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Integrating heat extraction into the General Lake Model (GLM v3.9.106)

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Abstract. The growing global demand for heating and cooling challenges decarbonization efforts, which requires a shift to renewable solutions. Inland waters, especially lakes and reservoirs, account for a significant portion of global land heat uptake, offering potential to help meet these demands. When used for heating, the resulting cooled lake could benefit from buffering climate-induced warming. However, existing lake models lack dedicated capabilities to simulate thermal energy extraction limiting the assessment of its environmental impacts on aquatic ecosystems. Here, we present a new thermal use module integrated into the General Lake Model (GLM) framework. The module features: (1) depth-flexible water extraction and injection at static or dynamic elevations; (2) user-defined operational parameters for flow rates, temperature spread, and heat flux; and (3) coupling with the Aquatic Ecodynamics (AED) library, enabling simulations of biogeochemical responses to thermal alterations. Heat transfer calculations are integrated with GLM's existing hydrodynamic and thermodynamic algorithms and maintain energy and mass conservation. We tested the module using a heat-extraction scenario (-2 K) for a drinking water reservoir in Germany with 19 years of monitoring data. The open-source module provides a new tool for both energy and lake management by enabling the evaluation of the thermal and ecological impacts of heat extraction.

1. Introduction

Heating and cooling account for a large and growing share of global energy use, and meeting this demand with low-carbon sources is one of the central challenges of decarbonization. Advanced heat pumps are a key technology in this transition because they are efficient and emit little carbon which make them well suited to sustainable energy systems (Eggimann et al., 2023; Shin et al., 2024). The performance of a heat pump depends, however, on the thermal stability and capacity of its source or sink. Globally, inland waters show a net heat uptake equal to 3.6% of the energy stored on land, with natural lakes accounting for most of this absorption (Vanderkelen et al., 2020). Standing water bodies, such as lakes and reservoirs, are therefore emerging as renewable thermal resources that can reduce CO_2 emissions and operational costs compared with conventional alternatives (Tokar et al., 2024).

The same anthropogenic climate change that drives the need for sustainable energy is also changing the thermal characteristics of these water bodies. Lake surface temperatures are rising rapidly and unevenly worldwide (up to 1.3 °C per decade), which

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is altering lake thermal regimes (O'Reilly et al., 2015; Schmid, 2019). While this warming trend poses ecological threats, it also raises the thermal potential of lakes as a stable heat source, even during peak winter heating. Although extracting thermal energy for heating purposes may appear as environmentally friendly because it lowers CO_2 emissions and counteracts the warming of lakes, it is nevertheless a further manipulation of the lake's thermal regime. The challenge, therefore, lies in developing methods and simulation tools to (i) quantify the thermal potential of a given lake over the season, (ii) assess the hydrodynamic changes of the thermal extraction and different regimes for injection of the cooler backflows, (iii) define a temperature threshold that minimizes potential environmental risks; and (iv) define the optimized depth for injection/extraction. Accurately managing these interactions requires reliable simulation tools capable of modeling the complex feedback between energy system operations and lake hydrodynamics. However, state-of-the-art mechanistic one-dimensional lake models lack dedicated capabilities to simulate targeted thermal energy exchange and its subsequent impacts. This limitation may appear surprising, given that most lake models allow the insertion of inflows and outflows at distinct discharges as well as pre-defined inflow temperature. However, simulating a continuous heat pump requires accounting for the thermal consequences of warm water extraction and cold-water injection (backflow) dynamically. It means these feedback loops must be resolved during the model's runtime. All this is important for an ecological impact assessment, ensuring that the system's operation does not disrupt the local ecosystem (Long et al., 2023; Gaudard et al., 2018).

To tackle this gap, the primary objective of this study is to introduce a new heat exchange module integrated into the General Lake Model (GLM) framework (Hipsey et al., 2019) that enables a dynamic inclusion of heat extraction by heat pumps. The new module is designed to account for various options for the heat pump with respect to technical features as well as to the applied discharge, temperature spread and insertion depth. Lastly, the model is designed to be linkable to biogeochemical/ecological model components. Such a tool is required for a thorough analysis of physical and ecological impacts and for a comparative analysis of alternative heat extraction options. While operational data from large-scale lake-source heat pumps remains scarce, existing installations are small-scale and lack monitoring. The model here presented can be verified against first principles (mass and energy conservation) and tested using a well-characterized reservoir dataset.

2. Methods

This section details the new heat exchange module for GLM. Firstly, we provide a brief overview of the host model before describing the implementation and operational features of the new module.

2.1 The General Lake Model (GLM)

The General Lake Model (GLM) is an open-source, one-dimensional hydrodynamic model designed to simulate the vertical profiles of temperature, salinity, and density in lakes and reservoirs (Hipsey et al., 2019). GLM conceptualizes a lake as a series of horizontal layers of variable thickness, which allows to accurately resolve the stratification dynamics and surface layer processes. The model uses a vertical Lagrangian layer structure originally based on the model DYRESM (Imberger et

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al., 1978; Imberger and Patterson, 1981) that adjusts the layer thicknesses dynamically to the development of stratification, turbulent mixing and volume changes. GLM solves the one-dimensional equations for mass, momentum, and light as well as heat energy, accounting for key physical processes including: surface heat and momentum fluxes, solar radiation attenuation, mixing driven by shear and convection, and inflows/outflows. The hydrodynamic model can be coupled with the Aquatic Ecodynamics library (AED) to enable water quality and lake ecosystem simulations.

GLM allows users to edit its source code to create new modelling features or improve existing models (Weber et al., 2017). While other approaches exist for simulating lake-source heat pumps (e.g., modifications to Simstrat by Gaudard et al. (2019), the GLM framework offers several advantages: (1) open-source availability under permissive licensing; (2) existing coupling with the AED biogeochemical library; (3) widespread use in the limnological community (>200 citations); and (4) active development and support.

2.2 The Thermal Exchange Module

We used the GLM submerged inflow option as a starting point for the heat pump module, which let us build on features already present in GLM. The module enables modelling the feedback between energy system operations and lake hydrodynamics that is needed when simulating the effect of heat pumps in lakes. It provides four main features shown in Figure 1: extraction and injection at the same or different elevations; user-defined operational parameters for flow rates, temperature spread and heat flux; depth-flexible extraction and injection at static or dynamic extraction/injection elevations; and coupling with the Aquatic Ecodynamics (AED) library, which allows biogeochemical responses to thermal alterations to be simulated.

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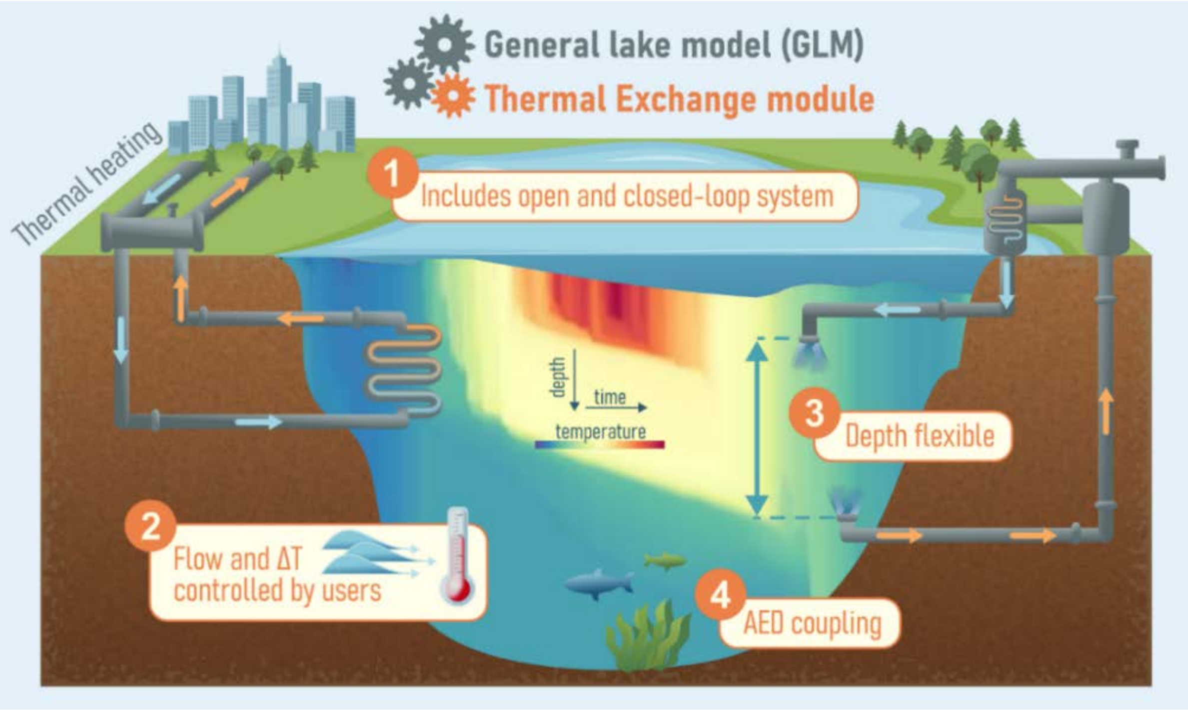

Figure 1 - Thermal Exchange Module main features.

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. The module follows four steps: i) Defines the heat pump intake as an outflow from the lake at a given depth (which can be configured as either a fixed elevation or a dynamic depth relative to the water surface); ii) captures its properties (flow, temperature, salinity and water quality variables); iii) applies the thermal alteration; and iv) re-injects the water as a modified inflow at a depth chosen by the user. The water mass balance is always maintained (i.e., total extraction and injection flow rates are equal), however, the discharged water can have an altered temperature (i.e. the heat budget changes). The heat transfer calculations are coupled with GLM's existing hydrodynamic and thermodynamic algorithms, so that both mass and energy (including the heat removed by the heat pump) are conserved throughout the simulations.

2.2.1 Governing Equations and operational mode

The thermal energy (heat) transfer rate, P (in Watts), is a function of water mass flow rate, i.e. the product of water density ρ (kg/m³) and volumetric flow q (m³/s), the specific heat capacity of water C_p (J kg⁻¹ K⁻¹), and the temperature spread between the extraction and injection ΔT (K), as given in Equation 1. The temperature spread ΔT computes as the difference between the temperature of water extracted from the lake (into the heat pump) T_{ext} (°C) and the temperature of water injected back into the lake (from the heat pump) T_{inj} (°C) as given in Equation 2. Throughout the text the relative spreads are denoted in K, while absolute thresholds are denoted in °C.

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$$P = \rho \cdot q \cdot C_p \cdot \Delta T \qquad \text{Equation (1)}$$

$$\Delta T = T_{inj} - T_{ext} \qquad \text{Equation (2)}$$

The user can specify the heat pump energy transfer using one of two modes. In Mode 1 the user defines the applied temperature difference (ΔT). This is typically preferred approach for complying with environmental legislations, which often dictates allowable temperature spreads. Alternatively, in Mode 2, the user defines the heat transfer rate (P), an approach generally preferred for local energy planning. In this case, the required temperature change is computed by rearranging Equation 1 to Equation 3. A positive P corresponds to net heat addition ($T_{inj} > T_{ext}$); a negative P corresponds to net cooling of the lake ($T_{inj} < T_{ext}$).

$$\Delta T = \frac{P}{\rho \cdot C_p \cdot q} \qquad \text{Equation (3)}$$

For Mode 2 the heat flux (P) may be defined as static or time-varying allowing for the simulation of dynamic operational patterns, such as diurnal or seasonal schedules. Time-varying extraction and injection elevation can also be specified via an external time-series file (.csv).

2.3 User configuration

The GLM heat exchange module is controlled through a new "`&heat_pump`" namelist section in the `glm.nml` configuration file. The system's operation is enabled and defined using the "`heat_pump_switch`" parameter, which allows the user to select the desired operational mode (e.g., 1 for mode 1, and 2 for mode 2). This can be defined either as a fixed value directly in the `.nml` file or provided via external time-series file (`.csv`) to simulate dynamic seasonal schedules. The extraction and injection configurations are set using the `heat_pump_outflow_idx` and `heat_pump_inflow_idx` parameters, which link the module to existing GLM inflow and outflow structures.

Furthermore, users can define environmental constraints, such as maximum and minimum extraction temperatures or flow rates, to control the heat pump's operation. For instance, a minimum injection temperature (default: 2 °C) prevents freezing, while a minimum withdrawal temperature (default: 2.0 °C) halts operation when the source water is too cold (Table 1). If these constraints are exceeded, the module automatically clamps the values to the established limits. The code is designed to be completely non-intrusive, meaning the standard GLM applications without integrated thermal uses will function exactly as before and do not require the new `&heat_pump` section. An example configuration file is provided in the supplementary information.

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Table 1 - Configurable operational constraints and default values for the heat pump module.

Operational Constraint	**Variable Name**	**Default**	**Purpose**
Minimum injection temperature	`heat_pump_min_temp`	2 °C	Prevents freezing
Maximum injection temperature	`heat_pump_max_temp`	35 °C	Avoids ecological harm
Maximum temperature spread	`heat_pump_max_delta_t`	10 K	Prevents thermal stress
Maximum flow rate	`heat_pump_max_flow`	10 m^3/s	Prevents hydraulic overload
Minimum withdrawal temperature	`heat_pump_min_withdraw_temp`	2.0 °C	Halts operation when source is too cold

The extraction depth can be configured as either a fixed or dynamic elevation (absolute height, `outlet_type = 6`) or as a floating offtake (`outlet_type = 2`) that automatically tracks a specified distance below the water surface. The injection depth is typically specified as a fixed elevation, although time-varying elevations can be provided via the 'elev' column in the CSV file corresponding to the heat pump. A complete list of the different outflow types in GLM, including the dedicated heat pump outflow (type 6) can be found in Table S3 in the supplementary information.

2.4 Workflow & Constraints

The heat exchange module operates synchronously within each GLM time-step, ensuring that heat capture and reinjection occur within the same computational step regardless of daily or sub-daily input intervals. The workflow (see Figure 2) is organized into four distinct phases: During the initialization Phase (`glm_init.c`) the heat_pump namelist block is parsed and validated. Then the `init_heat_pump()` function is called, followed by `check_heat_pump_config()` to verify configuration parameters. If withdrawal or injection layer indices are invalid, the model exits with an error. Finally, within the routine `glm_flow.c`, outflow calculations are made in `do_outflows()`, where the module checks if `heat_pump_switch > 0`. If active, `heat_pump_capture_outflow()` intercepts the withdrawal layer and stores the captured flow rate, temperature, and salinity.

When AED water quality coupling is enabled, water quality (WQ) variables are also stored; otherwise, WQ processing is skipped. Immediately after capture, the injection phase begins. The `heat_pump_insert_inflow()` computes the return temperature using the chosen mode (mode 1 or 2). Physical constraints are then validated. If limits are exceeded, values are clamped to the nearest allowable limit (e.g., if the calculated injection temperature of 0.3 °C falls below the minimum threshold of 2 °C, it is set to 2 °C and a warning is logged). The thermally altered water is injected into the layer at the configured elevation, combining temperature and salinity with existing layer properties. At the end of each time-step, `do_overflow()` and `check_layer_thickness()` are executed in `glm_model.c`. This sequence ensures that heat pump thermal contributions are computed within each model time step.

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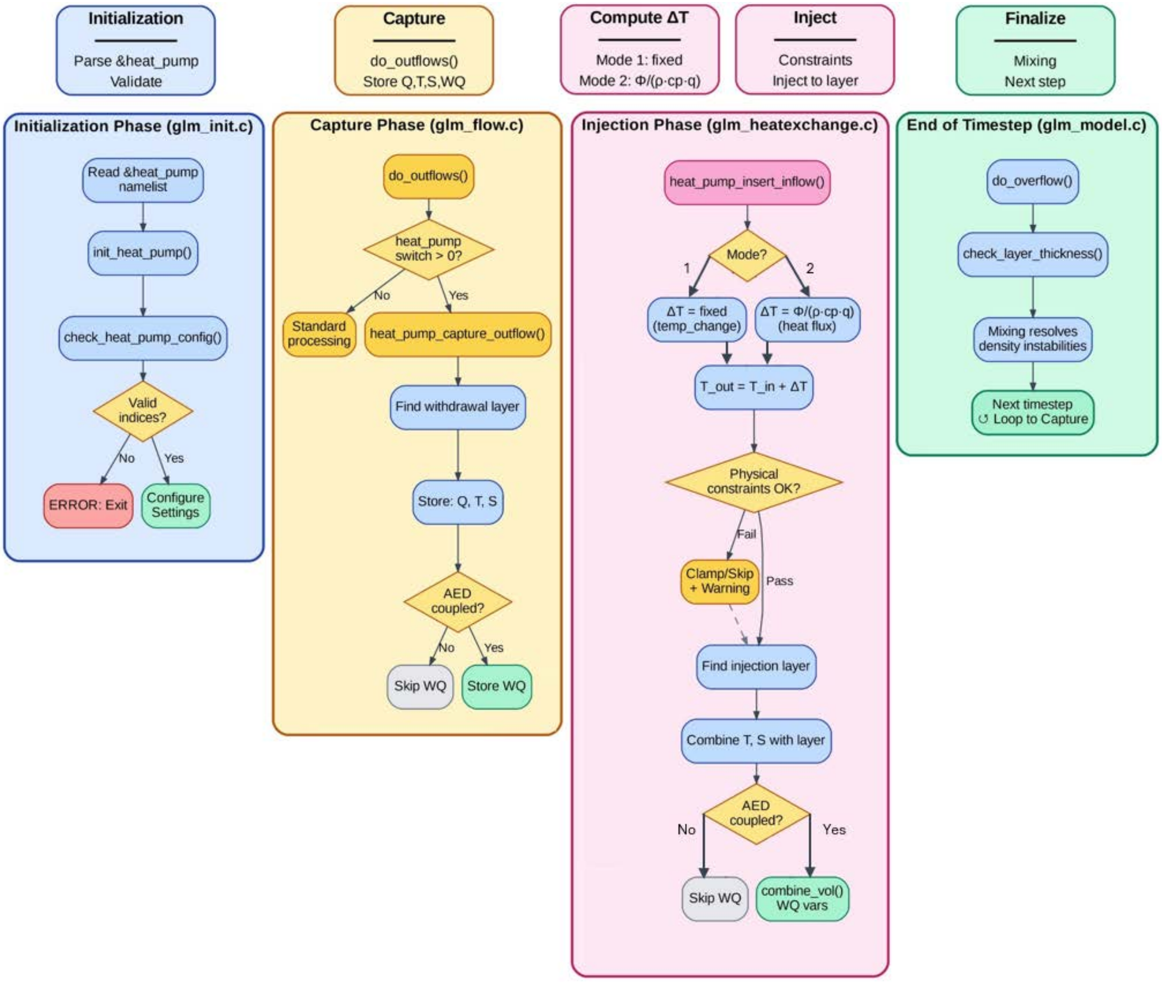

Figure 2 – Heat Exchange Module workflow and its integration into GLM's core files.

2.5 Coupling with the Aquatic Ecodynamics (AED) Library

To assess the biogeochemical impacts of thermal alterations, the module is designed for coupling with the AED library. When coupled with AED, GLM maintains water quality state variables in a shared array (`WQ_Vars`) accessible to both the hydrodynamic and the biogeochemical modules. During outflow capture, the heat exchange module stores water quality concentrations from the withdrawn layer. These values are stored and then injected back to the designed depth. During injection, the stored water quality concentrations are mixed with the receiving layer using volume-weighted averaging. This ensures that biogeochemical constituents (e.g., dissolved oxygen, nutrients, phytoplankton) are mass-conserved and returned to the lake along with the thermally altered water. The module assumes negligible residence time, it means that no biogeochemical transformations are calculated between intake and backflow. Due to this assumption, the module may not be

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suitable to represent systems with significant water retention time. When GLM is run without AED, coupling the water quality handling is bypassed, and only thermal and salinity properties are transferred through the heat pump loop.

2.6 Software and Computational Reproducibility

All data processing, statistical analyses, and visualizations were performed using Python (v3.12.3). Modifications to the GLM source code were implemented in C, C++, and Fortran, with Visual Studio Code (v1.108.1) serving as the integrated development environment (IDE). GitHub Copilot was used to assist with code completion and refactoring. To ensure reproducibility, all simulations were executed using specific software versions and library dependencies on a hardware platform described on Table 2.

Table 2 - Computational environment and software dependencies.

Component	Specification
Operating System	Ubuntu 24.04.3 LTS (Noble Numbat)
Core Model	GLM v3.9.106 commit 2814aab (4-alpha development line)
C/C++ Compiler	C/C++ GCC v13.3.0
Fortran Compiler	GFortran v13.3.0
Development IDE	Visual Studio Code v1.108.1
Data processing	Python v3.12.3
Hardware	Intel Core Ultra 5 125U (4.3 GHz), 15 GB RAM

2.7 Study case & dataset

The study site is Große Dhünn, an oligotrophic and monomictic drinking water reservoir in Germany that provides up to 42 million m^3 of raw water per year for 1 million people. The mean residence time of the reservoir at maximum water level is roughly 1.3 years. On average, the Große Dhünn Reservoir is supplied with 44 million m^3 of water per year from its own catchment plus water transfers of about 12 million m^3 per year from neighboring catchments. Vertical profile measurements of water temperature and dissolved oxygen (DO) concentration have been conducted by the reservoir authority (Wupperverband) biweekly since 1996 with a TORPHIL 406 multiparameter probe and in the period of 1997 to 2000 with a YSI multiparameter probe (series 6). Meteorological measurements of wind speed, solar radiation, air temperature and relative humidity have been carried out since 2014 on a buoy in the central basin of the reservoir (Weber et al., 2017). The dataset and configuration file used in the simulations of this paper, use approximately 19 years (1996 to 2014) of data and it is the same calibrated and validated (RMSE = 1.4 °C) used by Weber et al. (2017). The dataset is available in the GLM GitHub repository https://github.com/AquaticEcoDynamics/GLM.

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Since heat pump empirical data were unavailable, baseline parameters for the study case were selected using literature-based values (Table 3) (Forschungsstelle für Energiewirtschaft (FfE), 2024; Mehling, 2025; Fuchs et al., 2025). In a real case application, the parameters of Table 3 will vary based on specific heat demand, heat pump capacity, operating hours, and the physical characteristics of the water body (morphometry, temperature regime and location).

Table 3 – Configuration for the heat pump system.

Parameter	**Selected value**
Flow rate	1 m³/s
Temperature change	–2.0 K
Extraction elevation	25.0 m
Injection elevation	20.0 m
Mode	1

3. Model Evaluation and Discussion

3.1 Verification of the framework

The evaluation of the thermal exchange module follows this approach: (1) controlled verification; (2) mass and energy conservation checks; (3) assessment of simulated thermal dynamics; (4) physical constraint system behavior; and (5) computational efficiency. 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). The baseline simulation (HP OFF) has been previously validated against field observations (Weber et al., 2017). However, a validation against operational heat pump observations is at present not possible due to missing case studies or pilot plants (see discussion). This section demonstrates code verification through mass and energy conservation checks and assessment of physically consistent thermal dynamics.

3.2 Conservation verification

3.2.1 Mass

We ran a controlled verification to isolate the heat pump module from confounding factors. For mass conservation, we configured a simulation with disabled evaporation (ce = 0) and precipitation (rain_sw = .false.), together with zero natural inflows and reservoir outflows. Under these conditions, the only water flux is through the heat pump's extraction-injection system. Over the 19-year test period, the lake volume remained constant within numerical precision (relative change = 2.09×10^{-12} %) as shown in Table 4. The results confirm that the module correctly implements equal extraction and injection volumes (Fig. S1).

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Table 4 - Test conditions isolating the heat pump (evaporation ce=0; no precipitation, natural inflows, or reservoir outflows).

Parameter	Value	Unit
Initial volume (heat pump off)	47,737,495.500000000	m³
Final volume (heat pump on)	47,737,495.500000998	m³
Total volume change	9.98×10^{-07}	m³
Relative volume change	2.09×10^{-12}	%
Simulation period	6,937	days

3.2.2 Energy

To verify energy conservation, we utilized the same controlled configuration used for the mass balance test (Subsection 3.2.1). We compared two scenarios: (1) a simulation with safety constraints active (minimum injection temperature = 2 °C), and (2) a controlled test with constraints disabled. Temperature clamping occurred on 265 of 6,937 simulated days, corresponding to 3.82% of all heat pump operational timesteps. This resulted in a mean actual ΔT of –1.98 K instead of the configured –2.0 K. In the unconstrained test, the module achieved the theoretical heat flux ($\Phi=\rho\cdot q\cdot cp\cdot\Delta T$) with 0.0% deviation from theoretical predictions (Table 5). These results confirm that the module correctly implements the governing heat transfer equations. Additionally, total heat extraction was 1.11% below the theoretical maximum. This deficit is attributable to the safety constraints (minimum injection temperature of 2 °C), which limited ΔT on 3.82% of the simulated days.

Table 5 - Comparison of realistic operation (with safety constraints) vs. controlled test.

Parameter	With Constraints	Without Constraints
Configured ΔT	–2.0 K	–2.0 K
Mean actual ΔT achieved	–1.98 K	–2.0 K
Days with clamping	265	0
Theoretical daily flux	723.34 GJ/day	723.34 GJ/day
Actual daily flux	715.33 GJ/day	723.34 GJ/day
Flux ratio (Actual/Theory)	0.9889	1.000000
Energy difference	–1.11%	0.0%
Simulation period	6,937 days	6,937 days

3.3 Assessment of simulated thermal dynamics

Comparing the HP-ON and HP-OFF simulations highlights the secondary physical impacts of the system on lake dynamics (Table 6). The HP-ON scenario results in a slightly higher mean lake volume (+3,045 m³) mainly driven by a cumulative

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reduction in evaporative loss (274,959 m³ over the simulation period) due to lower surface water temperatures. These changes reflect the expected physical response and operational behaviors.

Table 6 - Physical impact summary comparing HP-ON and HP-OFF scenarios.

Metric	**Value**
Mean volume difference	+3,045 m³
Cumulative evaporation difference	274,959 m³

The thermal response to heat pump operation exhibits clear depth-dependent patterns (Figures 3 and 4, Table 7). Figure 3 shows how heat extraction creates a cold-water effect in the hypolimnion that accumulates over the simulation period. The HP ON contours (Figure 3b) displayed cooler deep-water temperatures compared to the reference case (Figure 3a), particularly during summer stratification when extracted heat cannot be replenished by surface mixing. The vertical distribution of temperature changes shows mean cooling at the extraction/injection range depth from 20 to 25 m (−1.46 and – 1.48 K respectively), increasing slightly upward toward the surface (+0.02 K) and diminishing downward toward the bottom (−0.79 K). This pattern is consistent with the physics of density-driven stratification: cooled water injected at 20 m elevation is denser than ambient hypolimnetic water, causing it to sink and gradually cool deeper layers through convective exchange.

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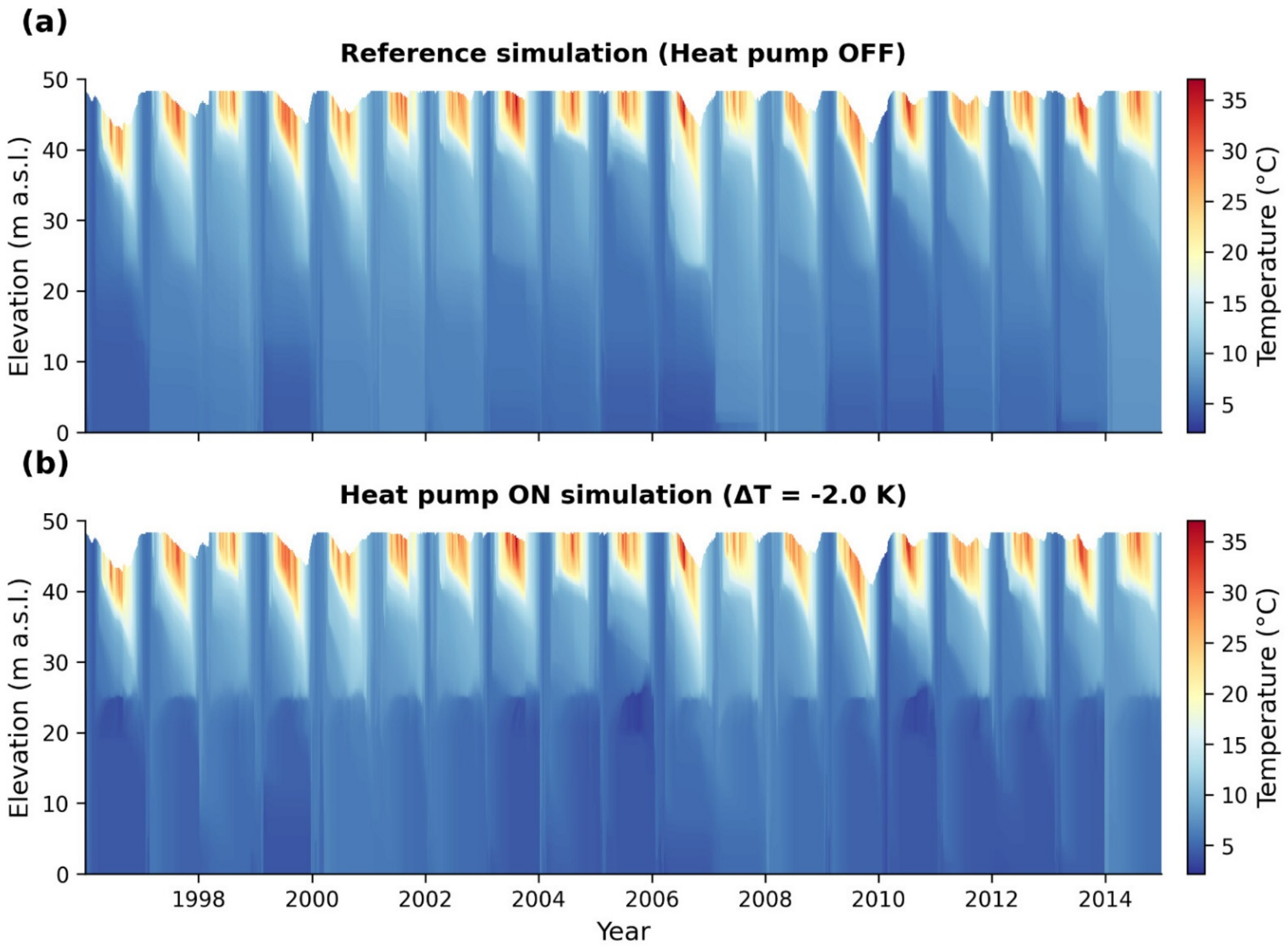

Figure 3 - Simulated water temperature (°C) as a function of elevation and time (from 1996 to 2014) for (a) the reference simulation without heat pump operation (OFF) and (b) the simulation with continuous heat pump operation (ON, ΔT = – 2.0 K). The white area above the contour occurs due to water level fluctuations arising from inflows and evaporation.

Figure 4 provides depth-specific heat pump impacts through time series at four key elevations. At an elevation of 40 m above bottom (Figure 4a), the mean temperature difference is 0.02 K, indicating the limited heat pump influence close to the surface and close to the bottom (5m above bottom. – 0.79 K). Higher temperature modifications occur in the deeper hypolimnion due to the convective intrusion of the colder backflow. This resulted in a mean cooling of –1.48 K at 25 m above bottom (where extraction is taking place) and a mean cooling of −1.46 K at 20 m above bottom (injection). The averaged temperature statistics reflect the heat pump effects quantitatively, (Table 7). A simulation example (Mode 1), featuring same extraction and injection, is provided in Table S4.

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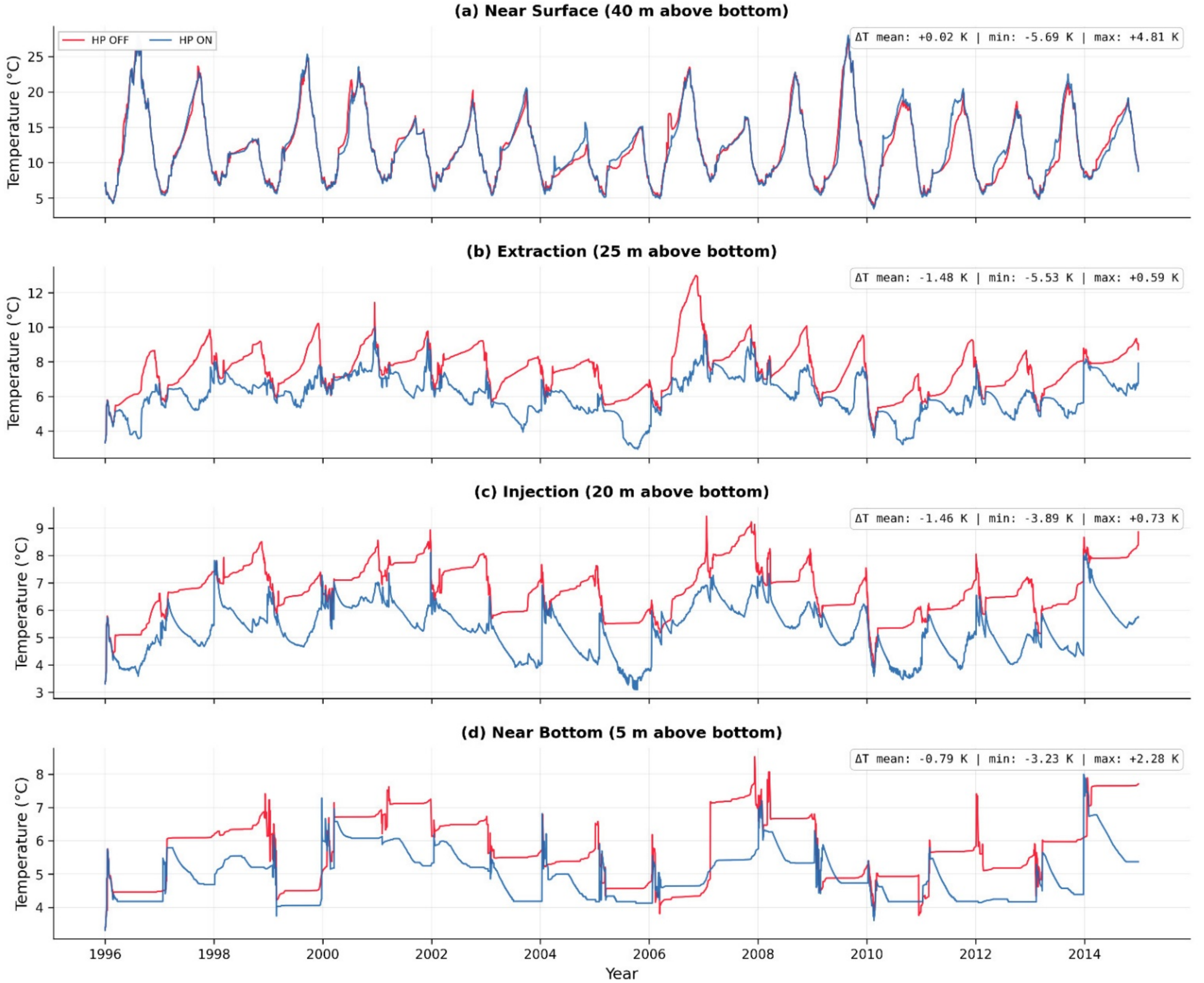

Figure 4 - Temperature time series at selected depth levels: (a) near surface (40 m elevation), (b) extraction elevation (25 m elevation), (c) injection elevation (20 m elevation), and (d) near bottom (5 m elevation). Mean temperature differences (ΔT = ON − OFF) are annotated for each depth level and given in K.

Table 7 - Metrics for simulations: heat pump OFF and heat pump ON including the differences of the values.

Metric	HP OFF	HP ON	Difference	Unit
Mean Lake Temperature	8.6107	7.9575	–0.6532	K
Mean Surface Temperature	17.0739	17.013	–0.0609	K
Max Temperature	37.0695	37.0547	–0.0148	K

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Min Temperature	2.8957	2.4602	–0.4355	K
Mean Temp at 25.0 m (extraction)	7.5267	6.0481	–1.4786	K
Mean Temp at 20.0 m (injection)	6.7419	5.285	–1.4569	K

3.4 Physical constraint system

The module's physical constraint system was needed to keep the thermal simulations realistic. During the 19-year simulation with ΔT = −2.0 K, the constraint system acted in 265 days, all triggered by the minimum injection temperature threshold of 2 °C. These events occurred only during winter, when extraction temperatures approached the configured minimum of 2.0 °C. On the first simulation day, for example, extraction temperature was 3.40 °C. Applying the requested ΔT of −2.0 K would have given an injection temperature of 1.40 °C, below the threshold. The constraint system clamped the injection temperature to 2.0 °C, giving an effective ΔT of −1.40 K for that timestep. The clamping behaviour prevents unrealistic scenarios, and allows site-specific adaptation based on regulations, ecological thresholds, or engineering requirements.

3.5 Computational efficiency

The heat exchange module adds low computational overhead (Table 8) to GLM. For the 19-year simulation (166,488 hourly timesteps), wall clock runtime shows approximately 10% overhead (10 trials were run on the same hardware under identical conditions). The peak memory usage increases by 152 KB. This aligns with the core development principles of GLM (Hipsey et al., 2019) prioritizing computational efficiency to ensure long-term simulations remain viable without excessive overhead. The module’s efficiency is achieved through integration with GLM's existing inflow and outflow structures, avoiding redundant calculations or memory allocations.

Table 8 – Average performance comparison for a 19-years simulation with heat pump ON and OFF.

Metric	Heat Pump OFF	Heat Pump ON	Overhead
Wall clock runtime	14.6 ± 0.29s	16.0 ± 0.27s	10%
Peak memory usage	20,152 KB	20,304 KB	+0.75%

4. Practical value, limitations and next steps

Our extension of the lake model GLM towards the inclusion of thermal heat use is timely given the high demand for heating energy at colder latitudes and the need for renewable energy bases for the heating sector. Lake managers that are confronted with upcoming thermal uses need to assess potential consequences on stratification, temperatures, and ecological conditions, which requires a modelling tool that is easy to apply, flexible, and fast. Such a model is provided by the new thermal exchange module integrated into GLM.

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It is an advantage and a limitation at the same time, to use a one-dimensional model for that. The advantage is the very fast simulation and short computation times, which allow scientists and managers to evaluate alternative operation modes and heat extraction regulations in a short time. Also, the full linkage to a biogeochemical and ecological lake model (AED libraries) is a clear advantage by allowing the assessment of ecological implications. However, the 1D assumption also comes with limitations, mostly associated with the inability to simulate horizontal heterogeneities. Since heat extractions are taking place at one specific point in the lake basin, they may give rise to heterogeneities. In such a case, a 3D simulation model would be required and the specification of a heat extraction module in a 3D model would be a valuable next step. But there are many lakes and heat extraction settings, where a 1D assumption is acceptable for several reasons: (i) horizontal mixing is strong and horizontal heterogeneities are quickly mixed away (Goudsmit et al., 1997), (ii) other studies successfully applied 1D models to this issue (Gaudard et al., 2019; Aguilera et al., 2022), and (iii) 1D models also provide accurate results/simulations in water bodies with high inflow volumes and short residence times where point-inputs also play a big role (Mi et al., 2019).

There are two ways of simulating inflows in GLM: the river inflow (with plunging) is based on river hydraulics, and the submerged inflows (with no entrainment). GLM addresses submerged inflows by redistributing the inflowing water directly to the layer where its density matches the surrounding water, based on the principles of buoyancy force, hydrostatic stability, and density equilibrium (Hipsey et al., 2019). A similar approach was applied in literature using the Simstrat model (Fink et al., 2014). By focusing on the final equilibrium state of the inflow, GLM's submerged inflow avoids the complexity and computational expense of simulating intermediate processes like shortcut currents or deep density-driven entrainment. Although these detailed processes are not explicitly simulated, their cumulative effects can still be captured. This simplification is therefore appropriate for seasonal/annual assessments (Gaudard et al., 2019) but may underestimate short-term mixing effects. For applications where highly detailed inflow dynamics and short-term profiles are critical, alternative models might be used such as 3D models as outlined above. From a certain volume flux and density difference, the injected water can start to plunge. Whether this effect will be visible depends on many other controlling factors like slope of the lake bed, lateral confinement, currents past the injection point and possible local cabbeling e.g. (Marks et al., 2026). This cannot be properly handled in a 1D model and hence must be left for further investigation. Again, validation against operational observations of the hydrodynamics of backflows from heat pumps remains a priority for future work.

Another general limitation in the emerging research field of thermal heat extraction is the lack of real-world pilot sites. In Germany and many other locations in Central Europe, existing lake heat pumps are at small scales and supply heat to a few households, with limited or no monitoring of thermal impacts on the lake (Technische Universität Darmstadt and Bundesverband Wärmepumpe E.V., 2026). We therefore lack practical demonstration sites where heat pumps exert a measurable impact on the lake's heat balance and stratification that could be used for model validation. The major reason behind this gap is simply that the technology is very new and water authorities are hesitant and unsure with granting the permissions for a safe operation without damaging the ecosystem. A major legal hurdle arises from the EU Water Framework

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directive (European Parliament and Council of the European Union, 2000) article 4(1) that prohibits any interventions that lead to a deterioration of the ecological status. We therefore could test our module just based on first principles and general modelling best practices. However, this tool is needed for these evaluations of heat pumps in the context of their impacts on the whole lake, also for supporting legally binding permission procedures. Validation against operational observations hence is a top priority for future work, once such large-scale demonstrator objects are available.

5. Conclusions

This paper presents a new thermal exchange module integrated into the General Lake Model (GLM) for simulating lake-source heat pump operations. The module offers flexible operational modes (fixed temperature or heat flux), together with dynamic depth configurations for water extraction and injection. The verification confirms that the module conserves mass and energy. Integrating the tool into the GLM framework adds only low computational overhead, allowing the scientific community to investigate the thermal and ecological impacts of heat pumps. Furthermore, the module's compatibility with the Aquatic Ecodynamics (AED) library enables evidence-based support for policies on sustainable lake energy use. Subsequent studies will use the GLM-AED coupling to quantify the specific impacts of various heat extraction regimes on water quality and aquatic habitat suitability, such as dissolved oxygen levels and thermal niche availability for fish. Future research should validate these simulations against long-term, in situ operational data from large-scale installations. The integration of this module advances GLM as a fast 1D model to predict the effect of heat extraction providing a support tool for managers of large heat pumps in lakes and reservoirs.

Code and Data Availability

The General Lake Model (GLM) is openly developed and available from the project repository at https://github.com/AquaticEcoDynamics/GLM under the GNU General Public License v3 (GPL-3.0). The exact version of the model used to produce the results in this paper, including the new thermal-use module, is archived on Zenodo at https://doi.org/10.5281/zenodo.21035097 (Fernandes et al., 2026), together with the configuration (namelist) files, and scripts. The development version, including the thermal_use branch, is also available at https://github.com/Taynarafernandes42/GLM/tree/thermal_use, provided as a download convenience in addition to, and not in place of, the archived version.

CRediT authorship contribution statement

Taynara Fernandes: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Matthew Hipsey:** Conceptualization, Supervision, Methodology, Writing – review and editing. **Laura Soares:** Writing – review and editing. **Bertram Boehrer:** Supervision, Conceptualization, Writing – review and editing. **Karsten Rinke:** Funding acquisition, Conceptualization, Project administration, Supervision, Writing – review and editing.

Competing interests

The authors declare that they have no conflict of interest.

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