Comments

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Response to "Comments on 'Theory for Source-Responsive and Free-Surface Film Modeling of Unsaturated Flow'"

I am grateful to Masciopinto (2012) for raising several issues from my study (Nimmo, 2010) that deserve elaboration or clarification. In this reply, I address these in what I judge to be the order of importance, the main ones being (i) the discrepancy of scales between the two domains that treat preferential and diffuse unsaturated flow, and (ii) the properties that must be evaluated to characterize the medium.

On the issue of scales, Masciopinto is correct in pointing out that the two domains of the source-responsive flux model (S for source responsive and D for diffuse) have different representative elementary volumes (REVs). The D domain is based on pore-scale phenomena for which the REV must include a representative sample of pores of the matrix material. The S REV must include a representative sample of the macropores and other features, most of them much larger than matrix pores, that determine its source-responsive characteristics $M(z)$ and $f(z,t)$. Strictly, then, the addition of S and D components (as in Nimmo, 2010 Eq. [1], [2], [10], [11], etc.) has to occur at the larger of the two REVs, with the D component being an effective average from multiple D REVs. This could be shown explicitly with an expression similar to Masciopinto's Eq. [1]. To avoid encumbrance of the model's equations, I have preferred to leave this matter implicit, although with no intention of denying its importance.

This scale issue is not unique to this model but is fundamental for dual-domain modeling with continuum formulations (e.g., Liu, 2011, p. 737). For hydraulic conductivity as used in Darcy's law, REVs for natural soils may be about 10^{-3} m^3 or more (Iversen et al., 2011), although much smaller REVs are often considered for more uniform media and simpler properties such as porosity (Costanza-Robinson et al., 2011). Preferential flow paths, which may individually extend across 1 m or more, require a larger REV. This divergence of scales motivates hybrid approaches—discrete pathway for preferential flow and continuum for matrix flow (Therrien and Sudicky, 1996). In principle, discrete pathways, if adequately characterized, lead to good results. Heterogeneous collections of discrete pathways are unwieldy, however, so continuum approaches are highly desirable, if not unavoidable. The interaction of two intermeshed continua with different characteristic scales is then a complication that has to be confronted.

Concerning the characterizing properties of an unsaturated medium, I do not agree that the ones I proposed will entail more difficulties than the traditional ones. The traditional unsaturated hydraulic conductivity and water retention relations are, among other problems, highly nonlinear, hysteretic, wide ranging across modest differences in moisture, sensitive to microstructural elements that vary tremendously within natural media, and difficult to the extent that they are virtually never directly measured! This is why unsaturated-zone scientists have expended tremendous effort in recent decades to develop parametric simplifications, pedotransfer functions, and other ways to facilitate their estimation or to avoid their measurement. Although the issue needs further testing and development, the properties I have suggested for the source-responsive model, such as the macropore facial area M, are conceptually less complex and potentially easier to work with.

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Concerning the shortcomings of Richards' equation, I did not intend an implication that Richards' equation can never be adequate on its own. Certainly there are media and applications for which it can be useful without augmentation. Because the Richards formulation can work well for matrix materials, I presented the source-responsive model in combination with it in Eq. [20] of Nimmo (2010). When the source-responsive factor *f* goes to zero, this equation becomes identical to Richards' equation. Actual shortcomings of Richards' equation do arise, often because of its requirement that when water content at a given depth increases, it has to have been in connection with an increase in water content in immediately adjacent portions of the soil. Utilization of multiple realizations in a stochastic approach does not change this fundamental restriction. Because typical field observations (e.g., Flury et al., 1994; Lin and Zhou, 2008) have found substantial increases in water content at depth that are not appropriately synchronized, in timing or magnitude, with water content increases at all shallower depths, the measurements demonstrate wetting behavior that is incompatible with Richards' equation. With further testing of alternatives such as the Nimmo (2010) source-responsive model and comparison with Richards-based predictions, these issues will become clearer.

Concerning the active area fraction $f(z,t)$, I don't see a contradiction with respect to the possibility of discontinuous, stagnant films. Water in the S domain is subject to flow by source-responsive processes, in Nimmo (2010) conceptualized as mobile films on macropore walls. Water in the medium that does not flow at all then is in the D domain. It would influence the relation between hydraulic conductivity and water content in the D domain but not the characterization of the S domain.

Concerning the adequacy of Eq. [29] of Nimmo (2010), developed for a particular case study, Masciopinto is right that it does not represent the situation in all details. This can't be expected at an early stage of model development—further work is obviously needed. Yet the case study is worthwhile because it illustrates how the source-responsive model can well represent features of system response that are problematic for traditional models.

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