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Hydrology and Earth System Sciences Discussions

Interactive comment on "Thermodynamics of the hydraulic head, pressure head, and gravitational head in subsurface hydrology, and principles for their spatial averaging" *by* G. H. de Rooij

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Reply to the review by Dr. Thomas Gimmi.

In the first four main points, Dr. Gimmi recommends to refocus the paper, indicates that one part of the paper reads like a review, and the other part like a research paper, and expresses his doubts about the significance of some of my upscaling efforts.

In view of these comments I considerably lessened the emphasis on the thermodynamic aspects of the work, and modified the title to reflect this. In response to the recommendations of the second reviewer (see my reply to that review) I brought the paper fully in line with the upscaling literature and better developed the argument to support

the simpler, more practicable approach I am advocating here in favor of mounting a full attack on the closure problem.

On re-reading the original work, I agreed with Dr. Gimmi’s objections against the weighting function for the upscaled hydraulic conductivity. To remedy this, I developed a more systematic approach to upscale Darcy’s Law, derived from that a formal definition of the upscaled hydraulic conductivity (thereby eliminating the need for the weighting function) and then used that formal definition to come up with simpler expression that are valid under less general circumstances accompanied by criteria for their validity. All this is new, and I hope and believe these significant modifications adequately address Dr. Gimmi’s concerns.

Comment 5:

Dr. Gimmi states the paper generalizes the work by Gray and Miller and does not resolve an existing paradox. However, the G&M-paper itself introduced the term paradox (in the main text as well as in the abstract), and I adopted it to establish a clear link between both papers. In my opinion, the paradox arises from the use of the gravity vector in G&M’s Eq. (6), instead of the gravitational potential favored by most soil physicists and groundwater hydrologists. This leads to a formulation of Darcy’s Law for horizontal flow in a body with a non-zero vertical cross-section without the gravitational potential (eq. (10) of G&M). The fact that the gravitational potential does not appear is ascribed to the fact that the gravity direction in the horizontal direction is zero. This clouds the fact that the gravitational potential is still there. This is reiterated by the averaging of the pressure but not the gravitational potential over the vertical cross-section (eq. 11 in G&M). The averaging operation is mathematically correct, but nevertheless incomplete. Then, in eq. (17), a formulation of Darcy’s Law is presented in which the heterogeneity of the porous medium is represented by a modified hydraulic conductivity, a suitably averaged pressure potential, but no gravitational potential. Therefore, this equation tacitly assumes the vertically averaged gravitational potential to be constant throughout the system, which can only be true if the weighting

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factor of the averaging operation is not influenced by the vertical variation of the local water content. This is inconsequential if the water content is vertically uniform, but the illustrative case discussed by G&M has a non-uniform water content. Since the averaging operation for pressure uses precisely this local water content as a weighting factor, this amounts to the use of different weighting procedures for the two components of the hydraulic potential. In the paper I argue this is not correct. Expanding eq. (17) for the illustrative case presented in G&M leads to their eq. (19), which predicts horizontal flow under zero gradient of the hydraulic head. It is this result that is called a paradox by G&M, and it is this finding that I aim to resolve.

Only in the second part of G&M is the gravitational potential introduced, and a weighting function is developed that is tailored to the case study. Note that the weighting factors of the pressure and the gravitational potential contain ‘correction terms’ in the words of G&M. This creates the suggestion of Darcy’s Law requiring a correction for heterogeneous media, and the resulting averaged equation is eq. (28) of G&M. I agree with Dr. Gimmi that this equation is correct, but I point out that the averaging operation proposed by G&M is problematic for complicated or unknown heterogeneities. If, on the other hand, the gravitational potential and the pressure potential had consistently been treated equally throughout the derivation, the paradoxical result would not have arisen, the correction factors would simply have been identified as proper weighting factors. This is the point that I make in the paper. I elaborate on that by solidifying the procedure in a superposition principle to clarify the need to treat all components of the hydraulic potential equally in any upscaling operation, and than demonstrate the power of the principle by using it in a set of consistent upscaling operations. Although the second reviewer claims these equations are not very novel, they rely on fewer assumptions than hitherto imposed (see below). The consistency with results that have been established by alternative analyses further corroborates the implicit claim that the paradox reported in the literature is in fact non-existent.

These upscaling operations also touch on the work by Nordbotten et al., whose work

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involved volume-averaged fluxes. I hope to demonstrate the limitations of this approach (see also my response to the second review) and advocate instead to average fluxes over surfaces. In this respect too, the paper is more than an extension to G&M. This section was expanded to accommodate comments by the other reviewer.

Points 6 and 7: The terminology to define the various spatial scales was updated and made unambiguous. The remaining detailed points were cleared in the overall rewriting op the paper.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 5, 1137, 2008.