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.

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.

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.

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.

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".

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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_Dev elopment_of_coastal_infrastructure_in_cold_climate_Summ ary_Guideline_SFI_SAMCoT_report_Version_01

Thanks. We will incorporate this reference.