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Lower summer lake levels in regulated perialpine lakes, caused by climate change

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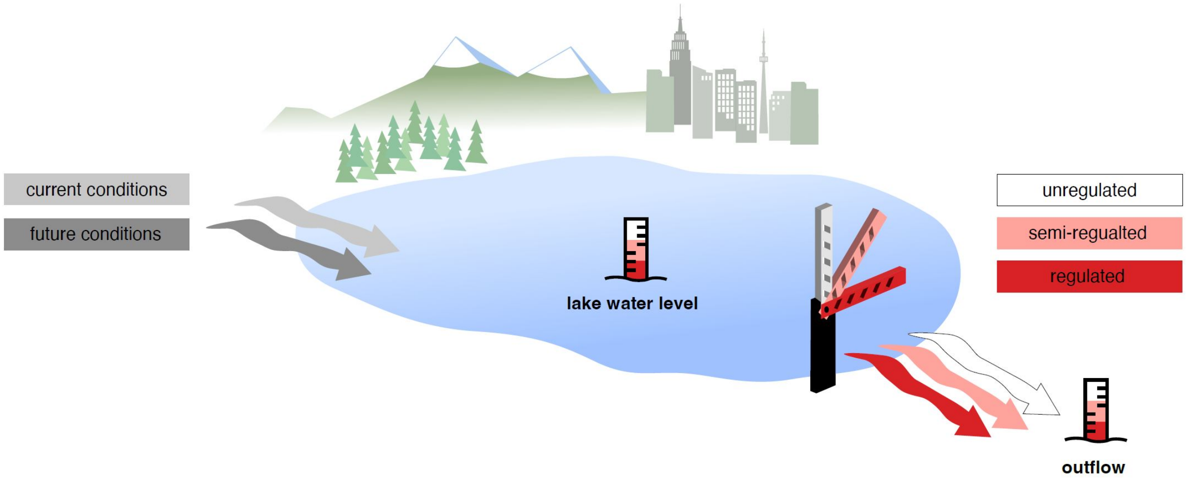
Abstract

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. Lake level management is the key challenge to bringing together diverse interests, such as fishery, shipping, energy production, nature conservation and mitigation of extremes. The question that remains open today is how to incorporate these regulatory effects into hydrologic models to project climate change impacts and to disentangle climatic and regulatory impacts. Despite the importance of lake level management, climate change studies on river systems only rarely include lakes or only in a simplified way. In this study, we focus on large perialpine lakes in Switzerland, which crucially influence the water cycle of all river basins. We combine a hydrologic model with the hydrodynamic model MIKE11 to simulate lake water level and outflow scenarios from 1981 to 2099, using the Swiss Climate Change Scenarios CH2018. We investigate one unregulated, one semi-regulated and two regulated lakes. The hydrological projections at the end of the century show a pronounced seasonal redistribution for both lake water levels and outflows, characterised by an increase in winter and a decrease in summer, intensifying with time and missing climate mitigation measures. In summer, the changes range from -0.39 m for the unregulated lake compared to -0.04 m to -0.22 m for the regulated lakes, which can lead to more frequent and severe drought events in late summer. Our climate change impact simulations demonstrate the importance of incorporating lake level management in hydrologic simulations and provide a data basis for disciplines such as limnology, water resources management and ecohydrology. Future work should focus on interannual variability to explore lake level management strategies under changing conditions.

Keywords— Lake level regulation, climate change, impact assessment, hydrologic & hydrodynamic modelling, perialpine lakes



Highlights

- Incorporating lake level regulation in a hydrologic model improves its performance
- Climate change leads to a seasonal redistribution of lake water levels and outflows
- The degree of lake level management affects water levels stronger than outflows
- Climate change impacts on lakes intensify with time and missing climate mitigation
- Climate change can lead to more frequent drought events in perialpine lakes

1 Introduction

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 attenuation. Their hydrologic and limnologic regime is highly likely to be impacted by climate change (CC) 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 CC 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]. Ecological studies also analyse how lake level regulation impacts littoral habitats [Aroviita and Hamalainen, 2008, Cifoni et al., 2022] and the work by Zohary and Ostrovsky [2011] discusses that the ecosystem functioning even of deep lakes "respond(s) adversely to excessive water level fluctuations". Despite growing pressure on the European large perialpine lakes [Salmaso et al., 2018] and the apparent 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 water 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, 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 water levels before the melt period onset to avoid flooding [Gibson et al., 2006b, Hinegk et al., 2022, BAFU, 2023a]. The question of how CC impacts the resulting lake level variability naturally arises: ongoing CC alters streamflow seasonality [Addor et al., 2014, Rössler et al., 2019, Muelchi et al., 2021] and thus the seasonal water input to lakes as well as evaporative losses [Gibson et al., 2006b]. In their study, Gibson et al. [2006b] investigate how climate and lake level management have influenced water 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. The results reveal that lake level regulation has decreased the magnitude of annual water level variations and an earlier occurrence of peak water levels. This shift in timing is attributed to both climatic and regulatory impacts and is consistent with the observed trend of earlier spring snow-cover disappearance since the 1950s.

Large perialpine lakes [Salmaso et al., 2018], the focus of this study, are particularly sensitive to CC due to the CC's 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 CC impacts streamflow [François et al., 2018, Hanus et al., 2021, Horton et al., 2022]. However, the large perialpine lakes were rarely the focus of hydrologic studies; they were often omitted or modelled in a simplified manner. In fact, 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 regulations 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]. According to Paiva et al. [2011], the relatively high computational costs associated with hydrodynamic models, as mentioned in several studies [Hoch et al., 2017, Papadimos et al., 2022], can probably explain the omission of lake level management. 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].

Some studies include the effect of large regulated lakes with a simplified reservoir approach [e.g. Hingray et al., 2007, Legrand et al., 2023]. The work of Hingray et al. [2007] used a simple water balance approach and storage-to-level functions to simulate the lake level management performance of the so-called three Jura lakes in Switzerland under CC. They found a slight decrease of mean monthly lake levels for May and June and of annual maximum lake levels under future climate scenarios. In addition, they simulated a decrease of annual water level fluctuations and of maximum water level fluctuations for future scenarios, which they did not further comment upon.

In this context of missing CC studies on natural perialpine lake water levels, we address the following research question: How does CC impact lake water level variability and how are these impacts modulated by varying degrees of lake level management? We selected four Swiss lakes with different degrees of lake level management. Compared to previous work [Hingray et al., 2007], the focus on regulated and unregulated lakes allows for disentangling the effect of lake level management and of CC impacts. 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 CC 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 conceptual hydrologic model PREVAH has frequently been used for water resources applications and CC impact studies in Switzerland [Speich et al., 2015, BAFU (Hrsg.), 2021]. MIKE11, a 1D hydrodynamic model, is widely used for modelling river systems [Doulgeris et al., 2012], sediment transport [Haghiabi et al., 2012], water quality [Cox, 2003] and lake systems [Papadimos et al., 2022].

To our knowledge, the present study is the first CC impact assessments on lake level variability in the perialpine region, explicitly disentangling the effects of lake level management and of CC. The study focuses on Switzerland, which has some of the largest European lakes, and a long history of lake level management and monitoring [BAFU, 2013]. Furthermore, Swiss lakes have a high share of meltwater input and are thereby potentially highly vulnerable to CC. The national focus has the main advantage of building upon a coherent set of CC simulations [BAFU (Hrsg.), 2021], resulting in a modelling framework that is readily transferable to other perialpine lakes. The relevance of this study is threefold: (i) the large Swiss lakes are significant reservoirs at the supraregional level, with several lakes spanning across the Swiss borders [Lanz, 2021]; (ii) CC-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, 1992] and urgently needs to be studied to understand further how CC threatens biodiversity. While the results are not directly transferable to other systems, the analysis shows important tendencies for similar cryosphere-influenced lake systems and points out critical research gaps for future work.

2 Swiss water resources and lake regulation

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 1 and Figure 2). Lake level management affects both the lake water 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, stakeholder interests both linked to upstream lake water levels and downstream river flow act upon lake level management, regarding ecosystem protection, water supply, further water-dependant economic interests and extreme event prevention [AWA, 2014, BAFU, 2023a].

Table 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

2.1 Lake level management

In Switzerland, lake levels are regulated by floodgates according to specific regulation diagrams. These are so-called line diagrams [Spreafico, 1980] that define a target lake outflow as a function of the calendar day and of the current lake water level (Figure 1). Nowadays, the actual lake level management is done by automatic regulators, with occasional manual intervention during exceptional situations such as flood or drought situations [BAFU, 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 water level targets include, e.g., maintaining sufficiently high levels during winter to guarantee access to harbours or sufficiently high 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. BAFU, 2020a]. A line diagram can be completed by a set of exceptions, e.g., a

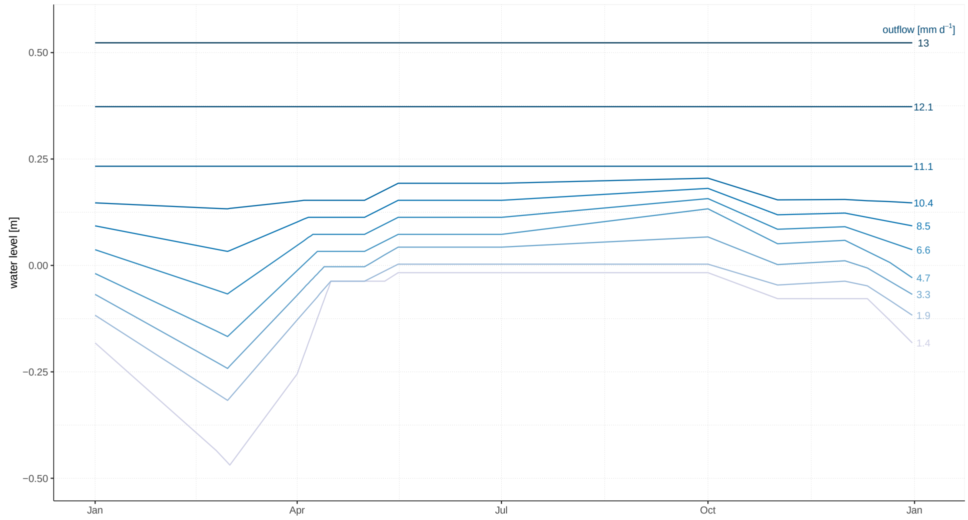


Figure 1: Example of a line diagram that defines a target outflow (blue lines) for each calendar day (x-axis) and for given lake water levels (y-axis).

preventive water level lowering to avoid flood events, a temporary minimum lake water level to ensure navigability or a certain minimum water level fluctuation to satisfy ecological needs [Spreafico, 1977, Kaderli, 2021].

2.2 Selected case studies

We retained a set of four Swiss lakes (Figure 2) representative of different degrees 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 interconnected lakes Walen (unregulated) and Zurich (regulated). Catchment II contains the two interconnected lakes Brienz (semi-regulated) and Thun (regulated). The lakes cover between 2 % and 5 % of their hydrological catchment area (Table 2). 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 2). Both lake systems have experienced flooding in the recent past [e.g., in the years 1999, 2005 or 2021 Hilker et al., 2009, BAFU, 2023d]. The unregulated Lake Walen had very low levels during the recent 2018 drought year [Blauhut et al., 2022, BAFU, 2023d] when the level dropped down to the 97.5 % exceedance percentile. The lowest observed August and September water levels of Lake Walen occurred in the drought year 2003. All lakes show consistently lower lake water levels in winter than in summer (Figure 3). For all four lakes, the monthly lowest observed levels date back to the late 1940s, early 1950s [BAFU, 2023c], i.e., before the onset of modern lake level management (Table 2).

Table 2: Catchment characteristics of the four case study lakes [Schwanbeck, Jan and Bühlmann, Alain, 2023, BFS, 2004]; catchment area, mean elevation, relative glacier cover (reference year: 2016), lake area, lake volume, ratio between lake area and catchment area, year with the latest update of lake level management rules.

lake name	catchment			lake			
	area [km^2]	Øelevation [m a.s.l.]	glacier [%]	area [km^2]	volume [km^3]	area ratio [%]	regulation [year]
Walen	1061	1581	2	24.2	2.5	2.3	-
Zurich	1828	1222	1	88.1	3.9	4.8	1977
Brienz	1137	1941	16	29.7	5.2	2.6	1992
Thun	2452	1743	9	47.7	6.5	1.9	2010

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

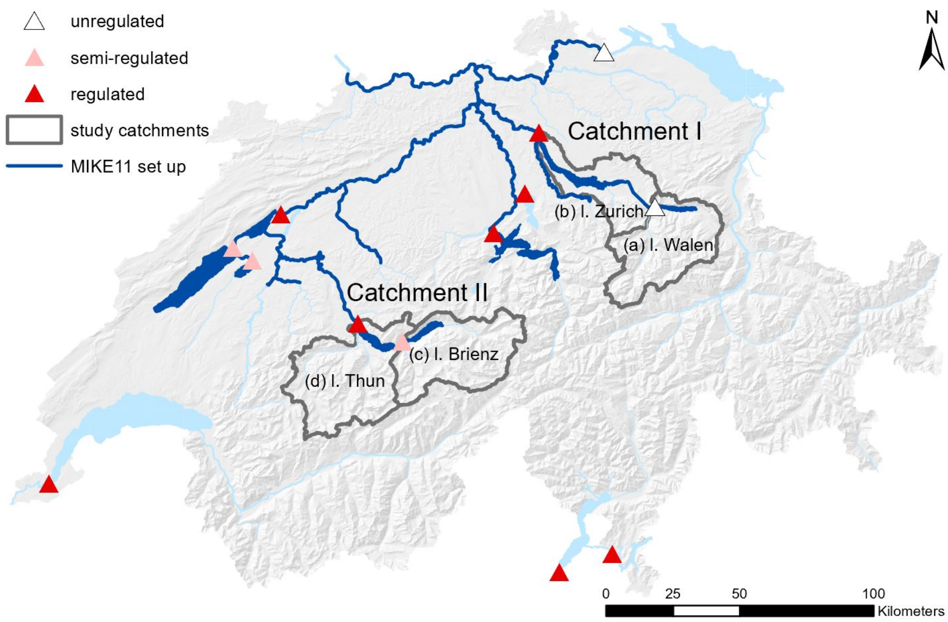


Figure 2: Location of the four case study lakes, located in pairwise nested catchments I and II. Rivers and lakes in dark blue represent the model set-up of the hydrodynamic model MIKE11. The coloured triangles indicate the degree of lake level management of all large lakes (surface area > 10 km^2) in Switzerland.

[Vischer, 2003]. In 1811, today's main tributary of Lake Walen was artificially diverted into the lake for flood protection [BAFU, 2016]. The river diversion doubled the lake's catchment area. Further downstream, the floodplain was corrected to gain cultural land. As a result of the correction, the mean lake water level of Lake Walen dropped by more than five meters. The outlet floodplain at the downstream of Lake Zurich was also exposed to flood risk [BAFU, 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 significantly reduced the annual water level fluctuations, from two meters down to 50 cm (see Figure 6 in the Results Section). The lake water level of Lake Brienz has been regulated by a sill since medieval times [BAFU, 2020c]. It was removed in 1850 for fishing, shipping and land reclamation, which lowered the lake level by two meters. The lowering left a relatively large fluctuation range without immediate flood risk, which only required a weak regulation, carried out 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 [BAFU, 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 water level and the flood limit. Consequently, a spillway has been operational since 2009 to increase the lake's outflow capacity during flood events.

2.3 Water level regimes

Lake level management reduces the seasonal water level fluctuations as clearly visible by comparing the within-year water level fluctuations of the four studied other lakes (Figure 3, top row). The unregulated Lake Walen shows the most natural water level dynamic, which is, however, slightly impacted by the seasonal redistribution of streamflow resulting from the hydropower production along the main tributary (SI Figures 1 and 2). The lake level of the regulated Lake Zurich is artificially lowered in late winter to provide retention capacity for the melt period in spring and is kept artificially high in summer for touristic purposes and fishery. The lake water level dynamics of Lake Brienz and Lake Thun are less impacted by water correction works than those of Lake Zurich and Lake Walen. The current management rules lead to annual lake water level fluctuations that are more narrow for Lake Thun than for Lake Brienz.

All lakes analysed here are large enough to strongly dampen daily inflow variability, but small enough to not (naturally) dampen the seasonal inflow variability. Accordingly, the annual streamflow cycle, with high flows in summer and low flows in winter (resulting mainly from snow and glacier melt), is clearly visible in all outflow regimes (Figure 3, 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- or unregulated lakes. This results from the artificial water 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

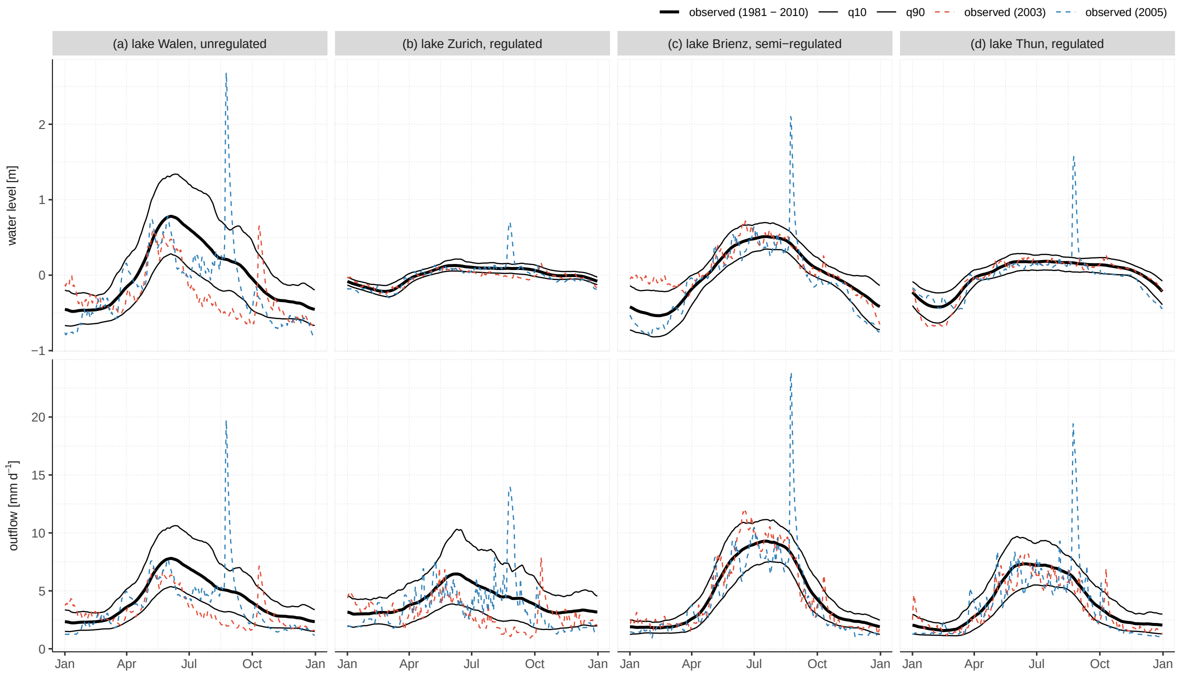


Figure 3: The observed mean 31-day (moving average ±15 days) lake water levels (top line) and outflows (bottom line) as well as the 10 % and 90 % percentile (confidence interval) for the reference period (1981 - 2010). Also shown is the extreme drought year of 2003 and the flood year of 2005.

[see Table 2 and the work of Stahl et al., 2016]. Finally, it is important to note that highly dampened lake water level dynamics do not necessarily translate into similarly dampened outflow dynamics (see Lake Zurich and Lake Thun in Figure 3). This depends on the stage-discharge relationship and on the line diagram.

3 Material and methods

3.1 General change assessment framework

The analysis framework of our study is based on comparing the current conditions of daily lake water levels and outflows and future conditions under CC. 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[CH2018, 2018]. The change analysis compares the simulations resulting from each available climate model ensemble member for the reference period and future periods. Thereby, we assume unchanged regulatory practices. The simulations are all based on climate model outputs (also for the reference period). Accordingly, the projected conditions are compared with the simulated current conditions but cannot be directly compared to lake level or outflow observations of the reference period. To disentangle climatic and regulatory impacts on lake levels and outflow, we combine a hydrologic model and a hydrodynamic model (Section 3.3) applied to the two catchments I and II (Figure 2). For the change assessment, we consider mean annual and mean monthly CC impacts over 30 years. Changes in extremes are assessed based on the 10 % and 90 % percentiles and based on indicators such as the frequency of reaching the drought and flood limits.

3.2 Hydrologic climate change scenarios

The transient daily streamflow scenarios used in this study were derived from the latest downscaled and de-biased Swiss CC Scenarios CH2018 [CH2018, 2018], which are based on the EURO-CORDEX dataset [Jacob et al., 2014]. The climate model ensemble CH2018 contains a total of 39 model members for three Representative Concentration Pathways, 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 members are listed in Table SI 1. The model ensemble provides daily air temperature, precipitation, relative humidity, global radiation and near-surface wind speed [Brunner et al., 2019].

3.3 Hydrologic and hydrodynamic models

The CC scenarios were translated into streamflow scenarios [BAFU (Hrsg.), 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]. 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 model was 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]. PREVAH 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 (SI Figures 1 and 2). 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]. PREVAH includes a rough simulation of the lake dynamics, with a simple mass balance approach assuming the filling of a reservoir with a fixed area and a known stage-discharge function. This allows to simulate the 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, including reservoirs and lakes, and their associated regulation structures. It was previously set up and calibrated by the FOEN for several large Swiss rivers and lakes (Figure 2) 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 3.3.1). The model allows the specification of the cross-sections, such as river geometry, roughness, lake characteristics to capture the hydraulic behaviour [DHI, 2003]. To simulate the fluid dynamics, MIKE11 employs the Saint-Venant equation, which accounts for flow velocity, water depth, and channel slope. Furthermore, lakes are modelled as a control volume at a cross-section at the lake outlet following the stage-discharge relation for natural lakes or the lake level management rules for regulated lakes, as defined in a look-up table. The time-dependent lake level management rules define a target lake outflow as a function of the calendar day and the current lake water level. The lake outflow changes when the lake water level exceeds a certain limit, defined in the lake level management rules. The combination of the hydrologic and hydrodynamic models is essential to assess the CC impacts on water-level-outflow dynamics, which is an expression of a complex balance of interests. 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. For model evaluation purposes, we assess the model performance (Section 4.1) by comparing daily observed lake water 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 that the model developed with observed input data remains valid with the downscaled climate model outputs as input, a standard assumption in comparable studies.

The comparison between simulated and observed lake levels and outflows is conducted for the combination of PREVAH and MIKE11 but also for the hydrologic model alone; in this last case, lake levels are obtained by simply solving the water balance equation for the filling of a reservoir with interpolated stage-area relation and stage-discharge relation (interpolated from observed data, see next section). The stage-discharge relation of the regulated lakes is interpolated without accounting for regulation rules.

3.3.1 Lake and river characteristics

The lake and river characteristics described here are used for the hydrodynamic simulations with MIKE 11 (Section 3.3). 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. All data is available in the provided data set [Wechsler et al., 2023]. The stage-area relationships were determined for different elevations and areas by the Federal Office for the Environment (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 discharges and then extrapolating the relation between discharge and stage with a polynomial function (degree 3). The cross-sections, used for the hydrodynamic simulations (Section 3.3) are surveyed by the FOEN every 10 years [BAFU, 2023e]. This data is assumed to remain constant throughout the entire simulation period.

3.4 Climate change impact assessment

The assessment of simulated changes is based on the comparison of future monthly (m) mean lake water levels ($h_{m,fut}$) to the reference period ($h_{m,ref}$):

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

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 years period. For February, the number of future time steps $n_{m,fut}$ can differ from the number of reference time steps $n_{m,ref}$. The average annual change (Δh_a) is computed analogously. The relative annual and monthly mean changes in lake outflow (ΔQ_m) are computed as:

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

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 [CH2018, 2018]. However, short-duration extreme events (daily to hourly scale) have less significant impacts on large lake systems. Therefore, we analyse the changes in extreme lake water levels and outflows in two ways: (1) by using the 10 % and 90 % percentiles of a moving average over 31 days (± 15 days) and (2) 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 water level $h(t)$ exceeds the flood limit (F), which is the critical water level that would lead to damage to infrastructure (defined for each lake, the so-called hazard level 4 [BAFU, 2023b]):

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

where n_p is the number of years in the simulation period p (n_p=30 for all periods). The critical (hazard) water levels are given in Table 3. There are no comparable critical low-water 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):

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

where (L) is the minimum outflow, specified in the lake level management rules for regulated lakes. For semi-regulated and unregulated lakes, we choose a value corresponding to the 30-year return period (Table 3).

Table 3: The flood limit F and drought limit L used for the frequency indicators.

lake name	F [m]	L [mm d^{-1}]
Walen	3.00	1.11
Zurich	0.67	1.42
Brienz	1.49	1.06
Thun	0.63	1.06

4 Results

4.1 Model validation

The model combination demonstrates a good agreement with the observed lake water levels (Figure 4) and with the observed outflows (Figure 5). The fit to water levels and outflows is significantly better than for the hydrologic model alone, not only for the regulated lakes but also for the unregulated Lake Walen. The simulated monthly lake water levels and outflows with the hydrologic-hydrodynamic framework and using the streamflow scenarios (Hydro-CH2018) show a certain deviation form the observed levels. This deviation is inherited from the hydrologic simulations that do not perfectly reproduce the observed mean monthly averages for the reference period [Brunner et al., 2019]. On an annual basis, the simulations effectively capture the seasonal variations.

By combining the hydrologic and the hydrodynamic models, we enhance the model's ability to simulate daily lake water levels and outflows (Table 4). The computation time for the 39 model members 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.

4.2 Climate change impact projections on lakes

4.2.1 Change in mean water levels and outflows

Figure 6 shows the observed and projected annual lake level variations for all four lakes, which underlines that historic lake level changes due to river diversion works (Lake Walen, Lake Brienz) and the introduction of lake

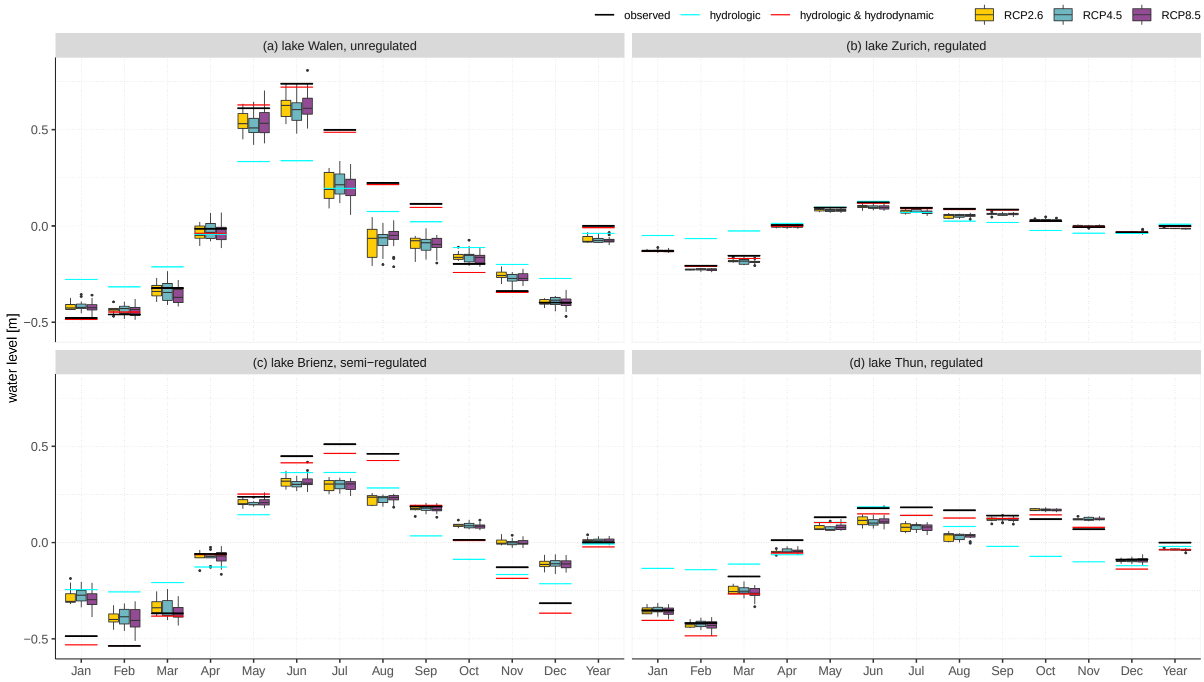


Figure 4: Normalised observed and simulated annual and monthly lake water levels for the four considered lakes during the reference period (1981 – 2010). The observations are compared to the hydrologic simulations with PREVAH and to the combination of the hydrologic and hydrodynamic models PREVAH and 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 5: As Figure 4 but for lake outflows.

Table 4: 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 water 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

level management (Lake Zurich, Brienz, Thun) had a far more substantial impact on annual lake levels than projected CC.

The simulations indicate a slight annual decrease in lake water levels for all four lakes, but a significant redistribution from summer to winter (Figure 7). 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 water level changes: for Lake Zurich, which is the most strongly regulated lake of the four (Figure 3), changes range from -0.05 m in summer to +0.04 m in winter. Lake Thun, also regulated, exhibits changes between -0.14 m and +0.08 m. The semi-regulated Lake Brienz shows changes ranging from -0.25 m to +0.19 m, while the unregulated Lake Walen shows the largest variations, with -0.40 m in summer to +0.30 m in winter. Monthly changes in lake water levels are shown in Figures SI 3, 7, 13 and 19.

Despite the simulated lower summer lake water levels, summer remains the season with the highest lake water levels. Towards the end of the century, the glacier- and snowmelt-influenced regime of lake water levels is still noticeable. However, the simulated mean melting peak ($q50$ = 50 % percentile in Figure SI 9) for the unregulated Lake Walen shifts from currently June to May and is expected to drop by 0.50 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 9, 15 and 21). However, a lower mean lake water level ($q50$) in late summer is visible for the regulated and semi-regulated lakes. For the lakes Brienz and Thun, the mean summer water levels decrease down to the current 10 % percentile. In conjunction with higher winter water levels, the simulation indicates a more balanced lake level regime for the end of the century, with less seasonal fluctuation on average.

The simulations for annual outflows also indicate relatively small changes, reaching up to -10 % without CC mitigation measures (RCP8.5) by the end of the century (Figure 8). As seen in observed data (Figure 3), the degree of lake level management has a smaller impact on lake outflows than on the lake water levels. This is also true for the simulated outflow changes (median): for the unregulated Lake Walen, a change of -35 % in summer and +21 % in winter is simulated, while for the regulated Lake Thun, the changes range from -39 % in summer to +22 % 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 8 times higher than for catchment I and the mean catchment elevation is 521 m higher (Table 2). The simulations for the semi-regulated Lake Brienz and the regulated Lake Thun indicate a more significant change in summer outflow (median) with -39 %, compared to -35 % for Lake Walen and -31 % for Lake Zurich. The monthly changes in outflows are even more pronounced than the seasonal changes (see Supplementary Information, Figures SI 4, 8, 14 and 20).

The simulations indicate that mean peak outflows ($q50$ in Figure 10 and Figures SI 10, 16 and 22) 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 Figure 10 and Figures SI 10, 16 and 22) are roughly reduced to 50 % compared to the reference period and towards the end of the century.

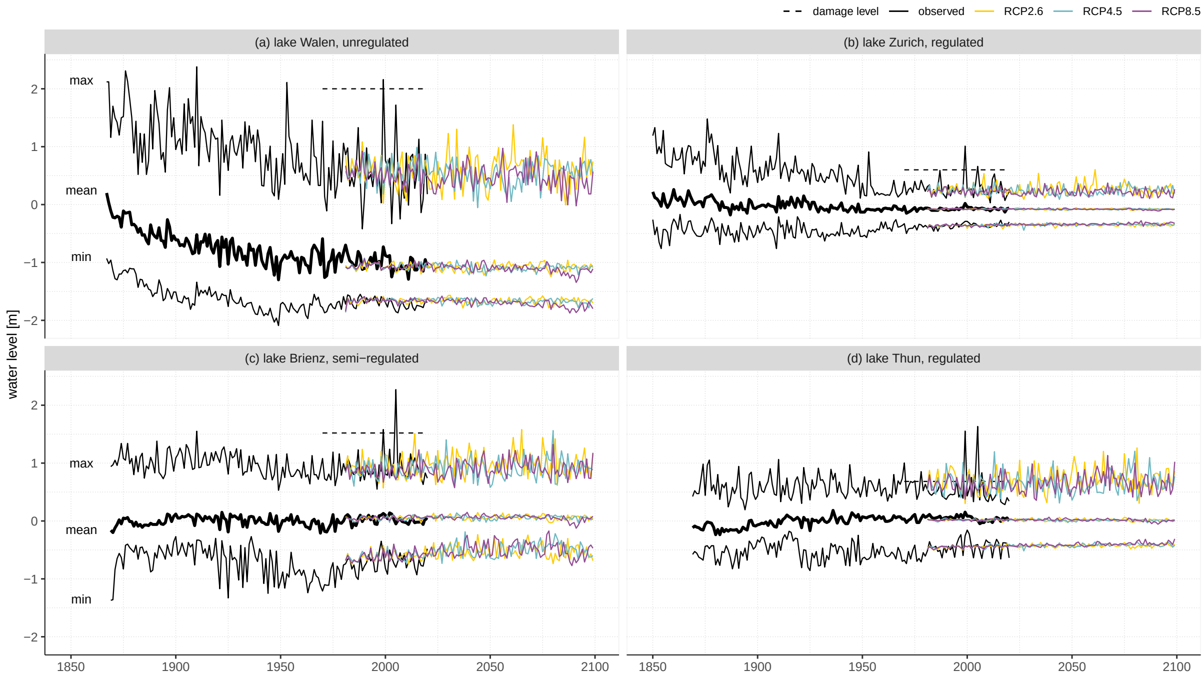


Figure 6: Normalised observed annual lake level variations: Shown are the observed annual mean, minimum and maximum water levels between 1850 and 2020 (black) and the future scenarios (Section 3.2) until the end of the century under CC (RCP2.6, RCP4.5, RCP8.5). The dashed line indicates the current flood limit for each lake.

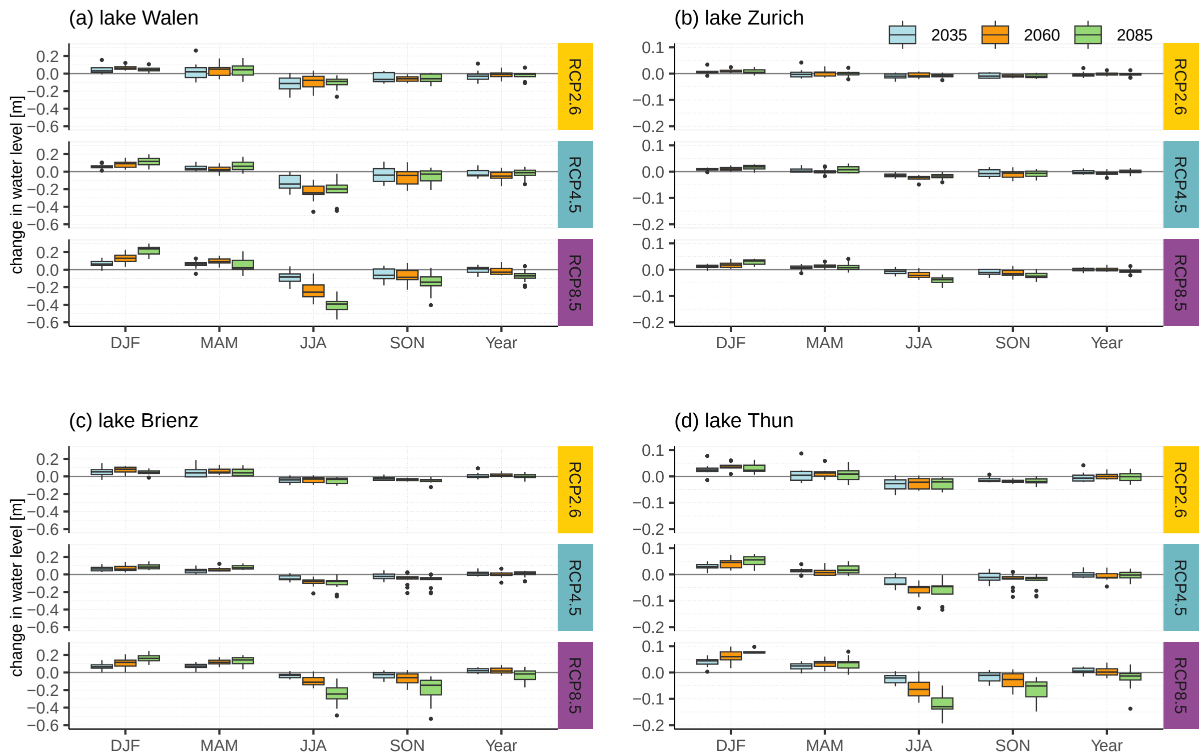


Figure 7: Simulated changes in seasonal mean lake water levels of Lake Walen (unregulated), Lake Zurich (regulated), Lake Brienz (semi-regulated) and Lake Thun (regulated), divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

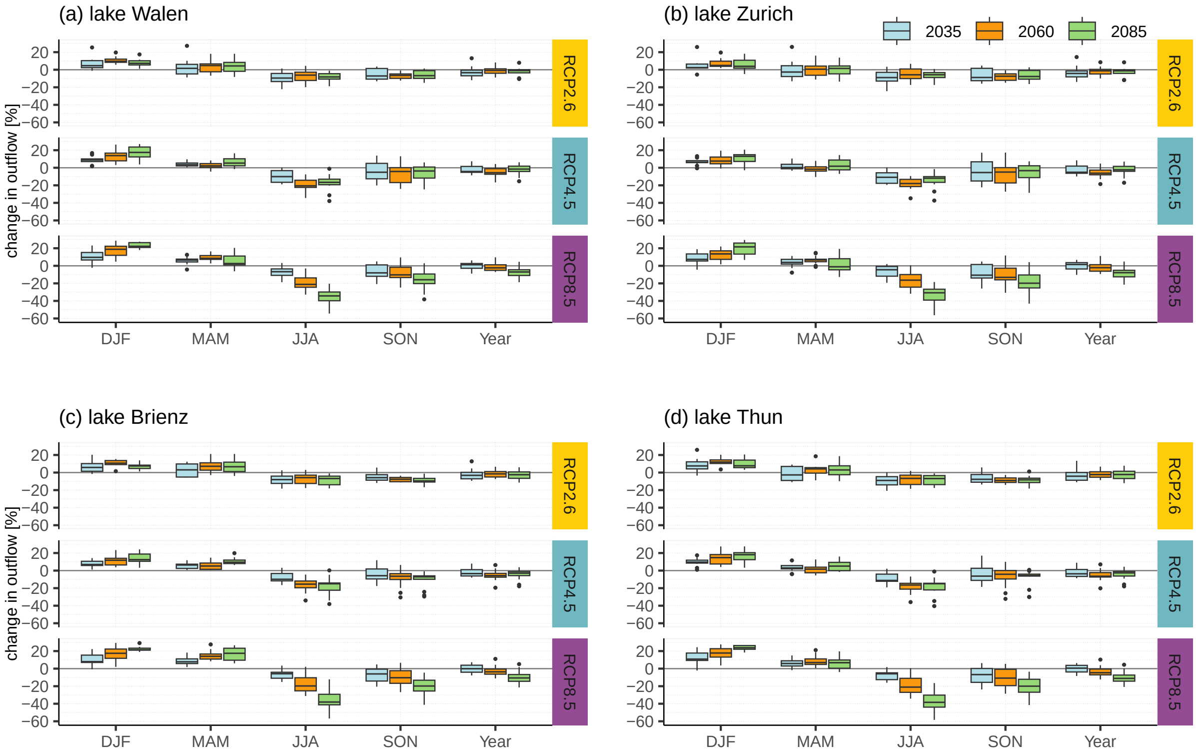


Figure 8: As Figure 7 but for the simulated changes in seasonal outflows.

4.2.2 Change in extremes

The simulations indicate an increase of high-water levels ($q90$) in winter but remain lower than in summer (Figure 9 and Figures SI 9, 15 and 21). The simulated high-peak lake water levels ($q90$) occur in early summer, similar to the reference period, and decrease noticeably throughout the summer. For the low-water levels ($q10$), the simulations indicate an increase in winter and a significant decrease in summer and autumn. Due to lake level management, the lake water level of the regulated lakes Zurich and Thun are artificially lowered in late winter (Section 2.3). For the two regulated lakes Zurich and Thun, and similarly for the semi-regulated Lake Brienz, less pronounced changes in the 90 % and 10 % percentiles and smaller shifts of the seasonal pattern are simulated (Figures SI 9, 15 and 21). The lowest $q10$ for these lakes continue to occur during winter. For the unregulated Lake Walen, the simulations indicate a decreases in $q10$ during summer and autumn and fall below the winter low-water levels of the reference period (Figure 9). Consequently, the lowest $q10$ in Lake Walen could shift from winter to late summer in the future. Similarly to the mean lake water levels, the $q90$ and the $q10$ also indicate more pronounced changes with time and without CC mitigation measures (RCP8.5).

For the simulated high ($q90$) and low ($q10$) outflows, the degree of lake level management has a lower impact compared to lake water levels (Figure 10 and Figures SI 10, 16, 22). Outflow changes in both the 90 % and 10 % percentiles are visible in the simulations, with increases in winter and decreases in late summer. The simulated peak outflows ($q90$) continue to occur in June and show little changes in terms of timing and magnitude. A significant decline of $q90$ is simulated in late summer high-outflows, approaching or even falling below the average outflows ($q50$) during the reference period. The simulated $q10$ in winter indicate a noticeable increase, approaching the $q50$ outflows of the reference period. By the end of the century and without CC mitigation measures (RCP8.5), the lowest outflows are simulated in late summer; for the two lakes of catchment I, for Lake Walen (Figure 10) and Lake Zurich (Figure SI 10), late summer $q10$ even fall below the current low outflows in winter.

The frequency indicator for floods (F), which counts the average number of simulated days exceeding the flood limit (Table 3), does not indicate clear changes. In the simulations, there are some occasional outlier years, but no significant trend is visible (Figures SI 5, 11, 17 and 23). For the reference period (and for observed data, not simulations), flood limit exceedences 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 taking place 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 water level falling below a defined minimum outflow (Table 3), indicates an increasing trend in the CC simulations (Figure 11). Lakes with a higher degree of lake level management (Lake Zurich and Lake

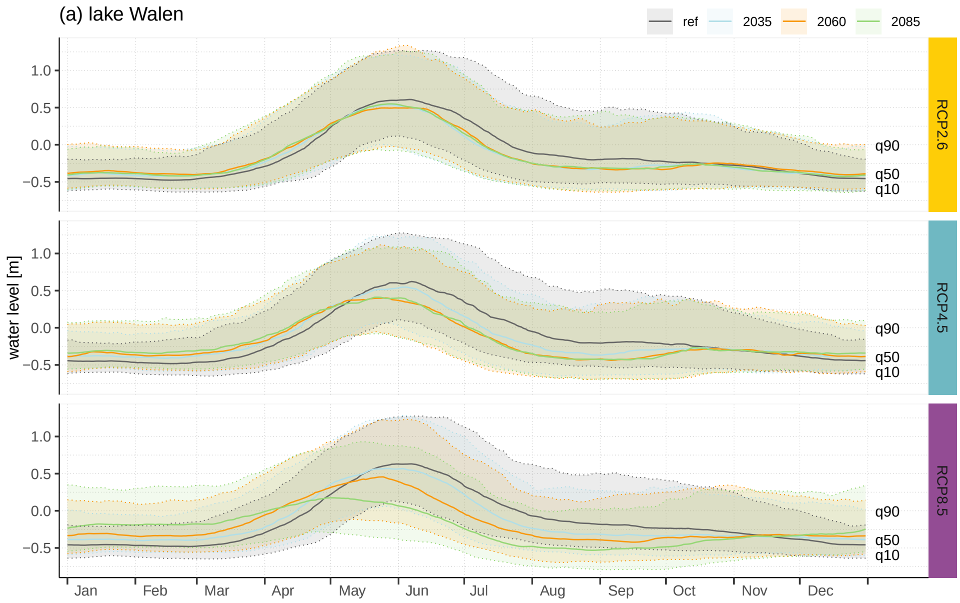


Figure 9: Simulated changes in the 10 % ($q10$) and 90 % ($q90$) percentiles of lake water levels (moving average ±15 days) of Lake Walen, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

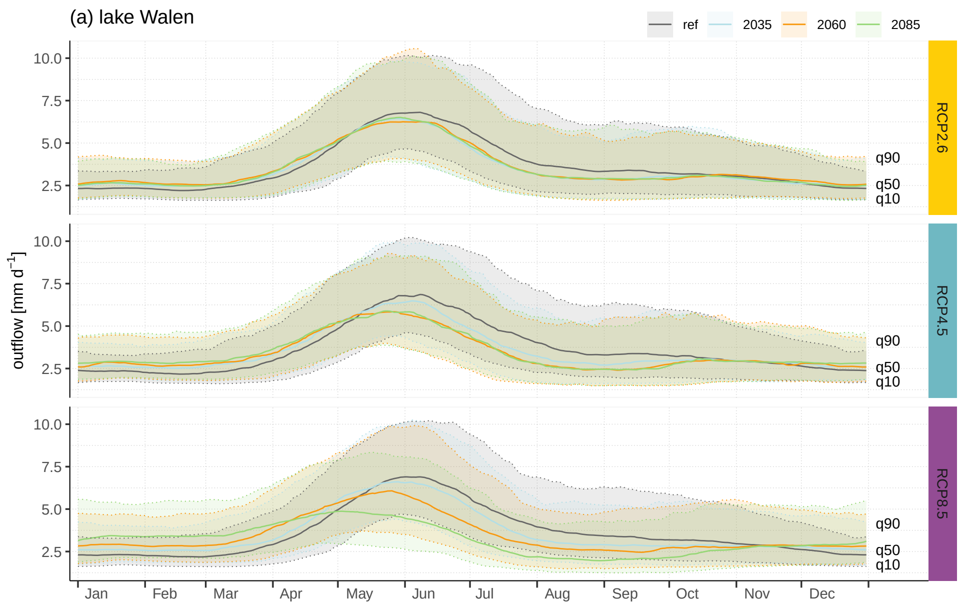


Figure 10: As Figure 9 but for the simulated changes in the 10 % ($q10$) and 90 % ($q90$) percentiles of outflows of Lake Walen.

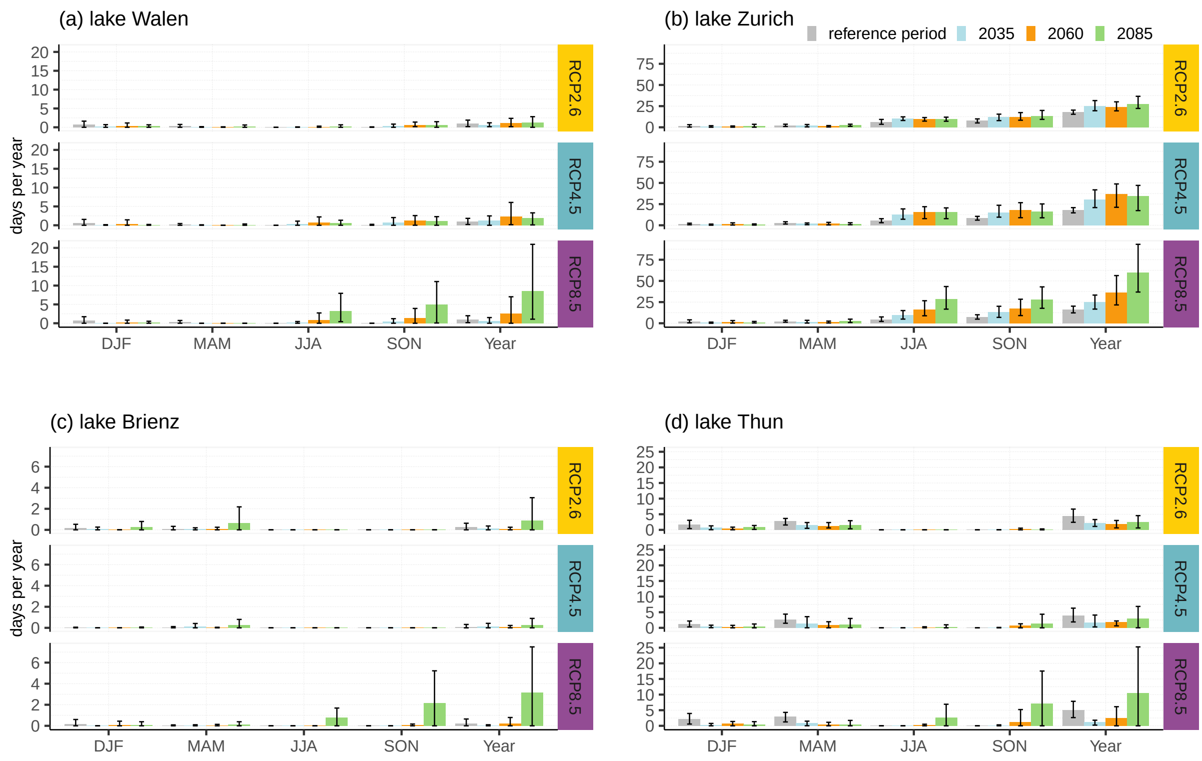


Figure 11: Simulated changes in days per month and per year the outflow undercuts the drought limit (L) of Lake Walen (unregulated), Lake Zurich (regulated), Lake Brienz (semi-regulated) and Lake Thun (regulated). Error bars refer to the 10 % and 90 % percentile range.

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 it significantly increases by the end of the century and with missing CC mitigation meassures. 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 6, 12, 18 and 24).

4.2.3 Synthesis of the simulated changes in lake water levels and outflows

The simulations of lake water levels and outflows for the studied lakes show a slight decrease of annual lake water levels across all four lakes and a significant redistribution from summer to winter. The simulated changes intensify with time and particularly in the absence of CC mitigation measures. The degree of lake level management has a direct impact on the simulated changes: regulated lakes exhibit smaller variations of a few centimeters compared to the unregulated Lake Walen, which shows variations of up to 0.39 m. Summer remains the season with the highest lake water 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 more balanced seasonal lake level regime, with less seasonal fluctuations due to higher winter lake levels. For annual outflows, the projected reductions of up to 10 % are smaller than the projected seasonal redistribution, which ranges from -39 % in summer to +21 % in winter. The impact of lake level management on outflows is less significant than for lake water levels. Changes in summer outflows are more influenced by the mean catchment elevation than by the degree of lake level management. The simulations also show changes in extremes, with decreases in high-water levels (90 % percentiles) in summer and autumn and also with decreases in low-water levels (10 % percentiles) in late summer already for the near future. For the unregulated Lake Walen, the lowest lake water levels may shift from winter to late summer by mid-century. 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 none of the emissions scenarios.

5 Discussion

The presented data set as well as our simulations show the extremely strong influence of lake level management on the lake water levels of the analysed perialpine lakes (Figure 3). This emphasises the importance of incorporating lake level management in hydrologic simulations. Furthermore, our simulations show that combining a hydrologic and hydrodynamic model significantly improves the model performance for lake outflows, especially for lake water levels (Section 4.1). The enhanced model performance specifically for regulated lakes (Table 4) underlines again the importance of considering lake management in hydrologic simulations. Depending on the degree of lake level management CC affects lake water levels and outflows differently in magnitude and timing. The study by Gibson et al. [2006b] attributes the observed shift in peak water levels to climatic and regulatory impacts. In contrast, our simulations of the unregulated perialpine lake indicate a seasonal shift in the peak-melt water level occurring one month earlier (Figure 9), which aligns with the findings of other studies [Muelchi et al., 2021, Stahl et al., 2022]. However, we do not observe a seasonal shift for the regulated lakes (Figures SI 9 and 21), and only a minor shift is observed for the semi-regulated lakes (Figure SI 15. These findings are crucial regarding the transferability of our results, as it suggests that similar analyses should be completed for other perialpine lakes to confirm this result.

The presented solution of using a hydrodynamic model resulted in a sevenfold increase of the computational costs and an increase of input data (the cross sections), compared to only using the hydrologic model. This increase in overall modelling work 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 selected because the model is also used for real-time purposes. 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.

We assess the changes in lake water levels and outflows based on climate model chains simulating the streamflow distributions during a reference period and three future periods. The model chains have been validated with observed meteorological input data by comparing the simulations and observations of lake water levels and outflows. Compared to previous hydrologic CC impact focusing on changes in streamflow [Rössler et al., 2019, Muelchi et al., 2021], our modelling framework allows us to assess CC impacts on lake water levels. The simulations reproduce the overall temporal patterns well, but show some biases for the monthly average water levels. Such deviations are expected for lake water level simulations because any bias in streamflow simulations accumulates at the lake systems levels, and there is some upstream hydropower production in both lake systems that results in a transfer of water from winter to summer. We tested the use of precipitation bias correction (quantile mapping method) to reduce these biases but showed no significant improvement (results not shown).

The simulations of the future annual water balance in catchments I and II (Figure 2) show changes in precipitation, evapotranspiration and icemelt contribution Figure 12. On the input side, the simulations indicate no clear trend in precipitation for both catchments; for catchment II, the icemelt contribution is simulated to increase slightly in the near future and will decrease from mid-century on. The glacierised area in catchment I is very small (Table 2) and its change under the CC scenarios is hardly noticeable in the lake input simulations used for the current study. On the output side, the simulations show an increasing water loss via evapotranspiration for both catchments, intensifying with time and missing CC mitigation measures. This increase of ET 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) compared to the reference period.

Our CC simulations further show a strong seasonal redistribution pattern of mean monthly lake water levels and mean outflows, with a water level decrease in summer of up to 0.39 m for the unregulated lake and between 0.05 m and 0.22 m for the regulated and semi-regulated lakes (RCP8.5, 2085). This seasonal redistribution is in agreement with published streamflow regime changes [Rössler et al., 2019, Muelchi et al., 2021] and is, 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 to less snowmelt in spring and summer [Stahl et al., 2016, Muelchi et al., 2021]. This redistribution due to reduced snowfall and snowmelt is enhanced by increased losses by evapotranspiration (Figure 12) and a decrease in summer precipitation by up to 39 % by the end of the century [CH2018, 2018]. Additionally, a reduced snow-cover extent leads to longer 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 significantly compensate for this reduction of available water. The potential CC-induced changes to lake water levels and outflows can accentuate the pressure from competing water uses, especially in the case of water shortages [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 11). Regarding the evolution of flood events in the simulated perialpine lake systems until the

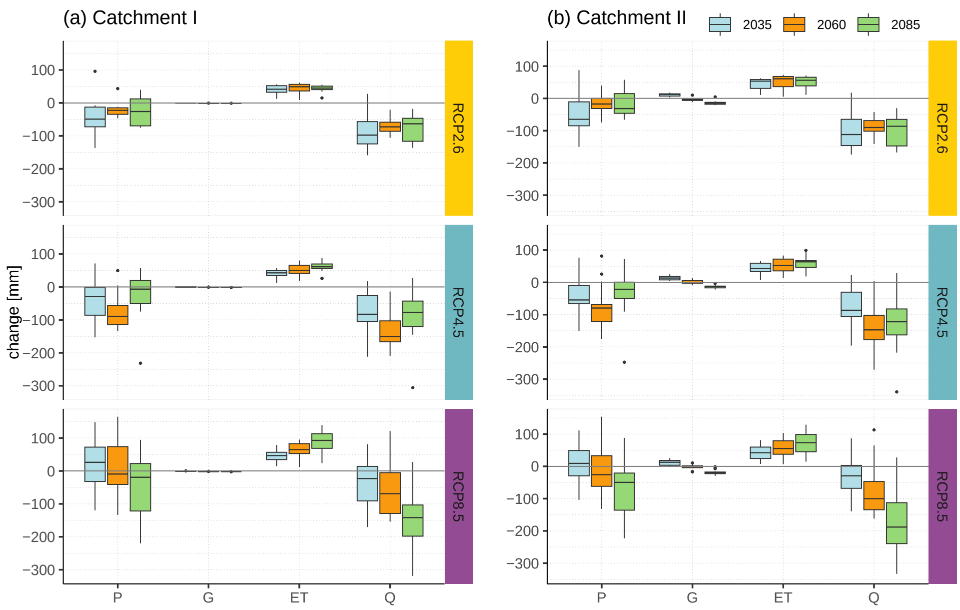


Figure 12: Simulated CC-induced changes in precipitation (P), glacier melt contribution (G), evapotranspiration for the entire catchment area (ET) and streamflow (Q) for catchment I (Lake Walen and Lake Zurich) and catchment II (Lake Brienz and Lake Thun).

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 [CH2018, 2018], our results show no clear changes (Figures SI 5, 11, 17 and 23). This can be explained by the reduced contribution from snowmelt, which despite of being more concentrated in time, leads to less critically high-water levels.

It is important to keep in mind that we assume current lake level management practices remain constant for future simulations, which permits disentangling climatic and regulatory impacts. A limit of our work is, however, the existing hydropower production in the headwater catchments of the analysed lakes (Figures SI 1 and 2), which results in transferring water from summer to winter, which complicates the ability to entirely disentangle the climatic and regulatory impacts. In this study, we do not consider potential adaptation measures for lake level management practices. Nevertheless, these projections can provide a foundation for considering potential adjustments in the early stages. Finally, we would like to underline that our results should not be used to judge as far as lake level management can be used as a CC 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 water levels [Wantzen et al., 2008], (2) it may affect the longitudinal disconnection of aquatic habitats [Stanford, 1992, Erős and Campbell Grant, 2015] and (3) despite the controlled lake outflow, smaller lake water level changes do not necessarily lead to less water scarcity or enhanced resilience [Kellner, 2021].

Finally, the projected changes in our study are limited to water supply and do not consider changes in water demand. In particular, such changes could become evident on a large scale with more frequent and severe drought years [Spinoni et al., 2016, Vicente-Serrano et al., 2022]. As Brunner et al. [2019] demonstrate, low-water levels can result in reduced outflows, imposing restrictions on competing water uses. However, it is important to note that low-water levels can also lead to elevated water temperatures [Michel et al., 2021], negatively impacting water quality [Hinegk et al., 2022] and exerting additional pressure on aquatic habitats [Woolway et al., 2020, Salmaso et al., 2018]. These factors highlight the challenge posed by existing interdependencies between upstream lake and downstream river water users, which may already be compromised, potentially resulting in impacts for both [BAFU, 2023d]. Our results, 30-year annual and monthly mean values, describe long-term trends, but no interannual variability. Future work could investigate the interannual variability, aiming to enhance our comprehension of year-to-year variations and estimate the occurrences of extreme events, including the possibility of several extreme years in a row.

6 Conclusion

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

Without climate mitigation measures (RCP8.5), the simulations demonstrate minor reductions of mean annual lake water levels by a few centimeters, accompanied by decreases in outflow by up to 10 % by the end of the century. The simulated seasonal redistribution of lake levels is much more pronounced, 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 water level changes: for the unregulated Lake Walen, the seasonal lake level changes can decrease by up to 0.39 m, while for regulated or semi-regulated lakes, the seasonal changes range from 0.04 to 0.23 m, compared to the reference period. The simulations show that the highest monthly lake water levels continue to occur in summer. In contrast, the impact of lake level management on outflows is comparatively weaker than on water levels. The simulations reveal seasonal patterns in the CC-induced changes that are consistent with those for the lake water levels (median): up to 21 % higher winter outflows and up to 39 % lower summer outflows and a consequently more balanced outflow regime. The simulated changes in extremes indicate decreases in both high and low water levels (10 % and 90 % percentiles) in summer and autumn. For the unregulated Lake Walen, the lowest lake water levels may shift from winter to late summer by mid-century. The drought frequency indicator suggests an accentuated increase in late summer, which can significantly impact water resources management and potentially lead to conflicts between various interest groups (e.g., whether during a dry period, in the case of a regulated lake, the minimum water level or minimum outflow cannot be guaranteed). Conversely, the flood frequency does not show clear changes for the four large perialpine lakes.

The main findings of our study are as follows:

- Lake level management has a significant impact on lake water levels. The study highlights the importance of incorporating lake level management in CC impact simulations, which is strongly understudied in the available literature. Relying on simple water balance models rather than full hydrodynamic models can lead to significant errors, especially in lake water levels, which might undermine the CC impact assessment.
- CC can lead to important redistributed patterns of mean monthly lake water levels and outflows, with summer lake levels declining. This decline and an increased occurrence of low-water level days can lead to more frequent and severe drought events in summer and autumn, with significant impacts on water availability, water quality and consequently more pressure on aquatic habitats.
- CC 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.

For our four studied lakes, the simulations indicate that lake level management rules and practices might need to be re-considered for the most extreme CC scenarios. This might hold well beyond our case studies for similar large perialpine lakes with similar degrees of lake level management. Future work should focus on interannual variability and the occurrence of sequences of low or high water level years, moving beyond the current focus on examining 30-year mean values. Such an in-depth analysis of interannual variability would build the basis for future lake level management adaptations and CC impacts mitigations.

Acknowledgements

The authors gratefully acknowledge collaboration and funding from the Swiss Federal Office for the Environment (FOEN). The action plan adaptation to climate change in Switzerland (Measure W5) forms the basis for this climate change analysis concerning lake management ([BAFU, 2018]). The objectives contained therein are the minimisation of both flood risk and negative impacts on ecology, as well as adjustments to water resources management. Measure W5 reviews the effectiveness of lake regulation regulations under climate change. The latest climate change scenarios were produced and made available by MeteoSwiss [CH2018, 2018], which were then translated into hydrological future scenarios in the frame of the FOEN program Hydro-CH2018 [BAFU (Hrsg.), 2021].

Data statement

The future lake water level and outflow scenarios of this study are publicly available in the provided data set Wechsler et al. [2023].

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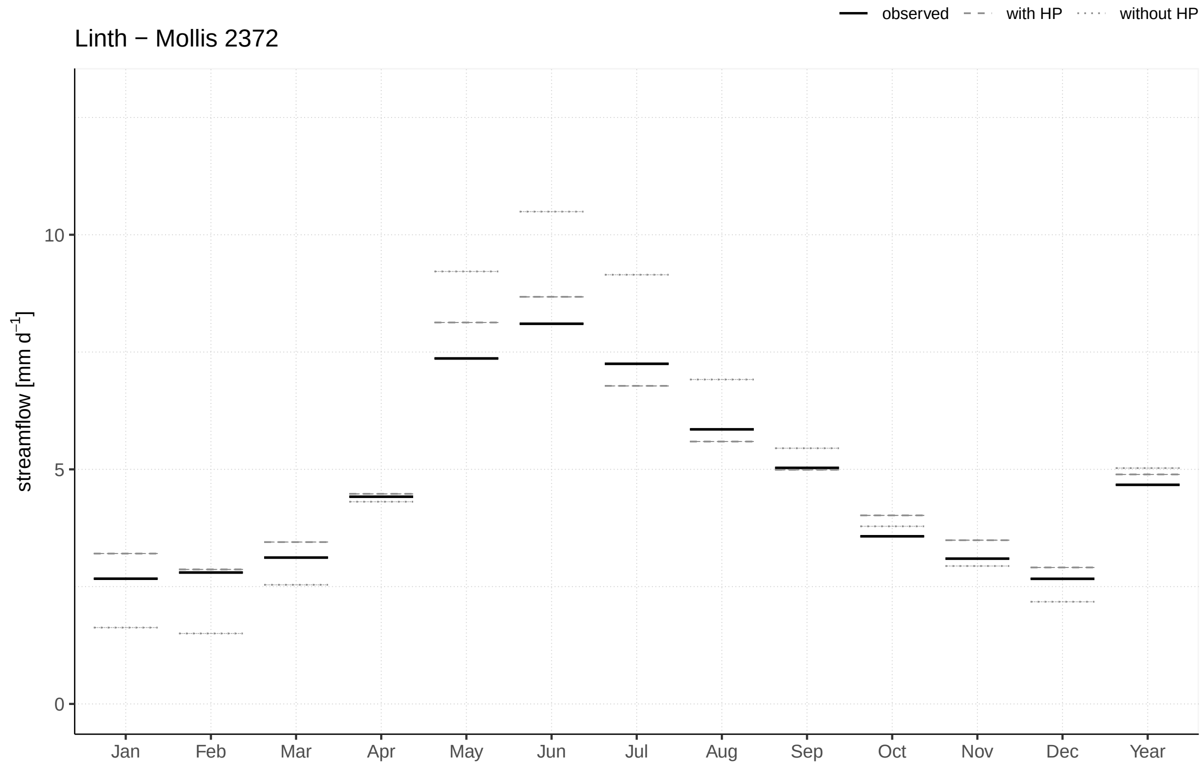
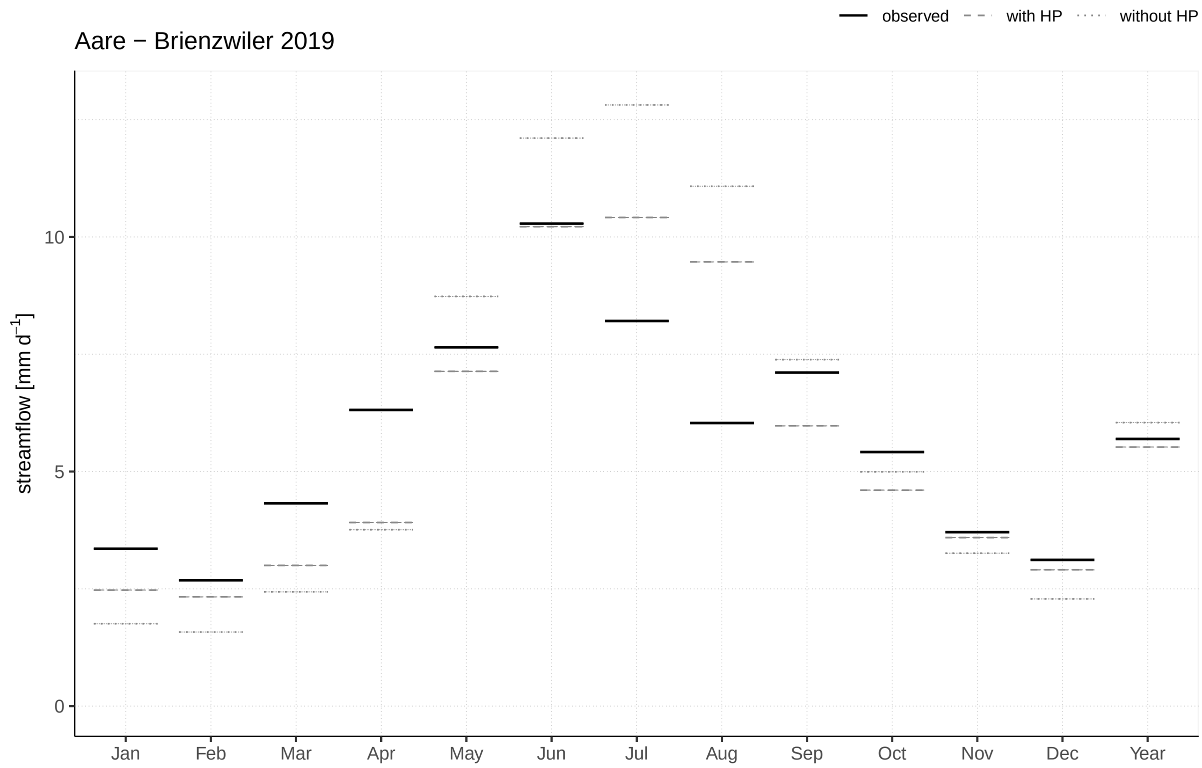
SI Table 1: The 39 climate model ensembles derived from the climate scenarios CH2018 [2018]. Each ensemble is a combination of TEAM (institute responsible), RCM (Regional Climate Model), GCM (General Circulation Models), RES (spatial resolution) and RCP (Representative Concentration Pathway, representing emissions scenarios).

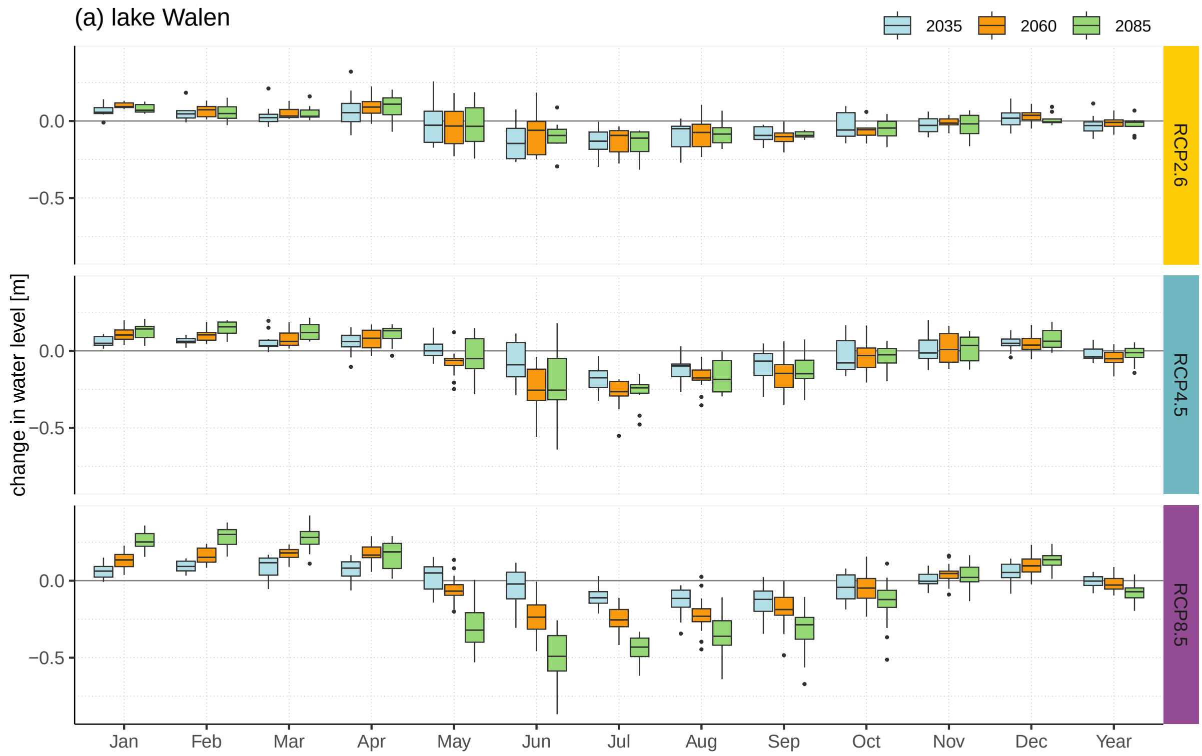
TEAM	RCM	GCM	RES	RCP	TEAM	RCM	GCM	RES	RCP
DMI	HIRHAM	ECEARTH	EUR11	RCP2.6	CLMCOM	CCLM4	HADGEM	EUR44	RCP8.5
KNMI	RACMO	HADGEM	EUR44	RCP2.6	CLMCOM	CCLM5	ECEARTH	EUR44	RCP8.5
SMHI	RCA	ECEARTH	EUR11	RCP2.6	CLMCOM	CCLM5	HADGEM	EUR44	RCP8.5
SMHI	RCA	ECEARTH	EUR44	RCP2.6	CLMCOM	CCLM5	MIROC	EUR44	RCP8.5
SMHI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



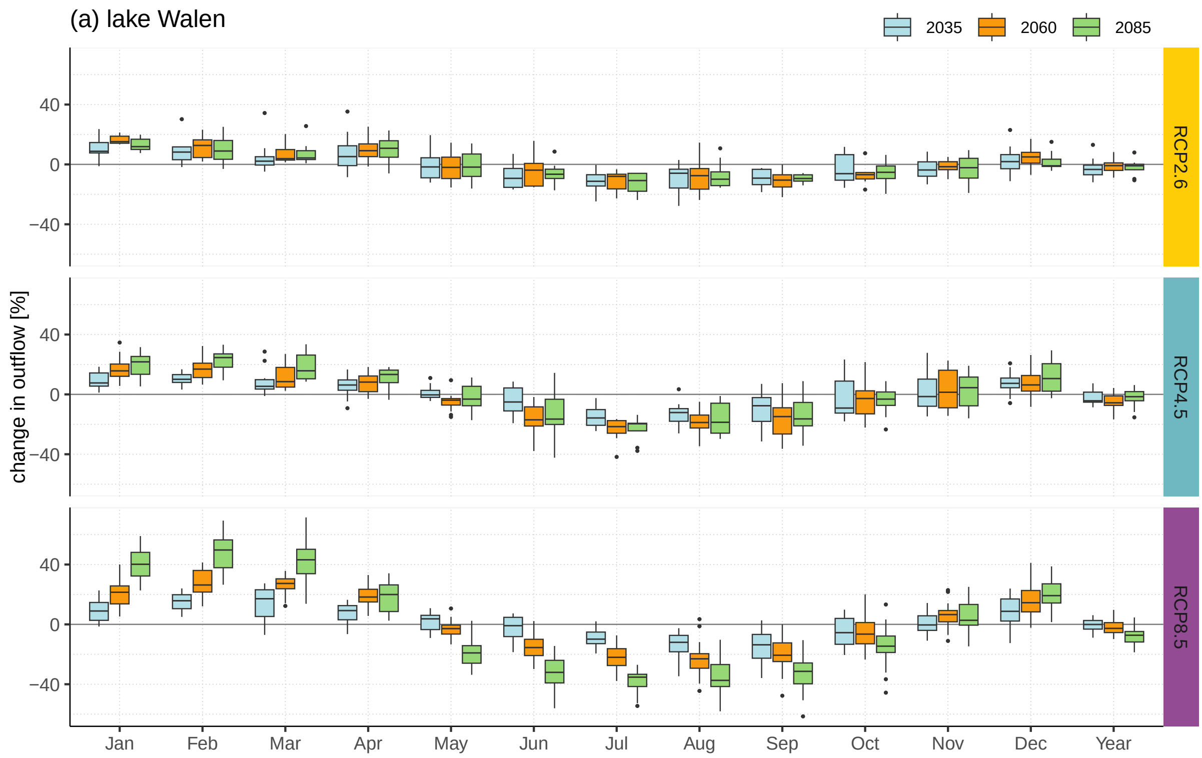
SI Figure 1: Hydropower impact in catchment I (Linth - Mollis 2372). The comparison of observed and simulated monthly mean streamflow. The black line represents the observed monthly mean streamflow, the dashed lines the simulated monthly means with and without consideration of hydropower, simulated with the hydrologic model PREVAH (section 3.2).



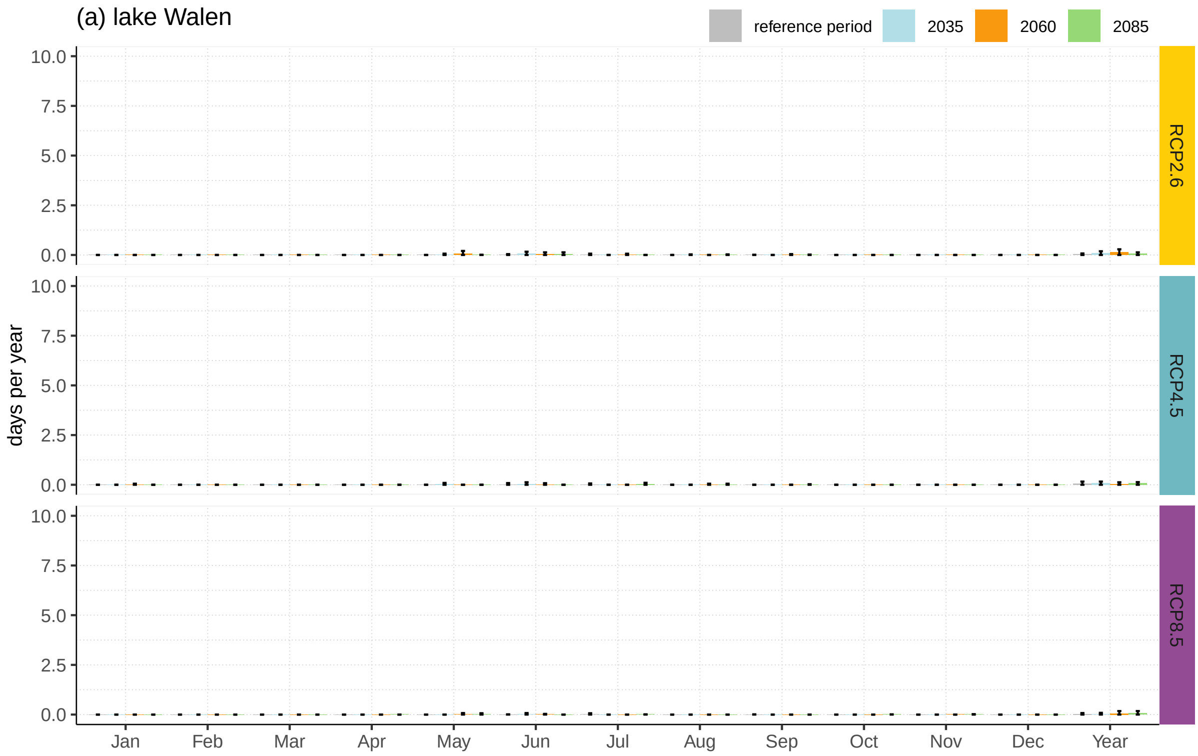
SI Figure 2: As Figure 1 but for hydropower impact in catchment II (Aare - Brienzwiler 2019).



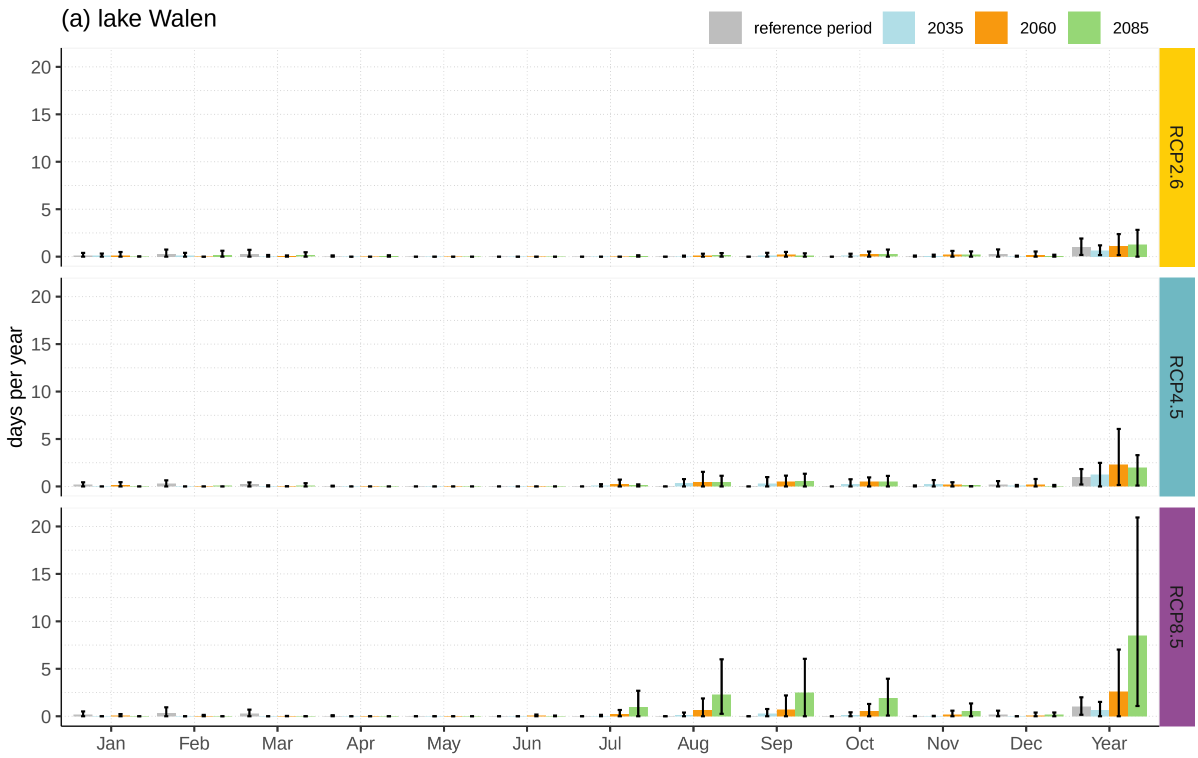
SI Figure 3: Simulated changes in annual and monthly mean lake water levels of Lake Walen, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



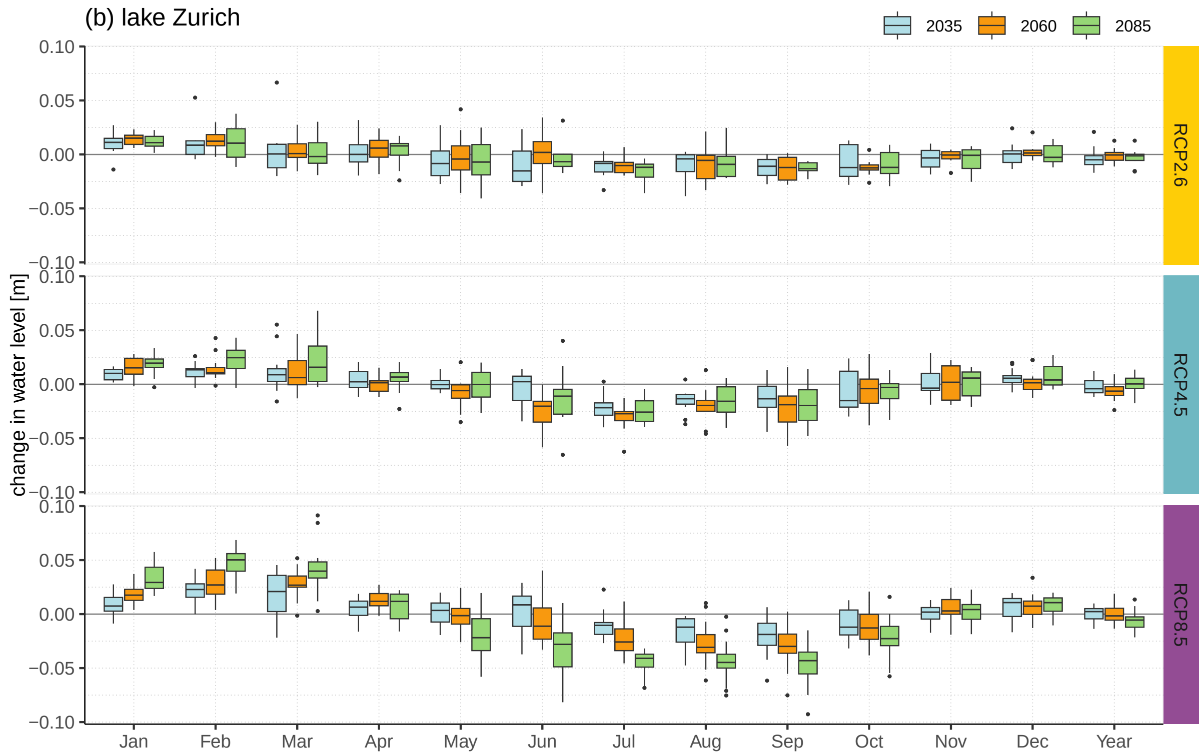
SI Figure 4: As Figure 3 but for the simulated changes in monthly and annual mean outflows of Lake Walen.



SI Figure 5: Simulated changes of the average number of days per year and month the lake water level exceeds the flood limit (F) of Lake Walen. Error bars refer to the 10 % and 90 % percentile range.

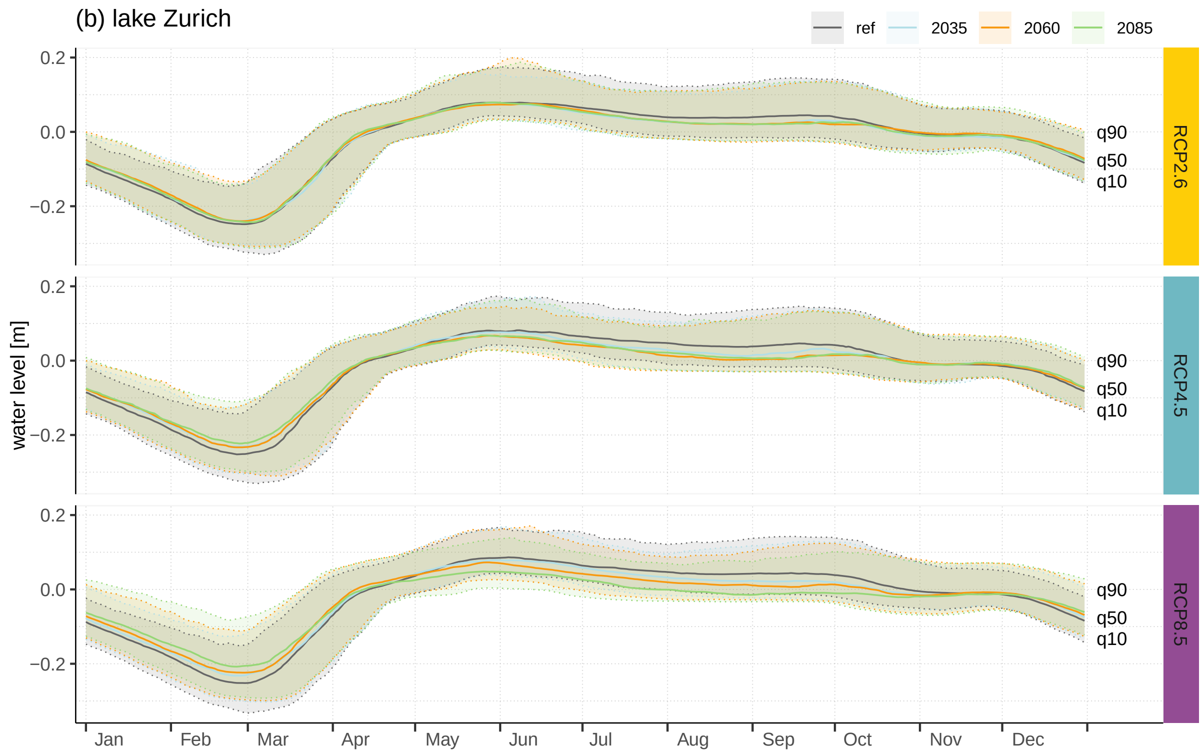


SI Figure 6: As Figure SI 5 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Walen.

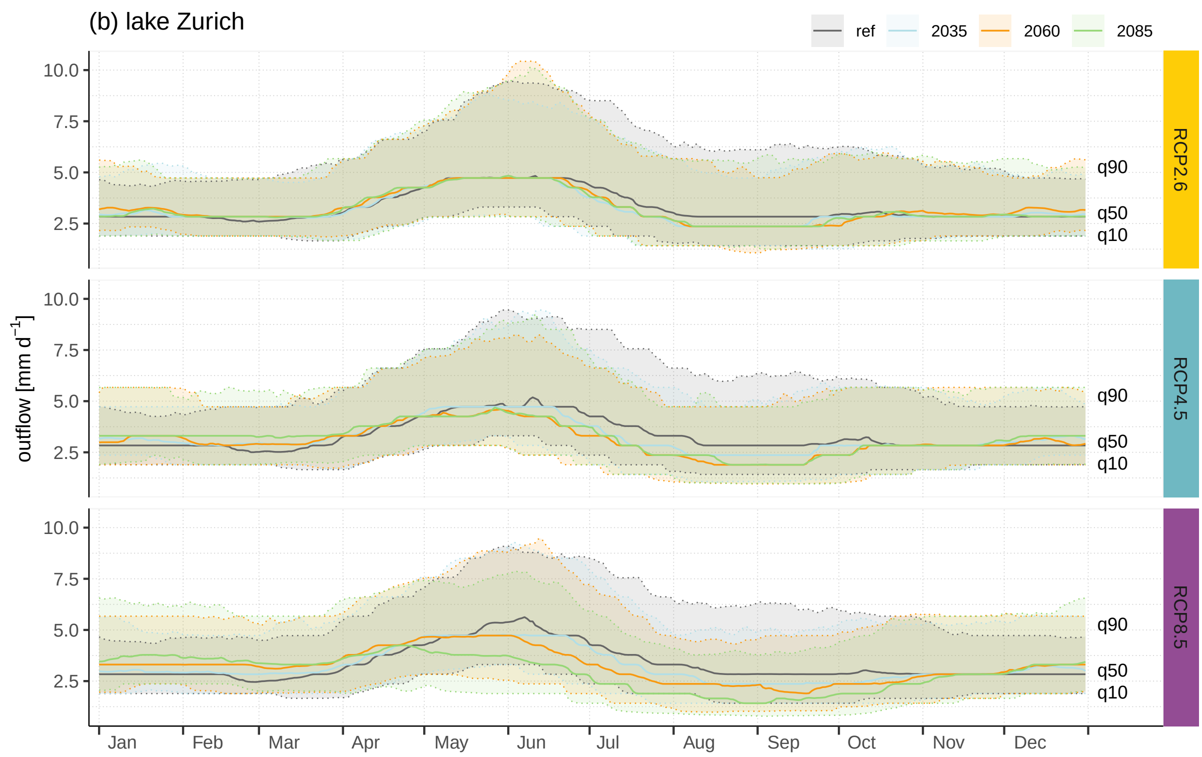


SI Figure 7: Simulated changes in monthly and annual mean lake water levels of lake Zurich, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

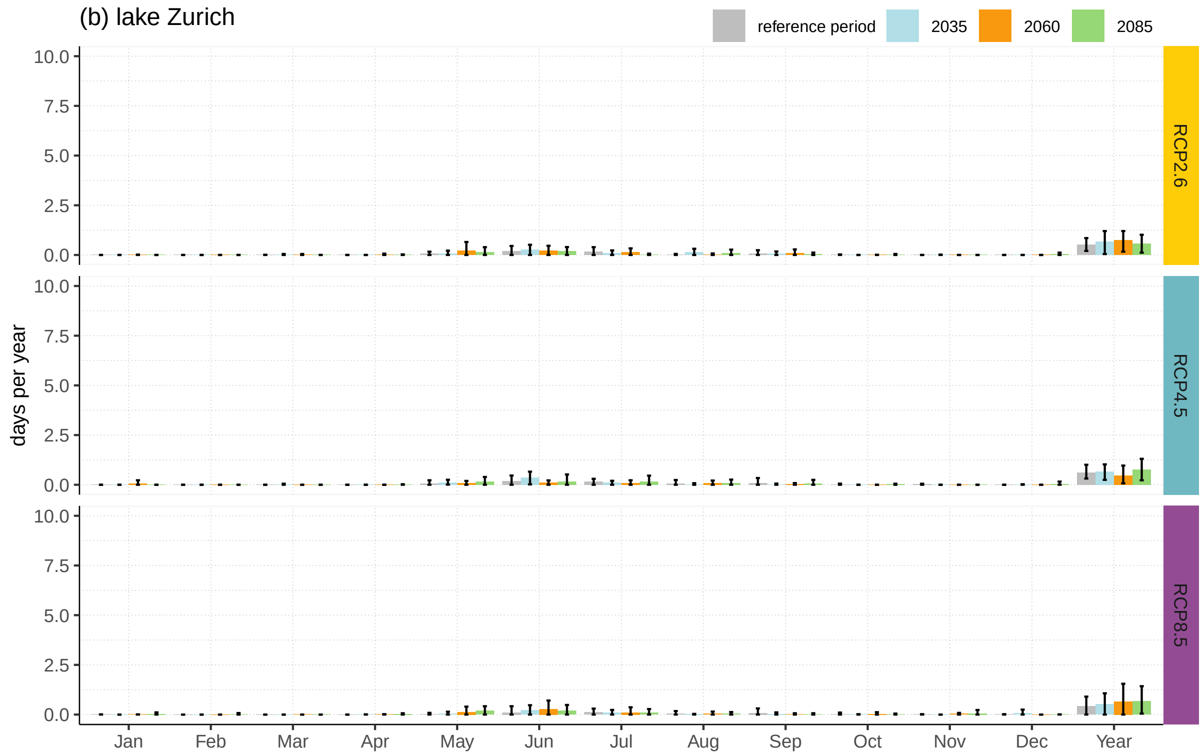
SI Figure 8: As Figure SI 7 but for the simulated changes in monthly and annual mean outflows of Lake Zurich.



SI Figure 9: Simulated changes in the 10 % and 90 % percentiles of lake water 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).

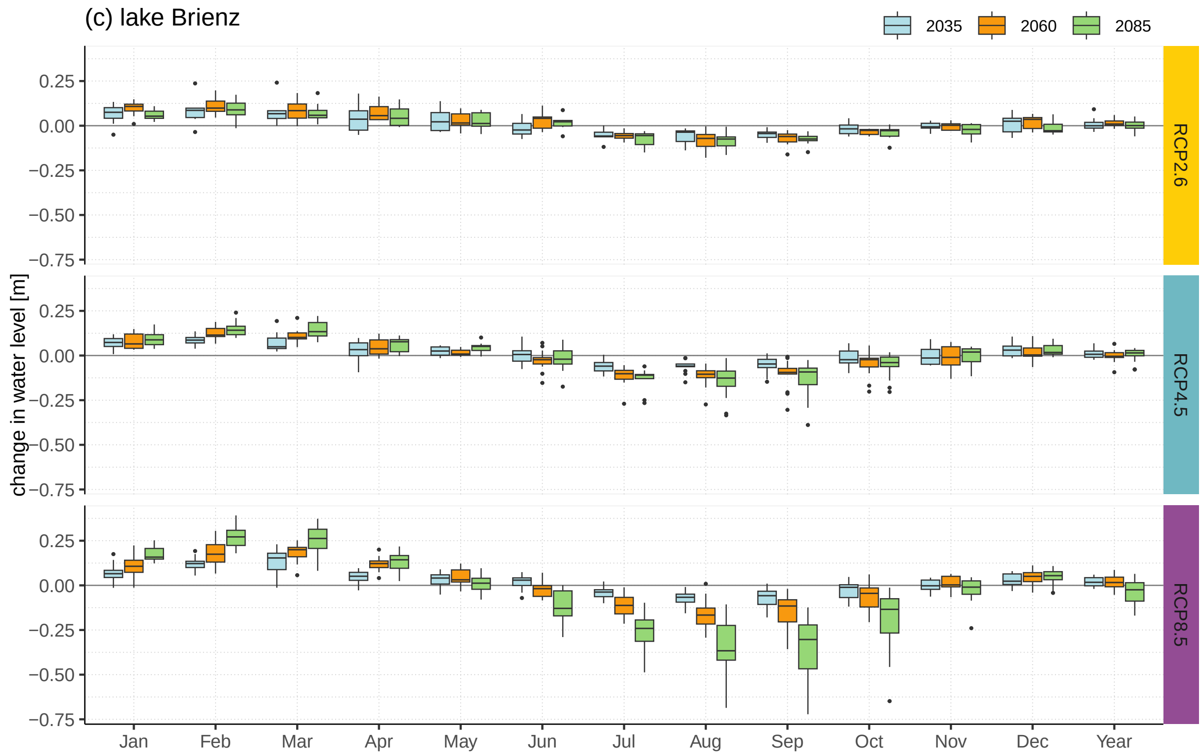


SI Figure 10: As Figure SI 9 but for the simulated changes in the 10 % and 90 % percentiles of outflows of Lake Zurich.

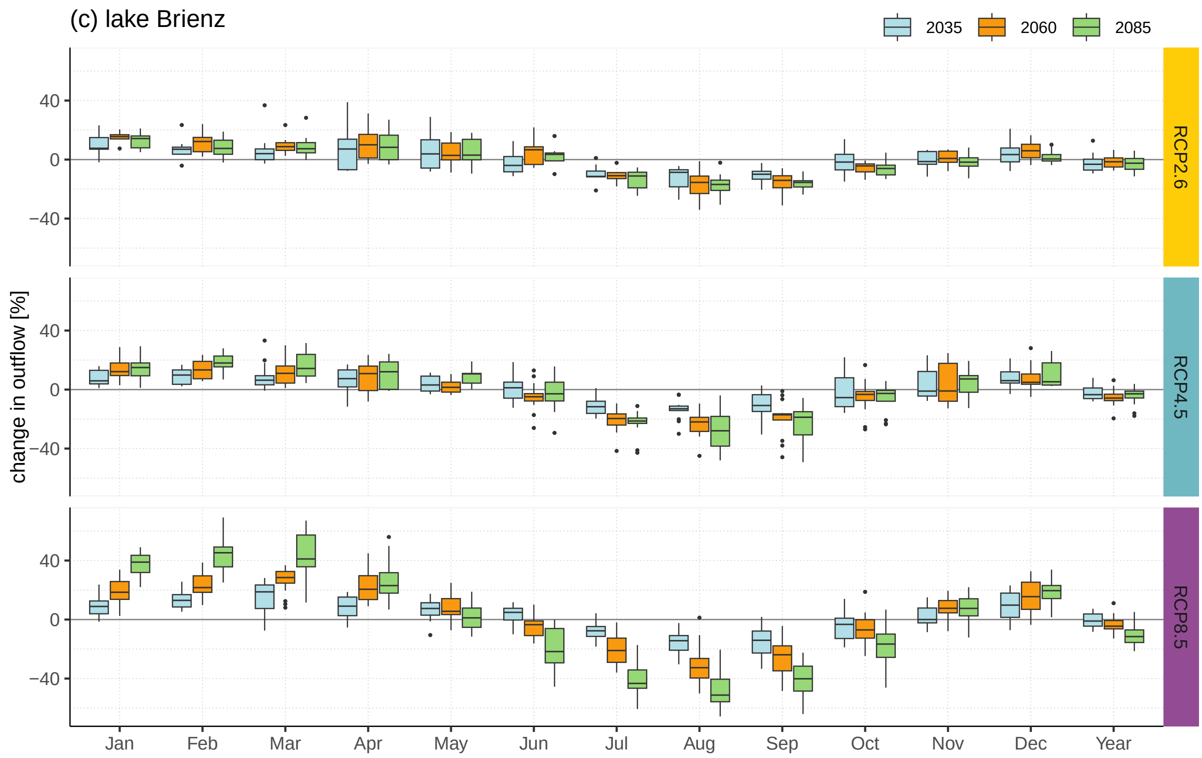


SI Figure 11: Simulated changes of the average number of days per year and month the lake water level exceeds the flood limit (F) of Lake Zurich. Error bars refer to the 10 % and 90 % percentile range.

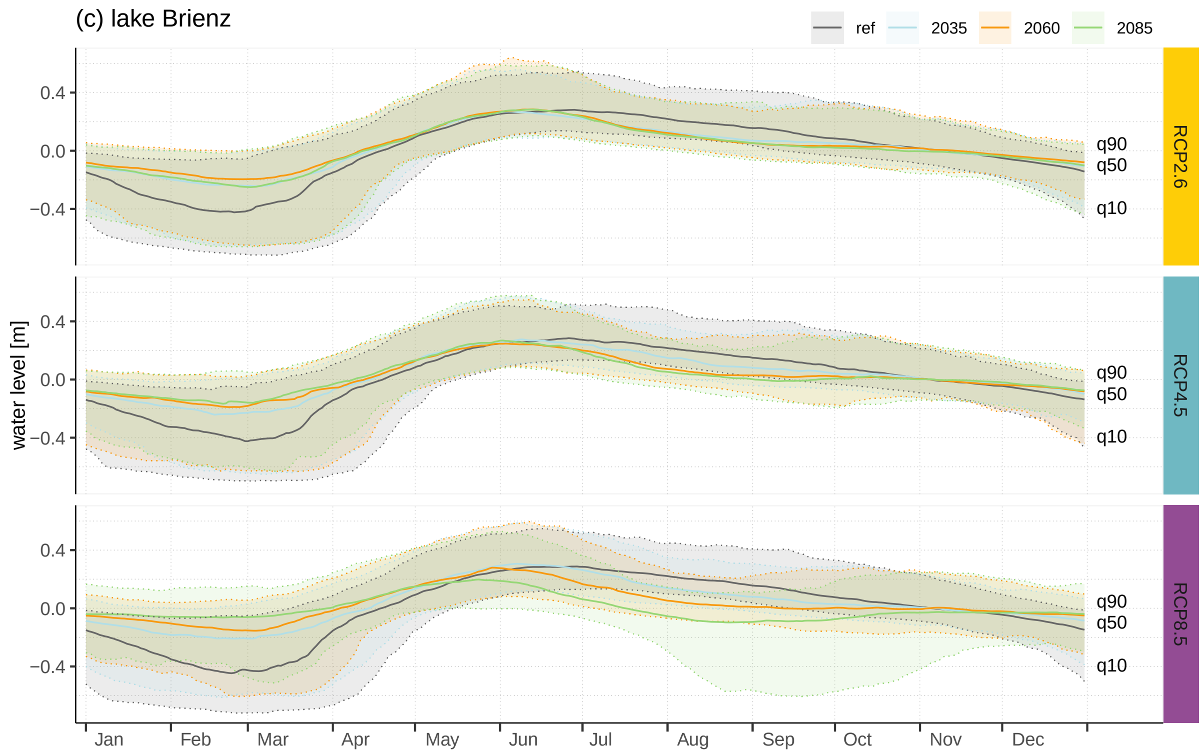
SI Figure 12: As Figure SI 11 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Zurich.



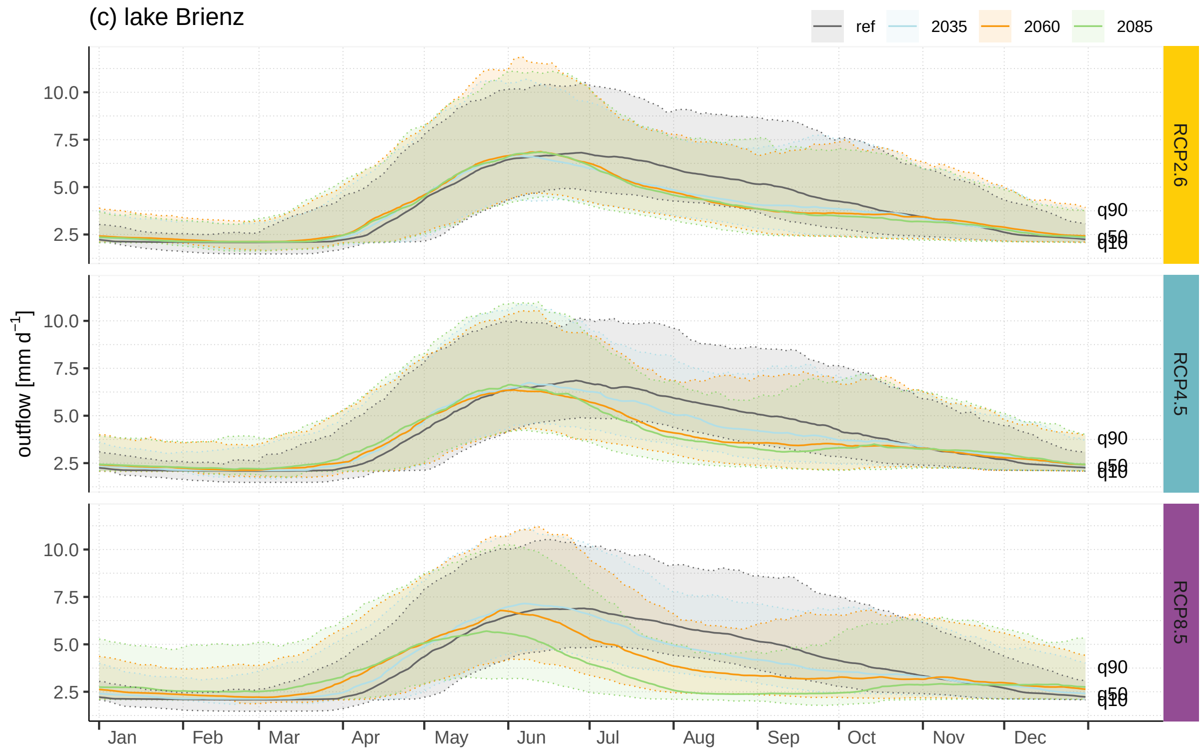
SI Figure 13: Simulated changes in monthly and annual mean lake water levels of Lake Brienz, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



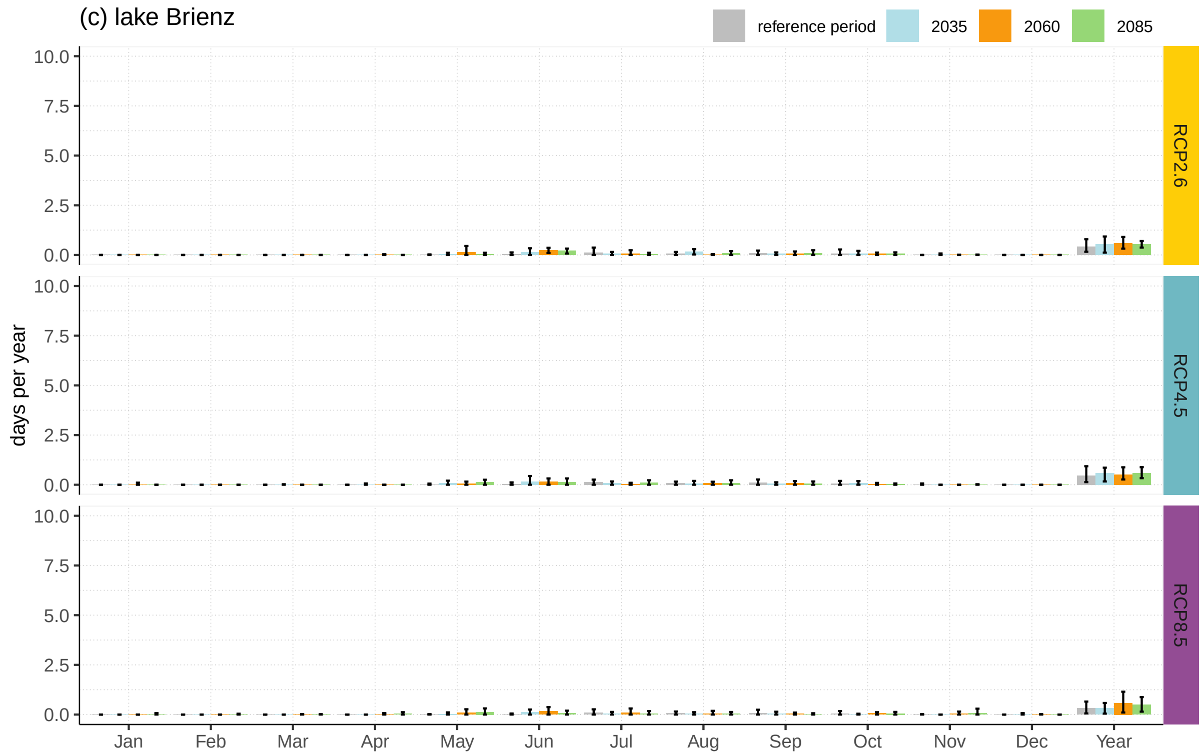
SI Figure 14: As Figure SI 13 but for the simulated changes in monthly and annual mean outflows of Lake Brienz.



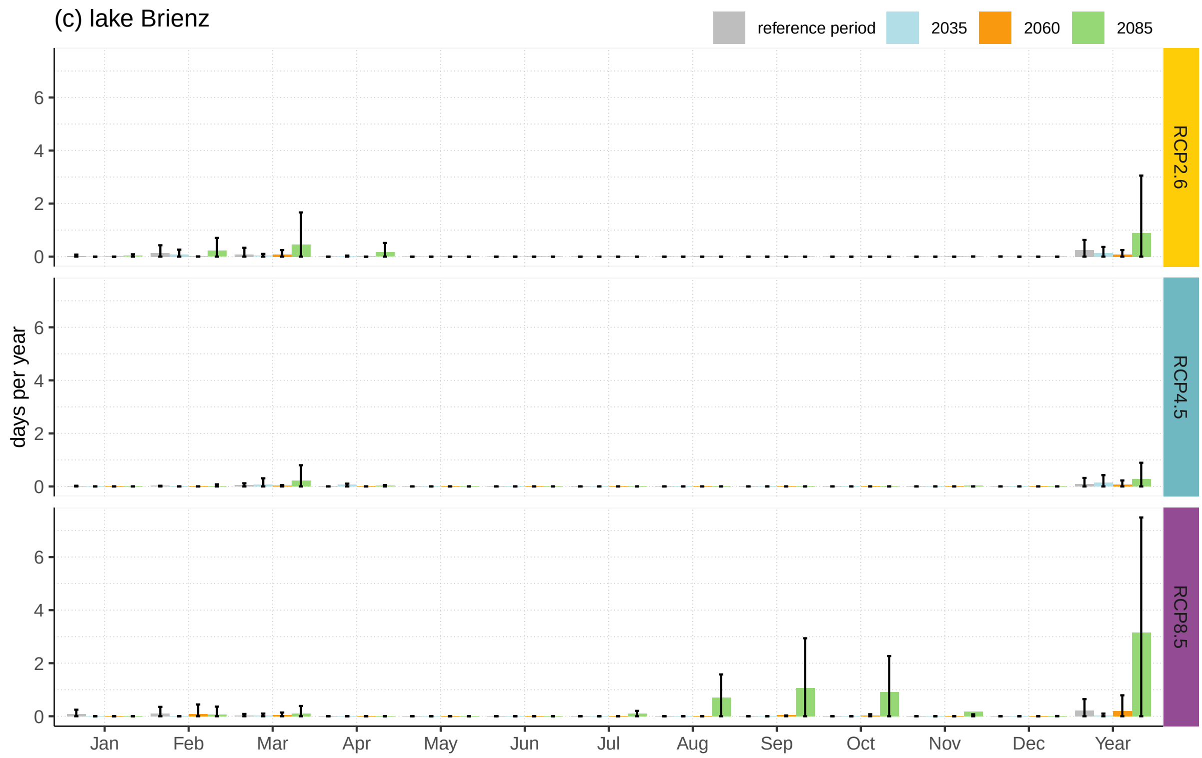
SI Figure 15: Simulated changes in the 10 % and 90 % percentiles of lake water levels (moving average ±15 days) of Lake Brienz, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



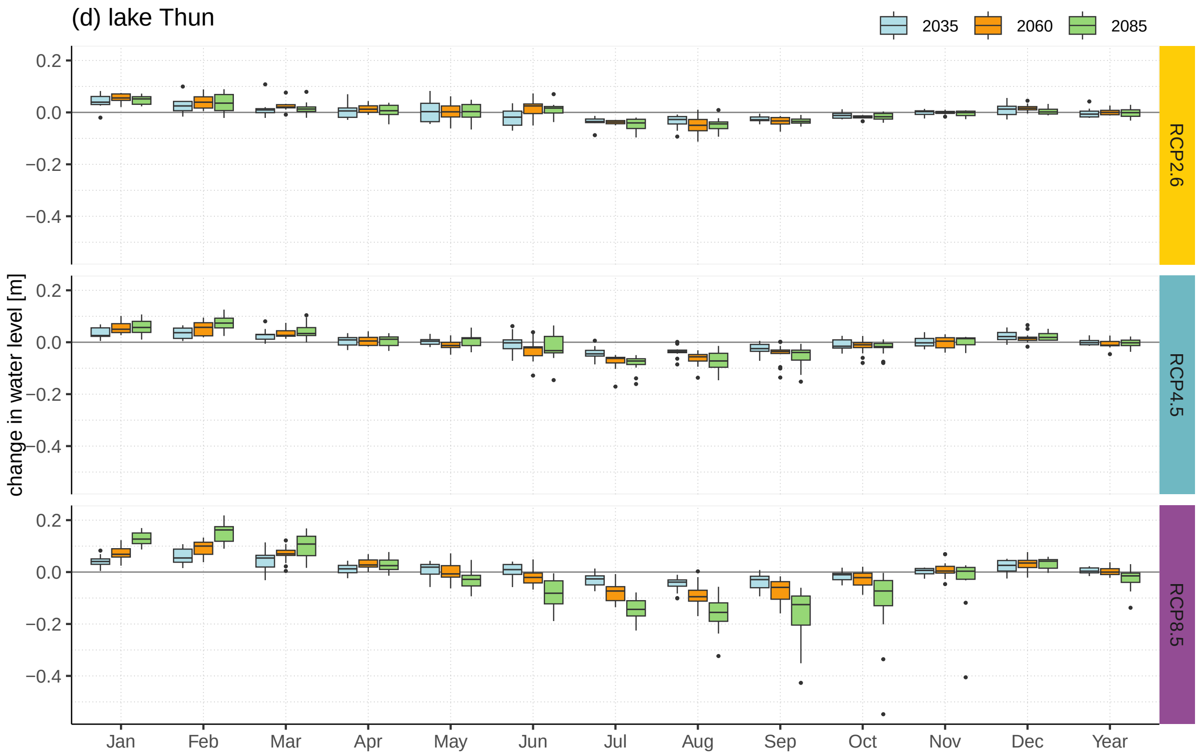
SI Figure 16: As Figure SI 15 but for the simulated changes in the 10 % and 90 % percentiles of outflows of Lake Brienz.



SI Figure 17: Simulated changes of the average number of days per year and month the lake water level exceeds the flood limit (F) of Lake Brienz. Error bars refer to the 10 % and 90 % percentile range.

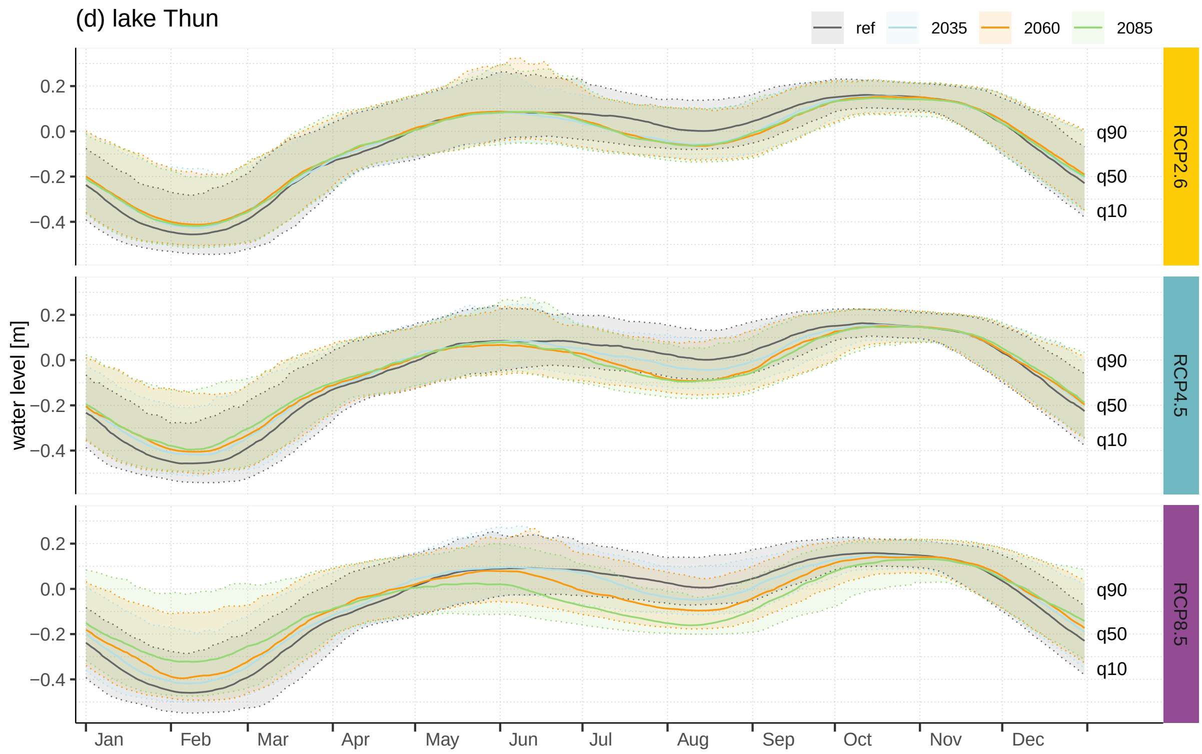


SI Figure 18: As Figure SI 17 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Brienz.

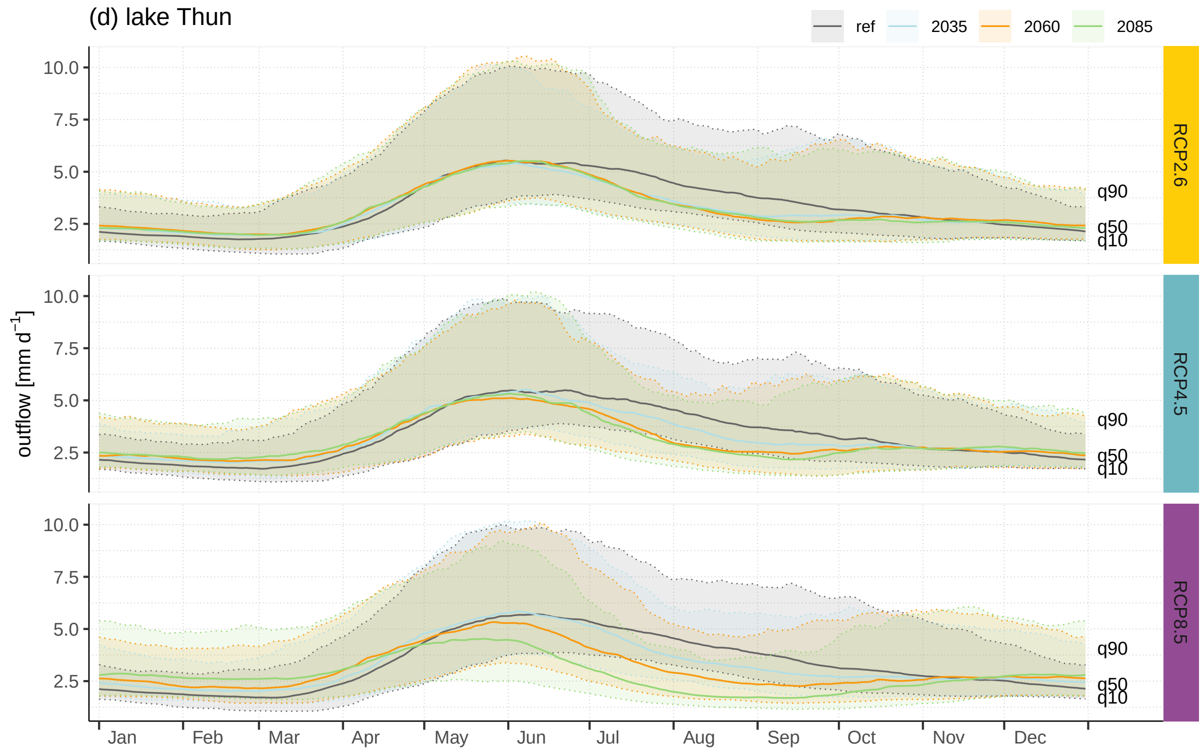


SI Figure 19: Simulated changes in monthly and annual mean lake water levels of lake Thun, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

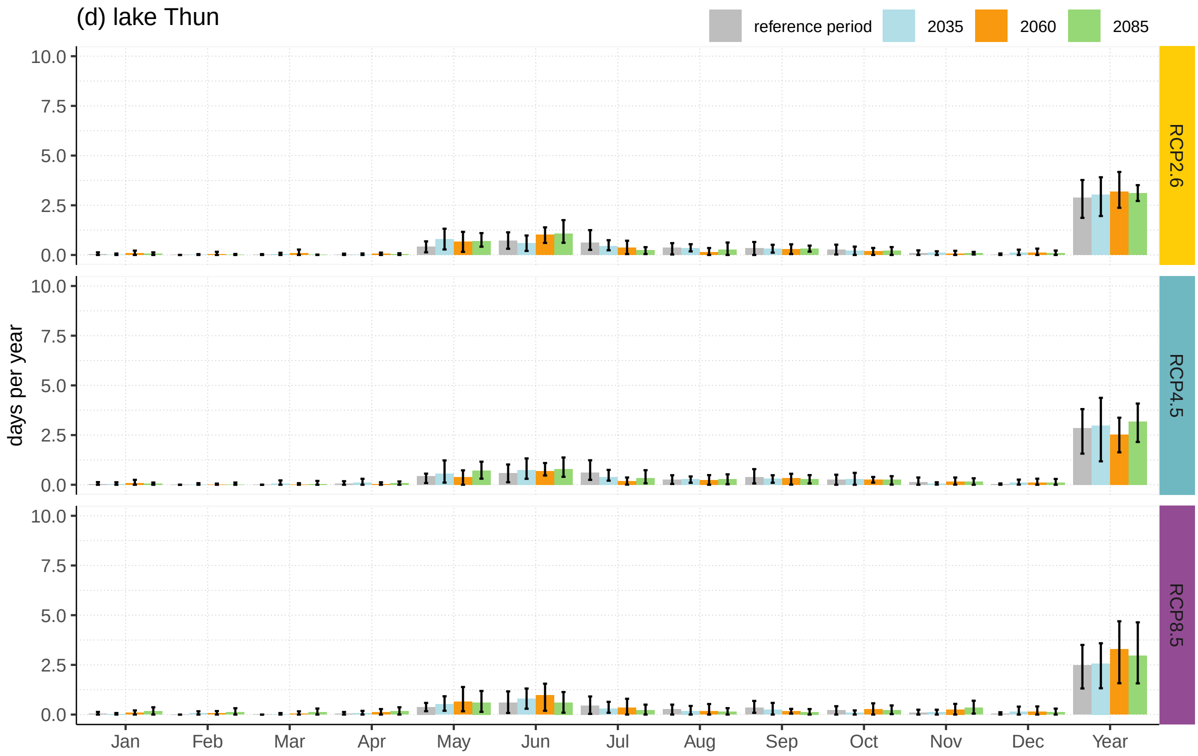
SI Figure 20: As Figure SI 19 but for the simulated changes in monthly and annual mean outflows of Lake Thun.



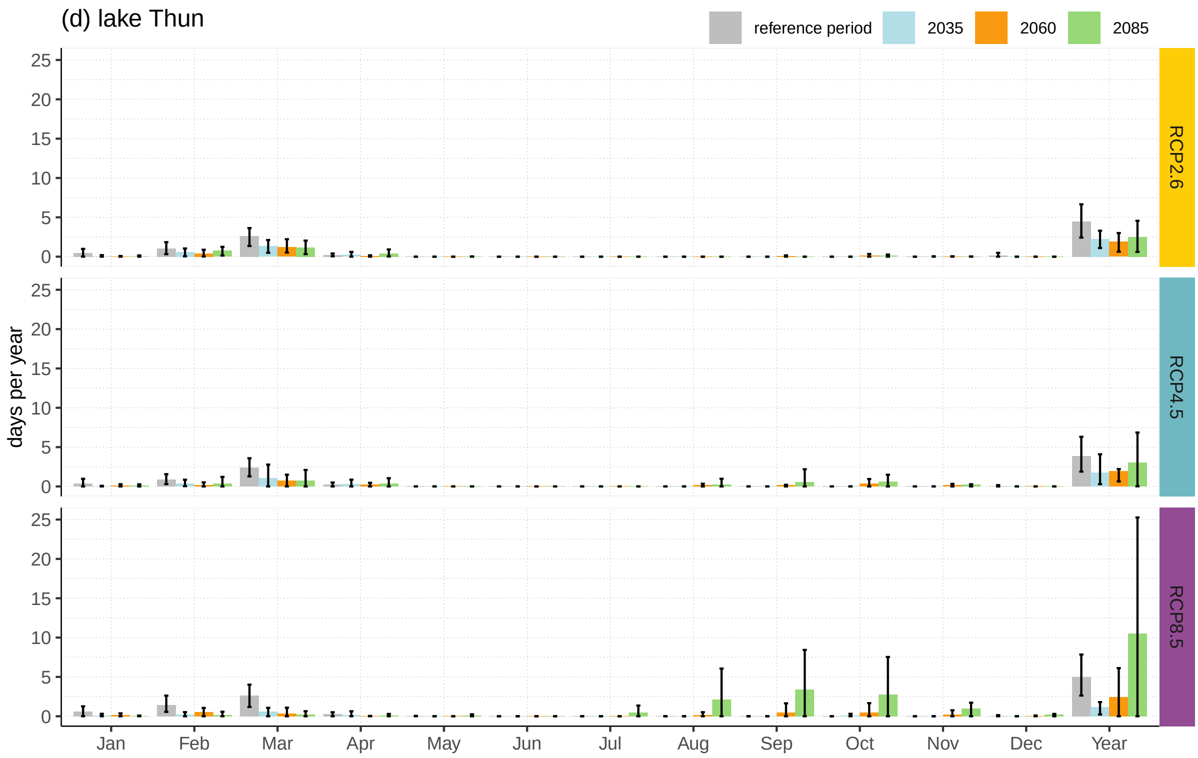
SI Figure 21: Simulated changes in the 10 % and 90 % percentiles of lake water levels (moving average ±15 days) of Lake Thun, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



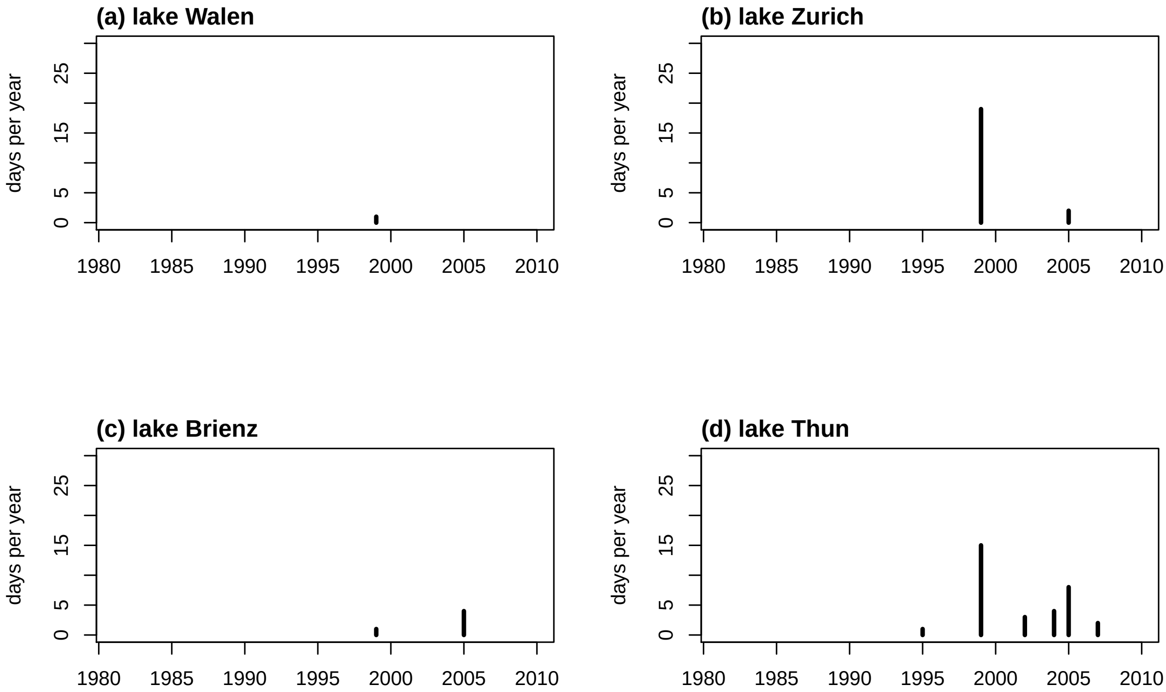
SI Figure 22: As Figure SI 21 but for the simulated changes in the 10 % and 90 % percentiles of outflows of lake Thun.



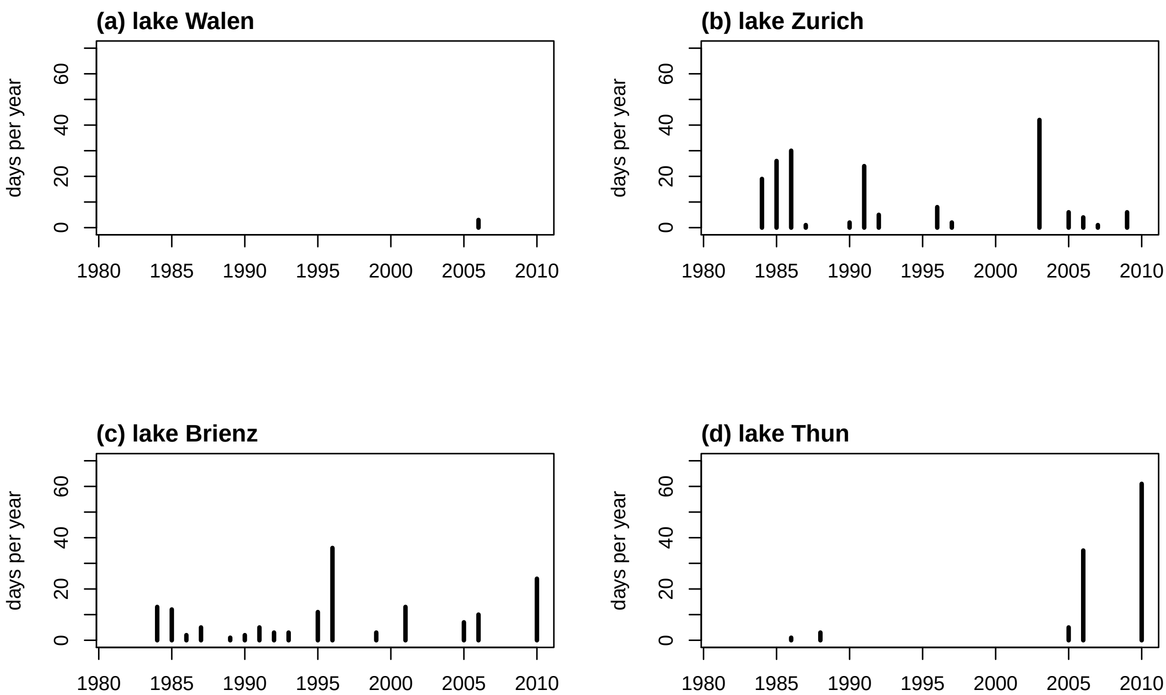
SI Figure 23: Simulated changes of the average number of days per year and month the lake water level exceeds the flood limit (F) of Lake Thun. Error bars refer to the 10 % and 90 % percentile range.



SI Figure 24: As Figure SI 23 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Thun.



SI Figure 25: Observed days per year the lake water levels exceed the flood limit (F) for Lake Walen (unregulated), lake Zurich (regulated), lake Brienz (semi-regulated) and Lake Thun (regulated).



SI Figure 26: As Figure SI 25 but for the observed outflows undercutting the drought limit (L).

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

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