

Generally, I think this is a good addition to the General Lake Model and will provide a useful tool to think about the effects of heat pump applications as we see increased shift to the carbon-neutral heating/cooling systems. Overall, I think the paper could be strengthened in places to fully considered the rationale for the development, in the context of both the research questions that have and could be answered as well as why a specific module (within GLM) is needed over and above the current modelling tools and implementations that are existing. I also think that the presentation of the results could be tidied up to better display the validation of the model and effect of the heat pump by combining some of the tables and presenting the model output more clearly.

Introduction:

1. The purpose of second paragraph (Lines 27-44) of the introduction is not very clear. I would suggest splitting into two. Then the second part about why the current configuration of the inflow/outflows that are current in GLM are not suitable for heat extraction studies should be put in a separate paragraph but I think this is relevant here. Some limited review of the literature in the introduction, e.g.:

Kirillin, G., Shatwell, T., & Kasprzak, P. (2013).

<https://doi.org/10.1016/j.jhydrol.2013.05.023>

Fink, G., Schmid, M., & Wüest, A. (2014). <https://doi.org/10.1002/2014WR015509>

Gaudard, A., Wüest, A., & Schmid, M. (2019).

<https://doi.org/10.1016/j.renene.2018.10.095>

Chen, X., Zhang, G., Peng, J., Lin, X., & Liu, T. (2006).

<https://doi.org/10.1016/j.applthermaleng.2006.03.009>

Råman Vinnå, L., Wüest, A., & Bouffard, D. (2017).

<https://doi.org/10.1002/2016WR019686>

Thank you for your valuable suggestions!

We have split the paragraph as recommended. The first paragraph now covers the thermal setting of lakes, the consequences of altering it, and the challenge that follows. The second covers why the pre-existing inflow and outflow configurations available in lake models are not sufficient for heat extraction. Please note that the mentioned citations, which fit well into the context, were integrated as outlined below.

2. The first part of this paragraph is also important to explain the rationale of this model development but needs more context. I would expect the text to refer to

existing research on the impact of anthropogenic heating/cooling from both empirical and simulation studies to show the reader why we need this development.

We agree and have added this context to a new paragraph that now precedes the statement of the challenge and draws on both empirical and simulation studies (L. 34):

“The physical effects of changing a lake's heat budget have been examined for both heat addition and heat extraction. Cooling water discharged from power plants has been shown to raise lake temperatures and to alter the strength and timing of stratification (Kirillin et al., 2013; Råman Vinnå et al., 2017). For heat extraction, simulation studies with Simstrat have assessed the capacity of lakes to supply heat, and found the effects on mean lake temperature to be modest at realistic demand but highly dependent on the depth at which water is extracted and returned (Fink et al., 2014; Gaudard et al., 2019). Operational installations have also been described, including a district heating and cooling system supplied by a lake in southern China (Chen et al., 2006). Such reports concentrate on system performance, and the response of the water body is rarely measured.”

Methods:

3. A bit more background on the current inflow configuration options would help the reader understand why and how this development is occurring. For example, the reference to the “submerged inflow option” is not that clear (Line 72). See my comment in the introduction as well.

We have added a short description of GLM's two inflow types at the beginning of Section 2.2, before the module is introduced (L. 80):

“GLM offers two ways of introducing water into a lake. A river inflow enters at the surface and forms an intrusion depending on its density, entraining ambient water as it progresses, until it reaches neutral buoyancy. A submerged inflow is inserted at the user-specified elevation with zero entrainment, and once inserted it may mix with the layers above or below depending on the density difference and the layer thickness criteria (Hipsey et al., 2019). We used the submerged inflow option as the starting point for the heat pump module, since Hipsey et al. (2019) name a piped inflow as one of its intended uses, which let us build on features already present in GLM.”

4. Use consistent terminology. Sometimes you refer to a “heat flux” (e.g. L105) and sometimes to “energy transfer rate” (e.g. L90).

The terminology was standardized both in the main text and in the supplementary material. Two sentences were added (L. 114):

“The rate of energy exchange between the lake and the heat pump is referred to throughout the text as the heat transfer rate, denoted P and expressed in W , i.e. it corresponds to the physical entity of power. The term heat flux is used only for area-related quantities in $W\ m^{-2}$, such as the surface heat fluxes resolved by GLM, which is power per square meter.”

5. Can you map the text more specifically on to Figure 2 using numbers for example. I found it difficult to see the link between the text and the Figure. This is a useful but complicated figure and I think a more detailed figure caption would be helpful. For example, is there a relevance to the colours/shapes of the boxes? Can it be made clear what is new and what is existing?

We incorporated the suggestion and edited Figure 2 that now carries numbered steps and Section 2.4 cites all of them. We have also restructured Section 2.4 so its paragraphs match the figure's panels. Figure 2 caption now reads (L. 172):

“Workflow of the heat exchange module that is executed within one GLM time step. Panels are labelled according to the respective code file involved: glm_init.c (steps 1–4), glm_flow.c (steps 5–10), the heat extraction module itself, glm_heatexchange.c (steps 11–20), and finally glm_model.c (steps 21–24).”

6. Is the “capture” referred to here (L130 – 140) related to the extraction phase?

Yes, it is the same thing. We have standardised on "extraction", and “injection”.

(L. 99.) *“Throughout this paper, “extraction” refers to water withdrawn from the lake into the heat pump, and “injection” refers to the thermally altered water returned to the lake.”*

7. Which are the “core files”? (Figure 2 caption)

The core files are now listed in the caption of Figure 2 (glm_init.c, glm_flow.c and glm_model.c) (L. 172). The whole caption is now expanded to better describe the figure (including the core files) accordingly with comment 5.

8. HP-ON/HP-OFF needs defining on first use and remain consistent.

Both are now done. HP-ON and HP-OFF are defined at their first appearance in Section 3.1 (L. 217) and used in that form consistently, in the text, table headers and the figure captions.

“We ran two simulations of Große Dhünn. In HP-ON the heat pump is active, with the configuration given in Table 2. In HP-OFF the heat pump module is turned off and the model runs as standard GLM simulation.”

9. In table 3 could you include the parameter names (as per the .nml file) used in the configuration of the study case.

The parameters name (as per the .nml files or .csv files) were added to the table (now Table 2) in a new column (L. 208).

Model evaluation:

10. It's not clear to me what is the data used as the heat pump in the HP-ON simulation? – L189: “In the absence of data of a lake with an operating heat pump, we used 19 years (1996 to 2014) of observational data from a well-characterized German reservoir (Große Dhünn).” I'm a little confused how the two set ups (HP-ON and HP-OFF are different).

Regarding the used data:

There is no heat pump installed at Große Dhünn reservoir and, unfortunately, no measurements of an operating heat pump are yet available to us. The 19 years of data from Große Dhünn are the meteorological and hydrological forcing of the reservoir together with the field observations used to calibrate and validate the lake model. The heat pump is a scenario that we simulated ourselves, and its settings are now given completely in Table 2. We have rewritten the sentence to clarify the meaning of each scenario.

Regarding the two set ups (HP-OFF and HP-ON):

HP-ON and HP-OFF scenarios are basically the same GLM simulation. They use the same meteorological forcing, the same river inflows and reservoir outflows, the same morphometry, the same calibrated parameters and the same 19-year period. The only difference is that the heat pump is switched on in the HP-ON scenario. Therefore, in the HP-ON scenario files, the &heat_pump block is present. In HP-OFF the &heat_pump block is absent and the model runs as standard GLM simulation without any active heat extraction. Because nothing else differs between them, every difference shown in Figures 3 and 4 and in Table 5 is caused by the heat pump alone.

We think the confusion also arose because a third set-up appears in Section 3.2. This is a controlled configuration in which evaporation, precipitation, natural inflows and reservoir outflows are all disabled so that the heat pump loop is the only

exchange acting on the lake. That configuration is used only for the mass and energy conservation checks, and not for the temperature results. Section 3.1 now names the two configurations and states which sections use which, and we have rewritten the sentence (L. 213): “

“We applied the module to Große Dhünn, a drinking water reservoir in Germany using its 19 years (1996 to 2014) of meteorological forcing and monitoring data (Weber et al., 2017) to drive and to validate the lake model. There is no heat pump installed at Große Dhünn reservoir and unfortunately measurements of a deployed heat pump are not yet available for this research, simply because the technology of lake heat pumps is rarely implemented in Germany. So, the heat pump was simulated as a scenario, with the configuration given in Table 2. We ran two simulations of Große Dhünn. In HP-ON the heat pump was active, with the configuration given in Table 2. In HP-OFF the heat pump module was turned off and the model ran standard GLM simulation, i.e. without heat extraction. The two runs were otherwise identical, using the same meteorological forcing, natural inflows and outflows, morphometry, calibrated parameters and 19-year period, so every difference between them was caused by the heat pump alone.”

11. For the temperature responses (L211-226), I guess this is a different configuration with the evaporation/precipitation turned on? Is this a different model set up to that used to validate the water and energy balance?

We hope this question was answered with the explanation and modifications generated by the previous question. We have edited the following paragraph to further clarify (L. 222):

“Before making that comparison, we verified the module in a third, controlled configuration. This was the HP-ON set-up with evaporation ($ce = 0$), precipitation ($rain_sw = .false.$), natural inflows and reservoir outflows disabled, so that the extraction and injection loop was the only exchange acting on the lake. Once the module was shown to conserve both mass and energy, the comparison of HP-ON and HP-OFF could be read as the response of the reservoir to heat pump operation.”

12. I would suggest removing some of the numerous results tables. Many of these are repeated in the text and do not provide significantly more information.

We have reduced the main text from eight tables to five, by moving (previous) Tables 2 and 8 to the supplementary information (Table S5 and S6). Table 6 has been entirely removed from the main text to avoid repetition.

13. Figure 3 may be better presented with the differences plotted to more clearly show these changes. In addition it would be helpful to have height of the extraction/injection height for reference, or in the caption.

We agree with this suggestion and have re-plotted Figure 3. It now has three panels. Panels (a) and (b) show the two simulations as before, and panel (c) shows the difference, HP-ON minus HP-OFF. With this panel the cooling below the extraction elevation can be seen directly. We also added both extraction and injection heights as labels.

14. L230 is difficult to read. I suggestion: "At an elevation of 40 m above bottom (Figure 4a), the mean temperature difference is 0.02 K and at 5m above the bottom is -0.79 K, indicating the limited heat pump influence close to the surface and close to the bottom."

We adopted as suggested. The sentence now reads (L. 278):

"At an elevation of 40 m above the bottom (Figure 4a) the mean temperature difference is 0.02 K, and at 5 m above the bottom it is -0.79 K, indicating the limited influence of the heat pump close to the surface and close to the bottom."

15. Figure 4 data are all in Celsius, but the results are reported in K in the text. I would add a second axis to allow reader to see both. Or report only the differences between HP on and off.

We followed the second suggestion and replotted Figure 4 (panel c) to show the temperature differences between HP-ON and HP-OFF in K.

16. Can you say anything about the seasonality or temporal variation in the responses? When are the largest differences observed between the two simulations?

The largest differences occur in autumn, at the end of the stratified period. We have added a second seasonality plot to the Supplementary Information (Figure S3).

We have added a paragraph about the seasonality effects in the main text (L. 293.):

"The response also varies strongly through the year (Fig. S2 and S3). At the extraction elevation the mean difference deepens from -0.34 K in February to -2.64 K in October, and at the injection elevation from -0.43 K to -2.03 K in November. The maximum effect is hence reached in autumn, because heat is removed at a constant rate while the hypolimnion is isolated from any heat exchange with the atmosphere, so the deficit builds up through the stratified season. It is smallest in February, when the water column is just initializing and stratification so that no

cumulative effects are at play: the difference then lies between -0.27 and -0.43 K at all four elevations. After accumulation of heat extraction effects over the stratified season, a temperature spread of almost 2.81 K occurs in October. Near the surface, however the response reverses sign, from -0.27 K in February to $+0.40$ K in August."

17. Table 8 is not necessary for the main text – move to SI or just retain the text

Table 8 has been moved to the SI as suggested and it is now labeled as Table S6.

18. L265: this paragraph topic sentence is not clear. What are "It" and "what".

We rewrote the sentence, it now reads (L. 332):

"Using a 1D model for this assessment has both advantages and limitations".

19. Can you say anything about how the effects shown here are similar/not to other heat pump/heat addition studies- e.g. Fink et al 2014.

We have added a paragraph at the end of Section 3.3 comparing our results with earlier assessments. (L. 301.):

"The HP-ON scenario removes 8.3 MW on average from a reservoir of 3.6 km², which means 2.3 W per square meter of lake surface. This is close to the 2 W m⁻² that Fink et al. (2014) treat as a realistic demand for a large, deep temperate lake, so the two studies can be compared. At that load they found mean water temperature changes below 0.2 K, but only as long as the injection was not discharged into the deepest layers. The smallest effects were found when both extraction and discharge were near the surface. Our configuration falls into the case their caveat sets aside, since the injection is returned at 20 m above the bottom, below the thermocline. A larger effect is therefore expected, and that is what we obtain: a volume-weighted mean cooling of 0.38 K, about twice their value, and 1.48 K at the extraction elevation. The two studies are consistent in this sense, and the present simulations quantify the configuration that Fink et al. (2014) set aside. The magnitude also falls within the range reported by Gaudard et al. (2019) for Swiss lakes, from -0.05 to $+0.02$ K for Upper Lake Constance to -0.60 to $+0.22$ K for Lower Lake Zurich."

20. L275 – not sure what the purpose of this paragraph is as it relates to the proposed new GLM module. Is this explaining why cannot just use the existing inflow/outflow dynamics for heat pumps? Or just generally about the configuration of inflows for the 1D GLM? If the former, perhaps it is better for the introduction – see my comment above. If the latter, I'm not sure it is that relevant and parts could be integrated with the paragraph above (L265-275).

It was the second of your two readings: the paragraph described GLM's inflow configuration in general rather than explaining why the existing options cannot be used for a heat pump. That argument is already made in the introduction.

We have handled it in two parts, as you suggested. The description of how GLM treats submerged inflows has moved forward to Section 2.2 (L. 80), where the option is first used and where your earlier comment asked for more background on the inflow configuration. The limitation it raised, that the submerged inflow does not resolve the intermediate stages of the intrusion, is now a short paragraph following the discussion of the one-dimensional assumption. The original paragraph has been removed, and Section 4 is one paragraph shorter as a result.

21. Again, I think some brief discussion on how this work relates to the work of Fink et al., 2014 and Gaudard et al., 2019 more specifically.

We hope this question was answered with the explanation and modifications generated by the previous question (comment 19).