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

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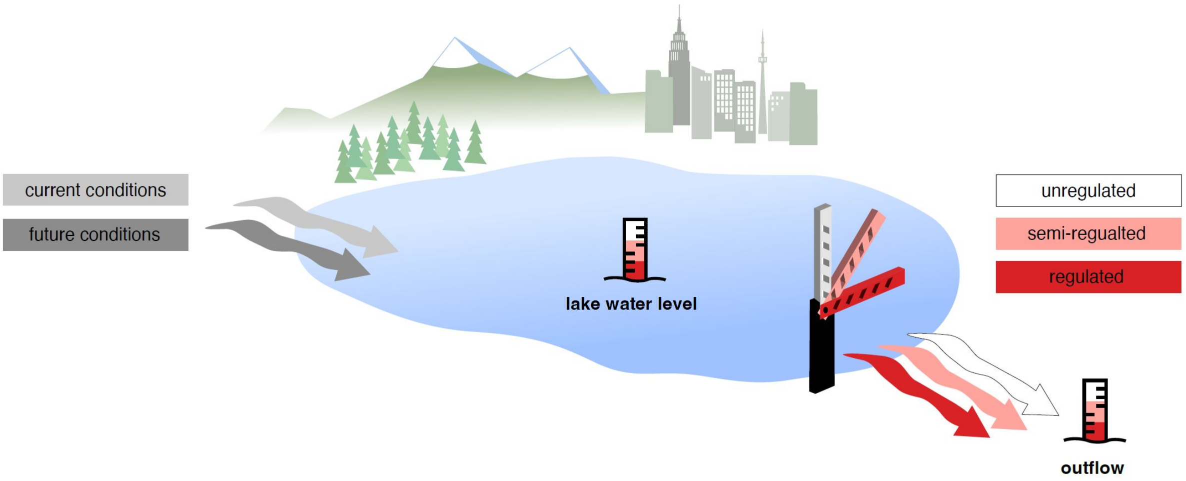
## Abstract

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, 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. This study focuses on four perialpine lakes in Switzerland, with different levels of lake level management. 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. 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

- Including lake level regulation in hydrologic simulations improves its performance
- Climate change leads to pronounced seasonal changes in lake levels and outflows
- The degree of lake level management affects lake levels stronger than outflows
- Climate change impacts on lakes intensify with time and missing climate mitigation
- Climate change can lead to more frequent summer droughts in perialpine regions



# 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. 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).

One of the few examples of such a study is the work of Gibson et al. (2006b); they 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. The results reveal that lake level management has decreased the magnitude of annual lake level variations and an earlier occurrence of peak lake 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 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). 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. In fact, besides the few modeling 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 modeling 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). According to Paiva et al. (2011), the high computational costs lake level management associated with hydrodynamic models can probably explain the omission of lake level management, as mentioned in several studies (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). 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 climate change. They found a slight decrease in mean monthly lake levels for May and June and in annual maximum lake levels under future climate scenarios. In addition, they simulated a decrease in annual lake level fluctuations and in maximum lake level fluctuations for future scenarios, which they did not further comment upon. For our study, we selected four Swiss lakes with different levels of lake level management.

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? We combine the hydrologic model PREVAH and the hydrodynamic model MIKE11 to investigate lake level variability. Our analysis is based on a modeling 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 modeling chains as input to a hydrodynamic model (MIKE11; DHI, 2003), for which we developed a specific methodology to account for lake level management rules. Compared to previous work (Hingray et al., 2007), the focus on regulated and unregulated lakes allows for disentangling climatic from lake level regulation impacts. To our knowledge, the present study is the first climate change impact assessment on perialpine lake level variability, also explicitly disentangling climatic from lake level regulation impacts. The study focuses on Switzerland, which has some of the largest European lakes and a long history of lake level management and monitoring (FOEN, 2013). Furthermore, Swiss lakes have a high share of meltwater input and are potentially highly vulnerable to climate change. The national focus has the main advantage of building upon a coherent set of climate change simulations (FOEN, 2021), resulting in a modeling 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 Hauer, 1992) and urgently needs to be studied to understand further how climate change 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 Material and methods

## 2.1 General change assessment framework

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).

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 disentangle climatic from lake level regulation impacts, 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. To disentangle climatic from regulatory impacts on lake levels and outflows, we combine a hydrologic model and a hydrodynamic model (Section 2.6) applied to the two selected catchments, including four lakes (Figure 2). We consider differences in simulated mean annual and monthly lake levels over 30 years for the change assessment. Changes in extremes are assessed based on the 10 % and 90 % percentiles of average monthly lake levels and based on indicators such as the frequency of reaching the drought and flood limits.

## 2.2 Lake level management

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 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 (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 modeling (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).

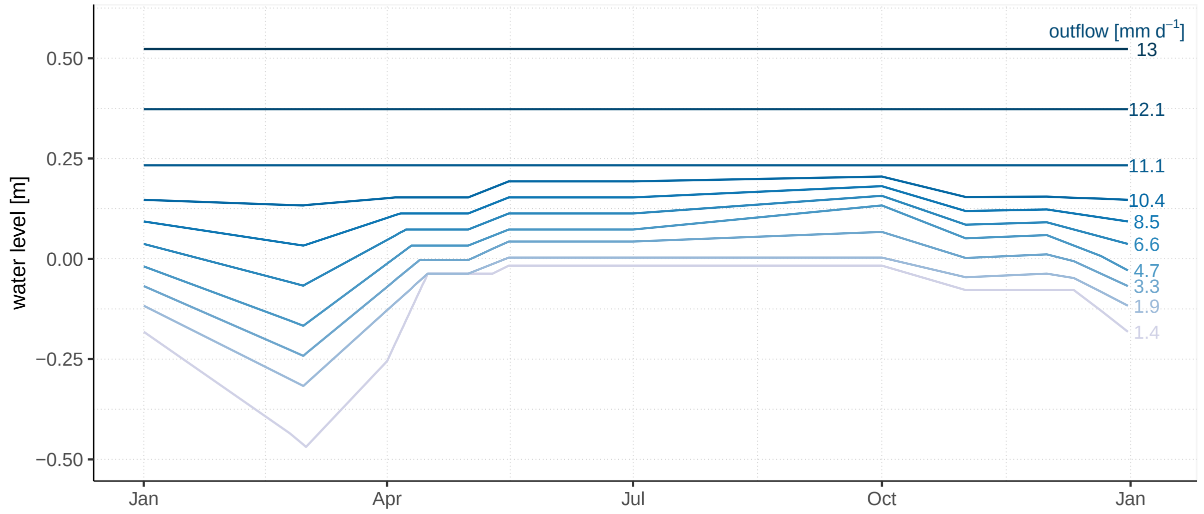


Figure 1: Example of a line diagram that defines a target outflow (blue lines) for each calendar day (x-axis) and for given lake levels (y-axis). Shown is the line diagram for Lake Zurich.

### 2.3 Selected case studies

We selected four perialpine lakes in Switzerland (Figure 2) 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). 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 3). 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).

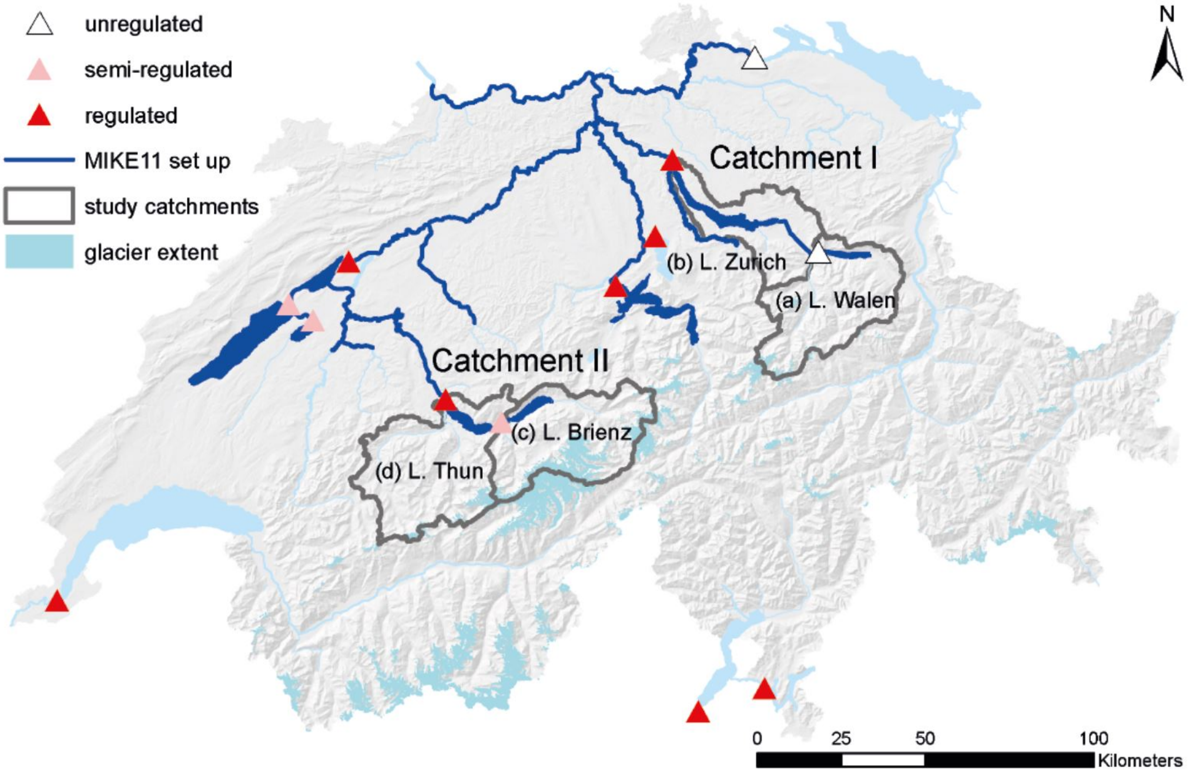


Figure 2: Location of the four case study lakes, located in pairwise nested catchments I and II. Rivers and lakes in dark blue represent the model set-up of the hydrodynamic model MIKE11. The coloured triangles indicate the degree of lake level management of all large lakes (surface area $> 10$ km$^2$) in Switzerland. Also shown is the glacier extent of 2016 (Linsbauer et al., 2021).

Table 1: 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 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$^2$] | Øelevation [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 |

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 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.

## 2.4 Lake level regimes

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 3, 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.

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 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-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 the work of 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 3). This depends on the stage-discharge relationship and the underlying line diagram.

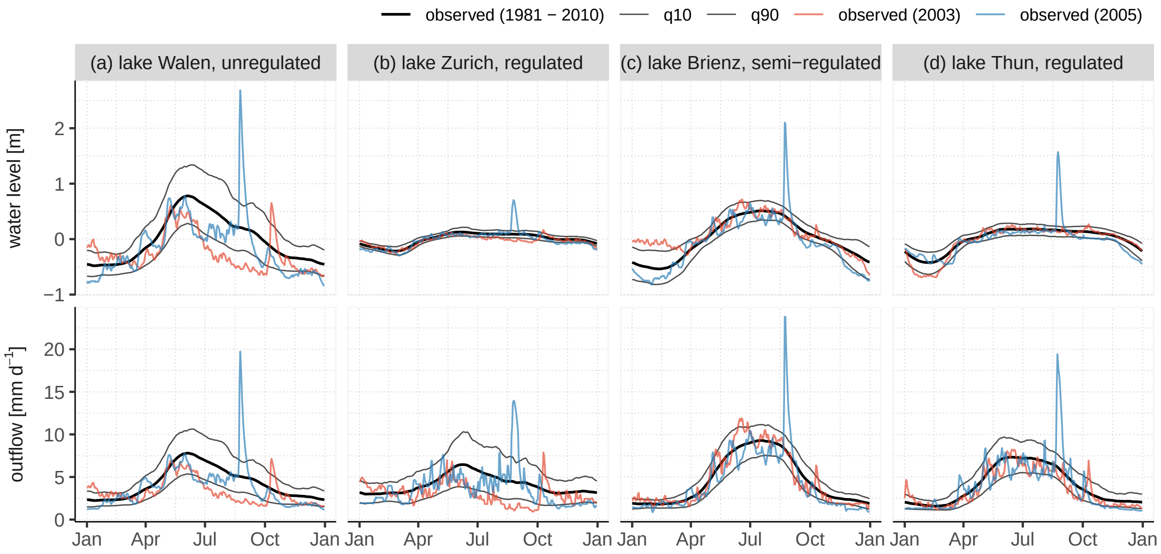


Figure 3: The observed mean 31-day (moving average ±15 days) lake levels (top line) and outflows (bottom line) as well as the 10 % and 90 % percentile (confidence interval) for the reference period (1981 – 2010). Also shown are the extreme drought year of 2003 and the flood year of 2005.

## 2.5 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). The climate model ensemble CH2018 contains a total of 39 model chains 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 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).

## 2.6 Hydrologic and hydrodynamic models

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. 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). PREVAH includes a rough simulation of the lake dynamics, with a simple mass balance approach assuming a reservoir filling with a fixed area and a known stage-discharge function. 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 modeling 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 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 2.6.1). To simulate the fluid dynamics, MIKE11 employs the Saint-Venant equation, which accounts for flow velocity, water depth, and channel slope. 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.

Combining the hydrologic and hydrodynamic models is essential to assess the climate change impacts on water-level-outflow dynamics, which expresses 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. 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), because they have not been coupled for operational purposes. The two models used for the CC impact assessment are loosely coupled: the hydrologic model provides inflows as input data for the hydrodynamic model.

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.

#### 2.6.1 Lake and river characteristics

The lake and river characteristics described here are used for the hydrodynamic simulations with MIKE11 (Section 2.6). 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 1). 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 2.6) 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 the comparison of future monthly ($m$) mean lake levels ($h_{m,fut}$) to the reference period ($h_{m,ref}$):

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

where $\Delta h_m$ [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 $n_{m,fut}$ can differ from the number of reference time steps $n_{m,ref}$. The average annual change ($\Delta h_a$) 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 ($\Delta Q_m$) are computed as:

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

We illustrate projected 30-year mean changes involving 39 model chains in boxplots and express them as follows: -0.4 m (** IQR: -0.5 m, -0.37 m). The number preceding the bracket represents the median value 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 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 (daily to hourly scale) have less significant impacts on large lake systems. Therefore, we analyse the changes in extreme lake 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 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)):

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

where $n_p$ is the number of years in the simulation period $p$ ($n_p$=30 for all periods). The critical (hazard) 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 ($L$):

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

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 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 2.6). 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).

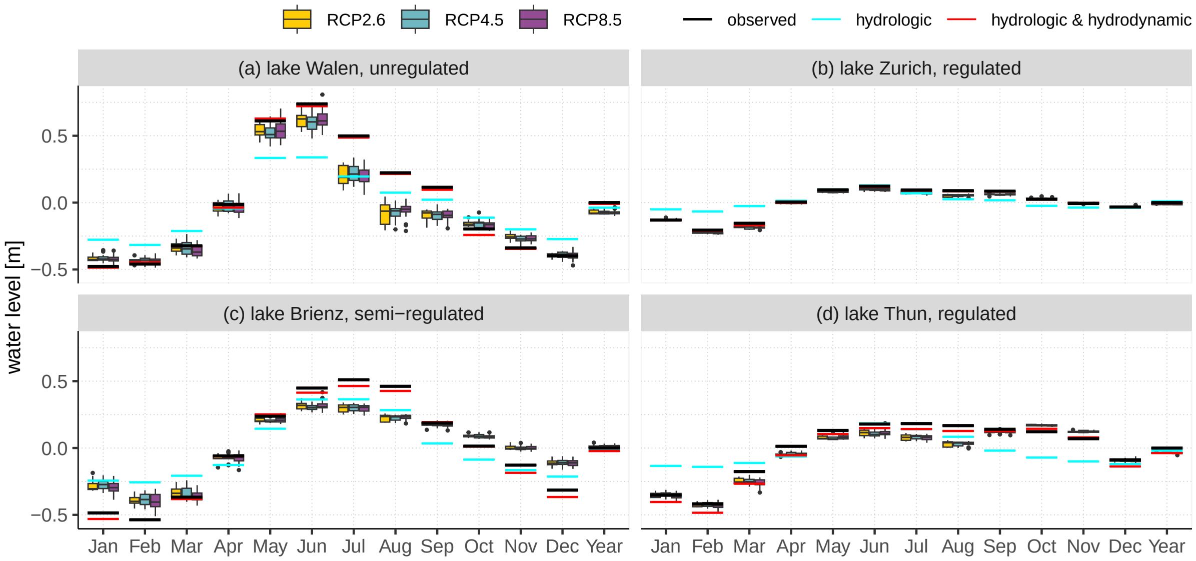


Figure 4: Normalised observed and simulated annual and monthly lake levels for the four considered lakes during the reference period (1981 – 2010). The observations are compared to the hydrologic simulations with PREVAH and the combination of the hydrologic and hydrodynamic models PREVAH and MIKE11. 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 3), 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.

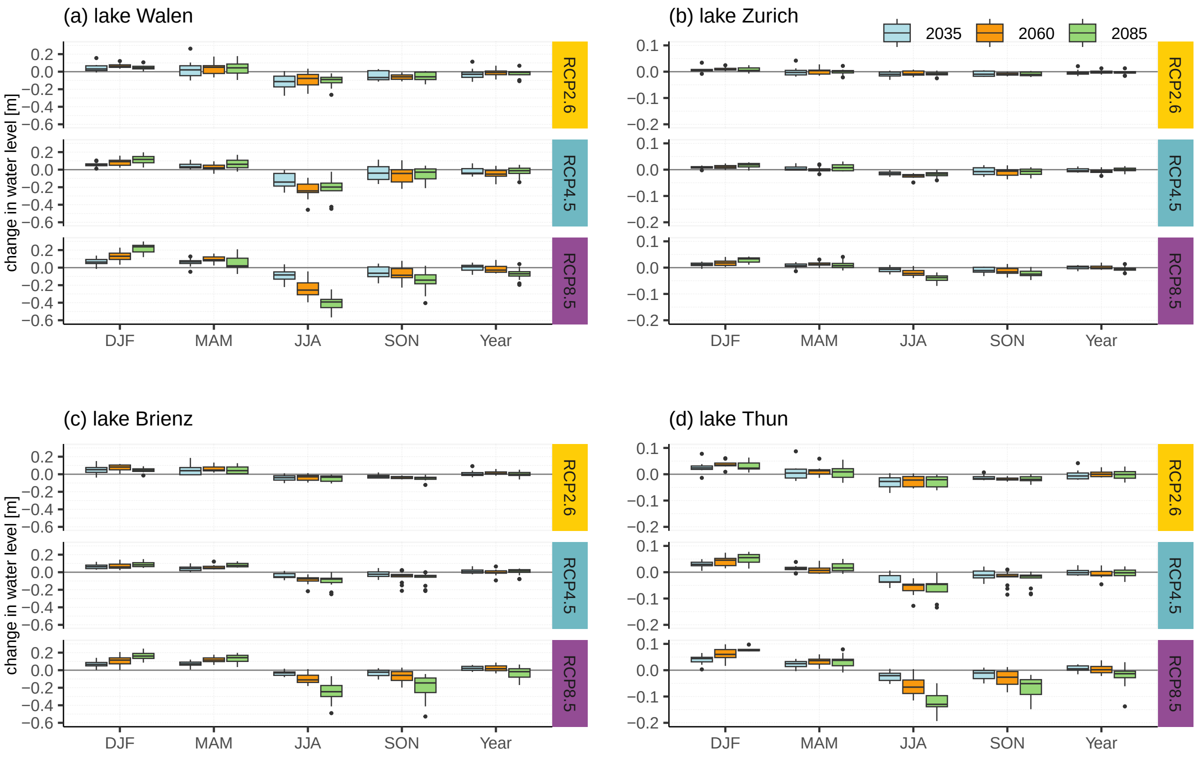


Figure 5: Simulated changes in seasonal mean lake levels of Lake Walen (unregulated), Lake Zurich (regulated), Lake Brienz (semi-regulated) and Lake Thun (regulated), divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

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 3), 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).

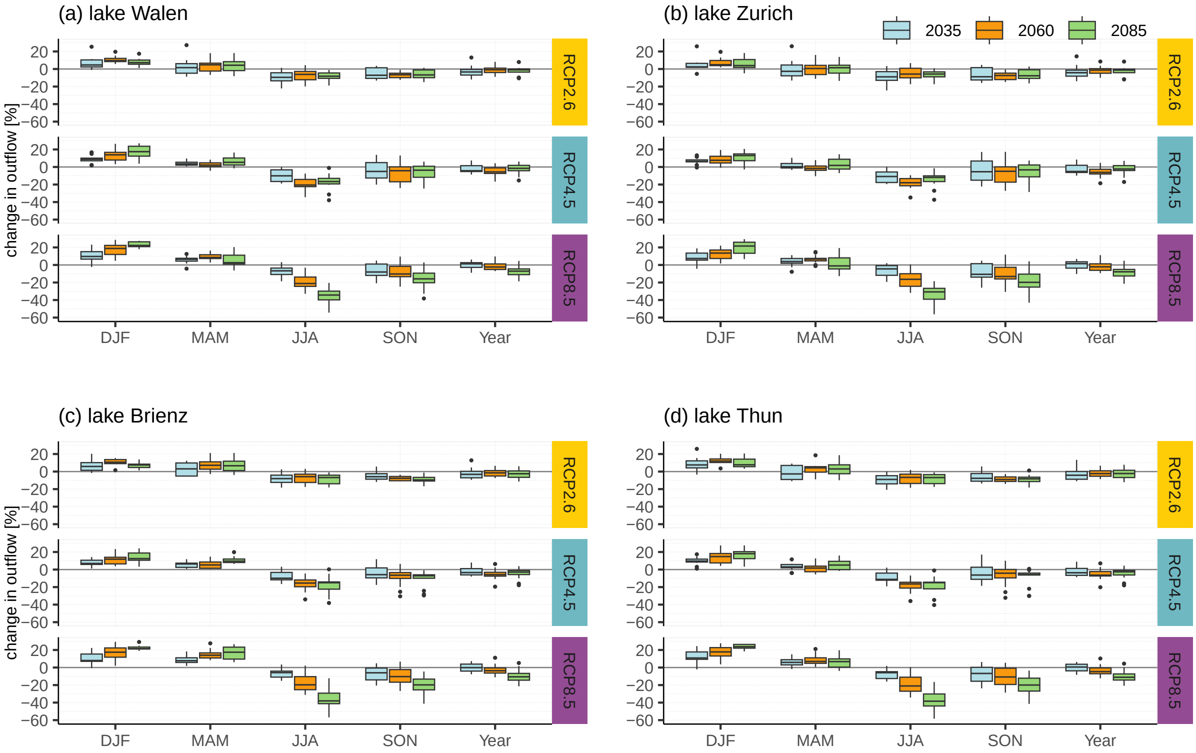


Figure 6: As Figure 5 but for the simulated changes in seasonal outflows.

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 monthly extremes

The simulations indicate an increase of high-lake levels ($q90$) in winter but they remain lower than in summer (Figures SI 8, 14, 20 and 26). For the future periods, the highest monthly lake levels ($q90$) occur in early summer, similar to the reference period, and decrease noticeably throughout the summer. The simulations indicate an increase in the low-lake levels ($q10$) in winter and a significant decrease in summer and autumn.

Due to lake level management, the lake level of the regulated Lake Zurich and Lake Thun are artificially lowered in late winter (Section 2.4). For the regulated Lake Zurich and Lake 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 14, 20 and 26). The lowest $q10$ for these lakes continue to occur during winter. For the unregulated Lake

Walen, the simulations indicate a decrease in $q10$ during summer and autumn and fall below the winter low-lake levels of the reference period (Figure SI 8). Consequently, the lowest $q10$ in Lake Walen could shift from winter to late summer in the future. Similarly to the mean lake levels, the $q90$ and the $q10$ also indicate stronger changes with time and without climate change 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 levels (Figures SI 9, 15, 21 and 27). Outflow changes in 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 strong 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 indicates a noticeable increase, approaching the $q50$ outflows of the reference period. By the end of the century and without climate change mitigation measures (RCP8.5), the lowest outflows are simulated in late summer; for the two lakes in catchment I, Lake Walen and Lake Zurich (Figures SI 9 and 15), 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 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).

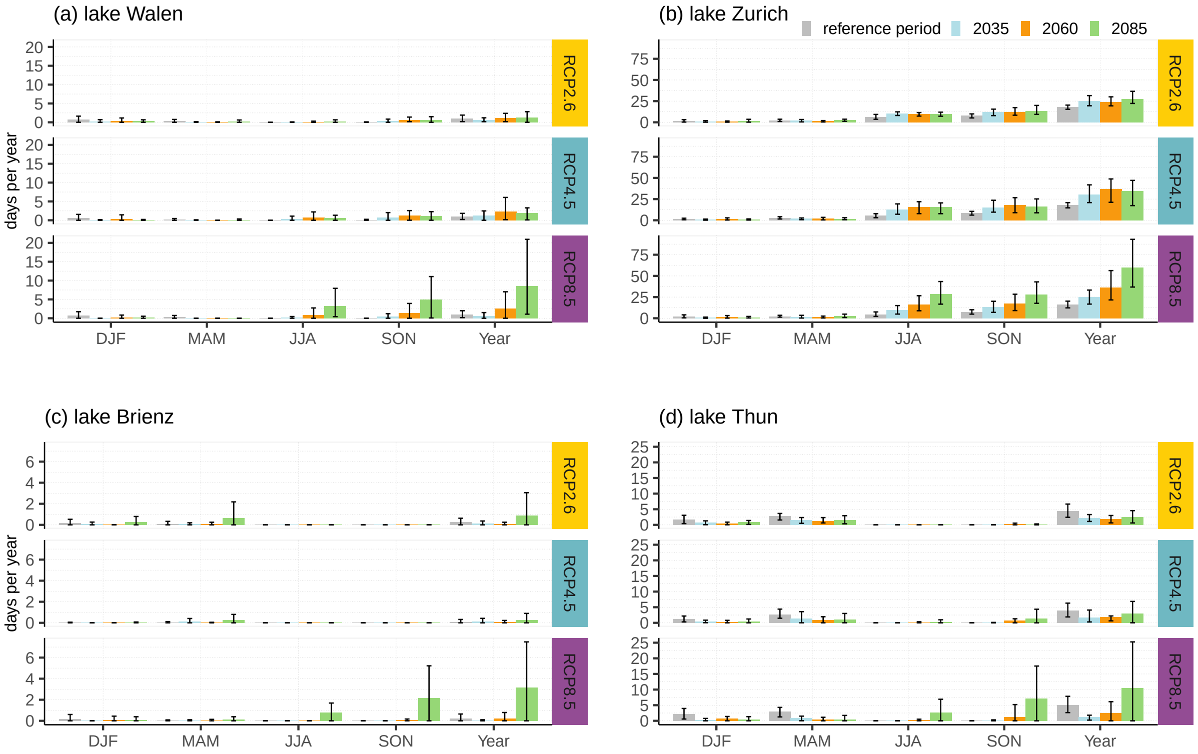


Figure 7: Simulated changes in days per month and per year the outflow undercuts the drought limit ($L$) of Lake Walen (unregulated), Lake Zurich (regulated), Lake Brienz (semi-regulated) and Lake Thun (regulated). Error bars refer to the 10 % and 90 % percentile range.

### 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 simulations also show changes in extremes, with decreases in high-lake levels (90 % percentiles) in summer and autumn and decreases in low-lake levels (10 % percentiles) in late summer already for the near future. 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

Compared to previous hydrologic climate change impact assessments focusing on changes in streamflow (Rössler et al., 2019; Muelchi et al., 2021), the presented modeling framework allows us to assess climate change impacts on lake levels. Our simulations show the strong influence of lake level management on the lake levels of the analysed perialpine lakes (Figure 3). Combining a hydrologic and hydrodynamic model greatly improves the model performance for lake outflows, especially for lake levels (Section 4.1). The enhanced model performance for regulated lakes (Table SI 2) underlines the importance of considering lakes and lake level management in hydrologic simulations. Depending on the degree of lake level management, climate change impacts on lake levels and outflows differ in magnitude and timing.

The presented solution of combining a hydrologic and a hydrodynamic model allows us to analyse climate change impacts on perialpine lake level variability for lakes with different degrees of lake level management. 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 has been 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 Variables contribution to change

The hydrologic simulations of the future annual water balance in catchments I and II (Figure 2) show changes in precipitation, evapotranspiration and icemelt contribution Figure 8. The simulations indicate no clear trend in annual precipitation for both catchments for all future scenarios. This also affects the annual streamflow projections, where no change signal is apparent (Figure 5 and 6). However, for the seasonal changes in winter and summer, the change signal of lake-level and outflow projections shows a 100 % agreement among all model chains under the high emission scenario (RCP8.5) by the end of the century. 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 1), and its change under the climate change scenarios is hardly noticeable in the lake input simulations used for the current study. The hydrologic simulations show an increasing water loss via evapotranspiration 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) compared to the reference period.

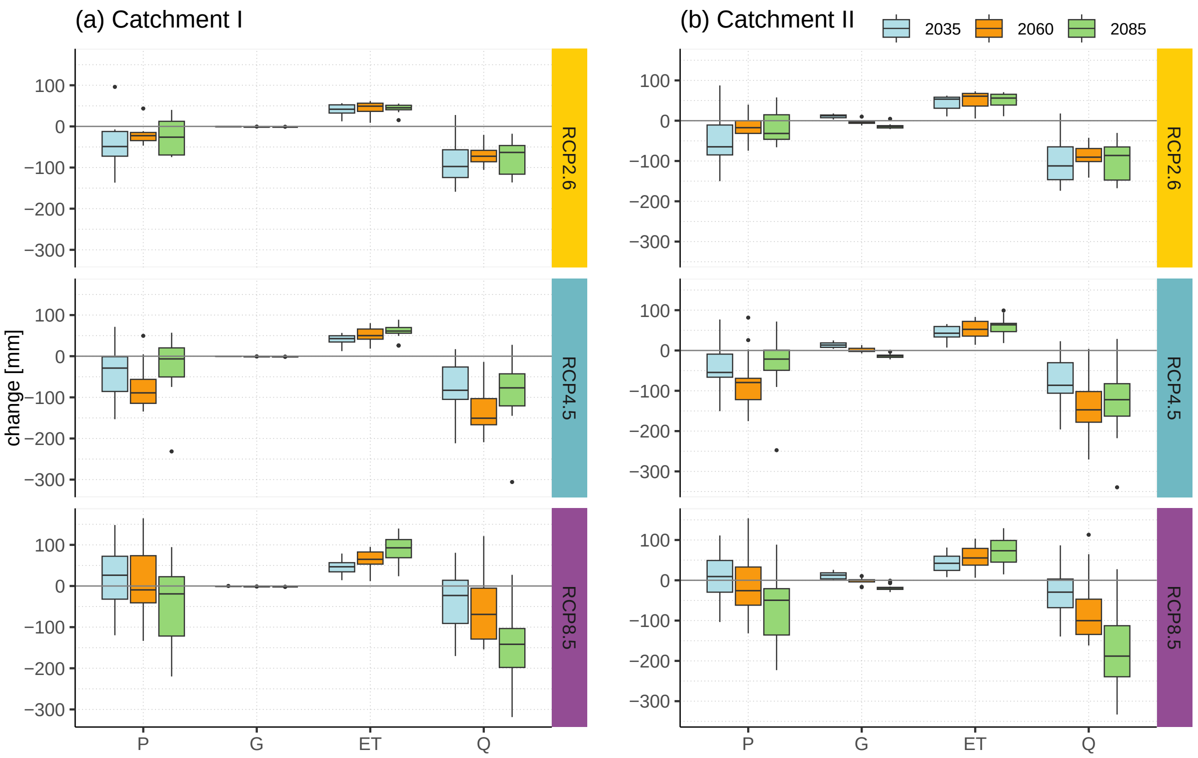


Figure 8: Simulated climate-induced changes in precipitation (P), glacier melt contribution (G), evapotranspiration for the entire catchment area (ET) and streamflow (Q) for catchment I (Lake Walen and Lake Zurich) and catchment II (Lake Brienz and Lake Thun).

## 5.3 Projected climate change impacts

Our climate change simulations further 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 are in agreement 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 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.

## 5.4 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 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 (Buehlmann 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, e.g. + -0.4 m (** IQR: -0.5 m, -0.37 m), the median value, the robustness of the change signal (in-/decrease), and the IQR (interquartile range). We analysed 30-year periods and compared the current conditions (the reference period) with three future conditions (near future, mid-century, and end of the century) to project mean lake level changes.

## 5.5 Deviations between observations and future scenarios

The combined simulations with the hydrologic and hydrodynamic model for the reference period reproduce the observed lake levels (Figure 4) and outflows (SI Figure 2) relatively well in terms of overall temporal patterns. They show, however, some biases for the monthly mean lake levels. Such deviations are expected for lake level simulations because any bias in streamflow simulations accumulates at the lake system's level. 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 addition to the inherited bias from the streamflow simulations, there is some upstream hydropower production in both lake systems, which results in water transfer from winter to summer. 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.

## 5.6 Modelling framework limitations

We assume that current lake level management practices remain constant for future simulations, which permits disentangling climatic from lake level regulation impacts. In this study, we do not consider potential adaptation measures for lake level management practices. A limit of our work is, however, the existing hydropower production in the headwater catchments of the analysed lakes (Figures SI 4 and 5), which results in transferring water from summer to winter, which complicates the ability to disentangle climatic from lake level regulation impacts. Nevertheless, these projections can provide a foundation for considering potential adjustments in the early stages. We would like to 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 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).

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-lake levels can result in reduced outflows, imposing restrictions on competing water uses. However, it is important to note that low-lake 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 (FOEN, 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 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.

# 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 disentangle climatic from lake level regulation impacts. 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 simulated changes in extremes indicate decreases in both high and low lake levels (10 % and 90 % percentiles) in summer and autumn. 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. 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). 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, 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.

## 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 ((FOEN, 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 (NCCS, 2018), which were then translated into hydrological future scenarios in the frame of the FOEN program Hydro-CH2018 (FOEN, 2021).

## 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 in order to improve language and readability. After using this tools, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

# References

N. Addor, O. Rössler, N. Köplin, M. Huss, R. Weingartner, and J. Seibert. Robust changes and sources of uncertainty in the projected hydrological regimes of swiss catchments. *Water Resources Research*, 50(10):7541–7562, 2014. doi: 10.1002/2014WR015549.

J. Aroviita and H. Hamalainen. The impact of water-level regulation on littoral macroinvertebrate assemblages in boreal lakes. *Hydrobiologia*, 613:45–56, NOV 2008. doi: 10.1007/s10750-008-9471-4.

AWA. Ansprüche an die Seeregulierung: Regulierung des Brienzersee Möglichkeiten und Grenzen. Technical report, Amt für Wasser und Abfall Kanton Bern (AWA), Bern, 2014.

L. Bernhard and M. Zappa. Schlussbericht CCHydrologie: Teilprojekt WHH-CH-Hydro. Natürlicher Wasserhaushalt der Schweiz und ihre bedeutendsten Grosseinzugsgebiete. Technical report, Federal Office for the Environment FOEN, Bern, 2009.

BFS. Die grössten Seen und höchsten Berge. `http://www.bfs.admin.ch`, 2004. Accessed on 18.04.2023.

V. Blauhut, M. Stoelzle, L. Ahopelto, M. I. Brunner, C. Teutschbein, D. E. Wendt, V. Akstinas, S. J. Bakke, L. J. Barker, L. Bartošová, et al. Lessons from the 2018–2019 european droughts: a collective need for unifying drought risk management. *Natural hazards and earth system sciences*, 22(6):2201–2217, 2022. doi: 10.5194/nhess-22-2201-2022.

T. Bosshard, S. Kotlarski, M. Zappa, and C. Schär. Hydrological climate-impact projections for the rhine river: Gcm–rcm uncertainty and separate temperature and precipitation effects. *Journal of Hydrometeorology*, 15(2):697–713, 2014. doi: 10.1175/JHM-D-12-098.1.

M. I. Brunner, A. B. Gurung, M. Zappa, H. Zekollari, D. Farinotti, and M. Stähli. Present and future water scarcity in switzerland: Potential for alleviation through reservoirs and lakes. *Science of the Total Environment*, 666:1033–1047, 2019. doi: 10.1016/j.scitotenv.2019.02.169.

A. Buehlmann and J. Schwanbeck. Data and analysis plattform, 2023. URL `https://hydromaps.ch`. Accessed on 26.08.2023.

M. Cifoni, A. Boggero, M. Rogora, M. Ciampittiello, A. Martinez, D. M. P. Galassi, B. Fiasca, and T. Di Lorenzo. Effects of human-induced water level fluctuations on copepod assemblages of the littoral zone of lake maggiore. *Hydrobiologia*, 849(16):3545–3564, SEP 2022. doi: 10.1007/s10750-022-04960-3.

A. H. Clites and F. H. Quinn. The history of lake superior regulation: Implications for the future. *Journal of Great Lakes Research*, 29(1):157–171, 2003. doi: 10.1016/S0380-1330(03)70424-9.

B. Cox. A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers. *Science of the total environment*, 314:335–377, 2003. doi: 10.1016/S0048-9697(03)00063-9.

M. Dembélé, M. Vrac, N. Ceperley, S. J. Zwart, J. Larsen, S. J. Dadson, G. Mariéthoz, and B. Schaefli. Contrasting changes in hydrological processes of the volta river basin under global warming. *Hydrology and earth system sciences*, 26(5):1481–1506, 2022. doi: 10.5194/hess-26-1481-2022.

D. DHI. Mike-11: a modelling system for rivers and channels, reference manual. *DHI–Water and Development, Horsholm, Denmark*, 2003.

C. Doulgeris, P. Georgiou, D. Papadimos, and D. Papamichail. Ecosystem approach to water resources management using the mike 11 modeling system in the strymonas river and lake kerkini. *Journal of environmental management*, 94(1):132–143, 2012. doi: 10.1016/j.jenvman.2011.06.023.

K. El kadi Abderrezzak and A. Paquier. One-dimensional numerical modeling of sediment transport and bed deformation in open channels. *Water Resources Research*, 45(5), 2009. doi: 10.1029/2008WR007134.

T. Erős and E. H. Campbell Grant. Unifying research on the fragmentation of terrestrial and aquatic habitats: patches, connectivity and the matrix in riverscapes. *Freshwater Biology*, 60 (8):1487–1501, 2015. doi: 10.1111/fwb.12596.

Z. Fan, Z. Wang, Y. Li, W. Wang, C. Tang, and F. Zeng. Water level fluctuation under the impact of lake regulation and ecological implication in huayang lakes, china. *Water*, 12(3): 702, 2020. doi: 10.3390/w12030702.

B. Fernandez Castro, O. Sepulveda Steiner, D. Knapp, T. Posch, D. Bouffard, and A. Wuest. Inhibited vertical mixing and seasonal persistence of a thin cyanobacterial layer in a stratified lake. *Aquatic Sciences*, 83(2):38, 2021. doi: 0.1007/s00027-021-00785-9.

G. Fink, M. Wessels, and A. Wüest. Flood frequency matters: Why climate change degrades deep-water quality of peri-alpine lakes. *Journal of Hydrology*, 540:457–468, 2016. doi: 10.1016/j.jhydrol.2016.06.023.

FOEN. 150 Jahre Hydrometrie in der Schweiz. `https://www.admin.ch`, 2013. Accessed on 06.06.2023.

FOEN. Faktenblatt: Der Walensee - Zustand bezüglich Wasserqualität. Technical report, Federal Office for the Environment FOEN, Bern, 2016.

FOEN. Anpassung an den Klimawandel in der Schweiz: Ziele, Herausforderungen und Handlungsfelder. `http://www.bafu.admin.ch`, 2018. Accessed on 07.06.2023.

FOEN. Regulierung Jurarandseen. `https://www.bafu.admin.ch`, 2020a. Accessed on 18.06.2023.

FOEN. Faktenblatt: Regulierung Zürichsee. `https://www.bafu.admin.ch`, 2020b. Accessed on 07.06.2023.

FOEN. Faktenblatt: Regulierung Brienzersee. `https://www.bafu.admin.ch`, 2020c. Accessed on 07.06.2023.

FOEN. Faktenblatt: Regulierung Thunersee. `https://www.bafu.admin.ch`, 2020d. Accessed on 07.06.2023.

FOEN. Hydro-CH2018: Auswirkungen des Klimawandels auf die Schweizer Gewässer. Hydrologie, Gewässerökologie und Wasserwirtschaft. Technical report, Federal Office for the Environment FOEN, Bern, 2021.

FOEN. Seeregulierung. Technical report, Federal Office for the Environment FOEN, 2023a. Accessed on 17.01.2023.

FOEN. Danger levels flood. `https://www.natural-hazards.ch`, 2023b. Accessed on 04.07.2023.

FOEN. Aktuelle Situation der Abflüsse und Wasserstände. `https://www.hydrodaten.admin.ch`, 2023c. Accessed on 18.06.2023.

FOEN. Hydrologische Ereignisse. `https://www.bafu.admin.ch`, 2023d. Accessed on 08.06.2023.

FOEN. Naturgefahren: Flussvermessung. `https://www.bafu.admin.ch`, 2023e. Accessed on 27.04.2023.

B. François, B. Hingray, M. Borga, D. Zoccatelli, C. Brown, and J.-D. Creutin. Impact of climate change on combined solar and run-of-river power in northern italy. *Energies*, 11(2):290, 2018. doi: 10.3390/en11020290.

B. François, B. Hingray, J.-D. Creutin, et al. Estimating water system performance under climate change: Influence of the management strategy modeling. *Water Resources Management*, 29: 4903–4918, 2015. doi: 10.1007/s11269-015-1097-5.

D. Freudiger, I. Kohn, J. Seibert, K. Stahl, and M. Weiler. Snow redistribution for the hydrological modeling of alpine catchments. *Wiley Interdisciplinary Reviews: Water*, 4(5):e1232, 2017. doi: 10.1002/wat2.1232.

J. Gibson, T. Prowse, and D. Peters. Hydroclimatic controls on water balance and water level variability in great slave lake. *Hydrological Processes: An International Journal*, 20(19):4155–4172, 2006a. doi: 10.1002/hyp.6424.

J. J. Gibson, T. D. Prowse, and D. L. Peters. Partitioning impacts of climate and regulation on water level variability in Great Slave Lake. *Journal of Hydrology*, 329(1-2):196–206, 2006b. ISSN 00221694. doi: 10.1016/j.jhydrol.2006.02.011.

A. H. Haghiabi, E. Zaredehdasht, et al. Evaluation of hec-ras ability in erosion and sediment transport forecasting. *World Applied Sciences Journal*, 17(11):1490–1497, 2012. ISSN 1818-4952.

S. Hanus, M. Hrachowitz, H. Zekollari, G. Schoups, M. Vizcaino, and R. Kaitna. Future changes in annual, seasonal and monthly runoff signatures in contrasting alpine catchments in austria. *Hydrology and Earth System Sciences*, 25(6):3429–3453, 2021. doi: 10.5194/hess-25-3429-2021.

F. Hicks, X. Chen, and D. Andres. Effects of ice on the hydraulics of mackenzie river at the outlet of great slave lake, nwt: a case study. *Canadian Journal of Civil Engineering*, 22(1): 43–54, 1995. doi: 10.1139/l95-005.

N. Hilker, A. Badoux, and C. Hegg. The swiss flood and landslide damage database 1972–2007. *Natural Hazards and Earth System Sciences*, 9(3):913–925, 2009. doi: 10.5194/nhess-9-913-2009.

L. Hinegk, L. Adami, G. Zolezzi, and M. Tubino. Implications of water resources management on the long-term regime of lake garda (italy). *Journal of Environmental Management*, 301, 2022. doi: 10.1016/j.jenvman.2021.113893.

B. Hingray, N. Mouhous, A. Mezghani, K. Bogner, B. Schaefli, and A. Musy. Accounting for global-mean warming and scaling uncertainties in climate change impact studies: application to a regulated lake system. *Hydrology and Earth System Sciences*, 11(3):1207–1226, 2007. doi: 10.5194/hess-11-1207-2007.

J. M. Hoch, J. C. Neal, F. Baart, R. Van Beek, H. C. Winsemius, P. D. Bates, and M. F. Bierkens. Glofrim v1. 0–a globally applicable computational framework for integrated hydrological–hydrodynamic modelling. *Geoscientific Model Development*, 10(10):3913–3929, 2017. doi: 10.5194/gmd-10-3913-2017.

P. Horton, B. Schaefli, and M. Kauzlaric. Why do we have so many different hydrological models? a review based on the case of switzerland. *Wiley Interdisciplinary Reviews: Water*, 9(1):e1574, 2022. doi: 10.1002/wat2.1574.

A. Inderwildi and G. R. Bezzola. Seeregulierung : von der Hydraulik zum Hochwassermanagement. `https://hdl.handle.net/20.500.11970/108407`, 2021.

D. Jacob, J. Petersen, B. Eggert, A. Alias, O. B. Christensen, L. M. Bouwer, A. Braun, A. Colette, M. Déqué, G. Georgievski, E. Georgopoulou, A. Gobiet, L. Menut, G. Nikulin, A. Haensler, N. Hempelmann, C. Jones, K. Keuler, S. Kovats, N. Kröner, S. Kotlarski, A. Kriegsmann, E. Martin, E. van Meijgaard, C. Moseley, S. Pfeifer, S. Preuschmann, C. Radermacher, K. Radtke, D. Rechid, M. Rounsevell, P. Samuelsson, S. Somot, J. F. Soussana, C. Teichmann, R. Valentini, R. Vautard, B. Weber, and P. Yiou. EURO-CORDEX: New high-resolution climate change projections for European impact research. *Regional Environmental Change*, 14(2):563–578, 2014. ISSN 1436378X. doi: 10.1007/s10113-013-0499-2.

K. Jasper and M. Ebel. 13th international interpraevent congress: Emergency management (emergency planning, early warning, intervention, recovery: Advanced flood forecasting for switzerland, erweiterte hochwasservorhersagen für die schweiz). Technical report, Interpraevent, Lucerne, 2016. Accessed on 18.07.2023.

T. Jiang, D. Wang, S. Wei, J. Yan, J. Liang, X. Chen, J. Liu, Q. Wang, S. Lu, J. Gao, et al. Influences of the alternation of wet-dry periods on the variability of chromophoric dissolved organic matter in the water level fluctuation zone of the three gorges reservoir area, china. *Science of the Total Environment*, 636:249–259, 2018. doi: 10.1016/j.scitotenv.2018.04.262.

R. Kaderli. *Reglemente für die Zukunft.* PhD thesis, ETH Zurich, 2021.

E. Kellner. The controversial debate on the role of water reservoirs in reducing water scarcity. *Wiley Interdisciplinary Reviews: Water*, 8(3):e1514, 2021. doi: 10.1002/wat2.1514.

N. Köplin, B. Schädler, D. Viviroli, and R. Weingartner. Seasonality and magnitude of floods in Switzerland under future climate change. *Hydrological Processes*, 28(4):2567–2578, 2014. ISSN 08856087. doi: 10.1002/hyp.9757.

K. Lanz. Auswirkungen des klimawandels auf die wasserwirtschaft der schweiz. *Beiträge zur Hydrologie der Schweiz, Bern*, (43):376, 2021. ISSN 978-3-9524235-5-4.

C. Legrand, B. Hingray, B. Wilhelm, and M. Ménégoz. Simulating one century (1902–2009) of river discharges, low flow sequences and flood events of an alpine river from large-scale atmospheric information. *Hydrology and Earth System Sciences Discussions*, 2023:1–35, 2023. doi: 10.5194/hess-2023-92.

A. Linsbauer, M. Huss, E. Hodel, A. Bauder, M. Fischer, Y. Weidmann, H. Bärtschi, and E. Schmassmann. The new swiss glacier inventory sgi2016: From a topographical to a glaciological dataset. *Frontiers in Earth Science*, 9:22, 2021. doi: 10.3389/feart.2021.704189.

D. Lohmann, R. Nolte-Holube, and E. Raschke. A large-scale horizontal routing model to be coupled to land surface parametrization schemes. *Tellus A*, 48(5):708–721, 1996. doi: 10.1034/j.1600-0870.1996.t01-3-00009.x.

J. P. Mesman, A. I. Ayala, R. Adrian, E. De Eyto, M. A. Frassl, S. Goyette, J. Kasparian, M. Perroud, J. A. A. Stelzer, D. C. Pierson, et al. Performance of one-dimensional hydrodynamic lake models during short-term extreme weather events. *Environmental Modelling & Software*, 133:104852, 2020. doi: 10.1016/j.envsoft.2020.104852.

MeteoSwiss. Climate ch2025, 2023. URL `https://www.meteoswiss.admin.ch/about-us/research-and-coop` Accessed on 28.08.2023.

A. Michel, B. Schaefli, N. Wever, H. Zekollari, M. Lehning, and H. Huwald. Future water temperature of rivers in switzerland under climate change investigated with physics-based models. 2021. doi: 10.5194/hess-26-1063-2022.

B. Moss. Cogs in the endless machine: lakes, climate change and nutrient cycles: a review. *Science of the Total Environment*, 434:130–142, 2012. doi: 10.1016/j.scitotenv.2011.07.069.

R. Muelchi, O. Rössler, J. Schwanbeck, R. Weingartner, and O. Martius. River runoff in switzerland in a changing climate–changes in moderate extremes and their seasonality. *Hydrology and earth system sciences*, 25(6):3577–3594, 2021. doi: 10.5194/hess-25-3577-2021.

J. Nash. River flow forecasting through conceptual models, i: A discussion of principles. *Journal of Hydrology*, 10:398–409, 1970. doi: 10.1016/0022-1694(70)90255-6.

NCCS. *CH2018 - Climate Scenarios for Switzerland. Techincal Report.* Zurich, 2018.

K. Neumann. Die Grundlagen für die Automatisierung der Thunerseeregulierung. *Wasser Energie Luft*, 4:3–7, 1983.

C. M. O'Reilly, S. Sharma, D. K. Gray, S. E. Hampton, J. S. Read, R. J. Rowley, P. Schneider, J. D. Lenters, P. B. McIntyre, B. M. Kraemer, et al. Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters*, 42(24):10–773, 2015. doi: 10.1002/2015GL066235.

R. C. Paiva, W. Collischonn, and C. E. Tucci. Large scale hydrologic and hydrodynamic modeling using limited data and a gis based approach. *Journal of Hydrology*, 406(3-4):170–181, 2011. doi: 10.1016/j.jhydrol.2011.06.007.

D. Papadimos, K. Demertzi, and D. Papamichail. Assessing lake response to extreme climate change using the coupled mike she/mike 11 model: Case study of lake zazari in greece. *Water*, 14(6):921, 2022. doi: 10.3390/w14060921.

M.-E. Perga, S. C. Maberly, J.-P. Jenny, B. Alric, C. Pignol, and E. Naffrechoux. A century of human-driven changes in the carbon dioxide concentration of lakes. *Global Biogeochemical Cycles*, 30(2):93–104, 2016. doi: 10.1002/2015GB005286.

L. Råman Vinnå, I. Medhaug, M. Schmid, and D. Bouffard. The vulnerability of lakes to climate change along an altitudinal gradient. *Communications Earth & Environment*, 2(1):2–11, 2021. ISSN 2662-4435. doi: 10.1038/s43247-021-00106-w.

J.-L. Redelsperger and T. Lebel. Surface processes and water cycle in west africa, studied from the amma-catch observing system. *Journal of Hydrology*, 375(1):1–2, 2009. doi: 10.1016/j.jhydrol.2009.08.

O. Rössler, S. Kotlarski, A. M. Fischer, D. Keller, M. Liniger, and R. Weingartner. Evaluating the added value of the new swiss climate scenarios for hydrology: An example from the thur catchment. *Climate services*, 13:1–13, 2019. doi: 10.1016/j.cliser.2019.01.001.

A. Saber, D. E. James, and I. A. Hannoun. Effects of lake water level fluctuation due to drought and extreme winter precipitation on mixing and water quality of an alpine lake, case study: Lake arrowhead, california. *Science of the Total Environment*, 714:136762, 2020. doi: 10.1016/j.scitotenv.2020.136762.

N. Salmaso, O. Anneville, D. Straile, and P. Viaroli. European large perialpine lakes under anthropogenic pressures and climate change: present status, research gaps and future challenges. *Hydrobiologia*, 824(1):1–32, 2018. doi: 10.1007/s10750-018-3758-x.

B. Schaefli. Projecting hydropower production under future climates: a guide for decision-makers and modelers to interpret and design climate change impact assessments. *Wiley Interdisciplinary Reviews: Water*, 2(4):271–289, 2015. doi: 10.1002/wat2.1083.

Schwanbeck, Jan and Bühlmann, Alain. Hydrologischer Atlas der Schweiz. `https://www.hydrologischeratlas.ch`, 2023. Accessed on 18.01.2023.

M. J. Speich, L. Bernhard, A. J. Teuling, and M. Zappa. Application of bivariate mapping for hydrological classification and analysis of temporal change and scale effects in Switzerland. *Journal of Hydrology*, 523:804–821, 2015. ISSN 00221694. doi: 10.1016/j.jhydrol.2015.01.086.

J. Spinoni, G. Naumann, J. Vogt, and P. Barbosa. Meteorological droughts in europe: events and impacts-past trends and future projections. 2016. doi: 10.2788/450449.

M. Spreafico. *Verfahren zur optimalen Regulierung natürlicher Seen*. PhD thesis, ETH Zurich, 1977.

M. Spreafico. Methods of developing regulation plans for lakes. *Water International*, 5(3):12–15, 1980. doi: 10.1080/02508068008685871.

K. Stahl, M. Weiler, I. Kohn, D. Freudiger, J. Seibert, M. Vis, K. Gerlinger, and M. Bohm. The snow and glacier melt components of streamflow of the river rhine and its tributaries considering the influence of climate change. *Synthesis Report I-25, International Commission for the Hydrology of the Rhine Basin, Lelystad, Netherlands*, 10, 2016. ISSN 978-90-70980-38-2.

K. Stahl, M. Weiler, I. Kohn, D. Freudiger, J. Seibert, M. Vis, K. Gerlinger, and M. Böhm. Impact of climate change on the rain, snow and glacier melt components of streamflow of the river Rhine and its tributaries. Synthesis Report. Technical Report I, International Commission for the Hydrology of the Rhine basin (CHR), Lelystad, 2022.

J. A. Stanford and F. Hauer Hauer. Mitigating the impacts of stream and lake regulation in the flathead river catchment, Montana, USA: An ecosystem perspective. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 2(1):35–63, 1992. ISSN 10990755. doi: 10.1002/aqc.3270020104.

N. Veijalainen, T. Dubrovin, M. Marttunen, and B. Vehviläinen. Climate Change Impacts on Water Resources and Lake Regulation in the Vuoksi Watershed in Finland. *Water Resources Management*, 24(13):3437–3459, 2010. ISSN 09204741. doi: 10.1007/s11269-010-9614-z.

S. M. Vicente-Serrano, D. Peña-Angulo, S. Beguería, F. Domínguez-Castro, M. Tomás-Burguera, I. Noguera, L. Gimeno-Sotelo, and A. El Kenawy. Global drought trends and future projections. *Philosophical Transactions of the Royal Society A*, 380(2238):20210285, 2022. doi: 10.1029/2018GL079807.

D. Vischer. Die Geschichte des Hochwasserschutzes in der Schweiz. Technical report, Bundesamt für Wasser und Geologie BWG, Biel, 2003.

D. Viviroli, M. Zappa, J. Gurtz, and R. Weingartner. An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools. *Environmental Modelling and Software*, 24(10):1209–1222, 2009. ISSN 13648152. doi: 10.1016/j.envsoft.2009.04.001.

K. M. Wantzen, K.-O. Rothhaupt, M. Mörtl, M. Cantonati, L. G. Tóth, and P. Fischer. *Ecological effects of water-level fluctuations in lakes: an urgent issue.* Springer, 2008. doi: 10.1007/s10750-008-9466-1.

T. Wechsler, F. Lustenberger, A. Inderwildi, J. Hirschberg, B. Schaefli, and M. Zappa. Lake climate change scenarios ch2018, 2023. URL `https://www.envidat.ch/dataset/lake`$_c c_s cenarios_c h$2018.

R. I. Woolway, B. M. Kraemer, J. D. Lenters, C. J. Merchant, C. M. O'Reilly, and S. Sharma. Global lake responses to climate change. *Nature Reviews Earth and Environment*, 1(8):388–403, 2020. doi: 10.1038/s43017-020-0067-5.

M. Yu, X. Liu, P. Wood, L. Wei, G. Wang, J. Zhang, and Q. Li. Simulation of poyang lake water levels and outflow under historical extreme hydrological scenarios. *Journal of Flood Risk Management*, 15(3):e12806, 2022. doi: 10.1111/jfr3.12806.

Z. Zajac, B. Revilla-Romero, P. Salamon, P. Burek, F. Hirpa, and H. Beck. The impact of lake and reservoir parameterization on global streamflow simulation. *Journal of Hydrology*, 548: 552–568, 2017. ISSN 00221694. doi: 10.1016/j.jhydrol.2017.03.022.

A. P. Zischg, G. Felder, R. Weingartner, N. Quinn, G. Coxon, J. Neal, J. Freer, and P. Bates. Effects of variability in probable maximum precipitation patterns on flood losses. *Hydrology and earth system sciences*, 22(5):2759–2773, 2018. doi: 10.5194/hess-22-2759-2018.

T. Zohary and I. Ostrovsky. Ecological impacts of excessive water level fluctuations in stratified freshwater lakes. *Inland waters*, 1(1):47–59, 2011. doi: 10.5268/IW-1.1.406.

# Supplementary Information

Tables and Figures submitted with the manuscript "Lower summer lake levels in regulated perialpine lakes, caused by climate change" 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 |
|---|---|---|---|---|
| DMI | HIRHAM | ECEARTH | EUR11 | RCP2.6 |
| KNMI | RACMO | HADGEM | EUR44 | RCP2.6 |
| SMHI | RCA | ECEARTH | EUR11 | RCP2.6 |
| SMHI | RCA | ECEARTH | EUR44 | RCP2.6 |
| SMHI | RCA | HADGEM | EUR44 | RCP2.6 |
| SMHI | RCA | MIROC | EUR44 | RCP2.6 |
| SMHI | RCA | MPIESM | EUR44 | RCP2.6 |
| SMHI | RCA | NORESM | EUR44 | RCP2.6 |
| DMI | HIRHAM | ECEARTH | EUR11 | RCP4.5 |
| DMI | HIRHAM | ECEARTH | EUR44 | RCP4.5 |
| KNMI | RACMO | ECEARTH | EUR44 | RCP4.5 |
| KNMI | RACMO | HADGEM | EUR44 | RCP4.5 |
| SMHI | RCA | CCCMA | EUR44 | RCP4.5 |
| SMHI | RCA | ECEARTH | EUR11 | RCP4.5 |
| SMHI | RCA | ECEARTH | EUR44 | RCP4.5 |
| SMHI | RCA | HADGEM | EUR11 | RCP4.5 |
| SMHI | RCA | HADGEM | EUR44 | RCP4.5 |
| SMHI | RCA | MIROC | EUR44 | RCP4.5 |
| SMHI | RCA | MPIESM | EUR11 | RCP4.5 |
| SMHI | RCA | MPIESM | EUR44 | RCP4.5 |
| SMHI | RCA | NORESM | EUR44 | RCP4.5 |
| SMHI | RCA | NORESM | EUR44 | RCP4.5 |
| CLMCOM | CCLM4 | HADGEM | EUR44 | RCP8.5 |
| CLMCOM | CCLM5 | ECEARTH | EUR44 | RCP8.5 |
| CLMCOM | CCLM5 | HADGEM | EUR44 | RCP8.5 |
| CLMCOM | CCLM5 | MIROC | EUR44 | RCP8.5 |
| CLMCOM | CCLM5 | MPIESM | EUR44 | RCP8.5 |
| DMI | HIRHAM | ECEARTH | EUR11 | RCP8.5 |
| DMI | HIRHAM | ECEARTH | EUR44 | RCP8.5 |
| KNMI | RACMO | ECEARTH | EUR44 | RCP8.5 |
| KNMI | RACMO | HADGEM | EUR44 | RCP8.5 |
| SMHI | RCA | CCCMA | EUR44 | RCP8.5 |
| SMHI | RCA | ECEARTH | EUR11 | RCP8.5 |
| SMHI | RCA | ECEARTH | EUR44 | RCP8.5 |
| SMHI | RCA | HADGEM | EUR11 | RCP8.5 |
| SMHI | RCA | HADGEM | EUR44 | RCP8.5 |
| SMHI | RCA | MIROC | EUR44 | RCP8.5 |
| SMHI | RCA | MPIESM | EUR11 | RCP8.5 |
| SMHI | RCA | MPIESM | EUR44 | RCP8.5 |
| SMHI | RCA | NORESM | EUR44 | RCP8.5 |

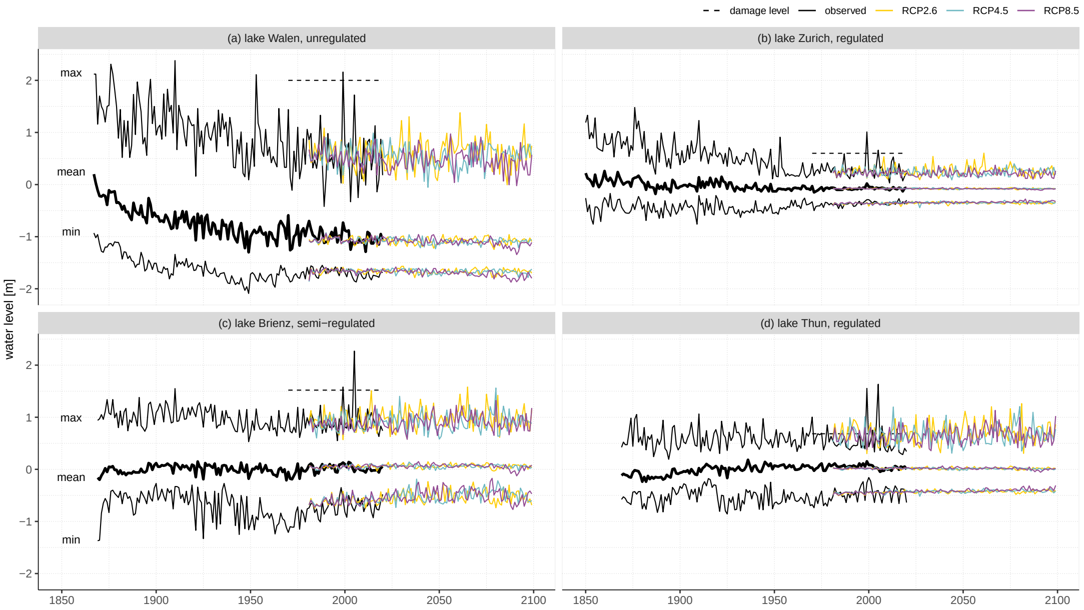


Figure SI 1: Normalised observed annual lake level variations: Shown are the observed annual mean, minimum and maximum lake levels between 1850 and 2020 (black) and the future scenarios (Section 2.5) until the end of the century under climate change (RCP2.6, RCP4.5, RCP8.5). The dashed line indicates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

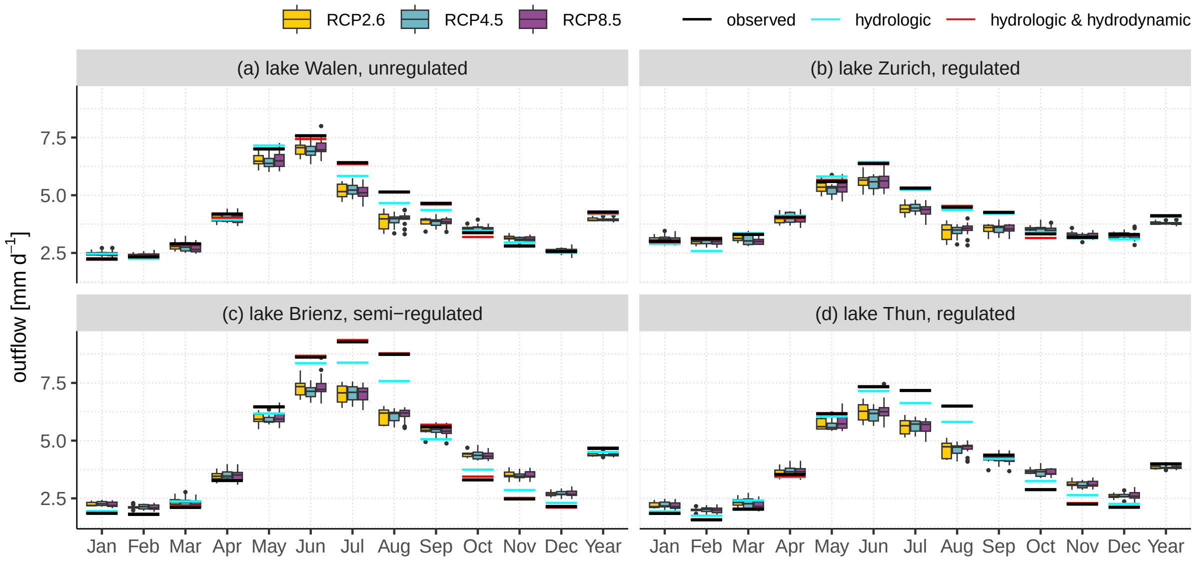


Figure SI 2: Normalised observed and simulated annual and monthly lake outflows for the four considered lakes during the reference period (1981 – 2010). The observations are compared to the hydrologic simulations with PREVAH and to the combination of the hydrologic and hydrodynamic models PREVAH and 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).

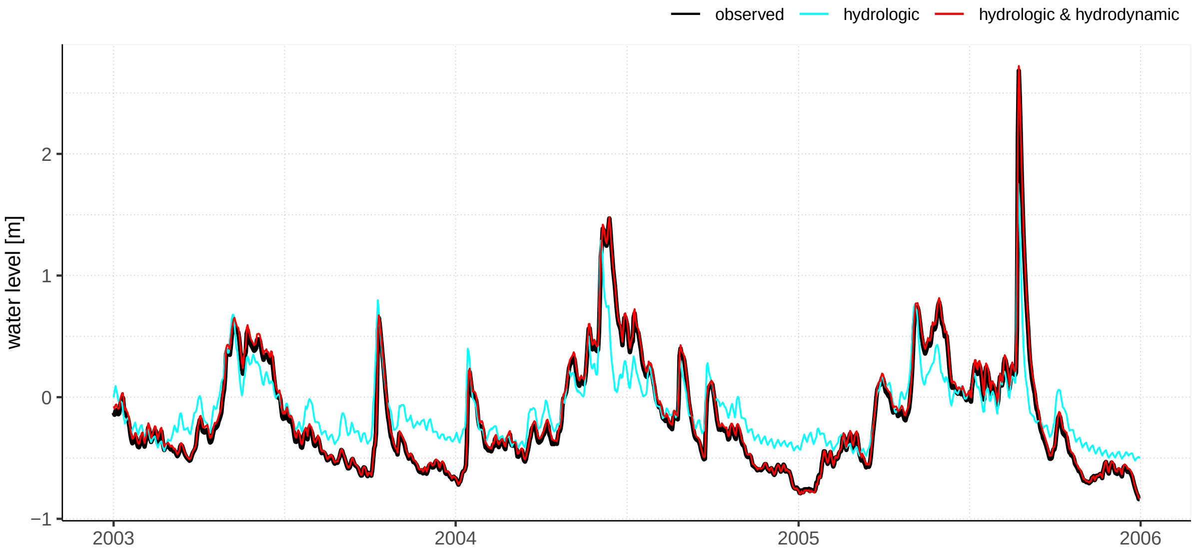


Figure SI 3: Observed and simulated lake levels of Lake Walen (2003 -– 2005). The shown simulations are computed with the hydrologic model PREVAH and the combination of the hydrologic and hydrodynamic models PREVAH and MIKE11.

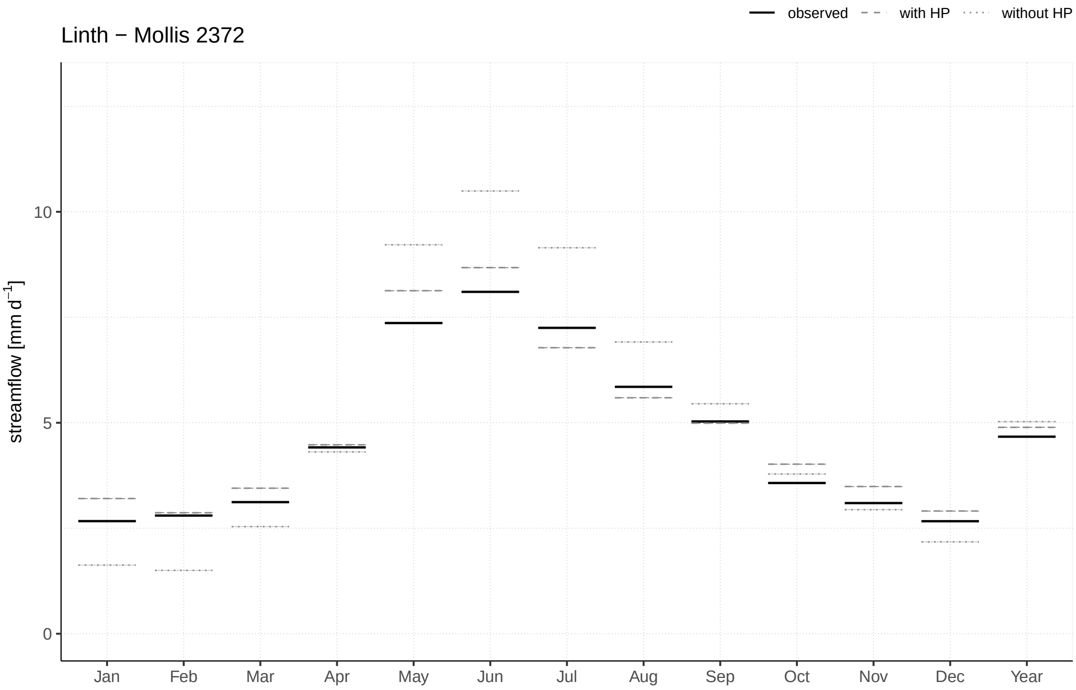


Figure SI 4: Hydropower impact in catchment I (Linth - Mollis 2372). The comparison of observed and simulated monthly mean streamflow. The black line represents the observed monthly mean streamflow, the dashed lines the simulated monthly means with and without consideration of hydropower, simulated with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

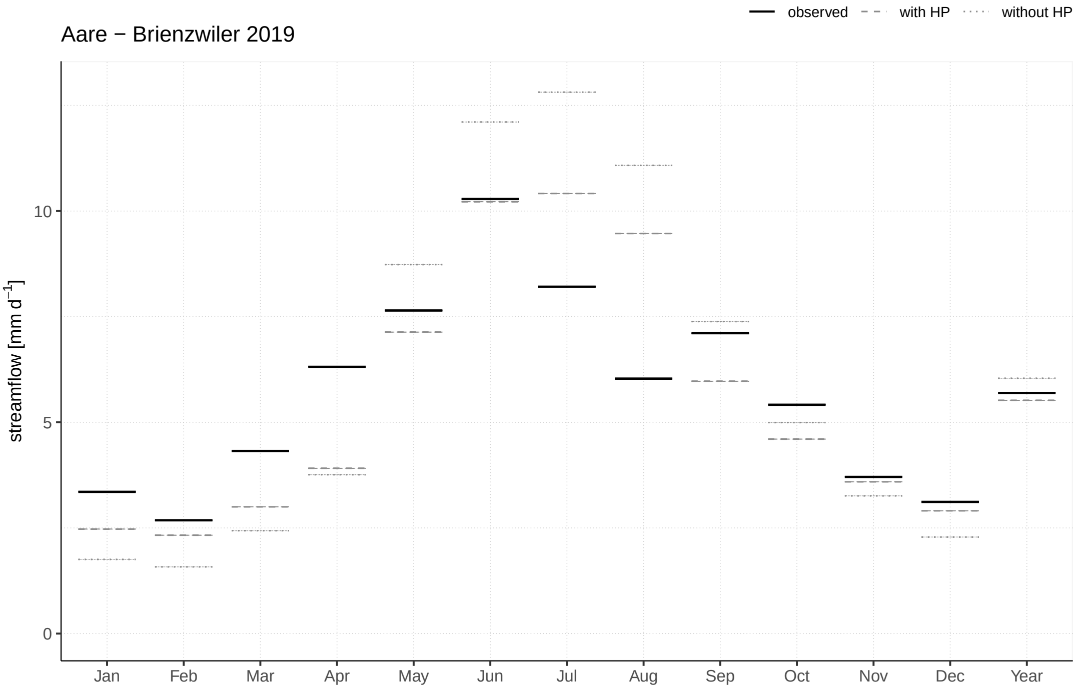


Figure SI 5: As Figure 4 but for hydropower impact in catchment II (Aare - Brienzwiler 2019).

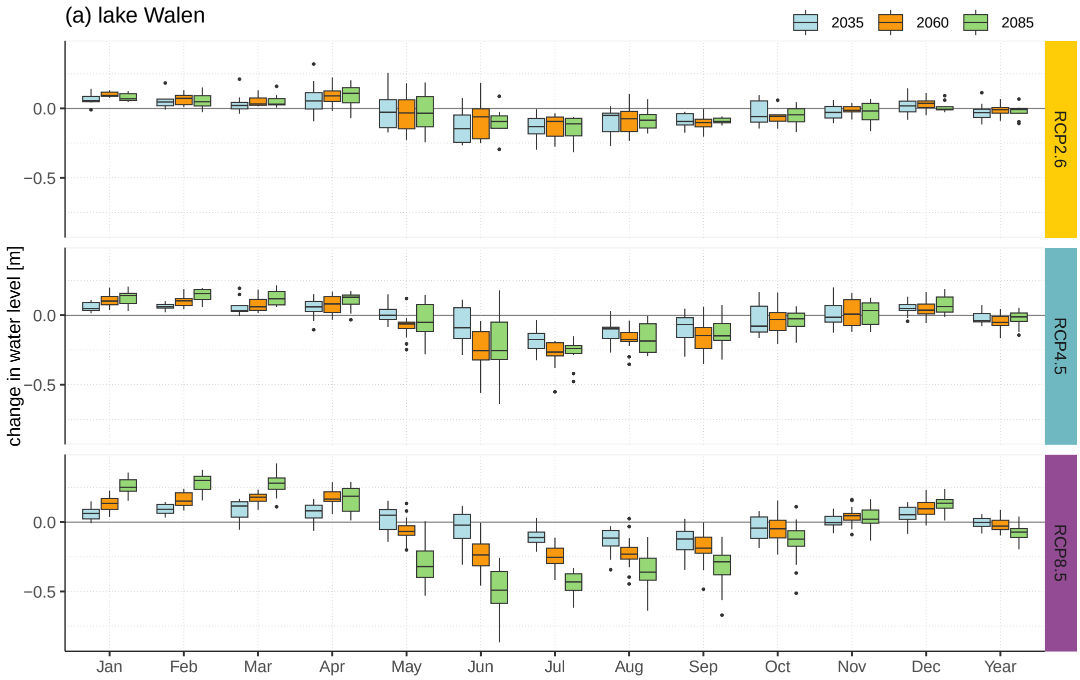


Figure SI 6: Simulated changes in annual and monthly mean lake levels of Lake Walen, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

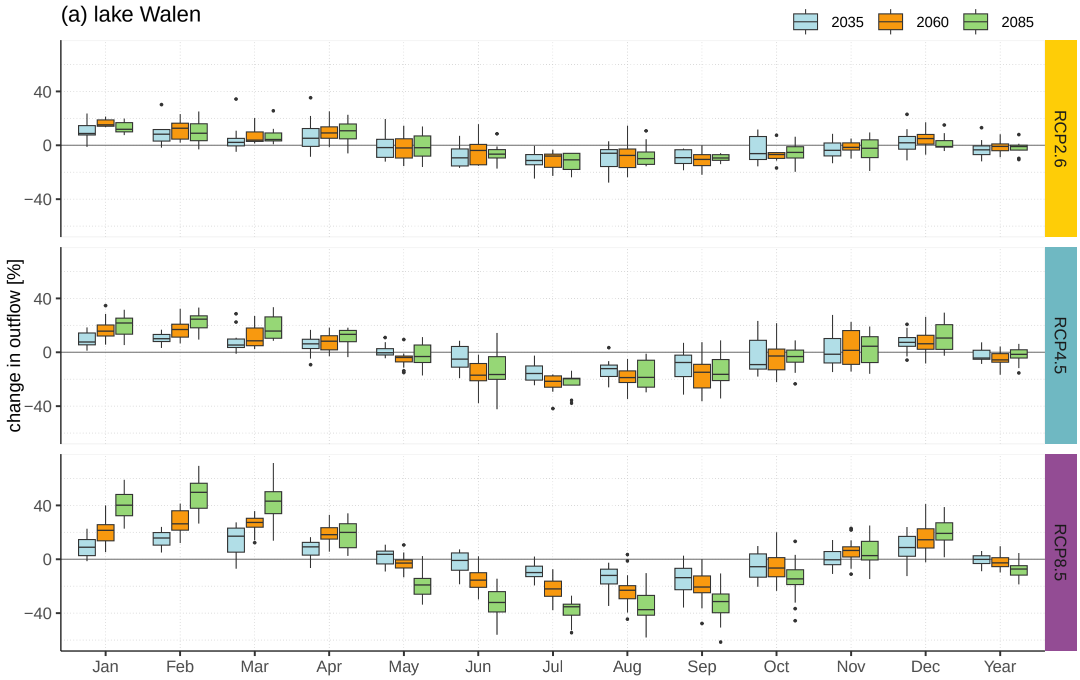


Figure SI 7: As Figure 6 but for the simulated changes in monthly and annual mean outflows of Lake Walen.

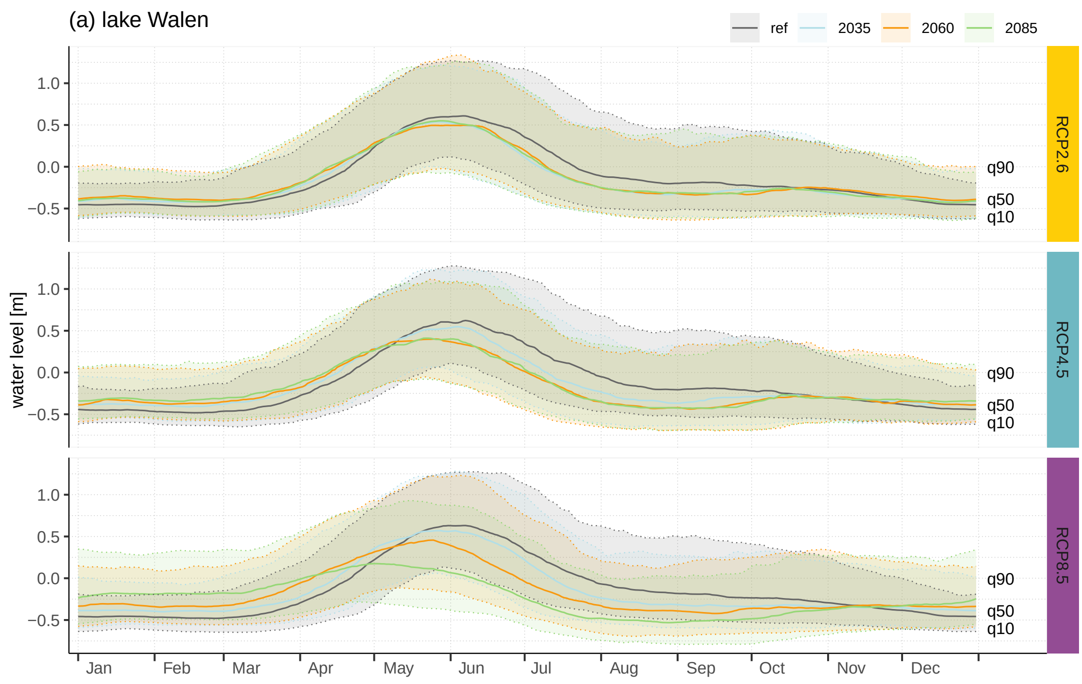


Figure SI 8: Simulated changes in the 10 % ($q10$) and 90 % ($q90$) percentiles of lake levels (moving average ±15 days) of Lake Walen, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

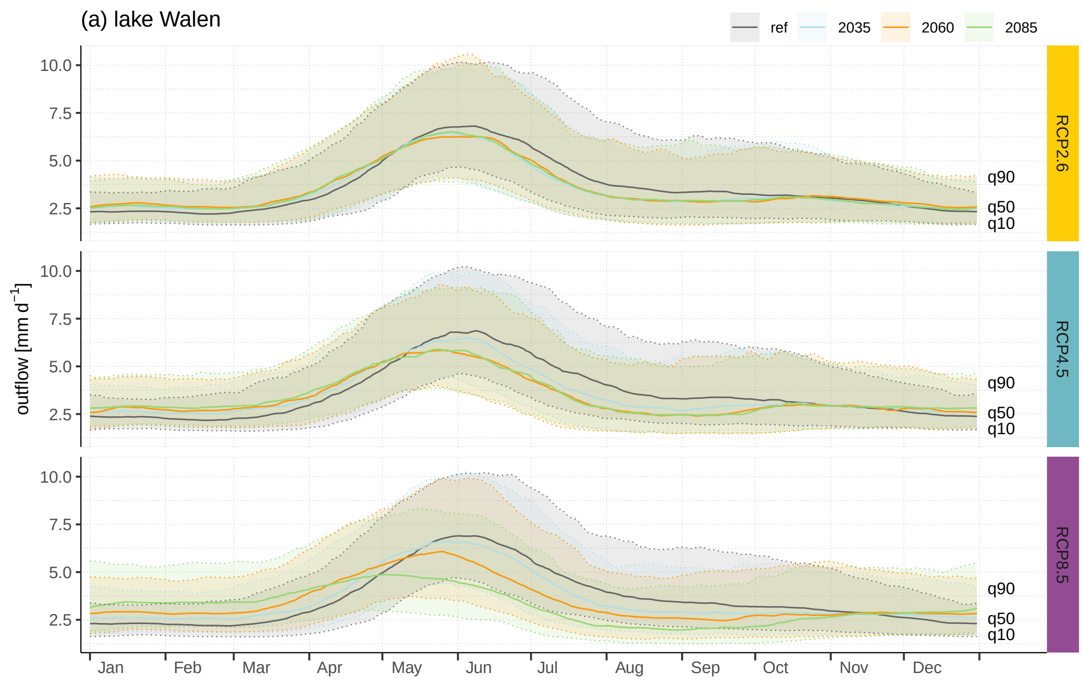


Figure SI 9: As Figure 8 but for the simulated changes in the 10 % ($q10$) and 90 % ($q90$) percentiles of outflows of Lake Walen.

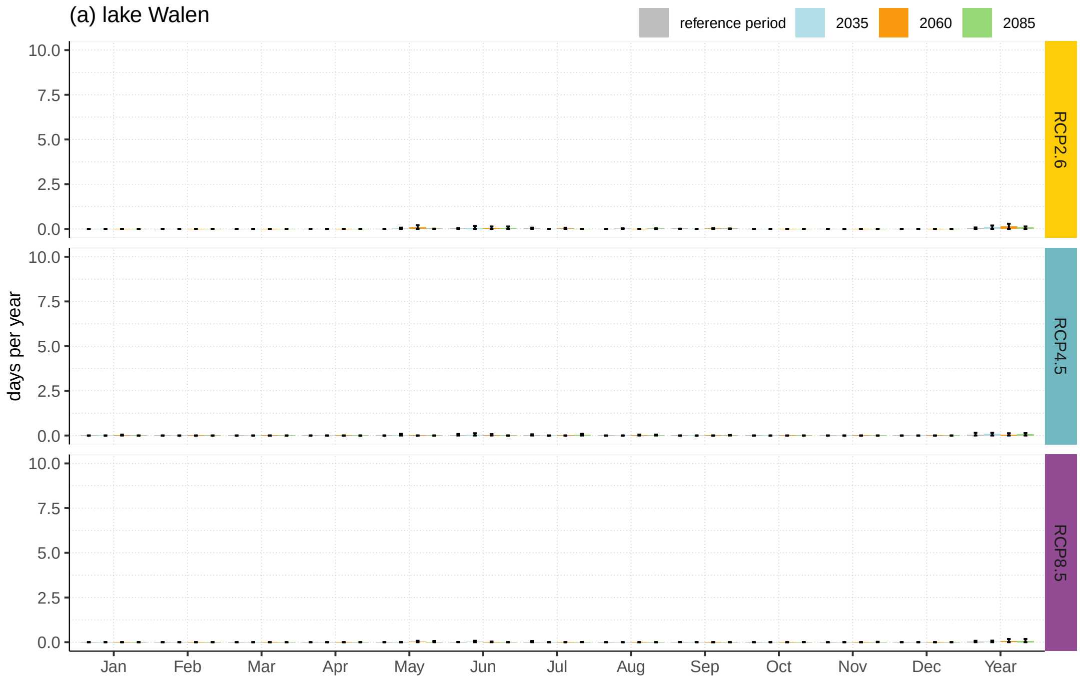


Figure SI 10: Simulated changes of the average number of days per year and month the lake level exceeds the flood limit ($F$) of Lake Walen. Error bars refer to the 10 % and 90 % percentile range.

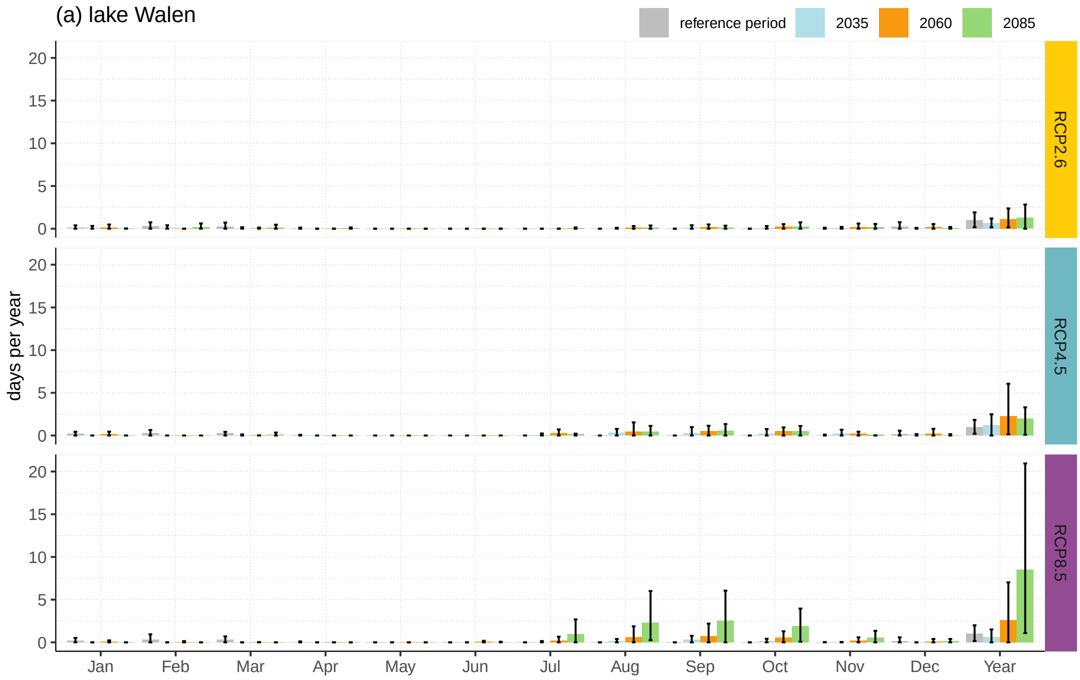


Figure SI 11: As Figure SI 10 but for the simulated changes the outflow undercuts the drought limit ($L$) of Lake Walen.

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 | * |

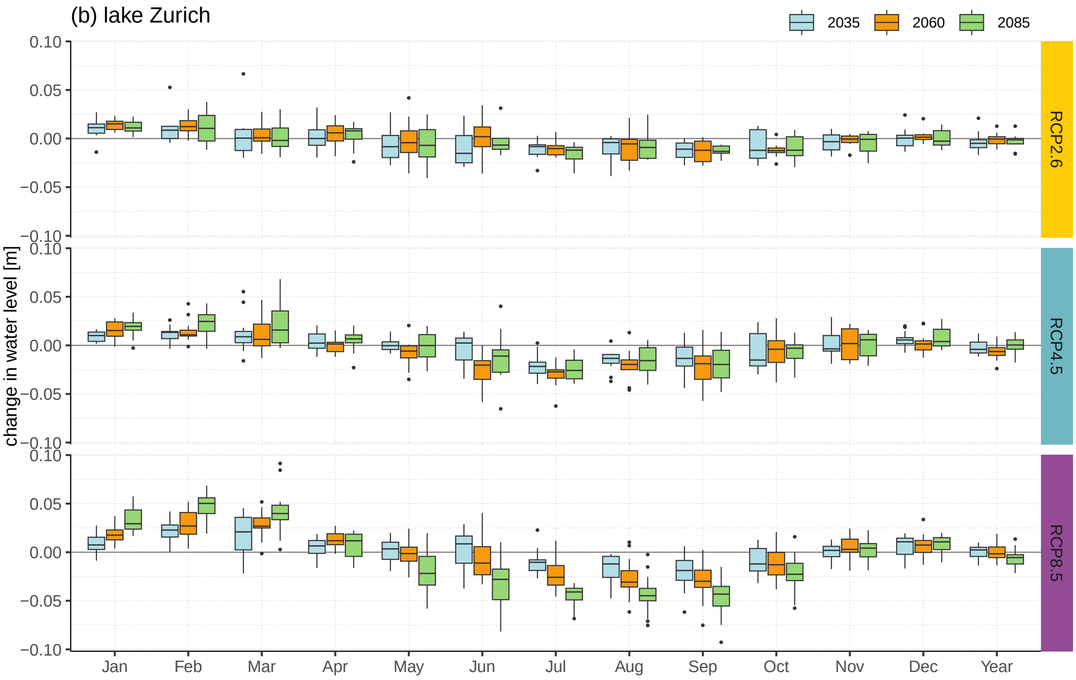


Figure SI 12: Simulated changes in monthly and annual mean lake levels of lake Zurich, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

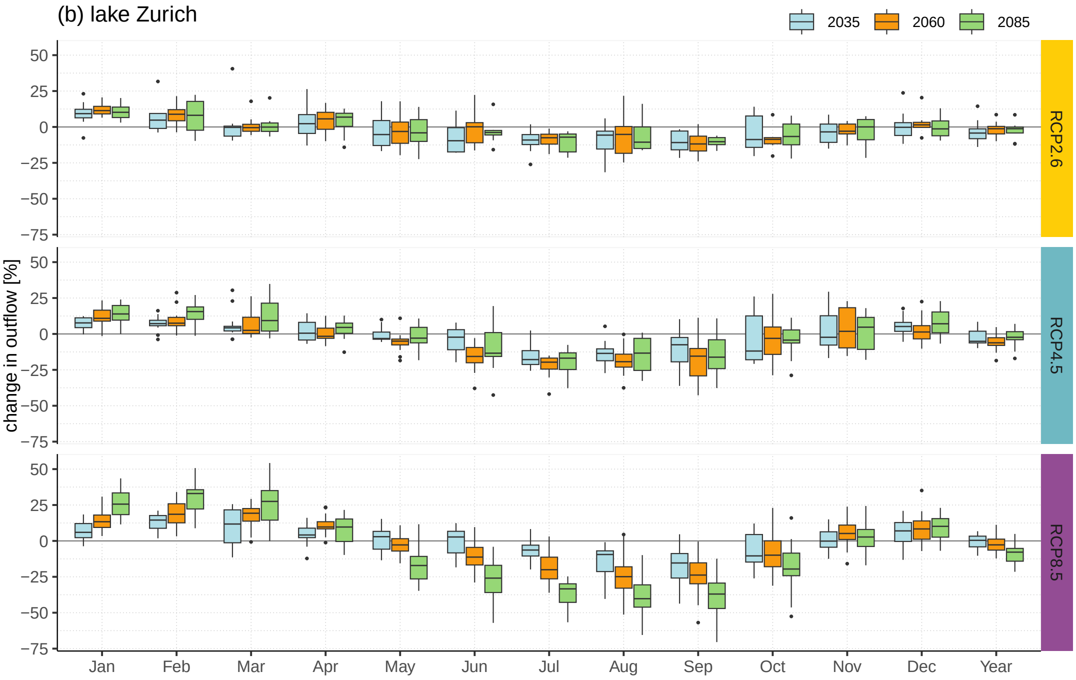


Figure SI 13: As Figure SI 12 but for the simulated changes in monthly and annual mean outflows of Lake Zurich.

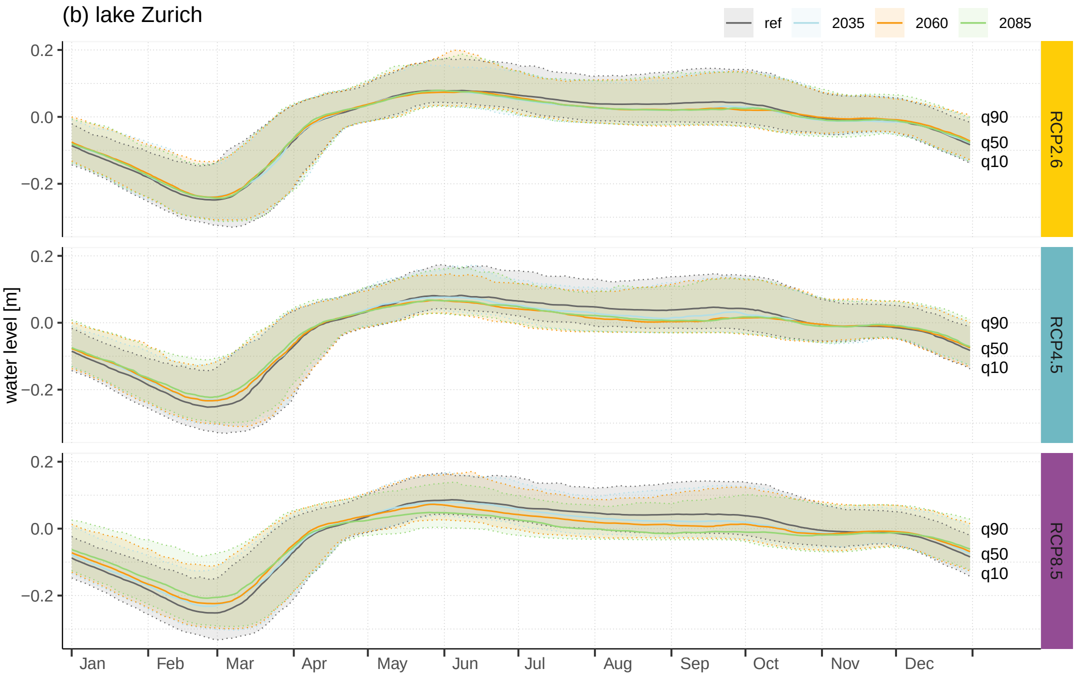


Figure SI 14: Simulated changes in the 10 % and 90 % percentiles of lake levels (moving average ±15 days) of Lake Zurich, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

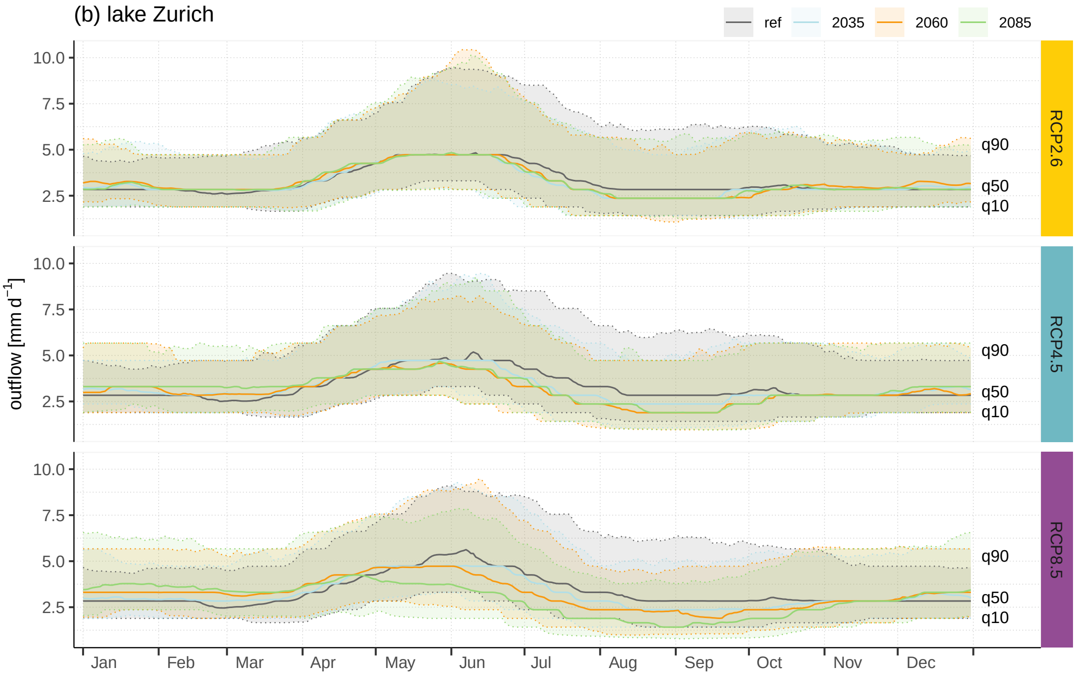


Figure SI 15: As Figure SI 14 but for the simulated changes in the 10 % and 90 % percentiles of outflows of Lake Zurich.

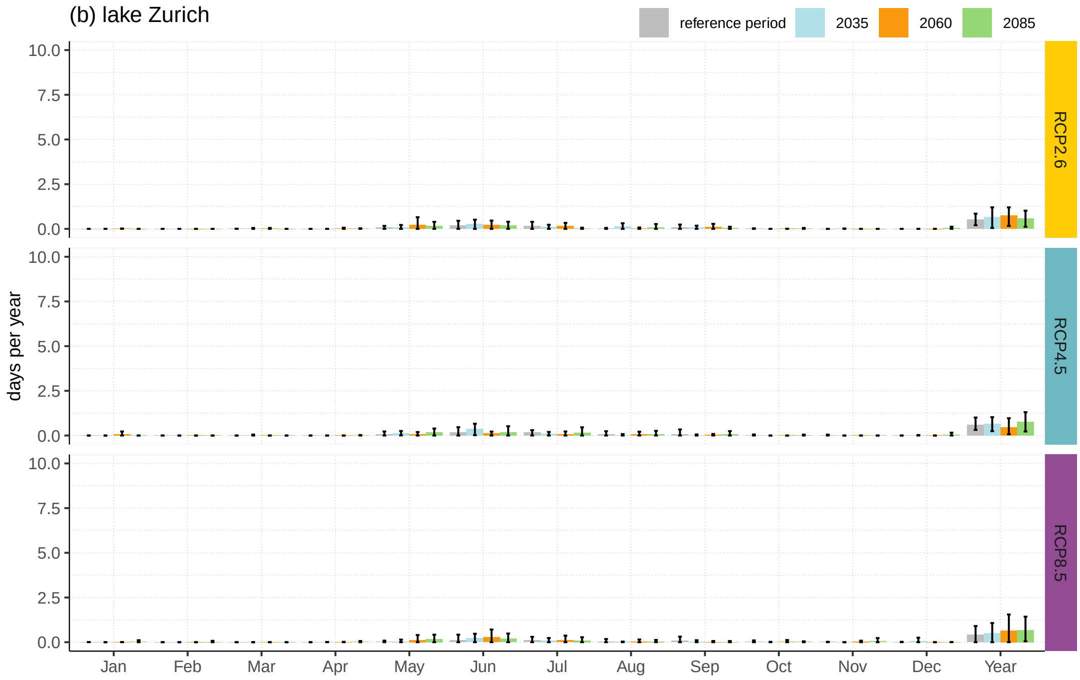


Figure SI 16: Simulated changes of the average number of days per year and month the lake level exceeds the flood limit ($F$) of Lake Zurich. Error bars refer to the 10 % and 90 % percentile range.

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 | * |

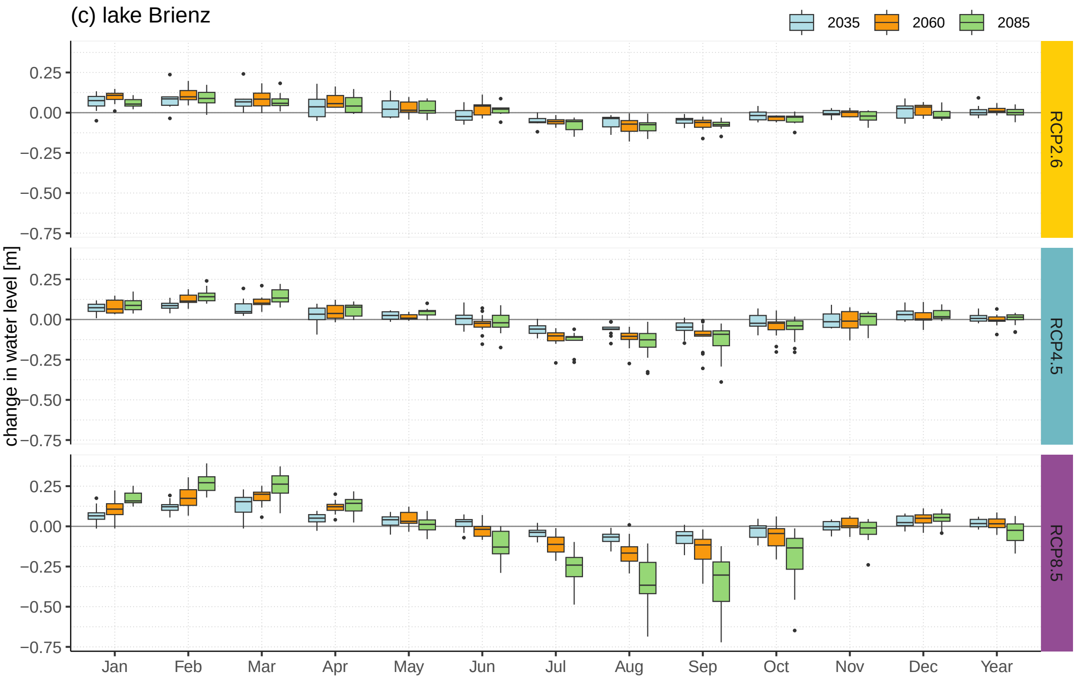


Figure SI 18: Simulated changes in monthly and annual mean lake levels of Lake Brienz, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

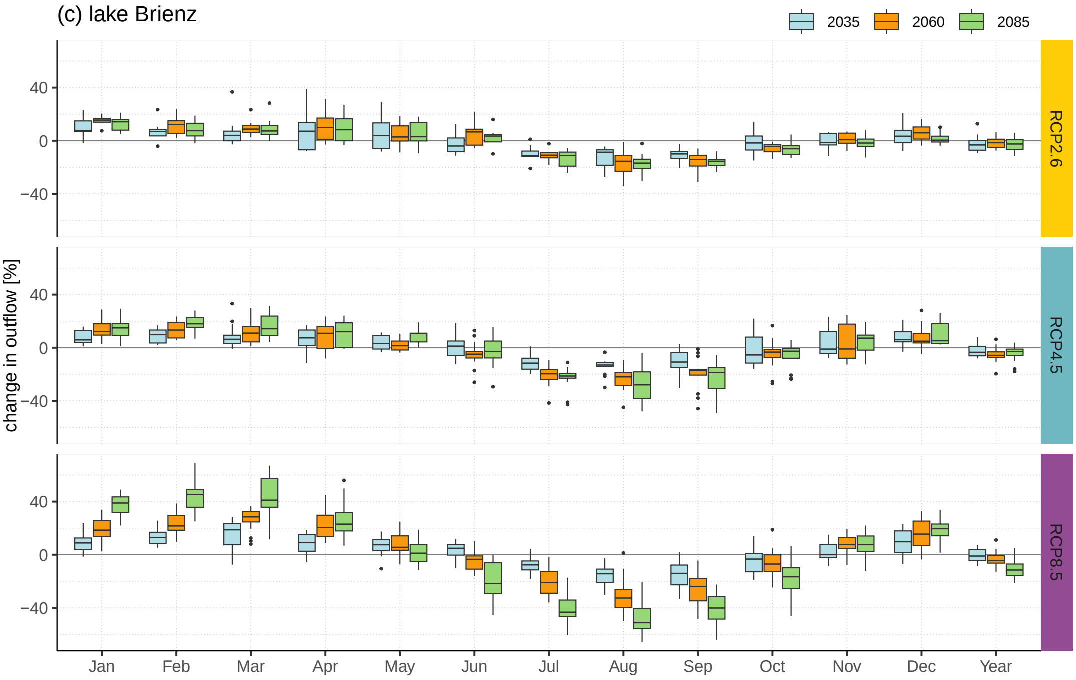


Figure SI 19: As Figure SI 18 but for the simulated changes in monthly and annual mean outflows of Lake Brienz.

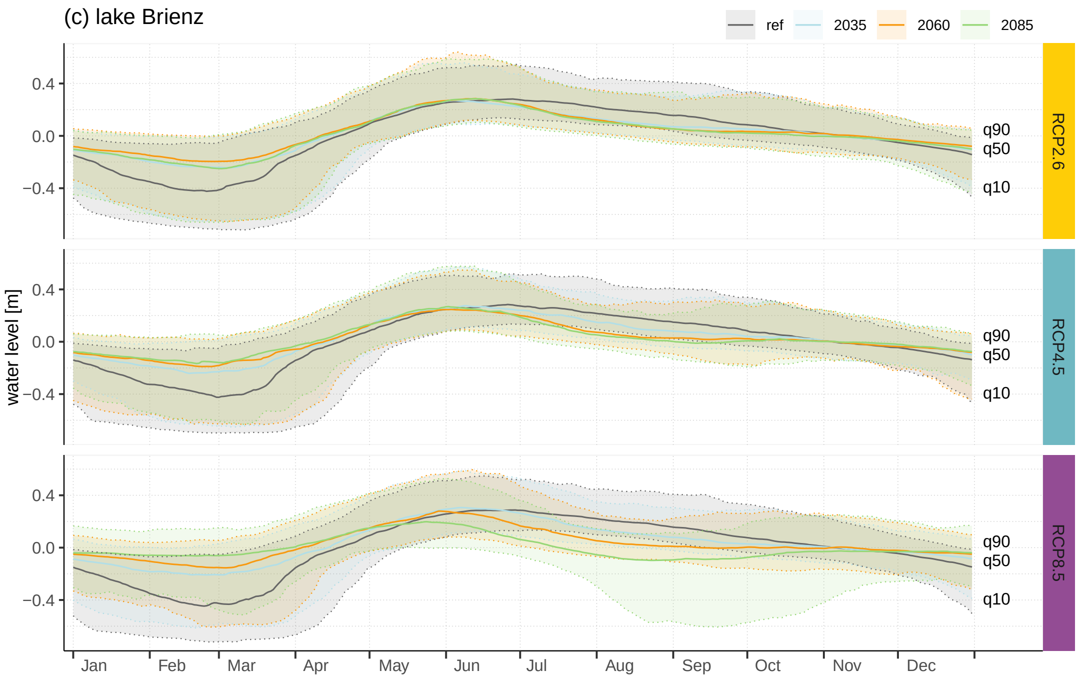


Figure SI 20: Simulated changes in the 10 % and 90 % percentiles of lake levels (moving average ±15 days) of Lake Brienz, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

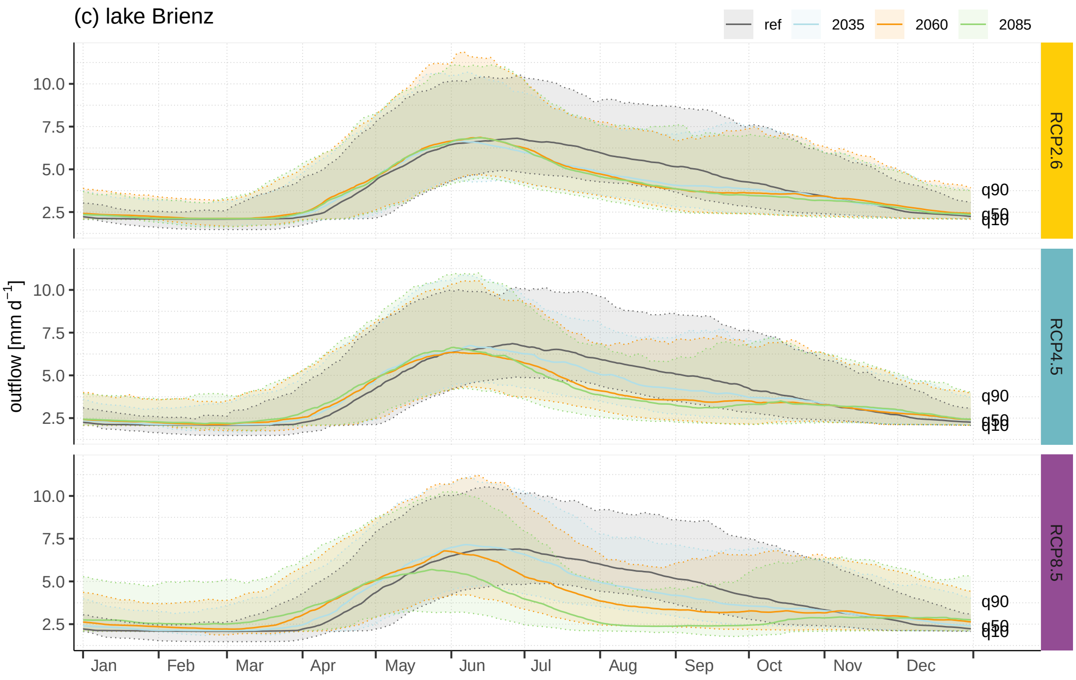


Figure SI 21: As Figure SI 20 but for the simulated changes in the 10 % and 90 % percentiles of outflows of Lake Brienz.

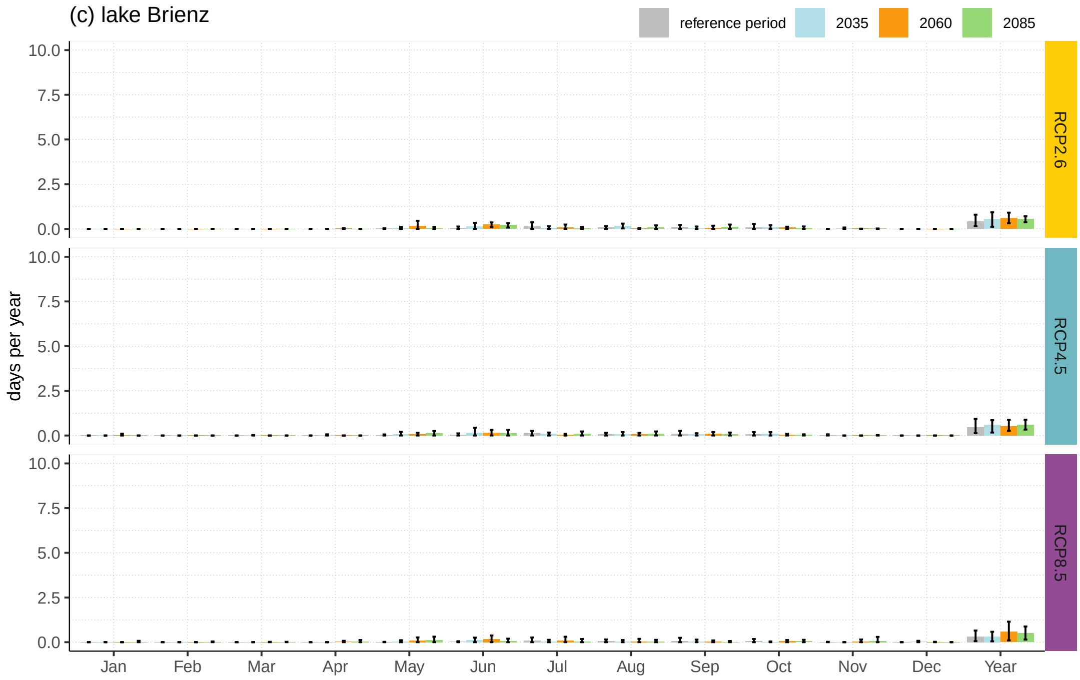


Figure SI 22: Simulated changes of the average number of days per year and month the lake level exceeds the flood limit ($F$) of Lake Brienz. Error bars refer to the 10 % and 90 % percentile range.

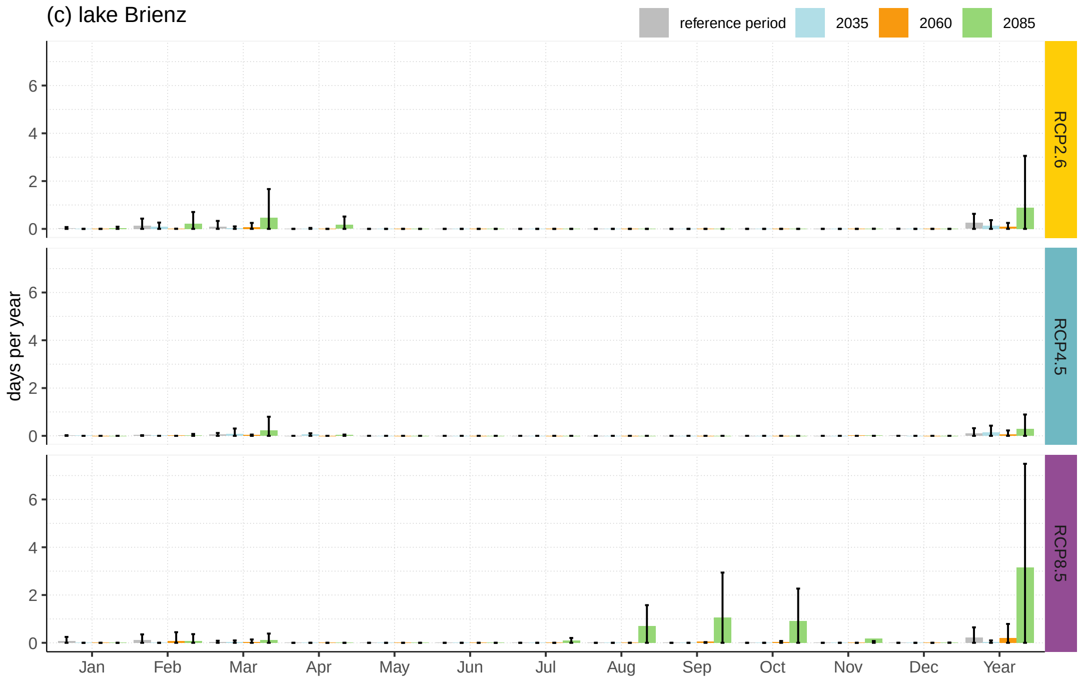


Figure SI 23: As Figure SI 22 but for the simulated changes the outflow undercuts the drought limit ($L$) of Lake Brienz.

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 | * |

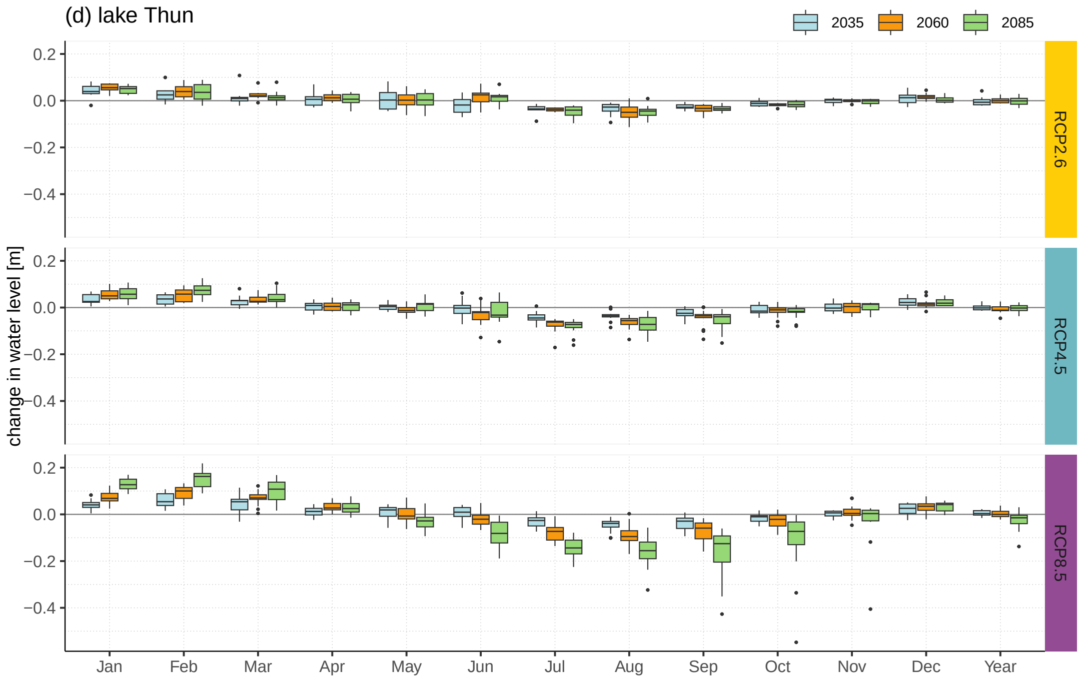


Figure SI 24: Simulated changes in monthly and annual mean lake levels of lake Thun, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

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

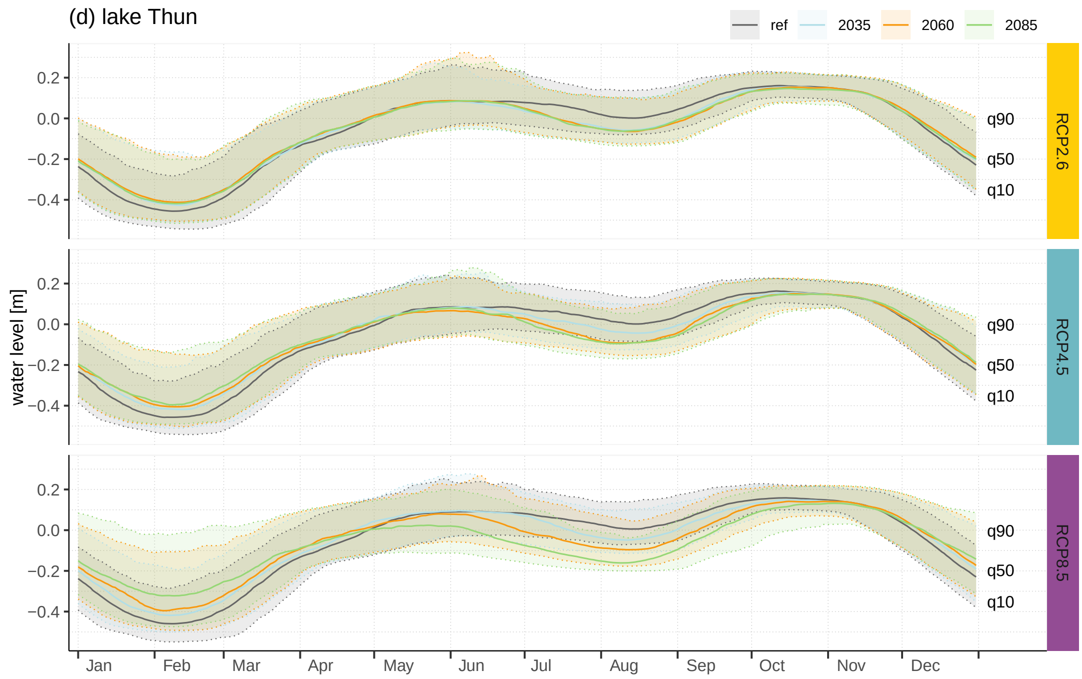


Figure SI 26: Simulated changes in the 10 % and 90 % percentiles of lake levels (moving average ±15 days) of Lake Thun, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

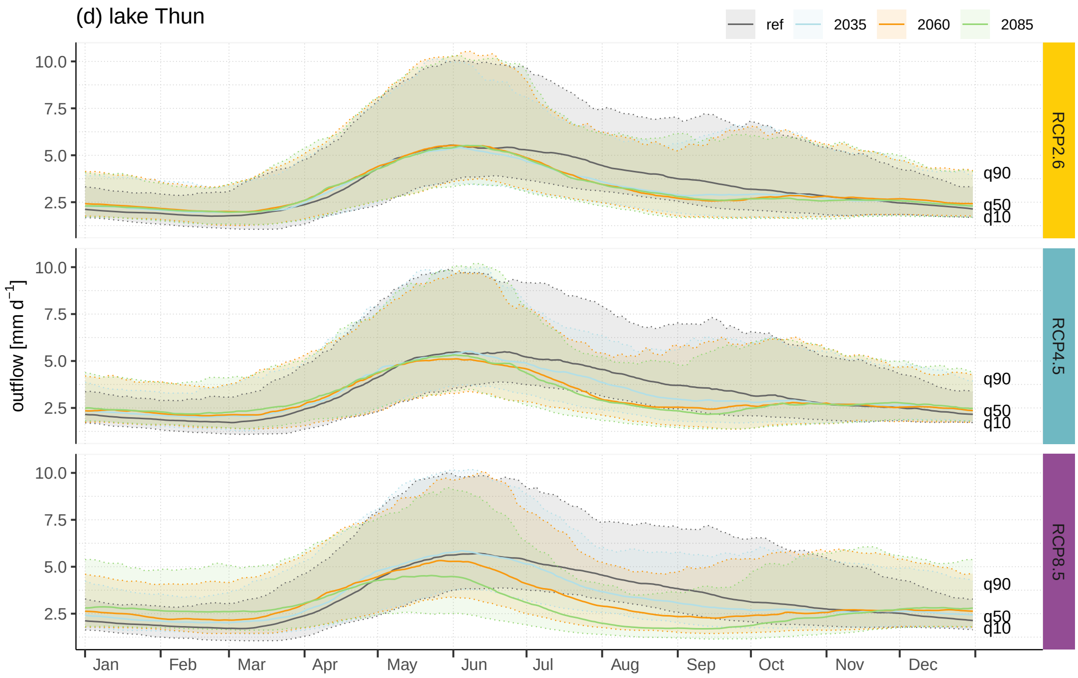


Figure SI 27: As Figure SI 26 but for the simulated changes in the 10 % and 90 % percentiles of outflows of lake Thun.

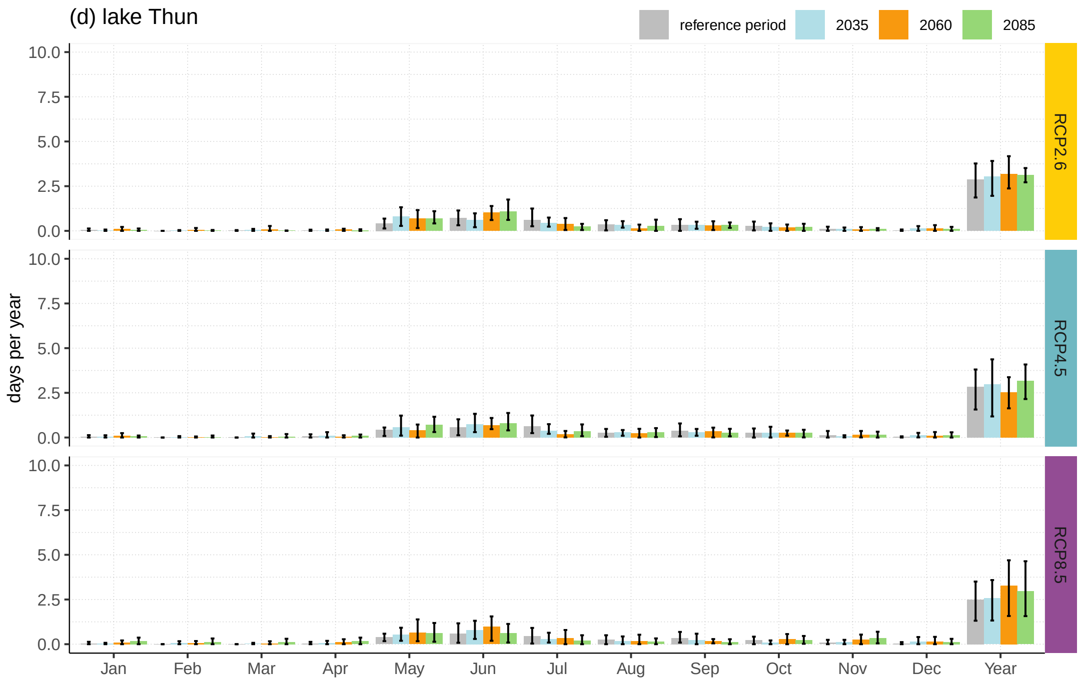


Figure SI 28: Simulated changes of the average number of days per year and month the lake level exceeds the flood limit ($F$) of Lake Thun. Error bars refer to the 10 % and 90 % percentile range.

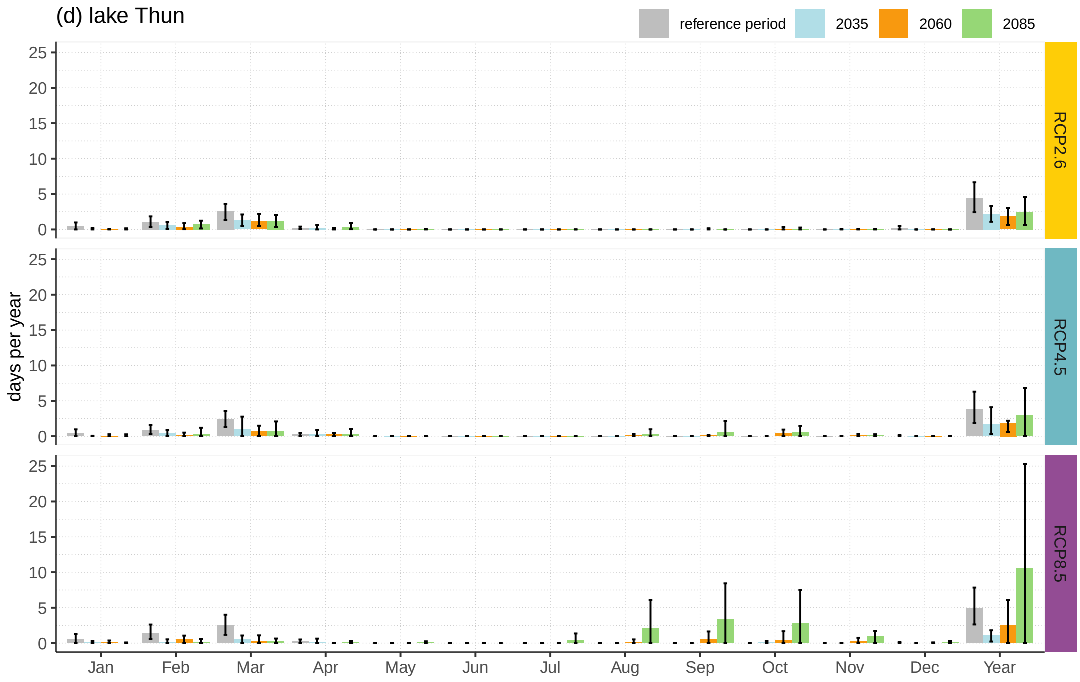


Figure SI 29: As Figure SI 28 but for the simulated changes the outflow undercuts the drought limit ($L$) of Lake Thun.

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 | * |

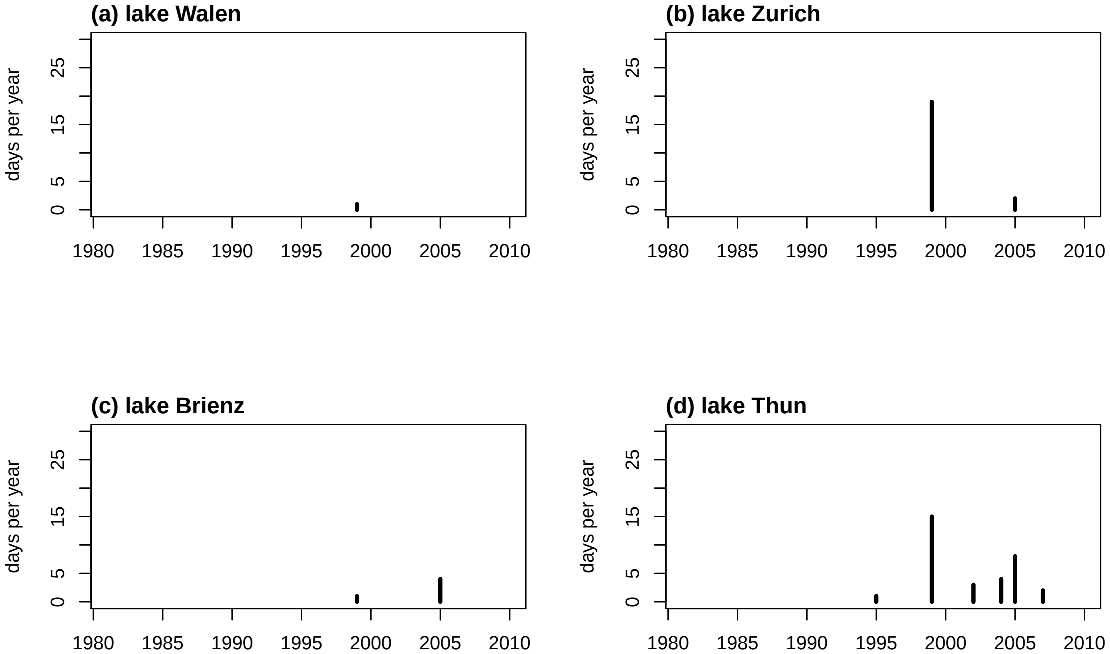


Figure SI 30: Observed days per year the lake levels exceed the flood limit ($F$) for Lake Walen (unregulated), lake Zurich (regulated), lake Brienz (semi-regulated) and Lake Thun (regulated).

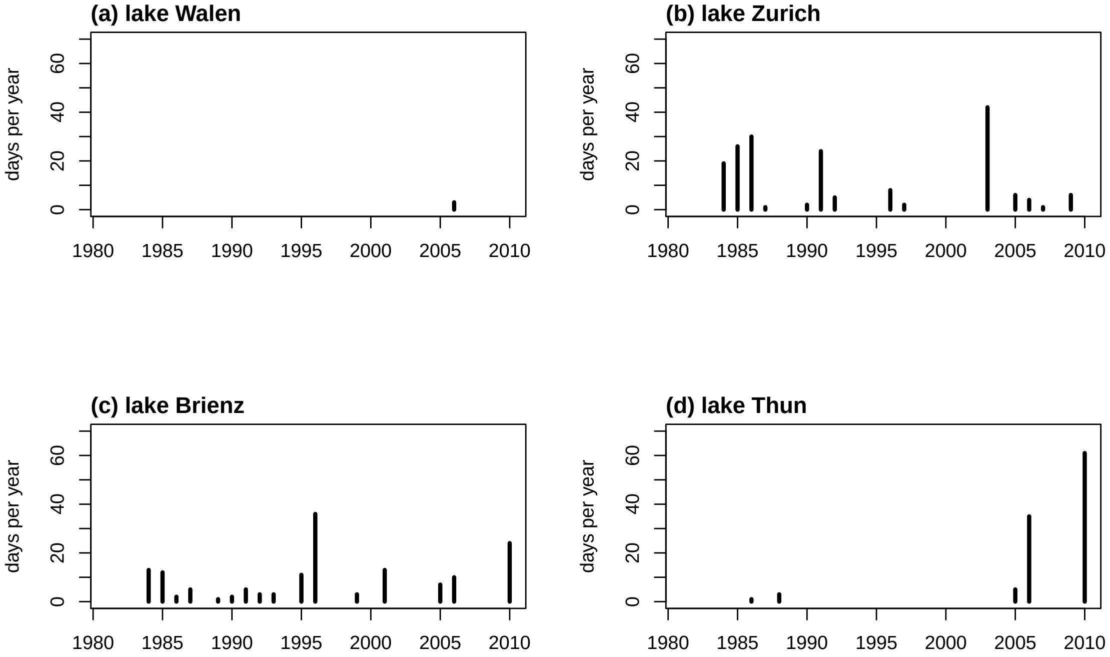


Figure SI 31: As Figure SI 30 but for the observed outflows undercutting the drought limit ($L$).