On the role of lake level management in modulating climate change impacts on perialpine lakes

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Abstract

Study region

Four perialpine lakes in Switzerland, with different levels of lake level management.

Study focus

Alpine regions are particularly sensitive to climate change due to the pronounced effect on snow and glacial melt. In this context, large perialpine lakes play a crucial role in modulating climate change impacts on water resources, which brings together diverse interests. However, climate change studies on river systems rarely include lakes or lake level management. An open question is how to incorporate lake level management effects into hydrologic simulations to project climate change impacts. We combine the hydrologic model PREVAH with the hydrodynamic model MIKE11 to simulate lake level and outflow scenarios from 1981 to 2099, using the Swiss climate change scenarios CH2018.

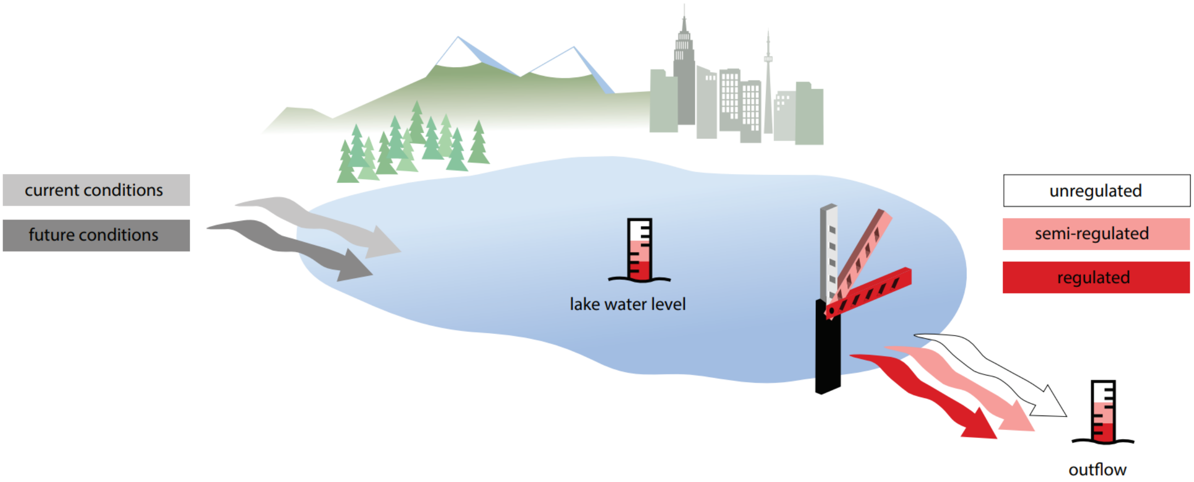
New hydrological insights for the region

The hydrological projections at the end of the century show pronounced seasonal changes in lake levels, characterised by an increase in winter and a decrease in summer when water demand is highest. Without climate mitigation measures, this summer decrease ranges from -0.04 m for a regulated lake to -0.4 m for an unregulated lake. In addition, the simulations indicate more frequent drought events. The projected changes intensify with time and missing climate mitigation measures. Future work could focus on interannual variability to explore regulatory strategies under changing conditions.

keywords: Lake level regulation, climate change, impact assessment, hydrologic & hydrodynamic modeling, perialpine lakes

Highlights

- Simulating lake level regulation by combining a hydrologic and a hydrodynamic model
- Climate change leads to lower summer lake levels but minor changes in other seasons
- The occurrence of low-level days can shift from winter drought to summer drought
- For the studied lakes, lake management affects lake levels stronger than outflows
- Climate change impacts on lakes intensify with time and missing climate mitigation



1 Introduction

In the Alpine region, natural and artificial lakes are essential elements of the water cycle, e.g., in terms of habitat, water retention and release, nutrient cycling or flood retention. Their hydrologic and limnologic regime is highly likely to be impacted by climate change in most world regions due to modifications in water input (streamflow) and output (evaporation; Zajac et al., 2017; Fan et al., 2020), but also due to alterations of chemical and physical conditions related to climate warming (Fink et al., 2016; Woolway et al., 2020) and CO_2 concentrations in the atmosphere (Perga et al., 2016). Most climate change impact studies on lakes focus on limnologic aspects, i.e., how climate warming modifies temperature (O'Reilly et al., 2015), mixing regimes (Råman Vinnå et al., 2021) or nutrient cycles (Moss, 2012). Some ecological studies analyse how lake level management impacts littoral habitats (Aroviita and Hamalainen, 2008; Cifoni et al., 2022). The work by Zohary and Ostrovsky (2011) discusses that the ecosystem functioning of lakes "respond(s) adversely to excessive lake level fluctuations", even for deep lakes. Large perialpine lakes, the focus of this study, are susceptible to climate change due to its pronounced effect on snow and glacier melt (Muelchi et al., 2021). Numerous water resources studies, therefore, focused on the cryosphere's role in modulating how climate change impacts streamflow (François et al., 2018; Hanus et al., 2021; Horton et al., 2022). Besides the few modelling studies that specifically target the interplay of streamflow (lake input) and lake levels (Gibson et al., 2006a; Veijalainen et al., 2010; Yu et al., 2022), the vast majority of hydrological modelling studies do not explicitly address the effect of lake level variations or management on streamflow, even for catchments including large lake systems (e.g. in the works of Bosshard et al., 2014; Jasper and Ebel, 2016; Zischg et al., 2018; Legrand et al., 2023).Despite growing anthropognic pressure on the European large perialpine lakes (Salmaso et al., 2018) and the importance of lake level variability for ecology and socio-economic activities, hydrologic analyses of lakes in terms of lake level variability are rare (e.g. Hingray et al., 2007; Veijalainen et al., 2010; Hinegk et al., 2022). This represents a critical knowledge gap, given that the lake level of many large perialpine lakes is heavily regulated to meet numerous natural resources and hazards management goals related to drinking and irrigation water supply, fishery, shipping, energy production, nature conservation, tourism and flood protection (Clites and Quinn, 2003; Hingray et al., 2007; Hinegk et al., 2022). These manifold objectives are generally implemented through lake level management rules that mitigate high and low extremes (Veijalainen et al., 2010; AWA, 2014). For perialpine lake systems which are influenced by snow and glacier melt in spring and summer, the lake level management typically consists of raising the winter levels (when there is little inflow due to snow accumulation in the catchment) and of lowering the lake levels before the melt period onset to avoid flooding (Gibson et al., 2006b; Hinegk et al., 2022; FOEN, 2023a). Additional provisions can be formulated, e.g. a recurring exceedance of a flood limit for ecological purposes or preventive lake level lowering to avoid flood events. The question of how climate change impacts the resulting lake level variability and management naturally arises: ongoing climate change alters streamflow seasonality (Addor et al., 2014; Rössler et al., 2019; Muelchi et al., 2021) and thereby affecting the seasonal water input to lakes. Additionally, evaporative losses can increase the outflow from lakes (Gibson et al., 2006b). As one of the few studies, Gibson et al. (2006b) investigate how climate and lake level management have influenced lake level variability in the Great Slave Lake (Canada) from the mid-20th century. They employ a comparison of pre-regulated and naturalised simulations to disentangle the individual impacts of these factors. Due to limited lake level observations, several studies have used satellite data to analyse anthropogenic influence on lake level variability (Cooley et al., 2021; Kostianoy et al., 2022), such as hydropower generation (Sinyukovich et al., 2024) or lake level management (Aminjafari et al., 2024). Further studies have investigated the impact of evaporation on lake levels, both in arid regions (La Fuente et al., 2022) and worldwide (Zhao et al., 2022), as this impact is projected to increase in this century.

Most conceptual hydrologic models operate on a physical basis (Paiva et al., 2011); however, the large perialpine lakes were often omitted or modeled in a simplified manner in such hydrologic studies. The high computational costs associated with hydrodynamic models can probably explain the omission of lake level management, as mentioned in several studies (Paiva et al., 2011, Hoch et al., 2017; Papadimos et al., 2022). To overcome corresponding limitations, the lake system is often considered as the control point (outlet) of the hydrologic model (e.g. Hicks et al., 1995; Dembélé et al., 2022). Other studies include the effect of large regulated lakes with a simplified reservoir approach (e.g. Hingray et al., 2007; Legrand et al., 2023). These simplified flow routing methods can adequately represent flood wave delay and attenuation but cannot handle other hydrodynamic processes, such as backwater or floodplain water retention effects (Lohmann et al., 1996; Paiva et al., 2011).

For our study, we selected four Swiss lakes with different degrees of lake level management. We combine the hydrologic model PREVAH and the hydrodynamic model MIKE11 to investigate lake level variability. Our analysis is based on a modelling framework that uses existing streamflow simulations from a catchment-scale precipitation-streamflow model (PREVAH; Viviroli et al., 2009; Speich et al., 2015) for 39 climate change modelling chains as input to a hydrodynamic model (MIKE11; DHI, 2003), for which we developed a specific methodology to account for lake level management rules. The expansion with a 1D hydrodynamic flow routing model, represented with cross-sections, can provide information on flow variables (e.g., river geometry, roughness, river stage, velocity, slope), which could be relevant for transport or diffusion processes (Cox, 2003; El kadi Abderrezzak and Paquier, 2009; Haghiabi et al., 2012; Mesman et al., 2020). Hydrodynamic models can incorporate lakes, considering stage-area relationships (Mesman et al., 2020; Papadimos et al., 2022) and built-in lake level management rules to account for the effect of lakes in the simulations (DHI, 2003). In this context of missing climate change studies on natural perialpine lake levels, we address the following research question: How does climate change impact lake level variability, and how do varying levels of lake level management modulate these impacts? Compared to previous work (Hingray et al., 2007), the focus on regulated and unregulated lakes allows for analysing climate change impacts on lake level management. To our knowledge, the present study is the first climate change impact assessment on perialpine lake level variability, analysing lakes with different degrees of lake level regulation. The national focus has the main advantage of building upon a coherent set of climate change simulations (FOEN, 2021), resulting in a modelling framework readily transferable to other perialpine lakes. The relevance of this study is threefold: (i) the large Swiss lakes are significant reservoirs at a supraregional level, with several lakes spanning across the Swiss borders (Lanz, 2021); (ii) climate-induced impacts depend on the degree of lake level management, which we can analyse here based on the selected case studies; (iii) lake level management also means an anthropogenic intervention in nature, which alters hydrologic patterns and affects the connectivity of aquatic habitats (Stanford and Hauer, 1992) and urgently needs to be studied to understand further how climate change threatens biodiversity.

2 Material and methods

2.1 General change assessment framework

The analysis framework of our study is based on comparing the current conditions of daily lake levels and outflows with future conditions under climate change. As current conditions, we define the reference period, T_{ref}: 1981 – 2010, and as future conditions, the three future periods: 2035: 2020 – 2049, 2060: 2045 – 2074, 2085: 2070 – 2099. These periods are typically used in studies with CH2018 data(NCCS, 2018). To analyse climate change impacts on different degrees of lake level management, we assume unchanged regulatory practices. The change analysis compares the simulations resulting from an ensemble of climate model chains (combinations of a Global Circulation Model and Regional Climate Model) for the reference period and for the selected future periods. The change analysis does not consider observed hydrologic variables (streamflows, lake levels) or simulations obtained with historical meteorological data. It compares climate-data-driven simulations for the reference period and for the future periods. This is a standard procedure in climate change impact analysis (Schaefli, 2015) to discount potential biases of the climate-data-driven simulations with respect to historic data.

Potential climate change impacts are further analysed in terms of simulated monthly average lake levels (averaged over the above 30-years period); direct comparison of the simulated daily lake levels (reference and future) is impossible given that they do not represent the same years.

Changes in extremes are assessed based on indicators such as the frequency of reaching the drought and flood limits.

2.2 Selected case studies

We selected four perialpine lakes in Switzerland (Figure 1) representative of different levels of lake level management: one lake is unregulated, two are fully regulated with line diagrams, and one is semi-regulated. The four selected lakes are located in pairwise nested catchments: catchment I contains the two connected lakes Walen (unregulated) and Zurich (regulated). Catchment II contains the two connected lakes Brienz (semi-regulated) and Thun (regulated). A channel connects the two lakes in catchment I and II, but the flow direction in the channel is unidirectional, due to the disparity in elevation between the two lakes. The lakes cover between 2 % and 5 % of their hydrologic catchment area (Table 1). The corresponding catchments show glacier covers between 1 % and 16 %. Catchment I, with 1 %, has a lower glacier cover than catchment II, with 9 % (Table 1). Part of the differences in lake levels and outflows between the two lake systems can be attributed to the hydrologic regime of the rivers feeding the lakes. However, both systems will continue to be fed by snow-influenced regimes in the future, resulting in high inflows during spring/early summer (FOEN, 2021; Stahl et al., 2022). Both lake systems have experienced flooding in the recent past (e.g., in the years 1999, 2005 or 2021 Hilker et al., 2009; FOEN, 2023d). The unregulated Lake Walen had very low levels during the recent 2018 drought year (Blauhut et al., 2022; FOEN, 2023d) when the level dropped down to the 97.5 % exceedance percentile. The lowest observed August and September lake levels of Lake Walen occurred in the drought year 2003. All lakes show consistently lower lake levels in winter than in summer (Figure 2). For all four lakes, the monthly lowest observed levels date back to the late 1940s and early 1950s (FOEN, 2023c), i.e., before the onset of modern lake level management (Table 1). Further details are described in the Appendix.

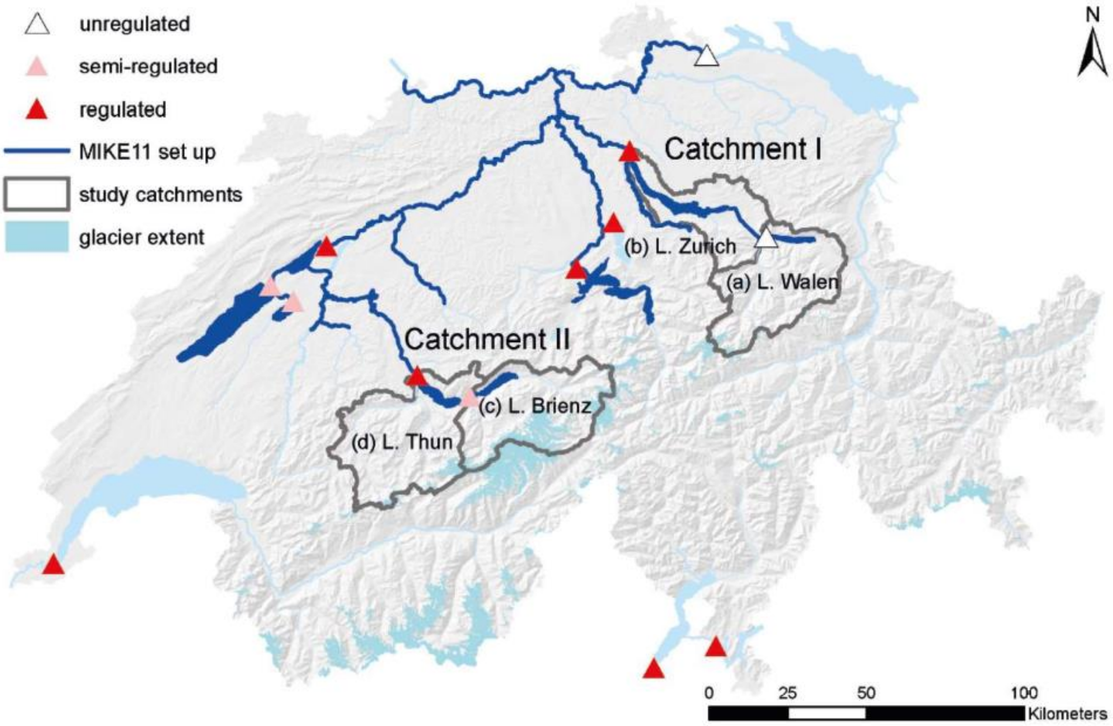


Figure 1. Location of the four case study lakes, located in pairwise nested catchments I and II. Rivers and lakes in dark blue represent the model set-up of the hydrodynamic model MIKE11. The coloured triangles indicate the degree of lake level management of all large lakes (surface area $>$ 10 km2) in Switzerland. Also shown is the glacier extent of (Linsbauer et al., 2016).

Table 1: Catchment characteristics of the four case study lakes (Schwanbeck & Bühlmann, 2023; BFS, 2004); catchment area, mean elevation, relative glacier cover (reference year: 2016), lake volume, lake area, ratio between lake area and catchment area, flood limit F and drought limit L used for the frequency indicators and year with the latest update of lake level management rules.

Lake Name	**Catchment**				**Lake**				
	area [km^2]	elevation [m a.s.l.]	glacier [%]	volume [km^3]	area [km^2]	ratio [%]	F [m]	L [mm d^{-1}]	regulation [year]
Walen	1061	1581	2	2.5	24.2	2.3	3.00	1.11	-
Zurich	1828	1222	1	3.9	88.1	4.8	0.67	1.42	1977
Brienz	1137	1941	16	5.2	29.7	2.6	1.49	1.06	1992
Thun	2452	1743	9	6.5	47.7	1.9	0.63	1.06	2010

2.3 Lake level regimes and management

Lake level management reduces the seasonal lake level fluctuations, as clearly visible by comparing the within-year lake level fluctuations of the four studied lakes (Figure 2, top row). The unregulated Lake Walen shows the most natural lake level dynamic, which is, however, slightly impacted by the seasonal change of streamflow distribution resulting from the hydropower production along the main tributary (Figure SI 4). The lake level of the regulated Lake Zurich is artificially lowered in late winter to provide retention capacity for the melt period in spring. It is kept artificially high in summer for tourism purposes and fishery. The current management rules lead to annual lake level fluctuations that are narrower for Lake Thun than for Lake Brienz.

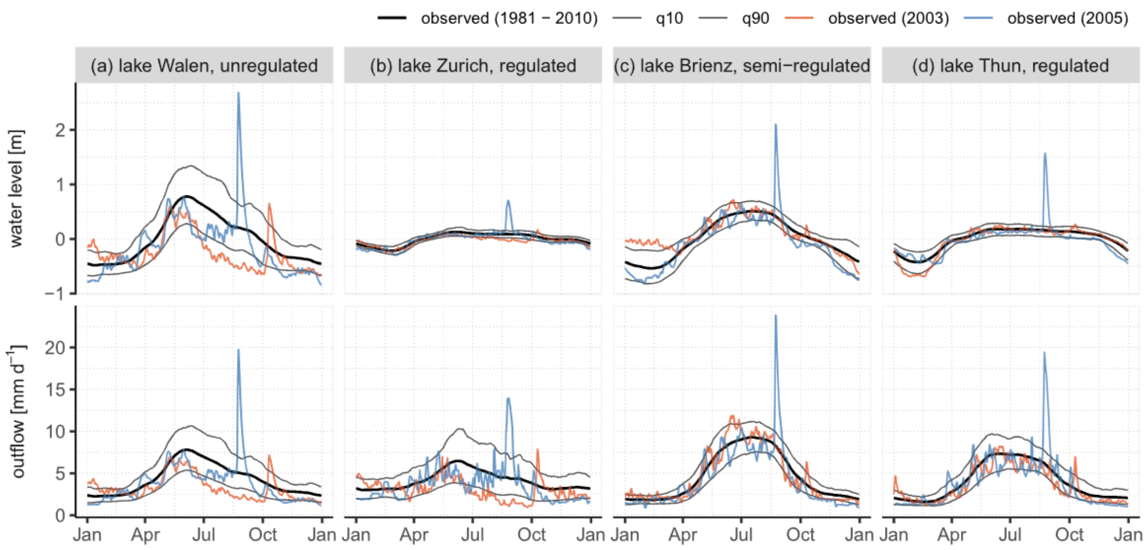


Figure 2. The observed mean 31-day (moving average ±15 days) lake levels (top line) and outflows (bottom line) as well as the 10% and 90% percentile (confidence interval) for the reference period (1981 - 2010). Also shown are the extreme drought year of 2003 and the flood year of 2005.

All lakes analysed here are large enough to dampen daily inflow variability but small enough not to (naturally) dampen the seasonal inflow variability. Accordingly, the annual streamflow pattern, with high flows in summer and low flows in winter, is visible in all outflow regimes (Figure 2, bottom row). Lake level management imprints, however, a modification on the outflow regimes in spring: the melt-related increase in outflow is less steep for the downstream regulated lakes than for the upstream semi-regulated or unregulated lakes. This results from the artificial lake level lowering in winter to provide additional retention capacity for snowmelt in spring. The two lakes Brienz and Thun (catchment II) show a higher and longer-lasting summer outflow peak due to the more snow and glacier melt influence inflow regime (see Table 1 and Stahl et al., 2016). Finally, it is important to note that highly dampened lake level dynamics do not necessarily translate into similarly dampened outflow dynamics (see Lake Zurich and Lake Thun in Figure 2). This depends on the stage-discharge relationship and the underlying lake level management rules.

In Switzerland, lake levels are regulated by floodgates according to specific management diagrams. These so-called line diagrams (Spreafico, 1980) define a target lake outflow as a function of the calendar day and of the current lake level (Figure 3). Nowadays, the actual lake level management is done by automatic regulators, with occasional manual intervention during exceptional situations such as flood or drought situations (FOEN, 2023a). The line diagrams result from compromises between level management targets formulated by different stakeholder groups for different periods of the year. Some of them were elaborated based on modelling (Spreafico, 1980). Lake level management targets, e.g., maintaining sufficiently high lake levels during winter to guarantee access to harbors or sufficiently high lake levels during fish spawning periods to ensure habitat availability for selected species (Neumann, 1983). Downstream river flow targets consist of maintaining river flow below flood limits at selected river cross sections (e.g. FOEN, 2020a). A line diagram can be completed by a set of exceptions, e.g., a preventive lake level lowering to avoid flood events, a temporary minimum lake level to ensure navigability or a certain minimum lake level fluctuation to satisfy ecological needs (Spreafico, 1977; Kaderli, 2021).

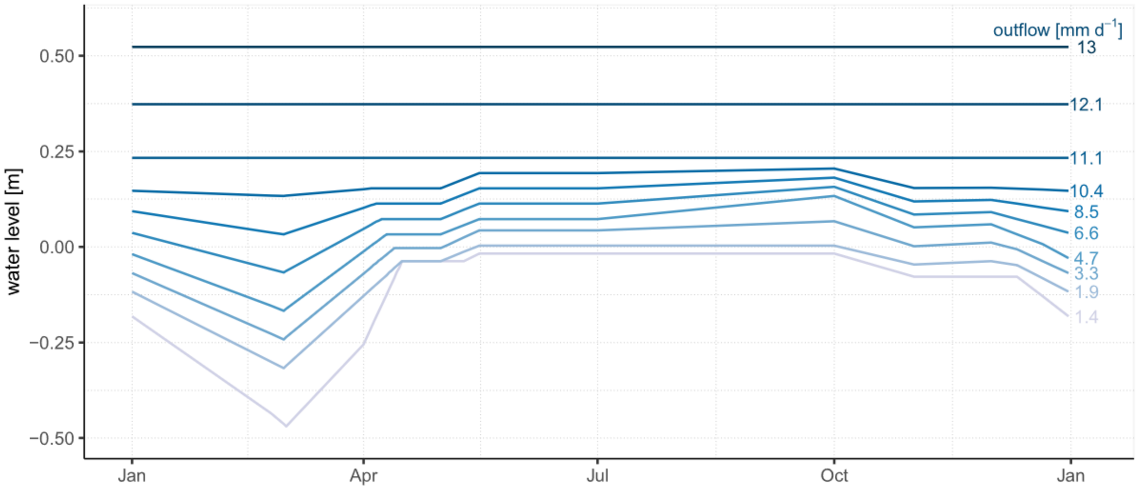


Figure 3. Example of a line diagram that defines a target outflow (blue lines) for each calendar day (x-axis) and for given lake levels (y-axis). Shown is the line diagram for Lake Zurich.

2.4 Hydrologic climate change scenarios

The transient daily streamflow scenarios used in this study were derived from the latest downscaled and de-biased Swiss climate change Scenarios CH2018 (NCCS, 2018), which are based on the EURO-CORDEX dataset (Jacob et al., 2014). For emission scenarios, different frameworks are currently employed: the RCPs (Representative Concentration Pathways), which delineate greenhouse gas concentrations and their effect on radiative forcing, and SSPs (Shared Socioeconomic Pathways; IPCC, 2023), which narrate societal evolution and its impact on climate change. In this study, we consistently adopt the RCPs as provided by the publisher of the CH-2018 climate scenarios. The climate model ensemble CH2018 contains a total of 39 model chains for three RCPs: RCP2.6 (concerted mitigation efforts), RCP4.5 (limited climate mitigation) and RCP8.5 (no climate mitigation measures). The CH2018 ensemble consists of different combinations of Regional Climate Models (RCMs) and General Circulation Models (GCMs), and the ensemble chains are listed in Table SI 3. The model ensemble provides daily air temperature, precipitation, relative humidity, global radiation and near-surface wind speed (Brunner et al., 2019). The climate change scenarios were translated into streamflow scenarios (FOEN, 2021) with the conceptual hydrologic model PREVAH (PREcipitation streamflow

EVApotranspiration HRU related Model; Viviroli et al., 2009) in its spatially explicit version (Speich et al., 2015).

2.5 Hydrologic and hydrodynamic models

Combining the hydrologic and hydrodynamic models allows us to assess the climate change impacts on water-level-outflow dynamics, which expresses a complex balance of stakeholder interests. The conceptual hydrologic model PREVAH computes streamflow by solving the water balance equation (Speich et al., 2015). The hydrodynamic model MIKE11 1D routing model allows for the modelling of river systems (Doulgeris et al., 2012), including reservoirs and lakes (Papadimos et al., 2022), and their associated regulation structures. The detailed model description is provided in the Appendix.

MIKE11 is run at a one-minute time step (a numerical choice related to its use in real-time applications), which we aggregate to daily values. We assess the model performance (Section 4.1) by comparing daily observed lake levels and outflows to simulated values (Table SI 2), where the simulations are obtained with observed meteorological data from the reference period (rather than with the climate model outputs). We assume the model developed with observed input data remains valid with the downscaled climate model outputs as input, a standard assumption in comparable studies. The two models are not dynamically coupled as, e.g., in the work of Papadimos et al. (2022); for the present CC impact on lake-level assessment we apply a loose one-way coupling. The hydrologic model provides input to the coupled lake system's boundary; the flow within and out of the system is simulated with MIKE11, ensuring mass is conserved.

To assess the added value of using an actual hydrodynamic model, simulated and observed lake levels are compared for the used set of models (PREVAH and MIKE11) and for a simplified case where lake levels are obtained by simply solving the water balance equation for the filling of a reservoir. In this simplified case, the lake levels are obtained from the simulated storage volumes based on interpolated stage-area relations. The stage-discharge relation of the regulated lakes is interpolated without accounting for management rules.

For the hydrodynamic simulations with MIKE11, we use the stage-area relations of all lakes, the stage-discharge relation of the unregulated lake and the lake level management rules for the regulated and semi-regulated lakes. The management rules for the regulated lakes specify a corresponding outflow for each day of the year and lake level (as illustrated in Figure 3). In the case of a semi-regulated lake, there are no inherent management rules for different days of the year. The outflow follows a stage-discharge relationship but is influenced by controlled outflow, resulting in a dampened lake level fluctuation compared to an unregulated lake. The stage-discharge relations and the management rules are available in the provided data set (Wechsler et al., 2023). The stage-area relationships were determined for different elevations and areas by the FOEN, which we then linearly interpolated. For the unregulated Lake Walen, the observed stage-discharge relation is parameterised by constructing a median observed lake level for observed outflows and then extrapolating the relation between discharge and stage with a polynomial function (degree 3). The cross-sections used for the hydrodynamic simulations (Section 2.5) are surveyed by the FOEN every ten years (FOEN, 2023e). This data is assumed to remain constant throughout the entire simulation period.

3 Calculations

The assessment of simulated changes is based on daily time steps but compares aggregated future monthly (m) mean lake levels ($h_{\mathrm{m,fut}}$) to the reference period ($h_{\mathrm{m,ref}}$):

$$\Delta h_m = \frac{1}{n_{m,fut}} \sum_{\forall i \in m} h_{i,fut} - \frac{1}{n_{m,ref}} \sum_{\forall i \in m} h_{i,ref} = \overline{h_{m,fut}} - \overline{h_{m,ref}}\,, (1)$$

where Δh_{m} [m] is the future monthly lake level change of month m, computed based on the daily simulations $h(t)$. n_{m} is the number of daily simulation steps within a month over the 30-year period. For February, the number of future time steps $n_{\mathrm{m,fut}}$ can differ from the number of reference time steps $n_{\mathrm{m,ref}}$. The average annual change (Δh_{a}) is computed analogously. Despite simulating with transient daily streamflow scenarios, we focus on changes over 30-year periods, as recommended by the publisher of the climate scenarios (NCCS, 2018). The relative annual and monthly mean changes in lake outflow (ΔQ_m) are computed as:

$$\Delta Q_m = \frac{\frac{1}{n_{m,fut}} \sum_{\forall i \in m} Q_{i,fut} - \frac{1}{n_{m,ref}} \sum_{\forall i \in m} Q_{i,ref}}{\frac{1}{n_{m,ref}} \sum_{\forall i \in m} Q_{i,ref}} = \frac{\overline{Q_{m,fut}} - \overline{Q_{m,ref}}}{\overline{Q_{m,ref}}}. (2)$$

We illustrate projected 30-year mean changes involving 39 model chains in boxplots and express them as follows: Q2 (** IQR: Q1, Q3). The number preceding the bracket represents the median value (Q2) of the model chains. The asterisk indicates the robustness of the change direction: one asterisk denotes an agreement of above 75 % (increase/decrease), whereas two asterisks signify a 100 % agreement. The two subsequent numbers (Q1 & Q3) denote the IQR (interquartile range). These results are presented in Tables SI 4, 5, 6 and 7.

The CH2018 projections are more reliable in capturing long-term changes in general trends than changes in extremes due to the larger sample size of long-term means (NCCS, 2018). However, short-duration extreme events, such as flash floods, have less significant impacts on large lake systems. Therefore, we analyse the changes in extreme lake levels by looking at changes in frequency indicators. The flood frequency indicator (I_F) describes the average number of days per month m (or per year a) for which the simulated daily lake level h(t) exceeds the flood limit (F), which is the critical lake level that would lead to damage to infrastructure (defined for each lake, the so-called hazard level 4 (FOEN, 2023b):

$$I_{F,m} = \frac{\sum_{\forall i \in p}(h_i > \mathrm{F})}{n_p}, (3)$$

where n_p is the number of years in the simulation period p (n_p=30 for all periods). The critical (hazard) lake levels are given in Table 1. There are no comparable critical low-lake level limits but critical low-outflow levels, for which we define an additional indicator: The low-outflow frequency indicator (I_L) describes the average number of days per month, for which the simulated daily outflow $Q(t)$ undercuts the drought limit (L):

$$I_{L,m} = \frac{\sum_{\forall i \in p}(Q_i < \mathrm{L})}{n_p}, (4)$$

where (L) is the minimum outflow specified in regulated lakes' lake-level management rules. For semi-regulated and unregulated lakes, we choose a value corresponding to the 30-year low flow return period (Table 1).

4 Results

4.1 Model performance

We first compared the model performance in terms of lake level and outflow simulation using (i) the hydrologic model PREVAH alone (with a simplified reservoir approach) and (ii) the combination of PREVAH and MIKE11. Both the hydrologic model PREVAH and the hydrodynamic model MIKE11 were previously calibrated and validated and are in operational use (Section 2.5). For the reference period, the model combination, run with observed precipitation and temperature input data, demonstrates better agreement with the observed lake levels (Figure 4) and with the observed outflows (Figure SI 2) than the hydrologic model alone. The performance improves not only for the regulated lakes but also for the unregulated Lake Walen. By combining the hydrologic and the hydrodynamic models, we enhance the model's ability to simulate daily lake levels and outflows (Table 2 and illustrated in Figure SI 3). Given the model performance increase, the combination of both models is used for future simulations, inspite of the computation cost: The computation time for the available 39 model chains over the entire period (1981 – 2099) on a personal computer with 64 gigabytes of RAM and 20 cores takes one day for the hydrologic model and one week for the hydrodynamic model.

For future scenarios, the simulated average monthly lake levels for the reference period show a certain bias (up to 30 centimetres for individual months and certain model chains) compared to observed lake levels (Figure 4). This bias is inherited from the hydrologic (streamflow) simulations that do not perfectly reproduce the observed mean monthly streamflow for the reference period (Brunner et al., 2019).

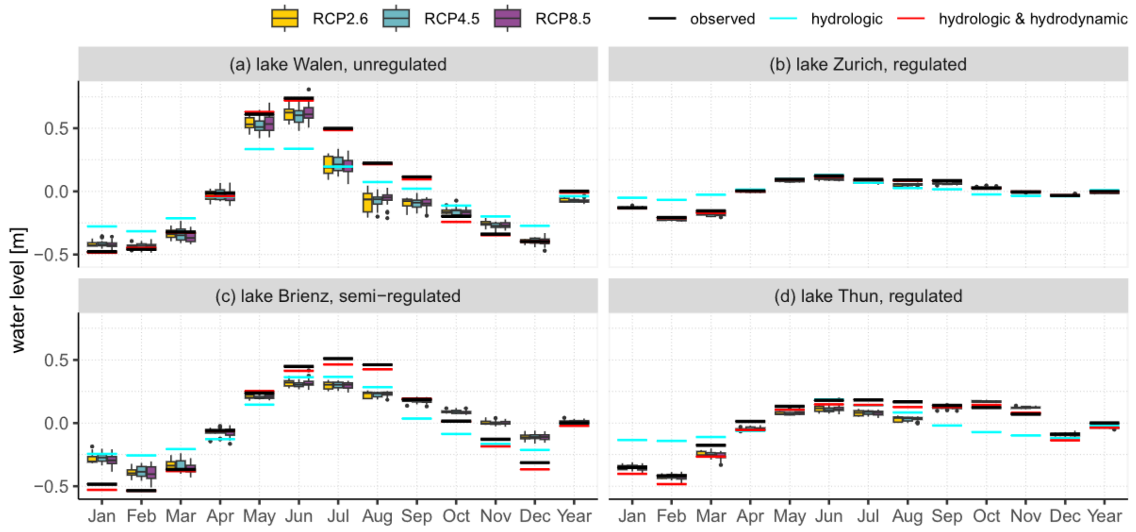


Figure 4. Normalised observed and simulated annual and monthly lake levels for the four considered lakes during the reference period (1981 - 2010). The observations are compared to the hydrologic simulations with PREVAH and the combination of the hydrologic and hydrodynamic models PREVAH and MIKE11. The coloured boxplots show the model variability of the 39 streamflow scenarios during the reference period, divided into three emission scenarios (RCP2.6, RCP4.5 and RCP8.5).

Table 2: Model performance comparison between daily simulations with the hydrologic model PREVAH and the combined simulations with PREVAH and the hydrodynamic model MIKE11 during the reference period. Shown are the Root Mean Squared Error (RMSE), the Nash-Sutcliffe Efficiency (NSE; Nash, 1970), the Kling-Gupta Efficiency (KGE; Redelsperger and Lebel, 2009) and the percent volume error (DV).

Lake Name		**Lake Level [m]**		**Outflow [mm d^{-1}]**			
	Model	RMSE [m]	NSE [-]	RMSE [mm d^{-1}]	NSE [-]	KGE [-]	DV [%]
Walen	hydrologic	0.31	0.69	0.93	0.86	0.92	-2.3
	combination	0.31	1.00	0.05	1.00	1.00	+0.0
Zurich	hydrologic	0.08	0.58	0.75	0.88	0.92	-1.3
	combination	0.02	0.98	0.29	0.98	0.99	+0.8
Brienz	hydrologic	0.21	0.73	1.02	0.89	0.87	-4.3
	combination	0.14	0.88	0.33	0.99	0.99	+0.1
Thun	hydrologic	0.18	0.44	0.74	0.92	0.92	-0.6
	combination	0.10	0.81	0.30	0.99	0.99	+0.0

4.2 Climate change impact projections on lakes

4.2.1 Change in mean lake levels and outflows

The simulations for the reference and the future periods show a slight annual decrease in lake levels for all four lakes but a pronounced change in seasonal streamflow distribution from summer to winter (Figure 5). This redistribution intensifies with time (2085) and without climate mitigation measures (RCP8.5). The degree of lake level management of a lake has a direct impact on the simulated lake level changes: for Lake Zurich, which is the most strongly regulated lake of the four (Figure 2), changes range from -0.04 m (** IQR: -0.05 m, -0.03 m) in summer to +0.03 m (** IQR: +0.02 m, +0.04 m) in winter without climate change mitigation measures (RCP8.5) by the end of the century. Lake Thun, also regulated, exhibits changes between -0.13 m (** IQR: -0.16 m, -0.1 m) and +0.11 m (** IQR: +0.08 m, +0.12 m). The semi-regulated Lake Brienz shows changes ranging from -0.25 m (** IQR: -0.30 m, -0.18 m) to +0.16 m (** IQR: +0.13 m, +0.19 m), while the unregulated Lake Walen shows the largest variations, with -0.4 m (** IQR: -0.5 m, -0.37 m) in summer to +0.24 m (** IQR: +0.18 m, +0.25 m) in winter. The Tables SI 4, 5, 6 and 7 contain the seasonal projections, and Figures SI 6, 12, 18 and 24 show the monthly projections.

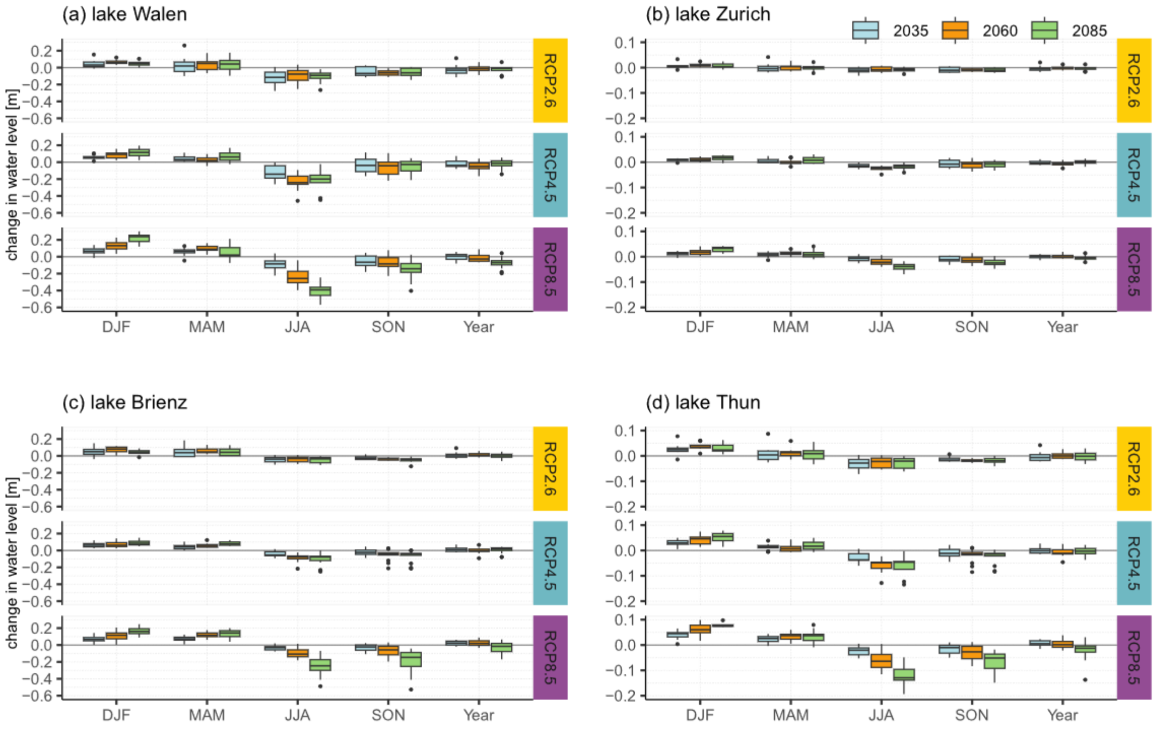


Figure 5. Simulated changes in seasonal mean lake levels of Lake Walen (unregulated), Lake Zurich (regulated), Lake Brienz (semi-regulated) and Lake Thun (regulated), divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

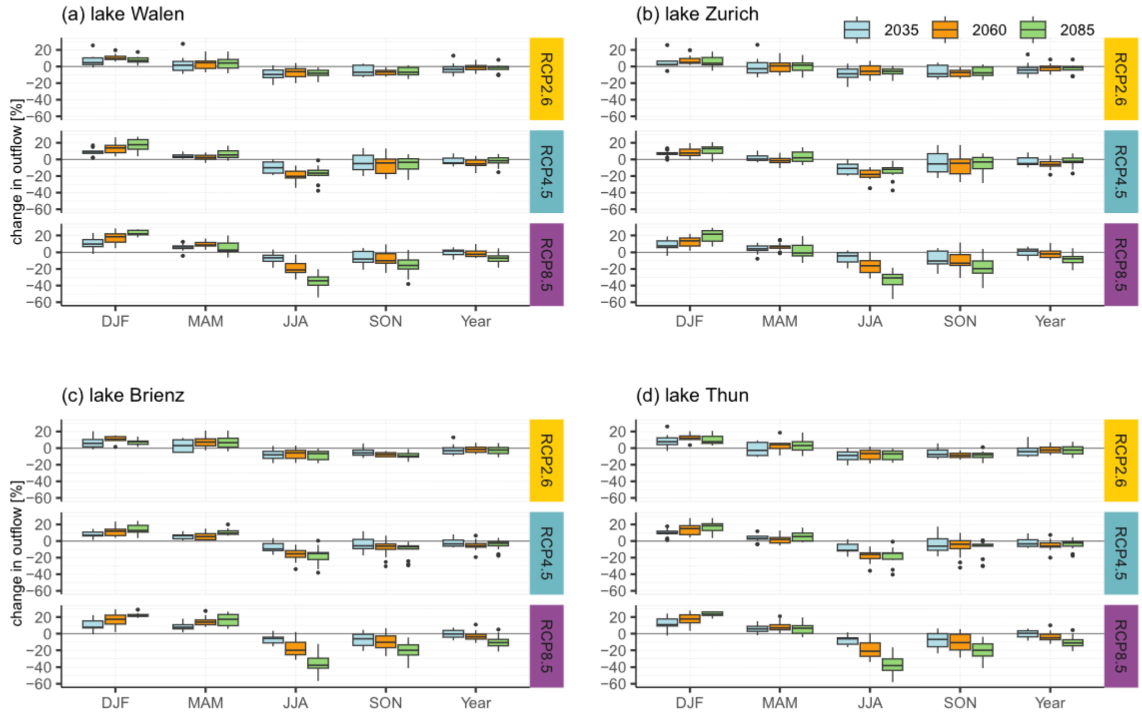


Figure 6. As Figure 5 but for the simulated changes in seasonal outflows.

Despite the simulated lower summer lake levels, summer remains the season with the highest lake levels. Towards the end of the century, the glacier- and snowmelt-influenced regime of lake levels is still noticeable. However, the simulated mean melting peak (q50 = 50 % percentile in Figure SI 8) for the unregulated Lake Walen shifts from currently June to May and is expected to drop by 0.5 m due to less melt contribution. This temporal shift is not simulated for the two regulated and the semi-regulated lakes, which still follow the temporal level management rules (Figures SI 14, 20 and 26). However, a lower mean lake level (q50) in late summer is visible for the regulated and semi-regulated lakes. For Lakes Brienz and Lake Thun, the mean summer lake levels decrease to the current 10 % percentile. In conjunction with higher winter lake levels, the simulation indicates a less pronounced seasonal lake level regime for the end of the century.

The simulations for annual outflows also indicate relatively small changes, reaching up to -11 % (* IQR: -14 %, -7 %) without climate change mitigation measures (RCP8.5) by the end of the century (Figure 6). As seen in observed data (Figure 2), the degree of lake level management has a smaller impact on lake outflows than on the lake levels. This is also true for the simulated outflow changes: for the unregulated Lake Walen, a change of -34 % (** IQR: -40 %, -30 %) in summer and +37 % (** IQR: +28 %, +42 %) in winter is simulated, while for the regulated Lake Thun, the changes range from 38 % (** IQR: -44 %, -30 %) in summer to +37 % (** IQR: +27 %, +45 %) in winter. The changes in summer outflow intensify with the mean catchment elevation and with the share of glacier cover: the glacier area for catchment II is eight times higher than for catchment I, and the mean catchment elevation is 521 m higher (Table 1). The simulations for the semi-regulated Lake Brienz and the regulated Lake Thun indicate a more significant change in summer outflow with -38 % (** IQR: -44 %, -30 %), compared to -34 % (** IQR: -40 %, -30 %) for Lake Walen and -31 % (** IQR: -39 %, -27 %) for Lake Zurich. The monthly changes in outflows are even more pronounced than the seasonal changes (see Supplementary Information, Figures SI 7, 13, 19 and 25).

The simulations indicate that mean peak outflows (q50 in Figures SI 9, 15, 21 and 27) continue to occur in June and little change is expected in terms of timing and magnitude, for all four perialpine lakes. Significant changes of lake outflows are simulated throughout the year: as a result of higher winter outflows and lower summer outflows, the simulated outflows show, already by mid-century, lower summer outflows than in winter (today, we see exactly the opposite). The simulated average summer outflows (q50 in Figures SI 9, 15, 21 and 27) are roughly reduced to 50 % compared to the reference period and towards the end of the century.

4.2.2 Change in extremes

The frequency indicator for floods (F), which counts the average number of simulated days exceeding the flood limit (Table 1), does not indicate clear changes. In the simulations, there are some occasional outlier years, but no significant trend is visible (Figures SI 10, 16, 22 and 28). For the reference period (and for observed data, not simulations), flood limit exceedances were only observed in May 1999 and August 2005. Only for Lake Thun, there were four additional occurrences where the flood limit was exceeded, all occurring between June and August. Our monthly projections do not indicate clear changes throughout the century under any of the emissions scenarios.

The frequency indicator for droughts (L), which counts the average number of simulated days with the lake level falling below a defined minimum outflow (Table 1), indicates an increasing trend in the climate change simulations (Figure 7). Lakes with a higher degree of lake level management (Lake Zurich and Lake Thun) show a higher L than the other lakes. Additionally, the simulations indicate a higher L with a lower mean catchment elevation (catchment I). Compared to the reference period, Lake Brienz and Lake Thun, with a higher mean elevation, first show a decreasing L, before strongly increasing by the end of the century and with missing climate change mitigation measures. On the other hand, the two lakes in the lower catchment I show an increasing trend throughout the entire century. For the regulated Lake Zurich, an increase of 400 % up to 60 days per year under the emission scenario RCP8.5 is simulated for the end of the century. This corresponds to an increase of 45 days compared to the reference period, with a strong increase in summer and autumn. The unregulated Lake Walen also shows strong increases of 400 % but, with up to 8 days per year, on a much lower level (monthly variations are depicted in Figures SI 11, 17, 23 and 29).

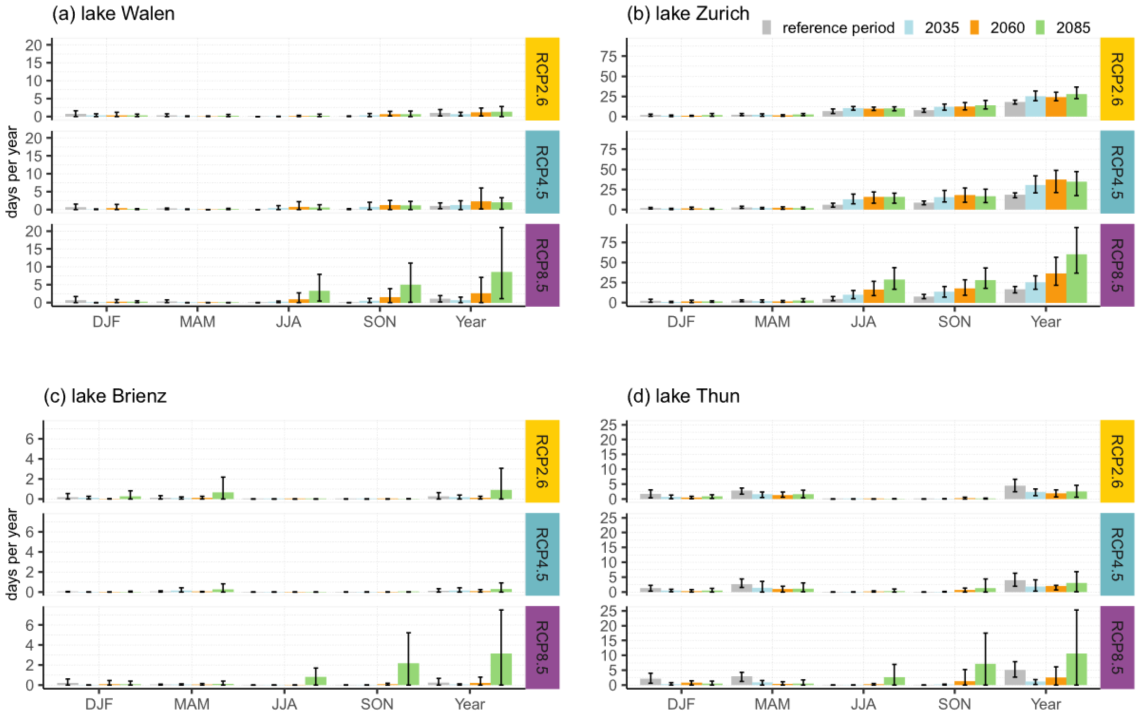


Figure 7. Simulated changes in days per month and per year the outflow undercuts the drought limit (L) of Lake Walen (unregulated), Lake Zurich (regulated), Lake Brienz (semi-regulated) and Lake Thun (regulated). Error bars refer to the 10% and 90% percentile range.

4.2.3 Synthesis of the simulated changes in lake levels and outflows

The simulations of lake levels and outflows for the studied lakes show a slight decrease in annual lake levels across all four lakes and a pronounced change in seasonal distribution from summer to winter. The presented changes by the end of the century and without climate change mitigation measures in summer and winter are very robust for all four lakes, both in lake levels and outflows. This indicates a 100 % agreement on the change signal (increase/decrease) among all model chains. The simulated changes intensify with time, particularly in the absence of climate change mitigation measures. The degree of lake level management directly impacts the simulated changes: regulated lakes exhibit smaller variations (of a few centimetres) compared to the unregulated Lake Walen, which shows variations of up to -0.4 m (** IQR: -0.5 m, -0.37 m). Summer remains the season with the highest lake levels despite the drastic decrease in summer. For the unregulated Lake Walen, the simulations show a temporal shift in the melt-influenced peak from June to May by the end of the century; for the regulated lakes, no similar shift is simulated. Additionally, the simulations indicate a less pronounced seasonal pattern in lake levels, with reduced seasonal fluctuations due to higher winter lake levels and lower summer lake levels. For annual outflows, the projected reductions of up to 10 % are smaller than the projected seasonal changes, which range from -38 % (** IQR: -44 %, -30 %) in summer to +37 % (** IQR: +27 %, +45 %) in winter. The impact of lake level management on outflows is smaller than for lake levels. Changes in outflows are more influenced by the mean catchment elevation than by the degree of lake level management.

The lowest monthly lake levels may shift from winter to late summer by mid-century for the unregulated Lake Walen. Based on our simulations, the indicator for drought frequency is expected to increase, particularly in lakes with a higher degree of lake level management and lower catchment elevation. Flood frequency does not exhibit clear changes between the reference period and the end of the century for any of the emissions scenarios.

5 Discussion

5.1 Incorporating lake level management in hydrologic simulations

Combining a hydrologic and hydrodynamic model greatly improves the model performance for both lake outflows and especially for lake levels (Section 4.1), underlining the importance of considering lakes and lake level management in hydrologic simulations. However, using a hydrodynamic model resulted in a sevenfold increase in computational costs and an increase in input data (the cross sections) compared to only using the hydrologic model. This increase in overall modelling work, which is also reported in other studies (Paiva et al., 2011; Hoch et al., 2017), is related to the choice of simulating the entire lake system and the connecting water ways with the hydrodynamic approach at a 1-minute resolution. This temporal resolution was imposed by the operational (real-time) setting for which the model was originally built. Besides the computational and data costs, the modelling solution presented here has the significant limitation that the software is not open source or freely available. The question arises as to whether a more straightforward approach, such as using time-dependent (e.g., in 2-week intervals) stage-discharge relations, could be employed to incorporate lake level management in a simplified manner into the hydrologic model. This is left for future work.

5.2 Projected climate change impacts

The underlying hydrologic simulations of the future conditions show changes in precipitation, evapotranspiration and icemelt contribution for both catchments (Figure 8). At annual scale, the simulations indicate no clear trend in precipitation. At seasonal scale, climate-change induced changes are visible for icemelt and evaporation: for catchment II, the icemelt contribution increases slightly in the near future before decreasing from mid-century on. For catchment I, the glacierised area is too small to show an impact (Table 1). Regarding evaporation, the simulations show an increase for both catchments, intensifying with time and missing climate change mitigation measures. This increase of evapotranspiration leads to an overall reduction of simulated streamflow throughout all simulated periods, with a more substantial decrease in the higher-elevation catchment II for all periods, despite the increased melt contribution in the near future (2035).

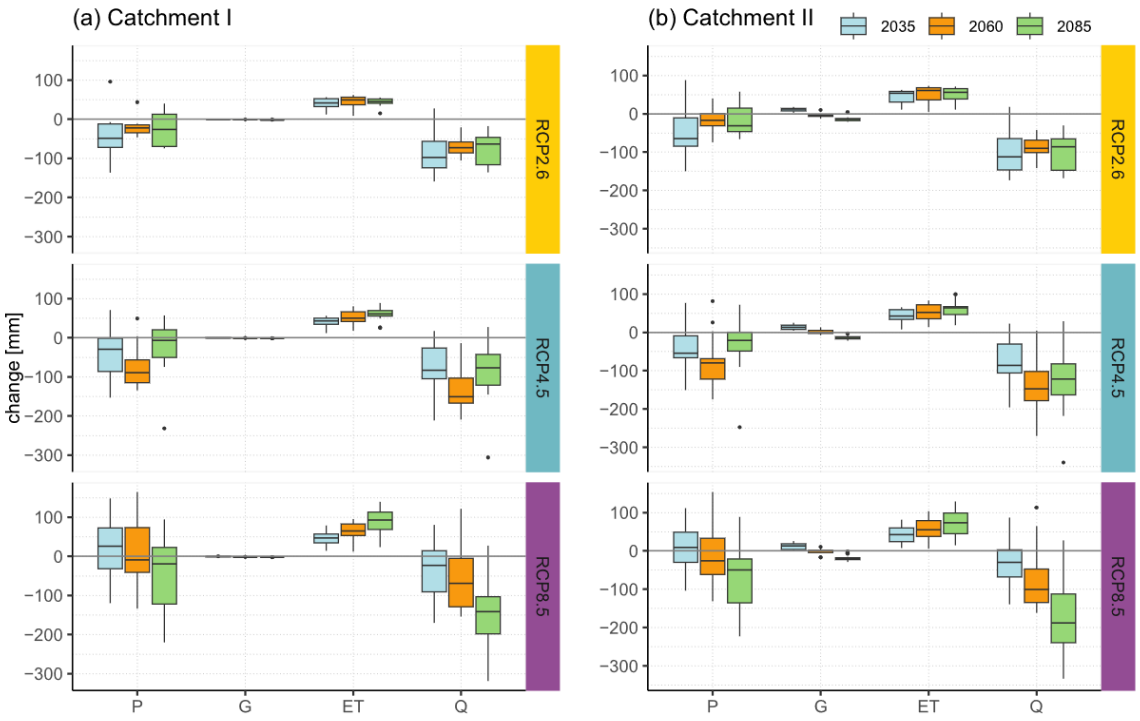


Figure 8. Simulated climate-induced changes in precipitation (P), glacier melt contribution (G), evapotranspiration for the entire catchment area (ET) and streamflow (Q) for catchment I (Lake Walen and Lake Zurich) and catchment II (Lake Brienz and Lake Thun).

The lake level simulations for the future periods show a substantial change in the seasonal pattern of mean lake levels and mean outflows, with a lake level decrease in summer of up to 0.4 m (** IQR: 0.5 m, 0.37 m) for the unregulated lake and between 0.04 m (** IQR: 0.05 m, 0.03 m) for the regulated Lake Zurich and 0.25 m (** IQR: 0.30 m, 0.18 m) for the semi-regulated lake Brienz (RCP8.5, 2085). These seasonal changes agree with published streamflow regime changes (Rössler et al., 2019; Muelchi et al., 2021) and are, among other things, a consequence of higher temperatures and the associated higher snowfall line, leading to less snow storage and more streamflow in winter and less snowmelt in spring and summer (Stahl et al., 2016; Muelchi et al., 2021). This change in seasonal distribution due to reduced snowfall and snowmelt is enhanced by increased losses by evapotranspiration (Figure 8) and a decrease in summer precipitation by up to 39 % (median) by the end of the century (NCCS, 2018). Additionally, a reduced snow-cover extent leads to more extended periods when larger catchment areas are not snow-covered (Brunner et al., 2019; Woolway et al., 2020) and consequently to more losses through evapotranspiration. The glaciers in the simulated catchments are already to date too small to fully compensate for this reduction of available water. Our simulations of the unregulated perialpine lake indicate a strong seasonal shift in the peak-melt lake level occurring one month earlier (Figure SI 8), which aligns with the findings of earlier studies (Muelchi et al., 2021; Stahl et al., 2022) on streamflow regime shifts. However, we do not observe such a seasonal shift for the regulated lakes (Figures SI 14 and 26), and only a minor shift is observed for the semi-regulated lakes (Figure SI 20). These findings are crucial regarding the transferability of our results, as they suggest that similar analyses should be completed for other perialpine lakes to confirm this result.

The median values of the projected changes in monthly means vary, depending on the degree of lake level management, from a few centimetres to almost half a meter. Compared to the seasonal lake level fluctuations, these changes amount to between 10 % and 30 %. Particularly in summer, projected changes are likely to impact the physical properties of lakes (Lewis et al., 2024), but also increase pressure on water resources management, especially in the case of water shortage (François et al., 2015; Brunner et al., 2019; Kellner, 2021). Our simulations suggest that especially Lake Zurich could face serious drought problems in the future, with more than 35 days per year where the drought limit is not met for the intermediate scenario RCP4.5 by 2060 already (Figure 7). In addition to anthropogenic aspects, such as water shortage (Brunner et al., 2019), dry periods can have implications for water temperature, water quality and aquatic ecosystems (Jiang et al., 2018; Saber et al., 2020; Fernandez Castro et al., 2021). These effects can take on considerable proportions; however, compared to flood events, they are less readily associated with monetary damage. Regarding the evolution of flood events in the simulated perialpine lake systems until the end of the century, it is worth noting that, despite the predicted rise in daily extreme precipitation intensity by up to 20 % in winter and up to 10 % in summer (NCCS, 2018), our results for large perialpine lakes show no clear changes (Figures SI 10, 16, 22 and 28). This can be explained by the reduced contribution from snowmelt, which, despite being more concentrated in time, leads to less critical high-levels. The simulated projections are conditional on the given ensemble of opportunities considered for the analysis, looking at 30-year mean changes.

5.3 Uncertainty in climate change impact assessments

Our climate change impact assessment contains uncertainties throughout the entire model chain, starting with the climate model ensemble and throughout the environmental models, i.e. the glacier retreat model (feeding the streamflow simulations), the hydrologic and the hydrodynamic model. The used climate model ensemble is based on the EURO-CORDEX ensemble (Jacob et al., 2014). It consists of different emissions scenarios (RCP = Representative Concentration Pathway), Global Circulation Models (GCMs), Regional Climate Models (RCMs), and different spatial resolutions (Table SI 3).

These climate model chains have previously been used with practically the same hydrologic model setup and data by Addor et al. (2014). Their detailed analysis shows that the highest source of uncertainty lies in the climate models and natural climate variability. In contrast, the uncertainty introduced by hydrologic models predominantly contributes to uncertainty in glaciated and hydropower-influenced catchment areas but plays a minor role in the kind of catchments considered here. Additional sources of hydrologic modelling uncertainty refer to water losses from the lakes via evaporation or groundwater. The lake area accounts for between 1.9 % and 4.8 % of the catchment area (Table 1). Therefore, lake evaporation is relatively small compared to the total catchment evapotranspiration. We may underestimate water losses through lake evaporation during some summer days (in the order of tens of mm). Compared to uncertainties in the simulated inflows, this remains negligible. Similarly, based on existing water balance estimates (Bühlmann and Schwanbeck, 2023), groundwater inputs into the four perialpine lakes are negligible. Accordingly, we did not further analyse the hydrologic and hydrodynamic modelling uncertainty but only examined the climate model ensemble uncertainty. This approach was adopted by all previous studies involving these streamflow scenarios (Muelchi et al., 2021; FOEN, 2021). In contrast to earlier studies that selected individual model chains for future scenarios, we consistently used the entire ensemble of opportunity. Thus, we present the complete spread of the 39 model chains with boxplots and communicate in the results as described in

Section 3: Q2 (** IQR: Q1, Q3), the median value, the robustness of the change signal (in-/decrease), and the IQR (interquartile range).

Our results, 30-year annual and monthly mean values, describe long-term trends but no interannual variability. Future work could investigate the interannual variability to enhance our comprehension of year-to-year variations. Regarding extreme events, we focused on the frequency of lake level drops below a drought limit or exceedance of the flood limit, without considering the magnitude. Detailed extreme event analysis will become possible once the next generation of climate change scenarios is available for Switzerland.

5.4 Modelling framework limitations

Climate-change impact modelling chains have classical limitations (Schaefli, 2015), first, in terms of modelling biases inherited from the climate input to the system's models and second, in terms of system changes other than those directly related to climate. Regarding potential biases, our simulations for the reference period reproduce the observed lake levels (Figure 4) and outflows (Figure SI 2) relatively well in terms of overall temporal patterns, they show, however, some biases for the monthly mean lake levels. Such biases are expected for lake level simulations because any bias in streamflow simulations accumulates at the lake system's level. We tested using a precipitation bias correction (quantile mapping method) to reduce the biases in the underlying streamflow simulations, but this showed no significant improvement (results not shown). Accordingly, we assume that comparing the simulations for the reference and the future periods leads to robust change assessments. A certain bias between observations and simulated streamflows during the reference period is a known concern for the CH2018 scenarios (MeteoSwiss, 2023), which also translates into the hydrologic simulations. Achieving a more precise alignment of observations and model simulations during the reference period is one of the goals for the upcoming update of climate scenarios (CH2025; MeteoSwiss, 2023).

In terms of changes to other system components, we assume that current lake level management practices remain constant for future simulations, rather than considering potential adaptation measures for lake level management practices. This assumption is conditioned by the very aim of the study (comparing regulated versus unregulated lakes), but it implies that we do not consider any changes from the demand side on the lake regulation. Such demand changes could become evident on a large scale with more frequent and severe drought years (Spinoni et al., 2016; Vicente-Serrano et al., 2022) and ensuing water use competition (Brunner et al., 2019). In light of this model framework limitation, we underline that our results should not be used directly to judge if lake level management can be used as a climate change adaptation measure. In fact, (1) lake level management controlled by floodgates may conflict with diverse interest groups such as the negative ecological impacts caused by smaller fluctuations in lake levels (Wantzen et al., 2008), (2) it may affect the longitudinal disconnection of aquatic habitats (Stanford and Hauer, 1992; Erős and Campbell Grant, 2015) and (3) despite the controlled lake outflow, smaller lake level changes do not necessarily lead to less water scarcity or enhanced resilience (Kellner, 2021).

6 Conclusion

We present a climate change impact study on four perialpine lakes in Switzerland, based on a modelling chain with incorporated lake level management to simulate changes in lake levels and outflows and to analyse climate change impacts on different degrees of lake level management. Our simulations reveal increasing changes in both lake levels and outflows with time and missing climate change mitigation efforts, which agrees with many climate change impact studies.

Without climate mitigation measures (RCP8.5) by the end of the century, the simulations show small reductions of mean annual lake levels (of a few centimetres), accompanied by decreases in outflow by up to 10 %. The simulations indicate a 100 % agreement of the change signal across all simulated climate model chains (for lake levels and outflows). The seasonal changes in lake levels are much more pronounced than annual changes, with projected increases during winter and decreases during summer. The degree of lake level management plays a dominant role in determining the magnitude of these lake level changes: for the unregulated Lake Walen, the seasonal lake level changes (median) can decrease by up to 0.4 m, while for regulated or semi-regulated lakes, the seasonal changes range from -0.04 m to -0.25 m, compared to the reference period. The simulations show that the highest monthly lake levels continue to occur in summer. In contrast, the impact of lake level management on outflows is weaker than on lake levels. The simulations reveal seasonal patterns in the climate-induced changes consistent with those for the lake levels (median): up to 21 % higher winter outflows, up to 39 % lower summer outflows, and a consequently less pronounced seasonal outflow pattern. The drought frequency indicator suggests an accentuated increase in late summer, which can strongly impact water resources management and potentially lead to conflicts between various interest groups (e.g., during dry periods when maintaining a minimum lake level conflicts with maintaining a minimum outflow). The lowest lake levels may shift from winter to late summer by mid-century for the unregulated Lake Walen, which underlines that climate change has a strong impact on this unregulated lake. Conversely, the flood frequency does not show clear changes for the four studied lakes.

The main findings of our study are as follows:

- The study highlights the importance of incorporating lake level management in climate change impact simulations, which is strongly understudied in the available literature. Relying on simple water balance models rather than full hydrodynamic modelling can result in underestimating the climate change impact assessment, especially for lake levels.
- Climate change can lead to essential changes in seasonal patterns of mean monthly lake levels and outflows, with summer lake levels declining. This decline and an increased occurrence of low-lake level days can shift from winter drought to summer drought in certain years, with severe impacts on water availability and water quality and, consequently, more pressure on aquatic habitats.
- Climate change affects lake levels and outflows differently depending on the degree of lake level management, which is important in terms of the transferability of our results to other perialpine lake systems and underlines the need for more case studies.

The simulations indicate that lake level management rules and practices might need to be re-considered under the most extreme climate change scenarios for our four studied lakes. This might hold well beyond our case studies for similar large perialpine lakes with comparable levels of lake level management. Future work should focus on interannual variability and the occurrence of sequences of low or high lake level years, to complement examining the changes of 30-year mean values. Accordingly, the transient changes could also be visualised. Such an in-depth analysis of interannual variability would build the basis for future lake level management adaptations.

Acknowledgements

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Data statement

The future lake level and outflow scenarios of this study are publicly available in the provided data set Wechsler et al. (2023). Declaration of generative AI and AI-assisted technologies in the writing process During the preparation of this work the author(s) used DeepL, Grammarly and ChatGPT to improve language and readability. After using these tools, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Appendix

More detailed information on the selected case studies, as well as on the models used for the simulations described in the manuscript 'On the Role of Lake Level Management in Modulating Climate Change Impacts on Perialpine Lakes' by Wechsler et al.

Historic background of the four studied perialpine lakes

In this study, we focus on large natural lakes and do not consider artificial reservoirs. In Switzerland, all large lakes (surface area > 10 km^2), except for two, are managed (Table SI 1). Lake level management affects both the lake levels and outflows. Accordingly, lake level management is crucial for downstream streamflow dynamics, as all major rivers in Switzerland flow through at least one lake before leaving the country. In today's Swiss context, various stakeholder interests, both linked to upstream lake levels and downstream river flow, act upon lake level management: ecosystem protection, water supply, further water-dependant economic interests (such as shipping and fishery) and flood protection (AWA, 2014; FOEN, 2023a).

Over the past two centuries, these four lakes have been subjected to different river correction works to reduce flooding in the upstream flood plains and modify their hydraulic functioning, altering their hydrologic dynamics (Vischer, 2003). In 1811, today's main tributary of Lake Walen was artificially diverted into the lake for flood protection (FOEN, 2016). The river diversion doubled the lake's catchment area. Further downstream, the floodplain was corrected for land reclamation. As a result of the correction, the mean lake level of Lake Walen dropped by more than five meters. The outlet floodplain downstream of Lake Zurich was also exposed to flood risk (FOEN, 2020b). Around 1900, the mills at the lake outlet were removed, and the riverbed deepened. In the 1950s, the 'needle dam' was replaced by a regulating weir, which reduced the annual lake level fluctuations from two meters down to 50 cm (see Figure SI 1). The lake level of Lake Brienz has been regulated by a sill since medieval times (FOEN, 2020c). It was removed in 1850 for fishing, shipping and land reclamation, which lowered the lake level by two meters.

The lowering of the lake level left a relatively large fluctuation range without immediate flood risk, which only required a weak regulation by two floodgates and two small hydropower plants. Similarly to Lake Walen, the main tributary of Lake Thun was diverted directly into the lake, but already 300 years ago. This significantly increased the catchment area (FOEN, 2020d). In addition, mills were removed at the lake outlet to enhance the outflow capacity. The floodgates were built in the late 18th century. However, the outflow capacity remained too low during flood events and even today, there is only a margin of 50 cm between the average summer lake level and the flood limit. Consequently, a spillway has been operational since 2009 to increase the lake's outflow capacity during flood events.

Detailed model description

The conceptual hydrologic model PREVAH computes streamflow by solving the water balance equation and uses air temperature, precipitation, potential evapotranspiration, wind speed, global radiation, sunshine duration and relative humidity as input. The conceptual hydrologic model PREVAH has frequently been used for water resources applications and climate change impact studies in Switzerland (Speich et al., 2015; FOEN, 2021), and previously calibrated for diverse water resources applications in Switzerland (Bernhard and Zappa, 2009; Köplin et al., 2014; Speich et al., 2015). It accounts for snow accumulation, snow and glacier melt, evapotranspiration, soil infiltration, water release via surface and subsurface runoff and streamflow routing (Brunner et al., 2019). The hydrologic model PREVAH considers the groundwater that has a hydraulic connection with the stream but does not account for larger or deeper groundwater aquifers in the catchment. Lake ice cover is not considered in the simulations due to the limited freezing of large perialpine lakes in Switzerland (Franssen and Scherrer, 2008). The model considers the seasonal redistribution of water resulting from high-head accumulation hydropower plants in a simplified manner: it does not use exact water turbining schedules, but it contains the main diversions and dams in the headwater of our study area (Figures SI 4 and 5). The model has recently been improved in terms of both snow accumulation simulation at high elevations (Freudiger et al., 2017) and glacier evolution simulation (Brunner et al., 2019). . This allows the simulation of water retention but not lake level management.

The hydrodynamic model MIKE11 is a 1D routing model developed by the Danish Hydraulic Institute (DHI, 2003; Papadimos et al., 2022) and allows for the modelling of river systems (Doulgeris et al., 2012), including reservoirs and lakes (Papadimos et al., 2022), and their associated regulation structures. It was previously set up and calibrated by the Federal Office for the Environment (FOEN) for several large Swiss rivers and lakes (Figure 1) and is used for real-time simulation of lake levels during flood events (Inderwildi and Bezzola, 2021). The basic functioning of MIKE11 to simulate complex water systems is dividing the river network, including lakes, into a series of cross-sections (Section 2.5). To simulate the fluid dynamics, MIKE11 employs the Saint-Venant equation, which accounts for flow velocity, water depth, channel slope, and momentum. Furthermore, lakes are modeled as a control volume at three cross-sections, of which the one at the lake outlet defines the outflow. This is defined with a stage-discharge relation for natural lakes or the lake level management rules for regulated lakes, as defined in a look-up table (all data are provided in Wechsler et al., 2023). The time-dependent lake level management rules define a target lake outflow as a function of the calendar day and the current lake level. As the management rules define, the lake outflow changes when the lake level exceeds a specific limit.

Supplementary Information

Tables and Figures submitted with the manuscript "On the role of lake level management in modulating climate change impacts on perialpine lakes" by Wechsler et al.

Table SI 1: Characteristics of Swiss lakes with a surface area greater than 10 km^2 (BFS, 2004).

lake name	area [km^2]	elevation [m a.s.l.]	volume [km^3]	max. depth [m]	outlet dam [yes:no]	regulation [-]
Geneva	345.4	372	89.9	310	yes	regulated
Constance	172.6	396	49.0	252	no	unregulated
Neuchâtel	215.0	429	14.2	153	no	semi-regulated
Maggiore	40.8	193	37.1	372	yes	regulated
Lucerne	113.7	434	11.8	214	yes	regulated
Zurich	88.1	406	3.9	143	yes	regulated
Lugano	30.0	271	6.6	288	yes	regulated
Thun	47.7	558	6.5	217	yes	regulated
Biel	39.4	429	1.2	74	yes	regulated
Zug	38.4	413	3.2	198	yes	regulated
Brienz	29.7	564	5.2	261	yes	semi-regulated
Walen	24.2	419	2.5	150	no	unregulated
Murten	22.7	429	0.6	46	no	semi-regulated
Sempach	14.4	504	0.7	87	no	regulated
Sihl	10.7	889	0.1	23	yes	regulated

Table SI 2: Gauging stations from which observed lake levels and outflows were used, provided by the Federal Office for the Environment (FOEN).

lake names	lake levels [m]		outflows [mm d^{-1}]	
	ID	Station	ID	Station
Walen	2118	Murg	2104	Weesen
Zurich	2209	Zurich	2099	Unterhard
			2176	Sihlhölzli
Brienz	2023	Ringgenberg	2457	Goldswil
Thun	2093	Kraftwerk BKW	2030	Thun

Table SI 3: The 39 climate model ensembles derived from the climate scenarios NCCS (2018). Each ensemble is a combination of TEAM (institute responsible), RCM (Regional Climate Model), GCM (General Circulation Models), RES (spatial resolution) and RCP (Representative Concentration Pathway, representing emissions scenarios).

TEAM	RCM	GCM	RES	RCP	TEAM	RCM	GCM	RES	RCP
DMI	HIRHAM	ECEARTH	EUR11	RCP2.6	CLMCOM	CCLM4	HADGEM	EUR44	RCP8.5
KNMI	RACMO	HADGEM	EUR44	RCP2.6	CLMCOM	CCLM5	ECEARTH	EUR44	RCP8.5
SMHI	RCA	ECEARTH	EUR11	RCP2.6	CLMCOM	CCLM5	HADGEM	EUR44	RCP8.5
SMHI	RCA	ECEARTH	EUR44	RCP2.6	CLMCOM	CCLM5	MIROC	EUR44	RCP8.5
SMHI	RCA	HADGEM	EUR44	RCP2.6	CLMCOM	CCLM5	MPIESM	EUR44	RCP8.5
SMHI	RCA	MIROC	EUR44	RCP2.6	DMI	HIRHAM	ECEARTH	EUR11	RCP8.5
SMHI	RCA	MPIESM	EUR44	RCP2.6	DMI	HIRHAM	ECEARTH	EUR44	RCP8.5
SMHI	RCA	NORESM	EUR44	RCP2.6	KNMI	RACMO	ECEARTH	EUR44	RCP8.5
DMI	HIRHAM	ECEARTH	EUR11	RCP4.5	KNMI	RACMO	HADGEM	EUR44	RCP8.5
DMI	HIRHAM	ECEARTH	EUR44	RCP4.5	SMHI	RCA	CCCMA	EUR44	RCP8.5
KNMI	RACMO	ECEARTH	EUR44	RCP4.5	SMHI	RCA	ECEARTH	EUR11	RCP8.5
KNMI	RACMO	HADGEM	EUR44	RCP4.5	SMHI	RCA	ECEARTH	EUR44	RCP8.5
SMHI	RCA	CCCMA	EUR44	RCP4.5	SMHI	RCA	HADGEM	EUR11	RCP8.5
SMHI	RCA	ECEARTH	EUR11	RCP4.5	SMHI	RCA	HADGEM	EUR44	RCP8.5
SMHI	RCA	ECEARTH	EUR44	RCP4.5	SMHI	RCA	MIROC	EUR44	RCP8.5
SMHI	RCA	HADGEM	EUR11	RCP4.5	SMHI	RCA	MPIESM	EUR11	RCP8.5
SMHI	RCA	HADGEM	EUR44	RCP4.5	SMHI	RCA	MPIESM	EUR44	RCP8.5
SMHI	RCA	MIROC	EUR44	RCP4.5	SMHI	RCA	NORESM	EUR44	RCP8.5
SMHI	RCA	MPIESM	EUR11	RCP4.5					
SMHI	RCA	MPIESM	EUR44	RCP4.5					
SMHI	RCA	NORESM	EUR44	RCP4.5					
SMHI	RCA	NORESM	EUR44	RCP4.5					

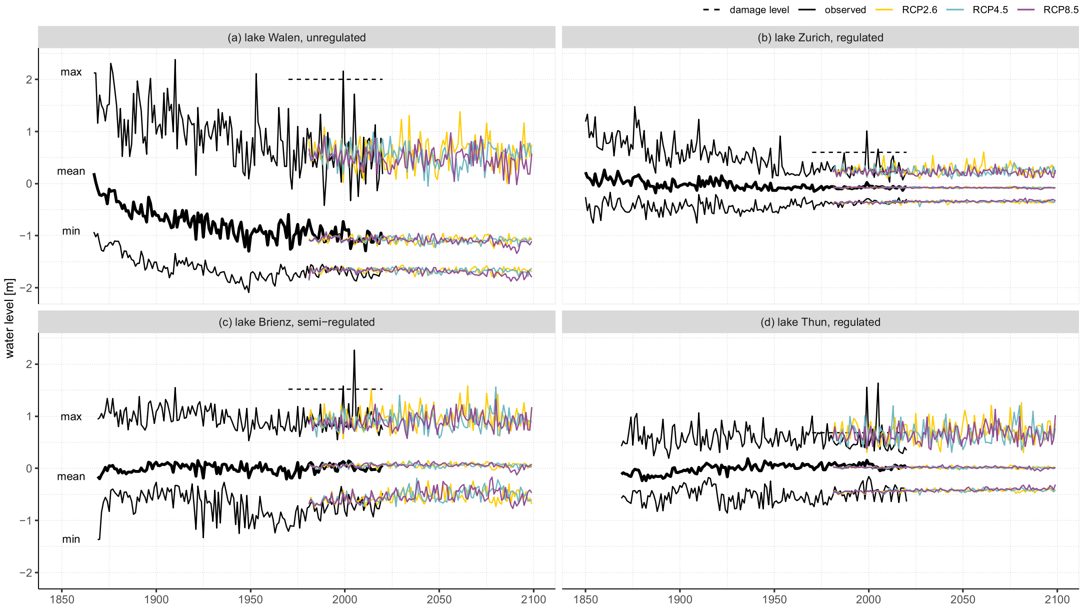

Figure SI 1: Normalised observed annual lake level variations: Shown are the observed annual mean, minimum and maximum lake levels between 1850 and 2020 (black) and the future scenarios (Section 2.5) until the end of the century under climate change (RCP2.6, RCP4.5, RCP8.5). The dashed line indicates the current flood limit for each lake.

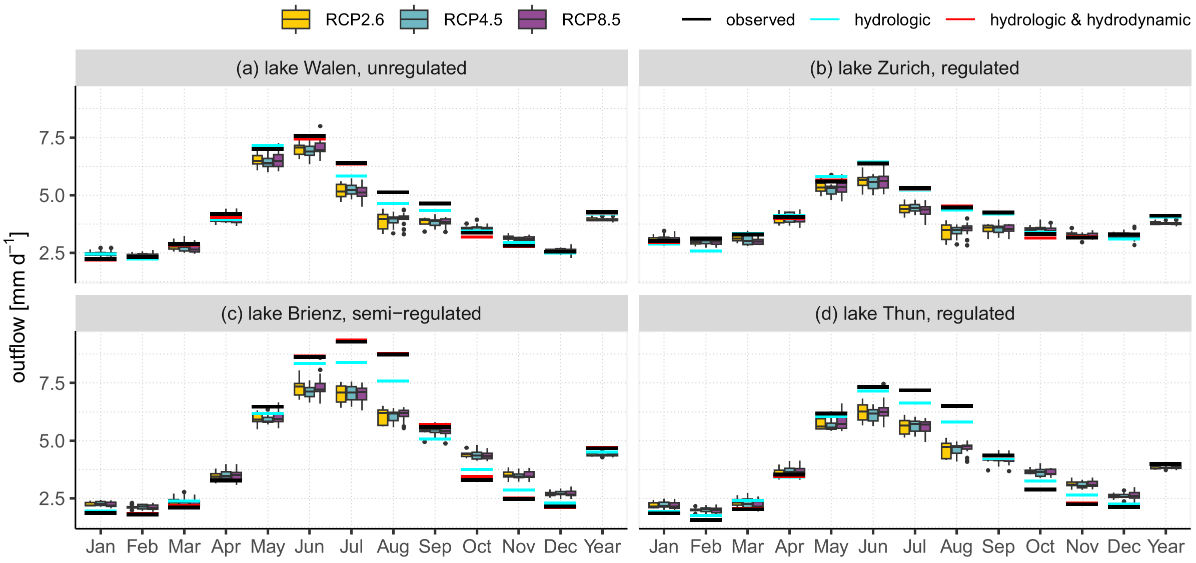

Figure SI 2: Normalised observed and simulated annual and monthly lake outflows for the four considered lakes during the reference period (1981 – 2010). The observations are compared to the hydrologic simulations with PREVAH and to the combination of the hydrologic and hydrodynamic models PREVAH and MIKE11. The coloured boxplots show the model variability of the 39 streamflow scenarios, divided into three emission scenarios (RCP2.6, RCP4.5 and RCP8.5).

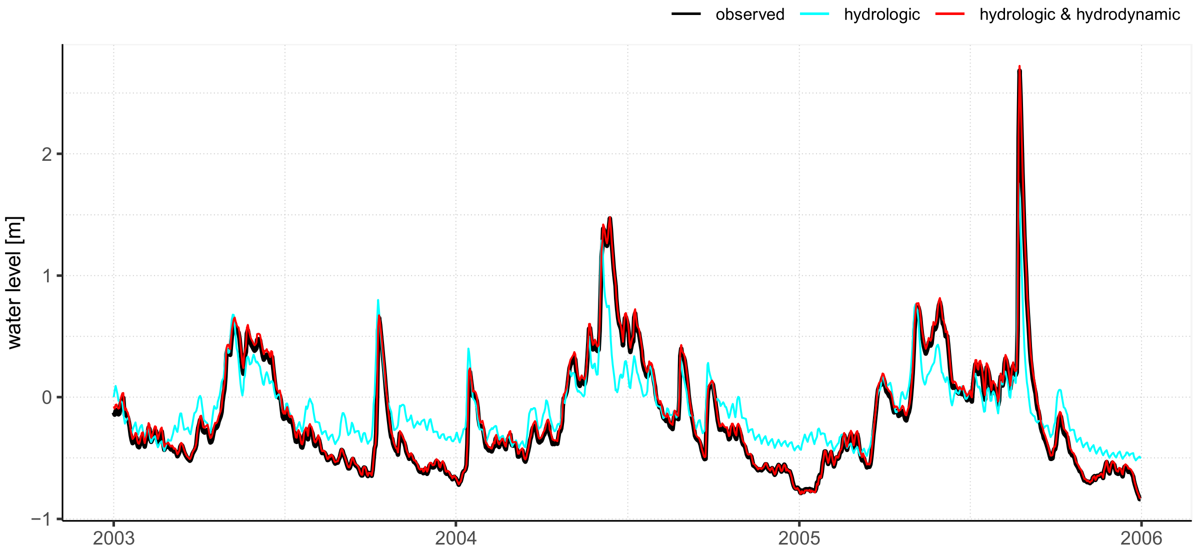

Figure SI 3: Observed and simulated lake levels of Lake Walen (2003 -– 2005). The shown simulations are computed with the hydrologic model PREVAH and the combination of the hydrologic and hydrodynamic models PREVAH and MIKE11.

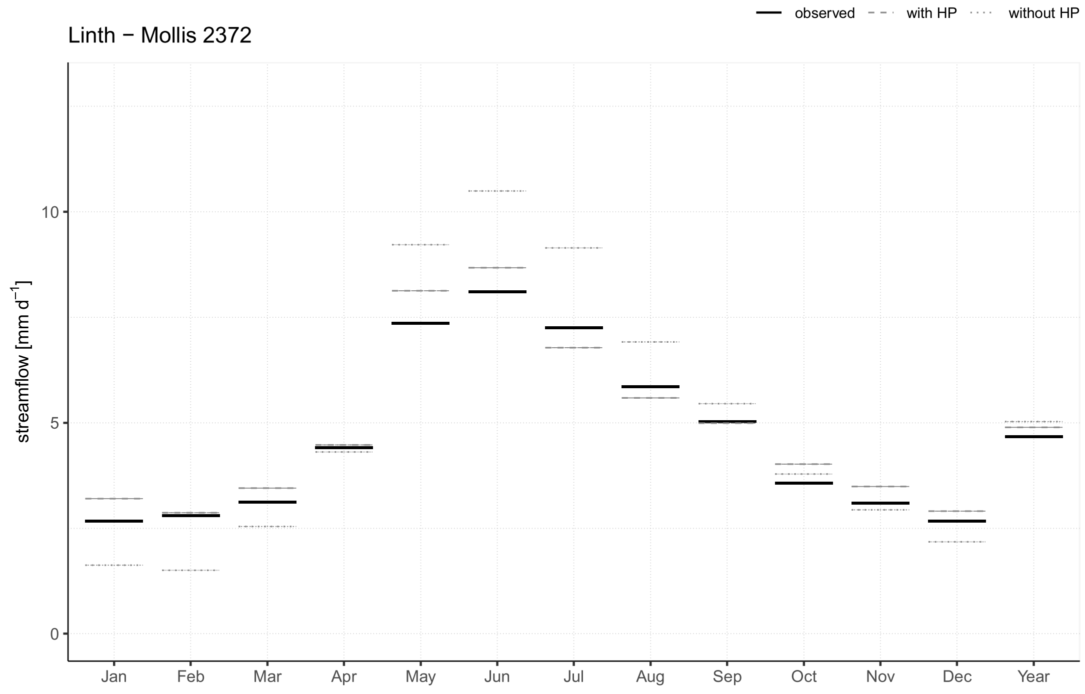

Figure SI 4: Hydropower impact in catchment I (Linth - Mollis 2372). The comparison of observed and simulated monthly mean streamflow. The black line represents the observed monthly mean streamflow, the dashed lines the simulated monthly means with and without consideration of hydropower, simulated with the hydrologic model PREVAH (section 2.5).

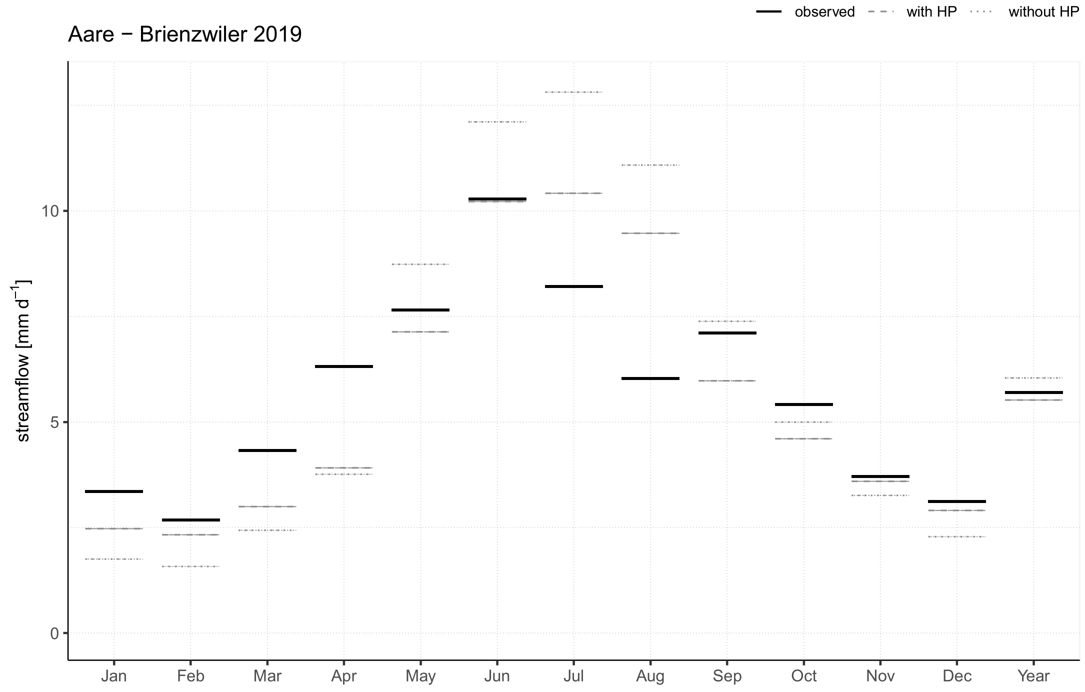

Figure SI 5: As Figure 4 but for hydropower impact in catchment II (Aare - Brienzwiler 2019).

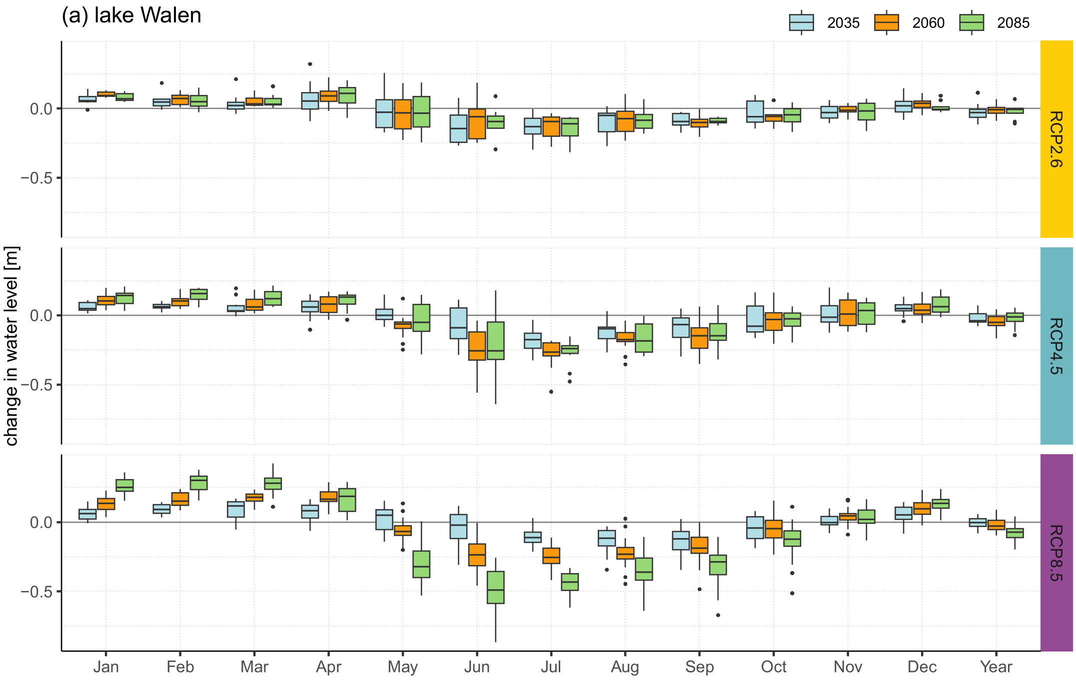

Figure SI 6: Simulated changes in annual and monthly mean lake levels of Lake Walen, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

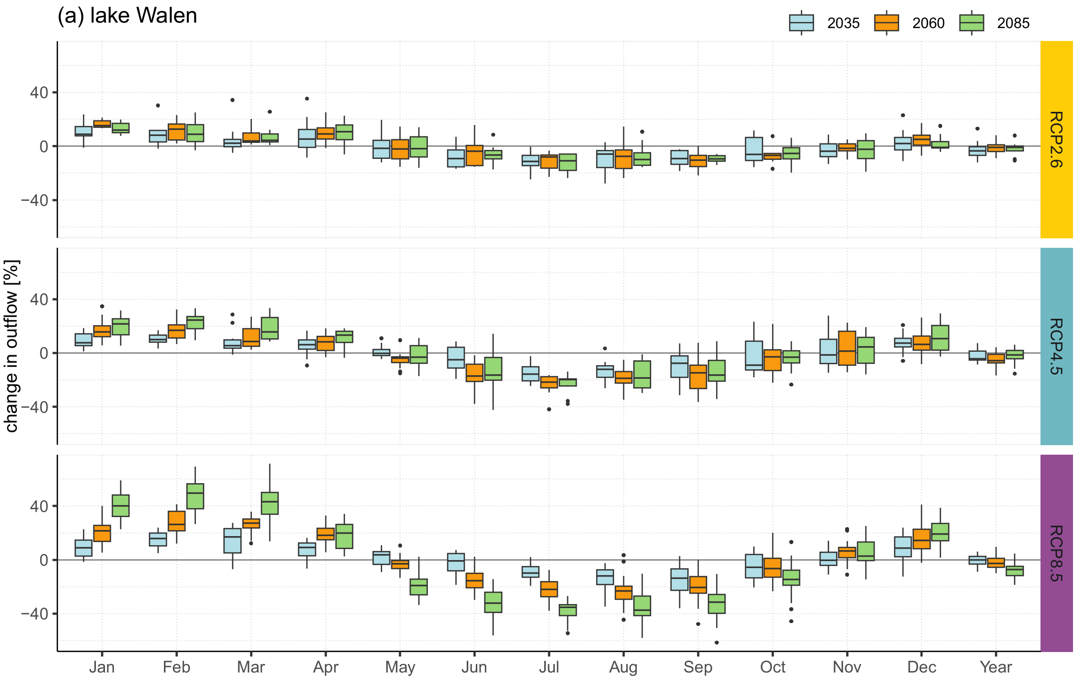

Figure SI 7: As Figure 6 but for the simulated changes in monthly and annual mean outflows of Lake Walen.

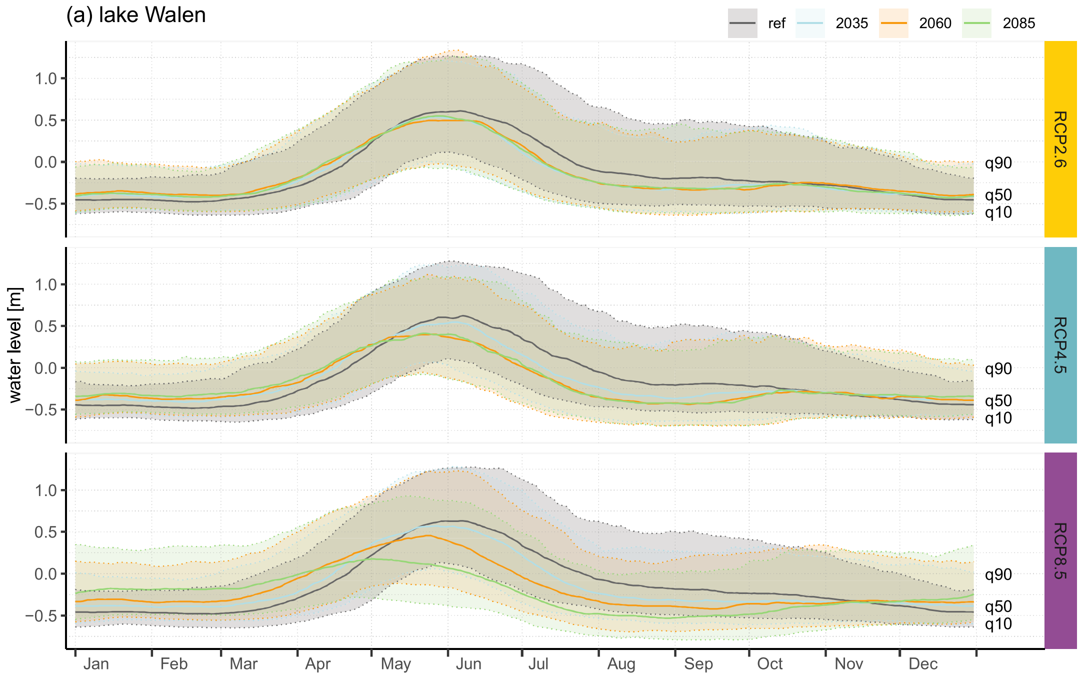

Figure SI 8: Simulated changes in the 10 % ($q10$) and 90 % ($q90$) percentiles of lake levels (moving average ±15 days) of Lake Walen, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

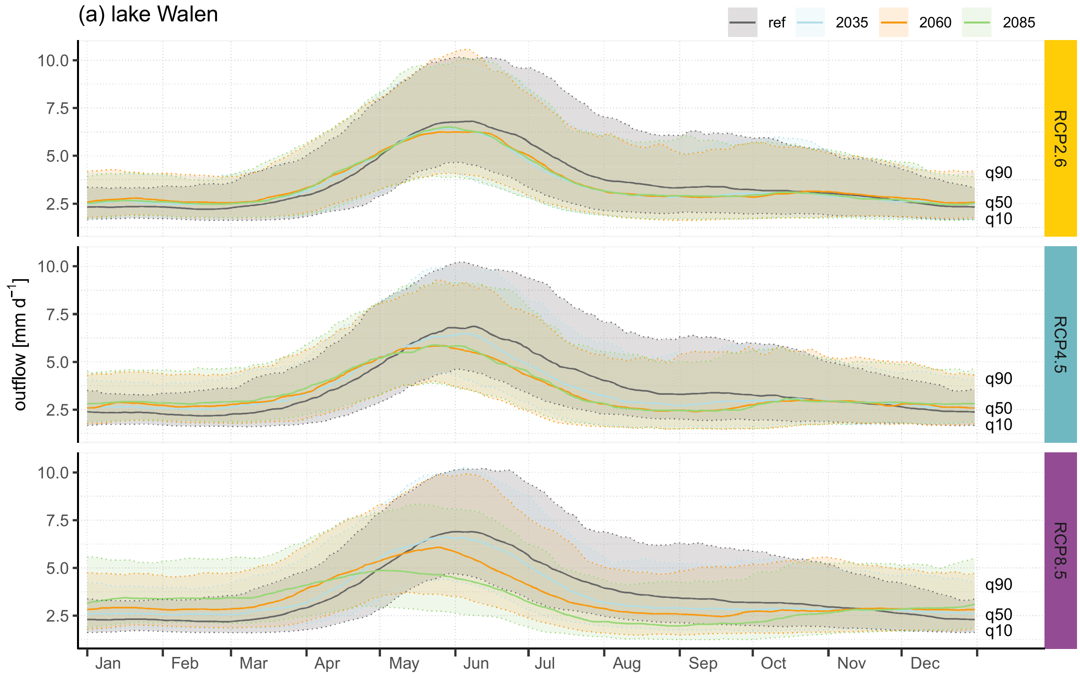

Figure SI 9: As Figure 8 but for the simulated changes in the 10 % ($q10$) and 90 % ($q90$) percentiles of outflows of Lake Walen.

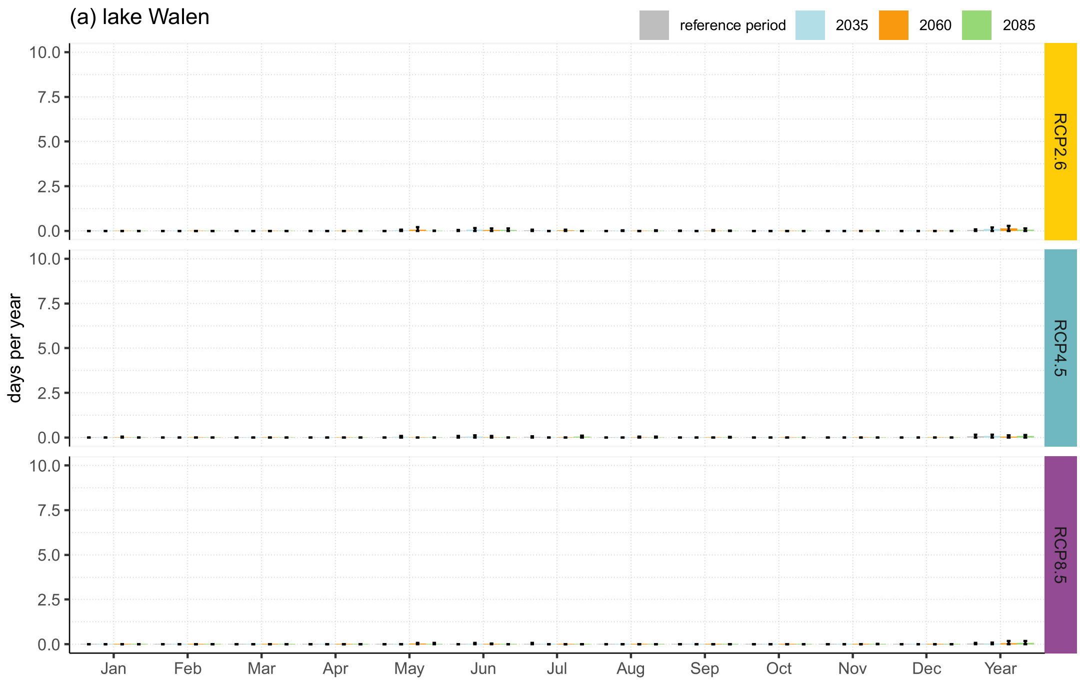

Figure SI 10: Simulated changes of the average number of days per year and month the lake level exceeds the flood limit (F) of Lake Walen. Error bars refer to the 10 % and 90 % percentile range.

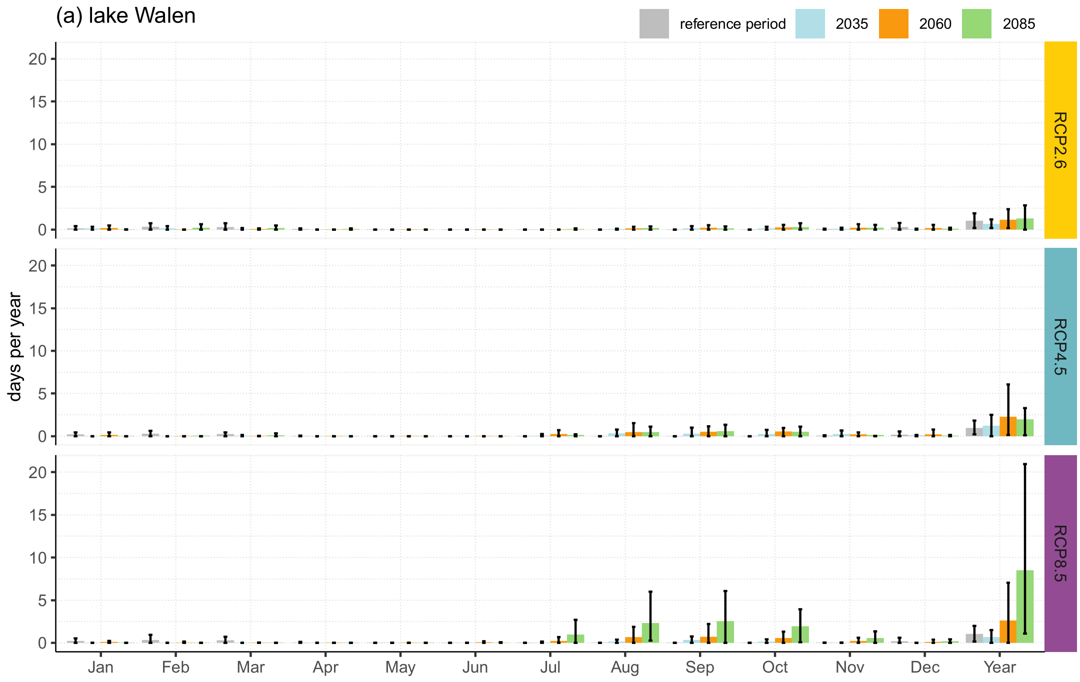

Figure SI 11: As Figure SI 10 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Walen.

Table SI 4: The seasonal and annual projections for lake levels and outflows of Lake Walen according to the three emission scenarios (RCP) and future periods. Shown are the 25 %, 50 %, and 75 % percentiles, the number of model chains projecting a decrease (neg) or increase (pos), the percentage agreement of model chains in the change signal (%), and its robustness (agree.), indicated by one asterisk for 75 % agreement and two for 100 % agreement.

Lake Walen			Lake level [m]							Outflow [%]						
season	RCP	period	q25	q50	q75	neg	pos	%	agree.	q25	q50	q75	neg	pos	%	agree.
DJF	RCP26	2035	0.01	0.03	0.07	1	7	0.88	*	2	5	10	1	7	0.88	*
DJF	RCP26	2060	0.05	0.06	0.08	0	8	1	**	8	10	12	0	8	1	**
DJF	RCP26	2085	0.03	0.05	0.06	0	8	1	**	5	7	10	0	8	1	**
DJF	RCP45	2035	0.05	0.06	0.07	0	13	1	**	7	9	10	0	13	1	**
DJF	RCP45	2060	0.05	0.09	0.11	0	13	1	**	8	14	17	0	13	1	**
DJF	RCP45	2085	0.08	0.12	0.15	0	13	1	**	13	18	24	0	13	1	**
DJF	RCP85	2035	0.05	0.06	0.09	1	17	0.94	*	7	10	15	1	17	0.94	*
DJF	RCP85	2060	0.09	0.13	0.17	0	18	1	**	14	21	26	0	18	1	**
DJF	RCP85	2085	0.18	0.24	0.25	0	18	1	**	28	37	42	0	18	1	**
MAM	RCP26	2035	-0.05	0.02	0.07	4	4	0.5		-5	2	6	4	4	0.5	
MAM	RCP26	2060	-0.02	0.05	0.07	3	5	0.62		-2	5	7	3	5	0.62	
MAM	RCP26	2085	-0.02	0.04	0.09	2	6	0.75	*	-2	4	8	2	6	0.75	*
MAM	RCP45	2035	0.02	0.03	0.06	0	13	1	**	2	4	5	0	13	1	**
MAM	RCP45	2060	0.01	0.02	0.05	3	10	0.77	*	0	2	5	3	10	0.77	*
MAM	RCP45	2085	0.02	0.06	0.11	2	11	0.85	*	2	5	10	2	11	0.85	*
MAM	RCP85	2035	0.05	0.07	0.08	1	17	0.94	*	4	7	8	1	17	0.94	*
MAM	RCP85	2060	0.08	0.09	0.12	0	18	1	**	7	9	12	0	18	1	**
MAM	RCP85	2085	0.01	0.02	0.11	4	14	0.78	*	1	3	11	4	14	0.78	*
JJA	RCP26	2035	-0.17	-0.11	-0.05	7	1	0.88	*	-13	-10	-4	7	1	0.88	*
JJA	RCP26	2060	-0.15	-0.08	-0.03	7	1	0.88	*	-12	-6	-3	6	2	0.75	*
JJA	RCP26	2085	-0.13	-0.09	-0.06	8	0	1	**	-11	-8	-5	8	0	1	**
JJA	RCP45	2035	-0.19	-0.14	-0.04	13	0	1	**	-17	-10	-3	12	1	0.92	*
JJA	RCP45	2060	-0.26	-0.24	-0.17	13	0	1	**	-22	-21	-14	13	0	1	**
JJA	RCP45	2085	-0.24	-0.20	-0.15	13	0	1	**	-19	-17	-13	13	0	1	**
JJA	RCP85	2035	-0.13	-0.08	-0.05	17	1	0.94	*	-11	-7	-4	17	1	0.94	*
JJA	RCP85	2060	-0.31	-0.26	-0.17	18	0	1	**	-24	-21	-14	18	0	1	**
JJA	RCP85	2085	-0.50	-0.40	-0.37	18	0	1	**	-40	-34	-30	18	0	1	**
SON	RCP26	2035	-0.09	-0.07	0.01	5	3	0.62		-11	-7	1	5	3	0.62	
SON	RCP26	2060	-0.09	-0.06	-0.04	8	0	1	**	-10	-6	-5	8	0	1	**
SON	RCP26	2085	-0.09	-0.06	-0.01	7	1	0.88	*	-10	-7	-1	7	1	0.88	*
SON	RCP45	2035	-0.11	-0.04	0.03	8	5	0.62		-13	-5	5	8	5	0.62	
SON	RCP45	2060	-0.14	-0.04	0.00	10	3	0.77	*	-17	-4	0	9	4	0.69	
SON	RCP45	2085	-0.11	-0.03	0.01	9	4	0.69		-12	-4	1	9	4	0.69	
SON	RCP85	2035	-0.10	-0.06	0.01	11	7	0.61		-12	-8	1	12	6	0.67	
SON	RCP85	2060	-0.11	-0.09	-0.01	14	4	0.78	*	-13	-10	-2	14	4	0.78	*
SON	RCP85	2085	-0.18	-0.14	-0.08	17	1	0.94	*	-20	-16	-9	17	1	0.94	*
Year	RCP26	2035	-0.07	-0.03	-0.01	6	2	0.75	*	-7	-3	0	6	2	0.75	*
Year	RCP26	2060	-0.03	-0.01	0.01	6	2	0.75	*	-4	-1	1	5	3	0.62	
Year	RCP26	2085	-0.04	-0.01	0.00	6	2	0.75	*	-4	-1	0	6	2	0.75	*
Year	RCP45	2035	-0.05	-0.04	0.01	7	6	0.54		-5	-4	2	7	6	0.54	
Year	RCP45	2060	-0.08	-0.05	-0.01	10	3	0.77	*	-7	-6	-1	10	3	0.77	*
Year	RCP45	2085	-0.04	-0.01	0.02	8	5	0.62		-4	-2	2	8	5	0.62	
Year	RCP85	2035	-0.03	0.01	0.03	8	9	0.53		-3	1	3	8	9	0.53	
Year	RCP85	2060	-0.05	-0.03	0.01	11	6	0.65		-5	-2	1	11	6	0.65	
Year	RCP85	2085	-0.10	-0.07	-0.05	15	2	0.88	*	-11	-7	-4	15	2	0.88	*

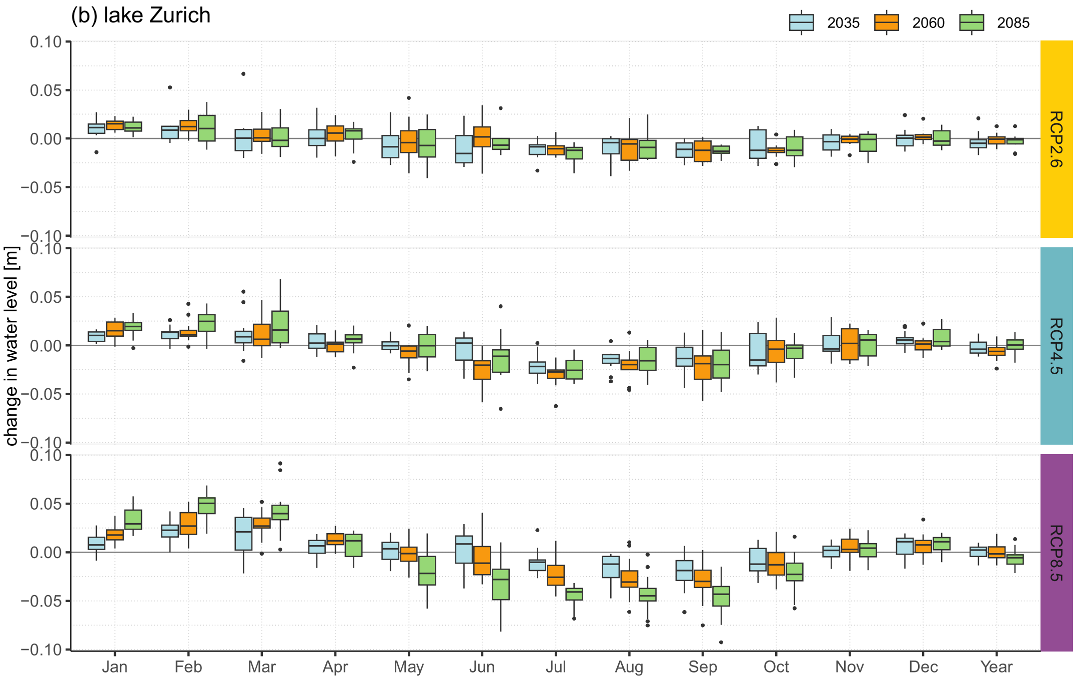

Figure SI 12: Simulated changes in monthly and annual mean lake levels of lake Zurich, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

Figure SI 13: As Figure SI 12 but for the simulated changes in monthly and annual mean outflows of Lake Zurich.

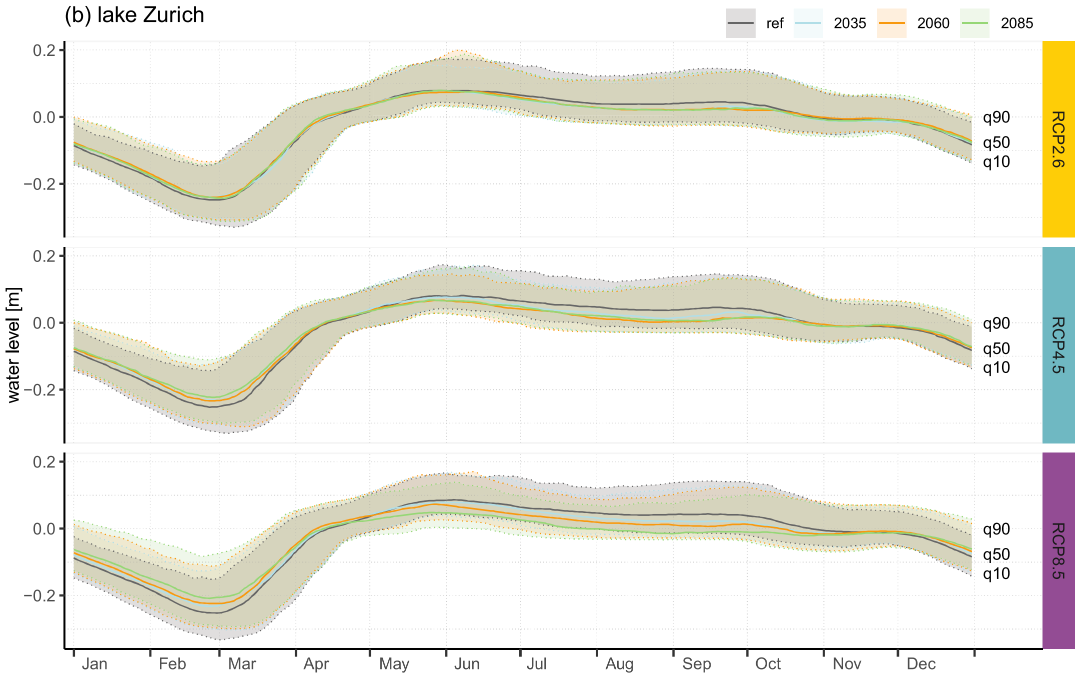

Figure SI 14: Simulated changes in the 10 % and 90 % percentiles of lake levels (moving average ±15 days) of Lake Zurich, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

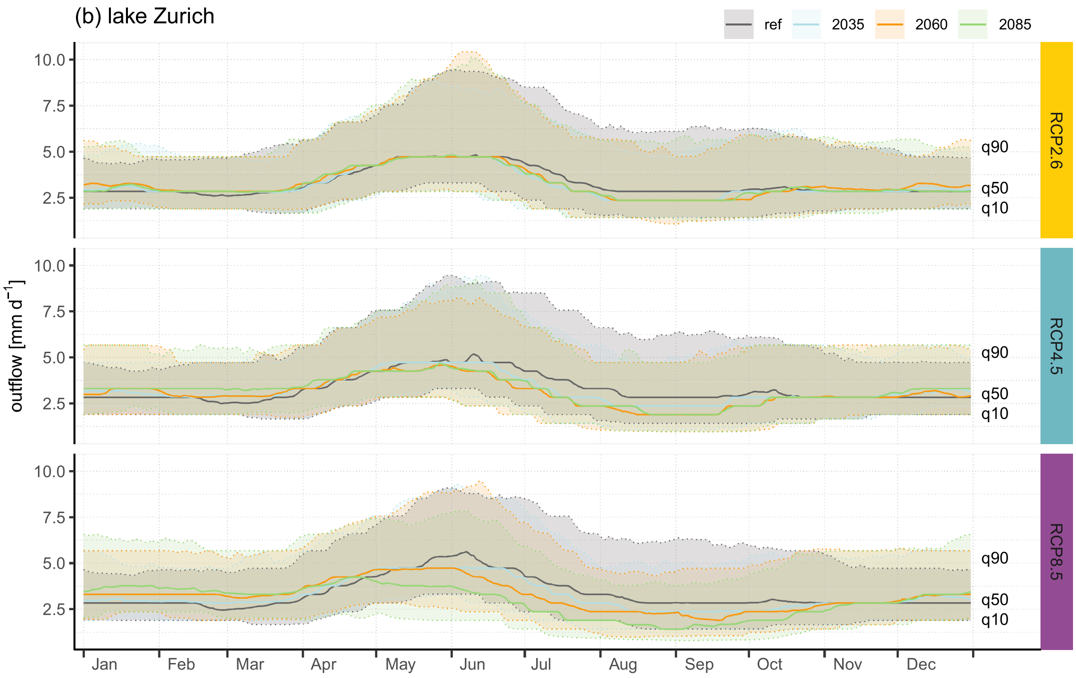

Figure SI 15: As Figure SI 14 but for the simulated changes in the 10 % and 90 % percentiles of outflows of Lake Zurich.

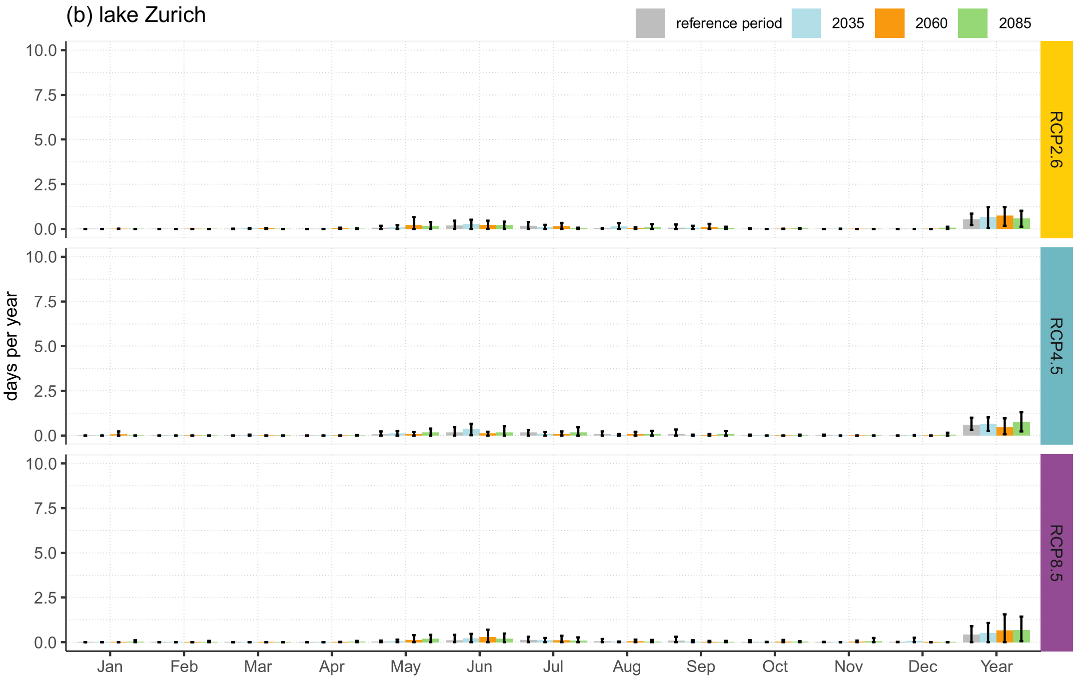

Figure SI 16: Simulated changes of the average number of days per year and month the lake level exceeds the flood limit (F) of Lake Zurich. Error bars refer to the 10 % and 90 % percentile range.

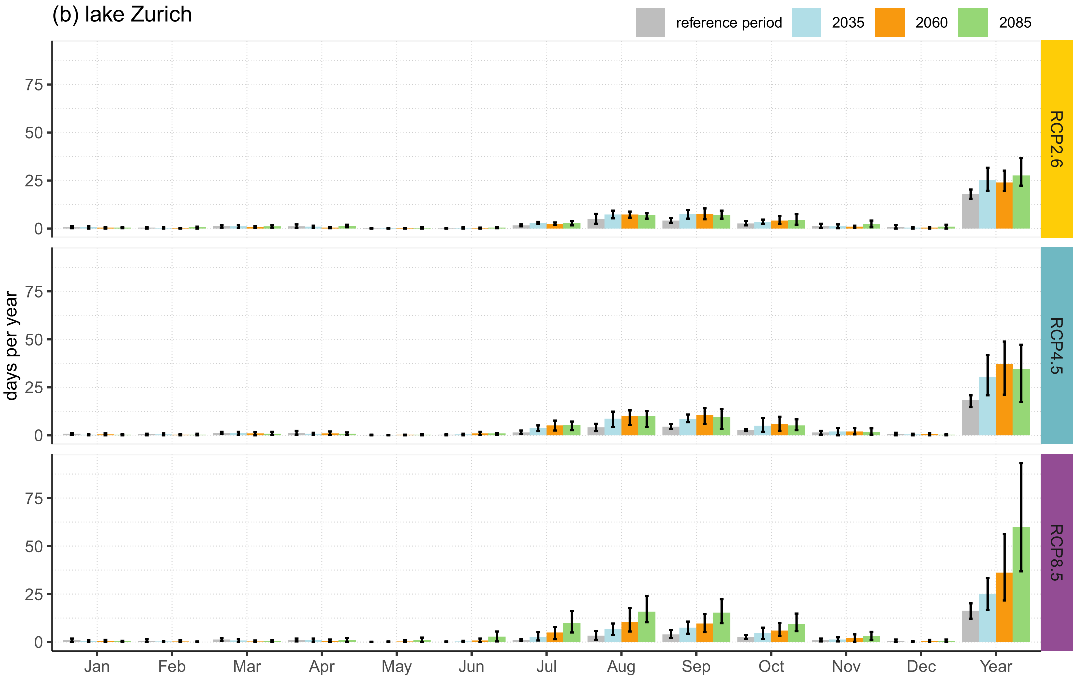

Figure SI 17: As Figure SI 16 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Zurich.

Table SI 5: The seasonal and annual projections for lake levels and outflows of Lake Zurich according to the three emission scenarios (RCP) and future periods. Shown are the 25 %, 50 %, and 75 % percentiles, the number of model chains projecting a decrease (neg) or increase (pos), the percentage agreement of model chains in the change signal (%), and its robustness (agree.), indicated by one asterisk for 75 % agreement and two for 100 % agreement.

Lake Zurich			Lake level [m]							Outflow [%]						
season	RCP	period	q25	q50	q75	neg	pos	%	agree.	q25	q50	q75	neg	pos	%	agree.
DJF	RCP26	2035	0.00	0.00	0.01	1	7	0.88	*	2	2	6	1	7	0.88	*
DJF	RCP26	2060	0.01	0.01	0.01	0	8	1	**	4	5	10	0	8	1	**
DJF	RCP26	2085	0.00	0.01	0.01	2	6	0.75	*	2	4	11	2	6	0.75	*
DJF	RCP45	2035	0.01	0.01	0.01	1	12	0.92	*	6	6	8	1	12	0.92	*
DJF	RCP45	2060	0.01	0.01	0.02	1	12	0.92	*	5	8	12	2	11	0.85	*
DJF	RCP45	2085	0.01	0.02	0.02	1	12	0.92	*	7	13	15	1	12	0.92	*
DJF	RCP85	2035	0.01	0.01	0.02	1	17	0.94	*	5	7	14	1	17	0.94	*
DJF	RCP85	2060	0.01	0.02	0.03	0	18	1	**	7	14	20	0	18	1	**
DJF	RCP85	2085	0.02	0.03	0.04	0	18	1	**	14	23	29	0	18	1	**
MAM	RCP26	2035	-0.01	0.00	0.01	4	4	0.5		-8	-3	5	4	4	0.5	
MAM	RCP26	2060	-0.01	0.00	0.01	3	5	0.62		-6	1	4	4	4	0.5	
MAM	RCP26	2085	-0.01	0.00	0.00	4	4	0.5		-5	1	4	3	5	0.62	
MAM	RCP45	2035	0.00	0.00	0.01	5	8	0.62		-1	0	4	6	7	0.54	
MAM	RCP45	2060	0.00	0.00	0.00	8	5	0.62		-4	-2	1	8	5	0.62	
MAM	RCP45	2085	0.00	0.01	0.02	5	8	0.62		-2	2	9	6	7	0.54	
MAM	RCP85	2035	0.00	0.01	0.01	3	15	0.83	*	2	4	7	3	15	0.83	*
MAM	RCP85	2060	0.01	0.01	0.02	1	17	0.94	*	5	7	8	3	15	0.83	*
MAM	RCP85	2085	0.00	0.01	0.02	4	14	0.78	*	-5	-1	8	10	8	0.56	
JJA	RCP26	2035	-0.02	-0.01	0.00	6	2	0.75	*	-13	-9	-3	7	1	0.88	*
JJA	RCP26	2060	-0.01	-0.01	0.00	5	3	0.62		-10	-6	1	6	2	0.75	*
JJA	RCP26	2085	-0.01	-0.01	0.00	6	2	0.75	*	-9	-6	-3	6	2	0.75	*
JJA	RCP45	2035	-0.02	-0.02	-0.01	13	0	1	**	-18	-11	-6	12	1	0.92	*
JJA	RCP45	2060	-0.03	-0.02	-0.02	13	0	1	**	-21	-18	-13	13	0	1	**
JJA	RCP45	2085	-0.02	-0.02	-0.01	13	0	1	**	-17	-12	-10	13	0	1	**
JJA	RCP85	2035	-0.02	-0.01	0.00	14	4	0.78	*	-12	-4	-1	14	4	0.78	*
JJA	RCP85	2060	-0.03	-0.02	-0.01	16	2	0.89	*	-24	-16	-10	17	1	0.94	*
JJA	RCP85	2085	-0.05	-0.04	-0.03	18	0	1	**	-39	-31	-27	18	0	1	**
SON	RCP26	2035	-0.02	-0.01	0.00	5	3	0.62		-12	-9	2	5	3	0.62	
SON	RCP26	2060	-0.01	-0.01	0.00	8	0	1	**	-12	-7	-5	8	0	1	**
SON	RCP26	2085	-0.02	-0.01	0.00	6	2	0.75	*	-11	-8	-1	6	2	0.75	*
SON	RCP45	2035	-0.02	-0.01	0.01	8	5	0.62		-15	-5	7	8	5	0.62	
SON	RCP45	2060	-0.02	-0.01	0.00	10	3	0.77	*	-17	-5	0	9	4	0.69	
SON	RCP45	2085	-0.02	-0.01	0.00	8	5	0.62		-11	-3	2	9	4	0.69	
SON	RCP85	2035	-0.02	-0.01	0.00	11	7	0.61		-14	-11	1	12	6	0.67	
SON	RCP85	2060	-0.02	-0.02	0.00	14	4	0.78	*	-16	-13	-3	15	3	0.83	*
SON	RCP85	2085	-0.03	-0.03	-0.01	17	1	0.94	*	-25	-20	-10	17	1	0.94	*
Year	RCP26	2035	-0.01	-0.01	0.00	6	2	0.75	*	-8	-4	-1	6	2	0.75	*
Year	RCP26	2060	-0.01	0.00	0.00	4	4	0.5		-5	-1	0	6	2	0.75	*
Year	RCP26	2085	-0.01	0.00	0.00	6	2	0.75	*	-4	-1	0	6	2	0.75	*
Year	RCP45	2035	-0.01	0.00	0.00	7	6	0.54		-6	-5	2	8	5	0.62	
Year	RCP45	2060	-0.01	-0.01	0.00	10	3	0.77	*	-8	-6	-3	10	3	0.77	*
Year	RCP45	2085	0.00	0.00	0.01	6	7	0.54		-4	-2	2	8	5	0.62	
Year	RCP85	2035	0.00	0.00	0.01	6	11	0.65		-4	1	4	8	9	0.53	
Year	RCP85	2060	0.00	0.00	0.01	10	7	0.59		-6	-2	1	11	6	0.65	
Year	RCP85	2085	-0.01	-0.01	0.00	14	3	0.82	*	-13	-8	-5	16	1	0.94	*

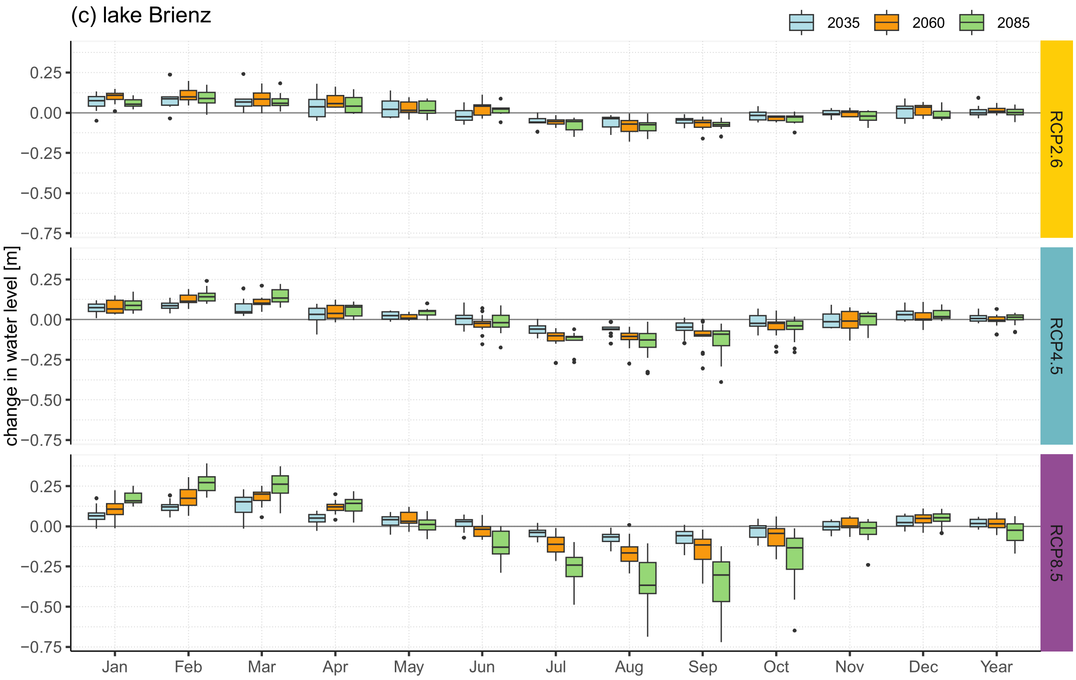

Figure SI 18: Simulated changes in monthly and annual mean lake levels of Lake Brienz, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

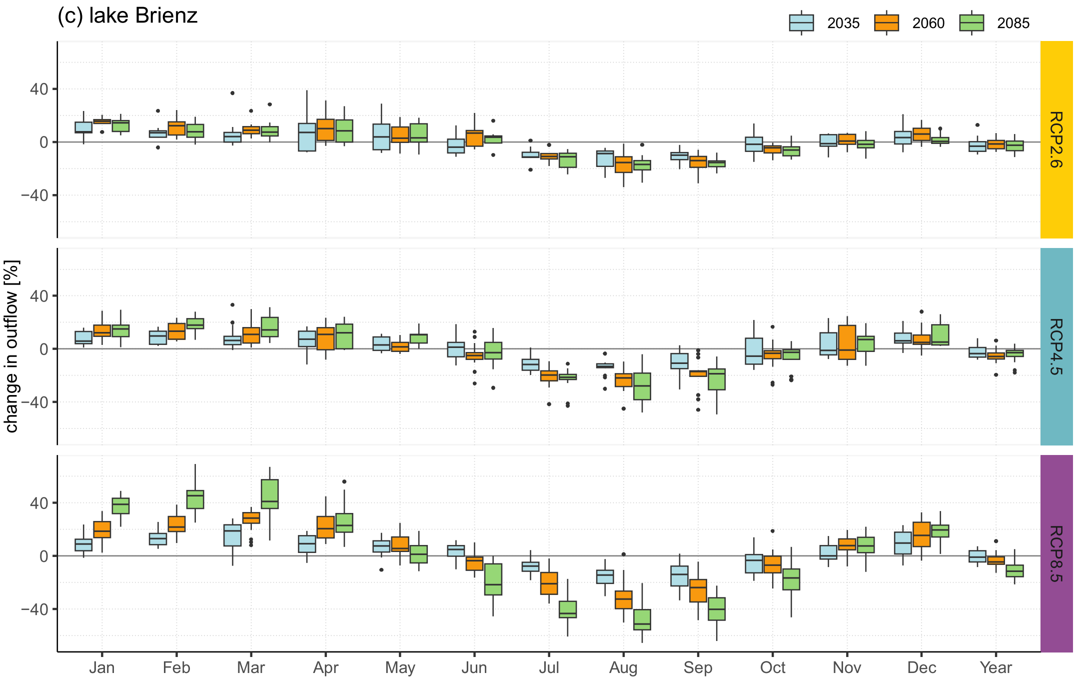

Figure SI 19: As Figure SI 18 but for the simulated changes in monthly and annual mean outflows of Lake Brienz.

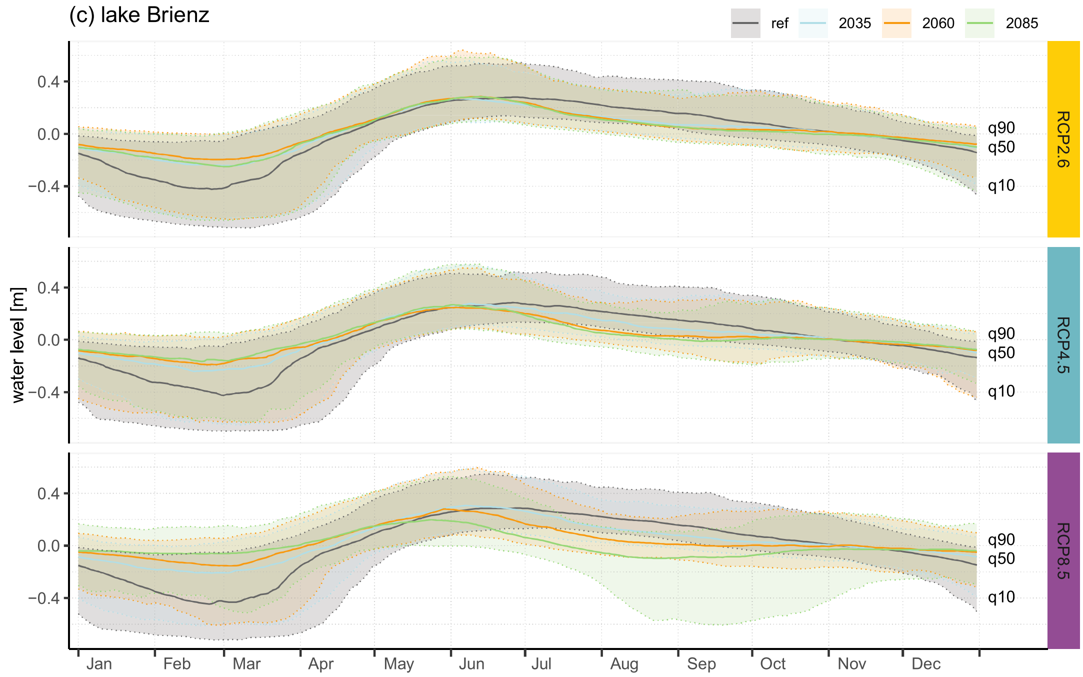

Figure SI 20: Simulated changes in the 10 % and 90 % percentiles of lake levels (moving average ±15 days) of Lake Brienz, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

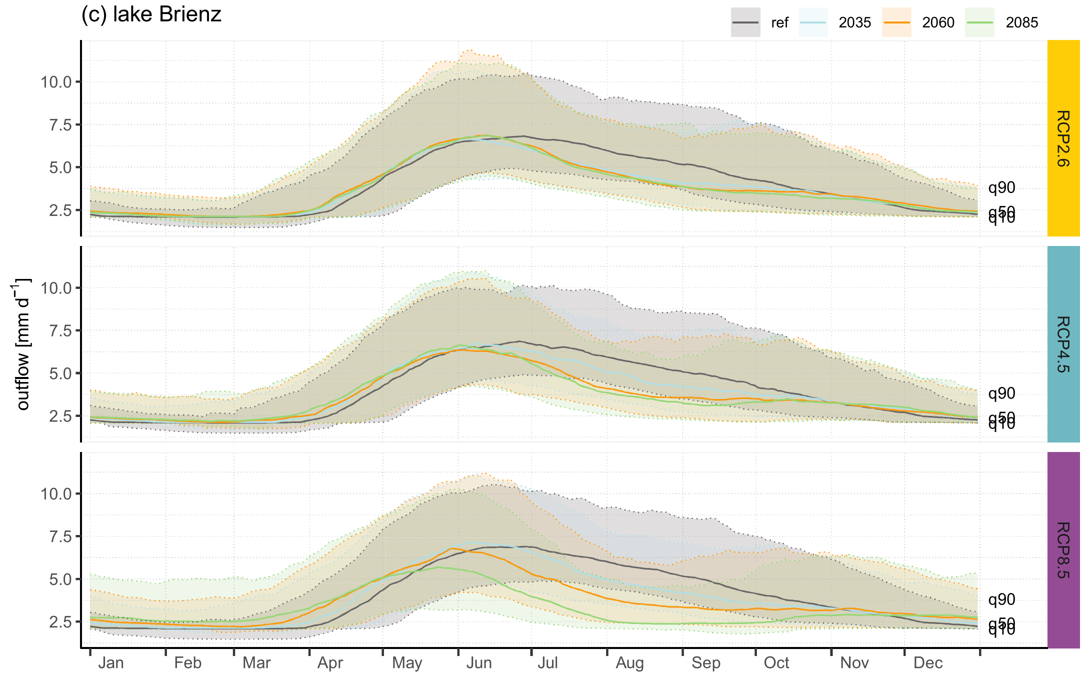

Figure SI 21: As Figure SI 20 but for the simulated changes in the 10 % and 90 % percentiles of outflows of Lake Brienz.

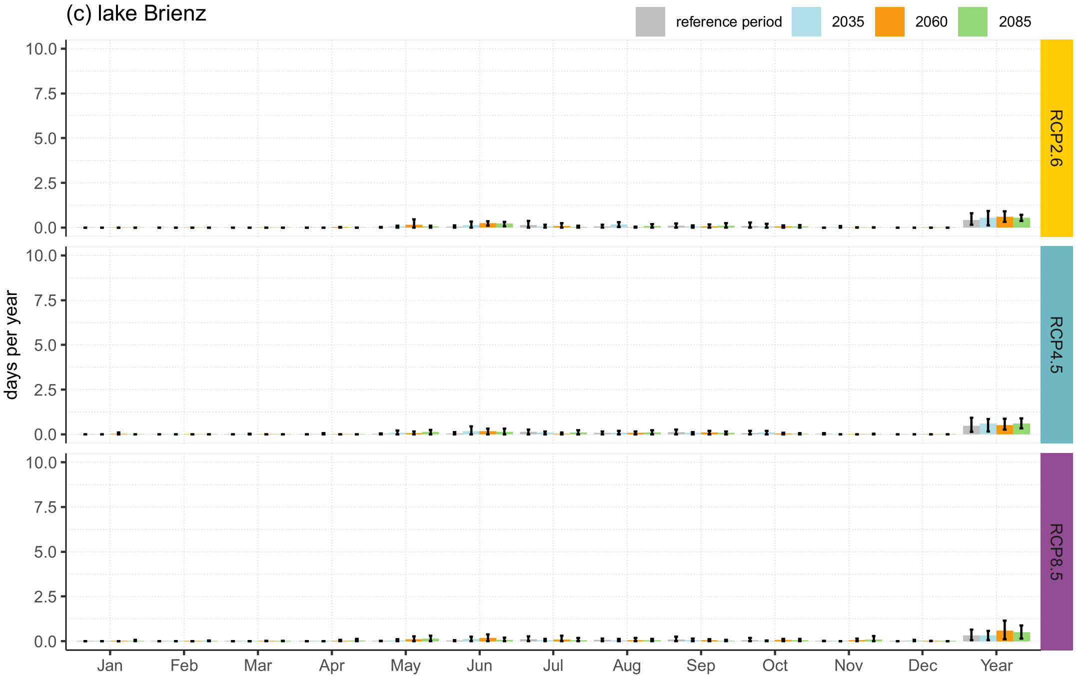

Figure SI 22: Simulated changes of the average number of days per year and month the lake level exceeds the flood limit (F) of Lake Brienz. Error bars refer to the 10 % and 90 % percentile range.

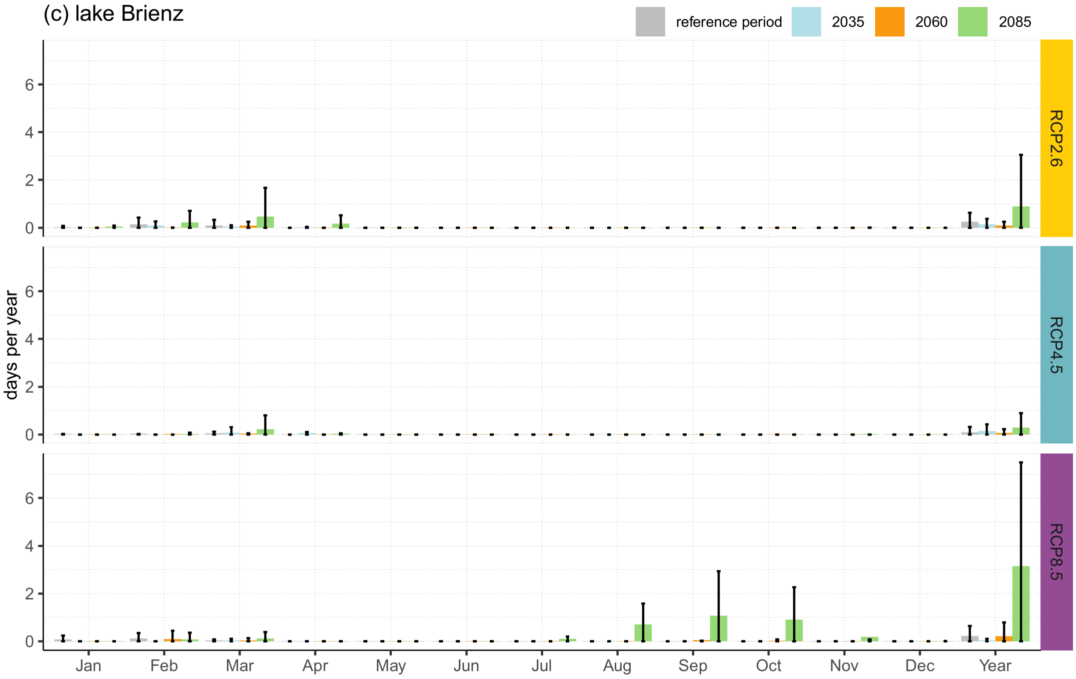

Figure SI 23: As Figure SI 22 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Brienz.

Table SI 6: The seasonal and annual projections for lake levels and outflows of Lake Brienz according to the three emission scenarios (RCP) and future periods. Shown are the 25 %, 50 %, and 75 % percentiles, the number of model chains projecting a decrease (neg) or increase (pos), the percentage agreement of model chains in the change signal (%), and its robustness (agree.), indicated by one asterisk for 75 % agreement and two for 100 % agreement.

Lake Brienz			Lake level [m]							Outflow [%]						
season	RCP	period	q25	q50	q75	neg	pos	%	agree.	q25	q50	q75	neg	pos	%	agree.
DJF	RCP26	2035	0.02	0.05	0.08	1	7	0.88	*	1	6	10	1	7	0.88	*
DJF	RCP26	2060	0.05	0.08	0.11	0	8	1	**	9	11	14	0	8	1	**
DJF	RCP26	2085	0.03	0.05	0.06	1	7	0.88	*	5	8	8	0	8	1	**
DJF	RCP45	2035	0.04	0.06	0.08	0	13	1	**	6	7	11	0	13	1	**
DJF	RCP45	2060	0.05	0.06	0.09	0	13	1	**	6	12	14	0	13	1	**
DJF	RCP45	2085	0.06	0.08	0.11	0	13	1	**	11	12	19	0	13	1	**
DJF	RCP85	2035	0.05	0.07	0.09	0	18	1	**	7	8	15	1	17	0.94	*
DJF	RCP85	2060	0.07	0.12	0.14	0	18	1	**	12	19	25	0	18	1	**
DJF	RCP85	2085	0.13	0.16	0.19	0	18	1	**	23	33	35	0	18	1	**
MAM	RCP26	2035	-0.01	0.04	0.08	3	5	0.62		-5	6	11	3	5	0.62	
MAM	RCP26	2060	0.04	0.05	0.08	0	8	1	**	3	7	11	1	7	0.88	*
MAM	RCP26	2085	0.01	0.04	0.08	0	8	1	**	1	7	12	2	6	0.75	*
MAM	RCP45	2035	0.02	0.04	0.06	1	12	0.92	*	2	6	7	0	13	1	**
MAM	RCP45	2060	0.04	0.05	0.07	0	13	1	**	1	5	9	0	13	1	**
MAM	RCP45	2085	0.06	0.08	0.10	0	13	1	**	8	10	12	0	13	1	**
MAM	RCP85	2035	0.06	0.07	0.09	0	18	1	**	6	8	11	0	18	1	**
MAM	RCP85	2060	0.10	0.12	0.14	0	18	1	**	11	14	19	0	18	1	**
MAM	RCP85	2085	0.10	0.14	0.17	0	18	1	**	10	17	23	0	18	1	**
JJA	RCP26	2035	-0.07	-0.04	-0.02	6	2	0.75	*	-12	-8	-4	6	2	0.75	*
JJA	RCP26	2060	-0.07	-0.03	-0.01	7	1	0.88	*	-12	-6	-3	7	1	0.88	*
JJA	RCP26	2085	-0.08	-0.03	-0.02	8	0	1	**	-14	-7	-4	8	0	1	**
JJA	RCP45	2035	-0.06	-0.05	-0.02	11	2	0.85	*	-12	-10	-3	11	2	0.85	*
JJA	RCP45	2060	-0.10	-0.08	-0.06	13	0	1	**	-20	-15	-12	13	0	1	**
JJA	RCP45	2085	-0.12	-0.08	-0.07	12	1	0.92	*	-22	-15	-14	12	1	0.92	*
JJA	RCP85	2035	-0.06	-0.03	-0.02	14	4	0.78	*	-11	-6	-4	14	4	0.78	*
JJA	RCP85	2060	-0.14	-0.11	-0.06	17	1	0.94	*	-25	-20	-10	17	1	0.94	*
JJA	RCP85	2085	-0.30	-0.25	-0.18	18	0	1	**	-41	-38	-29	18	0	1	**
SON	RCP26	2035	-0.04	-0.03	-0.01	6	2	0.75	*	-9	-6	-2	6	2	0.75	*
SON	RCP26	2060	-0.05	-0.03	-0.03	8	0	1	**	-10	-8	-6	8	0	1	**
SON	RCP26	2085	-0.06	-0.04	-0.03	8	0	1	**	-11	-10	-7	8	0	1	**
SON	RCP45	2035	-0.05	-0.02	0.00	8	5	0.62		-10	-6	2	8	5	0.62	
SON	RCP45	2060	-0.05	-0.04	-0.03	10	3	0.77	*	-10	-6	-3	10	3	0.77	*
SON	RCP45	2085	-0.06	-0.04	-0.04	13	0	1	**	-10	-7	-6	13	0	1	**
SON	RCP85	2035	-0.06	-0.02	0.00	14	4	0.78	*	-14	-6	-1	13	5	0.72	
SON	RCP85	2060	-0.12	-0.06	-0.02	15	3	0.83	*	-17	-10	-2	15	3	0.83	*
SON	RCP85	2085	-0.26	-0.15	-0.09	18	0	1	**	-25	-20	-13	18	0	1	**
Year	RCP26	2035	-0.01	0.00	0.02	4	4	0.5		-7	-3	0	6	2	0.75	*
Year	RCP26	2060	0.00	0.01	0.03	2	6	0.75	*	-5	-1	1	4	4	0.5	
Year	RCP26	2085	-0.01	0.00	0.02	4	4	0.5		-7	-2	1	5	3	0.62	
Year	RCP45	2035	-0.01	0.01	0.03	6	7	0.54		-6	-3	1	7	6	0.54	
Year	RCP45	2060	-0.01	0.00	0.02	7	6	0.54		-8	-6	-3	10	3	0.77	*
Year	RCP45	2085	0.00	0.02	0.03	5	8	0.62		-6	-3	-1	10	3	0.77	*
Year	RCP85	2035	0.00	0.02	0.04	5	12	0.71		-4	0	4	9	8	0.53	
Year	RCP85	2060	-0.01	0.02	0.05	6	11	0.65		-6	-4	-1	13	4	0.76	*
Year	RCP85	2085	-0.08	-0.02	0.02	11	6	0.65		-14	-11	-7	14	3	0.82	*

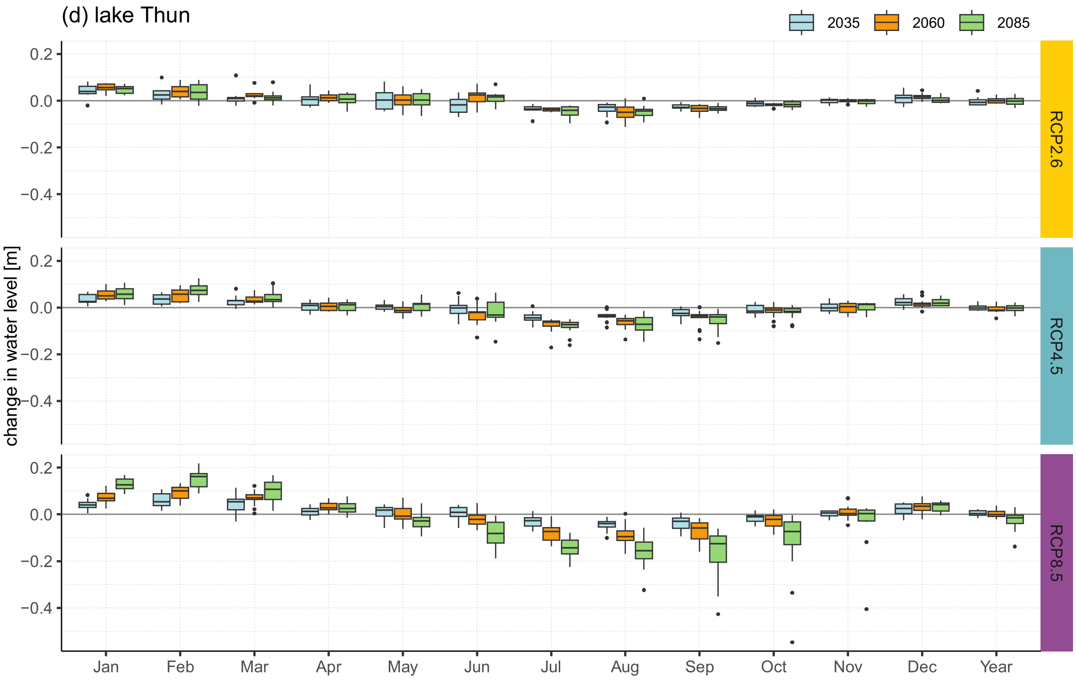

Figure SI 24: Simulated changes in monthly and annual mean lake levels of lake Thun, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

Figure SI 25: As Figure SI 24 but for the simulated changes in monthly and annual mean outflows of Lake Thun.

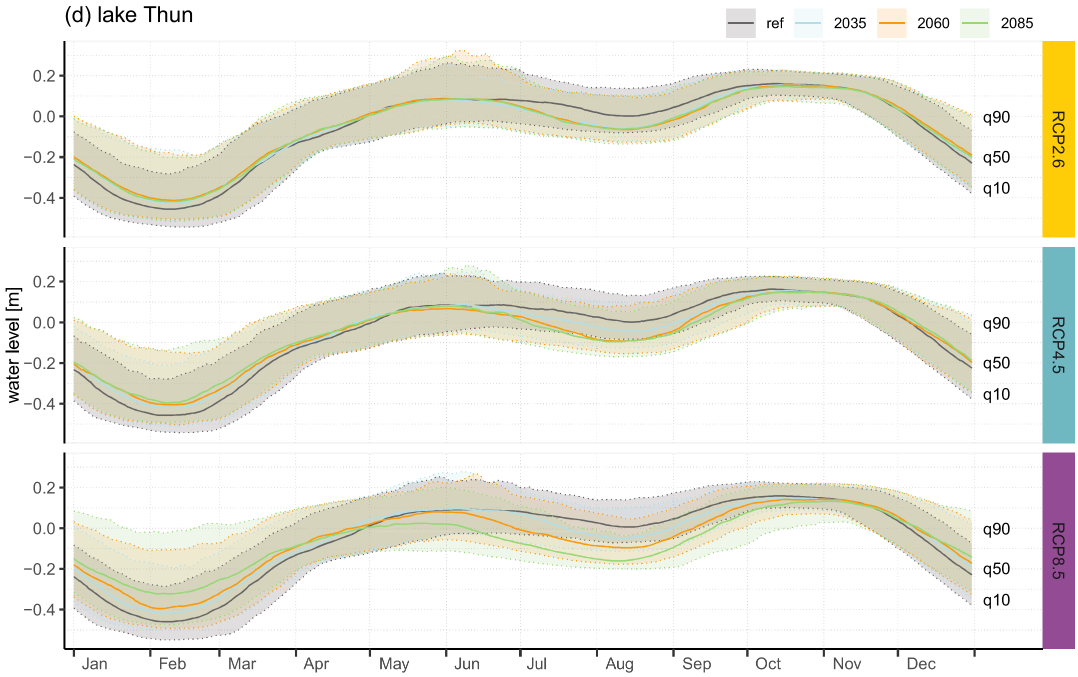

Figure SI 26: Simulated changes in the 10 % and 90 % percentiles of lake levels (moving average ±15 days) of Lake Thun, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

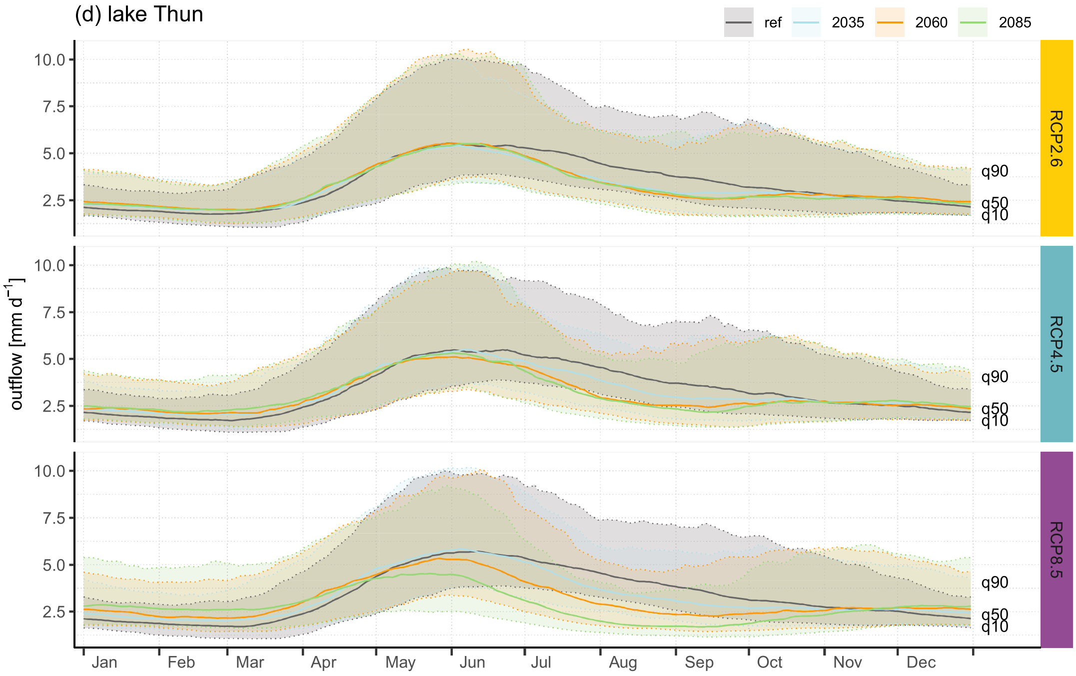

Figure SI 27: As Figure SI 26 but for the simulated changes in the 10 % and 90 % percentiles of outflows of lake Thun.

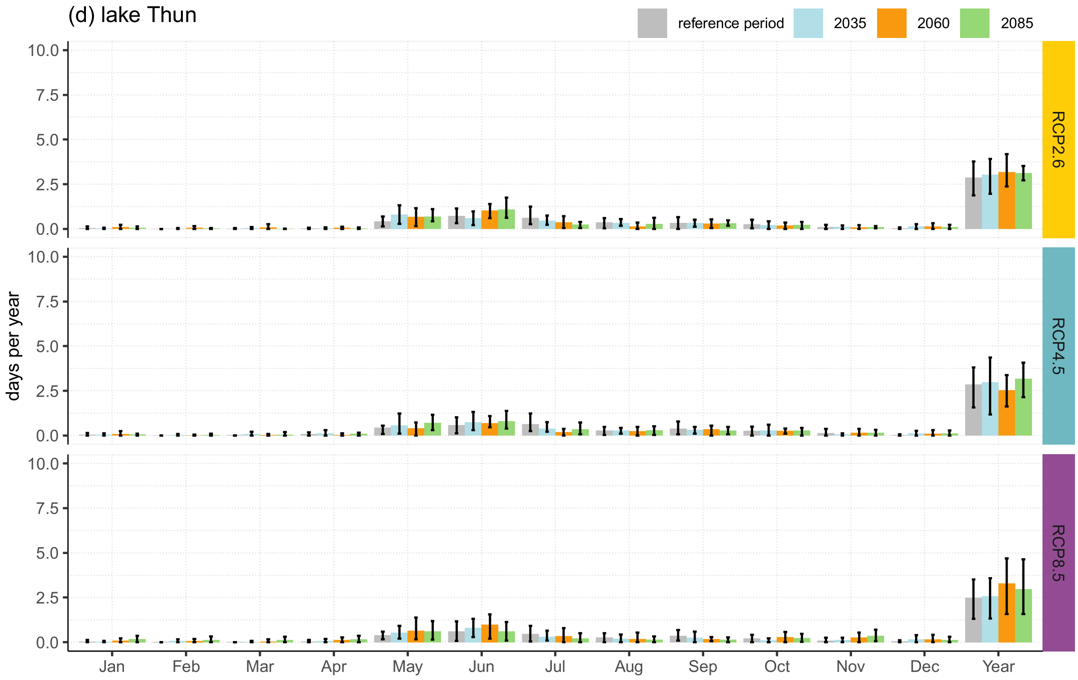

Figure SI 28: Simulated changes of the average number of days per year and month the lake level exceeds the flood limit (F) of Lake Thun. Error bars refer to the 10 % and 90 % percentile range.

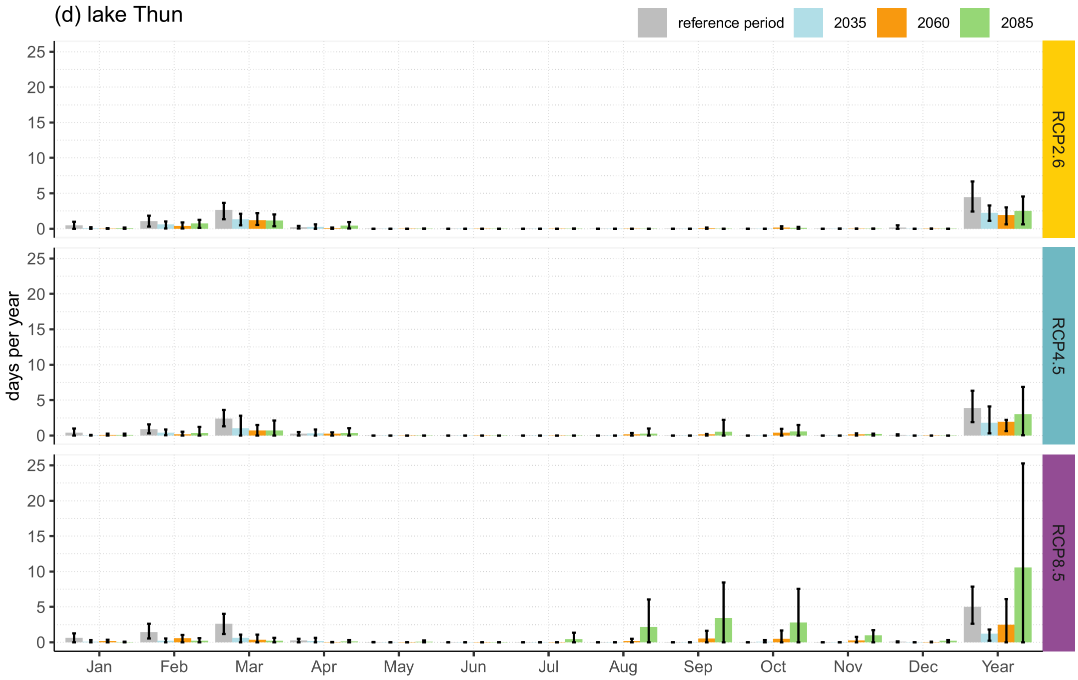

Figure SI 29: As Figure SI 28 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Thun.

Table SI 7: The seasonal and annual projections for lake levels and outflows of Lake Thun according to the three emission scenarios (RCP) and future periods. Shown are the 25 %, 50 %, and 75 % percentiles, the number of model chains projecting a decrease (neg) or increase (pos), the percentage agreement of model chains in the change signal (%), and its robustness (agree.), indicated by one asterisk for 75 % agreement and two for 100 % agreement.

Lake Thun			Lake level [m]							Outflow [%]						
season	RCP	period	q25	q50	q75	neg	pos	%	agree.	q25	q50	q75	neg	pos	%	agree.
DJF	RCP26	2035	0.02	0.02	0.03	1	7	0.88	*	4	8	12	1	7	0.88	*
DJF	RCP26	2060	0.03	0.04	0.04	0	8	1	**	10	12	14	0	8	1	**
DJF	RCP26	2085	0.02	0.02	0.04	0	8	1	**	6	8	14	0	8	1	**
DJF	RCP45	2035	0.03	0.03	0.04	0	13	1	**	9	10	12	0	13	1	**
DJF	RCP45	2060	0.03	0.05	0.05	0	13	1	**	8	15	18	0	13	1	**
DJF	RCP45	2085	0.04	0.06	0.07	0	13	1	**	12	18	20	0	13	1	**
DJF	RCP85	2035	0.03	0.04	0.05	0	18	1	**	9	11	18	1	17	0.94	*
DJF	RCP85	2060	0.05	0.06	0.08	0	18	1	**	15	23	30	0	18	1	**
DJF	RCP85	2085	0.08	0.11	0.12	0	18	1	**	27	37	45	0	18	1	**
MAM	RCP26	2035	-0.01	0.00	0.02	4	4	0.5		-9	2	8	4	4	0.5	
MAM	RCP26	2060	0.00	0.01	0.02	1	7	0.88	*	-1	4	6	2	6	0.75	*
MAM	RCP26	2085	-0.01	0.01	0.02	3	5	0.62		-2	3	8	3	5	0.62	
MAM	RCP45	2035	0.01	0.01	0.02	3	10	0.77	*	2	3	6	2	11	0.85	*
MAM	RCP45	2060	0.00	0.01	0.02	4	9	0.69		-3	2	4	5	8	0.62	
MAM	RCP45	2085	0.01	0.02	0.03	2	11	0.85	*	0	5	9	4	9	0.69	
MAM	RCP85	2035	0.01	0.03	0.03	1	17	0.94	*	3	6	9	2	16	0.89	*
MAM	RCP85	2060	0.02	0.04	0.04	0	18	1	**	5	7	11	0	18	1	**
MAM	RCP85	2085	0.02	0.04	0.04	1	17	0.94	*	0	7	10	4	14	0.78	*
JJA	RCP26	2035	-0.05	-0.03	-0.01	7	1	0.88	*	-14	-9	-5	7	1	0.88	*
JJA	RCP26	2060	-0.05	-0.02	-0.01	6	2	0.75	*	-14	-7	-3	6	2	0.75	*
JJA	RCP26	2085	-0.05	-0.02	-0.01	8	0	1	**	-14	-7	-3	8	0	1	**
JJA	RCP45	2035	-0.04	-0.04	-0.01	12	1	0.92	*	-12	-11	-4	12	1	0.92	*
JJA	RCP45	2060	-0.07	-0.05	-0.05	13	0	1	**	-21	-16	-14	13	0	1	**
JJA	RCP45	2085	-0.08	-0.05	-0.04	13	0	1	**	-22	-15	-14	13	0	1	**
JJA	RCP85	2035	-0.04	-0.02	-0.01	16	2	0.89	*	-13	-6	-5	15	3	0.83	*
JJA	RCP85	2060	-0.09	-0.06	-0.04	17	1	0.94	*	-27	-21	-11	17	1	0.94	*
JJA	RCP85	2085	-0.16	-0.13	-0.10	18	0	1	**	-44	-38	-30	18	0	1	**
SON	RCP26	2035	-0.02	-0.02	-0.01	6	2	0.75	*	-11	-8	-2	6	2	0.75	*
SON	RCP26	2060	-0.02	-0.02	-0.02	8	0	1	**	-11	-9	-6	8	0	1	**
SON	RCP26	2085	-0.02	-0.02	-0.01	7	1	0.88	*	-11	-8	-6	7	1	0.88	*
SON	RCP45	2035	-0.02	-0.01	0.00	8	5	0.62		-11	-6	3	8	5	0.62	
SON	RCP45	2060	-0.02	-0.02	-0.01	10	3	0.77	*	-10	-4	0	9	4	0.69	
SON	RCP45	2085	-0.02	-0.02	-0.01	11	2	0.85	*	-6	-6	-4	12	1	0.92	*
SON	RCP85	2035	-0.03	-0.01	0.00	14	4	0.78	*	-16	-7	0	13	5	0.72	
SON	RCP85	2060	-0.05	-0.03	-0.01	15	3	0.83	*	-19	-11	-1	13	5	0.72	
SON	RCP85	2085	-0.12	-0.07	-0.04	18	0	1	**	-27	-20	-12	18	0	1	**
Year	RCP26	2035	-0.02	-0.01	0.01	5	3	0.62		-9	-4	0	6	2	0.75	*
Year	RCP26	2060	-0.01	0.00	0.01	4	4	0.5		-5	-2	1	5	3	0.62	
Year	RCP26	2085	-0.02	0.00	0.01	4	4	0.5		-7	-2	1	5	3	0.62	
Year	RCP45	2035	-0.01	0.00	0.01	7	6	0.54		-7	-4	1	8	5	0.62	
Year	RCP45	2060	-0.01	-0.01	0.00	9	4	0.69		-7	-6	-2	10	3	0.77	*
Year	RCP45	2085	-0.01	0.00	0.01	7	6	0.54		-6	-3	-1	10	3	0.77	*
Year	RCP85	2035	0.00	0.01	0.02	4	13	0.76	*	-4	1	4	8	9	0.53	
Year	RCP85	2060	-0.01	0.00	0.01	8	9	0.53		-7	-5	0	13	4	0.76	*
Year	RCP85	2085	-0.03	-0.01	0.00	13	4	0.76	*	-14	-11	-7	14	3	0.82	*

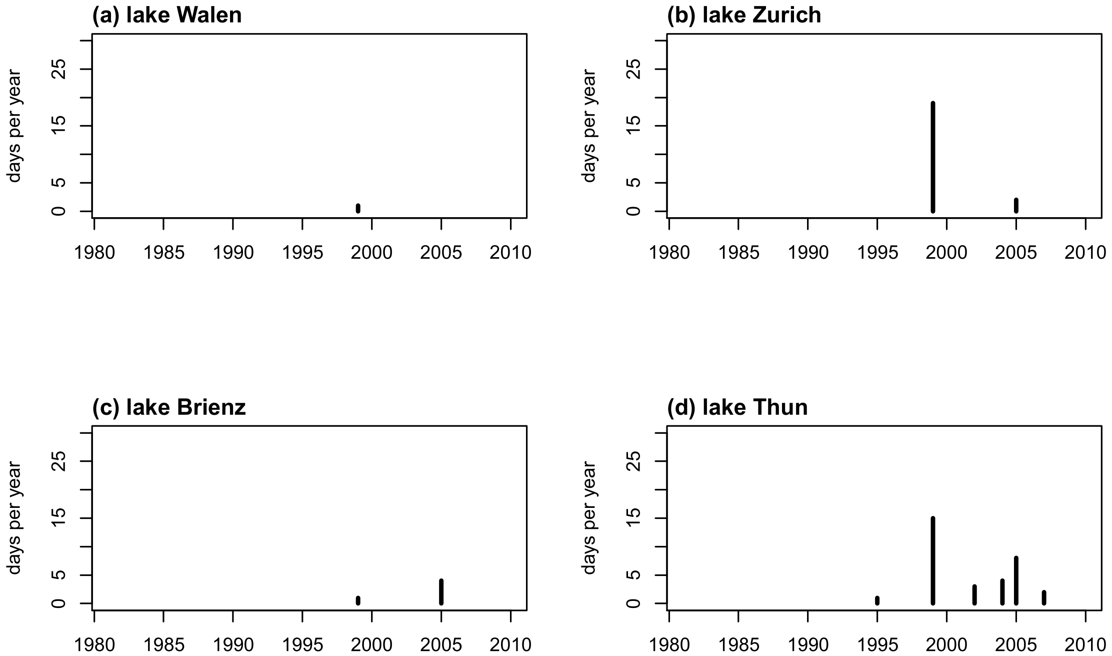

Figure SI 30: Observed days per year the lake levels exceed the flood limit (F) for Lake Walen (unregulated), lake Zurich (regulated), lake Brienz (semi-regulated) and Lake Thun (regulated).

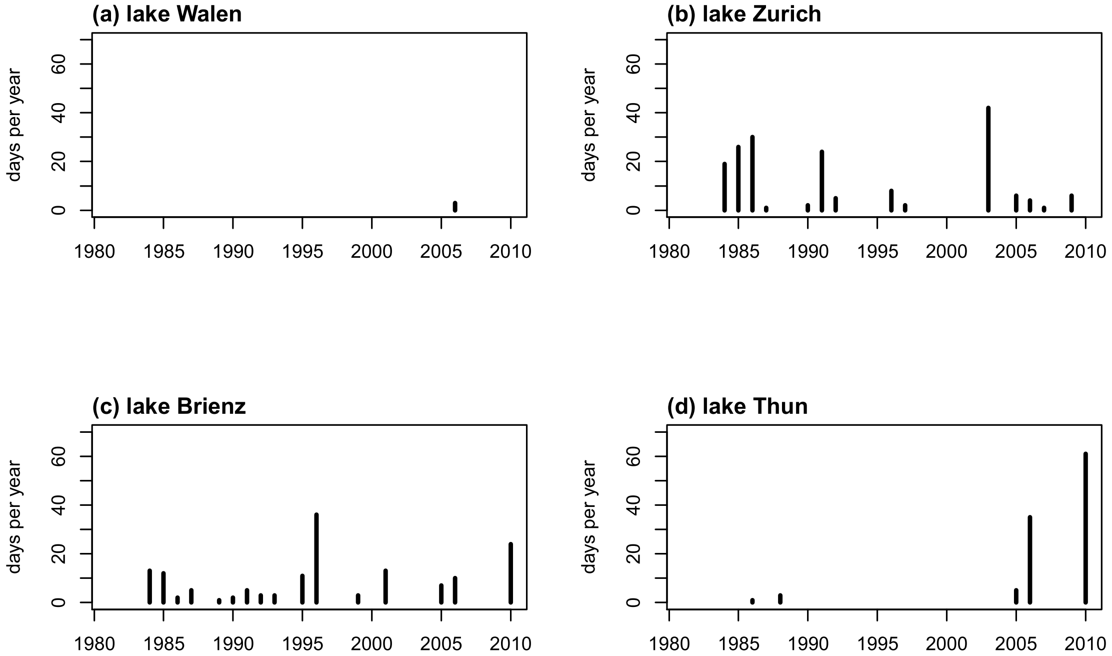

Figure SI 31: As Figure SI 30 but for the observed outflows undercutting the drought limit (L).