1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Ensemble modelling of ice cover for a reservoir affected by pumped-storage operation and climate change

Ensemble modelling of ice cover

Ulrike Gabriele Kobler^{1,2,*}, Martin Schmid¹

ORCHID-Identifiers: 0000-0003-4661-3876, 0000-0001-8699-5691

¹ Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters – Research and Management, CH-6047 Kastanienbaum, Switzerland

² EPFL, Physics of Aquatic Systems Laboratory – Margaretha Kamprad Chair, ENAC-IEE-APHYS, CH-1015 Lausanne, Switzerland

* Corresponding author: ulrike.kobler@icloud.com

Acknowledgements: We want to thank Dirk Schlabin for his insights on the weather generator. Moreover, we acknowledge P. Meier, who tackled Python library issues during the weather generator set up. Additionally, we would like to thank E. Calamita and D. Vanzo for assistance with set up and calibration of GLM, and F. Bärenbold, A. Gaudard and L. Răman Vinnå for their help with Simstrat configuration. Moreover, we would like to thank A. Wüest and M. Perroud for reviewing this manuscript. The authors would also like to thank Karsten Rinke and an anonymous reviewer for their helpful and constructive comments.

Funding: This study was funded by the Swiss Federal Railways (SBB AG).

Conflict of interest: None.

This document is the accepted manuscript version of the following article:
Kobler, U. G., & Schmid, M. (2019). Ensemble modelling of ice cover for a reservoir affected by pumped-storage operation and climate change. *Hydrological Processes*, 33(20), 2676–2690. <https://doi.org/10.1002/hyp.13519>

Data Availability Statement: The data that support the findings of this study are available as follows:

- The meteorological data for the following stations Wädenswil (WAE), Schmerikon (SCH), Einsiedeln (EIN) and Zurich Fluntern (SCM) can be ordered from the Federal Office of Meteorology and Climatology (MeteoSwiss) at <https://gate.meteoswiss.ch/idaweb/login.do?language=en>.
- The meteorological data of Segelclub Sihlsee are available from the authors, subject to permission by Segelclub Sihlsee.
- The hydrological data can be ordered from the Federal Office for the Environment (FOEN) at <https://www.hydrodaten.admin.ch/en/stations-and-data.html> under the following IDs 2300 (Minster), 2301 (Eubach), 2635 (Grossbach), 2104 (Linth). The inflow water temperatures were taken from the stations with the IDs 2609 (Alp, inflows to Sihlsee) and 2104 (Linth, inflows to Upper Lake Zurich).
- The pumped-storage scenarios are available from the authors, subject to permission by the Swiss Federal Railways AG.
- The outflows to River Sihl are available from the authors, subject to permission by the Swiss Federal Institute for Forest, Snow and Landscape Research.
- The projected temperature increase for north-eastern Switzerland in 2085 from CH2011 can be ordered from the Center for Climate Systems Modeling (C2SM) at <http://data.c2sm.ethz.ch/dataset/ch2011plus/>.
- The remaining data, including the bathymetry of Sihlsee, the water balance correction term, and the field observations used for model calibration are available on reasonable request from the authors.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Abstract

Ensemble modelling was used to assess the robustness of projected impacts of pumped-storage (PS) operation and climate change on reservoir ice cover. To this end, three one-dimensional and a two-dimensional laterally-averaged hydrodynamic model were set up. For the latter, the strength of the impacts with increasing distance from the dam was also investigated. Climate change effects were simulated by forcing the models with 150 years of synthetic meteorological time series created with a weather generator based on available air temperature scenarios for Switzerland. Future climate by the end of the 21st century was projected to shorten the ice-covered period by ~2 months and decrease ice thicknesses by ~13 cm. Under current climate conditions the ice cover would already be affected by extended PS operation. For example, the average probability of ice coverage on a specific day was projected to decrease by ~13% for current climate, and could further be reduced from ~45 to ~10% for future climate. Overall, the results of all models were consistent. Although the number of winters without ice cover was projected to increase for all one-dimensional models, studying individual segments of the two-dimensional model showed that the impact was pronounced for segments close to the PS intake/outlet. In summary, the reservoir’s ice cover is expected to partially vanish with higher probability of open water conditions closer to the PS intake/outlet.

Keywords

ice coverage; hydrodynamic and lake ice model; climate change; weather generator; pumped-storage hydropower

1 Introduction

Due to the increasing share of new renewable electricity production, additional storage capacity is needed, which explains the renewed interest in pumped-storage (PS) hydropower plants. PS hydropower plants convert surplus electric energy to potential energy by pumping water from a lower to an upper water body. When the electricity demand is high, water is released through turbines back to the lower water body to generate electricity. As of 2017, PS operations provided 95% of the global utility scale electricity storage capacity (REN21, 2017). However, they are also known to affect abiotic and biotic components of the connected water bodies (Bonalumi, Anselmetti, Kägi & Wüest, 2011). The duration and thickness of ice covers are important drivers for lake ecology (Salonen, Leppäranta, Viljanen & Gulati, 2009; Powers & Hampton, 2016), yet, they have been shown to be modified by PS operation (Bonalumi, Anselmetti, Wüest & Schmid, 2012; Kobler, Wüest & Schmid, 2018).

Climate change is another important driver affecting lake ice cover. Benson et al. (2012) analysed long-term ice phenology of a set of lakes in the Northern Hemisphere where ice-on was delayed on average by ~ 0.3 days per decade and ice-off was advanced by ~ 0.5 days per decade for the 100-yr period from 1905/06 to 2004/05. Magee, Wu, Robertson, Lathrop and Hamilton (2016) showed similar trends of delayed ice-on by ~ 0.9 days per decade and earlier ice-off by ~ 1.2 days per decade.

Besides observations, modelling approaches were used to project the effect of climate change on lake ice. Dibike, Prowse, Saloranta & Ahmed (2011) analysed climate change effects over a range of latitudes ($40\text{--}75^\circ\text{N}$) and a period of 80 years by modifying the atmospheric forcing according to SRES A2 emission scenarios with an air temperature increase of ~ 2 to 8°C and a precipitation increase ~ 10 to 50% in winter. They used the one-dimensional lake model MyLake and projected delayed ice-on by 5 to 20 days, advanced ice-off by ~ 10 to 30 days, and reduced ice thickness by 10 to 50 cm. Moreover, they indicated

that the snow cover on top of the lake ice would change from -15 to +5 cm, further affecting the white ice formation by -20 to +10 cm. Magee et al. (2016) also set up a one-dimensional hydrodynamic lake and ice model, DYRESM-WQ-I, to project the effect of a changing climate on lake ice thickness. They projected a decrease of thickness by ~1.3 cm per decade for a long-term simulation of the period 1911-2014 at Lake Mendota (Wisconsin, USA).

Changes in ice cover further affect ecological and socio-economic aspects. For example, diatom composition is influenced by changes of the length of the ice-covered period (Rühland, Paterson & Smol, 2015). Moreover, Shuter, Finstad, Helland, Zweimüller & Hölker (2012) summarize important implications of the under-ice lake environment: low light intensity and water temperature in combination with depleted oxygen levels, little primary production, reduced metabolism, and impediment of visual feeders from finding sparsely available prey. Therefore, changes in ice phenology could result in alterations of fish growth and reproduction (Shuter et al., 2012).

The socio-economic aspects involve recreational activities (Leppäranta, 2014), and changes in ice regimes may cause potentially hazardous conditions for the seasonal use of lake ice cover for transportation (Prowse et al., 2011).

Here, we investigate the combined effects of PS operations and climate change on ice cover in Sihlsee, the upper reservoir of a PS scheme in Switzerland. These effects were previously assessed using the laterally averaged two-dimensional model CE-QUAL-W2 both for different PS scenarios (Kobler et al., 2018) and interactions with projected future climate (Kobler, Wüest & Schmid, 2019). However, the modifications of the ice module of CE-QUAL-W2 by Kobler et al. (2018) were not tested comprehensively, and therefore, uncertainties about its applicability remained. Furthermore, the ice module of CE-QUAL-W2 does not consider effects of snow cover or the formation of snow ice. The major aim of the present study was, therefore, to get a more robust assessment of projected impacts of climate

change and PS operations on the extent and duration of ice cover and to reduce the structural uncertainty resulting from applying a single, model, which was only tested a few times. For this purpose, we implemented an ensemble model approach by applying three additional one-dimensional vertical models (GLM, Simstrat, and MyLake, the latter due to its structural limitations only for climate change simulations). In addition, we assessed the longitudinal variation of projected changes in the laterally averaged two-dimensional model.

2 Study site

Sihlsee is the upper artificial reservoir of Etzelwerk, which is currently operated as a PS hydropower plant (Figure 1). This reservoir, which was inundated in the 1930s, is on average 9 m deep, has a surface area and a volume of $\sim 11.3 \text{ km}^2$ and $96.1 \times 10^6 \text{ m}^3$, respectively. Its water level varies between 889.34 and 876.84 m a.s.l., thus, the storage capacity amounts to $89.4 \times 10^6 \text{ m}^3$ (Kobler et al., 2018). It is dimictic, with temperatures up to 25 and 15 °C in the epi- and the hypolimnion during summer stratification, and it is ice-covered in winter. Detailed information on the thermal structure and the water quality of this reservoir are given in Kobler et al. (2018). Under present PS operations, $\sim 10\%$ of the total inflows to Sihlsee are pumped from Upper Lake Zurich. Water is withdrawn from the hypolimnion of the reservoir, and $\sim 90\%$ of this water is used for power production, while the remainder is discharged as residual flow into River Sihl. The main effect of this present management on the thermal properties of the reservoir is a significant warming of the hypolimnion by up to 10 °C in autumn compared to a near-natural scenario, which further results in a shortening of summer stratification by approximately one month, and a corresponding reduction of the occurrence of suboxic conditions in the hypolimnion (Kobler

et al., 2018). These effects would be further enhanced in an extended PS scenario where the amount of water pumped from Upper Lake Zurich would be increased by a factor of ~20.

Ice cover has been observed weekly by the Swiss Federal Railways since 2001 in the northern part of the reservoir, closely located to the dam (Figure 1). Maximum ice thickness did not exceed 0.5 m. Its mean thickness during ice-covered periods ranged between 6.4 cm (2006/07) and 29 cm (2005/06). These point observations suggest that all winters in the period 2001 to 2015 were ice-covered with mostly one freeze-thaw cycle, except in winter 2006/07, when two freeze-thaw-cycles were observed. In some winters (2011/12 and 2014/15) the major freeze-thaw cycle was preceded by another short ice cover in early winter, which lasted for ~2 weeks. Additional information on the meteorological conditions from November to April of each winter season can be found in the Supplementary Material.

3 Methodology

3.1 Model description

An ensemble of four hydrodynamic models was set up to simulate ice cover on Sihlsee: the two dimensional, laterally averaged model CE-QUAL W2, and the three vertically resolved one-dimensional hydrodynamic models GLM, Simstrat, and MyLake. The application of MyLake was limited by the fact that it does not allow specifying outflows with a specific discharge or depth level different from the surface. Any withdrawal is computed internally and occurs at the surface in case of an overflow. Thus, MyLake was only used for simulating the near-natural case without PS operations. A conceptual diagram of the ice modules of all four models is depicted in Figure 2.

The first model is CE-QUAL-W2, version 3.71. It is a two-dimensional laterally averaged hydrodynamic and water quality model, which was set up for this study site by

Kobler et al. (2018), and allows for the direct coupling of the upper reservoir Sihlsee and the lower natural lake Upper Lake Zurich which are connected by PS operation. This model was developed at Portland State University in cooperation with the US Corps of Engineers (Cole & Wells, 2013), and requires bathymetric, meteorological, hydrological and water quality forcing, which has been described in detail by Kobler et al. (2018). The model is able to project stratification, dissolved oxygen and nutrient dynamics; however, the focus of this study lies on lake ice formation and decay. For this purpose, we use a modified version of CE-QUAL-W2. Instead of the original parameterisation of long-wave radiation, which did not accurately reproduce observations at the local meteorological stations, long-wave radiation was calculated externally using the same method that had already been successfully applied by Schmid and Köster (2016) for Lower Lake Zürich. In addition some modifications were made regarding the penetration of short-wave radiation through the ice cover (Supplementary Material; Kobler et al., 2018). The ice module of CE-QUAL-W2 only considers a single ice layer (Figure 2). Effects of snow and the formation of snow ice are not considered, except that the calibrated value for the ice albedo of 0.5 (Supplementary Material) lies in between the values for ice and snow albedo of the other models. Ice grows if the net heat flux at the ice-water interface is negative, and can melt both from the top or the bottom when the corresponding net heat fluxes are positive. Within this study, we extend the work of (Kobler et al., 2018; 2019), who analysed the effects of PS operation and climate change for only one model segment in the deeper part of the reservoir, to the investigation of five segments at different distances from the dam, where PS flows are withdrawn and released. This allows assessing how the effects of PS operation spread throughout the reservoir.

Two one-dimensional vertical hydrodynamic models were chosen based on their ability to define multiple in- and outflows, which could be specified either at a particular

depth or relative to the water surface. The first of those two is the General Lake Model (GLM), version 2.4.1, which was developed at the University of Western Australia (Hipsey et al., 2019). Its lake ice module is based on the model described by Rogers, Lawrence and Hamblin (1995). It includes the formation of black ice (congelation ice) by freezing at the water-ice interface, the accumulation of snow on top of the ice cover, and the formation of white ice (snow ice) when the weight of the snow exceeds the buoyancy of black ice. Light attenuation is considered individually for the visible and the infrared band. Comparing the publication by Rogers et al. (1995) to the source code of GLM revealed some bugs, which we corrected before model runs (Supplementary Material). To be able to use a hydrological forcing as similar as possible to that prepared by Kobler et al. (2018), we also introduced the option to switch off the effects of evaporation and precipitation on the water balance. Moreover, we introduced a scaling factor for the snowfall forcing, as first simulations revealed that using the entire snowfall would result in an overestimation of total ice thickness.

The second one-dimensional model is Simstrat, version 2.0, which is a modified version of the model originally published by Goudsmit, Burchard, Peeters and Wüest (2002). This model was developed at Eawag for the simulation of stratification and mixing dynamics in lakes. Its turbulence formulation is based on a k - ϵ -model, which includes transport equations for the turbulent kinetic energy (k) and its dissipation (ϵ). In version 2.0 of Simstrat a new lake ice module was implemented, which is based on the equations for lake ice formation and decay as used in the model MyLake (Saloranta & Andersen, 2007). In order to be able to compare the performance of the ice model implemented in Simstrat with the original model of Saloranta and Anderson (2007), we additionally set up MyLake, which, however, does not allow specifying outflows with a specific discharge or depth level different from the surface, and therefore, could not be used for simulating the PS scenarios. In both

models, ice growth at the water-ice interface is calculated using Stefan's law. Accumulation of snow and the formation of white ice are included, but white ice is assumed to have the same properties as black ice. Light attenuation is not specified separately for the visible and the infrared band. The main difference between the ice modules of the two models concerns the penetration of solar radiation: Simstrat assumes that the absorption of solar radiation is independent of ice and snow thickness, whereas MyLake considers a thickness-dependent exponential approach (Figure 2).

Hourly meteorological forcing, generated with the weather generator VG (Schlabing, Frassl, Eder Rinke & Bárdossy, 2014) for all four models, is based on previous studies of Kobler et al. (2018; 2019). MyLake runs only with daily meteorological forcing, which was calculated by averaging the hourly data. Dew point was converted to relative humidity for GLM and MyLake and to water vapour pressure for Simstrat. While GLM, Simstrat and CE-QUAL-W2 use long-wave radiation as input, MyLake calculates it from cloudiness, air temperature and relative humidity following the approach of Dickey and Manov (1994). Thus, long-wave radiation projections of the weather generator VG were converted to cloudiness using the concept presented in section 3.3 of Schmucki, Marty, Fierz and Lehning (2014), and the computed long-wave radiation forcing of MyLake differs slightly from that of the other models.

For simulations with GLM, rain and snowfall were required as additional inputs. Both were computed from precipitation observed by MeteoSwiss at Einsiedeln. Rain was set equal to the observed precipitation whenever air temperature was $>0^{\circ}\text{C}$. For snow only precipitation events with air temperatures $<0^{\circ}\text{C}$ were considered, and precipitation was converted from water equivalents to snow height using a snow density of 100 kg m^{-3} . MyLake also required daily air pressure, which is provided from observations of the Federal Office of Meteorology and Climatology MeteoSwiss at Einsiedeln.

In GLM, hourly values can be used for the meteorological forcing, but the hydrological forcing can only be specified with a daily resolution. The water balance correction term, which was necessary to correct for the measurement errors as well as missing inflows, groundwater exchange, evaporation and precipitation (Kobler et al., 2018), needed to be adapted by a few percent for GLM and Simstrat because the volume is approximated differently for the vertical layers of these two models than it is computed based on the two-dimensional grid of CE-QUAL-W2.

The natural inflows were implemented as surface inflows. For GLM this is the standard setting for inflows, for Simstrat the surface inflows were designed to always intrude in the top 2 meters of the water column. To depict the PS pumping flows, GLM offers the option of submerged inflows at a given distance from the lake bottom. In Simstrat inflows can be placed at a specific depth level or relative to the initial water surface. It also offers the choice to distribute an inflow over a depth range where we chose 5 m (between 867.75 and 872.75 m a.s.l.) to depict the outlet/intake situation of the PS hydropower plant.

The PS generating and the residual flow of River Sihl are both withdrawn from the same depth range as the PS pumping flow. The correction term is added to the natural inflows if it is positive, and withdrawn from the top 2 m relative to the surface if it is negative. For GLM the residual outflow and the PS generating flow are withdrawn by an outlet type 1, which corresponds to an outflow from a fixed depth (870 m a.s.l.). The correction term of the water balance is treated similarly to Simstrat if positive, and withdrawn at 1 m below surface using an outlet type 2 if negative. Salinity was assumed to be constant for both GLM and Simstrat.

The temperature of the PS pumping flow was taken from previous projections of the epilimnion temperature of Upper Lake Zurich for either considering observed meteorological

conditions (Kobler et al., 2018) or time series of current and future climate conditions developed with a weather generator (Kobler et al., 2019).

3.2 Sensitivity analysis

The sensitivity of ice formation to the model parameters is depicted and discussed in the Supplementary Material. The purpose of this analysis was to determine the influence of the most relevant model parameters on the snow, white ice and black ice formation. For GLM this analysis showed the necessity of introducing a scaling factor of the snow forcing.

3.3 Model calibration

Due to not considering any hydrological forcing MyLake could not be calibrated with the temperature available observations for Sihlsee, since the observed temperature in the reservoir for the present PS is strongly modified by the hypolimnetic withdrawal (Kobler et al., 2018).

GLM and Simstrat were both calibrated using PEST (Doherty, 2010) to observed water temperatures. PEST is a model-independent parameter estimation and uncertainty analysis software package. Through a robust variant of the Gauss-Marquardt-Levenberg method, computation time can be reduced compared to other optimization methods, yet, the risk that the optimization could get trapped at a local minimum prevails (Doherty & Johnston, 2003). Observed ice-thicknesses were not used for calibration.

Short-wave radiation was scaled for all four models similar to CE-QUAL-W2 with a factor of 0.85. This scaling was necessary to reproduce surface water temperature with CE-QUAL-W2. For GLM, the considered calibration parameters include a coefficient for hypolimnetic mixing (coef_mix_hypo), as well as factors for scaling long-wave radiation

(lw_factor) and wind speed (wind_factor). Simstrat was calibrated using the following model parameters: a parameter defining how much energy is transferred from wind to seicheing (a_seich), and scaling factors for wind speed (f_wind) and incoming long-wave radiation (p_radin). All model parameters and initial conditions are summarised in the Supplementary Material.

The root-mean-square-errors (RMSE) of simulated water temperatures using GLM were 1.35, 1.10 and 1.18 °C for the entire water column, the epi- and the hypolimnion, respectively. For Simstrat the RMSE attained values of 1.13, 0.80 and 1.31 °C. RMSE, mean absolute error (MAE) and the mean errors (ME) are also summarized in Table 1. Altogether, these RMSEs were slightly higher than those achieved with CE-QUAL-W2 (~0.94, ~0.93, ~0.94 °C) by manual trial and error calibration (Kobler et al., 2018).

3.4 Pumped-storage scenarios

Four different PS scenarios were developed by Kobler et al. (2018), the present and an extended PS operation scenario as well as two reference scenarios.

Under present PS operation Etzelwerk is mostly managed like a storage hydropower plant, with mean monthly artificial flows of ~6 to 8 m³ s⁻¹ for generating and ~1 m³ s⁻¹ for pumping. Water is withdrawn from the hypolimnion of Sihlsee and released to the epilimnion of Upper Lake Zurich during the generating cycle. Additionally, a residual flow is discharged from the hypolimnion to River Sihl (Supplementary Material). The current hydraulic residence time amounts to ~135 days (Kobler et al., 2018).

For extended PS operation the artificial flows are increased differently for generating and pumping with factors ranging between ~1 to 5 and ~9 to 40, respectively. The hydraulic residence time of the reservoir would change to ~40 days for this scenario.

The first reference scenario QNat (“quasi-natural”) depicts the “theoretical” natural state of the reservoir, if the dam were of natural origin. The outflow to River Sihl for this scenario was generated through the analysis of flow regime observations before the dam was built (LIMNEX AG, 2016, personal communication), and is discharged over a weir. The residence time would increase by ~15 days compared to the present PS scenario. In contrast to the other scenarios, water withdrawal takes place in the epilimnion.

For the second reference scenario (NoPS) the outlet of the residual flow is kept in the hypolimnion, yet, the discharge rate was computed similarly to that of the reference scenario QNat. Therefore, the residence time would be similar to that of QNat. This scenario was developed originally to disentangle the effects of deep-water withdrawal and those of PS operation.

In this publication we introduce a modified version of the first reference scenario, referred to QNat*, which differs from QNat by switching off all hydrological forcing. This scenario was used exclusively for setting up MyLake.

3.5 Climate scenarios

Similar to Kobler et al. (2019) we generated ten synthetic time series for current (1997-2012) and future (2077-2092) climate conditions. These time series were developed using the weather generator VG (Schlabing et al., 2014), which allows emulating the observed variables or generating future conditions by changing mean or variability. Similar to Kobler et al. (2019) air temperature was increased compared to present day conditions according to regional projections of the Swiss Climate Change Scenarios (CH2011, 2011) for the IPCC A2 emission scenario in 2085 for north-eastern Switzerland and each day of the year. VG was then utilized to compute all other meteorological forcing variables and inflow

water temperatures, maintaining the dependencies of observed values during the period 1997-2015. The air temperature increases from (CH2011, 2011) vary seasonally and range from ~3 °C (Sep) to ~4.5 °C (Aug).

3.6 Aggregation of results

All four models were run for the period 1997-2012, allowing for a spin-up phase of one year. Thus, the results presented hereafter, were generated for the time range 1998-2012. In Section 4.1 the simulations based on meteorological observations for that period are described. The projections for VG generated climate scenarios, each comprising a total of 150 synthetic years of simulations, were aggregated and are presented in Section 4.2.

For each day of the year, the probability of the presence of ice cover was estimated as the fraction of winters with ice on that day. Monthly means of ice thickness were calculated by averaging the projections for each scenario over the 150 simulated years.

The comparison of simulations for different segments of CE-QUAL-W2 does not include segment SEG 8 for the present PS scenario and segments SEG 8 and SEG 16 for the extended PS scenario, as these segments could fall dry during the ice-covered season (Supplementary Material).

4 Results

4.1 Comparison of observations and simulations

Mean and maxima of observed and simulated ice thickness for the present PS scenario are given in Table 2. The table also includes simulations using MyLake for the QNat* scenario. As the results further below show, the effect of the present PS on the ice

cover is minor, therefore these results can be compared. On average, simulated ice thicknesses by GLM exceed observations by ~33% for the mean of each winter and by ~9% for the maximum. Simstrat's mean and maximum ice thickness simulations deviate from observations by ~9 and ~2%, those of MyLake by ~4 and ~10% and those of CE-QUAL-W2 by ~7 and ~3%. The mean absolute error of simulated and observed ice thicknesses remains below 8 cm for all models.

For the winter period 2006/07, the ice thickness estimate exceeds the observations by between ~6 cm and ~17 cm for all considered models, which could result from the lowest average air temperatures of the entire studied period for that winter (Supplementary Material).

Observed and simulated ice-on and ice-off dates are summarized in Table 3. Since the time resolution of the measurements is weekly, the model results are also given with this resolution. For the cases of simulated multiple freeze-thaw-cycles that do not coincide with observations, the first date of ice-on is shown in brackets (Table 3). GLM generally simulates an earlier ice-on and a delayed ice-off with average differences of ice-on and ice-off of ~1.1 and ~2.7 weeks, respectively. Multiple freeze-thaw cycles like in 2006/07 and those in early winter of 2012/13 and 2014/15 are not captured by GLM simulations.

The current version of Simstrat suffers from the fact that the ice cover disappears rapidly as soon as all overlying snow has melted independent of its thickness. Ice-off is often simulated to occur earlier than observed with an average difference of ~0.9 weeks and up to ~8 weeks in the winter season 2002/03 (Supplementary Material), where the ice melts too early. This issue is likely related to the formulation used for the penetration of solar radiation. Moreover, in early winter the model produces multiple freeze-thaw-cycles (e.g., 2007/08, 2011/12), which were either not captured by the weekly observations or are a numerical artefact. However, ice-on simulations differ only by ~1.1 weeks from observations.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

The temporal dynamics of lake ice simulations with CE-QUAL-W2 show a slightly delayed ice-on by ~0.4 weeks and an earlier ice-off by ~0.9 weeks. The occurrence of multiple freeze-thaw-cycles matches well not only for 2006/07, but also for these episodes in early winter (2012/13 and 2014/15). Yet, the ice thickness simulations differ in some winters, which could result from the fact that only a fixed albedo is considered in this model.

Ice-on is on average simulated accurately with MyLake, while calculated ice-off has an average delay of ~1.1 weeks.

4.2 Effects due to pumped-storage operation and climate change

Climate warming reduces the probability that the upper reservoir is ice-covered in winter (Figure 3). The average probability that the lake is ice-covered on a specific day from November to April is reduced from 57% to 20% and 24%, respectively, for the reference scenarios QNat and NoPS (percentages for all cases are given in the Supplementary Material). PS operation has an additional influence on lake ice cover. However, the effect of present PS on the duration and thickness of the ice cover for the present climate is minor in all models. This may seem surprising, given the fact that summer stratification was estimated to be shortened by approximately one month by the present PS operations compared to the near-natural scenario QNat (Kobler et al., 2018). However, this shortening was caused by the warming of the hypolimnion, which allowed earlier mixing at higher surface temperatures, whereas early winter lake surface temperatures were almost unaffected. Under future climate all models show a slightly higher probability of ice coverage for the present PS scenario than for the two reference scenarios. For the extended PS scenario this probability decreases on average to ~45% considering current climate, and to ~10% for future climate. The reduced

probability of lake ice coverage is least pronounced for GLM and most evident for CE-QUAL-W2 (Figure 4).

Due to climate change, the duration of ice-covered periods will be shortened on average by ~1.9 months for the present PS and the two reference scenarios. For QNat* MyLake projections even result in a reduction of ~2.6 months. Extended PS operation also reduces the ice cover duration by ~0.8 months (mean of all model projections) already for the current climate. This reduction is most evident for the simulations of CE-QUAL-W2. Climate change results in another reduction of ~1.7 months (average of all model results), which is most pronounced for GLM.

For climate change alone, the ice-on of all models is delayed by ~2.4 to ~3.6 weeks, and three models (GLM, Simstrat and CE-QUAL-W2) project an earlier ice-off by ~3.4 to ~4 weeks. The MyLake predictions for QNat* even indicate an advancement of ice-off by ~7.1 weeks. Both an advanced ice-off (~1.1 weeks) and a delayed ice-on (~1.5 weeks) also result in a reduced duration of the ice-covered period for extended PS operation under current climate. Considering future climate for the extended PS operation, the effects on ice-on and ice-off are even more pronounced. Our results, furthermore, suggest that the effect on ice-off is stronger than on ice-on for extended PS operation.

Ice thickness is projected to decrease on average by ~13 cm under future climate (Figure 4, Supplementary Material). Extended PS alone already leads to reduced ice thickness ranging from ~3 to ~9 cm for current climate, and future climate results in an additional decrease of ~11 cm (mean of all models).

The simulations with CE-QUAL-W2 allow assessing the effects of the distance to the dam. In general, the probability of occurrence of an ice cover decreases towards the dam (Figure 5, Supplementary Material). For any reference scenario under current climate conditions, the average probability that the reservoir is ice-covered on a specific day in the

period from November to April ranges between 55 and 48% for segments SEG 8 and SEG 40, respectively. The reason for the reduced ice cover duration near the dam is that the ice cover generally forms first in the shallow parts of a lake, and the lake depth increases towards the dam. The additional effect of extended PS is also stronger closer to the dam, where the comparably warm water pumped from Upper Lake Zurich is introduced into the lake. In the extreme case, the combination of future climate and extended PS operation, the probability of ice coverage is reduced to ~13% at SEG 24 and to ~1% at SEG 40 close to the dam.

Ice thickness is also projected to decrease more for segments located closer to the dam (Figure 6, Supplementary Material). The mean reduction for future climate conditions amounts to <12 cm for the present PS and the two reference scenarios. For the extended PS operation ice thickness is already reduced on average by ~4 cm (SEG 24, SEG 32) and ~9 cm (SEG 40) for current climate. Future climate conditions would enhance this reduction by additional ~9 cm (SEG 24, SEG 32) and ~7 cm (SEG 40).

5 Discussion

All models project a decreasing probability of ice coverage with climate change. In the reference scenarios and the present PS scenario, less than every second winter will see ice cover under future climate, as estimated with CE-QUAL-W2 and Simstrat. Results from MyLake even suggest that an ice cover would form only about every fourth winter. This difference for MyLake might be explained by the fact that no hydrological forcing besides the natural inflows was considered. The projected ice coverage by GLM contrasts with the other three models, with the probability of ice cover formation remaining at ~90% or higher. This is also reflected in different ice thickness: while for GLM ice thickness amounts to ~16 cm

for both reference scenarios and the present PS scenario under future climate, the average ice thickness remains <10 cm for the other three models. The mean duration of the longest uninterrupted ice-covered periods is projected to be reduced from 98 to 38 days for QNat and from 97 to 42 days for NoPS. The advancement of ice-off is somewhat larger than the delay of ice-on, in agreement with previous findings in both observations and modelling studies (Latifovic & Pouliot, 2007; Dibike et al., 2011; Benson et al., 2012; Magee et al., 2016).

All models consistently project that extended PS would slightly delay ice-on and advance ice-off already under current climate. For all models, the shift in ice-off is more pronounced than that in ice-on, which is further enhanced by future climate. The stronger effect of extended PS on ice-off timing may seem surprising at first sight, since ice-off has been shown to be largely dependent on local climatic conditions whereas ice-on is known to be more strongly modified by individual lake properties (Weyhenmeyer et al., 2010). But it can be explained by the input of warmer water from the epilimnion of Upper Lake Zurich to Sihlsee in early spring which provides heat for melting the ice from below.

The average probability that the reservoir is ice-covered on a specific day in winter is reduced due to extended PS from 51% to 35% for Simstrat and from 49-53% to 13-48% for CE-QUAL-W2, where the probabilities are smaller and more affected by climate change closer to the PS intake/outlet. A comparably small reduction from 71% to 64% is projected by GLM. A reduction of the mean ice thickness by ≤ 5 cm is projected by GLM and Simstrat as well as for the segments of CE-QUAL-W2 located farther from the PS intake/outlet. For segments closer to the intake, the projections show a decrease by up to ~ 9 cm. Mean absolute ice thicknesses drop to ~ 25 cm (GLM), ~ 19 cm (Simstrat) and ~ 11 to 17 cm (CE-QUAL-W2).

The combination of extended PS operation and future climate results for all models in a massively reduced probability of ice coverage. For GLM the average probability of ice

cover on a specific day between November and April would be reduced to ~21%, for Simstrat even to ~3%, and for CE-QUAL-W2 this value ranges from ~1% to ~13% with larger values for segments located farther away from PS intake/outlet. While the projections of Simstrat and GLM suggest that there will still be ice cover during some winters for the entire lake, those of CE-QUAL-W2 draw a spatially variable picture. Ice cover is expected to completely vanish in segments close to the PS intake/outlet but will still occur occasionally in segments located further away.

Regarding climate change impacts on the ice cover, our findings are in line with those of Gebre, Boissy and Alfredsen (2014). They analysed climate change impacts on lake ice with regionally downscaled output of global climate models, with an air temperature increase for the 2080s ranging between 2.2 °C and 5.7 °C, and set up MyLake for a variety of hypothetical lakes all over Scandinavia. Their projections show a reduction of mean annual maximum ice thickness in a range of ~3 to 59 cm, along with a delayed ice-on (5 to 26 days) and a progressing ice-off (11 to 73 days). These projections are not significantly affected by the depth of these hypothetical lakes.

Similarly, Yao et al. (2014) projected shortening of the ice-covered seasons by ~48 days and decreases of ice thickness by 17 cm (average projections of all models) towards the end of the century, which corresponds to reductions of ~40% for ice cover duration and ~52 % for ice thickness. Their climate scenarios were based on the Canadian Regional Climate Model with an increase of the annual mean air temperature by ~6 °C but no significant changes for precipitation. Their projections varied quite strongly between different models for both ice duration and ice thickness.

While both Yao et al. (2014) and Gebre et al. (2014) considered a climate change effect on precipitation, our study did not include this forcing factor. In general the future climate impact on precipitation suggests for north-eastern Switzerland a small increase of

winter precipitation (CH2011, 2011) with an expected shift from snow to rain. The reduction of snowfall would result in thinner snow cover on top of the ice sheet, and, therefore, less white ice could be expected. Moreover, with less snow on top of the ice sheet the albedo would decrease, which further enhances the declining trend of ice thickness for future climate conditions. The increasing amount of liquid precipitation would also enhance the trend of a decreasing ice thickness.

Out of the four models in the study of Yao et al. (2014), GLM was least sensitive to climate change. This is supported by our findings, where GLM predicts only a comparably small reduction of the probability of ice coverage. We were not able to identify a clear cause for the weaker sensitivity of GLM compared to the other models, but nevertheless the recommendation of Bueche, Hamilton and Vetter (2017) to apply GLM for studying climate change effects, needs to be considered with care, particularly for ice-covered lakes.

Regarding the effects of PS operation on lake ice cover, our findings support the reduction of ice thickness described by Kobler et al. (2018) and Bonalumi et al. (2012). However, the analysis of additional segments adds another dimension to the conclusions given in Kobler et al. (2018; 2019). These two studies showed a decreasing trend of lake ice thickness of ~30% for a segment located close to the PS intake/outlet considering current climate and concluded that these results were valid for the entire reservoir. Yet, the more detailed analysis herein shows that this reduction mainly occurs close to the PS intake/outlet. Thus, only the probability of winters with a partial ice cover would increase and not that of completely ice-free winters. Similarly, the projection by Kobler et al. (2019) that ice cover would completely vanish for the combination of extended PS operation and climate change, is only valid for locations close to the intake/outlet, whereas ice cover is expected to still occur in some winters in other parts of the reservoir.

In general, the differences between modelled and observed ice-on, ice-off and ice thickness are in the range referred to in Dibike et al. (2011), who showed mean absolute deviations of 6.2 and 5.8 days for ice-on and ice-off, respectively, and 11 cm for ice thickness. However, our results suggest that the computed ice-on of GLM advances observations by ~2 weeks, which is contrary to the good agreement between GLM projections and observations described by Yao et al. (2014) and Mi et al. (2019). Yet, they are in line with the results of Bueche et al. (2017), who applied GLM to Lake Ammersee, which only froze over once during their studied period. Although they had only qualitative information of the ice coverage for that specific winter, their results suggest that the projected ice-on preceded the observations. In our study, ice-on is best predicted with MyLake, followed by CE-QUAL-W2 and then on par by Simstrat and GLM. Ice-off is predicted best with CE-QUAL-W2, followed by MyLake, Simstrat and GLM, like the results of Yao et al. (2014), where GLM was outperformed by two other models.

Interestingly, the ensemble mean performed similarly or better than the individual models for both the ice thickness and the timing. This is in line with the findings of Trolle et al. (2014) who used a model ensemble to simulate phytoplankton in a temperate lake and found that the ensemble mean was a better predictor than any individual model. However, this does not necessarily imply that the ensemble mean is also a more reliable projection for the assessment of climate and/or PS impacts. Further studies on systems with available long-term data will be needed to assess how well the individual models as well as the ensemble mean are able to reproduce observed trends in the ice cover of lakes caused by climate change.

Some models were able to project the occurrence of multiple freeze-thaw-cycles. Particularly, CE-QUAL-W2, Simstrat and MyLake, were able to capture the observed

dynamics of two freeze-thaw-cycles in 2006/07. In 2014/15 these three models reproduced the development of a freeze-thaw-cycle prior to the development of the main ice-covered period.

Although the ice model of Simstrat is based on MyLake, there are some relevant differences. Particularly in Simstrat, ice melts quickly once snow cover has disappeared, which is not projected with MyLake. One possible reason is the different formulation of the absorption of short-wave radiation in the ice cover (Supplementary Material). In case of MyLake, and also for GLM and CE-QUAL-W2, the attenuation is implemented through an exponential thickness-dependent approach, whereas for Simstrat a constant value is assumed independent of the ice thickness and the actual condition of the surface (ice or snow). Although MyLake does not consider different albedos for black and white ice (Cheng et al., 2008), it would be interesting to consider this for the further development of Simstrat. In summary, there is still potential for improving the physical description of the lake ice cover in all models used in the present study.

6 Conclusions

To assess the robustness of previous projections of the impact of PS operation and climate change on timing, duration and thickness of the ice cover on Sihlsee with the two-dimensional model CE-QUAL-W2, we additionally applied three one-dimensional vertical models, GLM, Simstrat and MyLake. Two of these models (GLM and Simstrat) were calibrated with PEST and could well reproduce observed water temperatures, particularly in the epilimnion.

Overall, these three models projected a reduction of ice thickness and the duration of the ice-covered period due to climate change ranging from ~1.4 months for GLM to

~2.6 months for MyLake. Mean ice thickness was projected to decline by up to ~16 cm (Simstrat). Projected impacts of extended PS differ between the models already under current climate conditions. While GLM only shows minor effects on both the thickness and duration of the ice cover, Simstrat and CE-QUAL-W2 project reductions of the ice thickness of ~5 cm and up to ~9 cm, respectively. For the combination of extended PS operation and future climate, the divergences between models are further amplified. For example, the longest uninterrupted ice-covered period remains up to ~40 days longer in GLM than in Simstrat and CE-QUAL-W2. The major differences between GLM and the other models might be explained by the fact that the overall ice thickness seems to be overestimated by GLM, despite reducing the formation of white ice by introducing a scaling factor for snowfall. The reasons for the overestimation of ice cover by GLM need further investigation.

Model ensembles have previously been only very rarely applied in lake modelling studies. The fact that the mean of the model ensemble was able to better reproduce observed ice thicknesses and ice cover duration, and the additional information gained on the structural uncertainty from the variability of the individual model projections highlight the value of applying such model ensembles also in limnology. Model ensembles are currently also applied to lakes within the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) as a promising approach to improve the robustness and assess the uncertainties in the projection of climate change impacts on lakes on a global scale (Pierson et al., 2018). For a thorough assessment of the effects of the different representations of the processes and the neglect of specific processes in the ice modules of the different models, an application to a more detailed dataset would be required that includes detailed information about the seasonal development of the different ice layers and ideally direct observations of the relevant heat fluxes.

1
2
3 In addition to the ensemble modelling, we also assessed the spatial variability of ice
4 cover projections in different segments of the two-dimensional model CE-QUAL-W2.
5
6 Results show that the ice thickness is decreasing less for segments located farther from the
7 dam. Considering only extended PS operation, the longest uninterrupted ice-covered period
8 would decrease by ~10, ~17 and ~60 days for segments 24, 32 and 40, respectively. Climate
9 change on the other hand would reduce this period by another ~38 days. Yet, the combination
10 of climate change and PS impacts would still result in a partial ice cover for most winters. As
11 our projections have already shown an impact on the ice thickness in late winter, it would be
12 interesting to study how this decreasing ice thickness would further affect ice movement
13 induced by wind and currents.
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

29 **Supplementary Material.** Additional information on model adaptation, model calibration,
30 sensitivity analysis and the projected effects due to PS operation and climate change.
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

References

Benson BJ, Magnuson JJ, Jensen OP, Card VM, Hodgkins G, Korhonen J, Livingstone DM, Stewart KM, Weyhenmeyer GA, & Granin NG. 2012. Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005). *Climatic Change*. 112(2):299-323.

Bonalumi M, Anselmetti FS, Kägi R, & Wüest A. 2011. Particle dynamics in high-Alpine proglacial reservoirs modified by pumped-storage operation. *Water Resources Research*. 47:W09523.

Bonalumi M, Anselmetti FS, Wüest A, & Schmid M. 2012. Modeling of temperature and turbidity in a natural lake and a reservoir connected by pumped-storage operations. *Water Resources Research*. 48(8):W08508.

Bueche T, Hamilton DP, & Vetter M. 2017. Using the General Lake Model (GLM) to simulate water temperatures and ice cover of a medium-sized lake: a case study of Lake Ammersee, Germany. *Environmental Earth Sciences*. 76:461.

CH2011. 2011. Swiss climate change scenarios CH2011, C2SM, MeteoSwiss, ETH, NCCR Climate and OcCC, Zurich, Switzerland.

Cheng B, Zhang Z, Vihma T, Johansson M, Bian L, Li Z, & Wu H. 2008. Model experiments on snow and ice thermodynamics in the Arctic Ocean with CHINARE 2003 data. *Journal of Geophysical Research*. 113:C09020.

- Cole TM, & Wells SA. 2013. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.71. User Manual, Department of Civil and Environmental Engineering, Portland State University.
- Dibike Y, Prowse T, Saloranta T, & Ahmed R. 2011. Response of Northern Hemisphere lake-ice cover and lake-water thermal structure patterns to a changing climate. *Hydrological Processes*. 25(19):2942-2953.
- Dickey TD, & Manov DV. 1994. Determination of longwave heat flux at the air-sea interface using measurements from buoy platforms. *Journal of Atmospheric and Oceanic Technology*. 11(4):1057-1078.
- Doherty J, & Johnston JM. 2003. Methodologies for calibration and predictive analysis of a watershed model. *Journal of the American Water Resources Association*. 39(2):251-265.
- Doherty J. 2010. PEST - Model-independent parameter estimation. User manual: 5th edition. Watermark Numerical Computing.
- Gebre S, Boissy T, & Alfredsen K. 2014. Sensitivity of lake ice regimes to climate change in the Nordic region. *The Cryosphere*. 8:1589-1605.
- Goudsmit G-H, Burchard H, Peeters F, & Wüest A. 2002. Application of k- ϵ turbulence models to enclosed basins: the role of internal seiches. *Journal of Geophysical Research C: Oceans*. 107(C12):3230
- Hipsey MR, Bruce LC, Boon C, Busch B, Carey CC, Hamilton DP, ..., & Winslow LA. 2019. A General Lake Model (GLM 3.0) for linking with high-frequency sensor data

from the Global Lake Ecological Observatory Network (GLEON). *Geoscientific Model Development*. 12:473-523.

Kobler UG, Wüest A, & Schmid M. 2018. Effects of lake-reservoir pumped-storage operations on temperature and water quality. *Sustainability*. 10:1968.

Kobler UG, Wüest A, & Schmid M. 2019. Combined effects of pumped-storage operation and climate change on thermal structure and water quality. *Climatic Change*. 152:427-443.

Latifovic R, & Pouliot D. 2007. Analysis of climate change impacts on lake ice phenology in Canada using the historical satellite data record. *Remote Sensing of Environment*. 106(4):492-507.

Leppäranta M. 2014. *Freezing of Lakes and the Evolution of their Ice Cover*. Heidelberg: Springer Science & Business Media.

Magee MR, Wu CH, Robertson DM, Lathrop RC, & Hamilton DP. 2016. Trends and abrupt changes in 104 years of ice cover and water temperature in a dimictic lake in response to air temperature, wind speed, and water clarity drivers. *Hydrology and Earth System Sciences*. 20:1681–1702.

Mi C, Sadeghian A, Lindenschmidt K-E, & Rinke K. 2019. Variable withdrawal elevations as management tool to counter the effects of climate warming in Germany's largest drinking water reservoir. *Environmental Sciences Europe*. 31:19.

- Pierson DC, Thiery W, Marcé R, Golub M, Debolskiy D, & Stepanenko V. 2018. Simulation strategy for the ISIMIP lake sector. Merging detailed knowledge with global evaluations. American Geophysical Union, Fall Meeting 2018, abstract #GC24B-04.
- Powers SM, & Hampton SE. 2016. Winter limnology as a new frontier. *Limnology and Oceanography Bulletin*. 25(4):103-108.
- Prowse T, Alfredsen K, Beltaos S, Bonsal BR, Bowden WB, Duguay CR, ..., & Weyhenmeyer GA. 2011. Effects of changes in Arctic lake and river ice. *Ambio*. 40(1):63-74.
- REN21. 2017. Renewables 2017: Global status report, REN21 Secretariat, Paris.
- Rogers CK, Lawrence GA, & Hamblin PF. 1995. Observations and numerical simulation of a shallow ice-covered mid-latitude lake. *Limnology and Oceanography*. 40:374-385.
- Rühland KM, Paterson AM, & Smol JP. 2015. Lake diatom responses to warming: reviewing the evidence. *Journal of Paleolimnology*. 54(1):1-35.
- Salonen K, Leppäranta M, Viljanen M, & Gulati RD. 2009. Perspectives in winter limnology: closing the annual cycle of freezing lakes. *Aquatic Ecology*. 43:609-616.
- Saloranta TM, & Andersen T. 2007. MyLake—A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations. *Ecological Modelling*. 207(1):45-60.

- Schlabing D, Frassl MA, Eder MM, Rinke K, & Bárdossy A. 2014. Use of a weather generator for simulating climate change effects on ecosystems: A case study on Lake Constance. *Environmental Modelling & Software*. 61(Supplement C):326-338.
- Schmid M, & Köster O. 2016. Excess warming of a Central European lake driven by solar brightening. *Water Resources Research*. 52(10):8103-8116.
- Schmucki E, Marty C, Fierz C, & Lehning M. 2014. Evaluation of modelled snow depth and snow water equivalent at three contrasting sites in Switzerland using SNOWPACK simulations driven by different meteorological data input. *Cold Regions Science and Technology*. 99:27-37.
- Shuter BJ, Finstad AG, Helland IP, Zweimüller I, & Hölker F. 2012. The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change. *Aquatic Sciences*. 74(4):637-657.
- Trolle D, Elliott JA, Mooij WM, Janse JH, Bolding K, Hamilton DP, & Jeppesen E. 2014. Advancing projections of phytoplankton responses to climate change through ensemble modelling. *Environmental Modelling & Software*. 61:371-379.
- Weyhenmeyer GA, Livingstone DM, Meili M, Jensen O, Benson B, & Magnuson JJ. 2011. Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology*. 17: 268–275.
- Yao H, Samal NR, Joehnk KD, Fang X, Bruce LC, Pierson DC, ..., & James A. 2014. Comparing ice and temperature simulations by four dynamic lake models in Harp

Lake: past performance and future predictions. Hydrological Processes. 28(16):4587-4601.

For Peer Review

Figure 1. Overview of the artificial upper reservoir Sihlsee, with all major natural in- and outflows as well as the location of PS intake/outlet and of ice observations

102x153mm (220 x 220 DPI)

A - GLM **B - MyLake** **C - Simstrat** **D - CE-QUAL-W2**

(M) Melting	(C) Continuity of heat flux and temperature	(G) Ice growth
(S) Snow accumulation	(F) Snow ice formation through flooding	(W) Warming of water column
(A) Variable snow albedo	(L) Light attenuation	(*) Stefan's law
(D) Variable snow density		

Figure 2. Conceptual diagrams of the ice models of (A) GLM, (B) MyLake, (C) Simstrat and (D) CE-QUAL-W2. The abbreviations refer to short-wave radiation (Q_{SW}), long-wave radiation (Q_{LW}), back (long-wave) radiation (Q_B), conductive heat flux (Q_C), latent heat flux (Q_E), net long-wave radiation ($Q_{LW,net}$), surface albedo of snow or ice (α_k), surface temperature (T_0), air temperature (T_{AIR}), incoming short-wave radiation entering the snow/ice layer (I_0), heat flux reaching water column (I_W), heat flux used for melting ($I_W - I_0$), snow height (h_S), height of white ice (h_{WI}), height of black ice (h_{BI}), ice height (h_I), attenuation coefficient of the visual spectrum for snow, white ice and black ice (λ_{S1} , λ_{WI1} , λ_{BI1}), attenuation coefficient of the infrared spectrum for snow, white ice and black ice (λ_{S2} , λ_{WI2} , λ_{BI2}), attenuation coefficient of snow and ice (λ_S , λ_I), conductive heat flux between snow (ice) cover and the atmosphere (q_0), heat flux in the ice at the ice-water interface (q_f), heat flux from the water column to the ice (q_W), heat flux due to white ice formation (Q_{WI}), heat flux through ice (q_I), temperature in the snow layer (T_S), temperature in the white ice layer (T_{WI}), temperature in the black ice layer (T_{BI}), temperature at the ice-snow-interface (T_{Ice}), water temperature of the first layer underneath the ice cover ($T_{W,1}$), freezing temperature (T_F), conductivity snow (κ_S), conductivity white ice (κ_{WI}), conductivity black ice (κ_{BI}), conductivity ice (κ_I), density snow (ρ_S),

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

fraction of incoming short-wave radiation absorbed in the uppermost water layer (β_{SW}), fraction of incoming short-wave radiation absorbed by snow and ice (β_{SI}), fraction of incoming short-wave radiation absorbed in the ice sheet (β_I), ice extinction coefficient (γ_I).

150x164mm (300 x 300 DPI)

Figure 3. Probability (%) of lake ice coverage for current (1998-2012; blue) and future (2078-2092; red) climate conditions for each day from mid-November to end of April, separated by model (columns) and by PS scenario (markers). ¹ For MyLake only the scenario QNat* is depicted. ² For CE-QUAL-W2 the projections for segment SEG 40 are depicted.

916x416mm (72 x 72 DPI)

Figure 4. Boxplot of ice thicknesses (cm) from December to March under current (1998-2012; blue) and future (2078-2092; red) climate conditions, separated by model (columns) and by PS scenario (rows). Numbers in blue indicate the maximum value out of the range of the y-axis. ¹ For MyLake the scenario QNat* is depicted. ² For CE-QUAL-W2 the projections for segment SEG 40 are depicted.

159x215mm (300 x 300 DPI)

Figure 5. Probability (%) of lake ice coverage for current (1998-2012; blue) and future (2078-2092; red) climate conditions for each day from mid-November to mid-April, separated by model segments of CE-QUAL-W2 (columns) and by PS scenario (markers). For segment SEG 8 neither of the two PS scenarios is depicted, and for SEG 16 the extended PS scenario is not shown.

916x416mm (72 x 72 DPI)

Figure 6. Boxplot of ice thicknesses (cm) for each month of the period December to March under current (1998-2012; blue) and future (2078-2092; red) climate conditions, separated by model segments of CE-QUAL-W2 (columns) and by PS scenario (rows).

666x916mm (72 x 72 DPI)

Table 1. Root-mean-square error (RMSE), mean absolute error (MAE) and mean error (ME) water temperature in °C for the entire water column, the epilimnion (uppermost 5 m of the water column) and the hypolimnion (lowermost 5 m of the water column) as well as of the ice thickness, averaged over either the entire year or only the observed ice-covered period at Sihlsee in cm.

Model		Water temperature [°C]			Ice thickness [cm]	
		Entire water column	Epilimnion	Hypolimnion	Entire year	Ice-covered period
GLM	RMSE	1.35	1.10	1.18	7.9	12.0
	MAE	1.01	0.87	0.94	3.9	9.5
	ME	-0.01	-0.01	-0.67	3.7	8.8
Simstrat	RMSE	1.13	0.80	1.31	6.3	11.6
	MAE	0.85	0.60	1.02	2.5	8.6
	ME	-0.11	-0.16	-0.08	0.2	-0.2
CE-QUAL-W2	RMSE	0.94	0.93	0.94	4.6	8.6
	MAE	0.71	0.69	0.75	1.9	6.6
	ME	0.41	0.58	0.28	0.2	0.4

Table 2. Mean and maximum of observed and simulated ice thicknesses (cm) for each individual winter period as well as the mean of all winter seasons, the mean absolute error (MAE) and the mean error (ME) of simulated and observed ice thicknesses.

Winter	Observed ice thickness [cm]		Simulated ice thickness [cm]									
	Mean	Max	CE-QUAL-W2		MyLake		GLM		Simstrat		Ensemble	
			Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
2000/01	14	28	12	27	16	28	19	26	12	28	12	26
2001/02	18	30	26	47	28	39	26	37	34	36	19	39
2002/03	26	42	22	39	24	37	24	39	25	39	19	39
2003/04	18	37	14	26	20	32	26	37	13	26	16	30
2004/05	22	43	29	48	22	41	30	51	22	44	22	46
2005/06	26	42	41	56	36	56	38	57	39	60	35	57
2006/07	6	18	8	25	7	17	18	24	7	20	6	21
2007/08	21	29	21	29	15	23	24	35	11	23	13	25
2008/09	25	44	24	35	22	34	28	39	30	43	24	37
2009/10	20	35	23	39	24	38	24	36	27	44	22	38
2010/11	20	29	18	27	17	23	24	33	19	26	17	26
2011/12	12	26	16	35	18	31	24	38	19	34	15	34
2012/13	15	34	15	29	20	28	23	36	15	22	14	28
2013/14	16	30	8	14	0	0	20	26	6	10	7	12
2014/15	13	25	14	25	11	18	16	23	17	27	12	23
Mean	18	33	19	33	19	30	24	36	20	32	17	32
MAE	-	-	4	7	5	7	6	5	5	7	3	6
ME	-	-	1	1	1	-3	6	3	2	-1	-1	-1

Table 3. Observed and simulated ice-on and ice-off (week number) for each individual winter (Supplementary Material) and the mean of all considered winter periods as well as the mean absolute error (MAE) and the mean error (ME) in days between simulations and observations; values in brackets indicate the first week with ice out of several freeze-thaw-cycles in early winter.

Winter	Cycle	Observations [week number]		Simulations [week number]									
		Ice-on	Ice-off	CE-QUAL-W2		MyLake		GLM		Simstrat		Ensemble	
				Ice-on	Ice-off	Ice-on	Ice-off	Ice-on	Ice-off	Ice-on	Ice-off	Ice-on	Ice-off
2000/01	1	2	15	3	11	53	13	52	15	(51)	10	1	12
2001/02	1	50	15	50	12	50	15	50	16	50	6	50	12
2002/03	1	49	14	(50)	14	1	17	50	17	2	13	52	15
2003/04	1	51	14	52	14	51	17	49	17	(49)	12	50	15
2004/05	1	1	14	50	14	50	15	49	17	(49)	13	50	15
2005/06	1	51	16	50	16	50	18	48	19	(48)	18	49	18
2006/07	1	50	2	52	2	51	3	51	14	51	1	51	5
2006/07	2	3	9	4	9	4	8	-	-	(4)	7	-	-
2007/08	1	49	11	51	10	50	15	50	16	(46)	8	49	12
2008/09	1	52	15	(50)	14	52	16	50	16	49	14	50	15
2009/10	1	52	14	51	13	51	15	51	15	51	14	51	14
2010/11	1	50	13	51	12	50	13	49	14	50	14	50	13
2011/12	1	51	1	-	-	-	-	-	-	49	50	-	-
2011/12	2	2	13	2	13	52	16	52	15	50	11	52	14
2012/13	1	50	2	50	52	-	-	-	-	(52)	13	-	-
2012/13	2	2	16	3	15	3	16	50	17	(49)	15	52	16
2013/14	1	49	12	50	11	-	-	50	14	(48)	11	-	-
2014/15	1	52	2	(1)	(2)	52	2	-	-	52	(2)	-	-
2014/15	2	2	13	4	13	4	14	3	15	3	13	4	14
Mean		52	11	52	11	52	13	50	16	50	10	51	14
MAE [days]		-	-	8	7	8	10	12	19	15	17	10	8
ME [days]		-	-	3	-7	1	7	-7	19	-8	-7	-4	2

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Ensemble modelling of ice cover for a reservoir affected by pumped-storage operation and climate change

Ulrike Gabriele Kobler*, Martin Schmid

Ensemble modelling was used to assess the impact of pumped-storage (PS) and climate change effects on lake ice. The extended PS operation already results in a shortened ice-covered period by ~23 days under current climate for the model ensemble. Climate change is projected to cause another reduction of ~50 days.

Supplementary Material to “Ensemble modelling of ice cover for a reservoir affected by pumped-storage operation and climate change”

Ulrike Gabriele Kobler^{1,2,*}, Martin Schmid¹

ORCID-Identifiers: 0000-0003-4661-3876, 0000-0001-8699-5691

¹ Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters – Research and Management, CH-6047 Kastanienbaum, Switzerland

² EPFL, Physics of Aquatic Systems Laboratory – Margaretha Kamprad Chair, ENAC-IEE-APHYS, CH-1015 Lausanne, Switzerland

* Corresponding author: ulrike.kobler@icloud.com

Selected segments in CE-QUAL-W2

Figure SM1. (A) Overview bathymetry of CE-QUAL-W2, with the location of all in- and outflows: natural inflows (blue), residual flow (green), and artificial intake/outlet (red); violet shows the selected segments and their distance from the dam is shown in brackets. **(B)** Water level elevation (m a.s.l.) for all four PS scenarios over the period 1998-2012: depicted are mean (black line) and range of minimum and maximum (shaded area) for each day of the year; in violet the minimal possible water level for segments SEG 8 and SEG 16 are shown.

Meteorological forcing

Figure SM2. Means of meteorological forcing for each winter period (November to April) from 1997/98 to 2014/15; depicted are values for air temperature T_{air} (°C), noon values of short-wave radiation $Q_{\text{SW},\text{noon}}$ (W m^{-2}), downward long-wave radiation Q_{LW} (W m^{-2}), vapor pressure VP (mbar) and wind speed Wind (m s^{-1}).

Figure SM3. Totals of each winter period (November to April) from 1997/98 to 2014/15 for precipitation Precip (m), which is separated for rain (black) and snow water equivalent SWE (white) as well as the fraction of the snow -water-equivalents (SWE) of the entire precipitation.

Adapted ice module CE-QUAL-W2

The original ice model of CE-QUAL-W2 significantly underpredicted duration of the ice-covered period in spring. This had already been previously observed by Bonalumi, Anselmetti, Wüest and Schmid (2012) and by Sadeghian, de Boer, Hudson, Wheeler and Lindenschmidt (2015). The latter assumed that this was due to a lack of insulation by snow cover, which is not included in the model structure, and they were able to improve the model performance by adding empirical coefficients that reduce the heat transfer from the atmosphere to the ice. However, we think that the fast melting was due to an incorrect representation of the short-wave radiation transfer through the ice cover. Therefore, we adapted the source code as described in the following section.

Before the do loop for computing the ice temperature the additional term heat flux RN2 (W m^{-2}) is introduced:

$$\text{RN2} = \text{SRON}(\text{JW}) / \text{REFL} * \text{SHADE}(\text{I}) * (1.0\text{D0} - \text{ALBEDO}(\text{JW})) * (1.0\text{D0} - (1.0\text{D0} - \text{BETAI}(\text{JW})) * \text{DEXP}(-\text{GAMMAI}(\text{JW}) * \text{ICETH}(\text{I}))) + \text{RANLW}(\text{JW})$$

with SRON(JW) as net short-wave solar radiation incident on the water surface in W m^{-2} for the water body JW, REFL as reflectance, SHADE(I) as shading coefficient at time I, ALBEDO(JW) ice albedo, BETAI(JW) as fraction of the incoming solar radiation absorbed in the ice surface, GAMMAI(JW) ice extinction coefficient in m^{-1} , ICETH(I) ice thickness at time I, RANLW(JW) incoming long-wave radiation in W m^{-2} .

The original function for computing the melting at the ice-water interface (ICETHU) is replaced by the following lines and it is made sure, that the ice temperature in case of melting ($\text{TICE} < 0^\circ\text{C}$) is reset to zero:

```
IF (TICE>0.0D0) THEN
    TICE=0.0D0
    CALL SURFACE_TERMS(TICE)
    RN(I)=RN2-RB(I)-RE(I)-RC(I)
    ICETHU=-DLT*RN(I)/RHOIRL1
END IF
```

with TICE as ice temperature in $^\circ\text{C}$, RB(I) as back-radiation at time I in W m^{-2} , RE(I) as latent heat flux at time I in W m^{-2} , RC(I) as sensible heat flux at time I in W m^{-2} , RN(I) as net heat flux at time I in W m^{-2} , ICETHU as ice melt in m, DLT as time step in s, RHOIRL1 as product of ice density in kg m^{-3} and latent heat of fusion in J kg^{-1} .

These changes in combination with a relatively high value of 0.5 for the ice albedo resulted in a good agreement of observed and simulated ice thicknesses.

Adaptation of GLM

The original source of GLM, version 2.4.1, was adapted in the following way:

- A Boolean variable was introduced which allowed to switch of the effect of precipitation on the water balance.
- The indices for computing the new surface temperature were differing from those of equation 4 presented in Rogers, Lawrence and Hamblin (1995). Thus, correction was needed for the variables BBB, FFF, DDD, GGG and EEE of the source code (file glm_surface.c).
- Originally, evaporation from snow and white ice were computed as long as snow height and the height of white ice were larger than zero. Yet, the computed evaporation, given in water equivalents, could exceed the height of snow or white ice. Thus, we changed this in the following way: evaporation from snow (white ice) is now only computed when the snow height (height of white ice) exceeds the computed value of evaporation.

Sensitivity analysis

All model parameters and the considered range of variation for the sensitivity analysis are depicted in Table SM1. Before model calibration a sensitivity analysis on lake ice model parameters was conducted. Therefore, the models were run with several variations of lake ice model parameters. The corresponding figures are presented for some selected years in the Supplementary Material. These results suggest that the projected ice thickness with GLM is not sensitive to the choice of maximum and minimum density of snow. Yet, the variation of the scaling factor of the snowfall results in ice thickness differences of up to ~25 cm (2005). Nevertheless, the variation of the snowfall forcing is of key importance to reproducing the ice thickness. This could, if this factor is set to 1 even lead to differences of observations and projections of ~40 cm (2005). Snow thickness on top of the ice sheet is also not affected by any density variation, which in turn is also valid for white ice formation. Comparing the white ice formation with the chosen scaling factor of snowfall forcing of 0.35 to that of 1.00 white ice thickness differs by ~40 cm. Cheng et al. (2008) mentioned that GLM is known to overestimate white ice formation, which seems to be linked to the overestimated ice thickness.

Simstrat was least sensitive to the variation of the ice albedo. Variations of parameters affecting the snow on top of the ice sheet (snow albedo, fraction of solar radiation that is absorbed at the air-ice/snow-interface, scaling factor of precipitation) resulted in some years in a multiple instead of a single freeze-thaw-cycle (2011). Also the variation of freezing temperature could cause this shift of temporal ice dynamics. Projections suggest, in general, that lake ice tends to disappear quite fast, once all overlying snow has melted. Therefore, the snow thickness is sensitive to similar parameter set than the ice thickness.

MyLake projections suggest that the model is rather robust to parameter variations, only the variation of precipitation input and the snow (in some cases also the ice) albedo would affect ice, white ice and snow thickness by ~5 to 10, < 5 and ~10 cm, respectively.

For CE-QUAL-W2 the variation of the ice albedo resulted in different ice thickness ranging between ~30 to ~70 cm in 2005. The variation of all other parameters affected the thickness less, however, for some years (2004) the ice-on was shifted. The results of the variation of three parameters, the fraction of the incoming solar radiation absorbed at the air-ice-interface, the ice extinction coefficient and the heat exchange coefficient at the water-ice-interface, show rather similar behavior. This could highlight a parameter identification problem.

Table SM1 Parameters and the analysed ranges for the sensitivity analysis for all models, and corresponding parameter values used in the simulations.

Model	Parameter Abbreviation	Explanation	Unit	Analysed range	Used value
GLM	$\rho_{\max, \text{snow}}$	Maximum density snow	[kg m ⁻³]	300-450	350
	$\rho_{\min, \text{snow}}$	Minimum density snow	[kg m ⁻³]	50-175	100
	f_{asnow}	Scaling factor snow albedo	[-]	0.50-1.20	1.00
	f_{snow}	Scaling factor snowfall	[-]	0.15-1.00	0.35
Simstrat	$\beta_{\text{snow,ice}}$	Fraction of the incoming solar radiation absorbed at the air-ice/snow-interface	[-]	0.30-0.50	0.40
	T_{freeze}	Freezing temperature	[°C]	0.00-0.20	0.10
	α_{ice}	Ice albedo	[-]	0.15-0.45	0.30
	f_{precip}	Scaling factor precipitation	[-]	0.80-1.20	1.00
	α_{snow}	Snow albedo	[-]	0.64-0.90	0.77
MyLake	α_{ice}	Ice albedo	[-]	0.15-0.45	0.30
	λ_{ice}	Attenuation coefficient ice	[m ⁻¹]	4-6	5.00
	f_{precip}	Scaling factor precipitation	[-]	0.80-1.20	1.00
	α_{snow}	Snow albedo	[-]	0.64-0.90	0.77
	λ_{snow}	Attenuation coefficient snow	[m ⁻¹]	12-18	15.0
CE-QUAL-W2	α_{ice}	Ice albedo	[-]	0.20-0.90 ¹	0.50
	β_{ice}	Fraction of the incoming solar radiation absorbed at the air-ice-interface	[-]	0.20-0.80	0.60
	γ_{ice}	Ice extinction coefficient	[m ⁻¹]	0.01-10.0	0.07
	$H_{\text{water,ice}}$	Heat exchange coefficient at water-ice-interface	[W m ⁻² °C ⁻¹]	5-500	10.0

¹ The range used for the ice albedo of CE-QUAL-W2 is different from the other models, as this model does not allow discriminating between snow and ice cover.

Figure SM4. Sensitivity of ice thickness to parameter variation for GLM; shown are simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (red line) as well as observed ice thicknesses (black markers). Parameters were varied in a range of 300 to 450 kg m⁻³ ($\rho_{\text{max,snow}}$: maximum density snow) and 50 to 175 kg m⁻³ ($\rho_{\text{min,snow}}$: minimum density snow), 0.5 to 1.2 ($f_{0,\text{snow}}$: scaling factor of snow albedo), 0.15 to 1.00 (f_{snow} : scaling factor snowfall).

Figure SM5. Sensitivity of white ice thickness to parameter variation for GLM; shown are simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (orange line). Parameters were varied in a range of 300 to 450 kg m⁻³ ($\rho_{\text{max,snow}}$: maximum density snow) and 50 to 175 kg m⁻³ ($\rho_{\text{min,snow}}$: minimum density snow), 0.5 to 1.2 (f_{usnow} : scaling factor of snow albedo), 0.15 to 1.00 (f_{snow} : scaling factor snowfall).

Figure SM6. Sensitivity of snow thickness to parameter variation for GLM; shown are simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (blue line). Parameters were varied in a range of 300 to 450 kg m⁻³ ($\rho_{\text{max,snow}}$: maximum density snow) and 50 to 175 kg m⁻³ ($\rho_{\text{min,snow}}$: minimum density snow), 0.5 to 1.2 ($f_{\text{albedo,snow}}$: scaling factor of snow albedo), 0.15 to 1.00 (f_{snowfall} : scaling factor snowfall).

Figure SM7. Sensitivity of ice thickness to parameter variation for Simstrat; shown are simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (red line) as well as observed ice thicknesses (black markers). Parameters were in a range of 0.3 to 0.5 ($\beta_{\text{snow,ice}}$: fraction of the incoming solar radiation absorbed at the air-ice/snow-interface), 0.0 to 0.2 °C (T_{freeze} : freezing temperature), 0.15 to 0.45 (α_{ice} : ice albedo), 0.8 to 1.2 (f_{precip} : scaling factor precipitation) and 0.64 to 0.90 (α_{snow} : snow albedo).

Figure SM8. Sensitivity of snow thickness to parameter variation for Simstrat; shown are simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (blue line). Parameters were varied in a range of 0.3 to 0.5 ($\beta_{\text{snow,ice}}$: fraction of the incoming solar radiation absorbed at the air-ice/snow-interface), 0.0 to 0.2 °C (T_{freeze} : freezing temperature), 0.15 to 0.45 (α_{ice} : ice albedo), 0.8 to 1.2 (f_{precip} : scaling factor precipitation) and 0.64 to 0.90 (α_{snow} : snow albedo)

Figure SM9. Sensitivity of ice thickness to parameter variation for MyLake; shown are simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (red line) as well as observed ice thicknesses (black markers). Parameters were varied in a range of 0.15 to 0.45 (α_{ice} : ice albedo), 4 to 6 m^{-1} (λ_{ice} : attenuation coefficient ice), 0.8 to 1.2 (f_{precip} : scaling factor precipitation), 0.64 to 0.90 (α_{snow} : snow albedo) and 12 to 18 m^{-1} (λ_{snow} : attenuation coefficient snow).

Figure SM10. Sensitivity of white ice thickness to parameter variation for MyLake; shown are simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (orange line). Parameters were varied in a range of 0.15 to 0.45 (α_{ice} : ice albedo), 4 to 6 m^{-1} (λ_{ice} : attenuation coefficient ice), 0.8 to 1.2 (f_{precip} : scaling factor precipitation), 0.64 to 0.90 (α_{snow} : snow albedo) and 12 to 18 m^{-1} (λ_{snow} : attenuation coefficient snow).

Figure SM11. Sensitivity of snow thickness to parameter variation for MyLake; shown are simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (blue line). Parameters were varied in a range of 0.15 to 0.45 (α_{ice} : ice albedo), 4 to 6 m^{-1} (λ_{ice} : attenuation coefficient ice), 0.8 to 1.2 (f_{precip} : scaling factor precipitation), 0.64 to 0.90 (α_{snow} : snow albedo) and 12 to 18 m^{-1} (λ_{snow} : attenuation coefficient snow).

Figure SM12. Sensitivity of ice thickness to parameter variation for CE-QUAL-W2; shown are observed ice thicknesses (black markers), simulations with varying model parameters (grey lines) and the simulation with the chosen parameter combination (red line). Parameters were varied in a range of 0.2 to 0.9 (α_{ice} : ice albedo), 0.2 to 0.8 (β_{ice} : fraction of the incoming solar radiation absorbed at the air-ice-interface), 0.01 to 10 (γ_{ice} : ice extinction coefficient) and 5 to 500 W m⁻² °C⁻¹ ($H_{water,ice}$: heat exchange coefficient at water-ice-interface).

Additional information model calibration

Figure SM13. Simulations of (A) GLM and (B) Simstrat (red lines) as well as observations (grey markers) of water temperatures (° C) in Sihlsee for the present PS scenario; depicted temperatures are taken in the specified distance from either the surface or the sediment surface.

The model parameters and initial conditions of GLM and Simstrat are shown in Tables SM2 to SM3. For the model parameters of MyLake similar values than those proposed for the test case of lake Vansjø were taken; initial conditions were taken similar to those presented in Table SM3.

Table SM2 Model parameters for GLM and Simstrat; values estimated with PEST are highlighted in red, those chosen after a sensitivity analysis in blue.

Parameter	Description	Value		Method
		Simstrat	GLM	
Kw	Extinction coefficient [m ⁻¹]	0.708	0.708	Observed
p_rad	Scaling factor long-wave radiation [-]	0.9539	-	CAL
α_{sw}	Albedo open water [-]	0.090	-	Default
α_{ice}	Ice albedo [-]	0.300	-	Default
α_{snow}	Snow albedo [-]	0.770	-	Default
T_freeze	Freezing temperature [° C]	0.100	-	Adapted ¹
$\beta_{snow,ice}$	Fraction of incoming solar radiation absorbed at the air-ice/snow-interface [-]	0.400	-	Default
β_{sol}	Absorption of short-wave radiation in first cell [-]	0.350	-	Default
cd	Bottom friction coefficient [-]	1.50E-03	-	Default
f_wind	Scaling factor wind speed [-]	0.3816	-	CAL
p_windf	Parameter for fitting wind function [-]	1.000	-	Default
c10	Wind drag coefficient [-]	1.000	-	Default
a_seiche	Fraction of wind energy to seiche energy [-]	5.282E-03	-	CAL
q_nn	Parameter for the distribution of seiche energy [-]	1.100	-	Default
k_min	Minimal value for TKE [J kg ⁻¹]	1.00E-09	-	Default
lat	Latitude [°]	47.1	-	Observed
p_air	Air pressure [mbar]	912	-	Observed
hgeo	Geothermal heat flux [W m ⁻²]	0.080	-	Default
coef_mix_conv	Mixing efficiency convective overturn [-]	-	0.125	Default
coef_mix_stir	Mixing efficiency wind stirring [-]	-	0.230	Default
coef_mix_shear	Mixing efficiency unsteady turbulence effects [-]	-	0.200	Default
coef_mix_turb	Mixing efficiency shear production [-]	-	0.510	Default
coef_mix_KH	Mixing efficiency Kelvin-Helmholtz turbulent billows [-]	-	0.300	Default
coef_mix_hyp	Mixing efficiency [-]	-	0.4778	CAL
deep_mixing	Model description deep mixing [-]	-	2	
wind_factor	Scaling factor wind speed [-]	-	0.9445	CAL
sw_factor	Scaling factor short-wave radiation [-]	-	0.850	Kobler, Wüest and Schmid (2018)
lw_factor	Scaling factor long-wave radiation [-]	-	0.9497	CAL
at_factor	Scaling factor air temperature [-]	-	1.000	Default
rh_factor	Scaling factor relative humidity [-]	-	1.000	Default
rain_factor	Scaling factor rain [-]	-	1.000	Default
f_snow	Scaling factor snowfall [-]	-	0.350	Sensitivity analysis
ce	Bulk aerodynamic coefficient for latent heat transfer [-]	-	1.50E-03	Default Delft3D
ch	Bulk aerodynamic coefficient for sensible heat transfer [-]	-	1.50E-03	Default Delft3D
cd	Bulk aerodynamic coefficient for momentum transfer [-]	-	1.50E-03	Default Delft3D
$\rho_{min,snow}$	Minimum density snow [kg m ⁻³]	-	100	Default
$\rho_{max,snow}$	Maximum density snow [kg m ⁻³]	-	350	Default
f _{q,snow}	Scaling factor snow albedo [-]	-	1.000	Default

¹ As temperature is only resolved vertically by 0.5 m, the freezing temperature was adapted to avoid the occurrence of negative water temperatures that could occur although the temperature of the first layer beneath the ice sheet is fixed to 0 °C during melting.

Table SM3 Initial conditions for all GLM and Simstrat simulations, with depth-dependent current velocities U and V (m s^{-1}), temperature ($^{\circ}\text{C}$), salinity ($\%$), turbulent kinetic energy k (J kg^{-1}), and dissipation rate of turbulent kinetic energy ϵ (W kg^{-1}).

	GLM & Simstrat	GLM	Simstrat				
Depth [m]	Temperature [$^{\circ}\text{C}$]	Salinity [psu]	Salinity [%]	U [m s^{-1}]	V [m s^{-1}]	k [J kg^{-1}]	ϵ [W kg^{-1}]
0.00	0.8	0.075	0.075	0.000	0.000	3.0E-06	5.0E-10
1.00	1.0	0.075	0.075	0.000	0.000	3.0E-06	5.0E-10
2.00	2.0	0.075	0.075	0.000	0.000	3.0E-06	5.0E-10
3.00	3.0	0.075	0.075	0.000	0.000	3.0E-06	5.0E-10
4.00	4.0	0.075	0.075	0.000	0.000	3.0E-06	5.0E-10
Maximum depth	4.0	0.075	0.075	0.000	0.000	3.0E-06	5.0E-10

For Peer Review

Temporal dynamics lake ice projections

Figure SM14. Observed ice thickness (black markers, depicted with negative values) and GLM simulations of ice (red, depicted with negative values), white ice (orange, depicted with negative values) and snow (blue) thickness (cm).

Figure SM15. Observed ice thickness (black markers, depicted with negative values) and Simstrat simulations of ice (red, depicted with negative values) and snow (blue) thickness (cm).

Figure SM16. Observed ice thickness (black markers, depicted with negative values) and MyLake simulations of ice (red, depicted with negative values), white ice (orange, depicted with negative values) and snow (blue) thickness (cm).

Figure SM17. Observed ice thickness (black markers, depicted with negative values) and CE-QUAL-W2 simulations of ice thickness (red, depicted with negative values) (cm).

Figure SM18. Observed ice thickness (black markers, depicted with negative values) and mean of the simulated ice thickness ensemble (red, depicted with negative values) (cm).

Additional information on the effects due to PS operation and climate change

Table SM4 Mean duration of the longest uninterrupted ice-covered periods (days) for the different models and the combination of different climate conditions (CC: current climate, FC: future climate) and PS scenarios.

		Reference QNat		Reference NoPS		Present PS		Extended PS	
		CC	FC	CC	FC	CC	FC	CC	FC
GLM		126	82	125	81	126	84	113	47
Simstrat		75	18	74	17	76	19	53	8
MyLake		102 ¹	23 ¹	-	-	-	-	-	-
CE-QUAL-W2	SEG 8	94	33	95	32	-	-	-	-
	SEG 16	92	30	94	31	92	31	-	-
	SEG 24	91	28	92	30	92	31	-	-
	SEG 32	89	27	91	27	91	27	74	17
	SEG 40	84	22	85	24	87	26	17	9
Mean		90	28	91	29	91	29	58	20
Mean of all models		98	38	97	42	98	44	75	25

¹ Without any in- and outflows

Table SM5 Average probability (%) that the lake is ice covered on a specific day during the winter period (November to April), for the different models and the combination of different climate conditions (CC: current climate, FC: future climate) and PS scenarios.

		Reference QNat		Reference NoPS		Present PS		Extended PS	
		CC	FC	CC	FC	CC	FC	CC	FC
GLM		71	41	70	44	71	46	64	21
Simstrat		49	13	48	13	51	16	35	3
MyLake		58 ¹	10 ¹	-	-	-	-	-	-
CE-QUAL-W2	SEG 8	54	19	55	19	-	-	-	-
	SEG 16	53	17	53	17	53	18	-	-
	SEG 24	52	16	52	16	53	17	48	13
	SEG 32	51	14	51	14	52	14	43	6
	SEG 40	48	10	48	10	49	12	13	1
Mean		52	15	52	15	52	15	35	7
Mean of all models		57	20	57	24	58	26	45	10

¹ Without any in- and outflows

Table SM6 Mean ice thickness (cm) over all ice-covered periods for the different models and the combination of different climate conditions (CC: current climate, FC: future climate) and PS scenarios.

		Reference QNat		Reference NoPS		Present PS		Extended PS	
		CC	FC	CC	FC	CC	FC	CC	FC
GLM		27	16	27	16	28	17	25	13
Simstrat		25	9.3	25	9.1	24	9.0	19	6.3
MyLake		22 ¹	8.4 ¹	-	-	-	-	-	-
CE-QUAL-W2	SEG 8	21	9.5	21	9.6	-	-	-	-
	SEG 16	20	9.6	21	9.6	21	9.5	-	-
	SEG 24	20	9.3	20	9.4	21	9.4	17	8.1
	SEG 32	20	9.1	20	9.2	20	9.3	16	7.2
	SEG 40	19	8.7	20	9.1	20	8.9	11	4.2
Mean		20	9.2	20	9.4	21	9.3	15	6.5
Mean of all models		24	11	24	11	24	12	20	8.6

¹ Without any in- and outflows

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

References

Bonalumi M, Anselmetti FS, Wüest A, & Schmid M. 2012. Modeling of temperature and turbidity in a natural lake and a reservoir connected by pumped-storage operations. *Water Resources Research*. 48(8):W08508.

Cheng B, Zhang Z, Vihma T, Johansson M, Bian L, Li Z, & Wu H. 2008. Model experiments on snow and ice thermodynamics in the Arctic Ocean with CHINARE 2003 data. *Journal of Geophysical Research*. 113:C09020.

Kobler UG, Wüest A, & Schmid M. 2018. Effects of lake – reservoir pumped-storage operations on temperature and water quality. *Sustainability*. 10(6):1968.

Rogers CK, Lawrence G, & Hamblin PF. 1995. Observations and numerical simulation of a shallow ice-covered midlatitude lake. *Limnology and Oceanography*. 40:374-385.

Sadeghian A, de Boer D, Hudson JJ, Wheeler H, & Lindenschmidt KE. 2015. Lake Diefenbaker temperature model. *Journal of Great Lakes Research*. 41:8-21.