December 3, 2020

Dear Dr. Isaksen,

We are excited to submit the final revision of our Invited Perspective for The Cryosphere entitled “What Lies Beneath a Changing Arctic?”

As described in our Responses to the Reviews, we have made numerous small changes to the manuscript. Additionally, we have made a few very minor changes and clarifications during our reread of the manuscript. These include some grammatical changes suggested by a USGS copy editor that improve readability.

On the following pages are:

1) the Review Response with the corresponding line numbers of the changes.
2) The manuscript edited with tracking changes, showing all the changes made to the manuscript.

Should you have any questions, or require additional changes please contact me.

Sincerely,

Jeffrey McKenzie

Earth and Planetary Sciences
McGill University

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].

Change made to
Line 43 + References

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.

Change made to Line 59-60.

+ 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.

Changes made in Line 135

---

[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.

No change required.

+ 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.

Change made to line 32.

+ 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.

No change required.

---

[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.

October 13, 2020

We thank reviewer Dr. Anatoly Sinitsyn for his thoughtful review of our invited perspective manuscript, “What Lies Beneath a Changing Arctic?”.

Following are Dr. Anatoly’s comments in italics, followed by our response in blue.

The article by McKenzie and co-authors provides philosophical view on the main impacts of groundwater in changing climate in three research areas, namely contaminant transport, modification to water resources, and infrastructure in permafrost conditions. The authors perform "screening" of the effects of groundwater on mentioned above research areas and point out the main consequences. The authors point out the factor of groundwater is overlooked in the analysis of those research areas, and conclude that this needs to be taken into account when setting the research agenda. I agree with the authors.

I may suggest to mention the cascading effects of new knowledge which the authors suggest to develop (in contaminant transport, modification to water resources, and infrastructure) on sustainable development of societies in the Artic. Obviously, the new knowledge build on better consideration of groundwater will help to mitigate the climate change impacts, and will make the Arctic societies more resilient. This would be useful to highlight, especially seeing that this article is aiming not only to scientists, but also to the authorities setting the scientific/research agenda.

The comments I provided are aiming to strengthen the article. I did not find critical point in the article, which I would not accept. Please find my comments in attached PDF.

We thank the reviewer for their comments and suggestions. Yes, we agree that incorporation of groundwater management (and how it impacts infrastructure and hydrology) must be part of sustainable development initiatives in the Arctic. We will add text to the revised manuscript to address a broader management framework. Changes to lines 143.

General scientific comment/wish: Line 26 or 35: I am lacking a sentence or paragraph explaining in more details the reasons behind appearance/activation of the phenomena of groundwater for permafrost. I.e., a link which connects groundwater to the atmospheric processes of higher hierarchy – warming of air temperatures, increase of precipitation, changes in snow patterns (more snow > warmer permafrost) and the permafrost thaw.

Yes, we agree a clearer description of the linkage between warming and permafrost thaw is required and will include such information, including possibly an additional figure, in addition to the new text from previous comment. Text added to line 37.

Specific scientific comment (see comments to #2.3 in PDF). I have got an impression, that thoughts the authors provide in #2.3 present the impacts of groundwater on infrastructure as something, in a way, new and unexpected/overlooked. It is not always the case. Issues with drainage, needs to reroute excess water, flow of groundwater beneath the structures, eventual floorings along the roads, issue with icings – all such issues usually arise from errors in the initial site investigations/design/constriction/maintenance.

These issues may be amplified by the climate change, but the design approaches are normally conservative and able to handle the impact of climate change. These points are reflected in my comments.

While engineering designs are inherently conservative, there are numerous examples, including work from coauthors of this manuscript[1], of situations where warming and permafrost has led to unanticipated engineering challenges. We are amenable in adjusting the text in specific instances in response to the reviewer's comments below.

No text change required.

In lines 83-85 authors point out that "infrastructure designs that typically rely on historical climate information to engineer necessary risk averting measures are becoming increasingly insufficient to keep pace with rapidly changing groundwater conditions". Would it be the case for the methods utilizing downscaled GCM (see for instance, (Instanes 2016; Incorporating climate warming scenarios in coastal permafrost engineering design – Case studies from Svalbard and northwest Russia)?

Yes, we agree that downscaled GCMs would be a potentially better method for forecasting future conditions.

Instanes now cited on line 83. Further text added to line 90 and 91.

Comments from annotated manuscript.

Line 14: General public might understand your phrase as energy goes by "itself", but not transferred by moving water. Just a suggestion, consider to edit: ..."for movements of ground water, which moves energy and solutes".

Agreed. We will make this change. We would use "transport" instead of "moves".

Change made in line 16.

Line 15: I would not call it "phenomena", consider using "consequences". To me (PhD in geotechnics), enhances rates of infrastructure damage is not a phenomena, it rather a consequence of errors (design/construction/maintenance) or consequences of applying design philosophies, which appeared to be inadequate (big research question if this can really be the case). But it perhaps OK using phenomena from the formal point of view.

We agree that "consequences" is a better term and will change text accordingly.

Changes made to line 18.

Line 19: I think that "included" is not fully current. I understand that the authors want to amplify(?) their main point by this word. However, I do not think that groundwater was practically absent in the research initiatives (I do not have a 100% overview of the initiatives), but think there might have been some. Hence, I would suggest pointing out that attention to GW shall be increased in the initiatives. But if there were indeed no initiatives then please keep the phrase as it is.

Agreed. This comment echoes that of comments from Reviewer 1. We will emphasize that cold regions groundwater research is not new, but that with climate change this research has new and evolving importance. To reiterate, it was not our intention to say that there has been no previous research in this

---

[1] Chen, L., Fortier, D., McKenzie, J. M. and Sliger, M.: Impact of Heat Advection on the Thermal Regime of Roads Built on Permafrost, Hydrol Process, doi:10.1002/hyp.13688, 2019.

field, but that as we think about northern change we need to consider featuring groundwater change as a more prominent part of the story. Changes made to Line 21.

Line 29: Here or after the line 35: I am lacking a sentence or paragraph explaining in more details the reasons behind appearance/activation of the phenomena of GW for permafrost. I.e., a link which connects GW to the atmospheric processes of higher hierarchy – warming of air temperatures, increase of precipitation, changes in snow patterns (more snow > warmer permafrost) and the permafrost thaw.

Yes, as described above we will make this change. Changes made to line 38.

Line 63: Term "coastal ocean" is absent in the arctic coastal studies dealing with engineering and coastal dynamics (coastal erosion). I do not know whether this term is used by the Ecology. Consider using "littoral zone of the ocean".

Coastal ocean is very common in oceanography literature, but we will change the term to coastal waters to be broader than the littoral zone.

Changes made to line 67.

Line 74: I do not think that the term "overlooked" should be used here. In case if such flow is present on a site then it means that it is a consequence of an error in design/construction/maintenance on the site. Engineering design in permafrost shall assure good drainage around the buildings. Hence, GW is not a factor in foundation design of buildings in permafrost as it is eliminated by the general design approaches. This can be different for design of dams, culverts, even road pavements working partly as dams.

Yes, in some cases groundwater is not a concern for design/construction/maintenance. In our experience in northern Canada, groundwater is included but *changing* groundwater regimes are often not included in geotech designs. We will adjust our wording of this sentence to ensure that we do not overstate the case.

Changes made to line 83.

Line 80: Which may point out that the initial design was wrong.

Line 80: Again, this should be revealed during the initial site investigations, then this will not appear as a surprise at the exploitation stage. But sometimes presence (known well before initiation of the project) of icings is simply disregarded in the design.

Yes, we agree that engineering design should account for groundwater systems, including features such as icings. That said, there are many examples we are familiar with where these factors are not properly accounted for. Further, in some settings, features such as icings may change in location from year to year creating further challenges.

No change required.

Lines 83-85: Please support with a reference or rephrase by presenting this point as a hypothesis. Is your suggestion relevant to the methods using downscaled GCM (as for instance (Instanes 2016, Incorporating climate warming scenarios in coastal permafrost engineering design – Case studies from Svalbard and northwest Russia)

We are not in complete agreement that our statement requires a reference. We are simply saying that if historical data were used to project future climate changes without incorporating the dynamics and mechanisms of the changing hydrologic system, the extrapolated result would likely underestimate the change. That said, we will include a refence to support this argument.

Changes made to line 90 and references.

Line 85: Lines 85-86: This may be the case for some infrastructures located in the areas with specific site conditions (drainage issues, ground ice content, thickness of unlithified sediment on slope terrain) where groundwater is an important factor for thermal regime of permafrost and/or stability of terrain; or, in broader sense, in the regions with high levels of precipitation now and even higher in the future. But there are site conditions where precipitation/groundwater will not have such impact (lithified sediment, low ice contend, good drainage). Hence, such scenario/prediction is not relevant for the whole Northern infrastructure. I suggest you to point out that it is relevant only for some infrastructure/infrastructure under certain conditions.

See response above to Line 74 comment.

No change required.

Line 89: Fully agree, but for certain problems (water retaining structures, etc.)/certain types of structures (see comments above) /certain types of conditions.

Agreed. We do not want to overstate the situation, and we will add a qualifying statement regarding the applicability of this thesis for particular circumstances.

Change in line 91.

Line 100: Coastal erosion of permafrost affected coastlines is not always has "thermal" component/driver. For clastic sediment beaches (sandy shores) the "thermal" component of erosion is absent, i.e. all geomorphological work performed by waves only. For cohesive shores (clay, ice-rich sediment) – yes, thermal factor plays a role. Hence, I suggest you avoid using "thermal" here.

Agreed. We will adjust text accordingly.

Change in line 106.

Line 137: This reference might be useful: (Sinitsyn et al., in press), see p. 33. Sinitsyn, A.O., Depina, I., Bekele, Y., Christensen, S., van Oosterhout, D. Development of coastal infrastructure in cold climate. Summary Guideline. SFI SAMCoT report (in press). SINTEF Research 70 Can be requested through ResearchGate: https://www.researchgate.net/publication/338711826_Development_of_coastal_infrastructure_in_cold_climate_Summary_Guideline_SFI_SAMCoT_report_Version_01

Thanks. We will incorporate this reference.

Added to references.

Invited Perspective: What Lies Beneath a Changing Arctic?

Jeffrey M. McKenzie[1], Barret L. Kurylyk[2], Michelle A. Walvoord[3], Victor F. Bense[4], Daniel Fortier[5], Christopher~~Chris~~ Spence[6], and Christophe Grenier[7]

[1]Department of Earth and Planetary Sciences, McGill University, Montreal, H3A 0E8 Canada
[2]Department of Civil and Resource Engineering and Centre for Water Resources Studies, Dalhousie University, Halifax, B3H 4R2, Canada
[3]U.S. Geological Survey, Earth System Processes Division, Denver, Colorado, United States~~Earth System Processes Division, U.S. Geological Survey, Denver, Colorado, United States~~
[4]Department of Environmental Sciences, Wageningen University and Research, Wageningen, The Netherlands
[5]Cold Regions Geomorphology and Geotechnical Laboratory, Department of Geography, Université de Montréal, Montréal, Canada
[6]National Hydrology Research Centre, Environment and Climate Change Canada, Saskatoon, Canada
[7]Laboratoire des Sciences du Climat et de l'Environnement, IPSL/LSCE, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France~~Laboratoire des Sciences du Climat et de l'Environnement, Université Paris-Saclay, Gif-sur- Yvette, France~~
Correspondence to: Jeffrey M. McKenzie (jeffrey.mckenzie@mcgill.ca)

Abstract. As permafrost thaws in the Arctic, new subsurface pathways open for the ~~movement~~ transport of groundwater, energy, and solutes. We identify different ways that these subsurface changes are driving observed surface consequences~~phenomena~~, including the potential for increased contaminant transport, modification to water resources, and enhanced rates of infrastructure (e.g. buildings and roads) damage. Further, as permafrost thaws it allows groundwater to transport carbon, nutrients, and other dissolved constituents from terrestrial to aquatic environments via progressively deeper subsurface flow paths. Cryohydrogeology, the study of groundwater in cold regions, should be ~~must be~~ included in ~~Northern~~ northern research initiatives to account for this hidden catalyst of environmental and societal change.

1 Introduction

Our understanding of congruent ~~Arctic~~ hydrologic transformations and climate change in cold regions is derived almost entirely from data collected at or near the land surface from localized field studies or through remote sensing observations (IPCC, 2019). While these studies yield extremely valuable information about shifts in surface water and shallow ground ice distribution, river discharge, and soil moisture (AMAP, 2017; Vaughan et al., 2013), the underpinnings of many of these water-related changes lie beneath the depths of these investigations. Thawing of ancient permafrost is opening and creating new subsurface pathways for groundwater flow (Walvoord and Kurylyk, 2016), thereby altering fluxes and distribution of water, energy, and solutes that can be observed at the Earth's surface. Scientific advances in predicting future climate change require integration of subsurface processes within a broader understanding of ~~Arctic change~~change in the Arctic, herein broadly defined to include arctic and subarctic regions~~as the region north of the present southern limit of the discontinuous permafrost~~

~~zone~~. ~~Herein, w~~We argue that groundwater is a catalyst of change in Arctic regions, and we call for a more prominent inclusion of cryohydrogeology, the study of groundwater in cold regions, in transdisciplinary research initiatives.

2 Groundwater - A catalyst of ~~arctic~~ Arctic change

2.1 Altered surface hydrology

Present and future groundwater systems in permafrost regions are subject to alteration in response to surface warming because average ground temperature conditions primarily control whether subsurface water is frozen or unfrozen. As Arctic air temperatures increase~~, precipitation~~ and snow patterns ~~will~~ change, ~~leading to warmer subsurface temperatures, warmer permafrost, and thawing~~permafrost is warming and thawing (Biskaborn et al., 2019). ~~As permafrost thaws, ground permeability can increase~~Permafrost thaw can increase ground permeability by orders of magnitude (analogous to the stark contrast in permeability of clay versus sand), allowing groundwater to infiltrate and circulate more deeply and across greater lateral distances (Williams and Everdingen, 1973; Walvoord and Kurylyk, 2016). Hydrologic and hydrogeologic regime shifts may occur following the formation of perennially unfrozen zones (taliks) that lie horizontally above the permafrost table and allow for groundwater flow and transport even during the winter months (Lamontagne-Hallé et al., 2018; Devoie et al., 2019; Walvoord et al., 2019). These changes not only increase the available storage and flux of liquid groundwater, but also enhance the potential for exchange of water between aquifers and surface water bodies (blue lines, Figure 1; Evans et al., 2020; Lemieux et al., 2020) and lead to shifts in vegetation (Christensen et al., 2004).

Historical increases in groundwater discharge during winter months to major rivers (Walvoord and Striegl, 2007; St. Jacques and Sauchyn, 2009; Duan et al., 2017) and accompanying nutrient and inorganic solute exports are being observed across the pan-Arctic region (Connolly et al., 2020). These data provide compelling evidence that proportionally more precipitation falling on the land surface is being routed through groundwater pathways in response to permafrost thaw. At local to regional scales, increased streamflow has been attributed to thaw-mediated groundwater connections between previously isolated upgradient wetlands and stream networks (Connon et al., 2014). Furthermore, wetter and warmer conditions slow freeze-back, permitting subsurface pathways for groundwater to persist through the winter. The net result of these changes is increased baseflow and discharge in Northern rivers, particularly during winter. These changes in the subsurface 'plumbing' can explain observed, non-intuitive wetting and drying transformations across the landscape that are manifested at the land surface (Smith et al., 2005; Avis et al., 2011; Lamontagne-Hallé et al., 2018; Pastick et al., 2018). Further, there are ~~and have important~~

implications and feedbacks ~~for~~ with vegetation, wildlife habitat, biological productivity, and greenhouse gas emissions (Christensen et al., 2004; McGuire et al., 2018; Elder et al., 2018).

2.2 New transport pathways

Thaw-activated groundwater flow influences the terrestrial to aquatic transfer of nutrients and contaminants in permafrost environments (green and red arrows, Figure 1). Of concern is the fate and transport of globally significant sources of carbon (Schuur et al., 2015) and mercury (Schuster et al., 2018) stored in permafrost, pathogens (Legendre et al., 2014), and localized anthropogenic contaminants such as organic compounds, heavy metals, and mine tailing runoff. As permafrost thaws, increased groundwater flow and connectivity will become more important for transporting these constituents released from thawing permafrost to aquatic systems (e.g. rivers, lakes) where they are processed or exported to the coastal ~~ocean~~ waters (Tank et al., 2020~~in press~~).

The fate of sequestered organic carbon in thawing permafrost has garnered considerable research attention with focus on decomposition and conversion to greenhouse gases in place, providing a positive feedback to climate change when released to the atmosphere (Schuur et al., 2015). However, large-scale ecosystem models aimed at addressing the strength of the permafrost carbon feedback (Lawrence et al., 2015; Parazoo et al., 2018) typically do not incorporate groundwater geochemical and microbial controls on subsurface processing of carbon, lateral carbon transport, and the potential for storage and burial of permafrost carbon as a mechanism for greenhouse gas attenuation (Neilson et al., 2018; Cochand et al., 2019; Vonk et al., 2019). Though recognized as sources of uncertainty in the net ecosystem carbon balance of permafrost regions (McGuire et al., 2018), these processes remain poorly constrained and thus difficult to adequately represent in ecosystem models due in part to the lack ~~of groundwater~~ knowledge about groundwater in the Arctic.

2.3 Accelerated infrastructure damage

Of paramount concern for Northern societies is the impacts of climate change on transportation infrastructure (e.g. roads, railways, runways), buildings, pipelines, and even trails for access to subsistence resources by i~~I~~ndigenous communities (Instanes et al., 2016). As permafrost thaws in ice-rich regions, the ground subsides unevenly leading to thermokarst features and unstable slopes, both of which are destructive to surface structures and incur local and regional costs to society (Figure 1; Instanes, 2016; Hjort et al., 2018). Although ~~it is generally~~ sometimes overlooked, ~~the~~ changing ~~flow of~~ groundwater flow conditions beneath structures built on permafrost can increase thaw and enhance subsidence rates (Chen et al., 2019). In some cases, erosion and water ponding around subsiding structures requires costly engineering solutions to reroute excess water. Icings (or Aufeis), ice masses due to freezing groundwater seepage, are widely distributed across Northern landscapes (Crites et al., 2020) and can cause flooding and create hazardous conditions on highways, railroads, and airfields. However, little is known regarding the influence of climate-mediated changes to groundwater flow dynamics on the occurrence of icings. Infrastructure designs that typically rely on historical climate information to engineer necessary risk averting measures ~~are~~ may be becoming increasingly insufficient to keep pace with rapidly (e.g., decadal timescales) changing climate forcing (Hinzman et al., 2005~~cite~~) and ~~, and~~ resultant groundwater conditions.. The potential for catastrophic Northern infrastructure failure in specific conditions from a changing groundwater regime presents threats to community security. Although predicting and planning for alterations to thermomechanical conditions that may arise due to changing groundwater conditions is an ongoing challenge, it is of critical importance.

2.4 Consequences for Northern water supply

Future climate change will impact Arctic water resources and incur both beneficial and detrimental consequences for water quality and security. Due to the remoteness and extreme cold, water supply and wastewater treatment is very expensive and technologically challenging for Northern communities. Climate change may positively impact Northern water supply in some locations, as previously dormant aquifers will be activated by permafrost thaw, leading to groundwater as a viable alternative or supplemental domestic and municipal water supply (Lemieux et al., 2016). Much work is needed to fully understand the potential for aquifer development in thawing permafrost systems.

Activation of groundwater systems also poses new risks to Arctic water supply. Mobilization of solutes by groundwater can degrade surface and subsurface water resource from pathogens (Legendre et al., 2014) or natural [e.g. mercury (Schuster et al., 2018) or and anthropogenic (e.g. toxic contaminants, landfill leachate) contaminants, raising human and ecosystem health concerns. Also, little is known regarding the impacts of coastal ~~thermal~~ erosion, sea level rise, and saltwater intrusion on Arctic coastal water resources. Some Northern coastal communities are already experiencing saltwater intrusion into surface water reservoirs via surface or subsurface pathways (Johnson, 2018).

3. Going below the surface

With projections of rapid and abrupt warming in the Arctic for the foreseeable future, groundwater processes will become increasingly important catalysts of environmental change. Groundwater and lateral chemical transport processes are typically ignored in current Earth System Models (ESMs) used for studying and projecting climate change, even though it is well established that riverine carbon exports, which are strongly influenced by groundwater processes, substantially impact ocean ecosystems and release/burial of carbon in marine environments (Vonk and Gustafsson, 2013). Furthermore, lateral redistribution of surface water and soil moisture across the landscape will impact greenhouse gas exchange in Arctic and Boreal regions, and the exclusion of this process from ESMs limits their ability to foresee and predict cascading effects on the hydrosphere and atmosphere (Fan et al., 2019).

We call for inclusion of *cryohydrogeology* within the larger scope of Arctic climate change research. While there has been limited activity in this field in the past decade, cryohydrogeology research has been conducted in isolation from other Arctic research programs. We propose the following ~~recommendations~~:

- *Northern field programs that address subsurface knowledge gaps are required*. Such programs, while expensive, should be integrated within existing multidisciplinary cryosphere programs. There is a need for improved characterization of Arctic subsurface hydrology to serve as a baseline for future comparison and as input for hydrogeologic and geomechanical models, including ESMs.

- *Groundwater-permafrost feedbacks need to be incorporated into ESMs to improve quantification of regional and global climate projections.* Climate models represent subsurface processes as confined to the vertical dimension with low vertical resolution. Without the incorporation of groundwater flow, lateral transfer of water, solutes (including carbon), and energy that can accelerate the landscape response to surface warming, vertical models may substantially under-represent the rate or magnitude of environmental changes. Recent advances in cryohydrogeological modeling (Grenier et al., 2018; Dagenais et al., 2020; Lamontagne-Hallé et al., 2020) can form the basis for inclusion of lateral processes into Arctic climate change simulations. Incorporation of groundwater dynamics in ecosystem models of permafrost regions will also allow for further exploration of vegetation response (e.g., type, phenology, and productivity) to thaw-mediated ~~plant available~~ water availability. There is also a need for further development of carbon transport via groundwater and conceptual and numerical models that may be incorporated with ESMs.
- *Long-term water management strategies for Arctic i~~I~~ndigenous communities, infrastructure, and industry must explicitly consider groundwater* as a potential future water resource, an accelerator of landscape change, and a driver of consequent infrastructure damage and water pollution. As the Arctic thaws, newly mobilized groundwater will directly impact infrastructure sustainability and water security. Water quantity and quality will be influenced by enhanced landscape hydrologic connectivity, altered water residence times, and mobilized contaminants.

Groundwater is a critical component of the Arctic response narrative to climate change and, disregard of hydrogeologic processes by the exciting interdisciplinary, international research programs risks the omission of an important catalyst of change and thereby, limiting understanding ~~, and the many exciting large international research programs need to account for hydrogeologic processes, or they will overlook an important catalyst of change~~(e.g. Sinitsyn et al., 2020). For Arctic development, incorporating hydrogeologic considerations in recommended best practices for design and monitoring of infrastructure overlying permafrost would help Arctic nations and communities actualize sustainable growth and development while balancing economic limitations~~Best practices for design and monitoring of infrastructure overlying permafrost should incorporate hydrogeologic considerations to help Arctic nations and communities actualize sustainable growth and development while balancing economic limitations~~.

Author Contribution

JMM led writing of the manuscript and received support and contributions from all authors.

Competing interests

The authors declare no competing interests.

References

Arctic Monitoring and Assessment Programme (AMAP): *Snow, Water, Ice, Permafrost in the Arctic* (SWIPA), Oslo, Norway, 2017.

Avis, C. A., Weaver, A. J. and Meissner, K. J.: Reduction in areal extent of high-latitude wetlands in response to permafrost thaw, Nat Geosci, 4(7), 444–448, doi:10.1038/ngeo1160, 2011.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J.-P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A. B. K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M. and Lantuit, H.: Permafrost is warming at a global scale, Nat Commun, 10(1), 264, doi:10.1038/s41467-018-08240-4, 2019.

Chen, L., Fortier, D., McKenzie, J. M. and Sliger, M.: Impact of Heat Advection on the Thermal Regime of Roads Built on Permafrost, Hydrol Process, doi:10.1002/hyp.13688, 2019.

Christensen, T. R., Johansson, T., Åkerman, H. J., Mastepanov, M., Malmer, N., Friborg, T., Crill, P. and Svensson, B. H.: Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, Geophys Res Lett, 31(4), doi:10.1029/2003gl018680, 2004.

Cochand, M., Molson, J. and Lemieux, J.: Groundwater hydrogeochemistry in permafrost regions, Permafrost Periglac, 30(2), 90–103, doi:10.1002/ppp.1998, 2019.

Connolly, C. T., Cardenas, M. B., Burkart, G. A., Spencer, R. G. M. and McClelland, J. W.: Groundwater as a major source of dissolved organic matter to Arctic coastal waters, Nat Commun, 11(1), 1479, doi:10.1038/s41467-020-15250-8, 2020.

Connon, R. F., Quinton, W. L., Craig, J. R. and Hayashi, M.: Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada, Hydrol Process, 28(14), 4163–4178, doi:10.1002/hyp.10206, 2014.

Crites, H., Kokelj, S. V. and Lacelle, D.: Icings and groundwater conditions in permafrost catchments of northwestern Canada, Sci Rep-uk, 10(1), 3283, doi:10.1038/s41598-020-60322-w, 2020.

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.

Devoie, É. G., Craig, J. R., Connon, R. F. and Quinton, W. L.: Taliks: A tipping point in discontinuous permafrost degradation in peatlands, Water Resour Res, doi:10.1029/2018wr024488, 2019.

~~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.~~

Duan, L., Man, X., Kurylyk, B. and Cai, T.: Increasing Winter Baseflow in Response to Permafrost Thaw and Precipitation Regime Shifts in Northeastern China, Water-sui, 9(1), 25, doi:10.3390/w9010025, 2017.

Elder, C. D., Xu, X., Walker, J., Schnell, J. L., Hinkel, K. M., Townsend-Small, A., Arp, C. D., Pohlman, J. W., Gaglioti, B. V. and Czimczik, C. I.: Greenhouse gas emissions from diverse Arctic Alaskan lakes are dominated by young carbon, Nat Clim Change, 8(2), 166–171, doi:10.1038/s41558-017-0066-9, 2018.

Evans, S. G., Yokeley, B., Stephens, C. and Brewer, B.: Potential mechanistic causes of increased baseflow across northern Eurasia catchments underlain by permafrost, Hydrol Process, doi:10.1002/hyp.13759, 2020.

Fan, Y., Clark, M., Lawrence, D. M., Swenson, S., Band, L. E., Brantley, S. L., Brooks, P. D., Dietrich, W. E., Flores, A., Grant, G., Kirchner, J. W., Mackay, D. S., McDonnell, J. J., Milly, P. C. D., Sullivan, P. L., Tague, C., Ajami, H., Chaney, N., Hartmann, A., Hazenberg, P., McNamara, J., Pelletier, J., Perket, J., Rouholahnejad-Freund, E., Wagener, T., Zeng, X., Beighley, E., Buzan, J., Huang, M., Livneh, B., Mohanty, B. P., Nijssen, B., Safeeq, M., Shen, C., Verseveld, W., Volk, J. and Yamazaki, D.: Hillslope Hydrology in Global Change Research and Earth System Modeling, Water Resour Res, 55(2), 1737–1772, doi:10.1029/2018wr023903, 2019.

Grenier, C., Anbergen, H., Bense, V., Chanzy, Q., Coon, E., Collier, N., Costard, F., Ferry, M., Frampton, A., Frederick, J., Gonçalvès, J., Holmén, J., Jost, A., Kokh, S., Kurylyk, B., McKenzie, J., Molson, J., Mouche, E., Orgogozo, L., Pannetier, R., Rivière, A., Roux, N., Rühaak, W., Scheidegger, J., Selroos, J.-O., Therrien, R., Vidstrand, P. and Voss, C.: Groundwater flow and heat transport for systems undergoing freeze-thaw: Intercomparison of numerical simulators for 2D test cases, Adv Water Resources, 114, 196–218, doi:10.1016/j.advwatres.2018.02.001, 2018.

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., Griffith, B., Hollister, R. D., Hope, A., Huntington, H. P., Jensen, A. M., Jia, G. J., Jorgenson, T., Kane, D. L., Klein, D. R., Kofinas, G., Lynch, A. H., Lloyd, A. H., McGuire, A. D., Nelson, F. E., Oechel, W. C., Osterkamp, T. E., Racine, C. H., Romanovsky, V. E., Stone, R. S., Stow, D. A., Sturm, M., Tweedie, C. E., Vourlitis, G. L., Walker, M. D., Walker, D. A., Webber, P. J., Welker, J. M., Winker, K. S. and Yoshikawa, K.: Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions, Climatic Change, 72(3), 251–298, doi:10.1007/s10584-005-5352-2, 2005.

Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V. E., Nelson, F. E., Etzelmüller, B. and Luoto, M.: Degrading permafrost puts Arctic infrastructure at risk by mid-century., Nat Commun, 9(1), 5147, doi:10.1038/s41467-018-07557-4, 2018.

Instanes, A.: Incorporating climate warming scenarios in coastal permafrost engineering design – Case studies from Svalbard and northwest Russia, Cold Reg Sci Technol, 131, 76–87, doi:10.1016/j.coldregions.2016.09.004, 2016.

Instanes, A., Kokorev, V., Janowicz, R., Bruland, O., Sand, K. and Prowse, T.: Changes to freshwater systems affecting Arctic infrastructure and natural resources, J Geophys Res Biogeosciences, 121(3), 567–585, doi:10.1002/2015jg003125, 2016.

IPCC: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.- O. Pörtner et al. eds.], ~~In Press~~, 2019.

Johnson, K.: Nunavut communities struggle with water shortage and supply issues, Environmental Science & Engineering Magazine, (April), 10–12, 2018.

Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L. and Zipper, S. C.: Changing groundwater discharge dynamics in permafrost regions, Environ Res Lett, 13(8), 084017, doi:10.1088/1748-9326/aad404, 2018.

Lamontagne-Hallé, P., McKenzie, J. M., Kurylyk, B. L., Molson, J. and Lyon, L. N.: Guidelines for cold-regions groundwater numerical modeling, Wires Water, doi:10.1002/wat2.1467, 2020.

Lawrence, D. M., Koven, C. D., Swenson, S. C., Riley, W. J. and Slater, A. G.: Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO2 and CH4 emissions, Environ Res Lett, 10(9), 094011, doi:10.1088/1748-9326/10/9/094011, 2015.

Legendre, M., Bartoli, J., Shmakova, L., Jeudy, S., Labadie, K., Adrait, A., Lescot, M., Poirot, O., Bertaux, L., Bruley, C., Coute, Y., Rivkina, E., Abergel, C. and Claverie, J.-M.: Thirty-thousand-year-old distant relative of giant icosahedral DNA viruses with a pandoravirus morphology, Proc National Acad Sci, 111(11), 4274–4279, doi:10.1073/pnas.1320670111, 2014.

Lemieux, J.-M., Fortier, R., Murray, R., Dagenais, S., Cochand, M., Delottier, H., Therrien, R., Molson, J., Pryet, A. and Parhizkar, M.: Groundwater dynamics within a watershed in the discontinuous permafrost zone near Umiujaq (Nunavik, Canada), Hydrogeol J, 28(3), 833–851, doi:10.1007/s10040-020-02110-4, 2020.

Lemieux, J.-M., Fortier, R., Talbot-Poulin, M.-C., Molson, J., Therrien, R., Ouellet, M., Banville, D., Cochand, M. and Murray, R.: Groundwater occurrence in cold environments: examples from Nunavik, Canada, Hydrogeol J, 24(6), 1497–1513, doi:10.1007/s10040-016-1411-1, 2016.

~~Lemieux, J.-M., Fortier, R., Murray, R., Dagenais, S., Cochand, M., Delottier, H., Therrien, R., Molson, J., Pryet, A. and Parhizkar, M.: Groundwater dynamics within a watershed in the discontinuous permafrost zone near Umiujaq (Nunavik, Canada), Hydrogeol J, 28(3), 833–851, doi:10.1007/s10040-020-02110-4, 2020.~~

McGuire, A. D., Lawrence, D. M., Koven, C., Clein, J. S., Burke, E., Chen, G., Jafarov, E., MacDougall, A. H., Marchenko, S., Nicolsky, D., Peng, S., Rinke, A., Ciais, P., Gouttevin, I., Hayes, D. J., Ji, D., Krinner, G., Moore, J. C., Romanovsky, V., Schädel, C., Schaefer, K., Schuur, E. A. G. and Zhuang, Q.: Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change, Proc National Acad Sci, 115(15), 3882–3887, doi:10.1073/pnas.1719903115, 2018.

Neilson, B. T., Cardenas, M. B., O'Connor, M. T., Rasmussen, M. T., King, T. V. and Kling, G. W.: Groundwater Flow and Exchange Across the Land Surface Explain Carbon Export Patterns in Continuous Permafrost Watersheds, Geophys Res Lett, 45(15), 7596–7605, doi:10.1029/2018gl078140, 2018.

Parazoo, N. C., Koven, C. D., Lawrence, D. M., Romanovsky, V. and Miller, C. E.: Detecting the permafrost carbon feedback: talik formation and increased cold-season respiration as precursors to sink-to-source transitions, Cryosphere, 12(1), 123–144, doi:10.5194/tc-12-123-2018, 2018.

Pastick, N. J., Jorgenson, M. T., Goetz, S. J., Jones, B. M., Wylie, B. K., Minsley, B. J., Genet, H., Knight, J. F., Swanson, D. K. and Jorgenson, J. C.: Spatiotemporal remote sensing of ecosystem change and causation across Alaska, Global Change Biol, 25(3), 1171–1189, doi:10.1111/gcb.14279, 2018.

Schuster, P. F., Schaefer, K. M., Aiken, G. R., Antweiler, R. C., Dewild, J. F., Gryziec, J. D., Gusmeroli, A., Hugelius, G., Jafarov, E., Krabbenhoft, D. P., Liu, L., Herman-Mercer, N., Mu, C., Roth, D. A., Schaefer, T., Striegl, R. G., Wickland, K. P. and Zhang, T.: Permafrost Stores a Globally Significant Amount of Mercury, Geophys Res Lett, doi:10.1002/2017gl075571, 2018.

Schuur, E., McGuire, A., Schädel, C., Grosse, G., Harden, J., Hayes, D., Hugelius, G., Koven, C., Kuhry, P., Lawrence, D., Natali, S., Olefeldt, D., Romanovsky, V., Schaefer, K., Turetsky, M., Treat, C. and Vonk, J.: Climate change and the permafrost carbon feedback, Nature, 520(7546), 171–179, doi:10.1038/nature14338, 2015.

Sinitsyn, A., Depina, I., Bekele, Y. W., Christensen, S. O. and van Oosterhout, D.: SINTEF Open: Development of coastal infrastructure in cold climate. Summary Guideline. SFI SAMCoT report, SINTEF akademisk forlag, ISBN: 978-82-536-1676-6, 2020.

Smith, L. C., Sheng, Y., MacDonald, G. M. and Hinzman, L. D.: Disappearing Arctic Lakes, Science, 308(5727), 1429–1429, doi:10.1126/science.1108142, 2005.

St. Jacques, J.-M. S. and Sauchyn, D. J.: Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada, Geophys Res Lett, 36(1), doi:10.1029/2008gl035822, 2009.

Tank, S., et al., Landscape matters: Predicting the biogeochemical effects of permafrost thaw on aquatic networks with a state factor approach, in Special Issue 2020 Transactions of the IPA in Permafrost and Periglacial Processes, doi: 10.1002/ppp.2057~~,~~ ~~In Press~~, 2020.

Vaughan, D. G. et al. Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Stocker, T.F. et al., eds.). Cambridge University Press, Cambridge, United Kingdom, 2013.

Vonk, J. E. and Gustafsson, Ö.: Permafrost-carbon complexities, Nat Geosci, 6(9), 675–676, doi:10.1038/ngeo1937, 2013.

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.

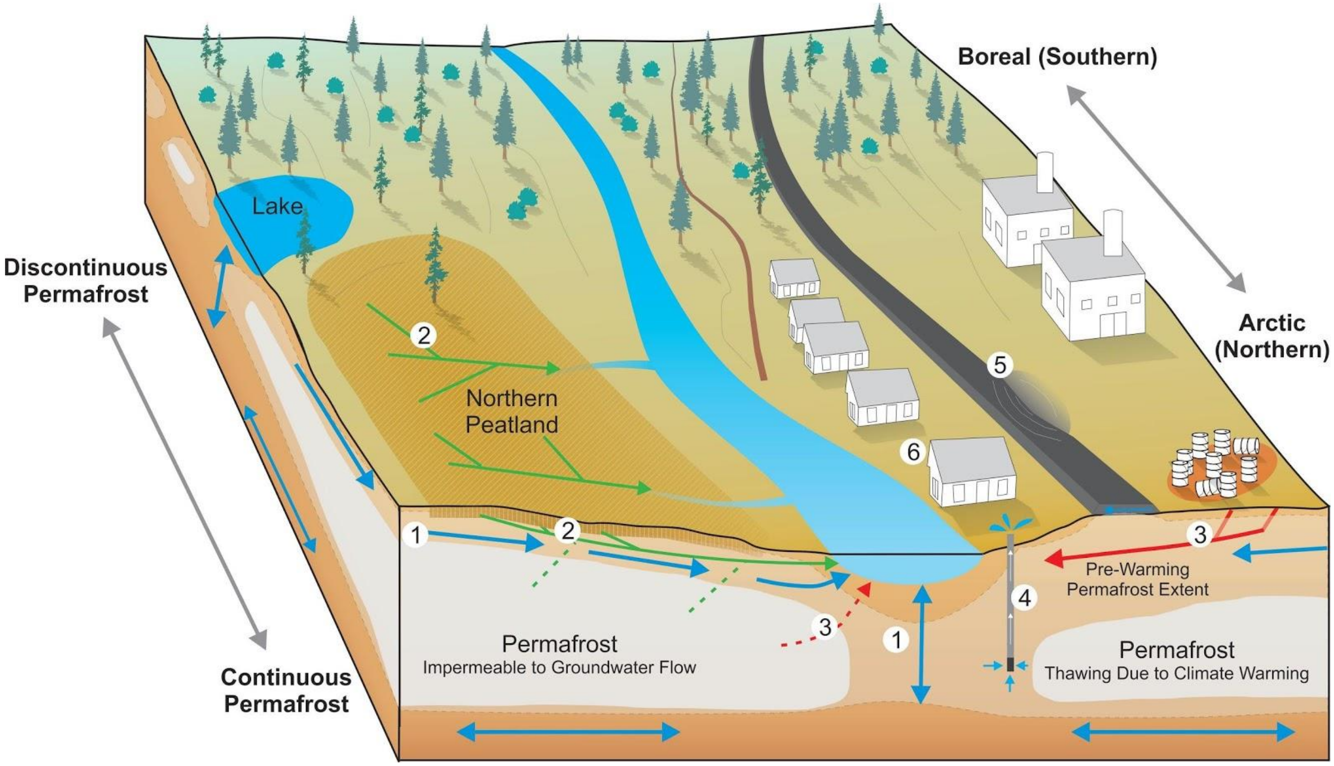
Walvoord, M. A. and Kurylyk, B. L.: Hydrologic Impacts of Thawing Permafrost—A Review, Vadose Zone J, 15(6), 0, doi:10.2136/vzj2016.01.0010, 2016.

Walvoord, M. A. and Striegl, R. G.: Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen, Geophys Res Lett, 34(12), doi:10.1029/2007gl030216, 2007.

~~Walvoord, M. A. and Kurylyk, B. L.: Hydrologic Impacts of Thawing Permafrost—A Review, Vadose Zone J, 15(6), 0, doi:10.2136/vzj2016.01.0010, 2016.~~

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.

Williams, J. R. and Everdingen, R. O. V.: 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.


Boreal (Southern)
Arctic (Northern)
Discontinuous Permafrost
Continuous Permafrost
Lake
Northern Peatland
Permafrost
Impermeable to Groundwater Flow
Permafrost
Thawing Due to Climate Warming
Pre-Warming Permafrost Extent
1
2
3
4
5
6

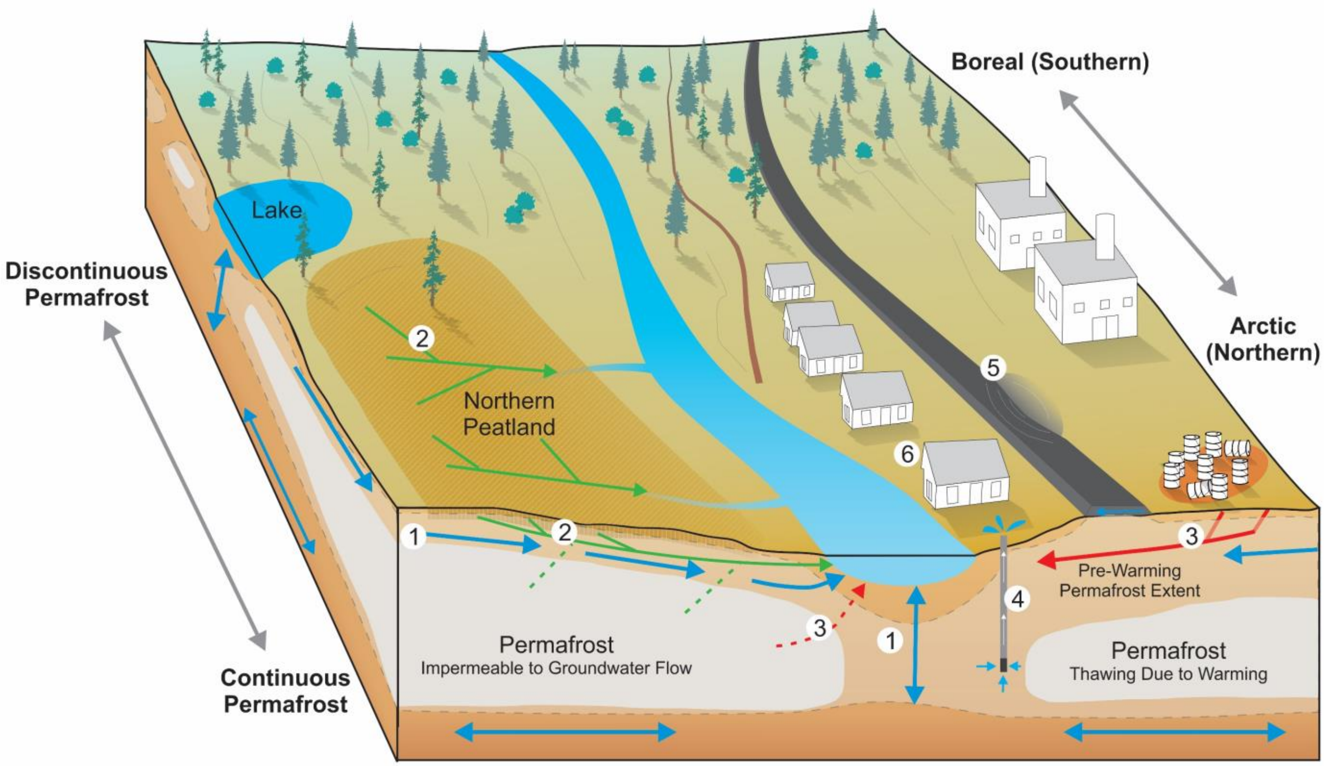


Figure 1: Pathways for groundwater to catalyse environmental change in the Arctic. (1) Arctic warming and permafrost thaw promote~~s~~ increased flux, circulation, and connectivity of groundwater above and below permafrost. (2) Groundwater transports carbon and nutrients from terrestrial to aquatic environments via progressively deeper subsurface flow paths with top-down permafrost thaw (green arrows). Permafrost carbon may be mobilized in the aqueous phase upon thaw and transported to inland waters (dashed green lines and arrows). (3) As permafrost thaws, there are opportunities for increased transport of contaminants (e.g. industrial waste, sewage, etc.) due to enhanced groundwater flow (red arrows). Sequestered contaminants, such as pathogens or mercury, are released as permafrost thaws and transported via groundwater flow (dashed red arrow). (4) Water resources will change as permafrost thaws, including increased potential for groundwater development. (5) Groundwater flow can enhance permafrost thaw rates, leading to land subsidence and destruction of surface infrastructure such as roads or buildings. (6) ~~Cryohydrogeology~~ The incorporation of cryohydrogeology ~~needs to be~~ ~~incorporated into~~in planning for Northern communities and future economic development would enhance resiliency and fortitude confronting environmental changes.