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Hydrology and Earth System Sciences Discussions

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Interactive Comment

Interactive comment on "Examining the effect of pore size distribution and shape on flow through unsaturated peat using 3-D computed tomography" *by* F. Rezanezhad et al.

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We appreciate the insight provided by Dr. Andy Baird, posted on 28 July 2009. We acknowledge his suggestions and constructive comments that were helpful for improving the paper. We agree with almost all his constructive suggestions and the remarks will be addressed in the final version of the article and will improve the quality of the paper.

Response to General comments (overview):

The Referee recommended four issues. Below, we answer the questions separately:

First, they use a single peat sample. How representative is this sample of a wider class of peat soils?

- This is the same concern that was made by Referee#3 that “the work has been undertaken on just one sample where it was divided up into three samples but then only one sample was focused on in this paper”. The reason for this single-sample analysis is explained below:

The peat profile contains two layers, an upper layer containing living and lightly decomposed fibric material, and a lower layer containing darker and more humified peat. Although the physical and hydraulic properties vary greatly between the two layers, the detailed microscopic image analysis coupled with field and laboratory permeability measurements (Quinton et al., 2009), demonstrated that these properties are relatively uniform within each layer. This study was focused on the upper peat layer extending to 20 cm depth since the lower layer is below the relatively impermeable frost table for the first several weeks of soil thaw, and therefore does not conduct runoff during the time when the majority of the annual subsurface runoff is conveyed through the peat to the base of hill slopes. Due to the similarity among the physical and hydraulic properties and the air-filled pore size distribution between the three upper, middle and lower cores (taken from the upper peat layer) of the same sub-samples obtained with 2D and 3D CT images analyses and presented in Quinton et al., 2009, only the lower core sub-sample was analyzed in detail for this study. Therefore, all three sub-samples were scanned, but as the 3D CT analysis is expensive and process of the images takes a lot of time, only one sub-sample was analyses for hydraulic conductivity calculation.

Furthermore, the scientific merits of this manuscript focus on development of feasibility/suitability of analytical technique and concepts, as opposed to site (Scotty Creek) characterization. It is the author’s hope that the methodology and application presented here will be taken and utilized by other researchers for expanded peat and earth material research. Finally, we should mention that the intention of this research is not to use the results somehow to be a parameter that describes runoff from Scotty Creek site.

Rather, it is trying to explore the nature of hydraulic properties in peat, and understand more about the role of its structure on the way water moves in it.

Secondly, the authors measure horizontal K when I would expect most water movement in the unsaturated zone to be vertical. In many Sphagnum peats there is a zone of collapse about 1-2 dm below the soil surface in which the orientation of Sphagnum stems and branches changes from vertical to horizontal. It would be useful to know more about the sample of peat studied and how stem orientation may have affected the pore-shape metric – c – and what implications such orientation may have for water movement in poorly-decomposed Sphagnum peat.

- We extracted the cores horizontally because the vertical travel time of water is so short due to the very high infiltration rates and the short travel distance the between the ground surface and water table. Therefore it is the horizontal pathway (through the saturated layer) that controls the overall travel time from the time of infiltration to the time that water arrives at the to the base of a hillslope. So, we didn't expect to be examining flow through the unsaturated layer. In response to the reviewer's comment on orientation, we used the CT images to understand the isotropy of peat in the upper ∼20 cm. We know that peat of sedge-origin shows preferential orientation of fibres in the horizontal direction, but we didn't think this was nearly as developed in moss-peats. Our sense is that while there may be some reason to suspect anisotropy (i.e. Kh not equal to Kv due to preferential orientation of fibres) but the difference in this peat would be small (i.e. not order of magnitude differences) in the upper 20 cm. We are not sure of the relative importance of vertical and horizontal k in treed peat plateau systems. We would suspect that horizontal redistribution of water following infiltration is also an important process affecting the flow and storage of water.

Thirdly, it would be useful to know whether the authors think it is practicable and desirable to model unsaturated water flow in poorly-decomposed Sphagnum using a Darcy-type equation. Previous studies (see detailed comments) suggest that flow of rain-water through poorlydecomposed near-surface peat is rapid, and, for many practical purposes, can be considered to arrive immediately at the water table. For situations where capillary rise of water from the water table is exceeded by evaporative water loss from Sphagnum capitula – so that capillarity theory cannot be used to describe the distribution of water content above the water table – a simple storage model may be a more satisfactory description of unsaturated water dynamics than a variant of Darcy's law.

- We thank the reviewer for this suggestion. However, the laboratory components of this study were not driven for modelling, so we believe that including modelling at this stage is not necessary and could be considered for further publication. We were just trying to sort out processes.

Finally, although I agree that it is interesting to discover the factors that control water flow in unsaturated peats, I wonder whether the authors are proposing their approach as a practical alternative to deriving K(p) empirically; i.e., as an alternative to by measuring K(p) directly? If so, I think it would be good to see an explanation of why they think their approach is better.

- Our paper, as manifested in its title, tries to take two central issues in the current scientific and technological scene. The main goal being to increase our understanding of the nature of peat soils physical properties (especially air-filled pore size distribution and geometry) that affect the K in the unsaturated condition, and demonstrate the validity by making a comparison with the standard method.

Several methods of indirect estimating hydraulic conductivity exist. One of the better methods is to obtain data on grain size and also porosity, sorting, packing, and grain/pore shape, as practicable, and to estimate hydraulic conductivity using empirical relationships. Most of the empirical relationships assume spherical pores and grains. The reason for the assumption is because until very recently, the ability to actually visualize and analyze of the grains did not exist. Nowadays, there is the ability to view in detail the pores and grains using Computer Tomographic (CT) imaging. An approach

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to measure the geometrical characteristics of the grain and pore morphology directly using undisturbed samples is the non-invasive X-ray MicroCT scans that has been applied previously in soil science (e.g. Perret et al., 1999; Ketcham and Carlson, 2001; Mooney, 2002; Wildenschild et al. 2002; Pires et al., 2005). MicroCT imaging is attractive because it provides detailed information on microscopic morphology of the grain and pore spaces, and is capable of evaluating the 3D grain and pore geometry with high resolution. Therefore, we can now check assumptions of grain/pore shape, and we now have the basis of replacing them with physically-based relations.

In the case of peat soils with the complex geometry of the pore space and solid interfaces, the pores are not spherical but highly irregular, so to make flow equations work, empirical relationships lose their intended meaning. The total pore volume, tortuosity of inter-particle pores, pore structure, and configuration are critical factors affecting the flux and storage of water in peat. These properties strongly control the resistance to flow, since decreased pore-size reduces the hydraulic conductivity (Quinton et al., 2008). In this research the frequency (i.e. number of pores) and morphology characteristics (i.e. pore volume and surface area) for each separable inter-particle pore are measured using 3D measurements derived from X-ray MicroCT scans to indirect estimation of the unsaturated hydraulic conductivity of peat. Using this estimation, we investigate how the size and geometry of pores and the physical properties affect the flow through peat soil.

In summary, in this study, estimates of unsaturated hydraulic conductivities were made for the purpose of testing the sensitivity of pore shape and geometry parameters on the hydraulic properties of peats and how to evaluate the structure of the peat and its affects on parameterization.

Responses to Specific Comments:

Page 3836, line 3, “peat structure which affects the air-filled porosity, pore size distribution and shape”. Surely, this should be the other way round; ‘structure’ is a term that

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describes porosity, pore shape, size and connectivity, bulk density and other physical properties of a soil.

- This sentence has been rewritten as:" The hydraulic conductivity of unsaturated peat soil is controlled by the air-filled porosity, pore size and geometric distribution as well as other physical properties of peat materials."

Page 3836, lines 9-10, "that pore distribution is dominated by a single large pore-space". I don't follow. Do the authors mean the flow of water through the soil is dominated by the single, large pore? What do they mean by 'pore distribution'? Are they referring to a single metric or measure of the pore size distribution?

- The dominance of a single pore is not unique to peat soil, and also occurs in mineral soils, and rock. For example, andesitic lava samples may contain large 3D pore clusters that account for >99% of the total porosity (Nakahima and Kaymiya, 2007). However, peat soils are unique in the sense that the single large pore-space dominates a total porosity which is approximately 2 to 3 times larger than that of mineral soils, and 4-times larger than that reported by Nakahima and Kaymiya (2007) for rock. For peat soils, a single large pore implies a more effective flowpath due to a greater degree of hydraulic connectivity among different soil regions, lower tortuosity of connected pores (Quinton et al., 2009).

In terms of pore size distribution the authors are referring to the cumulative pore volumes of all pores (an example of this is shown in Figure 3 of the Quinton et al., 2009).

References: Nakashima, Y., Kamiya, S., 2007. Mathematica programs for the analysis of hreedimensional pore connectivity and anisotropic tortuosity of porous rocks using X-ray computed tomography image data. Journal of Nuclear Science and Technology 44 (9), 1233–1247.

Quinton, W. L., Elliot, T., Price, J. S., Rezanezhad, F., and Heck, R.: Measuring Physical and Hydraulic Properties of Peat from X-ray Tomography, Geoderma, 153, 269-277,

2009.

Page 3837, line 10, “The reduction in the total porosity with depth is minimal, ”. I disagree; typically, total peat porosity declines from >0.95 in new peat litter (proto-peat) to ∼0.8 in welldecomposed, compressed peat. Such a change is not negligible.

- The sentence has been rewritten as: “The reduction in the total porosity with depth is small compared with the reduction in active porosity, while the . . ..”

Page 3837, lines13-15. Okay, but studies have shown that hydraulic conductivity (K) does not necessarily show a monotonic decline with depth. For example, Beckwith et al. (2003) (which is cited by the authors) showed that K varies dramatically with depth, and concluded that there was not a simple relationship between K and depth.

- The sentence has been rewritten as: “With the reduction in active porosity and decrease in pore size, the saturated hydraulic conductivity of peat typically decreases by several orders of magnitude between the ground surface and a depth of ∼0.5 m (Hoag and Price, 1995; Quinton et al., 2008). Although, some studies report that layering of peat and other factors give a more complicated relation between hydraulic conductivity and depth (e.g. Beckwith et al., 2003).”

Page 3839. I think the study of Kettridge and Binley (2008) should be cited somewhere in this part of the introduction because they went beyond thin sections and were able to construct metrics of Sphagnum stem and branch size and orientation (which in turn affect pore size and orientation) in a peat apparently similar to that studied by the authors.

Reference: Kettridge, N., and Binley, A. 2008. X-ray computed tomography of peat soils: measuring gas content and peat structure. Hydrological Processes, 22, 4827-4837, doi: 10.1002/hyp.7097.

- This study (Kettridge and Binley (2008)) is now cited in the final version.

Page 3840. It would be helpful to know more about the soil. Of what species of

Sphagnum was it composed? What other plant species were present. What did its decomposition profile look like? If the authors have any photographs of the block, then it would be useful to include one in a revised paper so readers are able to compare it with the profile of other peats. It would also be useful if the authors could justify briefly why they looked at this particular peat type.

At Scotty Creek, the major peatland types include peat plateaus, flat bogs and channel fens (Quinton et al., 2003), however, this study focussed on the peat plateaus because of their importance to runoff generation (Quinton and Hayashi, 2005). Peat plateaus support a diverse vegetation community that includes four tree species (Picea mariana, Larix laricina, Pinus contorta, Betula papyrifera), fifteen shrub species (predominantly Betula, Ledum, Kalmia and Salix), sixteen species of lichen (predominantly Cladina), thirteen species of bryophytes (predominantly Sphagnum), in addition to species of vine, club-moss, fungi, liverwort, sedges, grasses, aquatic plants, horsetails and wild flowers (Quinton et al., 2008). Underlying the vegetation is sylvic peat containing dark, woody material, and the remains of lichen, rootlets and needles. The organic cover contains an upper layer of living and vegetation and fibric peat, underlain by a darker, sylvic layer in a more advanced state of decomposition. The thickness of the upper layer is highly variable, but typically between 0.15 and 0.2 m. This type of peat occurs throughout the arctic and because of the similar botanical origin, the peat that is produced has similar range of pore sizes and therefore water conductance and storage properties.

Refrences: Quinton WL, Gray DM. 2003. Subsurface drainage from organic soils in permafrost terrain: the major factors to be represented in a runoff model. In: M. Phillips, S.M. Springman and L. Arenson (Editors), 8th International Conference on Permafrost. A.A. Balkema Publishers, Zurich, Switzerland, 6 p.

Quinton, W. L. and Hayashi, M.: The flow and storage of water in the wetland-dominated central Mackenzie Rriver basin: Recent advances and future directions, in: Spence C, Pomeroy, J.W., Pietroniro, A., (editors), Prediction in ungauged basins:

Approaches for Canada's cold regions, Canadian Water Resources Association, 45-66, 2005.

Quinton, W. L., Hayashi, M., and Carey, S. K.: Peat Hydraulic Conductivity in Cold Regions and its Relation to Pore Size and Geometry, Hydrological Processes, doi: 10.1002/hyp.7027, 2008.

Page 3841. Why did the authors look at horizontal hydraulic conductivity? I would have thought that most unsaturated water flow in bog or Sphagnum peats is vertical or approximately vertical. We know the latter from field and laboratory observations that show that rainfall is relatively rapidly transmitted through the unsaturated zone, which leads to water-table rise, with subsequent water-table lowering occurring in response to horizontal seepage below the water table and in response to evaporation and transpiration (e.g. Hayward and Clymo, 1982; Kettridge and Baird, 2007 and 2008). It seems somewhat odd (to me at least) that vertical K was not looked at.

References: Hayward, P. and Clymo, R. 1982. Profiles of water content and pore size in Sphagnum and peat, and their relation to peat bog ecology. Proceedings of the Royal Society of London, Series B, 215, 299–325.

Kettridge, N., and Baird, A.J. 2007. In situ measurements of the thermal properties of a northern peatland: Implications for peatland temperature models. Journal of Geophysical Research, 112, F02019, doi:10.1029/2006JF000655.

Kettridge, N., and Baird, A.J. 2008. Modelling soil temperatures in northern peatlands. European Journal of Soil Science 59, 327-338, doi: 10.1111/j.1365-2389.2007.010000.x.

- Please see above explanation for response to second general comment.

Page 3841, line 21. Q is defined by its units (mL s-1), but A, h, and L are defined by their dimensions. Only one or the other should be used.

- It is now corrected in the final version of the article with all is dimensions. Thanks.

Page 3842, line 20. There is a superfluous space and comma on this line. Are the air bubbles referred to those trapped in the quasi-saturated peat below the water table?

- Done. Extra commas are deleted. We had no a water table!. The air bubbles were trapped in pockets of saturated soil within the peat samples as they were wetted and during drainage. In peat sample preparation in laboratory, the sample was saturated from the bottom, and the procedure took several hours as care was taken to minimise the formation of air bubbles.

Page 3843, line 8. Was any attempt made to distinguish between the solid (peat) phase and the liquid phase?

- Because of the close relationship of water and cellular plant material, there is currently no lab-based bench-top X-ray CT imaging system commercially available, to which this author is aware, that could segment out the organic peat (inclusive of hyaline cells) from the surrounding water with a degree of verisimilitude that would suffice for consideration in a scientific paper, which is ultimately dependent upon the highly integrated nature of vascular peat and water. For a more complete exploration of the possible approaches please see Kettridge and Binley (2008), wherein a dual energy system and tracers were utilized in an attempt to visualize (not quantify) peat structure and pore space at a moderate resolution of 100 micrometers. The only systems capable of accomplishing such a separation would be extremely low energy (which have an inherently high signal-noise ratio that could mask the desired separation even with increased imaging times and image stacking), or a monochromatic source (i.e. synchrotron, which have limitations to sample sizes) x-ray units. We used a procedure that is based on the grey-level histogram, where the user applies a threshold value developed by the Elliot and Heck (2007) method, which operates on the equiprobability point that separate the grey level classes associated with solid and voids. For more details of the applied threshold algorithm, please see Elliot and Heck (2007).

Reference: Kettridge, N., and Binley, A. 2008. X-ray computed tomography of peat soils: measuring gas content and peat structure. Hydrological Processes, 22, 4827-4837, doi: 10.1002/hyp.7097.

Elliot, T. R. and Heck, R. J.: A comparison between 2D vs 3D thresholding of X-ray CT imagery. 2007. Canadian Journal of Soil Science, 84, 4, 405-412.

Page 3843, line 27, “before analysing the pore distribution analysis”. I recommend re-phasing; ‘analysing an analysis’ is an awkward expression.

- “analysis” is now deleted.

Page 3844, line 19. This should read “points that separate” or “point that separates”.

- “point that separate” is now replaced by “point that separates”.

Page 3844, line 23. Kettridge and Binley (2008) used lead (II) to help distinguish between the solid and liquid phases. Have the authors tried anything similar? Clearly, it would be useful to be able to image the whole pore network and to analyse that part of it in which water resides during drying so see if the peat behaves according to classical capillarity theory.

- The authors have previously utilized potassium chloride and iodine based tracers for binding to the starch component of the peat structure, and arrived at much the same conclusion that Kettridge and Binley (2008) have where “. . .visualization of the Sphagnum leaves appears an unrealistic goal with more widely available CT technology.” Considering that the hyaline cells can alter the flow pathway of a peat pore network, and that they currently are difficult to distinguish from the pore volume, it was decided that analyzing the air void under successive pressure heads would identify a significant portion of the functional pore network after a simulated flow event.

Page 3845, line 19, “little variation among them [the peat subsamples] in terms of their physical and hydraulic properties” (my parenthess). I find this surprising, given that the total porosity of the middle was substantially lower than the upper and lower subsamples (0.863, compared with 0.955 and 0.933).

- The middle sample was a bit anomalous because it contained some large woody fragments (roots?) that had the effect of lowering the porosity below the samples above and beneath it. Except for the roots, the rest of the sample (fibrous peat) was hard to distinguish from the other two samples.

Page 3846, line 20. “Rp is the pore radius factor measured between 0.001 to 2.36 cm”. I don’t follow what the authors are trying to say here. What is meant by “measured between 0.001 to 2.36 cm”? Do they mean the pore radius factor varies between the two values?

- The pore radius factor was calculated using equation 7 for each pore. The results showed that the pore radius factor vatries between 0.001 to 2.36 for the small pores and single large pore. The sentence has been rewritten as: “. . . , and Rp is the pore radius factor calculated between 0.001 to 2.36 cm using equation 7.”

Page 3847, lines 16-17. The wording here is unclear. On the one hand the authors seem to be suggesting that flow in the large pore is efficient, while on the other they seem to be saying that the large pore exerts more resistance to flow.

- This single large pore dominate in terms of flow because flow velocity increases with the square of pore diameters. The sentence has been rewritten as: “Therefore, this single large pore imparted a more effective flowpath, when it is saturated, compared to smaller pores and higher resistance to flow, when it is unsaturated, due to a larger air-filled pore space.” For more details of this single large pore space, please see Quinton et al., 2009.

Refrence: Quinton, W. L., Elliot, T., Price, J. S., Rezanezhad, F., and Heck, R.: Measuring Physical and Hydraulic Properties of Peat from X-ray Tomography, Geoderma, 153, 269-277, 2009.

Page 3847, lines 18-19. “All other smaller pores are contributing to the obstruction of flow and their contribution to flow may be neglected when a very large pore is active.”

Would it be better to reword this as follows: “Although smaller pores may contribute to the obstruction of flow, their contribution to flow may be neglected when a very large pore is active.”?

- The sentence is reworded as suggested. Thanks.

Page 3847, lines 22-23. This should read “the single large” (insert ‘the’).

- Done.

Page 3848, line 3. The sentence starting on this line is ungrammatical and would benefit from rewording.

- The sentence has been rewritten as: “Three dimensional CT digital image analysis of peat samples showed that the pore structure and configuration of peat soils are very complex and contains many variables.”

Page 3848, line 9. Why does “Pore” start with a capital letter?

- “Pore” is replaced with”pore”

Page 3848, line 18. Why simultaneous?

- “simultaneous” is now deleted.

Page 3849, line 24. This should read “the Hazen” (insert ‘the’).

- Done.

Page 3850, line 26. This should read “a standard” (insert ‘a’).

- Done.

Page 3851, line 2. I recommend rewording as follows: “drops by a similar amount to the”.

- Done.

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Page 3851, line 24. Sands are mineral soils. The statement here is perhaps too general. I doubt the equations used in this paper apply to some clay soils, especially those that swell and shrink, where flow is dominated by flow through planar macropores. In addition, I recommend rewording this line as follows "in peat soils in which" (insert 'in').

- The sentence is "sands or mineral soils". In conclusions of this article, we explained that "This novel approach is restricted to peat soils used in this study for the range of soil moisture levels that typically occur at the field site over a year. In order to apply this method of analysis, it is necessary to have a reliable direct measurement of pore properties and shape coefficient of pores . . .".

"in peat soils which" is now replaced by "in peat soils in which". Thanks.

Page 3852, line 4. Delete "that".

- Done.

Page 3852, line 22. Delete "developed".

- Done.

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