Integrating heat extraction into the General Lake Model (GLM)

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SUPPLEMENTARY INFORMATION

Code Structure & integration with GLM core modules

The heat exchange module is encapsulated in a new source file, glm_heatexchange.c, with its interface declared in glm_heatexchange.h. Hooks to these new functions are added to the existing core files glm_model.c, glm_flow.c, and glm_init.c (Table S1 and S2). The module communicates via global variables declared in glm_globals.h, while internal state such as the captured flow properties is maintained using file-scope static variables. Function arguments are used to transfer data during capture and injection calls, ensuring a clean interface with core routines. No dynamic memory allocation is currently required for time-series arrays, as the module relies on existing inflow/outflow data structures. This sequence ensures that the heat pump's artificial thermal contribution is added after natural surface heat exchanges are resolved, preserving the integrity of the overall energy budget. GLM's engine then handles density recalculation and volume updates, allowing any density instabilities introduced by the cooled reinjection to be resolved by subsequent mixing steps. The injected water is processed using GLM's standard submerged inflow dynamics, allowing the cooled (denser) return water to find its neutral buoyancy level.

Table S1 - Functions and hooks for the new module.

Function	What it does	Hooks core files
heat_pump_capture_outflow()	Intercepts outflow properties (flow rate, temperature, salinity, and water quality variables) during withdrawal calculations	glm_flow.c
heat_pump_insert_inflow()	Calculates injection temperature and injects thermally altered water into the appropriate lake layer	glm_model.c
init_heat_pump()	Initializes the heat pump system during GLM startup	glm_init.c
check_heat_pump_config()	Validates configuration and sets inflow dynamics	glm_init.c

Table S2 - Edited core GLM files

Edited core files	**What it does**	**When executed**
glm_flow.c	Calls heat_pump_capture_outflow() after do_single_outflow() for the designated heat pump outflow	During outflow processing
glm_model.c	Calls heat_pump_insert_inflow() after inflow averaging	At start of daily time-stepping loop
glm_init.c	Parses the &heat_pump namelist block and calls init_heat_pump() and check_heat_pump_config ()during initialization	During model initialization

NML FILE EXAMPLE

```
&heat_pump
  heat_pump_switch = 1
  heat_pump_inflow_idx = 0
  heat_pump_outflow_idx = 0
  heat_pump_temp_change = -2.0
  ! Physical constraints (optional - defaults shown)
  heat_pump_min_temp = 2.0
  heat_pump_max_temp = 35.0
  heat_pump_max_delta_t = 10.0
  heat_pump_max_flow = 864000.0    !m³/day; 864000 = 10 m³/s
  heat_pump_min_withdraw_temp = 2.0
  heat_pump_enforce_limits = .true.
/
```

Table S3 - Outflow types in GLM, including outflow 6 was created specifically for the heat pump module.

Outflow Type	Name	Description
1	Fixed	Fixed elevation above lake bottom
2	Floating	Distance below water surface (tracks surface automatically)
3	Fixed + O_2	Fixed elevation, but switches to alternate depth (bottom outlet) when hypolimnetic O_2 drops below critical threshold

4	Isotherm	Variable depth that tracks a target temperature (withdrawal follows a specific isotherm)
5	Temperature Time Series	Variable depth based on a temperature time series file
6	Submerged	Fixed or dynamic elevation above lake bottom (dedicated to heat pump extraction)

Extraction at 25m and injection at 20 m

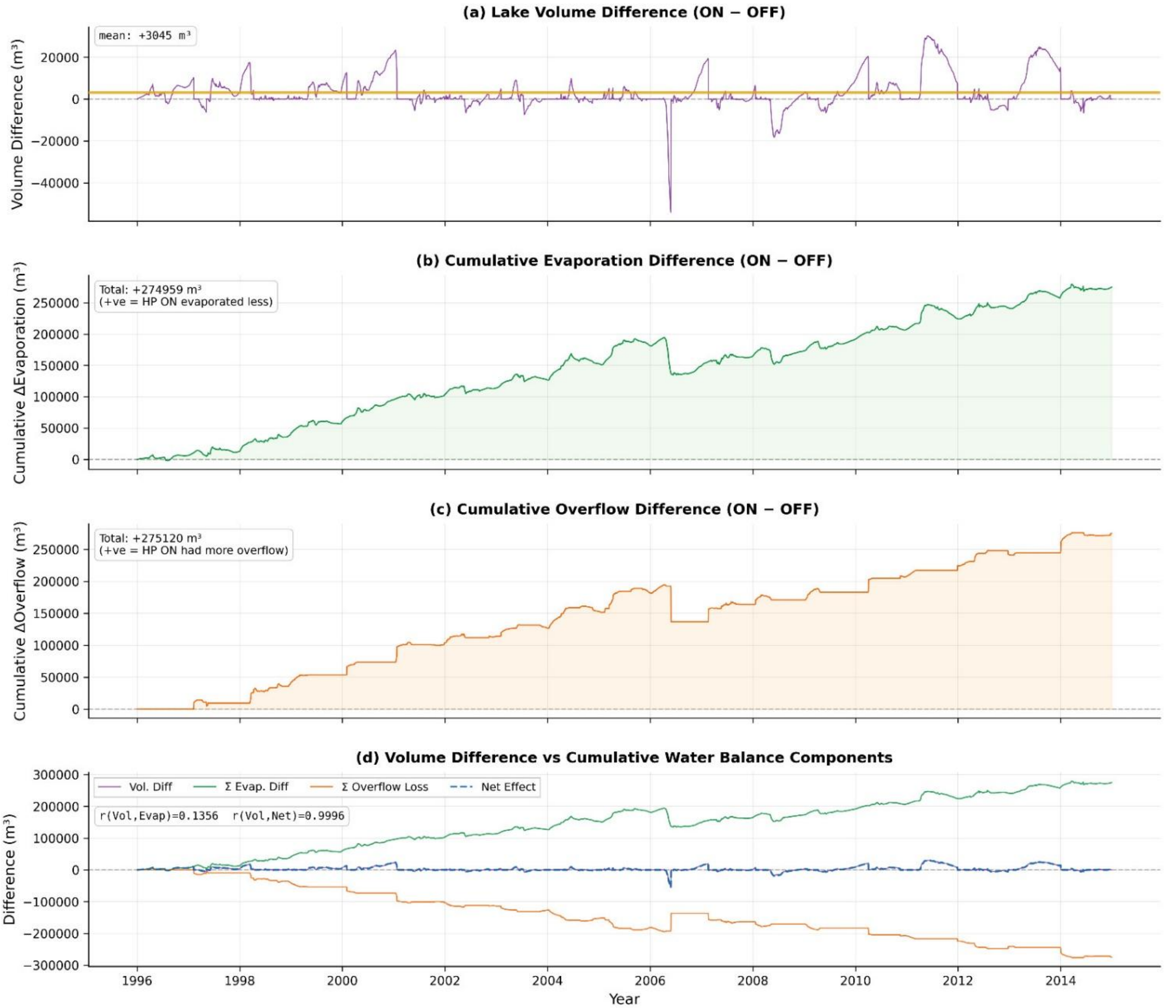

Figure S1 - Water balance components showing (a) instantaneous volume difference between scenarios (Heat pump ON and OFF), (b) cumulative evaporation difference, (c) cumulative overflow difference, and (d) overlay comparison of volume difference against cumulative evaporation and overflow effects. Correlation coefficients quantify the relationship between observed volume differences and the net effect of evaporation and overflow changes.

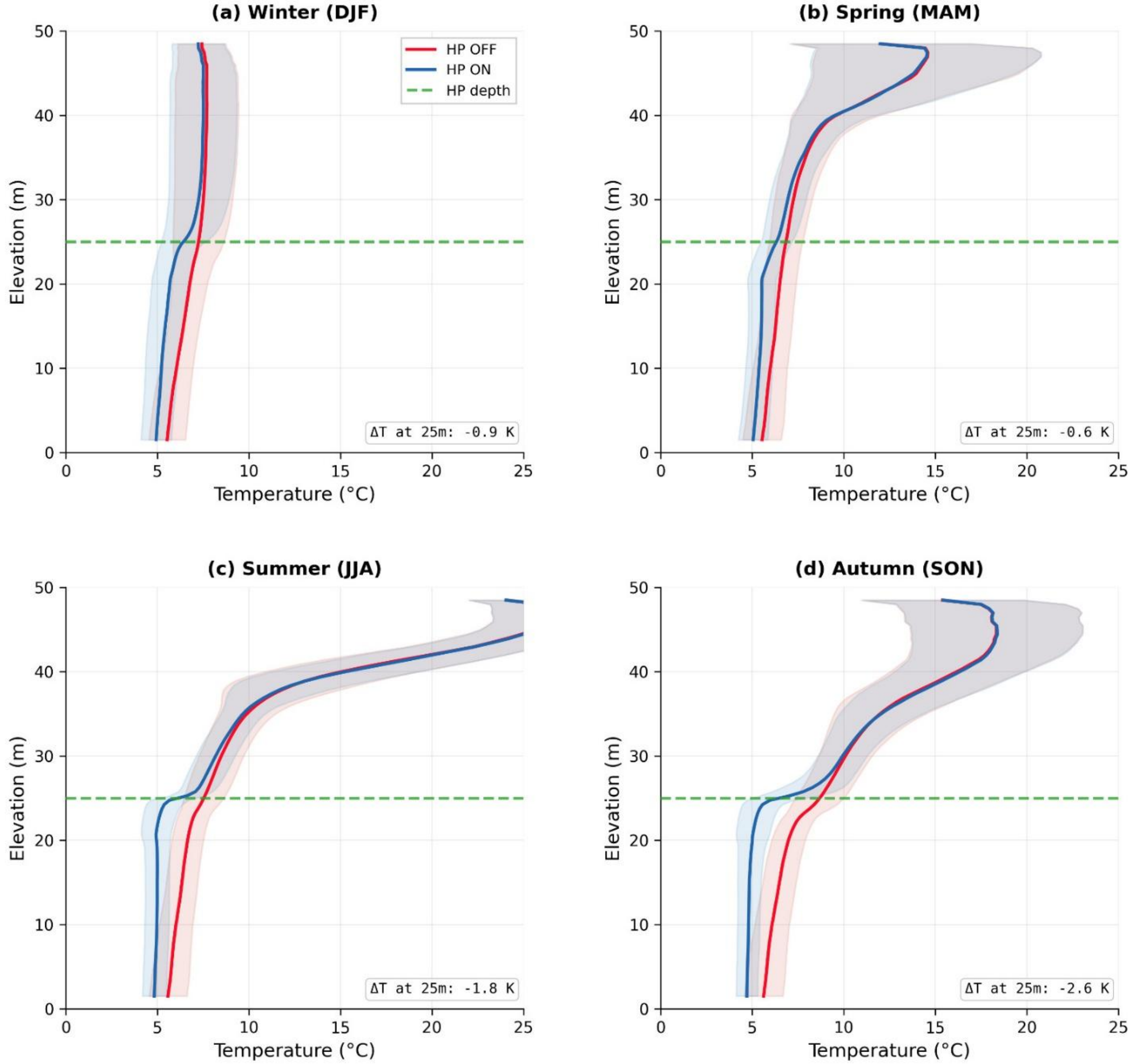

Figure S2 - Mean seasonal vertical temperature profiles showing heat pump OFF (red) and ON (blue) conditions for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) autumn (SON). Shaded regions represent ±1 standard deviation. The horizontal dashed green line indicates the heat pump extraction/injection elevation.

Extraction and injection both at 25 m elevation

Table S4 - 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	8.0885	–0.5222	K
Mean Surface Temperature	17.0739	17.0097	–0.0642	K
Max Temperature	37.0695	37.1178	0.0484	K
Min Temperature	2.8957	2.7555	–0.1403	K
Mean Temperature at 25 m above bottom	7.5267	5.8787	–1.648	K
Mean Stratification (dT/dz)	0.1834	0.1952	0.0118	K/m