Combined effects of pumped-storage operation and climate change on thermal structure and water quality

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Abstract

The assessment of ecological impacts of pumped-storage (PS) hydropower plants on the two connected water bodies is usually based on present climatic conditions. However, significant changes in climate must be expected during their long concession periods. We, therefore, investigate the combined effects of climate change and PS operations on water temperature and quality, as well as extent and duration of stratification and ice cover, using a site in Switzerland. For this purpose, a coupled two-dimensional hydrodynamic and water quality model for the two connected water bodies is run with 150-years long synthetic stochastic meteorological forcing for both current and future climate conditions under two PS and two reference scenarios. The results show relevant synergistic and antagonistic effects of PS operations and climate change. For example, hypolimnion temperatures in September are projected to increase by <0.6 °C in a near-natural reference scenario and by ~2.5 °C in an extended PS scenario. Ice cover, which occurs every year under near-natural conditions in the current climate, would almost completely vanish with extended PS operation in the future climate. Conversely, the expected negative impacts of climate change on hypolimnetic dissolved oxygen concentrations are partially counteracted by extended PS operations. We, therefore, recommend considering future climate conditions for the environmental impact assessment in the planning of new or the recommissioning of existing PS hydropower plants.

Keywords: weather generator, lake stability, ice cover

1 Introduction

Expansion of new renewable electricity sources is an important cornerstone of strategies to mitigate anthropogenic climate change (e.g., EU 2009; Ibrahim et al. 2011). However, their intermittent nature calls for additional electricity storage, which is, still today, most efficiently realized by pumped-storage (PS) hydropower plants. Yet, these PS operations affect abiotic and biotic characteristics of the two connected water bodies (Bonalumi et al. 2011). For example, for the case of Sihlsee, PS operations have been shown to increase hypolimnetic temperature and dissolved oxygen (DO) concentrations mostly due to pumping surface water from the lower lake to the hypolimnion of the upper reservoir, and the weakened reservoir stratification (Kobler et al. 2018). Moreover, Kobler et al. (2018) estimated that ice thickness would decrease due to extended PS operation.

Climate change also alters water bodies, e.g., by raising water temperature (O'Reilly et al. 2015), prolonging summer stratification (Dokulil et al. 2010; Livingstone 2003), which further results in increased oxygen depletion and, therefore, in increased mineralization and nutrient release from sediments (Delpla et al. 2009; Xia et al. 2014). Increased temperature and prolonged summer stratification further result in shortened ice cover duration (Benson et al. 2012; Magee et al. 2016) and inverse stratification, which refers to periods with cooler water (0 to ~4 °C) in the epilimnion on top of warmer hypolimnetic water (~4 °C). Shorter inverse stratification in turn leads to increased DO concentrations in winter and less accumulation of nutrients released from sediments in the hypolimnion. These abiotic impacts further affect lake ecology, e.g., through decreasing habitats for fish with low temperature preferences, such as trout (North et al. 2014).

Bonalumi et al. (2012) showed that PS effects on lake temperature are more pronounced in warmer years, as PS operation increased the efficiency of heat exchange with the atmosphere, further suggesting that climate change would likely aggravate PS impacts. Yet, the link between climate change and PS operation has so far not been quantified. Thus, with the present study we aim at investigating whether climate change will amplify or reduce the different impacts of PS operations on the thermal structure, ice cover and water quality of the two connected water bodies. As a study site we use Etzelwerk, where the impacts of different PS scenarios for the current climate have already been investigated in a previous study (Kobler et al. 2018). Here, we link the model applied in this previous study with climate scenarios generated with a vector-autoregressive weather generator to assess the combined effect of climate change and PS operations. The weather generator had been successfully tested at Lake Constance, where the synthetic meteorological forcing reproduced statistical dependencies of measured meteorological data, and was used to drive a lake model which could successfully emulate observed thermal and water quality dynamics (Schlabing et al. 2014).

We analyse (a) two different climate scenarios representing current and future conditions in combination with (b) four different management options. The latter include two different levels of PS operations, the present and an extended PS, and two reference cases, the quasi-natural case with surface outflow and a case with deep-water withdrawal. These PS and reference scenarios depict a typical set considered in the environmental impact assessment for the recommissioning of a PS hydropower plant. Based on the simulation results, we discuss the relevance of including expected climate change effects in environmental impact assessments when planning or recommissioning PS hydropower plants. Concessions are usually issued for many decades within which significant climate change must be expected. These results could, therefore, further reveal ecologically relevant synergistic and antagonistic effects of climate change and PS operations.

2 Study sites

The considered PS hydropower plant is Etzelwerk (Fig. 1), which is located in Switzerland. It connects Sihlsee, the upper artificial reservoir, with Upper Lake Zurich, the lower natural lake. Sihlsee is a dimictic reservoir, which is regularly inversely stratified and ice-covered in winter, whereas Upper Lake Zurich is mostly monomictic. In summer epilimnion temperatures at Sihlsee reach maxima of ~25 °C, those of the hypolimnion remain <17 °C. At Upper Lake Zurich maximum epilimnion temperatures are similar to those observed at Sihlsee, whereas hypolimnion temperatures stay ≤6 °C (Kobler et al. 2018). In both lakes DO depletion throughout the stratified summer period, causes hypolimnetic DO to drop to <4 mg L^{-1}. Total phosphorus concentrations remain <35 µg P L^{-1} at Sihlsee, and the annual mean at Upper Lake Zurich does not exceed 12 µg P L^{-1}.

Currently water is withdrawn from Sihlsee's hypolimnion by PS generation and discharged to the epilimnion of Upper Lake Zurich. For PS pumping water from the epilimnion of Upper Lake Zurich is brought to the hypolimnion of Sihlsee. Both basins are described in more detail in Kobler et al. (2018), and their characteristics are summarized in Table 1.

3 Materials and methods

3.1 Hydrodynamic and water quality model

We applied a modified version of the two-dimensional laterally-averaged hydrodynamic and water quality model CE-QUAL-W2 which was developed by the Portland State University in cooperation with the US Corps of Engineers (Cole and Wells 2013). The model was already applied to the study site for simulating the effects of different management scenarios under current climatic conditions in a previous study (Kobler et al., 2018), which includes a detailed description of the model, the calibration procedure, and the data sources for the bathymetric, meteorological, hydrological and water quality forcing needed to drive the model. The model grid and a conceptual diagram of the main processes considered are available in the Supplementary Material.

In short, the model is composed of a hydrodynamic module where temperature, stratification and mixing processes are calculated using a k-epsilon model, and a water quality module that includes the inputs, outputs and transformations of inorganic suspended solids, dissolved oxygen, organic matter, nitrogen and phosphorus. In the present version, the water quality model includes two algae and one zooplankton group as well as a sediment compartment. The code of the publicly available version 3.71 of CE-QUAL-W2 was modified to enable direct input of incoming long-wave radiation with the meteorological forcing file, and to improve the performance of the ice module to reproduce observed ice cover thickness and duration (Kobler et al., 2018).

The meteorological and the hydrological forcing were obtained from several monitoring stations close to the study site (Kobler et al. 2018). The numerical grids of both water bodies were divided into segments of 200 m width (longitudinal direction) and layers of 0.5 m height (vertical direction). The model had been calibrated manually based on long-term monitoring data from Upper Lake Zurich and two years of observational data from Sihlsee collected for this purpose. The corresponding root-mean-square-errors (RMSE) for the entire water column of Sihlsee reached values of 0.94 °C, 1.2 mg L^{-1} and 4.5 µg P L^{-1} for temperature, DO and total phosphorus, respectively. At Upper Lake Zurich the RMSE amounted to 0.93 °C, 1.3 mg L^{-1} and 4.1 µg P L^{-1}. These values are well within the range typically achieved with CE-QUAL-W2 for similar applications (Kobler et al. 2018).

3.2 Climate scenarios

Ten synthetic time series of 15 years duration for the periods 1998-2012 (current climate) and 2078-2092 (future climate) were calculated with the weather generator VG (Schlabing et al. 2014). Air temperature was increased compared to present day conditions according to regional projections of the Swiss Climate Change Scenarios CH2011 (CH2011 2011) for the IPCC A2 scenario in 2085 for north-eastern Switzerland. The projected air temperature increases vary seasonally in the range of 3 °C (April) to 4.5 °C (August). All other meteorological forcing variables and inflow water temperatures were computed by VG, maintaining the dependencies of observed values during the period 1997-2015. A detailed comparison of VG-generated and observed variables is given in the Supplementary Material.

3.3 Pumped-storage scenarios

Four different management scenarios were used in the simulations that had been previously developed to simulate the impacts of PS operations (Kobler et al. 2018). The water balance of all scenarios is shown in Table 1, and additional information on the position of all in- and outflows is given in the Supplementary Material.

The present PS scenario describes the current state, where water is withdrawn from the hypolimnion of Sihlsee for both, generating electricity and the residual flow to River Sihl, with installed capacities of ~135 MW for generating and ~65 MW for pumping. Pumping brings water from Upper Lake Zurich to the hypolimnion of Sihlsee. At Upper Lake Zurich, PS intake and outlet are situated in the epilimnion. The seasonal variation of PS operation is minor, with mean monthly flows ranging from 6.1 to 7.81 $m^3 s^{-1}$ for generating and from 0.7 to 1.1 $m^3 s^{-1}$ for pumping, respectively.

The extended PS scenario corresponds to an extension with installed capacities for generating and pumping increased to ~525 MW and ~265 MW, respectively Compared to the present PS scenario, both PS flows are increased by factors of up to ~4 to 5 (generating) and of ~20 to 40 (pumping) from November to March and by factors of ~1 to 3 (generating) and ~9 to 23 (pumping) during the rest of the year.

The “quasi-natural” reference scenario (QNat) corresponds to the “natural lake state” of the reservoir, if the dam were of natural origin. The discharge to River Sihl is calculated based on a regime analysis of discharges observed before dam construction (LIMNEX AG 2016, personal communication). It is implemented with a discharge over a weir. Thus, water is withdrawn from the epilimnion in contrast to the other scenarios where all water is withdrawn from the hypolimnion. No artificial PS flows are considered for this reference scenario.

When comparing QNat and present as well as extended PS projections, it is difficult to clearly assign the observed effects to either the PS flows or to water withdrawal from the hypolimnion. To disentangle these two processes, a second reference scenario (NoPS) was designed, where water is withdrawn from the hypolimnion through the present residual flow outlet, but no PS operation takes place. The downstream discharge of River Sihl is equal to that in the reference scenario QNat. NoPS is also a possible future management option in case hydropower operations were to be discontinued.

3.4 Aggregation of results

The climate ensemble consisting of ten simulations with a total of 150 simulated years included in each studied period (1998-2012 for current climatic conditions, and 2078-2092 for future climatic conditions) were combined to the aggregated results as presented below. Means, minima and maxima of the simulated temperatures and concentrations of DO and phosphate were calculated for each day of the year, separately for the epilimnion (uppermost 5 m of the water column) and the hypolimnion (lowermost 5 m). The differences between the current and the future climate were calculated at each depth for each climate scenario.

The durations of summer and inverse stratification were defined similar to Kobler et al. (2018) as the longest uninterrupted periods with temperature differences >0.2 °C and <-0.2 °C between the upper- and the lowermost layer. Schmidt stability was computed according to Idso (1973). Ice-on, ice-off, duration of ice-cover and its maximum thickness were estimated for the longest uninterrupted ice-covered periods for all winters.

For the boxplots, values were aggregated to the mean of each day of the year for both the epilimnion and the hypolimnion, and for each combination of PS and climate scenarios. The results presented hereafter focus on Sihlsee, the upper reservoir of the PS plant. The results for Upper Lake Zurich, the lower lake, are summarized in the Supplementary Material.

4 Results

In the following the impacts of current and future climate conditions are discussed on the basis of projected time series (i) of water quality in the epilimnion (Fig. 2) and hypolimnion (Fig. 3) as well as (ii) of differences between current and future climate (Fig 4).

Climate change increases the water temperature at Sihlsee throughout the water column for all PS scenarios. Yet, projected temperature changes (ΔT) vary among the different PS scenarios. The earlier onset of summer stratification results in maximum ΔT in the epilimnion in April of ~2.5 °C, ~3.0 °C and ~2.9 °C for both reference scenarios QNat and NoPS and the present PS scenario, respectively. The smallest ΔT of ~1.0 °C (reference scenarios QNat) and ~1.3 °C (reference scenario NoPS and present PS scenario) occur in February. The seasonal minima in winter can be explained by the fact that water temperature cannot fall below 0 °C. The seasonal minimum is less pronounced in the extended PS scenario, where the ice-covered period with surface temperatures of 0 °C is already significantly shortened for the present climate. For the extended PS scenario the projected ΔT range between ~1.4 (January) and ~2.6 °C (August).

In the hypolimnion, ΔT is small in the reference scenario QNat compared to all other scenarios. For QNat, ΔT remains <0.6 °C except for November and December when it reaches a maximum of ~1.0 °C, resulting from prolonged stratification. The reference scenario NoPS as well as the present and the extended PS scenarios show similar behaviour with a minimum hypolimnetic ΔT of <0.4 °C in January and a maximum of ~2.4 to 2.5 °C in September. Summer stratification is prolonged due to climate change (Fig. 5). Its duration increases by ~33, ~27, ~26 and ~26 days for the reference scenarios QNat and NoPS and for the present and the extended PS scenarios, respectively. This is primarily due to an earlier onset of stratification in spring. The end of summer stratification is delayed by ~12 days from mid to end of November for QNat, and by less than one week for all other scenarios. The summer stratification is also intensified: Schmidt stability increases during the stratified period by ~22%, ~12%, ~12% and ~11% for the reference scenarios QNat and NoPS and the present and extended PS scenarios, respectively (Table 2 and Supplementary Material).

Conversely, the duration and intensity of inverse stratification are reduced (Fig. 5). For the two reference scenarios QNat and NoPS as well as the present PS scenario it is shortened by ~2.1 months, and for the extended PS scenario by ~1.3 months to a remaining duration of a few days. This shortening is caused by a delayed onset and an earlier end of the inverse stratification.

With few exceptions, Sihlsee develops an ice cover with a thickness >5 cm in all 150 simulated winters under present climate conditions for the present PS and both reference scenarios. The frequency of ice coverage exceeding 5 cm thickness is reduced to ~83% (124 of 150 years) for the extended PS scenario (Table 2). Climate change is projected to reduce the frequency of ice cover even more to values between ~57% and ~60% for the present PS and the reference scenarios, respectively, and to ~13% (19 of 150 years) for the extended PS. The average duration of the ice-covered period is reduced by ~82% for the extended PS scenario and by ~71% for all other scenarios. In winters with ice cover, the ice thickness is projected to decrease by ~54% for both reference scenarios as well as the present PS scenario, and by ~64% for the extended PS scenario (Supplementary Material). In Fig. 5 for the extended PS scenario the ice-covered period is depicted as lasting longer than the inverse stratification, which can be explained by the definition of the latter since we only considered the longest uninterrupted period of each winter.

The prolongation of summer stratification also causes changes of DO concentrations (Fig. 5). In the current climate, DO concentrations fall below the 4 mg L^{-1} threshold in almost every simulated summer period of both reference scenarios. PS operations supply oxygen-rich water from Upper Lake Zurich to the hypolimnion of Sihlsee, and therefore, the occurrence of DO <4 mg L^{-1} is reduced to ~92% of the years (138 of 150) for the present PS scenario and to ~31% (47 of 150) for the extended PS scenario (Table 2). These frequencies increase to ~99% (149 of 150) and ~69% (103 of 150) for the future climate scenarios due to prolonged stratification. Also, the average duration of the period with DO concentrations <4 mg L^{-1} is prolonged by ~1 month for QNat, ~2 to 3 weeks for NoPS and present PS, and ~3 days for the extended PS.

Shortened inverse stratification and ice-covered period result in an increase of both epi- and hypolimnetic DO concentrations for the reference scenarios QNat and NoPS and the present PS scenario, whereas for the extended PS scenario, this effect is minor, as inverse stratification is already strongly reduced for current climate conditions. Throughout the rest of the year hypolimnetic DO concentrations are reduced by up to 3.3, 1.0, 1.0 and 0.7 mg L^{-1} for QNat, NoPS, the present and the extended PS scenario, respectively. Additionally, warmer temperature in summer causes reduced solubility and, therefore, epilimnetic DO concentrations decrease by up to 0.6 mg L^{-1} for all PS scenarios.

The effects of changing stratification on hypolimnetic phosphate concentrations are approximately inverse to those on DO concentrations, as phosphate is released from the sediments and accumulates in the hypolimnion during stratified periods in summer. The shorter inverse stratification in winter and the corresponding higher probability of open water conditions for future climate lead to increased DO concentrations and, thus, to reduced hypolimnetic phosphate concentrations in winter by up to~3.6, ~2.5, ~1.9 and ~4.5 µg P L^{-1} for QNat, NoPS, the present and extended PS scenario, respectively. For the extended PS scenario, these concentrations are additionally decreasing in the hypolimnion of Sihlsee due to an earlier onset of primary production in Upper Lake Zurich. The decline of hypolimnetic phosphate concentrations can be propagated to the epilimnion where concentrations decrease by up to 3.0 µg P L^{-1}. While for QNat changing mixing dynamics can increase hypolimnetic phosphate concentrations by up to ~2.6 µg P L^{-1}, concentrations remain unaffected for all other PS scenarios.

5 Discussion

For both Upper Lake Zurich and Sihlsee, the simulated climate change effects for the reference scenario QNat are in line with effects that have previously been observed or projected for dimictic or monomictic lakes (Ficker et al. 2017; North et al. 2014): (a) an increase in epilimnetic temperature, (b) a comparably small increase in hypolimnetic temperature as stratification decouples the hypolimnion form the atmosphere, (c) prolonged summer stratification, which further results in (d) reduced hypolimnetic DO and (e) increased hypolimnetic phosphate concentrations. For Sihlsee, climate change is projected to (f) shorten the ice-covered period, (g) reduce ice thickness, (h) shorten the duration of inverse stratification in winter, and consequently, (i) increase hypolimnetic DO and (j) decrease hypolimnetic phosphate concentrations. Again, these findings agree with observations and projections for other ice-covered lakes (Benson et al. 2012; Prowse et al. 2011).

In addition to these established effects, our simulations show relevant interactions between the effects of PS operations and those of climate change. In the PS scenarios, the projected warming rate in the hypolimnion of Sihlsee is almost as large as that in the epilimnion. This is due to deep-water withdrawal and the corresponding drawdown of surface water, as well as the transfer of epilimnetic water from Upper Lake Zurich. Hypolimnetic temperature in Sihlsee is already now increased by 5 to 10 °C throughout summer due to PS operations (Kobler et al. 2018), and our simulations show that this effect is further exacerbated by climate change. This is relevant as increasing hypolimnetic temperatures cause intensified mineralization of organic matter (Gudasz et al. 2010) and may promote anoxic conditions in the surface sediments (Jensen and Andersen 1992).

The further warming of the hypolimnion results in weaker and shorter summer stratification. Altogether, the combined effects of climate change, prolonging stratification, and of PS operations, shortening it, almost compensate each other. Thus, the average duration with extended PS under future climate is similar to that of QNat under current climate. But the properties of the stratification would be very different, as it is projected to (i) start and end earlier by ~1 month, and to (ii) be significantly less stable due to the much smaller temperature difference between the epi- and the hypolimnion. Such seasonal shifts affect the timing of various processes in an ecosystem differently and thus modify interactions between them. For example, earlier warming in spring has been shown to disrupt trophic linkages between phyto- and zooplankton (Winder and Schindler 2004), especially if warming is seasonally heterogeneous (Straile et al. 2015).

The shorter duration of stratification and the input of epilimnion water from Upper Lake Zurich increase DO availability and reduce phosphate concentrations in the hypolimnion of Sihlsee (Kobler et al. 2018). These effects are partially offset by climate change, which extends the average duration of DO concentrations <4 mg L^{-1} by ~2 weeks for the present PS and by <1 week for the extended PS scenario. However, this effect, caused by climate change, is even stronger for the reference scenario QNat, where the duration of DO <4 mg L^{-1} is extended by ~1 month.

Ice-cover is already affected by PS pumping: particularly, for the extended PS scenario, increased epilimnion temperatures were projected to decrease ice thickness and shorten the ice-covered period (Kobler et al. 2018). Climate change further reduces Sihlsee's ice cover by two processes: the direct impact of warmer epilimnion and air temperatures, which shortens the ice-covered period by ~71% (Table 2). Combined with the increased temperature of the PS pumping flow, the ice-covered period is even shortened by 82% for extended PS. The number of winters exceeding an ice thickness of 5 cm is reduced by ~17% due to extended PS and by ~40% due to climate change, but by ~85% if both effects are combined (Table 2). Since both PS and climate change lead to shorter inverse stratification and reduced ice cover, it is important for the ecosystem to consider their combined effects. These may include reduced likelihood of winter anoxia, but also modified survival rates of different species, leading to altered community composition (Adrian et al. 2006; Rühland et al. 2015). Additionally. changes in winter phenology could result in alterations of fish growth and reproduction (Shuter et al. 2012).

Combined effects of deep-water withdrawal and climate change were also found by Prats et al. (2018) who analysed different management scenarios for a Mediterranean drinking water reservoir. They concluded that reservoirs should be more sensitive to meteorological forcing than natural lakes as the deep-water withdrawal transports climate-induced excess heat to lower layers. For their current management scenario with deep-water withdrawal both epi- and hypolimnion temperatures would increase, while the seasonal dynamics of thermocline depth and stratification would hardly be affected (Prats et al. 2018). For a scenario with surface water withdrawal, they projected longer and more stable summer stratification as well as less warming of epi- and hypolimnion. They showed that surface water withdrawal and dam heightening combined with long-term climate change would lead to similar mean hypolimnion temperatures as with deep-water withdrawal under the present climate, which is not the case for Sihlsee.

The projected increases in epilimnion temperature in Sihlsee are ~50% of those in air temperature. According to physical principles, if only air temperature is modified and all other forcing remains equal, epilimnion temperatures in equilibrium with the atmospheric forcing should increase by ~70 to 90% of increases in air temperature (Schmid et al. 2014). An additional simulation without any inflows resulted in higher epilimnetic warming of ~60 to 70% of those of air temperature. Moreover, the weather generator projects a reduction of relative humidity, which explains the remaining difference of ~10% to the expected warming. Climate models often project a decrease of relative humidity over land (Byrne and O'Gorman 2016). However, the projected reduction in relative humidity by the weather generator is based on correlations between current air temperature and humidity for the present climate, and it remains uncertain whether these are also valid for future climate. Similar arguments apply for the projected inflow temperatures.

Besides air temperature, climate change is also likely to modify precipitation and discharge patterns. For central and north-eastern Switzerland, most regional climate models agree that precipitation will decrease during summer months, whereas the direction of changes during the rest of the year remains uncertain (Fischer et al., 2015). Significant changes in precipitation would also modify river discharge, external nutrient loading (Dokulil et al. 2010) and would require modifications of the PS operations. Furthermore, in the catchment of Sihlsee, the duration of snow cover would be reduced, leading to a change of the seasonal discharge pattern. Fenocchi et al. (2017) analysed that riverine inflows can play a crucial role for hypolimnetic temperatures for the example of Lake Maggiore. Significant changes in discharge could also have an impact on lake-internal processes and stratification in Sihlsee, especially for the reference scenario QNat. However, these effects will likely be much smaller than the differences between the ”quasi–natural” scenario and the scenarios with deep-water withdrawal.

The water flows of the extended PS scenarios were derived based on the traditional operation strategies for a PS hydropower plant, which will likely change in future. Pérez-Díaz et al. (2015) summarize future trends of the operation of PS hydropower plants, and highlight the importance of providing power regulation reserves by means of variable speed design of pump-turbines or hydraulic short-circuiting. Nevertheless, as the studied PS hydropower plant is operated by the Swiss Federal Railways (SBB AG) and mainly supplies power to trains, one could argue that the future operation might not differ a lot from present conditions.

A possible option to reduce the PS effect for the hypolimnion is to shift the PS intake/outlet to the epilimnion. Bonalumi et al. (2012) showed that for a deeper inlet/outlet, a larger volume is significantly affected, as mostly the volume between the intake/outlet and the thermocline is warming. As a consequence of the large water level fluctuations, shifting the PS intake/outlet to the epilimnion, which would be favourable with respect to temperature changes, would require the construction of a multi-level offtake structure and the implementation of an adaptive withdrawal strategy as analysed by Weber et al. (2017). Including such a selective withdrawal was, however, beyond the focus of this study.

In summary, our simulations show ecologically relevant synergistic and antagonistic effects of climate change and PS operations within the typical time scale for which concessions of hydropower plants are usually issued. Without consideration of climate change scenarios, an environmental assessment for a hydropower plant, therefore, can only incompletely assess the expected impacts on ecological processes in the affected water bodies during its lifetime. We thus recommend including projections for future climate effects in environmental impact assessments. Furthermore, our results show that estimated impacts of both PS and climate change may differ for different reference scenarios, highlighting the importance to have clear guidelines for defining the reference.

6 Conclusions

Coupled effects of PS operations and climate change have not been studied, to our knowledge, up to now. Thus, we generated meteorological and inflow water temperature forcing using a vector-autoregressive weather generator for current and future conditions. With this forcing, we drove a two-dimensional hydrodynamic and water quality model for two different PS and two reference scenarios. This allowed us to quantify the impact of both climate change and PS operation on temperature, DO and phosphate concentrations. Our results showed a synergistic effect of PS operation and climate change on hypolimnion temperatures, whereas epilimnion temperature increased similarly in all PS scenarios.

The increased surface water temperatures were projected to cause increased water column stability, prolonged summer stratification, and subsequently lower DO concentrations. An antagonistic effect resulted for the duration of summer stratification, which is prolonged by climate change and shortened by PS operation. However, the combination of climate change and the extended PS scenario advanced summer stratification by almost one month. In winter, DO concentrations increased due to diminished ice cover and weakened inverse stratification. The projected changes further imply changes for lake ecology. The reduced phosphate availability after the ice-covered period would likely affect spring algal growth. The increased overall temperature, especially in case of climate change acting along with the extended PS operation, in combination with decreasing DO concentrations, reduces the available habitat for temperature-sensitive fish species.

For a comprehensive environmental impact assessment of PS hydropower plants, we recommend to quantify not only the changes involved due to the PS operation itself, but also those due to climate change as well as their interactions. This is especially important when the intake/outlet of the PS hydropower plant is located in the hypolimnion, as warming rates were shown to be increased by the combination of deep-water withdrawal and climate change.

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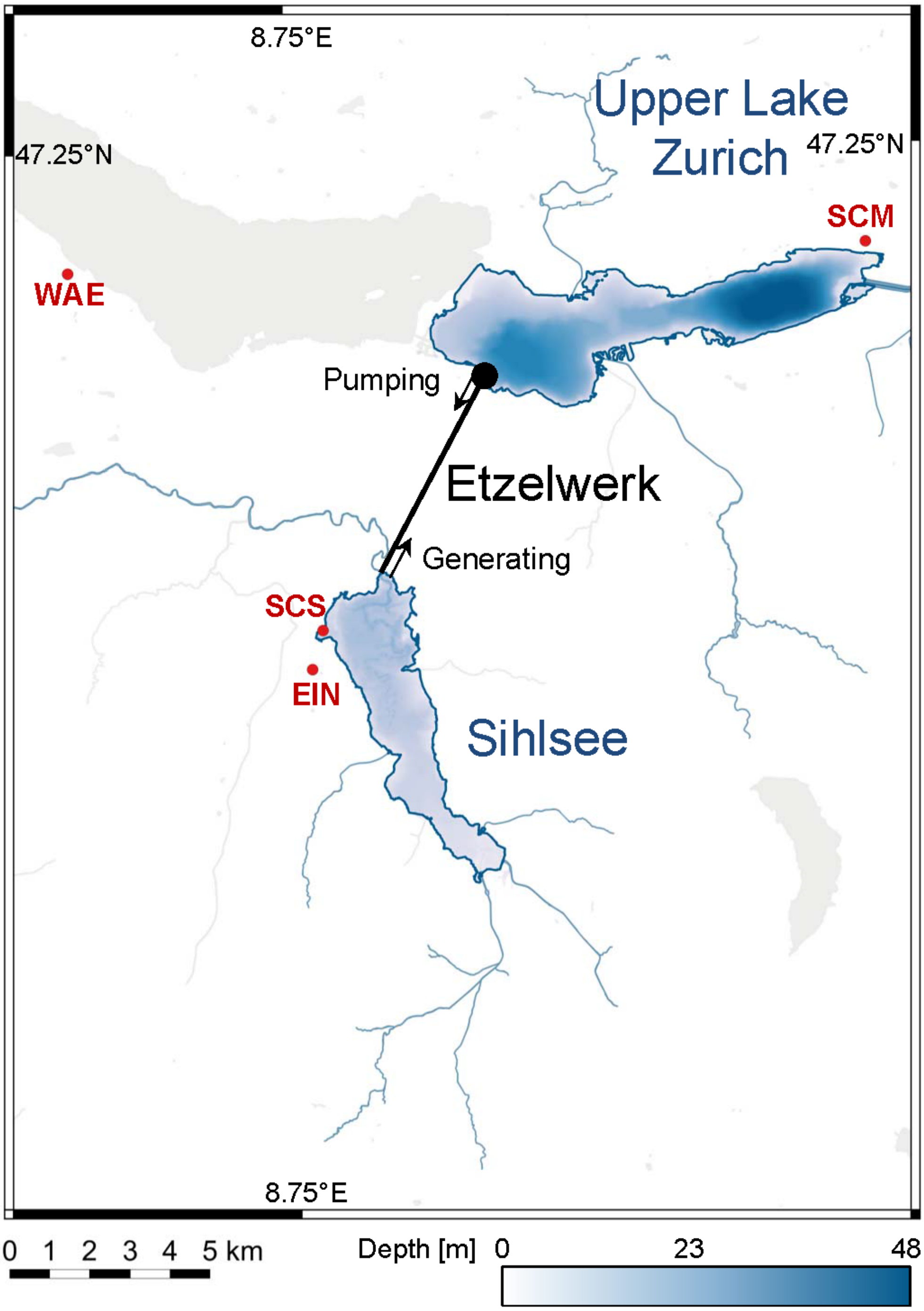

Fig. 1 Overview of study site with meteorological observations taken from stations indicated in red: SCS meteorological stations Segelclub Sihlsee, all others are stations operated by MeteoSwiss: EIN (Einsiedeln), SCM (Schmerikon), and WAE (Wädenswil). The MeteoSwiss station SMA (Zurich Fluntern) is located outside the map at 8.56573°E, 47.37789°N.

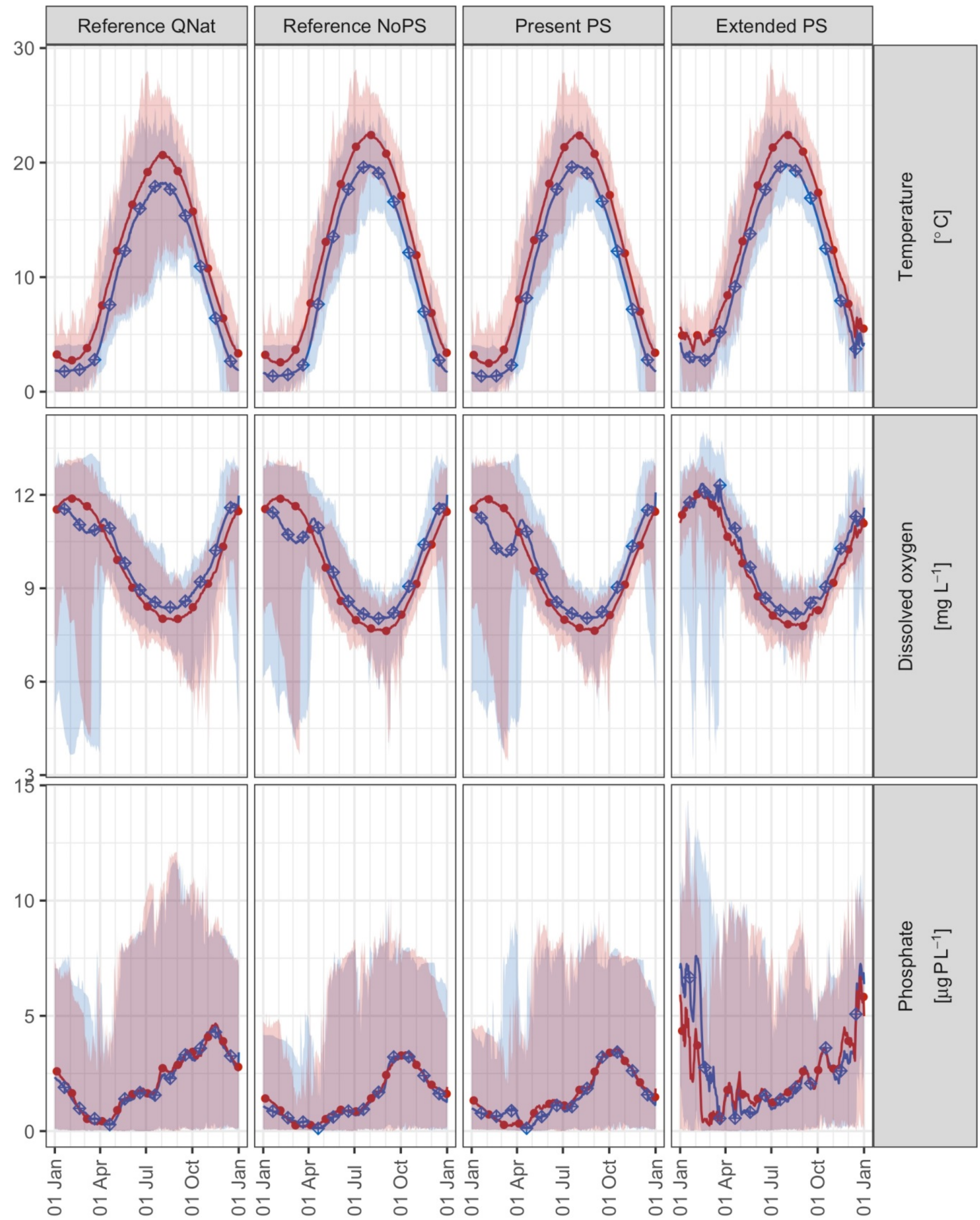

Fig. 2 Absolute values of temperatures (°C), DO (mg L^{-1}) and phosphate (µg P L^{-1}) in the epilimnion (from surface to 5 m depth) of Sihlsee for future (red) and current climate scenario (blue). Shown are means (lines and markers) as well as minima and maxima (shaded areas) for each day of the year and each PS scenario.

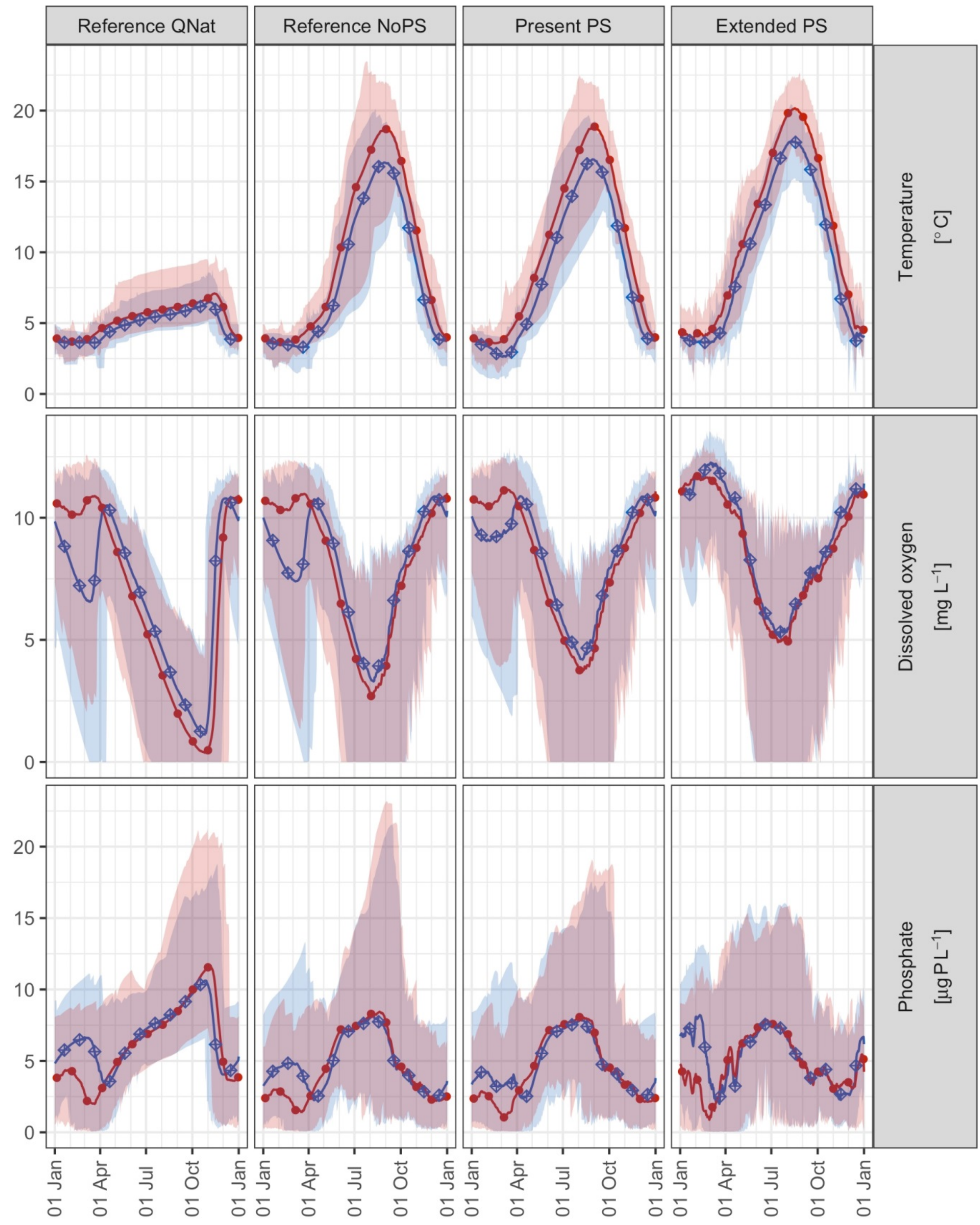

Fig. 3 Absolute values of temperatures (°C), DO (mg L^{-1}) and phosphate (μg P L^{-1}) in the hypolimnion (lowest 5 m of the water column) of Sihlsee for future (red) and current climate scenario (blue). Shown are means (lines and markers) as well as minima and maxima (shaded areas) for each day of the year and each PS scenario.

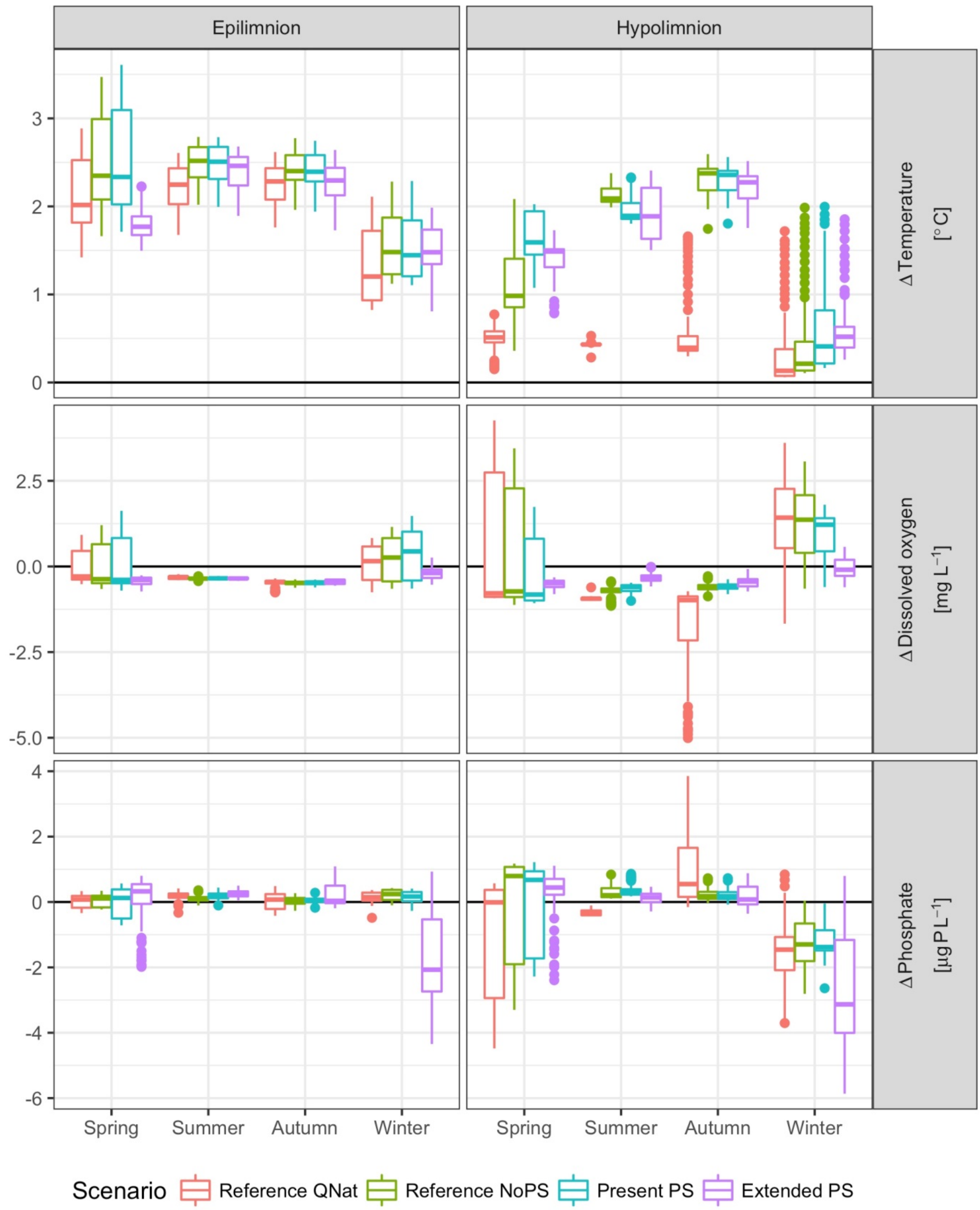

Fig. 4 Boxplot of differences between future and current values of temperature (°C), DO (mg L^{-1}) and phosphate (μg P L^{-1}) at Sihlsee for all PS scenarios and each season (spring: March-May, summer: June-August, autumn: September-November, winter: December-February) for the epi- and the hypolimnion.

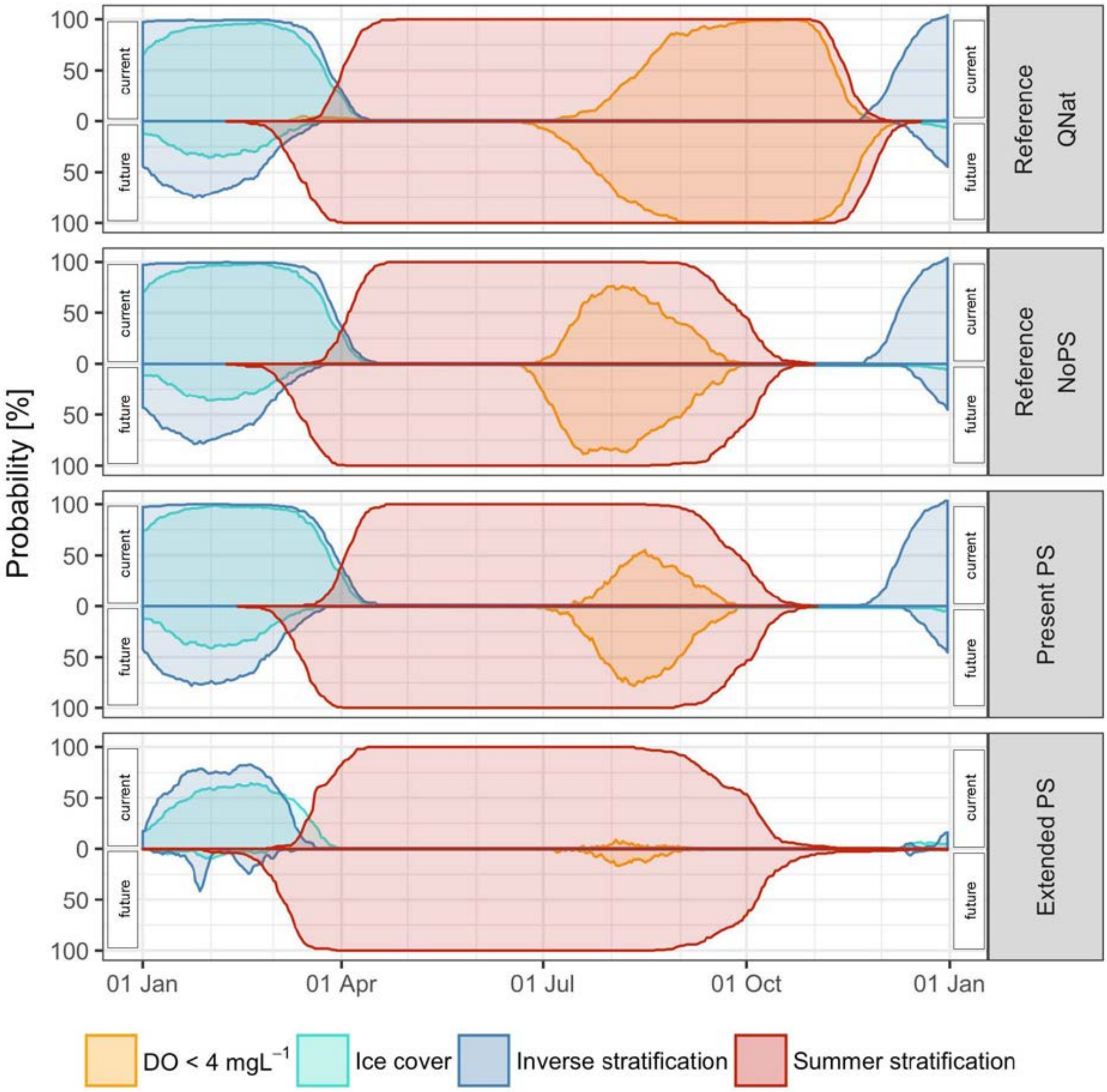

Fig. 5 Comparison for all four PS scenarios of current (upper half) and future (lower half) probability (%) for each day of the year that the lake is ice-covered (dark blue), inversely stratified (light blue), stratified (red) or that hypolimnetic DO concentrations are <4 mg L^{-1} (orange) at Sihlsee. For the extended PS scenario, the ice-covered period ends after the inverse stratification, which results from the fact that only the longest uninterrupted period of inverse stratification was considered.

Table 1 Characteristics of Sihlsee (upper reservoir) and Upper Lake Zurich (lower lake) including their mean annual water balance (1997-2015) for the considered PS scenarios: "quasi-natural" reference (QNat), reference without PS (NoPS), present PS and extended PS scenarios.

		Sihlsee			**Upper Lake Zurich**		
Max. depth	[m]	23			48		
Max. surface area	[km^2]	11.3			20.25		
Max. volume	[10^6 m^3]	96.1			470		
Storage capacity	[10^6 m^3]	89.4			-		
Catchment area	[km^2]	156.5			1,564		
Mixing category	[-]	dimictic			monomictic		
		Sihlsee			**Upper Lake Zurich**		
		Reference scenarios	Present PS	Extended PS	Reference scenarios	Present PS	Extended PS
PS generating power	[MW]	0	~135	525	0	~135	525
PS pumping power	[MW]	0	~65	265	0	~65	265
Residence time	[days]	~150	~135	~40	~70	~70	~70
Sum of inflows	[10^6 m^3 yr^{-1}]	235	235	235	2410	2410	2410
Sum of outflows	[10^6 m^3 yr^{-1}]	-220	-32	-32	-2410	-2598	-2598
Correction term	[10^6 m^3 yr^{-1}]	-15	-15	-15	0	0	0
PS generating flow	[10^6 m^3 yr^{-1}]	0	-214	-778	0	214	778
PS pumping flow	[10^6 m^3 yr^{-1}]	0	26	590	0	-26	-590

Table 2 Aggregated differences between current (CC) and future climate conditions (FC) calculated from all 150 years for Sihlsee.

Scenario	Current climate (CC)	Future climate (FC)	Δ = FC - CC	Δ/CC [%]
Years with hypolimnetic DO concentrations <4 mg L^{-1} [-]				
Reference QNat	150	150	0	0
Reference NoPS	147	150	3	2
Present PS	138	149	11	8
Extended PS	47	103	56	119
Years with ice cover [-]				
Reference QNat	149	112	-37	-25
Reference NoPS	150	106	-44	-29
Present PS	150	118	-32	-21
Extended PS	130	39	-91	-70
Years with ice thickness >5 cm [-]				
Reference QNat	148	87	-61	-41
Reference NoPS	149	86	-63	-42
Present PS	150	91	-59	-39
Extended PS	124	19	-105	-85
Mean duration ice-covered period [days]				
Reference QNat	84	24	-60	-71
Reference NoPS	87	25	-62	-71
Present PS	89	25	-64	-71
Extended PS	47	9	-38	-81
Mean ice thickness during ice-covered period [cm]				
Reference QNat	19	9	-10	-53
Reference NoPS	20	9	-11	-55
Present PS	20	9	-11	-54
Extended PS	12	4	-8	-64
Mean Schmidt stability during periods of inverse stratification [J m^{-2}]				
Reference QNat	14	8	-6	-44
Reference NoPS	17	9	-8	-47
Present PS	14	8	-6	-43
Extended PS	4	2	-2	-45
Mean Schmidt stability during periods of summer stratification [J m^{-2}]				
Reference QNat	308	375	67	22
Reference NoPS	195	218	23	12
Present PS	185	208	23	12
Extended PS	93	104	11	11