The Cryosphere
Discussions

Interactive comment on "New insights into the drainage of inundated Arctic polygonal tundra using fundamental hydrologic principles" *by* Dylan R. Harp et al.

Anonymous Referee #2

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Low-centered ice-wedge polygon networks are nearly ubiquitous in Arctic lowlands, and thus a better understanding of ice-wedge polygon drainage patterns (timing and pathways) will inform on such issues as nutrient or carbon flushing from polygons, advective heat transport from polygon centres to the network of ice-wedge troughs that separate the polygons, and possibly on the transition from methane to carbon dioxide emissions with drainage and polygon drying. "New insights into the drainage of inundated Arctic polygonal tundra using fundamental hydrologic principles" by Harp et al. presents an investigation of inundated low-centered polygon drainage using a 3D-axisymmetric analytical model (Zlotnik et al. In Review). The authors purport this paper to be the first one to present a fundamental hydrological investigation of low-centered

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ice-wedge polygon drainage. The authors importantly recognize that "fundamental hydrology dictates that ice-wedge polygon geometry and heterogeneity will explicitly govern subsurface drainage pathways and time spans", and explore the effects of polygon aspect ratio and vertical versus horizontal hydraulic conductivity anisotropy on hydrological dynamics of low-centered ice-wedge polygon drainage.

The model used is presented in another paper that is still under review, so as a reader I am not able to fully assess its merits, but there is a helpful abbreviated set of solutions in the Appendix. The model is based on the authors' assumption that an idealized polygon drainage domain is adequately represented by a cylinder, and that drainage will occur at a "vertical outer boundary" (P15, L255; Figure1). Drainage is allowed to occur uniformly in a ring around the cylinder as indicated by the maps shown of the percent of thawed soil accessed by 95% of the drainage flow (Figs. 2-4 and 9). The effect of aspect ratio on drainage is explored by altering the depth of the cylinder versus its radius. Recognizing that there are heterogeneities in internal hydraulic conductivities, the authors explore the effects of anisotropy by varying the ratio between vertical and horizontal hydraulic conductivities.

The paper is easy to read and results are clearly presented. It is actually quite a straightforward paper with effective figures. There are several minor corrections that I noticed, such as "MacKay" when it should be "Mackay", and the last sentence in the caption for Figure 4 is wrong, but nothing too distracting. I do find the title of the paper to be somewhat misleading as the focus of the work is on drainage of ponded water from within a single polygonal cell rather than drainage of polygonal tundra (the network of cells).

However, despite the generally good presentation, I think that there is a major problem that relates to the representation of the boundary conditions of the model's drainage domain. I began to wonder this as soon as I saw the diagram in Figure 1. The boundary that retains water within low-centered ice wedge polygons is bowl shaped, not cylindrical, and this bowl shape is constrained by the permafrost table that is mirrored in the

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active layer by the frost table as it penetrates into the ground throughout the summer. If the boundary conditions of the model domain reflected a bowl-shaped geometry, there would likely be substantial implications on drainage, such as derived equipotential hydraulic heads or stream function, or the change in volume of ponded water within the polygon, as examples.

Water in a low-centered ice-wedge polygon is retained by the frozen core of the polygon rim, so flow occurs over the frozen rim of the bowl. Logically, the frozen rim of the bowl lowers over the thaw season as frost table progresses deeper into the ground, with drainage accompanying thaw-depth progression. Helbig et al. (2013), referenced by the present authors, indicate that the barrier function of polygon rims is strongly controlled by thaw. In the present paper, however, what each model run solves for is drainage potential of a cylinder full of water with a vertical outer boundary barrier determined by the given polygon thaw depth, L. That is, the model solutions are of "hydraulic heads and stream function in the thawed soil layer below a polygon center" (P6, L150). How can the cylinder retain water to depth L and develop the modelled hydraulic heads and streams if the ground has already thawed completely to depth L? Instantaneous thaw is not realistic. How does the system behave if the thaw occurs progressively downward at the vertical boundary? the model does not appear to be designed for transient boundary conditions, but perhaps transient boundary conditions could be represented by a set of stepwise models.

In any case, no matter how far into the thaw season the system is, water flow will always concentrate at any low spot in the rim of the bowl. This is critical. Wales et al. (2020), who are cited in the manuscript, show that drainage from low-centred ice-wedge polygons is very heterogeneous and preferential flow occurs at locations where the frost table is lowest. They state that "changing elevation of the frost table and its topography", though not shown in their conceptual diagram, "plays an important role in inhibiting infiltration and influencing preferential flow." Thus, the base case for low-centered ice-wedge polygon drainage is high heterogeneity in the polygon outer

boundary condition; however, Harp et al. consider such conditions to be "anomalous heterogeneities" (P4, L98). Instead they assume that homogeneous cylindrical geometry is the base case scenario. The clear demonstration that the focus of drainage at low points in the rim by Wales et al. (2020) breaks down the logic of the importance of aspect ratio in the cylindrical model as presented. Low-centered ice-wedge polygons have preferential flow locations at the rim, and are not dominated by diffuse flow across the entire rim, thus the cylindrical model as presented cannot stand as globally applicable. The overgeneralization of the model renders the results presented in Harp et al. to a limited state of usefulness.

Regarding the internal hydraulic conductivities, the authors recognize that radial and vertical hydraulic conductivities are often different, but it would be much more informative if the model domain were based more on reality and included, at minimum, a 2-layer system with an organic soil over a mineral soil. The authors describe this 2-layer system in the introduction (P. 3, L39), and it is typically the case (see for instance, Figure 1a, Wales et al. 2020). If a 2-layer system were replicated in the model, along with a more realistic boundary layer geometry, perhaps these changes may help explain the hydrology of low-centred ice-wedge polygons as observed in the field. Wales et al. (2020) find that the "general pattern in tracer dynamics in both polygon types was to first infiltrate vertically until it encountered the frost table, then to be transported horizontally, highlighting the influence of the frost table on horizontal flux." It is not clear how such field results can be represented according to the hydrological principals represented in the present model.

Finally, a comparatively minor point, even if there was no focus of flow at low points in the frost table and there was instantaneous thaw, I wondered how much the assumption of a circular planar geometry is really appropriate? An ice-wedge network is a set of polygons. Understandably, a circle is relatively straightforward to model, but most ice-wedge polygons are typically 4- to 6-sided. As the incircle radii for a unit area square, regular pentagon, regular hexagon, and circle are about 0.500, 0.525, 0.537,

and 0.564, respectively, I wondered if aspect ratios and resulting ponded water volumes modelled according to a cylinder should really be used to represent the planar geometry of polygons in the field? In other words, for a unit area, the perimeters of the polygons are greater than the circumference of a circle ($\sim$13% and $\sim$ 8% greater for a square and regular pentagon, respectively), so flow across the outer boundary of the polygon becomes increasingly diffuse as the polygon order decreases. For example, would the estimates of ponded height depletion curves according to radius underestimate depletion rates with respect to natural geometries within polygonal tundra? There may not be that much difference with respect to drainage from a single polygon, but there probably is if one considers a network that is representative of Arctic polygonal tundra.

In summary, the focus of the paper is not really on the drainage of Arctic polygonal tundra, but on drainage of a single cell within Arctic polygonal tundra. The results presented in the manuscript are consistent with the model, but the model is overidealized and does not well represent base conditions of a single low-centred ice-wedge polygon. Therefore, the reader is left to conclude that the results and conclusions have limited implications. Until the above major points are addressed, I wouldn't recommend the paper for publication.

References

Helbig, M., Boike, J., Langer, M., Schreiber, P., Runkle, B. R., and Kutzbach, L.: Spatial and seasonal variability of polygonal tundra water balance: Lena River Delta, northern Siberia (Russia), Hydrogeology Journal, 21, 133–147, 2013.

Wales, N. A., Gomez-Velez, J. D., Newman, B. D., Wilson, C. J., Dafflon, B., Kneafsey, T. J., Soom, F., and Wullschleger, S. D.: Understanding the relative importance of vertical and horizontal flow in ice-wedge polygons, Hydrology and Earth System Sciences, 24, 1109–1129, 2020.

Zlotnik, V., Harp, D. R., and Abolt, C. J.: Edge effect on polygon drainage in permafrost

areas: implications for heat and mass transport, Water Resources Research, In Review.