The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-7-RC1, 2020

The Cryosphere
Discussions

Interactive comment on "Numerical modelling of permafrost spring discharge and open-system pingo formation induced by basal permafrost aggradation" *by* Mikkel T. Hornum et al.

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Received and published: 11 March 2020

Summary:

In this paper, the authors investigate permafrost aggradation and the associated increase in subpermafrost groundwater pressures over millennial scales as the potential cause of pingo springs in a high Arctic valley (Aventdalen, Svalbard). Continuous permafrost, high desert conditions, and a lack of wet-based glaciers in the adjacent highlands preclude recent groundwater recharge as a source of the spring water. Using a 1D heat flow model the authors quantify potential rates of permafrost aggradation. This aggradation is then related to a water flux which is applied as recharge in a 3D ground-

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water flow model. These processes are fully decoupled. The groundwater flow model represents the steady state flow of groundwater to the pingos (and the adjacent Fjord) that results from the additional subpermafrost water flux. Although validating field data is limited to sporadic spring flow measurements and hydraulic head measurements at a single borehole, what is available is compared to this data to support the development of the model and the proposed conceptualization of the pingo spring flow.

The mechanism proposed by the authors is new, and their use of numerical models to illustrate and quantify this mechanism is of value. The discharge of subpermafrost groundwater to the surface has the potential to introduce methane to the environment and other solutes to freshwater systems. Understanding of the mechanism that generates the driving hydraulic heads in a variety of geological settings improves our ability to forecast future conditions under a changing climate. Overall the conceptual model and the numerical approach is well presented. However, the paper gives the sense that the modelling work proves the conceptual model to be correct. In general, assumptions are made in numerical modelling to align the numerics with the conceptualization. The modelling presented in this paper is no different, and as such, the model output does not prove the conceptual model to be correct. Some factors that warrant further investigation to support the numerical modelling assumptions are detailed below. Value could be added to the paper by using the model to further explore the physical factors required to form pingo springs under this conceptual model.

The boundaries of the numerical groundwater flow model create a closed "bathtub" like system. Although the amount of recharge added is quite low (<1 mm/year), the presence of permafrost throughout the top of the model domain, a lower boundary that is within 100 m of the base of the permafrost, and no flow across lateral boundaries, leaves only the Fjord and the pingo springs as discharge points. Additional details, or discussion would be useful in supporting the boundary selection for the groundwater flow model as follows:

- The paper investigates the effect of the lower boundary position by lowering the model depth by 100 m. A more illustrative demonstration of the effect of the lower boundary may be to lower the boundary to the detachment zone that separates the upper overpressured and lower underpressured groundwater flow systems (i.e., to a depth where there is field evidence of a no-flow boundary);

- There is no evidence provided for the presence of hydraulic divides at the flanks of the valley that would support the use of lateral no flow boundaries in the groundwater flow model as specified. This boundary prevents any regional flow in to or out of the valley. Were groundwater flow to follow the modest slope of the formations, flux through the Festningen Member may be sufficient to dissipate the recharge flux specified in the model. If field data is not available, the sensitivity of model results to deeper regional flow across the valley should be explored;

- As stated by the authors, the drain boundaries used to represent the pingo springs are placed within the upper most active cells closest to the spring, but within the Festningen Sandstone. Additional details and discussion of this placement would be of use. Figure 2(a) and Figure 4 indicate that the sandstone is not present at the Innerhytte Pingo. Figure 7 shows that the drain associated with the Førstehytte Pingo is opposite the valley axis from the surface expression. It is understood that the fractured nature of this sandstone could permit the required subhorizontal flow to the pingo; however the paper would benefit from additional discussion of this conceptualization (what is the inferred orientation of the fracturing that allows formation of the pingos). The sensitivity of the model results to the geological unit that the drain boundary is placed in should be discussed;

- The boundary representing the Fjord is described as being applied to the relevant cells. Please describe this assignment in more detail (are the boundaries assigned to the upper most active layer only, or are they assigned to several layers to the approximate seafloor depth in the Fjord). As the boundary at the Fjord represents the highest flux from the model (approximately 40% to 90% of the total flux) model results can be expected to be very sensitive to the vertical location of this boundary, and should be investigated further; and,

- The potential for subpermafrost discharge to the Adventdalen River has not been considered in the conceptual model development. Rossi et al. (2017) suggest that this discharge may occur near the Innerhytte Pingo. Although the rate of subpermafrost discharge to this River may be low, the potential for it to occur should be considered in the overall balance of flows.

In general, further investigation of the effect of these various boundary conditions on the groundwater model results are required before it could be concluded that the model results show that the basal permafrost aggradation produces the hydraulic pressures to sustain the pingo spring water outflows as the authors have stated at the start of Section 7.

The observed hydraulic head at DH4 is stated to range from 9 m to 60 m above hydrostatic. It is unclear if this range is due to temporal variability, or the range in the correction for the effect of dissolved gasses. With limited field data for model validation, this warrants further discussion. As shown on Figure 7 (2a, 3b, 3a) simulations in which the hydraulic head at DH4 is on the lower end of this range (and with the lower to middle recharge flux) do not produce sufficient flow at the pingo springs.

The equivalent recharge applied to the model ranges from 25.4 m^3 /day to 56.7 m^3 /day. This range is related to the porosity of the formation through which permafrost aggradation is occurring. Based on the 1D columns shown on Figure 4, and the model results shown on Figure 5, much of this aggradation would occur within the shale units. The porosity of the Janusfjellet subgroup has been derived from Manger (1963). How was the range from 0.1 to 0.3 selected from the values provided in Manger (1963). The higher porosity units in this reference are related to high clay content shales or claystones. Is this valid for the Janusfjellet formation? Given that the higher porosity

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ranges were required to produce a water flux that could sustain the pingo flows, further details should be provided on the derivation of these values.

How is the lower boundary of the 1D heat transfer model specified? If the geothermal gradient from surface is maintained, does that imply that temperature of the lower boundary changes with time? How would the rate of permafrost aggradation be changed if the depth of the 1D model was extended such that the heat flux at the bottom boundary could be kept constant through time? How would a cessation of permafrost aggradation up valley effect results?

In Table 3, the rock unit hydraulic conductivities derived from literature (the Festingen sandstone, the Janusfjellet subgroup, and the detachment zone) range within one order of magnitude across the three scenarios. While this could be considered a large range in this type of study, comparison to the observed hydraulic head at DH4 indicates that Scenario 1 (low hydraulic conductivity) values are unlikely, leaving a more reasonable half order of magnitude range. For the rock units with field data (the Carolinefjellet and Hevetiafjellet formations), the hydraulic conductivities applied range over two orders of magnitude. Does this range represent the maximum and minimum of tested values? It would be of value to plot the probability density function for the hydraulic conductivity values for each formation, selecting the geometric mean as scenario 2, and a more realistic percentile as scenarios 1 and 3 to tighten the potential range for these formations. As stated on line 406, the hydraulic conductivity is the most important parameter in determining the distribution of outflows between the pingos and the Fjord. Assignment of this parameter should be constrained where possible.

On line 515 it is stated that the steady-state assumption for the groundwater flow model results in an underestimate of the present-day pressures. This statement may oversimplify the transient groundwater dynamics that could occur as permafrost aggrades and the sea level retreats. Permafrost aggradation is highest in proximity to the Fjord, which is also where the greatest potential for discharge to the Fjord occurs. It is possible that any excess pressure would be dissipated as the sea level retreats, and that a transient simulation may not show higher pressures.

On line 635 it was stated that simulated flows to the pingo springs are likely underestimated as basal permafrost aggradation outside of the model domain is not included. Were this aggradation to contribute to the pingo spring flows, it would imply that the lateral boundaries of the model domain are not hydraulic divides (i.e., no flow boundaries). This statement should be reconciled with the boundary selection.

Technical Corrections:

Line 13: ...wet-based glaciers ***are not present*** in the adjacent highlands

Line 18: ..and groundwater (***3D*** -Steady-state)

Line 229 Equation 1: The δz in the denominator should be δz^2

Line 235: ...heat conduction will flow ***heat will be conducted*** through a matrix of ***solids (i.e sediment or rock)*** and ***liquid water***, ice or a mixture

Line 288: ..The fraction of ***liquid*** water

Line 247: ...When temperature change occur***s***

References

Rossi, G., Accaino, F., Boaga, J., Petronio, L., Romeo, R., Wheeler, W., 2018. Seismic survey on an open pingo system in Adventdalen Valley, Spitsbergen, Svalbard. Near Surface Geophysics 16, 89–103. https://doi.org/10.3997/1873-0604.2017037