. R. Nielsen, Department of Land, Air and Water Resources, University of California, Davis, CA 95616.
M. Th. von Genuchten, U. S. Salinity Laboratory, USDA, ARS, 4500 Glenwood Drive, Riverside, CA 92501.

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