Modeling of temperature and turbidity in a natural lake and a reservoir connected by pumped-storage operations

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Received 12 January 2012; revised 12 June 2012; accepted 13 June 2012; published 14 August 2012.

[1] Pumped-storage (PS) systems are used to store electric energy as potential energy for release during peak demand. We investigate the impacts of a planned 1000 MW PS scheme connecting Lago Bianco with Lago di Poschiavo (Switzerland) on temperature and particle mass concentration in both basins. The upper (turbid) basin is a reservoir receiving large amounts of fine particles from the partially glaciated watershed, while the lower basin is a much clearer natural lake. Stratification, temperature and particle concentrations in the two basins were simulated with and without PS for four different hydrological conditions and 27 years of meteorological forcing using the software CE-QUAL-W2. The simulations showed that the PS operations lead to an increase in temperature in both basins during most of the year. The increase is most pronounced (up to 4°C) in the upper hypolimnion of the natural lake toward the end of summer stratification and is partially due to frictional losses in the penstocks, pumps and turbines. The remainder of the warming is from intense coupling to the atmosphere while water resides in the shallower upper reservoir. These impacts are most pronounced during warm and dry years, when the upper reservoir is strongly heated and the effects are least concealed by floods. The exchange of water between the two basins relocates particles from the upper reservoir to the lower lake, where they accumulate during summer in the upper hypolimnion (10 to 20 mg L^{-1}) but also to some extent decrease light availability in the trophic surface layer.

Citation: Bonalumi, M., F. S. Anselmetti, A. Wüest, and M. Schmid (2012), Modeling of temperature and turbidity in a natural lake and a reservoir connected by pumped-storage operations, *Water Resour. Res.*, *48*, W08508, doi:10.1029/2012WR011844.

1. Introduction

[2] Pumped-storage (PS) operation systems are currently developed in the European Alps, with the future goals (i) to meet peak electricity demand and (ii) to store untimely generated electricity. *Deane et al.* [2010] reviewed existing and projected PS plants and listed projects for a total of 7.4 GW installed capacity in Europe, 2.1 GW of which in Switzerland. In the meantime, especially since the Fukushima Daiichi nuclear accident, these numbers have massively increased. In Switzerland alone, projects with a total installed capacity of 4.5 GW are projected or under construction [*Federal Department of the Environment, Transport, Energy and Communications*, 2011], corresponding to an investment of several billion USD. While the technical potential for additional PS is also available in the United States, the economic boundary conditions are currently less favorable for this technology than in Europe [*Yang and Jackson*, 2011].

[3] PS operations connect two water basins (reservoirs and/or lakes) where water is pumped from the lower to the upper basin during low-energy demand, and released back through turbines for peak energy production. The exchange of water between the two basins located at different altitudes affects their thermal regime and the stratification as well as oxygen and nutrient cycling in the water column [*Potter et al.*, 1982], entrains larval fish and organic compounds [*Hauck and Edson*, 1976; *Anderson*, 2010], and entrains or removes particles, modifying the turbidity of lakes, reservoirs and downstream rivers involved [*Miyanaga*, 1986; *Bonalumi et al.*, 2011].

[4] Thermal stratification is a typical characteristic of almost all lakes and reservoirs in perialpine and high mountain regions [*Livingstone et al.*, 1999; *Boehrer and Schultze*, 2008]. The strength of stratification depends, besides the main meteorological boundary conditions [*Effler et al.*, 1986; *Wüest and Lorke*, 2003], on various factors such as the exposure and morphometry (including depth and surface area) of the reservoir [*Ford and Stefan*, 1980], the hydrology that characterizes volumes and temperature of the inflows and outflows [*Finger et al.*, 2006], as well as the occurrence of turbidity currents [*De Cesare and Boillat*, 2003; *De Cesare et al.*, 2006]. Natural variations of those external forces (meteorology, hydrology etc.) are responsible for different stratification every year.

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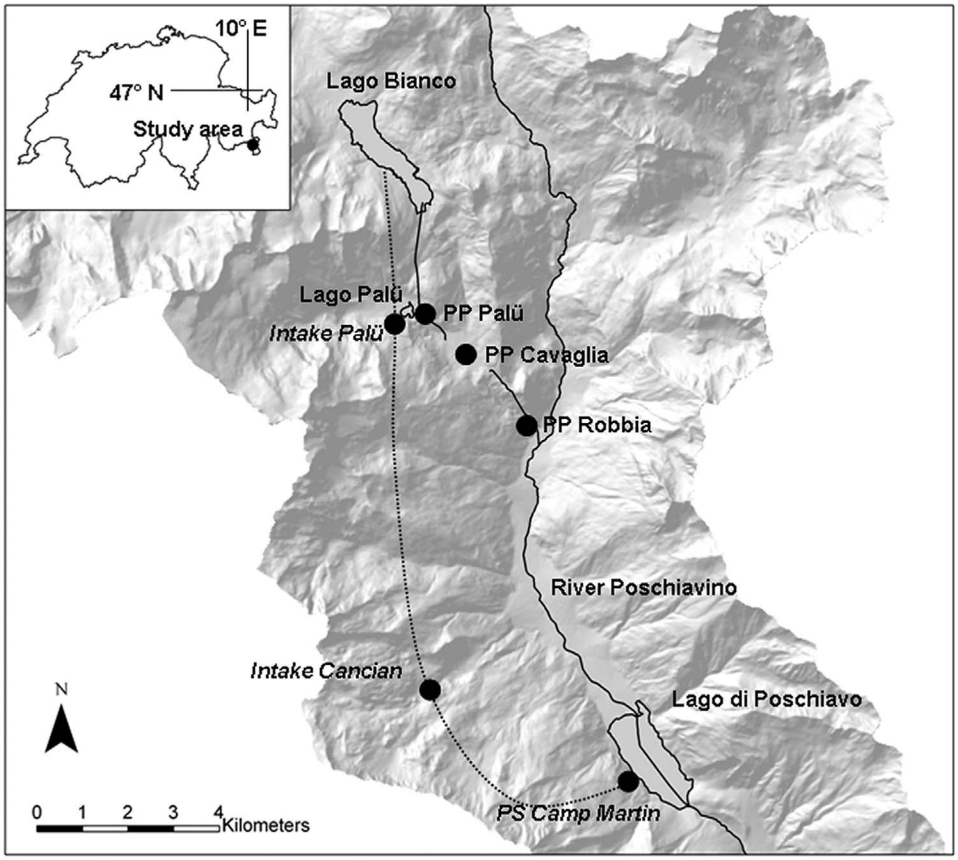


Figure 1. Study area showing the upper reservoir (Lago Bianco) and the lower natural lake (Lago di Poschiavo), as well as the current three power plant stages (PP; normal font) and the planned pumped-storage (PS) plant with the two intakes (italic font) to the penstock (dotted line).

Furthermore, stratification controls reservoir dynamics such as vertical transport of particles, oxygen and nutrients and therefore primary production [*Martin et al.*, 1985; *Owens and Effler*, 1989; *Wetzel*, 2001].

[5] Suspended particles are relevant reservoir parameters, as they affect water quality, such as turbidity of the surface water, where primary production takes place [*Hart*, 1988; *Chung and Gu*, 1998; *Rellstab et al.*, 2007]. Moreover, if the particle runoff is shifted through time, this can affect primary production and then subsequently the food web in a downstream lake [*Chanudet and Filella*, 2007; *Finger et al.*, 2007]. Particles are transported by the inflows into the lakes and reservoirs, where they eventually settle with a velocity that depends on their size and density [*Cuker et al.*, 1990; *Cuker and Hudson*, 1992]. In glaciated catchments, erosion is more effective [*Hallet et al.*, 1996], causing higher particle concentrations in proglacial than in nonglacial lakes [*Koenings et al.*, 1990; *Anselmetti et al.*, 2007].

[6] The main objective of this paper is to investigate the effects of PS operations on temperature and particle mass concentration (PMC) of two basins, Lago Bianco and Lago di Poschiavo, located in the southeastern part in Switzerland (Figure 1), and to understand to what extent these effects are modified by variable meteorological and hydrological conditions. In contrast to the PS system investigated by *Bonalumi et al.* [2011], where two artificial reservoirs with similar properties were connected and mainly the impacts on the rivers and lakes further downstream were of ecological relevance, the PS system considered in the present study would connect a natural lake to an artificial reservoir. As a consequence, the ecological impacts are of higher importance, as a natural ecosystem is affected and thus much stricter regulations apply than in artificial reservoirs. In the present case, the Swiss Federal Act on the Protection of Waters (Swiss Legislation 814.20) applies, which states that "if water is withdrawn from or discharged into a natural lake, the stratification and flow conditions in the lake may not be substantially modified, and no water level fluctuations potentially harmful to the riparian zone may be allowed to occur." The respective ordinance (Swiss Legislation 814.201) further specifies that "living and breeding conditions for organisms must not be negatively affected." Similar regulations apply in many other countries where environmental impact assessments are required for such large-scale projects.

[7] In order to assess the effect of the PS scheme, we simulated the physical characteristics of the two basins using a coupled two-dimensional hydrodynamic model. During the years 1988 and 2007, sampling campaigns were conducted in the two basins and in the different inflows. Combined with existing hydrological records, these data were used to calibrate the model. In order to evaluate the relationships and feedbacks between natural variability of the external forcing and the impact of the PS system, simulations were performed based on 29 years of observed meteorological forcing combined with four different hydrology scenarios. These include two dry years of different intensity,

Table 1. Most Important CE-QUAL-W2 Model Parameters Used in This Study

Parameter	Value
Horizontal eddy viscosity	$0.1\ m^2\ s^{-1}$
Horizontal eddy diffusivity	$0.1\ m^2\ s^{-1}$
Ice albedo (reflection/incident)	0.25
Pure water extinction coefficient	$0.195\ m^{-1}$
Mass-specific extinction coefficient of suspended particles	$0.095\ m^{-1}\ mg^{-1}\ L$
Suspended solids settling rate	$7^a/0.2^b\ m\ d^{-1}$
Wind sheltering coefficient	1
Shading coefficient	1
Turbine/pump efficiency	90%

[a]Particles with diameter size >4 μm.
[b]Particles with diameter size <4 μm.

one average year and one wet year. Moreover, we simulated three planned alternative inlet/outlet depths in Lago di Poschiavo, which are expected to considerably affect the temperature and PMC pattern. To our knowledge, this is the first study where the sensitivity of the impacts of a hydropower scheme on a natural lake to external forcing has been investigated in such detail.

[8] The paper is organized as follows: after introducing the setting of the case study, the research questions are provided in more detail before the modeling approach is explained. The results include the effect of PS operations on temperature and PMC in the two basins as well as the ecological implications of these changes.

2. Study Area

[9] The most powerful (1000 MW) of the PS operation schemes in Switzerland is planned to be built in the Bernina and Valposchiavo region in the Southeastern part of the country. The hydropower plant Camp Martin, operated by Repower, will connect two basins, Lago Bianco and Lago di Poschiavo, located near the Bernina Pass and 5 km South of the town of Poschiavo, respectively, and collect water from two intermediate intakes Palü and Cancian (Figure 1).

[10] The upper basin, Lago Bianco, is a reservoir created in 1910/1911 by damming two small natural lakes (original Lago Bianco and Lago della Scala). At the maximum surface elevation of 2234 m above sea level (asl), Lago Bianco has a surface area of 1.43 km^2 and a maximum depth of 26 m. The planned PS scheme will raise the dams by 4 m and the volume from the current 22.4×10^6 to $\sim 29 \times 10^6\ m^3$. The lower basin, Lago di Poschiavo, is a natural lake located at 962 m asl, with a surface area of 1.95 km^2, a maximum depth of 85 m and a volume of $\sim 111 \times 10^6\ m^3$. In the following, we use the terms "upper reservoir" for Lago Bianco and "lower lake" for Lago di Poschiavo. Sixteen and 5% of the catchments of the upper reservoir and the lower lake are covered by glaciers, respectively. The glacial tributary inflow results in high PMCs and low water transparency in the upper reservoir, which is the origin of its name ("Lago Bianco" translates to "White Lake" in English). In contrast, the lower lake is a relatively clear natural lake with regional importance for tourism and fisheries.

[11] The seasonal temperature stratification is significantly different in the two basins. The lower lake is dimictic with a permanently cold hypolimnion, strong summer stratification and usually weak winter stratification topped occasionally by a thin ice cover. The upper reservoir, however, is ice covered during several months in winter. The summer stratification in the upper reservoir is weaker and the hypolimnion is more exposed to the atmospheric forcing than in the lower lake for several reasons: the upper reservoir is shallower, it is exposed to stronger winds, the high turbidity reduces the ability of short-wave solar radiation to support the formation of a stable stratification, and particle-laden inflows can plunge deep and warm up its hypolimnion. For this reason, summer hypolimnetic temperatures are higher in the upper reservoir than in the lower lake despite the elevation difference of almost 1300 m and the cold water (glacial) inflows.

[12] Today the water from the upper reservoir is used for hydropower production in three stages before being released into the River Poschiavino, the main tributary of the lower lake (Figure 2). The daily variation of power production

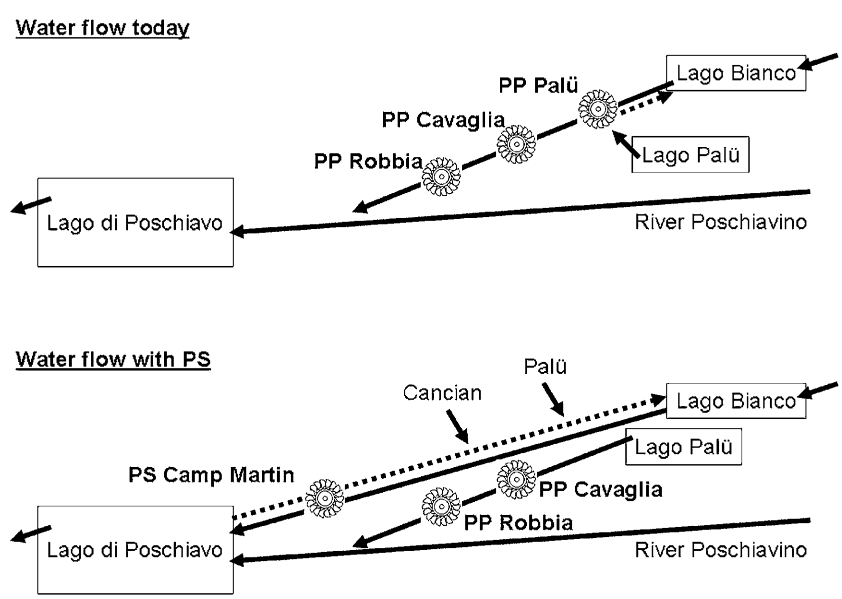


Figure 2. Schematics of the water flow (top) as today without PS and (bottom) as planned with PS. Indicated are the power plants (PP), the pumped-storage plant (PS) and the intake/inflows (short arrows).

leads to hydropeaking flow in Poschiavino. Moreover, water enters from a secondary valley into Lago Palü (1923 m asl), from where it is partially pumped into the upper reservoir. In the future, this water will be used through the existing stages, while pumping water from Lago Palü into the upper reservoir will be dismantled when the new PS plant is in operation.

3. Aims of Present Study

[13] The new PS scheme will connect the hypolimnia of the two basins and lead to a continuous exchange of water between them. As a consequence, differences between the two water bodies will be partly evened out. Hypolimnetic temperatures are expected to decrease in the lower lake and increase in the upper reservoir during winter and vice versa during summer. In addition, temperature in the whole water volume will increase to some extent due to the heat production by the frictional losses in the penstocks, pumps and turbines. Furthermore, PS operations will reduce the water residence time in the upper reservoir. As a consequence, part of the particles formerly settling in the upper reservoir will be flushed into the lower lake, where they can accumulate during summer near the inlet depth [*Schmid et al.*, 2008], from where they can be entrained to the surface layer by turbulent mixing during wind events and by seasonal mixing in autumn, affecting surface water clarity and primary production.

[14] The present study aims at quantifying these predicted changes, and to evaluate their dependence on meteorological and hydrological conditions in order to determine worst-case scenarios for the environmental impact assessment. Simulations are performed using 29 years (1981–2009) of observed meteorological conditions in combination with four different hydrologic years (one average year, one wet year, and two dry years), summing up to a total of 116 simulated years covering the full range of naturally occurring boundary conditions. Furthermore three different penstock inlet/outlet depths in the lower lake are simulated to estimate the potential for mitigation by such technical measures.

4. Methods: Model Description

4.1. Software

[15] The software CE-QUAL-W2, which was employed in our study, was developed by the U.S. Army Corps of Engineers and can simulate water movements, for instance PS operations-driven water exchange between two basins as well as determine the temperature conditions and PMCs along a longitudinal and vertical direction [*Cole and Wells*, 2008]. CE-QUAL-W2 assumes lateral homogeneity and is well applicable to long and narrow lakes, as well as dammed rivers and reservoirs. CE-QUAL-W2 was used in many reservoirs to describe thermal regimes, water quality and also particle transport [*Cole and Wells*, 2008; *Kim et al.*, 2004; *Kim and Kim*, 2006].

[16] The original software was known as LARM (Laterally Averaged Reservoir Model) and was developed by *Edinger and Buchak* [1975]. CE-QUAL-W2 has been under continuous development since 1975. Our simulation applies the software version 3.6 [*Cole and Wells*, 2008]. In the following, we describe the geometric data, initial and boundary conditions as well as the major model parameters required to run the model.

[17] The model setup requires geometric data, initial and boundary conditions, hydraulic and kinetic parameters and calibration data [*Cole and Wells*, 2008]. Geometric data include the bathymetric grid, segment orientation, as well as inflow and outflow locations (Figure 3). Initial conditions encompass, among others, beginning and ending time, initial temperature and constituents' concentrations (in our case PMC), and initial surface water elevation. The model recognizes as boundary conditions inflows and outflows (upstream and tributary, which can occur also in an internal segment) and surface boundary conditions that are surface heat exchange, solar radiation absorption, and wind stress. Hydraulic and kinetic parameters include diffusion coefficients, the Chézy coefficient, the light extinction coefficient and suspended solids settling rate (Table 1).

4.2. Model Grid

[18] The model simulates the water body as a grid of cells consisting of segments in longitudinal and vertical direction (Figure 3). The bathymetry of the two basins consists of 43 segments in the longitudinal directions, which are the segments 2–16 for the upper reservoir, corresponding to 3.0 km length with a resolution of 200 m, and the segments 19–42 for the lower lake, corresponding to 2.4 km length with a resolution of 100 m (Figure 3). The model requires one additional empty segment upstream and downstream as well as at the top and the bottom of each lake. In the vertical direction, the maximum depth consists of 27 segments in the upper reservoir (depth of 54 m) and 42 segments in the lower lake (depth of 84 m). The total number of grid cells is 1055 (223 + 832) but the number of active cells changes during the simulation depending on the water level. In the model, the water is thought to be transferred directly from one basin to the other. The time in which the water passes through the penstock is neglected. For the planned maximum water flows during pumping (95 m^3 s^{-1}) and turbining (74 m^3 s^{-1}), the water residence time in the penstock would be about 80 and 100 min, respectively. In the PS scenarios simulated here, the effective water exchange between the two basins is therefore overestimated by $\sim$15%. As a consequence, the impacts of the pumped-storage system may be somewhat overestimated. However, previous simulations with average annual flow rates for pumping and turbining ranging between 8 and 30 m^3 s^{-1} had shown that at the projected average flow rates of $\sim$25 m^3 s^{-1} (section 4.3) the simulated temperatures and especially PMCs are only weakly sensitive to a further increase in the flow rates [*Schmid*, 2009].

[19] The inflows to the upper reservoir are usually cold and rich in particles and thus have a higher density than the lake water. They are therefore expected to plunge into the hypolimnion. In the model they are distributed between 2226 m asl and the deepest point of the lake. The inflows to the lower lake are expected to stratify either in the surface layer or in the thermocline during most of the year, similar to what has been observed and simulated for the inflows of Lake Brienz [*Finger et al.*, 2006]. During flood events or during winter, the inflows can also plunge into the hypolimnion. In the model, the inflows are distributed to the surface layer from the surface down to 946 m asl (top 16 m at full supply). The model would also allow for density-dependent inflow levels. However, tests with this feature were not successful in reproducing observed temperatures and PMC and therefore inflow depths were prescribed. The

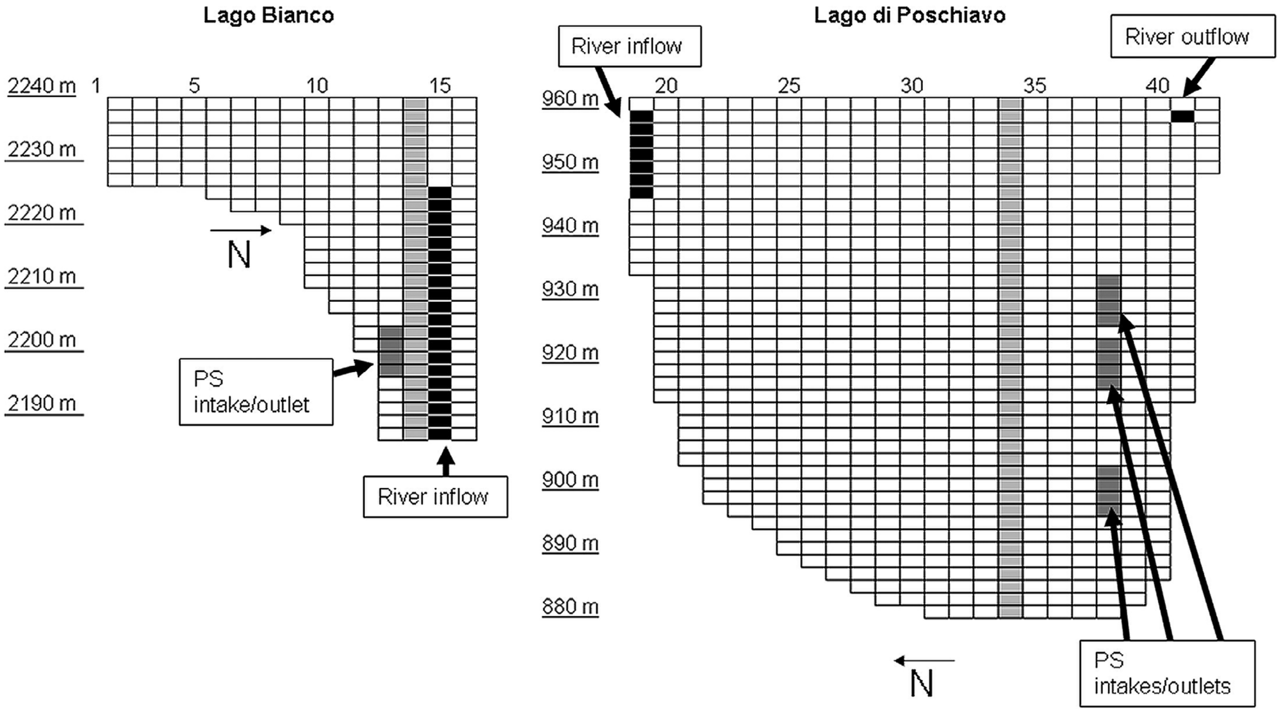


Figure 3. Two-dimensional bathymetric grid arrangement for the simulation of the two basins. Our results are based on the simulation output in the segments 14 and 34 (bright gray) at the deepest locations of the upper reservoir (Lago Bianco) and the lower natural lake (Lago di Poschiavo), respectively. The numbers on the left of the grids indicate elevations above sea level.

PS inlet/outtakes are defined by the construction plans. In addition to the original location, two alternative locations 10 and 30 m deeper were implemented in the lower lake.

[20] The efficiency of turbination and pumping was fixed at 90% each. Considering the hydraulic head between the two basins (1270 m), the frictional heat loss of 10% of the potential energy results in a warming of the water passing through the penstocks by ~0.3°C. This warming is included in the model. However, the software does not provide the possibility to add a heat input without a corresponding water flow. We therefore introduced an arbitrary water inflow, corresponding to 0.01% of the water turbinated/pumped and exhibiting a temperature of 3000°C.

4.3. Boundary Conditions

[21] Hydrologic boundary conditions were obtained from Repower AG and ecowert gmbh. They consist of the hydrological data of 4 years (Table 2) representing one average year (1988) with a flood event in fall, one wet year (2001), one extremely dry year (2005) and one normal dry year (2007). The data include the inflows to the upper reservoir (Figure 4a) and the lower lake (Figure 4b) and the outflows of both basins (Tables 2 and 3). Moreover, Repower AG provided PS operation scenarios for the four hydrologic years (Table 3 and Figure 4c), calculated for optimizing the profit based on assumptions for the power market and keeping the water levels within the legal limits. During the summer months, operations are further restricted by regulations

Table 2. Hydrological Characteristics Without PS (Annual Averages) and PMC in the Inflows and Outflows of the Two Basins for Four Years of Different Hydrological Characteristics

Quantity (Flow, Load, PMC)	1988	2001	2005	2007
Upper Reservoir (Lago Bianco)				
Natural inflow (m^3 s^{-1})	0.59	0.87	0.39	0.46
Pumped water from Lago Palü to Lago Bianco (m^3 s^{-1})	0.16	0.01	0.13	0.02
Turbinated water from Lago Bianco (m^3 s^{-1})	0.86	1.16	0.58	0.72
Particle load (inflow) to Lago Bianco (kt yr^{-1})	6.44	10.2	4.47	5.30
Lower Lake (Lago di Poschiavo)				
Natural inflow[a] (m^3 s^{-1})	6.34	9.23	3.54	4.38
Outflow from Lago di Poschiavo (m^3 s^{-1})	7.22	10.8	4.12	5.23
Particle load (inflow) to Lago di Poschiavo (kt yr^{-1})	11.0	36.6	2.05	3.71
Average PMC in Poschiavino[a] (mg L^{-1})	55.0	125.9	18.4	26.9

[a]Without water turbinated from Lago Bianco.

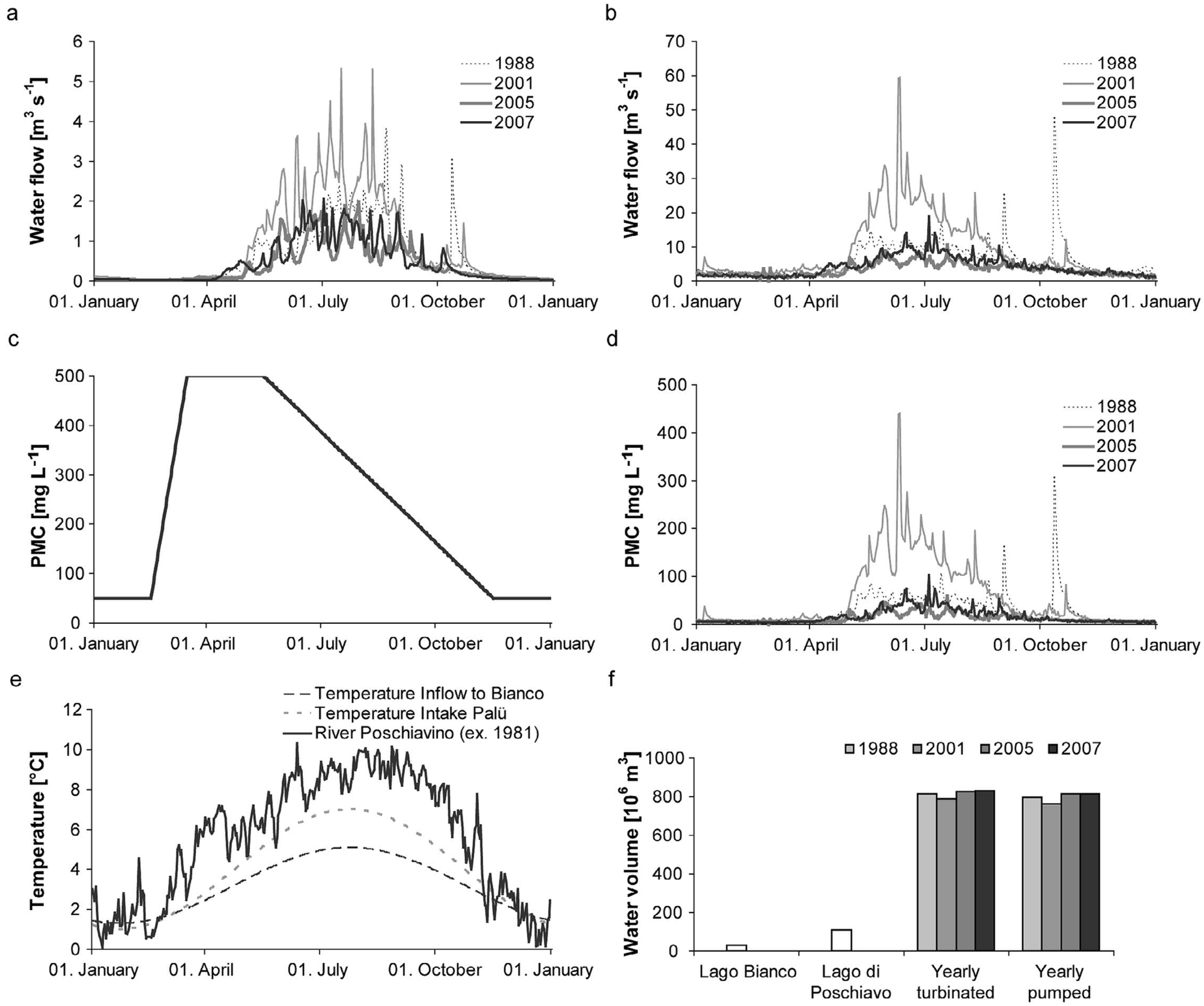


Figure 4. Water inflow to (a) the upper reservoir (Lago Bianco) and to (b) the lower lake (Lago di Poschiavo) for the four hydrological years (with PS). PMC in inflow to (c) the upper reservoir and to (d) the lower lake. (e) Assumed temperature in inflow to the upper reservoir, in Palü intake, and measured (1981) temperature in River Poschiavino, the main tributary of the lower lake. (f) Volumes of the two basins compared to annually pumped/turbinated volumes.

Table 3. Hydrological Characteristics with PS (Annual Averages) and PMC in the Inflows and Outflows of the Two Basins for the Four Simulated Hydrological Years[a]

Quantity (Flow, Load, Concentration)	1988	2001	2005	2007
Upper Reservoir (Lago Bianco)				
Natural inflow (m^3 s^{-1})	0.58	0.86	0.39	0.45
Turbinated water from Lago Bianco (m^3 s^{-1})	25.8	25.0	26.2	26.3
Particle load (inflow) to Lago Bianco (kt yr^{-1})	6.41	10.2	4.45	5.27
Lower Lake (Lago di Poschiavo)				
Pumped water from Lago di Poschiavo (m^3 s^{-1})	25.2	24.2	25.8	25.8
Inflow from Palü and Cancian intakes to penstock (m^3 s^{-1})	0.30	0.47	0.18	0.21
Natural inflow to Lago di Poschiavo[b] (m^3 s^{-1})	6.04	8.76	3.36	4.16
Outflow from Lago di Poschiavo (m^3 s^{-1})	6.92	10.1	3.93	4.82
Particle load (inflow) to Lago di Poschiavo (kt yr^{-1})	10.4	34.6	1.91	3.49
Average PMC in Poschiavino and Palü/Cancian intakes (mg L^{-1})	54.5	125.4	18.0	26.6

[a]The difference in the inflow to Lago Bianco (upper reservoir) between the simulation with and without PS is due to model adjustments.
[b]Without water turbinated from Lago Bianco.

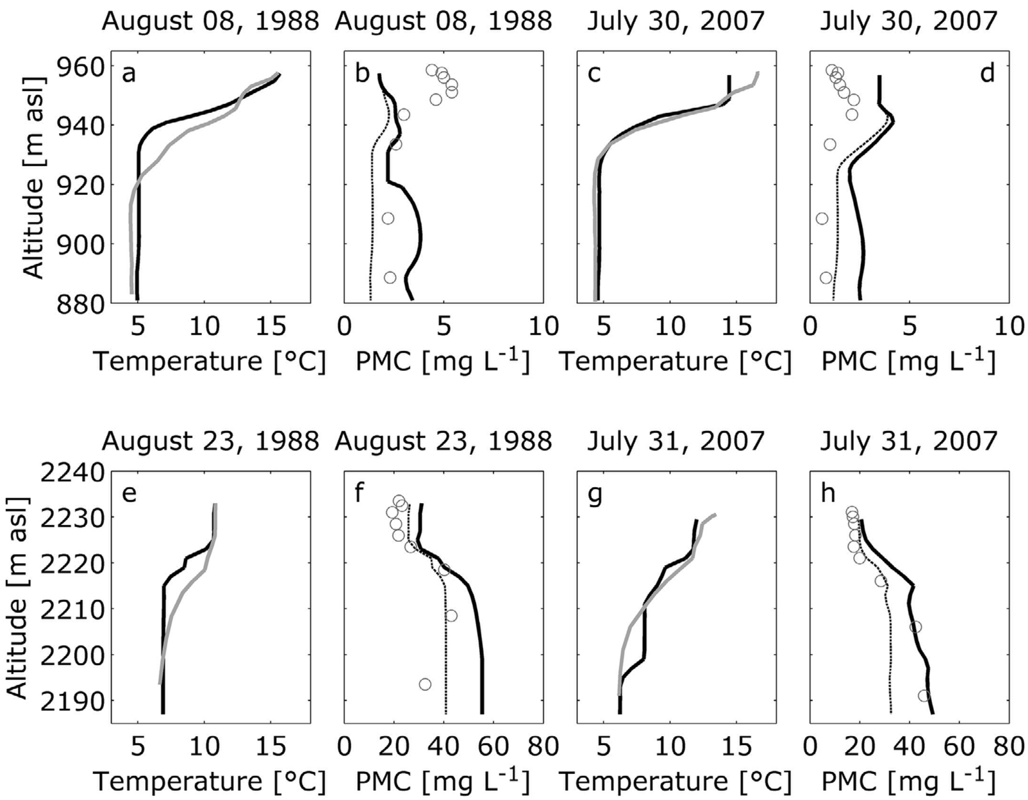


Figure 5. Examples of temperature and PMC model data (black line) compared to collected field data (gray symbols and gray lines): Temperature and PMC in the upper reservoir in summer (a and b) 1988 and (c and d) 2007; temperature and PMC in the lower lake in summer (e and f) 1988 and (g and h) 2007. The dotted black lines represent particles <4 μm only.

of the maximum lake level variations. From the point of view of the environmental impact assessment, these scenarios are worst-case scenarios as they only allow for full-scale operations, whereas in reality operations are expected to often run at reduced levels. The pumped-storage scenarios feature only relatively small differences between the four simulated hydrological years. Furthermore, the boundary conditions include two minor hydropower inlets/outflows, that is the pumped water from Palü to Bianco (Table 2) and the water inflow of the intakes Palü/Cancian (Table 3). The time step for the hydrologic flows is 1 day, except for the PS operations and the artificial outflows, which have a time resolution of 1 h. Since the simulations were run for several consecutive years, the original water flows had to be modified in order to arrive at the initial lake levels at the end of each simulation year. In order to achieve this, the outflows of the two basins were scaled such that they were equal to the total inflows. For the wet year 2001, in addition, a fraction of the outflow had to be shifted from winter to summer in order to avoid the level of the lower lake exceeding the physical limits.

[22] The inflow temperatures of the lower lake were calculated as follows [*Schmid et al.*, 2008]: first, a linear relationship was derived between mean monthly temperatures in Poschiavino and in the River Inn at S-chanf based on measurements from the years 1988/1989; this relationship was then applied to calculate the mean temperature of the Poschiavino for each day of the year based on temperature measurements by the Federal Office for the Environment (FOEN) from the River Inn for the years 1997–2009. The mean temperature for each day was then finally corrected by 30% of the difference of the current air temperature (shifted by 4 hours to account for the time delay of river temperatures compared to air temperatures) to the mean air temperature for this day of the year for the same period. This procedure allowed reproducing both the seasonal and the daily dynamics of temperatures observed in the River Poschiavino in 1988/1989. The resulting temperatures for one simulation year are shown in Figure 5. Temperatures of the inflow (Figure 4f) to the upper reservoir and of the intakes Palü and Cancian were derived from a sine curve model [*Federal Office of the Environment*, 2008]. The inflow to the upper reservoir was compared with measurements obtained in the River Lonza (Blatten, Switzerland), which is situated in a similar environment, while the temperatures of the intakes Palü and Cancian were adjusted based on measurements in 1988 and 2007.

[23] In the absence of direct measurements, PMCs of the inflow of the upper reservoir (Figure 4d) were derived from measurements obtained in Oberaarbach [*Arn*, 2002], which is located upstream of Oberaarsee in the Central Alps at a similar altitude as the upper reservoir and also in a partially glaciated catchment [*Bonalumi et al.*, 2011]. The same PMCs were used for the four hydrological years. These PMCs were successfully used to reproduce the seasonal trend of average PMCs in the upper reservoir [*Schmid et al.*, 2008]. PMCs in the inflow of the lower lake were obtained with hourly resolution from a direct correlation with the inflow discharge (Figure 4e), based on a discharge-concentration

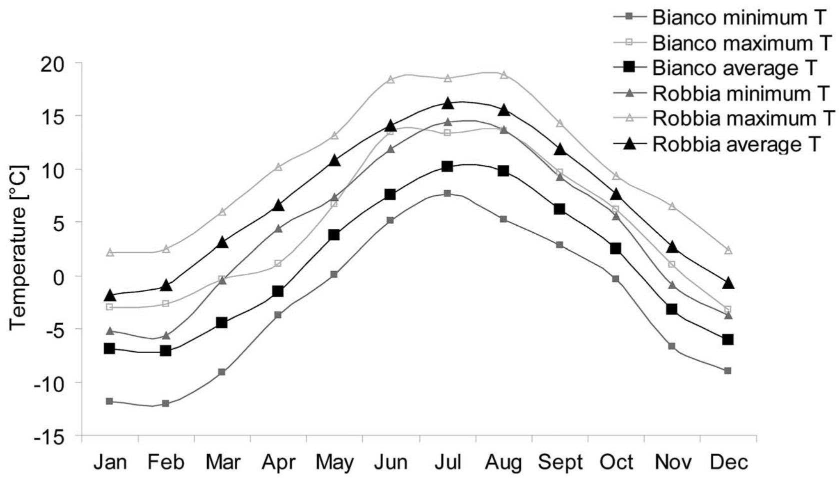


Figure 6. Monthly averaged minimum, maximum and mean air temperature from the two meteorological stations Bernina (near the upper reservoir) and Robbia (near the lower lake) during the 29 years (1981–2009) used for the simulations in this study.

relationship supplied by the Limnex AG. This relationship had been developed based on observations as part of a previous environmental assessment. The highest particle input occurs in 2001, followed by 1988 and the dry years 2007 and 2005.

[24] Suspended particles were divided in two classes, namely those with a diameter smaller and larger than 4 μm. The model assumes that the large particles sink with a velocity of 7 m d^{-1}, and the small particles with a velocity of 0.2 m d^{-1}. These velocities correspond to particle diameters of 11.5 and 2.0 μm, respectively. In order to reproduce the PMCs observed in the basins, it is assumed that the PMC of the inflow to the upper reservoir consists to 80% of particles >4 μm, while in the inflow to the lower lake, which contains less glacial particles, PMC consists to 95% of particles >4 μm. Grain size distribution measurements from the upper reservoir yielded average fractions of 69% and 92% of particles <4 μm on 31 May and 25 October 2007, respectively. The model yielded average fractions of 71% and 97% for the same dates.

[25] Meteorological surface boundary conditions required by the model consist of air temperature (Figure 6), wind velocity and direction, humidity, solar radiation and cloudiness. These were obtained from three meteorological stations of MeteoSwiss: Robbia (7 km north of the lower lake, all parameters for the lower lake), Corvatsch (15 km west of the upper reservoir, wind direction and wind speed after 2004 for the upper reservoir), and Bernina (near the shore of the upper reservoir, all remaining parameters for the upper reservoir). Solar radiation in the upper reservoir was calculated from cloudiness using the algorithm implemented in CE-QUAL W2 v3.6. The wind velocities at the station Robbia were found to be different from those on the lower lake, especially in summer so that additional corrections, with the help of measurements on the lake itself performed in 1988, were necessary [*Bonalumi and Schmid*, 2011]. Wind velocities on the upper reservoir were multiplied with a factor 1.3 to account for the lower time resolution (one measurement a day) of these measurements, which would otherwise lead to an underestimation of the energy input that is proportional to the third power of the wind speed. However, also with these corrections, wind-induced mixing was underestimated in both basins during the summer stratification. Therefore, wind speeds were multiplied with additional factors for 1.8 in June to August for the lower lake and 1.4 in June and July for the upper reservoir. Simulations were run with the meteorological observations of the years 1981–2009.

4.4. Initial Conditions

[26] The simulations without PS were initialized on 1 January 1981 and run continuously until 31 December 2009. The simulations with PS had to be reinitialized on 1 January 1997 because the restriction of the number of significant digits in the input files would have led to too large truncation errors in the duration of the pumped-storage flows for simulations longer than 1000 days. The following initial conditions were used for all simulations for 1 January 1981: homogeneous water temperatures of 4°C in the lower lake and 1.3°C in the upper reservoir, PMCs of 2 mg L^{-1} in the lower lake (50% particles <4 μm) and 10 mg L^{-1} in the upper reservoir (80% particles <4 μm). The choice of the initial conditions had significant impacts on the simulation results only in the first few months of the simulations, but impacts were minimal for the following years. The initialization years 1981 and 1997 were therefore excluded from the following analysis of the results, resulting in a total of 27 years of meteorological boundary conditions used for the analysis.

4.5. Model Parameters and Calibration

[27] Several default parameters were adjusted during the model calibration in order to reproduce the measurements obtained in the basins. The most important and characteristic parameters for our study are listed in Table 1. Vertical profiles of temperature and PMC observed in the upper reservoir (1988, 5 profiles; 2007, 7 profiles) and in the lower lake (1988, 16 profiles, 2007, 6 profiles), as well as temperature time series obtained with moored temperature loggers in the lower lake were used for calibrating the model. Figure 5 shows a few representative results of the calibration. More information on the data and the calibration is provided by *Schmid et al.* [2008] and *Bonalumi and Schmid* [2011].

[28] With respect to preliminary simulations [*Schmid et al.*, 2008], the horizontal eddy viscosity and diffusivity were reduced from 1.0 to 0.1 $m^2\ s^{-1}$, while the mass of particles <4 μm in the River Poschiavino was halved from 10 to 5% providing better reproduction of the PMCs measured in the lower lake. Predictions of lake mixing were improved by correcting wind velocities (section 4.3) and by stratifying the river input into the surface layer of the upper reservoir, without considering its density. Some differences between the model and the observed data could, however, not be eliminated, especially in the surface layer of the basins, where the model tends to overestimate the heating in spring and underestimate it in summer.

5. Results and Discussion

5.1. Temperature: Overview

[29] The distance between the upper reservoir and the lower lake is only ~15 km but the elevation difference of more than 1200 m implies very different meteorological conditions. Air temperature is ~5°C lower at the upper reservoir than at the lower lake throughout the year (Figure 6). Moreover, the upper reservoir is exposed to stronger winds which drive vertical mixing in the lake. In combination with the different shapes and average depths of the basins, these meteorological differences result in different seasonal evolution of water temperature and thermal stratification.

[30] Since the upper reservoir has a smaller volume and, more important, a lower mean depth than the lower lake, and because of the higher exposure to strong winds, the hypolimnion of the upper reservoir during summer is more strongly influenced by variations in meteorological conditions than that of the lower lake. Contrarily, the upper reservoir is ice covered for several months during winter and at that time largely decoupled from the atmosphere.

[31] PS operations modify temperatures in the basins by three different processes. First, due to the exchange of large volumes of water, temperature differences between the intake/outlet depths in the two basins are largely removed. Second, the alterations of temperatures at the intake depths can affect density stratification, mixing processes and therefore vertical temperature profiles in the basins. Third, temperature in both basins is increased due to the heat added by frictional losses during turbining and pumping. In the model, a turbine/pump efficiency of 90% each is assumed (Table 1) [*Gorban et al.*, 2001].

5.2. Particle Mass Concentrations: Overview

[32] Because of the high concentrations of suspended particles in the inflows (Figures 4c and 4d), PMCs are much higher in the upper reservoir than in the lower lake. Particle-rich inflows tend to stratify near the bottom of the upper reservoir. Without PS, the water residence in the reservoir allows PMCs to increase strongly after snowmelt and to decrease afterward, due to the inflow of clearer water and the sedimentation of particles from the water column. PS operations will connect the two basins and as a consequence decrease water residence time, especially in the smaller upper reservoir. This will imply a lower sedimentation in the upper reservoir and an inflow of clearer water from the lower lake. Conversely, the lower lake will experience massive additional particle inputs from the upper reservoir at the inlet depth. Due to turbulent mixing, some of these particles will be entrained into the surface layer of the lower lake (Table 5), where they will reduce light penetration and thus affect primary production (Table 6).

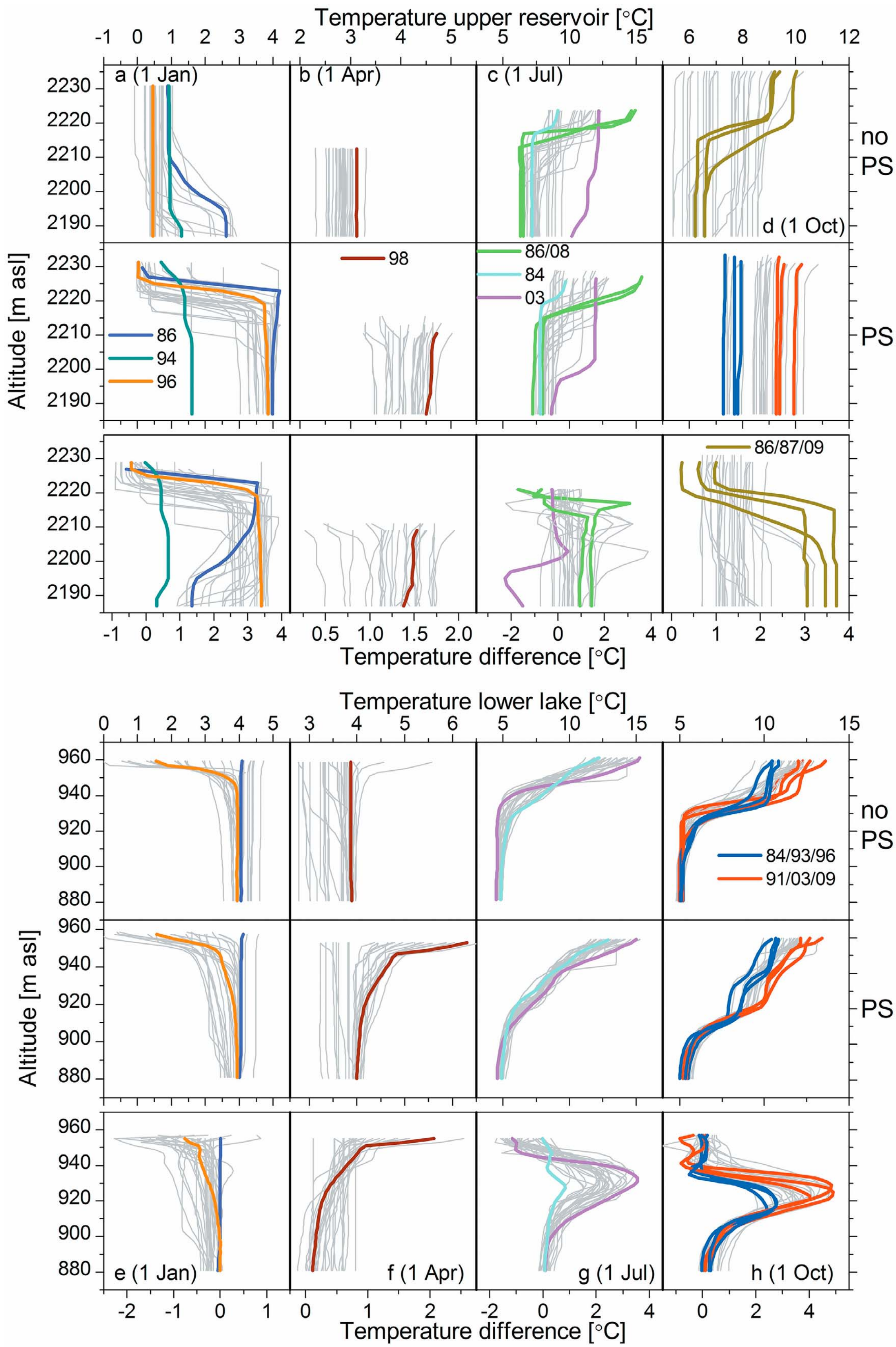
5.3. Seasonal Development and Impacts of Meteorological Conditions

[33] In the following, we evaluate the impacts of PS on temperature and PMC in the two basins in the course of the year based on vertical profiles simulated for the average hydrological year 1988 and 27 years (1982–1996, and 1998–2009) of meteorological forcing (Figures 7 and 9), and use specific years to exemplify the impacts of meteorological conditions. It should be noted that differences between the simulations with and without PS in the surface layer, especially of the upper reservoir, should be interpreted with care, as temperatures and PMCs at the same elevation are compared and the surface elevation might be different in the two scenarios.

5.3.1. Early Winter (January)

[34] *Temperature.* In January, the ice-covered upper reservoir (Figure 7a) is typically almost completely mixed without PS, exhibiting temperatures around 1°C, as exemplified by the year 1996. The lower lake (Figure 7e) is inversely stratified, with hypolimnetic temperatures near the temperature of maximum density of 4°C. With PS, the hypolimnion of the upper reservoir is flushed with water from the lower lake and thus warmed to almost 4°C. The additional heat input delays the simulated freezing date of the upper reservoir on average by 40 days from the second half of November to the beginning of January. However, for average January conditions and a surface temperature of 0°C, the heat flux out of the reservoir, calculated using the method of *Livingstone and Imboden* [1989], is on the order of 150 W m^{-2}. With an average PS water exchange of 25 $m^3\ s^{-1}$ and a typical reservoir surface area of 1 km^2 at this time of the year, the temperature difference between the pumped and the turbined water would have to be at least 1°C in order to compensate for this heat flux. This is not the case, as the temperatures at the inlet/outlet depths are converging due to PS. The reservoir therefore becomes inversely stratified, and ice formation occurs also with PS. Consequently, near-surface temperatures in the upper reservoir are generally near 0°C with and without PS, whereas PS increases hypolimnetic temperatures by ~3°C. Conversely, the upper hypolimnion of the lower lake is cooled down by the exchange with the water from the upper reservoir, supporting a slightly earlier formation of an inverse stratification. On 1 January, the lower lake is inversely stratified in 21 out of 27 years, compared to 16 years without PS. Most of the cooling induced by the inflow of cold

Figure 7. Simulated temperature profiles at the locations specified in Figure 3 without PS, with PS and the difference between the two for the hydrological year 1988 and for 27 years of meteorological data (1982 to 2009, except 1997): (a) 1 January, (b) 1 April, (c) 1 July and (d) 1 October for the upper reservoir and (e–h) on the same dates for the lower lake. Colored lines indicate profiles for specific meteorological years that are discussed in the text; gray lines indicate all other meteorological years, showing the range of variation.



Temperature upper reservoir [°C]
a (1 Jan)
b (1 Apr)
c (1 Jul)
d (1 Oct)
no PS
PS
Altitude [m asl]
86
94
96
98
86/08
84
03
86/87/09
Temperature difference [°C]
Temperature lower lake [°C]
84/93/96
91/03/09
e (1 Jan)
f (1 Apr)
g (1 Jul)
h (1 Oct)

Figure 7

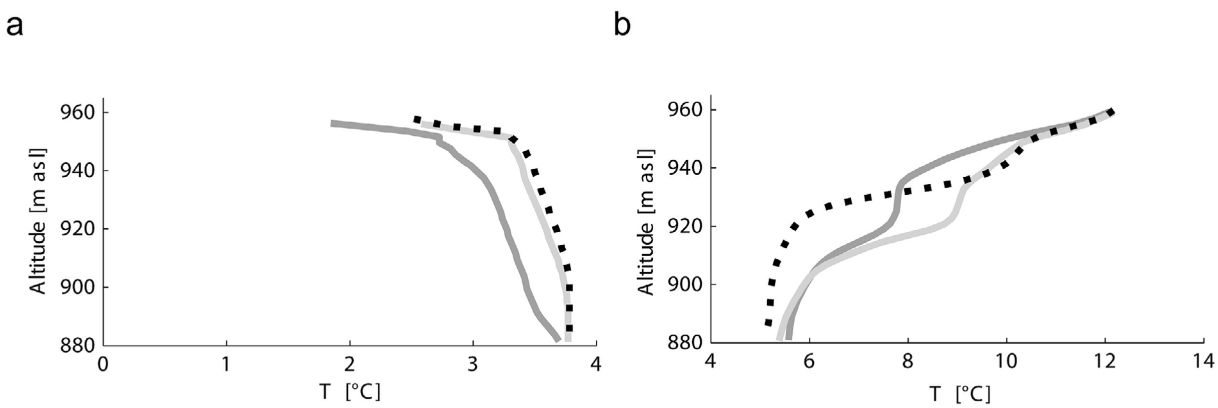


Figure 8. Temperature profiles based on hydrology and meteorology of 1988 on (a) 1 February and (b) 1 October in the lower lake at the location specified in Figure 3 simulated with (light gray) and without (dark gray) the heat input due to the friction in the penstocks and the hydraulic machines. For comparison, simulated temperature without PS (dotted black).

water from the upper reservoir during winter is, however, balanced by the heating due to friction in the pumps and turbines, as shown by a comparison of two simulations with and without the heat input due to friction (Figure 8a).

[35] In some winters, mixing of the upper reservoir is incomplete without PS, with bottom temperatures of up to 3°C, as exemplified by the 1986 profile (wind speed in October and November 1985 only 2.8 m s^{-1} compared to the average for all years of 4.5 m s^{-1}). Consequently, the PS-induced warming of the hypolimnion is below average in these winters. A special case is the year 1994, when a strong wind event on 1 January led to mixing of the whole reservoir at 2°C in the PS scenario and consequently the difference to the state without PS was small. However, this was a transient situation, and a few days later, the hypolimnion was filled again with 4°C water from the lower lake.

[36] *Particle mass concentrations.* During winter, simulated PMCs in both basins continuously decrease, as particles are settling while the discharge and PMCs of the inflows are low (Figure 4). In January, without PS, PMC in the upper reservoir (Figure 9a) ranges between 5 and 10 mg L^{-1}. Depending on the stratification particles are either vertically homogeneously distributed (1996), or increase with depth (1986 and 1994). In the lower lake (Figure 9e), PMCs are around 2.5 mg L^{-1} with little vertical variation. With PS, PMCs are almost homogeneously distributed in both lakes, with concentrations near 4 mg L^{-1}.

5.3.2. Late Winter (April)

[37] *Temperature*. On 1 April, the upper reservoir (Figure 7b) is still ice covered without PS, but solar radiation penetrating through the ice cover has warmed the water up to 2.5 to 3.0°C. At the same time, the lower lake (Figure 7f) is in transition between inverse winter stratification and summer stratification. With PS, the model predicts usually thawing of the upper reservoir at around this time due to an increase in water temperature by ~1°C compared to the situation without PS. However, it should be noted that the ice model has not been calibrated due to lack of data and seems to significantly underpredict ice cover duration in spring. The permanent input of heat due to friction has warmed up the hypolimnion of the lower lake by a few tenths of a degree compared to the situation without PS, despite the exchange with the colder upper reservoir. As a consequence, PS supports an earlier build-up of summer stratification in the lower lake, on average by ~15 days for all simulated cases (Table 4). On 1 April, first signs of summer stratification are simulated in only 2 out of 27 years without PS (while five other years still show winter stratification). With PS, summer stratification has started to develop already in 14 out of 27 years. These processes are exemplified by the year 1998 when solar radiation in February and March was strongest and the simulated ice cover on Lago Bianco already disappeared on 4 April without PS.

[38] *Particle mass concentrations.* Until 1 April, particle settling has further decreased PMCs in both basins (Figures 9b and 9f) to values of 2.5 to 4.0 mg L^{-1} in the upper reservoir and 1.5 to 2.0 mg L^{-1} in the lower lake. During winter stratification (e.g., 1982), PMC in the lower lake can decrease to 1 mg L^{-1} in the surface layer, but remains above 2 mg L^{-1} in the hypolimnion. With PS, PMCs are typically decreased by 0.5 mg L^{-1} in the upper reservoir, and increased by 0.5 to 0.8 mg L^{-1} in the lower lake. PMC can be increased by more than 1 mg L^{-1} in the surface layer in years where spring mixing – entraining particles from the hypolimnion – has already occurred with PS but not without PS (e.g., 1982).

5.3.3. Early Summer (July)

[39] *Temperature*. On 1 July, summer stratification in the lower lake (Figure 7g) is fully developed, with surface temperatures of 12 to 16°C and hypolimnion temperatures of 4.0 to 4.5°C. Stratification in the upper reservoir (Figure 7c) is comparably weaker, with surface temperatures between 9 and 12°C and hypolimnion temperatures around 7°C, but the variability is larger. In summers with weak wind forcing during the month of June (1986, 2.0 m s^{-1}, 2008; 2.1 m s^{-1}, compared to an average of 4.1 m s^{-1}), stratification is stronger and the hypolimnion remains colder, while the opposite is the case in summers with strong winds (2003, average wind in May and June 5.2 m s^{-1}, combined with warm air temperatures). PS generally leads to an accumulation of heat in the hypolimnia of both basins. In the upper reservoir, the temperature of the whole hypolimnion is increased by ~1°C, except for years when the hypolimnion is naturally warm and the cooling by the input of hypolimnetic water from the lower lake exceeds the warming due to friction (such as 2003). In the lower lake, heat accumulates mainly in a layer between 920 and 940 m asl. In this layer,

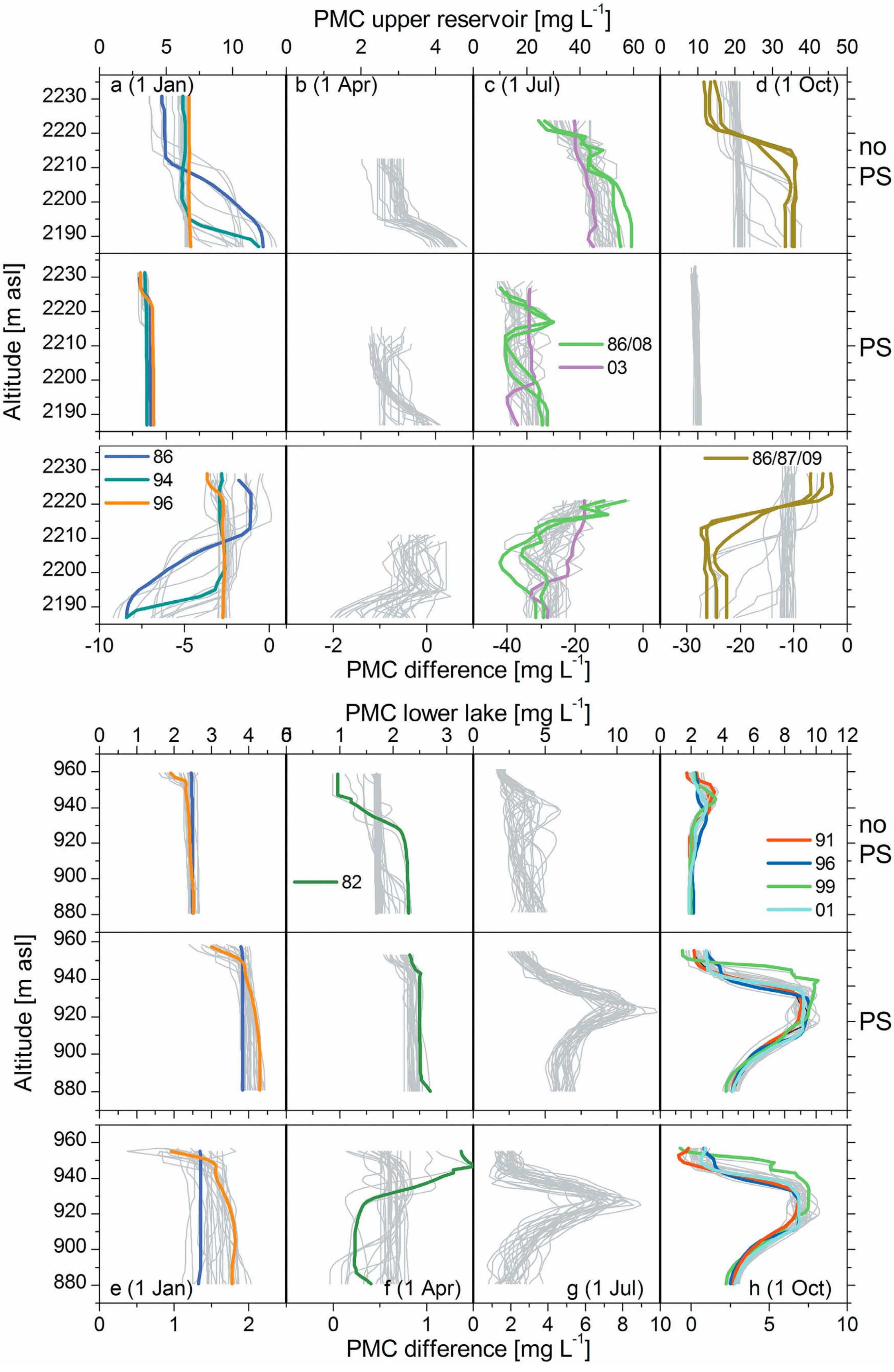

PMC upper reservoir [mg L-1]
a (1 Jan)
b (1 Apr)
c (1 Jul)
d (1 Oct)
no PS
PS
Altitude [m asl]
86/08
03
86
94
96
86/87/09
PMC difference [mg L-1]
PMC lower lake [mg L-1]
82
91
96
99
01
e (1 Jan)
f (1 Apr)
g (1 Jul)
h (1 Oct)

Figure 9

Table 4. Impact of Pumped Storage on Timing and Duration of Stratification in the Lower Lake for the Four Different Hydrological Years (Average and Standard Deviation of the Simulation Results for the 27 Meteorological Years 1982–1996 and 1998–2009)

	1988	2001	2005	2007
Without pumped storage				
Onset of summer stratification[a] (day of year)	107 ± 7	120 ± 30	107 ± 7	102 ± 9
End of summer stratification[b] (day of year)	307 ± 7	300 ± 13	312 ± 8	311 ± 6
Duration of summer stratification (days)	200 ± 10	180 ± 37	205 ± 10	209 ± 12
Date of complete mixing (day of year) [c]	333 ± 6	319 ± 4	349 ± 9	345 ± 7
With pumped storage				
Onset of summer stratification[a] (day of year)	91 ± 12	98 ± 22	94 ± 12	91 ± 12
End of summer stratification[b] (day of year)	299 ± 15	307 ± 15	314 ± 8	317 ± 8
Duration of summer stratification (days)	208 ± 19	209 ± 27	220 ± 14	226 ± 15
Date of complete mixing[c] (day of year)	327 ± 5	318 ± 4	336 ± 6	333 ± 6

[a]The onset of summer stratification is defined here as the last day in spring when the temperature difference between the second grid cell from the top and the bottom grid cell is smaller than 0.2°C.

[b]The end of summer stratification is defined here as the first day in autumn when the temperature difference between the second grid cell from the top the grid cell at 30 m depth is smaller than 0.2°C.

[c]The date of complete mixing is defined here as the first day in autumn when the temperature difference between the second grid cell from the top and the bottom grid cell is smaller than 0.2°C.

maximum temperature differences range for most summers between 1.5 and 3.0°C. Interestingly, the simulated temperature variability in this depth range is larger without than with PS, and consequently the maximum temperature difference is mainly determined by the temperature in the scenario without PS. The largest difference of 3.6°C was simulated for the summer 2003 (Figure 7g) when unusually warm conditions in combination with strong winds resulted in a large heat input to the upper reservoir (Figure 7c) that was transferred by PS to the lower lake.

[40] In contrast, the lowest temperature difference of 0.8°C in the lower lake was simulated for the year 1984 (Figure 7g), when strong wind in combination with relatively weak stratification produced a mixing event in the lower lake on 11/12 June that warmed the upper hypolimnion significantly. At the same time, cool weather in May and June kept the hypolimnion temperature in the upper reservoir at a low level (Figure 7c), and the warming of the lower lake by the water exchange was comparably weak.

[41] *Particle mass concentrations.* The snowmelt in spring leads to a strong increase in PMC in the upper reservoir to values around 40 to 50 mg L^{-1} in July (Figure 9c). In the lower lake (Figure 9g), PMCs are highly dynamic, as the distribution of particles introduced by the river depends on currents in the lake and thus on wind conditions. Background PMCs are around 3 mg L^{-1}, while peak PMCs from recent inflows reach up to 5 or 6 mg L^{-1} but vary on a daily basis. With PS, particles are transferred from the upper reservoir to the lower lake where they accumulate near the inlet depth. PMCs in the upper reservoir are reduced to 15 to 25 mg L^{-1}. In the lower lake, PMCs reach maximum values of 9 to 11 mg L^{-1} at 930 m asl, and increase by a factor of ~3 compared to background conditions. In the surface layer, PMCs increase by ~2 mg L^{-1}. Simulated PMCs vary on a daily basis within the range depicted by the profiles in Figure 9g.

5.3.4. Autumn (October)

[42] *Temperature*. The accumulation of heat in the upper part of the hypolimnion of the lower lake (Figure 7h) continues throughout the stratified period, and its extent depends largely on air temperature (R^2 for the correlation between average air temperature in July to September and maximum temperature difference between the two scenarios is 0.45). This is exemplified by the three summers with highest (1991, 2003, and 2009) and lowest (1984, 1993, and 1996) average air temperature in July to September, and has two reasons: first, the heat input from the atmosphere via the water in the upper reservoir to the lower lake is higher in warm years, and second, the heat input to the upper hypolimnion of the lower lake without PS is lower in warm summers with strong stratification and a shallow mixed surface layer. Almost half of the total warming in October is due to the heat input from friction in the pumps and turbines (Figure 8b).

[43] In the upper reservoir without PS (Figure 7d), the water column is already mixed in some years and still stratified in others on 1 October. The dark yellow profiles in Figure 7d show 3 years (1986, 1987, and 2009) with wind speeds in September below 3 m s^{-1}, and average air temperatures above 6.5°C, when stratification still persisted on 1 October. With PS, the upper reservoir is mixed on this date for all years considered.

[44] *Particle mass concentrations.* During the summer, PMC starts to decrease again in the upper reservoir, reaching average values of ~20 mg L^{-1} on 1 October (Figure 9d). Depending on the stratification (Figure 7d), the particles are either evenly distributed, or PMC in the hypolimnion is in the range of up to 35 mg L^{-1}, while surface PMCs range between 10 and 20 mg L^{-1}. In the lower lake (Figure 9h),

Figure 9. Simulated PMC profiles at the locations specified in Figure 3 without PS, with PS and the difference between the two for the hydrological year 1988 and for 27 years of meteorological data (1982 to 2009, except 1997): (a) 1 January, (b) 1 April, (c) 1 July and (d) 1 October for the upper reservoir and (e–h) on the same dates for the lower lake. Colored lines indicate profiles for specific meteorological years that are discussed in the text; gray lines indicate all other meteorological years, showing the range of variation.

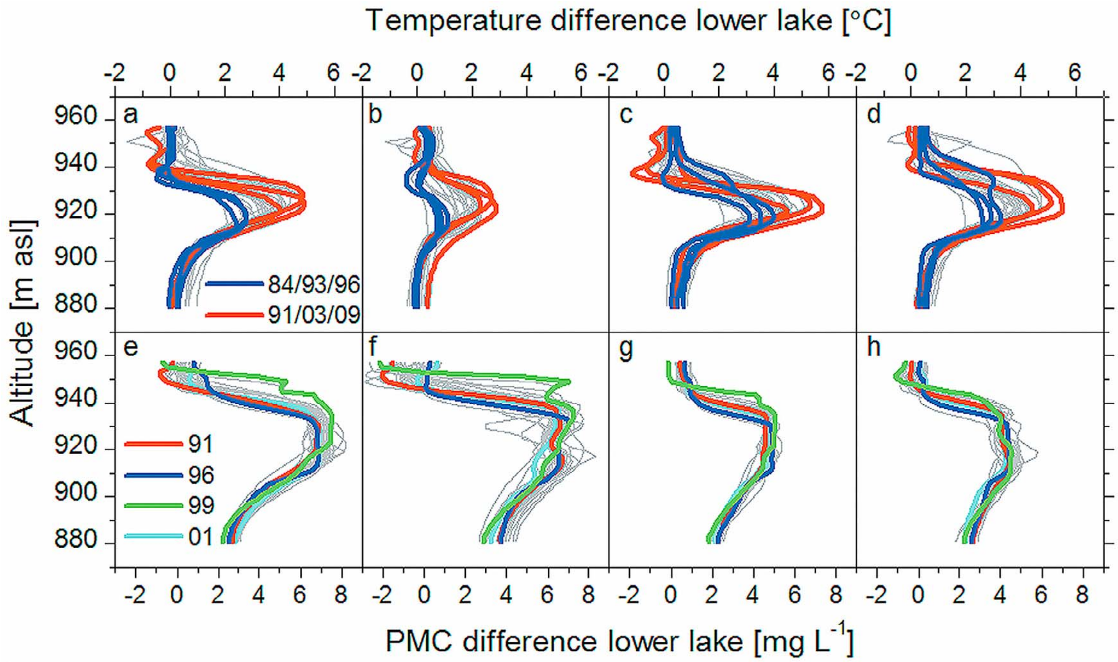


Figure 10. Differences in temperature (Figures 10a–10d) and PMC (Figures 10e–10h) between the simulations with and without PS at the locations specified in Figure 3 for the four hydrological years (a and e) 1988, (b and f) 2001, (c and g) 2005 and (d and h) 2007 on 1 October in the lower lake, for meteorological forcing from 27 different years (1982 to 2009, except 1997). The colored profiles mark special meteorological years discussed in the text; the gray profiles indicate the other years to show the full variability of the data set.

PMC is typically ~2 mg L^{-1} and slightly elevated (~3 mg L^{-1}) in the metalimnion. With PS, PMC in the upper reservoir is reduced by half to 10 mg L^{-1}, and homogeneously distributed, as the reservoir is already completely mixed. In the lower lake, particles accumulate near and below the inlet depth, and PMCs reach maxima of 8 to 10 mg L^{-1} in a 20 m thick layer between 915 and 935 m asl. The transfer of particles from this layer to the surface layer is inhibited by stratification. PS therefore increases PMC in the surface layer only by 0 to 1 mg L^{-1}. Occasionally PMC in the surface layer is even slightly lower than without PS, because the amount of particles introduced by the river to the surface layer is reduced by the PS system. The increase of PMC in the surface layer is enhanced by strong wind (2001) or cold temperatures (1996) in the previous months, which both promote entrainment of particles to the surface layer by mixing, and conversely diminished by weak winds (1999) and high air temperatures (1991) which reduce vertical entrainment.

5.4. Effect of Pumped-Storage Operations for Variable Hydrology

[45] The effects of PS operations on lake temperatures depend not only on meteorological but also on hydrological conditions. During rainy years, the higher inflow from the tributaries contrasts and attenuates the impact of PS operation on the lake. Conversely, the largest impacts on water temperatures in the two basins are predicted for dry years.

[46] The accumulation of heat during summer in the upper hypolimnion of the lower lake is highest for the dry years 2005 and 2007 (Figures 10c and 10d), when maximum temperature differences range between 2.5 and 5.5°C. For the average year 1988 (Figure 10a), maximum temperature differences are about 0.5°C lower; for the wet year 2001 (Figure 10b), they range between 0.5 and 3.0°C. For all considered hydrologies, the effect of summer air temperatures on the maximum temperature difference on 1 October discussed in section 5.3.4 is obvious. Temperature differences in the upper reservoir are less sensitive to hydrological conditions (data not shown).

[47] PMC decreases in the upper reservoir due to PS operations for all hydrological conditions (Figures 11a, 11b, 11c, and 11d). Summer volume-averaged PMC differences tend to be similarly high at 30 to 40 mg L^{-1} in the wet year 2001 and the dry year 2005 and lowest at ~10 mg L^{-1} in the dry year 2007. The low value for 2007 is partly due to dilution, as the reservoir level is significantly higher for the scenario without PS than for the PS scenario, and the inflowing particles are thus distributed over a larger volume. Relatively speaking, the impact is highest for the dry year 2005 where summer PMCs are reduced to a third, compared to half in the wet year 2001.

[48] The lower lake shows an increase in the whole water column (Figures 11e, 11f, 11g, and 11h), inclusive the surface layer, where low turbidity generally favors primary production (Table 5 and Figures 8a, 8b, 8c, and 8d). The PMC difference is quantitatively higher for the wet and the average year (Figures 11a and 11b), but even more than for the upper reservoir, the relative difference is much lower for the wet year 2001. PMCs in the lower lake in this year are largely dominated by the direct, highly dynamic and inhomogeneous turbid inflows from River Poschiavino, while the additional contribution of particles from the upper reservoir is comparatively small. Therefore individual

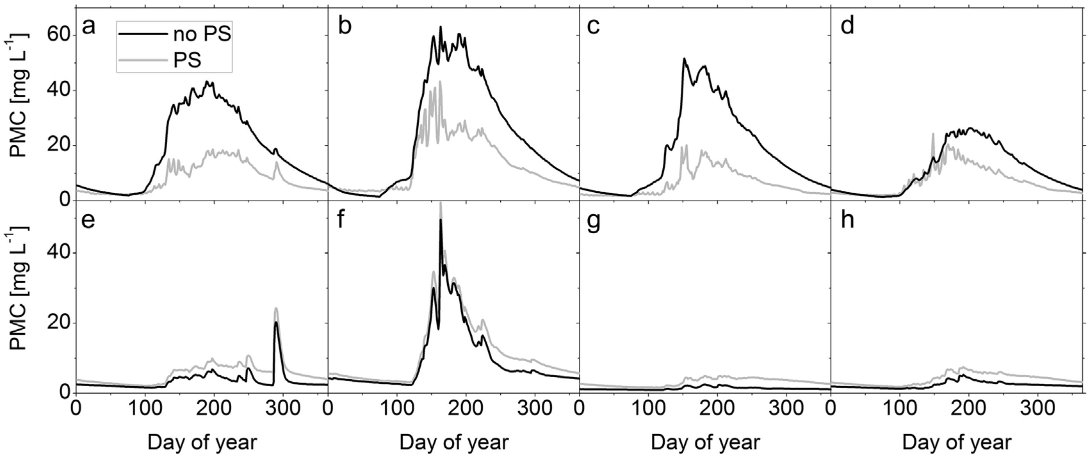


Figure 11. Simulated volume-averaged PMC in the two basins (upper reservoir, Figures 11a–11d; lower lake, Figures 11e–11h) for the hydrological and meteorological years (a and e) 1988, (b and f) 2001, (c and g) 2005 and (d and h) 2007, with and without PS operations.

concentration profiles can be strongly modified by slight changes in stratification and horizontal mixing patterns invoked by the PS operations (Figure 8f). Nevertheless, the increase in PMC in the surface layer due to PS is still higher under windy and cool conditions, as shown above for the average year 1988 (Figure 9h).

5.5. Effect of Variable Inlet/Outlet Depths

[49] With the goal to mitigate the effect of PS operation on lake temperatures, we modified the inlet/outlet depth of the penstock in the lower lake. The two alternative inlet/outlet depths were simulated at 920 and 900 m asl, respectively, i.e., 10 and 30 m deeper as the originally planned location (Figure 3). In May and October, the lower lake exhibits mostly higher temperatures with PS than without (Figures 12a and 12b). However, depending on the depth of the penstock inlet/outlet, the temperature profile changes: the deeper the inlet/outlet is located, the larger is the volume that is significantly affected, as the warming affects mainly the volume between the inlet/outlet and the thermocline. The simulation based on the original inlet/outlet depth shows the highest temperature increase at 930 m asl but only a slight increase in the bottom water. The inlet/outlet at 920 m asl distributes the temperature increase to the whole water column below the thermocline and this effect is enhanced with the inlet/outlet situated at 900 m asl, for which the bottom temperature increases to 8°C in October (Figure 12b). In autumn, the differences between the three simulations are most pronounced, except for the surface layer, which is not significantly affected by the PS operations (Figure 12b).

[50] The PMC distribution is modified by the inlet/outlet depth in a similar way (Figures 12c and 12d). In spring, the maximum PMC difference is located at the inlet/outlet depth (Figure 12c). Especially with the inlet/outlet at 930 m asl and 920 m asl PMC also increases significantly in the surface water. A similar feature is visible in October (Figure 12d), when PMC difference increases with depth following the increasing depth of the inlet/outlet. In the photic zone at the surface, both deeper alternative inlet/outlet locations would imply a slightly lower PMC. In fact, in summer, in comparison to the simulations with the inlet/outlet at 930 m asl, the PS-driven PMC increase is attenuated on average by 40% (inlet/outlet at 920 m asl) and 60% (inlet/outlet at 900 m asl), respectively [*Bonalumi and Schmid*, 2011].

Table 5. PMC in the Surface Layer of the Lower Lake (Average of Top 10 m) for Four Simulated Years With and Without PS Operations and Percentage Difference[a]

	1998			2001			2005			2007		
	Without PS (mg L^{-1})	With PS (mg L^{-1})	Diff (%)	Without PS (mg L^{-1})	With PS (mg L^{-1})	Diff (%)	Without PS (mg L^{-1})	With PS (mg L^{-1})	Diff (%)	Without PS (mg L^{-1})	With PS (mg L^{-1})	Diff (%)
January	2.53	3.81	51	4.26	5.52	30	1.06	2.37	124	1.94	3.07	58
February	1.99	2.75	38	3.66	3.96	8	1.03	2.02	96	1.62	2.39	48
March	1.96	2.56	31	3.04	3.68	21	1.29	1.49	16	1.31	2.01	53
April	1.69	2.20	30	2.61	3.20	23	0.98	1.73	77	1.27	1.65	30
May	1.27	1.69	33	2.18	2.55	17	0.89	1.49	67	0.90	1.15	28
June	2.84	3.36	18	13.7	23.0	68	1.28	1.35	5	1.46	1.42	−3
July	1.83	3.03	66	13.7	18.6	36	1.81	2.37	31	3.08	2.6	−16
August	2.72	3.56	31	5.95	7.84	32	1.58	2.26	43	3.32	2.91	−12
September	1.71	3.52	106	4.70	4.84	3	1.14	2.42	112	2.49	2.17	−13
October	2.27	2.44	7	3.94	4.68	19	0.96	1.44	50	2.22	1.51	−32
November	3.54	4.82	36	3.87	4.66	20	1.10	1.88	71	2.15	2.97	38
December	2.56	4.87	90	4.84	6.81	41	1.23	3.03	146	2.12	3.77	78

[a]The data were obtained by averaging the results of 27 meteorological years.

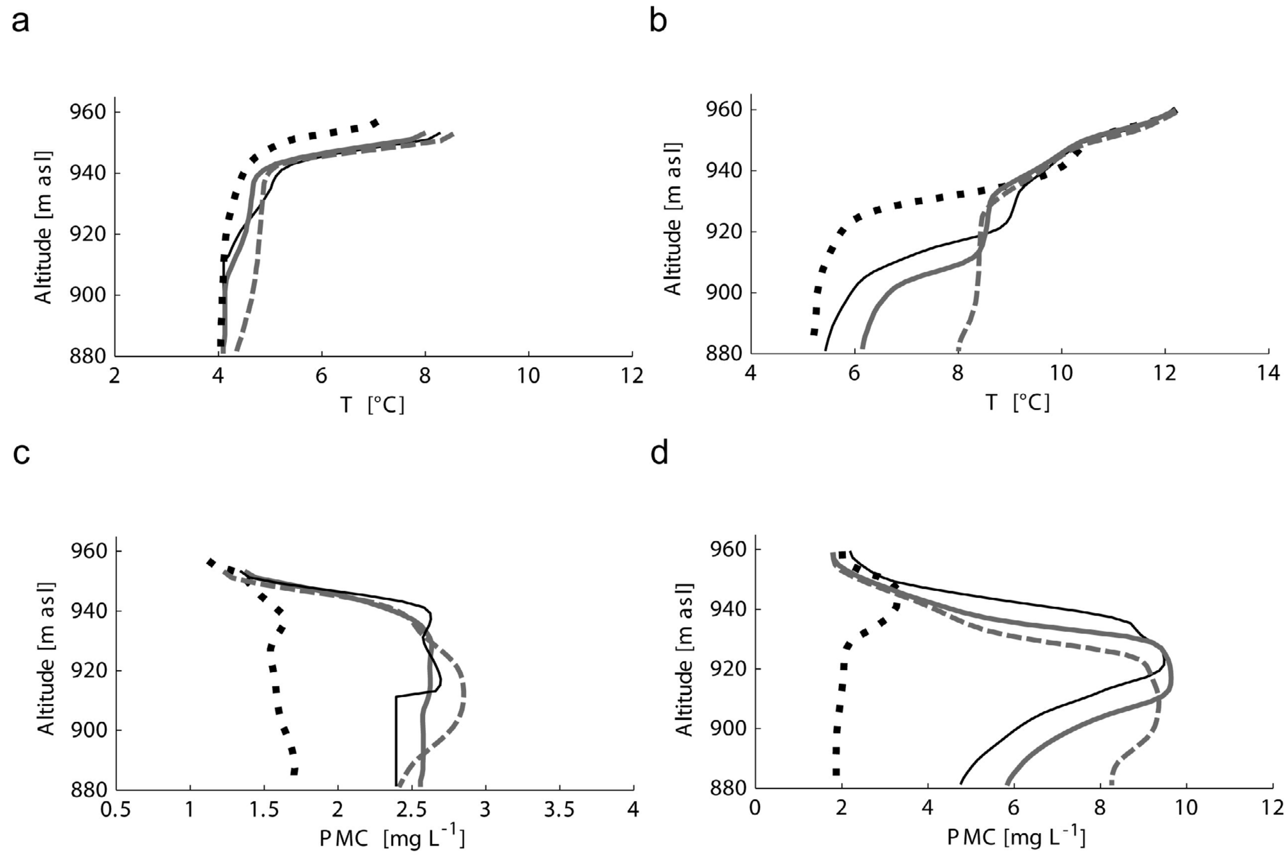


Figure 12. Temperature profiles based on hydrology of 1988 on (a) 1 May and (b) 1 October in the lower lake simulated with the planned inlet/outlet at 930 m height (black line), and the alternative altitudes 920 m (gray line) and 900 m (dashed gray); (c and d) PMC profiles for the same dates. For comparison, simulated temperature and PMC without PS (dotted black) are shown.

5.6. Ecological Implications

[51] The impacts of the PS operations, described in the previous sections, are subject of concern, especially regarding the lower lake. Due to its natural origin, management standards and impacts on the lake have to fulfill the legal regulations for lakes. The predicted changes in PMC, temperature, and stratification are undoubtedly significant compared to the natural variability. Furthermore, the PS operations lead to important lake level variations. The negative impacts of these changes on aquatic organisms and the extent to which they can be compensated for by reducing hydropeaking in the River Poschiavino need further evaluation in the course of the environmental impact assessment. In the following, we shortly discuss the potential ecological implications of the changes in PMC, temperature and stratification.

[52] The heating of the upper reservoir during the winter season will shorten the period of ice cover as well as reduce the ice thickness. Mixing of the upper reservoir will occur earlier in spring and fall, when the pumped water from the lower lake is warmer and colder than the hypolimnion temperature of the reservoir, respectively. In the lower lake, summer stratification is expected to develop about two weeks earlier, while there is no clear trend for the end of summer stratification, defined as the time when mixing reaches 30 m depth (Table 4). In summary, a prolonged and earlier summer stratification is predicted. This is on top of an increase in the duration of summer stratification that is expected to occur due to climate warming, and which has been predicted to result in an earlier onset of the spring phytoplankton bloom [*Peeters et al.*, 2007]. Such shifts in stratification can potentially disrupt interactions between different trophic levels and thus lead to significant changes in phytoplankton and/or zooplankton composition [*Winder and Schindler*, 2004]. Complete mixing of the lower lake in fall occurs on average about one week earlier, and is supported by increased hypolimnion temperatures. PS operations thus promote homogenization and oxygen supply to the hypolimnion in winter and could help to avoid a potential shift to facultative monomixis of the deep lower lake that may be induced by climate warming as has been shown for Lake Zurich [*Rempfer et al.*, 2010].

[53] PMC increase in the lower lake is due to the connection with the upper reservoir. Even if the surface is less affected than the deep water, PMC in the surface layer still increases by $\sim$1 mg L^{-1} for the average hydrological year 1988 (Table 5 and Figure 13). Consequently, light penetration into the lake will be reduced, decreasing thereby the photic zone and the space for primary production. The average euphotic depth (i.e., the depth at which light availability is 1% of that at the lake surface) was calculated for each month for all four hydrological scenarios (Table 6) based on a relationship between PMC and light absorption

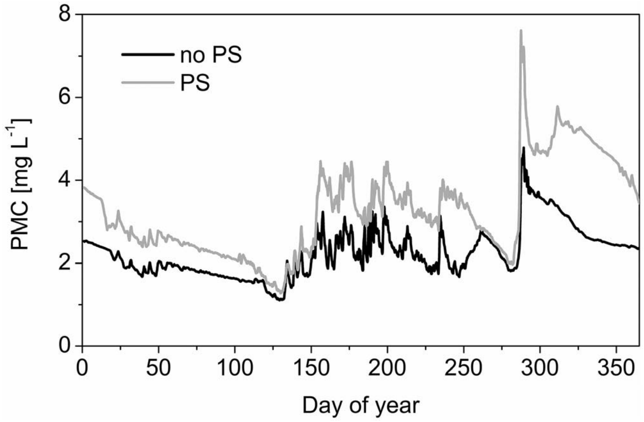


Figure 13. Simulated average PMC in the surface layer of the lower lake for the hydrological and meteorological year 1988 (daily average of simulated values at 0, 4 and 8 m depth).

derived from measurements [*Bonalumi and Schmid*, 2011]. For most months and hydrological scenarios, a decrease of the euphotic depth by 10 to 20% was predicted. The increased turbidity in the lake may also negatively affect fish that locate their prey visually, including the brown trout (*Salmo trutta*) and the Arctic char (*Salvelinus alpinus*), the two important species for recreational fisheries in the lower lake. However, as the simulations for the hydrological year 2007 show, if conditions are calm and entrainment of particles to the surface layer is reduced, light availability in the surface layer can even be increased by PS operations during summer months, as the direct riverine input of particles is reduced.

[54] The mitigation measures in the lower lake, that is lowering the inlet/outlet position, were thought to diminish the temperature and PMC modifications, especially in the lower lake. However, as shown above, shifting the inlet/outlet will mainly result in a different vertical distribution of PMC and temperature. A deeper inlet/outlet will diminish the PMC increase in the surface layer of the lower lake and therefore reduce the impact on light availability, primary production and visibility. However, a deepening of the penstock will strongly modify the pattern of thermal stratification causing temperatures of up to 8°C in the deep waters, which is unnatural for lakes in the Swiss Alps. The overall changes in the temperature stratification compared to the natural state of the lake are thus larger than with a shallower inlet. This trade-off between impacts on surface turbidity and deep-water temperatures needs to be evaluated in detail for an optimal choice of the inlet depth.

6. Conclusions

[55] The effects of PS operations on temperature, stratification and turbidity in two basins have been investigated by simulating a coupled system where water is exchanged between a reservoir (upstream) and a natural lake (downstream) located at different altitudes (hydraulic head ~1300 m) and with different characteristics regarding depth, volume and turbidity. Simulations were performed with a coupled two-dimensional model using the software CE-QUAL-W2. Even though the results from this study are site-specific, similar conditions occur and similar processes need to be considered also at other PS systems.

[56] Particle concentrations in the two basins are mainly affected by the reduction of the residence times in the upper reservoir and the large exchange of water masses between the turbid upper reservoir and the much clearer lower natural lake. PMC in the upper reservoir is reduced by at least a factor of two, while particles accumulate during summer in a layer beneath the metalimnion in the lower lake, creating a turbid layer at this depth. The density gradient between this layer and the epilimnion constrains the transport of particles to the surface layer, but nevertheless PMC also increases to some extent in the surface layer. The euphotic depth during summer is reduced, affecting negatively primary production and visibility.

[57] Temperatures are influenced not only by the exchange of water masses, but also by the more intense connection of the deep water to the atmosphere when residing in the shallower upper reservoir. During the stratified period, cold deep water from the lower lake is brought to the upper reservoir, where it is heated up before being transferred back to the lower lake. Heat thus accumulates in the same layer below the metalimnion as the particles, where differences to the state without PS reach several °C toward the end of summer. In the upper reservoir, PS operations cause heating in all

Table 6. Euphotic Depth in the Lower Lake for Four Simulated Years With and Without PS Operations and Percentage Difference[a]

	1998			2001			2005			2007		
	Without PS (m)	With PS (m)	Diff (%)	Without PS (m)	With PS (m)	Diff (%)	Without PS (m)	With PS (m)	Diff (%)	Without PS (m)	With PS (m)	Diff (%)
January	10.6	8.3	−22	7.7	6.4	−17	15.6	11.0	−30	12.1	9.5	−22
February	12.0	10.1	−16	8.5	8.1	−5	15.7	11.9	−24	13.2	10.9	−17
March	12.1	10.5	−13	9.5	8.5	−11	14.5	13.7	−6	14.4	11.9	−17
April	13.0	11.4	−12	10.4	9.2	−11	16.0	12.8	−20	14.6	13.1	−10
May	14.6	13.0	−11	11.5	10.5	−8	16.5	13.7	−17	16.4	15.1	−8
June	9.9	9.0	−10	3.1	1.9	−37	14.5	14.2	−2	13.8	14.0	1
July	12.5	9.5	−24	3.1	2.4	−24	12.6	11.0	−13	9.5	10.4	10
August	10.2	8.6	−15	6.1	4.9	−19	13.3	11.2	−16	9.0	9.8	8
September	12.9	8.7	−32	7.2	7.0	−2	15.2	10.8	−29	10.7	11.5	8
October	11.2	10.8	−4	8.1	7.2	−11	16.1	13.9	−14	11.3	13.6	20
November	8.7	7.1	−19	8.2	7.2	−12	15.4	12.3	−20	11.5	9.7	−16
December	10.5	7.0	−33	7.0	5.5	−22	14.8	9.5	−35	11.6	8.3	−28

[a]The data were calculated from the PMCs in Table 5 from a relationship between PMC and light attenuation, and averaged over 27 meteorological years.

seasons, as well as a significant reduction of the ice cover duration.

[58] Unavoidable frictional losses in the PS system significantly increase the heating of the two basins. Toward the end of summer, when the temperature increase near the inlet depth in the lower lake is at its highest, almost 50% of the temperature increase in the lower lake is due to the frictional energy dissipation in the penstocks and hydraulic machines. This observation underlines the necessity of taking into account the heating by frictional heat losses in the evaluation of the impact of PS systems with a high hydraulic head.

[59] Furthermore, PS operations are predicted to prolong summer stratification in the lower lake by approximately two weeks, mainly by supporting an earlier onset of stratification in spring. They may thus amplify trends that are expected to occur due to climate warming, and alter the boundary conditions for phytoplankton growth and trophic interactions.

[60] The proposed mitigation measure of deepening the inlet in the lower lake has ambiguous effects: While the impacts on PMC in the surface layer can be successfully reduced, a larger part of the water column of the lake is affected by temperature increases of several °C toward the end of the stratified period.

[61] The complex interactions between meteorological and hydrological forcing and the impacts of the PS operations were analyzed by simulating the difference between the scenarios with and without the PS system for 27 years of local meteorological conditions in combination with four real and distinctly different hydrological years. The results show that meteorological conditions, in particular atmospheric temperature, can attenuate or intensify the effect of PS operations. In our case study, warm summer temperatures increase the heating effect on the lower lake, due to the more efficient heat exchange of the upper reservoir with the atmosphere. Hydrology affects both temperature and PMC of both basins. Higher inflows by the tributaries in wet years can to some extent conceal the effect of PS operation on the lake physical properties. Therefore the highest relative changes in temperature and PMC profiles occur in dry years. In summary, the impacts of the PS operations on the lower lake are strongest in dry and warm summers, indicating that the impacts of the PS system may be enhanced by future climate change, which is expected to increase the frequency of warm and dry summers in the Southern Alps [*Center for Climate Systems Modeling*, 2011]. These results highlight the importance of covering the full variability of boundary conditions in the environmental impact assessment of PS systems.

[62] **Acknowledgments.** We acknowledge the companies ecowert gmbh, Repower AG, as well as Limnex AG and especially Jakob Grünenfelder, Roberto Ferrari, Daniele Pandocchi and Urs Vogel for providing input data used for the simulations and for the excellent and constructive collaboration.

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