October 13, 2020

We thank reviewer Dr. Sean Carey for his thoughtful reviews of our invited perspective manuscript, "What Lies Beneath a Changing Arctic?".

Following are Dr. Carey's comments in italics, followed by our response in blue.

The paper by McKenzie and co-authors brings together leaders in cryohydrogeology to provide an invited perspective on how thawing permafrost will influence groundwater in cold regions. They touch on a number of key issues and then present recommendations for future research. Perspective papers are always worthwhile, as it makes the reader reflect on the opinions expressed and more thoughtfully consider issues that may have been ignored by the broader community. They argue that cyrohydrogeology should be included more in transdisciplinary research initiatives. Very fair.

There is little doubt that groundwater is a critical aspect for understanding hydrological and chemical change in permafrost regions as the world warms. The authors state that it has been limited work in the past decade (line 114), but the issue of permafrost thaw and changes to groundwater has in fact been of interest for many decades now, and while cryohydrogeology is a new term, Van Everdingen, Michel, and others made strong advances in this field over three decades ago. Ultimately, and I agree with the authors, very few people actually study northern groundwater. In contrast to ecological studies in the north, there has not been an 'explosion' of research in hydrogeology (or hydrology for that matter), and in some ways this has deprived earth system modellers and others of a more nuanced understanding of change.

Yes, we agree there has been extensive previous research focused on groundwater in cold regions. In fact, much of the basic theoretical underpinnings of our current understanding are based on research from the 1970s. What is different now is the inclusion of climate change as a strong driver of changing groundwater conditions. Recently, it seems every week there is a new high-profile report, study or news article on the impacts of warming on the Arctic ecology or greenhouse gasses [e.g. 1], but the ecohydrology linkages due to changing surface water and groundwater are usually missing. Hence, part of the motivation for this manuscript. We will add text indicating how our work builds on the historical foundations of Williams, van Everdingen and others [e.g. 2].

I very much enjoyed reading this article. There have been good review articles on this topic, yet this one is more of an 'agenda setting' document which is nice. That said, and in the spirit of discussion, I have a number of comments that I would like the authors to consider. Perhaps they believe they are out of scope, but this is simply what came to mind after reading the manuscript several times.

+ Is it important to mention that other changes, notably precipitation phase, rate and timing may influence baseflow? This along with the unknown effects of vegetation change? People have long argued

[1] Harvey, C.: A New Arctic Is Emerging, Thanks to Climate Change, Scientific American, https://www.scientificamerican.com/article/a-new-arctic-is-emerging-thanks-to-climate-change/, 2020.
[2] Williams, J. R. and van Everdingen, R. O.: Groundwater investigations in permafrost regions of North America: a review, in Permafrost: North American Contribution to the Second International Conference, pp. 435–446, National Academy of Sciences, Washington, 1973.

that thawing permafrost influences baseflow (of course), but are there other mechanisms that can explain some of this?

Given the strong physical basis for thaw-induced baseflow enhancement, pervasive positive trends in baseflow observed across pan-Arctic permafrost regions, and the contrasting lack of pervasive patterns in precipitation metrics, vegetation change (including wild fires[3]) across pan-Arctic permafrost regions, we contend that permafrost thaw is a primary driver of increased baseflow [e.g. 4]. That said, we appreciate the reviewer's point. The secondary influence of changes in precipitation and vegetation that affect recharge magnitude and seasonality on baseflow in permafrost regions has yet to be well-established and deserves a mention in the revised manuscript.

+ The authors indicate that earth system models (largely land surface models with biogeochemical processes included) ignore croyhdrogeology. This is largely true! However, cryohydrogeology models largely ignore land surface and biogeochemical processes (particularly with regard to carbon). Surely it is not just the ESM's fault here. Parameterization and incorporation of processes into larger ESM are often incongruent with the granularity that hydrogeological models operate. My comment here is that is this really someone ignoring the issue or not having appropriate tools/guidance on how to address it?

+ Similarly, there are hydrogeological models that ignore freezing/thawing processes that are widely used. This group is well aware of this as they are associated with intercomparison projects.

This is an excellent comment. There is often a gap between the local-scale abiotic cryohydrogeology modeling approaches and the more biochemical ESMs. While we make the case to the ESM community to 'please include groundwater processes!', we will also change the manuscript to note that there is a clear need also for the groundwater community to:

(1) include the transport of solutes, including carbon. There has been some research on this topic, such as Vonk et al. (2019)[5]. Further, there are numerous present initiatives, by some of the co-authors of this paper and others, to include solute transport processes into cryohydrogeologic models.
(2) develop conceptual and numerical methods to incorporate groundwater within ESMs. On the side of catchment scale hydrology and hydrogeology of cold regions, recent advances in cryohydrogeological modeling [e.g. 6,7] can form the basis for inclusion of lateral processes into Arctic climate change simulations or to build spatially distributed reference cases for upscaling projects.

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[3] Rey, D. M., Walvoord, M. A., Minsley, B. J., Ebel, B. A., Voss, C. I. and Singha, K.: Wildfire-Initiated Talik Development Exceeds Current Thaw Projections: Observations and Models From Alaska's Continuous Permafrost Zone, Geophys Res Lett, 47(15), doi:10.1029/2020gl087565, 2020.
[4] Qin, J., Ding, Y., Han, T. and Liu, Y.: Identification of the Factors Influencing the Baseflow in the Permafrost Region of the Northeastern Qinghai-Tibet Plateau, Water-sui, 9(9), 666, doi:10.3390/w9090666, 2017.
[5] Vonk, J. E., Tank, S. E. and Walvoord, M. A.: Integrating hydrology and biogeochemistry across frozen landscapes, Nat Commun, 10(1), 5377, doi:10.1038/s41467-019-13361-5, 2019.
[6] Grenier, C., et al.: Groundwater flow and heat transport for systems undergoing freeze-thaw: Intercomparison of numerical simulators for 2D test cases, Adv Water Resour, 114, 196–218, doi:10.1016/j.advwatres.2018.02.001, 2018.
[7] Dagenais, S., Molson, J., Lemieux, J.-M., Fortier, R. and Therrien, R.: Coupled cryo-hydrogeological modelling of permafrost dynamics near Umiujaq (Nunavik, Canada), Hydrogeol J, 1–18, doi:10.1007/s10040-020-02111-3, 2020.

+ There is a recent LSM-based paper (Teuful and Sushama 2019) that discusses infrastructure and permafrost thaw. I am curious as to why it is not included on the list? Is it because the LSM largely simulates something that has never been seen and permafrost scientists do not believe the results? This of course reveals my bias for field investigations to advance our understanding of processes. I am often bemused by LSM outputs with sweeping and startling results that are often model artifacts.

We did not cite the publication by Teuful and Sushama[8] as it has led to some disagreement as to the veracity of the results [9,10]. The manuscript uses a LSM to simulate soil drainage and permafrost thaw, and the resulting impact on Arctic infrastructure. Much of the subsequent discussion focused on how subsurface drainage is represented when permafrost thaws and the realism of the results. The paper is an example of the previous comment regarding the need for two-way communication between groundwater focused researchers and the land surface modeling community, and to include lateral water flow and transport.

+ Would it be helpful to define Arctic? Simply because the issues discussed here are perhaps even more pressing in the subarctic.

Yes, we will include a definition of our usage of *Arctic* in our revised manuscript. Our definition is broad and is probably best defined as the region north of the southern limit of the discontinuous permafrost zone. Essentially regions that have the presence of perennially frozen ground.

+ On Line 85 you state 'rapidly changing groundwater conditions'. Can the authors give an indication of how rapid is rapid? Climate is changing rapidly which immediately affects surface hydrology - can an indication of 'how far behind' the subsurface is be touched upon.

For shallow groundwater systems with little to no data, the best inference of changing groundwater systems is changing patterns of surface water systems (e.g. winter baseflow). Winter baseflow patterns have been observed to be changing over the past few decades, so the changes are happening on a decadal scale [e.g. 11, 12]. It is not clear that changes in shallow groundwater is lagging surface water change. Further, these systems have been in disequilibria for decades, and are continuing to change in response to ongoing climate change. Changes in hydrometeorology are linked to baseflow and vice versa, and the surface water systems may or may not be changing simultaneously.

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[8] Teufel, B. and Sushama, L.: Abrupt changes across the Arctic permafrost region endanger northern development, Nat Clim Change, 9(11), 858–862, doi:10.1038/s41558-019-0614-6, 2019.
[9] O'Neill, H. B., Burn, C. R., Allard, M., Arenson, L. U., Bunn, M. I., Connon, R. F., Kokelj, S. A., Kokelj, S. V., LeBlanc, A.-M., Morse, P. D. and Smith, S. L.: Permafrost thaw and northern development, Nat Clim Change, 10(8), 722–723, doi:10.1038/s41558-020-0862-5, 2020.
[10] Teufel, B. and Sushama, L.: Reply to: Permafrost thaw and northern development, Nat Clim Change, 10(8), 724–725, doi:10.1038/s41558-020-0861-6, 2020.
[11] Walvoord, M. A., Voss, C. I., Ebel, B. A. and Minsley, B. J.: Development of perennial thaw zones in boreal hillslopes enhances potential mobilization of permafrost carbon, Environ Res Lett, 14(1), 015003, doi:10.1088/1748-9326/aaf0cc, 2019.
[12] Evans, S. G. and Ge, S.: Contrasting hydrogeologic responses to warming in permafrost and seasonally frozen ground hillslopes, Geophys Res Lett, doi:10.1002/2016gl072009, 2017.