Response to Anonymous Referee #1

Thank you for your thoughtful feedback that will help us improve our manuscript.

General

In this paper, the authors analyze flow of brine through subglacial channels. Classic analysis for subglacial channels, e.g. R¨othlisberger (1972), neglects the role of solutes in the subglacial flow, which is unlikely to be the case in the natural environment. The authors present the first analysis, as far as I know, of the role of solutes in the subglacial hydrologic system. I found the paper to be interesting to read, yet a bit thin and confusing in places. I was surprised to learn that the major effect is the density of the water, rather than the melting point depression, but that leads me to wonder about the model construction. I will likely support publication but would be interested in one or two rounds of revision to clarify some of my questions.

We have responded to each of your comments below.

Remarks

1. I am a bit skeptical that the main effect is the density change, given that the salt can so effectively lower the melting point. My rationalization is that the water is already at the local melting point (even in the pure water case) and the salt would just allow channels to exist at lower water temperatures. However, the ice temperature will be warmer, suggesting that the salt can melt the ice and there will be heat transfer. I think this is what is captured by equation (7) but I don't yet fully understand.

We agree that the main effect of a saline fluid is the lowering of the melting point. If a hypersaline fluid was circulated through a glacier that is at the local melting point for freshwater, this would have interesting consequences and density may not be the dominant effect. However, in this manuscript we are considering the case where initially the ice is at the melting point of the saline fluid. We will add a statement in the Introduction to make this clearer (see below, line 63). We do state this in the conclusion (lines 292-296),"Salt allows fluid to exist below the freezing point of freshwater and increases the density of the fluid. We show that if a channel exists, hypersaline fluid can flow through ice-walled channels at the same subzero temperature. Our results suggest that higher salt concentration increases the peak discharge and decreases the duration of time for a fixed volume to drain from a subglacial lake. The main driver of this difference is the higher fluid density." While we do claim that the main effect is a result of a higher density fluid, this is under the assumption that the ice and liquid are in thermal equilibrium. Thermal equilibrium is what we would expect in a subglacial lake system so we set the ice and saline fluid temperature to be the same at the beginning of each simulation. The saline fluid in a subglacial lake will not be colder than the surrounding ice temperatures. Given the different salinities and therefore assumed ice/brine temperatures, the main impact of an increase in salt concentration is through the increased density of the fluid. We will clarify that the influence of density is only under the assumption of equal temperatures at the melting point by making the changes listed below.

Line 8:
“The model results show that given a subglacial system at the salinity-dependent melting point, channel walls grow more quickly when fluid contains higher salt concentrations which lead to higher discharge rates. We show this is due to a higher density fluid moving through a gravitational potential which generates more energy for melting.”

Line 63:
“The results show that the fluid flux is greater with saline fluid than the fresh water equivalent when both glacier-lake systems are at their respective salinity and pressure-dependent melting points. The larger channel cross-sections affect the temporal and spatial evolution of fluid flux for saline fluid.”

Line 233:
“Modeling all other changes related to salinity (including the treatment of the melting point and fluid temperature) while holding the density of the brine constant and equal to that of fresh water results in the discharge rates shown in Fig. 3b.”

Line 293:
“We show that if a channel exists, hypersaline fluid can flow through an ice-walled channel when the brine and ice are at the salinity and pressure-dependent melting point.”

Line 295:

“The main driver of the increased discharge rates as a function of salinity is the higher fluid density associated with higher salt concentrations. More energy is generated and available for melting the channel walls when a higher density fluid moves through a gravitational potential. While some of this energy is used to warm the ice to the new pressure melting point down the channel as the brine is diluted by meltwater, the melt is minimal compared to the discharge from the lake and therefore does not impact the discharge rates. Aside from the influence of salinity on the depression of the melting point, the greatest difference on fluid flux when considering saline fluids is related to the change in density.”

2. In the summary of model equations, I am not sure that there are enough equations listed to close the system. It seems like the 7 unknowns are N, S, m, ψ, m, Q, β, and ˆθ and there are 5 equations listed. The other two are the statement of ψ and the melting point ˆθ, which are described earlier, but I think it would be clearer if they were stated here as well. Also, I think it would be useful to include a statement of the boundary conditions and initial conditions in this section. As a counting exercise, it would be useful to see all of the conditions required.

You are correct that there are five model equations, which are solved simultaneously. The model contains 5 unknowns (N, S, m, Q, β) which are represented by the 5 model equations (Eq. 3, 4, 5, 7, and 8). The model derived variables ˆθ, ρ, and ψ are updated spatially and temporally at each space and time step after the updated salt concentration β is known using Eqs. 1 and 6, and the equation for ˆθ listed in line 114. We note that we do eliminate the equation one unknown (m) and one equation (Eq. 7) after non-dimensionalizing the system and making the assumptions discussed in Section 4.4. However, the number of unknowns and equations always remain the same.

We realize now that the number of unknowns is not stated and we are not clear in distinguishing between variables, derived variables, equations, and parameters. We will be more accurate and consistent in our language by making the changes listed below.

1. We will change the first sentence of the caption in Table 1 to say “List of model parameters and variables.”
2. We will also change line 73 to “For a list of model variables and parameters along with the consistently used parameter values see Table 1”.
3. Additionally, we will change line 168 to read, “The full model contains five unknowns (N, S, m, Q, β) and five model equations (Eq. 3, 4, 5, 7, and 8) which are solved simultaneously. The model equations contain the derived variables ˆθ, ρ_b, and ψ which depend on salinity. The model equations written in terms of the salinity-dependent derived variables are listed below.” We will add an equation number to reference in line 114.

Specific comments

A few small things that I thought of:
1. A self citation is fair in the section on outburst floods.

We will add a citation for Jenson et al. (2022) to line 24.

2. equation (1): the assumptions here imply that $\psi = \rho b g \sin(B)$, is that correct? If not, what is ψ? 1

Yes, that is correct. We will clarify this by adding to line 79, "...the change in ice-overburden pressure along the channel is zero and $\psi = \rho_b g \sin(B)$."

3. line 101: "is therefore non-constant" could be "therefore varies"

Agreed.

4. line 184: I think it would be useful to add the units after the list of β values.

We agree and the text has been updated to "beta = {0, 50, 100, 150, 200 psu}".

5. line 288: I am confused about the effective pressure values coming out of the model: are they all negative and extremely small? I would expect some in the kPa range, rather than something like −100 Pa. Am I missing something?

Yes, the effective pressures are all essentially zero, which implies that the water pressure remains high throughout the channel. A common boundary condition at the end of the channel is $N = 0$, which is approximately what we see here even with the Neumann boundary condition. The reason the values are very slightly negative is due (i) the cross-sectional area is smallest at the end of the channel which is related to the additional energy needed to melt the channel walls after the brine is diluted and the melting point increases and (ii) the density of the fluid is less at the end of the channel which is also a result of the dilution of the brine. Although the water pressures are slightly higher than ice overburden pressure, we believe this qualitatively does not affect the results. We will add at line 288, "The effective pressure at the end of the channel for all simulations is extremely close to zero ($-200 < N \leq 0$ Pa) and therefore we claim that the sign of the effective pressure is negligible and does not qualitatively affect our results."

6. line 306: the authors state that they are using 'somewhat arbitrary' parameters. Which ones specifically? And why? Would it be better to add a citation of possible better values?

Thanks for this comment. We agree this is a vague statement. We will change this to say, "We make a number of simplifying assumptions in the model and use arbitrary parameters for ice thickness, lake volume, channel length, bed slope, and initial channel radius due to a lack of available data on subglacial hypersaline systems.”

7. In the appendix, where the dimensionless model is written out, what are the boundary conditions on β? I don’t think they are stated and would be useful.

We discuss the imposed boundary conditions on β in lines 147-150, but we agree that they should be listed here as well.

Your comment has pointed out to us that we have used β_0 in both the non-dimensionalization and as the salinity of the lake (in lines 147-150). We will change lines 147-150 to read, “The salinity in the lake is constant in time since no fluid is being added to the lake which gives the boundary condition $\hat{\beta}(0,t) = \beta(0,t) * 1000/\rho_b$ where $\beta(0,t)$ is in [psu] is prescribed at the beginning of the simulation. When the cross-sectional area of the channel is small, there is less melting and the dilution of the brine is minimal so at the beginning of the simulation we assume that the salt concentration in channel is equal to the concentration in the lake, that is $\hat{\beta}(s,0) = \hat{\beta}(0,t)$.”

8. I think some of the model development that is included in the appendix could be useful to put back into the main text.

From information previously stated in the appendix, we will add to the end of the model development section, “The system of equations are solved using a constant time step of approximately 3 seconds and a constant grid spacing of 20 m. After the solution to the salt concentration equation is obtained at each time and space step, the melting point $\hat{\theta}$, and the density ρ_b are updated along with the basic hydraulic gradient ψ, which is a function of density using Eqs. 7, 6, 1 respectively.”

9. I am not a fan of the notation $Q(s = 1, t)$ since it looks cluttered (e.g. equation A9) and it is an odd statement. I prefer Q at $s = 1$ or $Q(1, t)$, if absolutely necessary.

Okay, we will change this notation to $Q(1, t)$. We will also change all other places in the manuscript such as in Section 4.4 where the same convention is used.

References

H. R¨othlisberger. Water pressure in intra- and subglacial channels. J. Glaciol., 11(62): 177–203, 1972. doi: 10.3198/1972JoG11-62-177-203.