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

Germann's (2010) comment helpfully presents supporting evidence that I have missed, notes items that need clarification or correction, and stimulates discussion of what is needed for improved theory of unsaturated flow. Several points from this comment relate not only to specific features of the content of my paper (Nimmo, 2010), but also to the broader question of what methodology is appropriate for developing an applied earth science. Accordingly, before addressing specific points that Germann identified, I present here some considerations of purpose and background relevant to evaluation of the unsaturated flow model of Nimmo (2010).

The main goal of Nimmo (2010) was to represent preferential flow in terms of measurable properties and to predict items of importance in current applications. Development was largely aimed toward a source-responsive model that could be mathematically combined with Richards' equation to encompass situations for which Richards' equation alone is inadequate. In some ways the issues concern practicality. Even if investigative resources were abundant, it is not feasible to undertake the fine-scale, total-medium characterization of the spatially variable and hysteretic unsaturated hydraulic properties needed to rigorously apply Richards' equation at the field scale. Other, more fundamental concerns with Richards' equation include that it is often used to model flow that includes sharp wetting fronts, whose fundamentally pore-scale behavior and propensity for unstable flow cannot be described by Richards' equation (Jury et al., 2003; Shiozawa and Fujimaki, 2004; DiCarlo, 2010). Another problematic practice related to Richards' equation is the routine use of saturated hydraulic conductivity as the matching factor when predicting unsaturated hydraulic conductivity with capillary-bundle models. Saturated hydraulic conductivity is determined primarily by the conductance of the largest pores, which empty first on drying and therefore contribute only marginally to the unsaturated hydraulic conductivity. This sets up the tenuous situation that the only dynamic property information going into the solution of a flow problem is a quantity that is nearly irrelevant to most unsaturated flow.

At the other extreme, exact formulations combining basic fluid dynamics, thermodynamics, physical chemistry, and other fields may work at the pore scale or in media of simple and uniform structure, but not for the assemblage of unknown microscale complexities that comprise natural soils and rock. We assume that known principles of classical physics govern unsaturated flow, but given the unattainability of knowledge needed to apply them to all the critical properties, active processes, and microstructure of a natural medium, we necessarily simplify and take shortcuts. In other words, we choose to ignore certain known physical phenomena as insignificant with respect to the problem at hand. The Nimmo (2007, 2010) source-responsive models embody some choices of this nature that differ from the usual ones.

Different methodologies are in use for developing new unsaturated flow theory. One can start by applying the known physics of fluid flow to the natural medium, simplifying later where necessary. This approach suffers from the unknown and intractable complexities of pore-scale geometry, materials, and boundary conditions. Another established path, sometimes called a downward approach (Sivapalan et al., 2003), is to start simply and add complexity as needed. An example is the pioneering kinematic-wave model of Germann (1985). This model neglected hydrodynamic dispersion, whose effects were significant

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and obvious in the data sets to which the kinematic-wave model was applied. Modifications were developed later (e.g., Di Pietro et al., 2003) to account for dispersion and other effects. But the simplicity of the initial development allowed the effects of the kinematic-wave concept alone to be seen and evaluated. With minimal complexity it is easier to discern what features of the model are working well, so that they can be retained and improved upon. Especially during early development, ignoring certain known phenomena helps to avoid creation of a many-parameter model that can fit essentially any data set just because of its many degrees of freedom. These reasons underlie major assumptions such as universal film thickness in the source-responsive model of Nimmo (2010).

Germann raises several specific issues: (i) the compatibility of source-responsiveness with transience of flow, (ii) previously unmentioned fundamental constraints on the thickness range of flowing films, (iii) the negligibility of variation in film thickness, (iv) the appropriateness of an exponential function to represent the decline in water table level after recharge, and (v) the similarity, in spite of alleged weaknesses, of the Nimmo (2010) approach to that of Germann (2001).

The compatibility of transience and source-responsiveness is one issue where starting from simplicity leaves certain physical processes unaddressed. Aimed at a usable representation of unsaturated flow in natural geologic media having great complexity over large and small scales, the source-responsive model does not capture all possible correspondence with previous theory. Correspondence is lacking for the phenomena mentioned by Germann that depend on time raised to different powers. In this and other regards the source-responsive model's value ultimately depends on how well it agrees with measurements. It has not yet been rigorously tested in the Richards' equation–combined form (Eq. [5] and others), but I put this equation forward as being worth examination and trial. The combination of diffusive and source-responsive terms by Nimmo (2010) has several important features, including that it (i) facilitates implementation, through parallelism to the many proposed modifications of Richards' equation that in effect add a term to the basic formula (especially, root-uptake modifications that are mathematically similar to Eq. [20]); (ii) relieves some of the burden on the unsaturated hydraulic conductivity, which the standard formulation forces to embody all dynamic properties at all time and space scales; and (iii) potentially represents flow modes that are difficult or impossible to represent with Richards' equation alone. The most apt comparisons are not so much with models developed directly from basic physical laws, but rather with models involving drastic simplifications such as the parameterization of unsaturated hydraulic properties lumped for large volumes of heterogeneous material and estimated with high uncertainty.

I am pleased Germann has pointed out additional fundamental reasons why flowing films in porous media are limited to a certain range of thickness. Constraints from the standpoint of stability have also been evaluated by others (e.g., Tokunaga and Wan, 2001; Ghezzehei, 2004), although with some divergence in what is assumed to dominate the pore-scale physics.

Concerning the negligibility of variation in film thickness (implying also a negligibly varying flow velocity under the assumption of Stokes flow), there is some degree of experimental support. Germann is correct, however, in pointing out my mistake in citing the Germann et al. (2007) data, which being from a single soil column are inappropriate for this purpose. The Hincapié and Germann (2009) analysis of data of Germann and Hensel (2006) is more relevant to this issue, and I was aware at the time of writing that my proposed 6-μm value falls at the lowest extreme of those results. However, 80% of the 215 in situ measurements fall within the range of 10 to 30 micrometers, with corresponding wetting front velocities of 2×10^{-4} to 1×10^{-3} m s^{-1} (see Fig. 5 of Hincapié and Germann, 2009). Whether one takes this evidence to favor or oppose the idea of a minimally varying film thickness depends on the use to which the results are applied, and the magnitude of other uncertainties (e.g., in unsaturated K) surrounding that application. There is additional support from the measured results of Tokunaga and Wan (1997), especially apparent in their Fig. 8.

A universal film thickness was in part adopted to limit the degrees of freedom in early-stage development, as explained above. The practice of lumping together a broad range of media for representation with a single parameter set is very common in unsaturated flow investigations. A prominent example is the widely used scheme of Carsel and Parrish (1988) that designates 12 sets of unsaturated hydraulic properties to represent all soils. All silt loam soils, for example, are lumped into a single box for the full suite of hysteretic unsaturated hydraulic properties. Other examples include Mualem's (1974) assignment of the value 90% as the universal degree of saturation attained in soil when saturated without exclusion of trapped air, and also Mualem's (1976) designation of the value 0.5 as the exponent of water content in his model of unsaturated hydraulic conductivity. In these cases the values were obtained by averaging measurements from a finite number of soils. Nimmo (2007) likewise obtained a value for maximum transport velocity V_0 as an average of a finite number of measurements for diverse media. In all such cases it should be understood that later adjustments based on additional data and information are not only acceptable but desirable. In Nimmo (2010) I chose not to update the value of V_0 because addition of the material needed to justify a modest adjustment did not hold prospects of significantly improving the paper. In any case, the present formulation can be easily applied with other values of V_0 and film thickness, perhaps designating separate values for specific types of media or conditions.

Concerning the assumed exponential decline in water table level after its peak, in the examples presented I considered two primary influences on this level: preferential unsaturated zone flow that transports water rapidly enough to elevate the water table, and flow by various processes, largely within the saturated zone, that bring the water table closer to equilibrium. On p. 300 I discussed "the recession rate (behavior after peak H), which is not a source-responsive feature and is improvable with a more realistic treatment of recession than the linearity embodied in [28]." I applied the common assumption that recession-controlling processes could be approximated by assuming their aggregate effect is equivalent to decline at a rate proportional to water table height above a base level, i.e., an exponential decline over time. In the example, the source-responsive model affects only the rise of water table, not the decline, so the source-responsive test is in the rising limb only, unaffected by model choice for the declining limb. There remains the unexplored possibility that source-responsive concepts could be used in a new approach to water-table recession.

Concerning the comment that "there might be an almost insignificant difference between Nimmo's approach and Germann's (2001) Stokes flow analysis," I agree. In fact, in reading papers from Germann's research group, I am routinely startled by how our two approaches coincide in their underlying principles while they differ in language. My research has benefitted tremendously from Germann's insights. I disagree, however, concerning the scientific value of the particular assumptions and simplifications I have put forth in Nimmo (2010). For the reasons I mentioned above, I do not see the possibility of working exclusively with exact, reductionist, classically physical theory to address routine unsaturated flow in applications such as water supply, agriculture, contaminant transport, and natural hazards. These problems are unavoidably approached with gross simplifications. Progress will come as we develop simplifications that are more widely applicable, more far-reaching in their results, more closely tied to the critical issues we need to address, and more closely representative of the phenomena that are observed to occur.

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