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Physical effects of thermal pollution in lakes

Love Råman Vinnå¹ , Alfred Wüest^{1,2} , and Damien Bouffard^{1,2}

Key Points:

- Hydraulic residence time determines local and downstream fate of thermal pollution
- Variability of responses to climate change in lakes are partly explained by point sources of heat
- Overall thermal pollution effects in lakes are well resolved in 1D; local evaluations require 3D

Supporting Information:

- Supporting Information S1

Correspondence to:

L. Råman Vinnå,
love.ramanvinna@epfl.ch

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¹Physics of Aquatic Systems Laboratory, Margaretha Kamprad Chair, École Polytechnique Fédérale de Lausanne, Institute of Environmental Engineering, Lausanne, Switzerland, ²Department of Surface Waters - Research and Management, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Kastanienbaum, Switzerland

Abstract Anthropogenic heat emissions into inland waters influence water temperature and affect stratification, heat and nutrient fluxes, deep water renewal, and biota. Given the increased thermal stress on these systems by growing cooling demands of riparian/coastal infrastructures in combination with climate warming, the question arises on how to best monitor and manage these systems. In this study, we investigate local and system-wide physical effects on the medium-sized perialpine Lake Biel (Switzerland), influenced by point-source cooling water emission from an upstream nuclear power plant (heat emission ~ 700 MW, $\sim 18 \text{ W m}^{-2}$ lake wide). We use one-dimensional (SIMSTRAT) and three-dimensional (Delft3D-Flow) hydrodynamic numerical simulations and provide model resolution guidelines for future studies of thermal pollution. The effects on Lake Biel by the emitted excess heat are summarized as: (i) clear seasonal trend in temperature increase, locally up to 3.4°C and system-wide volume mean $\sim 0.3^\circ\text{C}$, which corresponds to one decade of regional surface water climate warming; (ii) the majority of supplied thermal pollution ($\sim 60\%$) leaves this short residence time (~ 58 days) system via the main outlet, whereas the remaining heat exits to the atmosphere; (iii) increased length of stratified period due to the stabilizing effects of additional heat; (iv) system-wide effects such as warmer temperature, prolonged stratified period, and river-caused epilimnion flushing are resolved by both models whereas local raised temperature and river short circuiting was only identifiable with the three-dimensional model approach. This model-based method provides an ideal tool to assess man-made impacts on lakes and their downstream outflows.

1. Introduction

Anthropogenic excess heat, discharged as cooling water from power plants, has been recognized as a form of pollution in lakes, reservoirs, and rivers since the middle of the twentieth century [Davidson and Bradshaw, 1967; Dracup and Fogarty, 1974; Scherer, 1975]. These emissions of heat, commonly known as “thermal pollution,” affects water temperature and therefore water quality and biota. In lakes effects can be seen both locally and on system-wide scales, including mixing regime shifts from dimictic to warm monomictic [Kirillin *et al.*, 2013], modification of nutrient cycling [Chen *et al.*, 2000], or reduction of ice cover [Dingman *et al.*, 1968]. In rivers introduced excess heat can be traced for long distances ($\sim 10^2$ to $\sim 10^3$ km) downstream from the point of input [Prats *et al.*, 2012]. Physical effects of thermal pollution in lakes and rivers affect the entire aquatic food web from benthic organisms [Barnett, 1971] to plankton [Cairns, 1971; Vandysh, 2009] and fish [Sylvester, 1972; Luksiene *et al.*, 2000].

The horizontal dispersion of thermal plumes is mainly driven by wind-induced currents [He *et al.*, 2006; Choi and Wilkin, 2007; Cardoso-Mohedano *et al.*, 2015]. Near-shore regions close to the emitting source are therefore especially sensitive to thermal pollution since heat plumes can be trapped by coastal currents without being dispersed across the water body [Raithby *et al.*, 1988; Salgueiro *et al.*, 2015].

Future thermal stress on aquatic systems is likely to increase due to intensified use of water bodies as sources and sinks of anthropogenic heat [Fink *et al.*, 2014] as well as due to ongoing climate warming [Mulholland *et al.*, 2016]. Many water management authorities have enforced three kinds of limitations to heat use: (i) a maximum temperature of water used for cooling, (ii) a maximum temperature increase in the natural waters receiving the thermal effluents, and (iii) a maximum temperature in the receiving waters. The latter condition will restrict the suitability of various waters as heat recipient under the perspective of climate change, due to the expected increase of water temperature as well as changes in discharge/rain patterns

[Van Vliet *et al.*, 2012; Quijano *et al.*, 2016]. Hence, it is of utmost importance to thoroughly assess how aquatic systems are affected by thermal pollution in order to improve management and mitigate harmful effects on water quality and biota. Previous studies have mainly focused on large lakes where system-wide effects are limited [Reutter and Herdendorf, 1976] or on small lakes with severe implications to the ecosystem [Koschel *et al.*, 2002].

Inland waters are often a complex web of rivers, streams, lakes, and reservoirs. In such systems, studies of thermal pollution should include inter/intrasystem transport of heat to comprehensively assess the spatial extent of negative effects. In the present study we investigate the impact of thermal pollution emitted from a nuclear power plant into a medium-sized lake with short hydraulic residence time. We focus on the influence of thermal pollution on water temperature and the subsequent effects on stratification and heat fluxes in the lake as well as the change of temperature in the downstream outflow. The physical processes responsible for flushing heat out of the lake ultimately determine how extensive the effects are in the lake versus at the outflow.

Prats *et al.* [2012] highlighted the importance of using sufficient spatial model resolution in order to correctly assess the downstream development of thermal pollution in rivers. We build on this work to further examine the capabilities of different spatial model resolutions, in one (1D) and three (3D) dimensions, to follow the propagation of thermal pollution across the lake toward the main outflow. Our goal is to provide guidelines specifying which of these modeling strategies are appropriate for reconstructing the effects of thermal pollution. We furthermore compare the importance of thermal pollution to the ongoing climate change. This analysis is based on the thermal response of Lake Biel (LB) to the future planned decommission of the Mühleberg Nuclear Power Plant (MNPP), located upstream alongside the Aare River.

2. Method

2.1. Site Description and Thermal Pollution

LB is a meso-eutrophic warm monomictic perialpine lake located in the northwestern part of Switzerland (7°10'E, 47°5'N, Figure 1) at 429 m above sea level. It has a maximum depth of 74 m (mean depth 30 m), surface area of 39.3 km², and a volume of 1.18 km³. Three tributaries enter the lake (Table 1). The Aare River, originating in the Alps, is both the main inflow (station 2085) and the only outflow (station 2029). It was redirected into LB during the Jura Correction in 1878 effectively reducing the average hydraulic residence

Figure 1. Area of investigation: (a) Lake Biel (LB) with watershed and monitoring stations (black diamonds), arrows indicate river flow direction (map modified from Thevenon *et al.* [2013]), (b) LB Multibeam/LIDAR bathymetry [Hilbe, 2015] with locations for field sampling points (M1, M2, M3, and CB).

Table 1. River Stations

Station Name (ID Number) ^a	Drainage Area (km ²)	Discharge (m ³ s ⁻¹) ^b	Station Feature
Hagneck (2085)	5104	175	Aare main inflow
Zihlkanal (2446)	2672	55	In and outflow ^c
Schüss (2307)	150	5	Inflow
Aegerten (2029)	8293	240	Aare outflow

^aLocation indicated in Figure 1a.

^bYearly mean from 1985 to 2014.

^cIn 3D model depending on the water level of LB relative to other tributaries/outflow.

time in LB from 253 to 58 days [Liechti, 1994]. Other tributaries include the Schüss (station 2307), originating in the Jura Mountains, and the Zihlkanal (station 2446) connecting LB to Lake Neuchâtel (Figure 1a).

MNPP is situated on the banks of the Aare River (7°16'E, 46°59'N, Figure 1a) ~19 km upstream of LB. The plant, with a net electricity production of 373 MW, was commissioned in 1972 and is planned for decommission in 2019 (<http://www.bkw.ch/ueber-bkw/unsere-infrastruktur/kernkraftwerk-muehleberg/#c1925>).

The plant discharges cooling water with an excess heat of ~700 MW (Figure 2a) into the Aare River [Meier et al., 1997] corresponding to ~18 W m⁻² for LB. This emission has been shown to increase the temperature at station 2085 by ~2.4°C in January and ~0.7°C in June [Hanafiah, 2013]. In order to investigate the effect on LB by the upcoming plant decommission we calculate the change in river temperature ΔT_R (Figures 2b and 2c) at station 2085 due to the removal of the heat supplied by MNPP. The discharge-dependent (Figure 2d) loss of heat to the atmosphere between the point of cooling water input and LB is calculated as described in Supporting Information Text S1. The gray area in Figure 2 (and in subsequent figures) marks the time when MNPP undergoes routine maintenance, during which only a small amount of standby cooling is emitted. Upstream of LB, the Aare River and its tributary Sarine (responsible for much of the temperature and discharge variability at station 2085) are influenced extensively by hydropower electricity production (closest facility ~400 m upstream from LB). This anthropogenic river discharge control (Figure 2d) causes thermo-peaking events with daily temperature fluctuations of ~2°C (Figures 2b and 2c).

2.2. Model Descriptions

2.2.1. One-Dimensional Model

We applied the 1D SIMSTRAT model, which is described in detail by Goudsmit et al. [2002]. The model is used to quantify the long-term impact of MNPP on LB as well as to investigate which system-wide thermal pollution effects can be resolved in 1D. It simulates the heat fluxes across the air-water interface and the kinetic energy uptake and dissipation using a $k-\epsilon$ turbulence closure scheme. It has previously been adapted and validated for multiple lakes including Lake Zürich [Peeters et al., 2002], Lake Geneva [Perroud and Goyette, 2010; Schwefel et al., 2016], and Lake Constance [Fink et al., 2014; Wahl and Peeters, 2014]. The hydraulic residence times for these lakes are in the order of a few years—compared to two months for LB—and river inflows are usually neglected.

In this work, we included the influence of the surrounding watershed on LB by adding a simple (without entrainment) river intrusion scheme to SIMSTRAT which provides a lower limit of the river intrusion depth by locating the level of equal density between river and lake water. Due to model limitations the volume leaving the lake was set equal to the volume entering the lake. The intrusion scheme was applied to the three rivers entering into LB given in Table 1 (Figure 1a). Following Schwefel et al. [2016], we seasonally varied the parameter α for kinetic energy transfer from wind to basin-scale internal waves: α_S for the summer (April–September) and α_W for winter (October–March), with $\alpha_S > \alpha_W$ (see section 2.4 below).

2.2.2. Three-Dimensional Model

To investigate local effects of MNPP on LB, we used the 3D open source hydrodynamic model Delft3D-Flow version 4.001 (<http://oss.deltares.nl/web/delft3d>). The model has successfully been applied to simulate circulation patterns, water quality, and climate impact in multiple Lake systems [Zhu et al., 2009; Razmi et al., 2013; Wahl and Peeters, 2014]. From the different options of turbulence closure schemes, we use the $k-\epsilon$ method as implemented in the 1D model. We apply the *Horizontal Large Eddy Simulation* for subgrid processes and the *Ocean Heat Flux Model* [Gill, 1982; Lane, 1989] for heat transfer across the lake surface.

Rivers are entering the model domain through open boundaries. Propagation of river plumes was modeled by the advection-diffusion equation used for system-wide water movements. The intrusion of the Aare River into LB was tracked by a decaying tracer (half lifetime 7.0 days). The tracer decay and the fact that the pathway of the river water in LB is not constant in time and space enables us to monitor the temporally varying maximum intrusion depth of the river plume.

Figure 2. Aare River data for the cold (2010/2011) and warm period (2013/2014): (a) Thermal pollution heat input to Aare by MNPP, the rapid change on 1 January 2014 is an artifact due to annual-averaged data, (b) temperature T at station 2085 (Figure 1) with (orange) and without (black) thermal pollution, (c) resulting temperature change ΔT_R due to removal of thermal pollution, and (d) Aare River flow Q into LB. Gray bars denote periods of MNPP maintenance, when negligible heat is emitted into the Aare River.

2.3. Data

Both models required air temperature, vapor pressure, wind speed/direction, solar radiation, and cloud cover as atmospheric forcing. Here we used two different meteorological forcing data sets. One weather station-based data set (available since 1989) for long-term 1D simulations and one weather model-based data set (available since 2008) for short-term 3D simulations.

Hourly resolved atmospheric forcing data for 1D was obtained from multiple weather stations surrounding LB. These were Cressier (Figure 1a, $7^{\circ}03'E$, $47^{\circ}03'N$), Grenchen ($7^{\circ}25'E$, $47^{\circ}11'N$), Biel ($7^{\circ}15'E$, $47^{\circ}07'N$), Neuchâtel ($6^{\circ}57'E$, $47^{\circ}00'N$), and Chasseral ($7^{\circ}03'E$, $47^{\circ}08'N$). Cressier was our main station in regard to air temperature, solar radiation, wind and vapor pressure. As cloud cover was not available at Cressier, we used Biel as our main station for this parameter. Data gaps at the main stations given above were filled with data

Table 2. Percentage of Replaced Atmospheric Forcing Data at Main Station

Main Station	Cressier				Biel
Replacement Data Station	Air Temperature	Solar Radiation	Wind	Vapor Pressure	Cloud Cover
Grenchen	1.1	0	0.7	0	0
Neuchâtel	0.1	79.6	0	0	14.4
Chasseral	0	0	0	49.4	0

from the closest available station. Replacement data were scaled in order to match the variable-specific amplitude of daily fluctuations observed at the main stations. The amount and origin of added data is indicated in Table 2.

To correctly include spatial variability in 3D, we used hourly resolved atmospheric forcing data from the highly resolved ($2.2 \times 2.2 \text{ km}^2$) meteorological COSMO-2 model (<http://www.cosmo-model.org>). This model has been validated for the region surrounding LB [Hug et al., 2010; Weusthoff et al., 2010]. Here we compare the two forcing data sets in regard to air temperature and wind speed at Cressier station from May 2013 to April 2014. The COSMO-2 model and observations match excellently in regard to air temperature with a root-mean-square-deviation (RMSD) of 0.02°C . Wind speed deviation between the two data sets are still reasonably small with a RMSD of 0.40 m s^{-1} .

River forcing data were obtained from the stations given in Table 1, with positions indicated in Figure 1a. Measured inflows (including rain) very closely match (by 96%) the measured outflow for the period 2010–2014. Ground water intrusions, as well as discharge measurement errors ($\sim 1\%$ range), could explain the 4% mismatch. Although groundwater intrusions at pockmarks have indeed been reported in the nearby Lake Neuchâtel (Figure 1) [Reusch et al., 2015]. This lake is surrounded by similar bedrock as LB. However, the small number of minor pockmarks observed in LB [Hilbe, 2015] do not indicate relevant groundwater inflows. Nevertheless, to obtain a water budget in balance for the 3D model, we adjusted the discharge at station 2446 (mean volume change $< 1\%$) by scaling the discharge to keep the modeled water level in line with observations at Ligerz ($7^\circ 09' \text{E}$, $47^\circ 06' \text{N}$). No adjustment is made to the 1D forcing since the model version used here lacks adequate representation of water level fluctuations. Furthermore, in the 3D model the Aare outflow from LB is directed through two channels, Zihl and Nidau. Measurements at station 2029 were conducted $\sim 4 \text{ km}$ downstream from LB (Figure 1). At this point the two channels have converged. Therefore, based on the channels cross-section area relationship, we assume that 10% of the outflowing volume leaves the lake through Zihl and 90% through Nidau.

For 1D model hypsometry and 3D model bathymetry we used the Swisstopo digital height model DHM25 (https://shop.swisstopo.admin.ch/en/products/height_models/dhm25). Furthermore, the 1D model requires Secchi depth (measured on a monthly basis at CB station) while this parameter is provided as a constant in the 3D model.

Initial conditions for both models was based on monthly temperature (accuracy: 0.002°C) profiles from station CB (Figure 1). These profiles were furthermore used for 1D model evaluation and inter-model performance comparison. For evaluation of the 3D model, we performed a 2.4 year long field campaign (May 2013 to September 2015) using three moorings M1, M2, and M3 (Figure 1b). Temperature measurements were obtained with two types of loggers, Vemco Minilog II-T (accuracy 0.1°C , response time 2 min) and Richard Brancker Research TR-1060 (accuracy 0.002°C , response time 4 s). Current measurements were conducted with Teledyne RD Instruments Workhorse Sentinel Acoustic Doppler Current Profilers (ADCPs) in the 300, 600, and 1200 kHz frequency range (accuracy 0.3–0.5% of water velocity). The ADCPs were moored on the bottom facing upward within a distance of 50 m from the temperature moorings. Due to LBs variable water level the depth of the temperature loggers had to be adjusted. For this purpose we used high resolved RBR temperature and pressure sensors. One RBRduo T.D (temperature and depth, accuracy 0.002°C and 0.05% of pressure range) sensor at M1 and one RBRconcerto T.D.FI.Tu (temperature, depth, fluorescence, and turbidity, accuracy 0.002°C and 0.05% of pressure range) at M2. Instrumentation setup details are shown in Supporting Information Table S1.

2.4. Model Setup, Calibration, Validation, and Sensitivity

Calibration and validation was performed by minimizing *RMSD* between temperature measurements at station CB for both models and stations M1, M2, and M3 for 3D (Figure 1b). Using the Fourier Norm (*FN*), we furthermore calibrated/validated the 3D model toward measurements of current speed and direction at M1, M2, and M3. We follow the method described in *Paturi et al. [2015]* and define *FN* as

$$FN = \sqrt{\frac{1}{n} \sum_n |\mathbf{M} - \mathbf{R}|^2} / \sqrt{\frac{1}{n} \sum_n |\mathbf{R}|^2}, \quad (1)$$

where $\mathbf{M}$ represents model current vector, $\mathbf{R}$ is measured current vector, and n is the number of samples. A good model is considered to have a *FN* ratio between 0 and 1.

The ability of the models to reproduce temperature in the epilimnion, metalimnion, and hypolimnion is demonstrated in Figure 3. The water column stability $N^2 = -(g/\rho) d\rho/dz$, where $g = 9.81 \text{ m s}^{-2}$ is gravity, ρ density of water, and N Brunt-Väisälä frequency, was used to determine the extent of the epilimnion, metalimnion, and hypolimnion. During stratified conditions ($N^2 > 2 \times 10^{-4} \text{ s}^{-2}$) we defined the metalimnion as the region containing N^2 values greater than 0.4 times the temporally varying maximal observed N^2 . The epilimnion and hypolimnion is consequently the water body above and below the metalimnion.

Figure 3. Taylor diagram for model performance showing the part of root-mean-square-difference *RMSD* that is attributable to variance or pattern correlation [Taylor, 2001]. The radial distance from origo specifies the standard deviation σ . *RMSD* is the radial separation from measurement to model values. The Pearson product-moment correlation coefficient R is given by the azimuthal position. 1D (square) and 3D (diamond) models compared to temperature measurements (circle) at station (a) CB, (b) M1, (c) M2, and (d) M3 from May 2013 to April 2014. Evaluation was performed in the epilimnion (red), metalimnion (orange), and hypolimnion (blue).

Table 3. Model Performance and Best Fit Shown by Bold Numbers

	1D Model	3D Model			
Station	CB	CB	M1	M2	M3
Depth (m)	74	74	20	47	30
Calibration					
RMSD (°C)	0.73 ^a /0.67 ^c	Cressier Wind Forcing			
		1.35 ^b	1.8 ^b	1.25 ^b	1.35 ^b
FN			0.92 ^b	0.88 ^b	0.96 ^b
RMSD (°C)	0.88 ^c	COSMO-2 Wind Forcing			
		1.03 ^b	1.06 ^b	0.98 ^b	1.05 ^b
FN			0.91 ^b	0.88 ^b	0.99 ^b
RMSD (°C)	0.96 ^a	Without River Intrusion			
		1.14 ^b	1.59 ^b	1.18 ^b	1.55 ^b
FN			1.08 ^b	1.00 ^b	1.01 ^b
Validation					
RMSD (°C)	0.68 ^d	0.86 ^e	1.17 ^e	1.31 ^e	1.09 ^e
FN			1.07 ^e	0.99 ^e	1.03 ^e

^aJanuary 1995 to December 2004.

^bMay 2013 to April 2014.

^cJanuary 2008 to December 2015.

^dJanuary 2005 to December 2015.

^eMay 2014 to April 2015.

Suspended particles contribute to the density of water and influence the river intrusion depth [Fink *et al.*, 2016]. For the Aare River, which flows through several upstream sediment-trapping dams and lakes, high suspended particles concentration is only a concern at the onset of high discharge events mostly related to flash-rainfalls occurring in summer. At this time of year the effect of MNPP on LB is at its lowest (section 3). We therefore regard suspended particles as outside the scope of this study and omit their impact on river intrusion depth. The impact of salinity on river intrusion depth was tested for both models but was not implemented due to its negligible role (<2 m during 90% of the time).

2.4.1. One-Dimensional Model

Tunable model parameters for the heat flux includes p_1 , p_2 , and K . While kinetic energy was tuned by the seasonal varying α , the empirical parameter q , the wind drag coefficient C_{10} , and the bottom friction coefficient C_{Bot} . The calibration was performed using a 6^{7-3} fractional factorial design setup (total 1296 runs; 7 is the number of variables and 3 is the number of generators) in order to incorporate the intraparameter dependency. The model time step was varied from 1 h to 5 min. We found that a time step of 10 min was sufficient to resolve the vertical temperature structure. No significant improvement was achieved past this point. A similar sensitivity analysis was conducted for the spatial resolution. The vertical model resolution was varied from 1 to 10 cm. We found that no significant improvement occurred past 25 cm (*RMSD* improvement < 0.1°C), which we used for the vertical resolution. A model spin-up period of 1 year (1994) was adopted in order to remove any transient effects caused by initial conditions.

The impact of different forcing data sets as well as the effect of the intruding rivers were investigated by preforming the calibration of the model four times. Three times with river intrusion active in combination with atmospheric forcing from weather stations (long term 1995–2004 and short term 2008–2015) as well as with COSMO-2 model data (2008–2015). The fourth time we turned off the river intrusion and used weather station data from 1995 to 2004. The results are shown in Table 3 and justify both the use of the river intrusion scheme as well as the use of meteorological forcing data from weather stations surrounding LB rather than COSMO-2. The best fit parameter setup (Table 4) was obtained with weather station forcing data from 1995 to 2004 and river intrusion scheme active. The setup was validated from 2005 to 2014 (Table 3). As seen in Figure 3a, model performance is equally good (*RMSD* between 0.4 and 1.1°C) in both the epilimnion and the hypolimnion. The deviations are as expected largest in the metalimnion since baroclinic (vertical) movements are intrinsically unresolved in the 1D model.

2.4.2. Three-Dimensional Model

In the horizontal direction we adapted a curvilinear grid enclosed by the LB shoreline. We evaluated several different horizontal resolutions ranging from 500 to 25 m sized cells, where 200–50 m proved to be optimal.

Table 4. Tunable Model Parameters Used in Present Simulations^a

1D Model									
p_1	p_2	K	q	C_{Bot}	C_{10}	α_s	α_w		
1.30	1.20	0.70	1.30	5.0×10^{-3}	1.60×10^{-3}	6.0×10^{-3}	4.0×10^{-3}		
3D Model									
W_{10}^{b}	C_{10}	$\nu_{\text{H}}^{\text{c}}$	$\nu_{\text{V}}^{\text{c}}$	D_{H}^{c}	D_{V}^{c}	$z_{\text{sec}}^{\text{d}}$	k_5	c_{H}	c_{e}
0.008	1.60×10^{-2}	1.0	1.0×10^{-3}	1.0	5.0×10^{-6}	3.00	3.0×10^{-2}	5.0×10^{-3}	2.0×10^{-3}
4.00	1.18×10^{-3}								
50.00	4.10×10^{-3}								

^aAll 1D model parameters as well as C_{10} , k_s , c_H , and c_e are nondimensional.

^bWind speed references ($m s^{-1}$) at 10 m height for identifying C_{10} .

^cUnits: $m^2 s^{-1}$.

^dUnit: m.

Grid refinement past this point did not improve model results substantially (*RMSD* improvement at $M2 < 0.1^\circ C$). A vertical bottom boundary-fitted Sigma coordinate grid was tried but produced unacceptable artificial mixing due to the steep bathymetry of the lake. This is in accordance with previous observations made by *Stelling and Van Kester* [1994]. A Cartesian coordinate (Z-layer) grid was therefore adapted in order to minimize numerical mixing. We evaluated vertical resolutions with grid cell sizes between 0.2 and 5 m. Best results was obtained with a vertical resolution ranging from 0.2 to 1.5 m. In order to obtain ideal conditions for heat transfer and to incorporate the annual water level fluctuations of ~ 1 m, we kept the topmost meter in the model domain at a constant vertical resolution of 0.2 m. Below the vertical grid was exponentially increased up to 1.5 m at the deepest point, resulting in a total of 100 vertical spaced layers. To maintain developed flows as the rivers enter LB, we extended the grid into the surrounding tributaries (~ 200 m), while keeping the river cross-sectional area in line with river mouth bathymetry. Final resolution settings in the horizontal and the vertical direction resulted in a total of 115,778 grid cells. Multiple different model time steps were tried ranging from 10 min to 10 s, where 30 s proved to be optimal.

Tunable model parameters (Table 4) include the minimum background level for the horizontal eddy viscosity ν_H , eddy diffusivity D_H , vertical eddy viscosity ν_V , and diffusivity D_V as well as the Secchi depth z_{Sec} , Stanton number c_H , Dalton number c_e , and wind speed-dependent wind drag coefficient C_{10} (required at three different wind speeds in the model). For bottom roughness we apply a horizontal uniform White-Colebrook formulation with the tunable Nikuradse roughness length parameter k_s . C_{10} is dependent on both wave development and wind velocity [*Jones and Toba*, 2008]. Given the weak winds over LB (mean $2.5 m s^{-1}$ at Cressier in 2013) with the expected difference in surface roughness from the ocean, we follow *Wüest and Lorke* [2003] for C_{10} . For wind speeds $< 4 m s^{-1}$ we apply

$$C_{10} = 0.0044 W_{10}^{-1.15}, \quad (2)$$

and for wind speed exceeding $4 m s^{-1}$ we use

$$C_{10} = \left[k^{-1} \ln \left(\frac{10g}{C_{10} W_{10}^2} \right) + K \right]^{-2}, \quad (3)$$

where $k = 0.41$ (von Kármán's constant), $K = 11.3$ [*Yelland and Taylor*, 1996], and W_{10} is the wind speed at 10 m above the surface. Equations (2) and (3) were used as a base level for optimization of C_{10} during the calibration process.

3D model calibration (May 2013 to April 2014) was performed by varying the above mentioned parameters within reasonable limits. Through the calibration process we found that model performance in regard to temperature could be improved by utilizing spatially varying atmospheric forcing from the highly resolved meteorological COSMO-2 weather model (Table 3). Minor changes in performance regarding modeled current speed/direction was also achieved. However, the difference in wind speed between modeled (COSMO-2) and observed wind (compared here at Cressier in Figure 4a) still leads to differences between measured and modeled currents (Figures 4b and 4c) with occasionally slower (example 23–27 June) or faster (example

Figure 4. Modeled and measured wind, current, and temperature. Wind 10 m above surface W_{10} (a) measurements (black) at Cressier (Figure 1a) compared to the weather forecasting model COSMO-2 (orange). Temporal model performance at station M2 (Figure 1b) for current speeds (b) measured Q_R and (c) modeled Q_M in 3D as well as temperature (d) measured T_R (e) modeled in 3D T_{3D} and (f) 1D T_{1D} . Percentage of occurrences for current velocities and direction (May 2013 to April 2014) between 0 and 10 m depth for (g) measurements Q_R and (h) 3D model Q_M .

2 July) modeled surface currents. Nevertheless, the use of space-varying atmospheric forcing still resulted in a better representation of lake conditions (Table 3). We therefore forced the 3D model with COSMO-2 model-based data instead of weather station-based data. In total, 86 calibration runs were performed resulting in the best parameter set in Table 4 which was validated from May 2014 to April 2015 (Table 3).

Table 5. Model Scenarios

Period	1D Model ^a	3D Model ^b	Thermal Pollution
April 2010 to March 2011 ^c	1D-2010-In	3D-2010-In	Included
April 2010 to March 2011 ^c	1D-2010-Ex	3D-2010-Ex	Excluded
April 2013 to March 2014 ^d	1D-2013-In	3D-2013-In	Included
April 2013 to March 2014 ^d	1D-2013-Ex	3D-2013-Ex	Excluded

^aOne-dimensional (1D) model.

^bThree-dimensional (3D) model.

^cCold (2010) period with (In) and without (Ex) thermal pollution.

^dWarm (2013) period with (In) and without (Ex) thermal pollution.

reproduces spatial and temporal temperature fluctuations. The 3D model resolves vertical pycnocline movements and consequently perform better in the metalimnion compared to the 1D model (Figure 3a, orange) as illustrated in Figures 4d–4f. The current velocity is satisfactorily reproduced by the 3D model as illustrated for the mixed layer (0–10 m) at station M2 in Figures 4g and 4h.

As part of the model sensitivity analysis, the impact of rivers entering and exiting LB was analyzed by running the model without river intrusion while using the best parameter setup. This resulted in drastically decreased model performance in regard to both temperature and current compared to the case with river intrusion active (Table 3). This, in combination with similar findings made for the 1D model (section 2.4.1), highlights the importance of the surrounding watershed for the hydrodynamics of LB.

2.5. Model Scenario Classification

The impact of the upcoming decommission of MNPP on LB was investigated using eight model scenarios: four reference scenarios and four scenarios with modified river temperature. The scenarios are summarized in Table 5. Effects on LB were assessed in both 1D (1D-X-X) and 3D (3D-X-X). To accurately represent the range of different seasonal patterns that can be expected in LB, we run the models during two 12 months periods (April–March). The periods were chosen to include a cooler and a warmer winter (October–March). April 2010 to March 2011 (X-2010-X) will be referred to as the “cold period.” For this scenario the median and minimum winter air temperature at Cressier station (Figure 1a) was 4.4 and -6.9°C , respectively. The period April 2013 to March 2014 (X-2013-X) will be called the “warm period” with a median and minimum winter temperature at Cressier of 6.1 and -1.0°C , respectively. For the reference scenarios (X-X-In) containing thermal pollution, we used the unmodified Aare River temperature measured at station 2085 (Figure 2b). This is compared to the modified scenarios (X-X-Ex) where the MNPP heat release has been removed from the Aare River (Figures 2b and 2c). This heat removal is explained in Supporting Information S1. As an example, scenario 3D-2013-Ex represent the three-dimensional model run from April 2013 to March 2014 without MNPP thermal pollution.

The impact of the upcoming decommission of MNPP on temperature, stratification, and heat fluxes in LB is hereafter referred to as the change Δ in the respective variable. Δ was calculated by taking the change in the variable from scenarios including thermal pollution (X-X-In) to scenarios where thermal pollution has been removed (X-X-Ex), i.e., variable in X-X-Ex - variable in X-X-In. Long-term interannual variability of our results was tested using the 1D model (April 1995 to March 2014) with and without thermal pollution.

3. Results

3.1. Water Temperature

The removal of the thermal pollution supplied to LB by the MNPP results in significant changes in lake temperature, ΔT . Interestingly, ΔT varies both spatially and temporally as shown in Figure 5 and Table 6. The seasonal dependence is mainly driven by the magnitude of river volume (Figure 2d) available for dilution of the thermal pollution (Supporting Information Equation (S3)). The 1D and 3D models both show a temperature decrease in the epilimnion throughout the year, while the hypolimnion is comparatively isolated from the Aare inflow during the stratified period. Consequently, the effects on ΔT in deeper layers is mostly observed during winter. The seasonal impact of MNPP on LB is summarized in Figure 6, where the contributions to ΔT are scaled with volume, such that the histogram mean correspond to the volume-average. Figure 6 furthermore demonstrates that the overall effect of thermal pollution is reproduced similarly by both

The best 3D model parameterization is a trade-off between satisfactory fits with temperature and currents. In such conditions, the model slightly overestimates vertical mixing which results in a slightly larger model error in the hypolimnion compared to the epilimnion at all stations (Figure 3). Performance does not vary significantly between the four stations indicating that the model correctly

Figure 5. Water temperature change ΔT due to thermal pollution removal. 1D model (black) and horizontal volume-weighted mean temperature change in 3D model (gray) for the (a) cold and the (b) warm period. Gray bars denote MNPP maintenance with negligible heat emission into Aare River.

Table 6. Seasonal Change in Temperature ΔT

Depth (m)	Horizontal Volume-Weighted ΔT (°C)				Maximum ΔT (°C)			
	1D Model		3D Model		1D Model		3D Model	
	Winter ^c	Summer ^d	Winter	Summer	Winter	Summer	Winter	Summer
Cold Period^a								
1	-0.32	-0.24	-0.33	-0.26	-0.63	-0.36	-3.40	-2.71
10	-0.30	-0.33	-0.31	-0.31	-0.42	-0.68	-2.43	-2.07
20	-0.31	-0.20	-0.31	-0.12	-0.66	-0.32	-2.09	-2.09
30	-0.22	-0.08	-0.28	-0.06	-0.35	-0.20	-1.42	-1.42
40	-0.19	-0.04	-0.24	-0.04	-0.40	-0.15	-0.86	-0.61
50	-0.20	-0.07	-0.20	-0.04	-0.66	-0.12	-0.76	-0.52
60	-0.22	-0.08	-0.20	-0.04	-0.79	-0.11	-0.71	-0.44
70	-0.24	-0.08	-0.19	-0.04	-0.76	-0.11	-0.54	-0.30
Warm Period^b								
1	-0.32	-0.23	-0.28	-0.21	-0.39	-0.45	-3.18	-1.82
10	-0.33	-0.30	-0.26	-0.27	-0.61	-0.82	-1.06	-1.90
20	-0.39	-0.23	-0.27	-0.18	-0.99	-0.32	-1.86	-2.03
30	-0.31	-0.17	-0.25	-0.14	-0.67	-0.29	-1.31	-1.06
40	-0.31	-0.19	-0.24	-0.16	-0.48	-0.29	-1.11	-0.53
50	-0.34	-0.22	-0.24	-0.17	-0.63	-0.29	-0.56	-0.46
60	-0.44	-0.22	-0.25	-0.17	-1.29	-0.29	-0.48	-0.38
70	-0.52	-0.23	-0.26	-0.18	-1.65	-0.29	-0.43	-0.37

^aApril 2010 to March 2011.

^bApril 2013 to March 2014.

^cOctober–March.

^dApril–September.

Figure 6. Water temperature change ΔT due to thermal pollution removal relative to percentage of total volume affected. (a, c) 3D model and (b, d) 1D model during (a, b) cold and (c, d) warm periods.

models. However, as shown in Table 6, the range of extreme ΔT fluctuations are locally more pronounced in 3D (ΔT up to -3.4°C) compared to 1D (ΔT up to -1.7°C). On a system wide and temporal scale the warm period (2013) is more affected than the cold period. However, during the cold period (2010) we observed the strongest local impacts. The seasonality of the impact is furthermore apparent in our long-term (1995–2014) 1D simulation (see Supporting Information Table S2).

The ability of the 3D model to resolve flow and temperature in horizontal directions enable us to follow the Aare River as it enters LB. The river plume has two dominant flow directions: north-west into the center of LB or north-east following the shallow eastern shore. The plume direction depends on the overall lake circulation in combination with the plume depth. During shallow intrusion events, the direction of the plume can be linked to the direction of the surface wind stress. Prevailing winds from the north-east (wind stress toward south-west) result in a clockwise gyre in the deep eastern basin which carries the Aare plume into the central parts of LB (Figure 7a). Prevailing winds from south-west (wind stress toward north-east) sets up a counter-clockwise rotation in the central parts of the lake. This circulation moves the plume toward the southern shoreline and conveys the river water toward the main outflow in the north-east (Figure 7b).

3.2. Stratification

Here we assess the impact of the upcoming closure of MNPP on stratification during the summer period in LB. For quantifying stratification strength we applied the Schmidt stability S [Schmidt, 1928]. For length of the stratified period we used the method proposed by Foley *et al.* [2012]. We consider the lake to be stratified if the surface (2 m) and deep water (70 m) temperature differ more than 0.5°C . As part of a sensitivity analysis for both models, three additional criteria for stratification length was tested (Supporting Information Text S2 and Table S3).

Figure 7. 3D modeled temperature change ΔT in LB at four depth levels (1, 20, 40, and 60 m) caused by removal of the thermal pollution on (a) midday 2 December 2013 and (b) midday 23 December 2013. Rose diagrams represent the wind drag τ (mN m^{-2}) supplied to the model during a 6 h span prior to the displayed scene.

Absolute values of S as well as changes in stratification strength ΔS are shown in Figure 8. During the stratified period (April–November) S decreases by $\sim 5\%$ as MNPP heat is removed. For the weakly stratified winter period (December–March) we observe an increase in the water column stability, except in 3D-2013-X. The effect is largest in 1D with a mean increase of $\Delta S = 6.6$ ($\text{max } 24$) J m^{-2} and smallest in 3D with a mean increase for 3D-2010-X of $\Delta S = 3.4$ ($\text{max } 10$) J m^{-2} . The increase of ΔS in winter is due to the weak stratification combined with the intrusion of Aare water colder than 4°C .

The removal of thermal pollution generally shortens the length of the stratified period. For the cold scenarios (comparisons X-2010-X) we observe a decrease of only -1 day in 1D and -4 days in 3D. Likewise, the corresponding change during the warm scenarios (X-2013-X) was only -2 days in 1D and -1 day in 3D.

Figure 8. Modeled water column Schmidt stability S (right scale) with thermal pollution present in 1D (black) and 3D (gray) calculated using horizontal volume-weighted mean temperature [Schmidt, 1928; Foley et al., 2012]. The change in stability ΔS (left scale) resulting from the removal of thermal pollution in 1D (red) and 3D (orange). Gray bars denote MNPP maintenance with negligible heat emission into the Aare River.

From Figure 8 we estimate the response time of LB to thermal pollution from MNPP. The response time was defined as the time required for ΔS to decay past a threshold value (1%) during the plants maintenance period. For all scenarios, this was accomplished by fitting an exponential function to ΔS during both maintenance periods shown in Figure 8 (gray areas). From these four curves the mean response time was calculated to ~ 40 days, which is roughly 70% of the hydraulic residence time of LB (~ 58 days) and consistent with the two residence times defined by the hydraulic and the thermal throughflows (section 3.3).

3.3. Heat Fluxes

The removal of the MNPP thermal pollution will only affect the heat flux terms which are dependent on lake temperature. The change in the heat flux terms for shortwave and longwave absorption are thus equal to zero. The total change in heat flux ΔH_{Net} is therefore only determined by the change in longwave emission ΔH_W , evaporation/condensation ΔH_E , heat convection ΔH_C , and throughflow ΔH_F :

$$\Delta H_{Net} = \Delta H_W + \Delta H_E + \Delta H_C + \Delta H_F. \quad (4)$$

For both models the changes in each flux term in equation (4) were calculated using the method described in *Livingstone and Imboden* [1989] and *Fink et al.* [2014]. For H_W , H_E , and H_C we used the modeled surface temperature in each grid cell. H_F was obtained using the inflows and outflow river discharges and temperatures. The saturated vapor pressure e_s used for calculations of H_E was approximated by the Magnus formula [WMO, 2008], where T_W is the water surface temperature

$$e_s = 6.112 \exp[(17.62T_W) \times (243.12 + T_W)^{-1}]. \quad (5)$$

The median seasonal change of the considered heat flux terms in equation (4), with corresponding 25th and 75th percentiles, are presented in Figure 9. In Supporting Information Table S4 we provide the seasonal changes in mean heat fluxes and relate these to the present-day fluxes. Heat flux changes in the 3D model shows a larger variability compared to the 1D model (Figure 9). The range of extreme values is 4–6 times larger in 3D compared to 1D. The total change in heat flux ΔH_{Net} amounts for both models to $\sim 17 \text{ W m}^{-2}$, which is in excellent agreement to the MNPP input of 18 W m^{-2} .

The majority of the change ($\sim 60\%$ of ΔH_{Net}) is concentrated in ΔH_F . Most of the thermal pollution is thus transported through the system and transferred to downstream Aare River. This corresponds to the observed relationship between the thermal response time (section 3.2) and the hydraulic residence time of LB ($60\% \approx 40 \text{ days} / 58 \text{ days}$). In order to evaluate how far heat can reach downstream of LB, we apply the method described in Supporting Information Text S1. The adjustment distance, where 37% of the heat remains, was calculated to $\sim 350 \text{ km}$ under the assumption that river properties do not change downstream. The remaining heat ($\sim 40\%$ of ΔH_{Net}) leaves LB through the lake surface. H_E and H_C are only marginally affected while H_W is the least affected of all heat flux terms (Supporting Information Table S4).

The models differ regarding how the thermal pollution is transported from the Aare inflow (station 2085) to the outflow (station 2029). Therefore, the change in 1D and 3D modeled heat flux at the outflow $\Delta H_{F, out}$ will be affected differently by the closure of MNPP. The deviation between 3D and 1D modeled heat leaving LB ($3D \Delta H_{F, out} / 1D \Delta H_{F, out}$) is presented in Figure 10a. Surprisingly, the removal of thermal pollution leads to larger changes for $H_{F, out}$ in 3D compared to 1D. This is shown in Figure 10a by the long tail of the distribution toward higher values (topmost 10%, to the right of the solid orange line). As shown in section 3.1, the circulation in the lake and the spatial extent of the Aare inflow plume is governed by the local wind field. We note that the tail of the distribution coincides mainly with winds from the south-west as indicated by the orange bars in Figure 10b. We thereby conclude that the pathway of the Aare plume, resolved in 3D but not in 1D, determines how much of the MNPP heat that is removed to the downstream Aare.

3.4. Intrusion Depth

The Aare inflow intrudes into the metalimnion during the stratified period (March–November). The intrusion depth is generally deeper in 1D compared to 3D. By removing the thermal pollution from the Aare River the water density generally increases. This deepens the river intrusion in both models. The magnitude of intrusion depth increase varies with the seasons and is strongest during winter. At this time a removal of thermal pollution increases the mean intrusion depth by 8.3 m in 1D and 3.2 m in 3D. The effect is much less pronounced in summer with 0.8 m (1D) and 1.1 m (3D) average deeper intrusions. The observed seasonality of

Figure 9. Modeled heat flux changes due to removal of thermal pollution during the cold (X-2010) and warm (X-2013) periods in 3D (3D-X) and 1D (1D-X) during summer (April–September) in red and winter (October–March) in blue. The central black dots denote the median and the box extends the first and third quartile. Heat flux terms include (a) longwave emission H_w , (b) evaporation and condensation H_E , (c) heat convection H_C , and (d) throughflow H_F .

the intrusion depth change is due to both the seasonal varying impact of thermal pollution on Aare water (largest in winter), and the strong lake stratification during summer.

Hydropower-induced thermo-peaking results in large subdaily temperature fluctuations in the Aare inflow. This rapidly changing density of the river water leads to oscillations in intrusion depth. The effect is stronger in the 1D model (no entrainment) compared to the 3D model (including entrainment). Entrainment of ambient lake water into the river plume buffers rapidly changing densities in the inflow and thereby limits the effect of thermo-peaking on intrusion depth in 3D.

4. Discussion

4.1. Temperature Change

The MNPP thermal pollution enters LB via the Aare River inflow. Dispersion of the river water across the lake determines the heat distribution. Our results indicate that the upcoming decommission of MNPP will decrease the temperature in LB as a function of season, with the largest impact in winter which is in

Figure 10. Intermodel difference of outflowing heat and wind direction for the cold and the warm scenarios combined (April 2010 to March 2011 and April 2013 to March 2014). (a) Distribution (x bin resolution 0.07) of 3D and 1D model ratios of the change in heat outflow $\Delta H_{f out}$ due to decommission of MNPP. The orange line marks the ninetieth percentile (90%) of the distribution. (b) Dominant wind direction (origin of the wind; COSMO-2 data) in % of occurrences within a 6 h period prior to $\Delta H_{f out}$ output in Figure 10a. Gray bars in Figure 10b represent wind direction during the complete period. Orange bars in Figure 10b denote the dominant wind direction corresponding to the instances to the right side of the 90% orange line in Figure 10a, i.e., to instances where the heat outflow from the 3D model is at least 65% larger than in the 1D model.

accordance with previous results published by *Mulhollem et al.* [2016]. At this time of year the available inflow from the Aare River is at its lowest level, resulting in considerable temperature fluctuations in LB of up to $\sim 3.4^{\circ}\text{C}$. This discharge-dependent sensitivity to thermal pollution is in line with previous findings made by *Prats et al.* [2012]. On a system-wide scale the effect is smaller and we find that LB volume-weighted mean temperature is likely to drop by $\sim 0.3^{\circ}\text{C}$ (Figure 6) between October and March. This is in the same order of magnitude as the observed global decadal increase (between 1985 and 2009) of summer lake surface temperature due to climate change [*O'Reilly et al.*, 2015]. Consequently, for a limited period of time, point sources of anthropogenic heat can have an equal impact as climate change as previously suggested by *Fink et al.* [2014]. The MNPP decommission could therefore affect the reaction of LB to the ongoing climate change.

Our results furthermore show that the upcoming plant decommission will have a smaller impact (mean volume-weighted temperature drop $\sim 0.1^{\circ}\text{C}$) during summer when the lake is strongly stratified. At this time of year the river discharge peaks, resulting in the thermal pollution being dispersed across a larger water volume and hence limiting local effects. Furthermore, the strong summer stratification captures the intruding river water in the metalimnion. The intruding Aare water lifts the epilimnion toward the surface and out of the lake. Here we refer to this phenomenon as “flushing.” The flushing effect is strengthened by the short hydraulic residence time of LB. It is thus expected to be present in similar aquatic systems which have small volume to inflow ratios.

The residence time of the MNPP heat in LB can be further shortened if the river plume is advected by lake-wide circulation along the eastern shore toward the outflow, potentially reducing the effect of mixing the thermal pollution across the lake. We refer to this process as “short circuiting,” which generally occurs during shallow intrusion events in combination with winds from south-west (Figure 7b). This follows results by *Schimmelpfennig et al.* [2012] who linked river water residence time in a small lake to wind-induced lake-wide circulation patterns. The seasonal peak in river discharge volume and the removal of heat from the lake through the outflow thus limits the effects of MNPP thermal pollution during summer.

Flushing and short circuiting were likewise present during winter but due to the smaller inflow and in general deeper intrusion of the Aare inflow, the effects were much smaller. However, for river temperatures $< 4^{\circ}\text{C}$ the effect of short circuiting can be substantial, as the inflow floats at the lakes surface. Flushing was present in both models, while short circuiting only takes place in the 3D model.

Our results can be compared to findings made by Hanafiah [2013], who modeled the signature of the MNPP thermal pollution downstream of LB. By resolving LB using shallow riverine segments, she found that heat remaining from MNPP at the outflow station 2085 would raise the river temperature by ~ 0.5 to $\sim 0.8^\circ\text{C}$. In our study we resolved the spatial and temporal processes taking place in LB to a considerable higher degree. Thus, at the outflow station 2085 we found corresponding temperature increases of ~ 0.2 to $\sim 0.4^\circ\text{C}$. We conclude that the impact of MNPP thermal pollution on LB is seasonal and strongest during warm winters, when the lower temperature gradient between atmosphere and lake/river water is limiting the transfer of heat from the water to the atmosphere.

4.2. Water Column Stratification

Our study shows that thermal pollution entering LB prolongs the stratified summer period. The added heat strengthens the stratification and thus opposes vertical convection. Stronger stratification has been shown to decrease the concentration of dissolved oxygen in lakes [Foley *et al.*, 2012]. The impact of enhanced stratification combined with high primary productivity results in lower hypolimnion oxygen concentrations in LB. Between 2000 and 2016 the oxygen concentration in LB at 74 m depth annually drops to less than 3 mg L^{-1} in late autumn. We find that a removal of MNPP thermal pollution from the Aare inflow would weaken the water column stability and decrease the duration of the stratified period in summer. This will slightly improve oxygen conditions in the hypolimnion.

Thermal pollution hinders the Aare River temperature to drop below 4°C for most of the winters (Figure 2b). We show that the upcoming decommission of MNPP will result in river temperatures colder than 4°C . This can drive LB toward dimictic conditions with inverse stratification in winter (Figure 8). Our findings are thus in line with observations made in Stechlinsee [Kirillin *et al.*, 2013]. Increased stratification in winter generally limits deep water reoxygenation [Golosov *et al.*, 2007, 2012; Schwefel *et al.*, 2016]. However, for LB the effect is expected to be minor since the relative increase in stratification is small (section 3.2). By using the mean wind speed over LB of 2.5 m s^{-1} and C_{10} from the 3D model, we find that a stratification strength increase of $\sim 20\text{ J m}^{-2}$ would be opposed by wind-induced mixing after ~ 3 weeks. Furthermore, the effect is larger in 1D (which lacks short circuiting) compared to 3D.

4.3. Heat Budget and Heat Fluxes

Our findings indicate that the majority ($\sim 60\%$) of the thermal pollution leaves the lake via the main outflow (Figure 9d). This is a substantial anthropogenic thermal contribution to the downstream Aare and Rhine Rivers which are extensively used for industrial cooling. As we remove the thermal pollution, the inflowing Aare water density increases. The river plume entering LB will therefore intrude deeper. River water that could previously quickly exit the lake via the outflow may thus reach the hypolimnion and thereby limit the short circuiting effect. For river water colder than 4°C the likelihood of short circuiting increases. The short circuiting is thus the main cause behind the larger fluctuations in $\Delta H_{F\text{ out}}$ observed in Figure 10a for 3D compared to 1D model results.

The contribution of MNPP to H_E , the second most affected flux term, leads to an evaporation of $\sim 0.1\text{ mm d}^{-1}$ ($\sim 4\text{ cm yr}^{-1}$). This evaporation remains negligible compared to the annual water level fluctuations in LB of $\sim 1\text{ m}$. Kirillin *et al.* [2013] showed that cooling water emitted from a nuclear power plant into a small lake mainly leaves the water body via H_E fluxes. Our results, however, suggests that the throughflow is the dominant sink of heat in short retention time systems.

4.4. Model Divergences

The overall impact of the MNPP thermal pollution on LB temperature are well reproduced in both 1D and 3D as seen in Figure 6. However, the fine-scale processes such as local temperatures and short circuiting are, as expected, better resolved in 3D, whereas extreme temperature fluctuations are smoothed out by the 1D approach. Therefore, harmful local effects on biota by extreme temperatures, up to $\sim 3.4^\circ\text{C}$ in this study, cannot be investigated with a 1D model. As rapid changing temperature conditions have been shown to be destructive for biota [Barnett, 1971; Sylvester, 1972; Reutter and Herdendorf, 1976; Vandysh, 2009; Bruno *et al.*, 2013], it is important to consider 3D models when local heat emissions matter. This is particularly evident in lakes like LB, where the river plume often flows along shallow shores.

Surprisingly, we find that flushing compensates the lack of short circuiting in 1D as seen by the overall good fit between 1D and 3D in the amount of heat leaving the lake via the outflow (Figure 10a). We

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interpret this as the consequence of both the short residence time of the surface layer in LB, and the long distance (~ 8 km) between the Aare River in/outflow. We expect a larger influence of short circuiting in aquatic systems where in/outlets are located closer together.

The two models reproduce the temperature equally well in the epilimnion (Figure 3a) which is the most important zone for the heat fluxes. The 3D model includes baroclinic motions of the water column (Figure 4e) and is therefore better suited for the metalimnion compared to the 1D model (Figure 3a). In turn, the 1D model performs better in the hypolimnion compared to the 3D model (Figure 3a). This is mainly due to the fact that the 3D model was optimized toward both temperature and current velocity at several locations. The 1D model, in contrast, was optimized only for temperature at the central station CB.

The temperature difference between both models and observations (*RMSD* from 0.4 to 2.3°C; Figure 3 and Table 3) were larger than the mean volume-weighted temperature change ($\sim 0.3^\circ\text{C}$) induced by the MNPP closure. However, for the analyses concerning the effects of the MNPP closure, the modeled temperature divergences from measurements can be disregarded since identical biases are present in all model runs made with and without thermal pollution and with otherwise unchanged forcing. Furthermore, the excellent agreement between thermal pollution (18 W m^{-2}) in relation to modeled changes in heat fluxes (17 W m^{-2}) in both 1D and 3D also proves the adequacy of the models. These arguments strengthens our confidence in the expected change of water temperature, heat flux, and stratification after decommission of MNPP in 2019.

5. Conclusions

Aquatic ecosystems are often used as sinks for thermal pollution from anthropogenic activities. Here we studied the impact of heat emission (equivalent to 18 W m^{-2}) from a nuclear power plant on the perialpine Lake Biel, which has a short hydraulic residence time of ~ 58 days. We quantified the impact of thermal pollution on temperature, stratification, and heat fluxes using both 1D and 3D models.

A clear seasonal trend was observed for the effect of thermal pollution on lake temperature, caused by seasonal varying discharge in the inflowing river. Maximal effects occurred in winter (lowest discharge) with up to 3.4°C increase of local temperature. On system-wide scale, the mean volume-weighted lake temperature increased by $\sim 0.3^\circ\text{C}$. The effect was strongest during warm winters compared to cold winters. Anthropogenically increased temperature strengthened stratification and prolonged the stratified period by up to 4 days. Furthermore, the majority ($\sim 60\%$) of the emitted thermal pollution traversed the lake and was transported further downstream. The remaining heat ($\sim 40\%$) left the lake via the surface to the atmosphere mainly due to increased evaporation. The upcoming power plant decommission will thus shorten the stratified period as well as lower the temperature in the lake and in the downstream river.

The increase of volume-weighted lake temperature ($\sim 0.3^\circ\text{C}$) is in the same range as the observed global increase of summer surface water temperature due to climate change [O'Reilly *et al.*, 2015]. We therefore recommend that local anthropogenic/natural sources and sinks of heat should be included in studies evaluating the response of aquatic systems to climate change.

For future studies of thermal pollution in lakes and reservoirs we recommend the following model selection guidelines. The main processes only identifiable in 3D were spatial inhomogeneity of altered lake temperature caused by local wind patterns and distance to the thermal sources, resulting in short circuiting between river inflow and outflow. Both 1D and 3D were sufficient to determine system-wide effects on lake temperature and stratification as well as tributary-induced epilimnion flushing.

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